MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE

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PLANNING OF MANUFACTURING METAL-CUTTING PROCESSES. CALCULATIONS OF OPERATION DIMENSIONS

Manual to Term Projects

Kharkiv «KhAI» 2016

UDC 621.7.018:658.512 (075.8)

LBC 34.6я73

К64

Викладено організаційно-методичні основи проектування технологічних процесів механічної обробки. Описано алгоритм проектування технологічних процесів виготовлення деталей з термопокращуваних, цементованих і азотованих сталей. Наведено методики розрахунків операційних діаметральних розмірів і розмірів-координат між торцовими поверхнями. Подано приклад розроблення маршрутного технологічного процесу і розрахунків операційних розмірів.

Для студентів механічних спеціальностей при виконанні курсових і дипломних проектів.

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К64 Planning of Manufacturing Metal-Cutting Processes. Calculations of Operation Dimensions: Manual to Term Projects / M. K. Knyazyev, S. E. Markovych, B. S. Bilokon. – Kharkiv: M. Ye. Zhukovsky National Aerospace University “Kharkiv Aviation Institute”, 2016. – 144 p.

ISBN 978-966-662-453-9

Organisational and methodical fundamentals for planning of manufacturing metal-cutting processes are submitted. Algorithm for planning of manufacturing processes for production of parts from hardening and tempering, carbonised and nitrated steels is described. Methods for calculations of operation dimensions for round surfaces and dimensions-coordinates between flat surfaces are stated. Example of development of route manufacturing process and calculations of operation dimensions is submitted.

The manual is for students of mechanical specialties for performance of term and diploma projects.

UDC 621.7.018:658.512 (075.8)

LBC 34.6я73

Figures 30. Tables 6. Bibliogr.: 18 references

ISBN 978-966-662-453-9

INTRODUCTION

Main task of manufacturing technology is obligatory performance of all requirements of a drawing under conditions of the minimum labour and material expenses and the maximum productivity. The task is extremely actual for the aerospace branch producing items, which operate at complex conditions of forces and thermal loads. Special requirements to aerospace manufacturing technologies are explained by application of expensive high-strength hard-to-process materials in the designs of aerospace items. Combination of the needed high accuracy, reliability and unique properties of materials results in high production costs of the products. The listed requirements make a production engineer to develop and realize manufacturing processes with especial care.

This book is based on the works [1–4] and includes four chapters and appendices. The first three chapters are devoted to the theory of development of metal-cutting manufacturing processes. The chapter 4 is an example for planning of route manufacturing process for the part "shaft-gear". The chapter also contains explanations that make the book more understandable for people, who have no experience in planning of manufacturing processes. The appendices are aimed to make easier the search of the reference information.

The paragraphs devoted to determination of machining allowances and calculations of operation dimensions in planning of manufacturing processes are of great importance. Unfounded increased allowances result in over-expenditure of material and introduction of additional manufacturing steps (operations), increased expenditures of cutting tools and electric energy, raised labor expenditures and finally result in too high production cost of a product. On the other hand, understated values of allowances do not ensure removal of surface defective layer of a blank material, providing the required accuracy and increase probability of rejects (bad quality parts). Unfounded increased tolerances for initial blank dimensions make difficult machining in the machines set for operation dimensions, reduce machining accuracy. Understated values of tolerances significantly increase production cost of items.

According to the standard GOST 14.301-83 "Unified system of technological documentation. General rules for planning of manufacturing processes" the following stages in development of manufacturing process should be performed: selection of type of initial blank and method for its manufacture, selection of manufacturing datums, calculations of necessary number of manufacturing steps (operations) for machining of separate surfaces by accuracy and roughness, development of routes for machining of separate surfaces, development of sequence of manufacturing operations, development of sequences of steps in manufacturing operations, preliminary selection of technological tooling (equipment and workholding devices). This approach allows determining values of machining allowances taking into account the peculiarities of a considered manufacturing process.

Recommendations given in this book are valid mainly for small and middle batch production conditions. The peculiarities of development and realization of manufacturing processes under conditions of large-batch and mass-scale production are not analysed in the book.

1. ORGANISATION OF MACHINE-BUILDING MANUFACTURE

1.1. Main terms, concepts, definitions

Object of machine-building manufacture is an item.

Item is a product of a final stage of manufacture. It is any good or set of manufactured goods made at an enterprise. For engine-building factory it is an engine, for aggregate plant – a regulator pump mounted on engine, for piston factory – a piston.

GOST 2.101-68 states the following *types of items*: parts, assembly units, complexes, sets.

Part is a non-specified item produced at a considered enterprise without assembling operations.

Assembly unit (***unit***) is a specified item, constituent parts of which are joined with each other by assembling operations (screwing, riveting, welding, soldering, etc.) at an enterprise-manufacturer.

Complex is two or more specified items, each of which performs *main functions* assigned to whole complex (automated workshop, automobile, etc.).

Set (***kit***) is two or more specified items having common exploitation purpose of *auxiliary character* (spare parts kit, set of tools, etc.).

Terms having direct relation to the production object according to the GOST 3.1109-82 are the following.

Semi-finished product (***semi-product***) is an item of enterprise-supplier subjected to additional processing or assembling.

Workpiece (blank) is a manufacture good, from which a part or non-detachable assembly unit is produced by changing a shape, dimensions, roughness of surfaces and material properties.

Initial blank is a workpiece (a forged blank, a casting, etc.) before the first machining operation of a manufacturing process.

Typical item is an item belonging to items similar by design and having the biggest quantity of design and technological features of a considered group.

Production type is a general organization and technical characteristic of production and determined by specialisation level of work places, nomenclature of manufacture objects, form of workpieces transportation along work places. Specialisation level of work places is characterised by *index of operations fixation* $\boldsymbol{K_{of}}$, which means quantity of different operations performed at one work place during calendar period (month). According to the GOST 3.1108-74 its value is stated as: $20 < K_{of} < 40$ for small-batch production, $10 < K_{of} < 20$ for middle-batch production.

Batch production is characterised by manufacture of limited nomenclature of items in batches (series, lots) repeated in predetermined periods and by wide specialisation of work places. Batch production is divided to *large*-, *middle*- and *small batch* depend on prevailing group of work places.

Small batch production is characterised by manufacture of essentially wide nomenclature of items.

Production process (GOST 3.1109-82) is a collection of all actions of people and production means necessary at this enterprise for manufacture or repair of produced items.

Manufacturing process is a segment of production process containing only those actions, which are connected with changes and sequent determination of a manufactured good (object) condition. When realising a manufacturing process the sequent changes of shape, dimensions, material properties of workpiece or semi-product occur with a goal of item manufacture.

Manufacturing equipment (primary equipment) is implements of production, in which materials or blanks, means of actions and energy sources (casting machines, presses, metal-cutting machines, furnaces, testing stands, etc.) are placed in order to perform definite portion of manufacturing process.

Manufacturing tooling are implements of production applied together with manufacturing equipment and attached to it in order to perform definite portion of manufacturing process (dies, workholding devices, cutting and measuring tools, gauges, etc.).

Workholding device is an additional to primary manufacturing equipment designed device for placing (locating) of workpiece in work zone of machine in a selected coordinate system and its clamping to prevent its displacement under the action of applied manufacturing forces.

Several *main principles of rational organisation of production processes* at middle- and small production conditions are given below.

Specialisation is one of forms of labour differentiation, which means that an enterprise as a whole and its separate departments should make products of limited nomenclature.

Rhythm means that all manufacturing processes and production process as a whole are repeated in strictly specified periods.

Forms of organisation of manufacturing processes are *group* and *flow-line*. Their selection depend on the determined sequence for performance of operations, location of manufacturing equipment, quantity of items and direction of their motion during their manufacture.

Group form is used when items have similar design and manufacture characteristics and there is unity of manufacturing tooling for one or several manufacturing operations and specialisation of work places.

1.2. Dimensions

The following definitions are stated by the Unified System of Tolerances and Fits (USTF) [5, 6] and by other sources.

Dimension is a numerical value of linear feature (diameter, length, etc.) expressed in the selected measurement units.

Limit dimensions are two extreme permissible dimensions – maximum limit dimension and minimum limit dimension, between which an actual dimension should be located or it may be equal to one of limit dimensions. Maximum limit dimension is an algebraic sum of nominal dimension and upper limit deviation. Minimum limit dimension is an algebraic sum of nominal dimension and lower limit deviation.

Nominal dimension (d_{nom}, D_{nom}, l_{nom}, L_{nom}) is a dimension, relative to which the limit dimensions are specified. Nominal dimension also determines position of *zero line* for deviations. Often symbols without subscript "***nom***" (***d***, ***D***, ***l***, ***L***) are used in order to simplify the symbolic forms of dimensions with upper and lower deviations.

Actual dimension is a dimension revealed by measurement with acceptable error.

In machine-building the dimensions of features (elements) of final parts and workpieces are divided in **design dimensions** and **manufacture dimensions** by form of writing.

There are three groups of **design elements** of parts [7]: *shafts*, *holes* and *elements not relating to shafts and holes*.

Design dimensions of the first group (*shafts*) include dimensions of external (male) surfaces. Design dimensions of the second group (*holes*) include dimensions of internal (female) surfaces. Design dimensions of the third group (*neither shafts nor holes*) include dimensions coordinating positions of various elements (features) relative to other features: steps and flat spots (position of one flat surface relative to another flat surface); holes depths; slots depths; bosses heights; dimensions coordinating starts or/and finishes of threaded, conical, curvilinear surfaces; positions of axes and planes of symmetry for holes, slots, ribs, etc.; dimensions of rounding radii, fillets, chamfers, etc. Feature is any point, line or surface.

Basic distinction in understanding and forms of writing of ***design and manufacture dimensions*** is originated, by the author's opinion, from different meanings of terms "***element of part***" and "***element of workpiece***".

Thus, according to the USTF, dimension of shaft is a *dimension of any external element* of part including non-cylindrical elements. In such ***design understanding*** of term "**shaft**" an external element may be created by ***one*** or ***several surfaces***, for example, dimension of external element – cylindrical surface ***d*** (Fig. 1.1-i). Here the design element is created by segment of one surface having diametrical dimension. In another case – dimension ***l*** (Fig. 1.1-ii) – the design element is created by three features: two flat surfaces (faces) and segment of cylindrical surface, located between two faces. Dimensions ***d*** and ***l*** are related to the bodies of rotation. In prismatic bodies shaft-type elements are ribs, beads, etc. with width dimension ***b*** (Fig. 1.1-iii). In this case the design element is created by two faces and one flat surface located between the faces.

This approach is quite reasonable since a designer does not take into account *processing* of surfaces, but only geometric parameters of separate surfaces and a whole item in the considered aspect of analysis.

In manufacturing engineering related to *metal-cutting* (*machining*) *processes* the term "***element of workpiece***" includes, by the authors' opinion, only one feature (surface, line or point), but not their combination. In manufacturing metal-cutting processes most often machining of several surfaces (features) is considered and performed separately and in a definite sequence. Therefore design element "shaft" created by only one surface is accepted in manufacturing engineering as "shaft" too. For example, manufacture dimension $\boldsymbol{d_h}$ (Fig. 1.1-xii) corresponds to design dimension of shaft ***d*** (Fig. 1.1-i). Here the difference is that design dimension ***d*** can be specified with any basic deviation (a, b, c, … , zb, zc – 28 letter symbols), and manufacture dimension $\boldsymbol{d_h}$ – only as a *basic shaft* with basic deviation **h**.

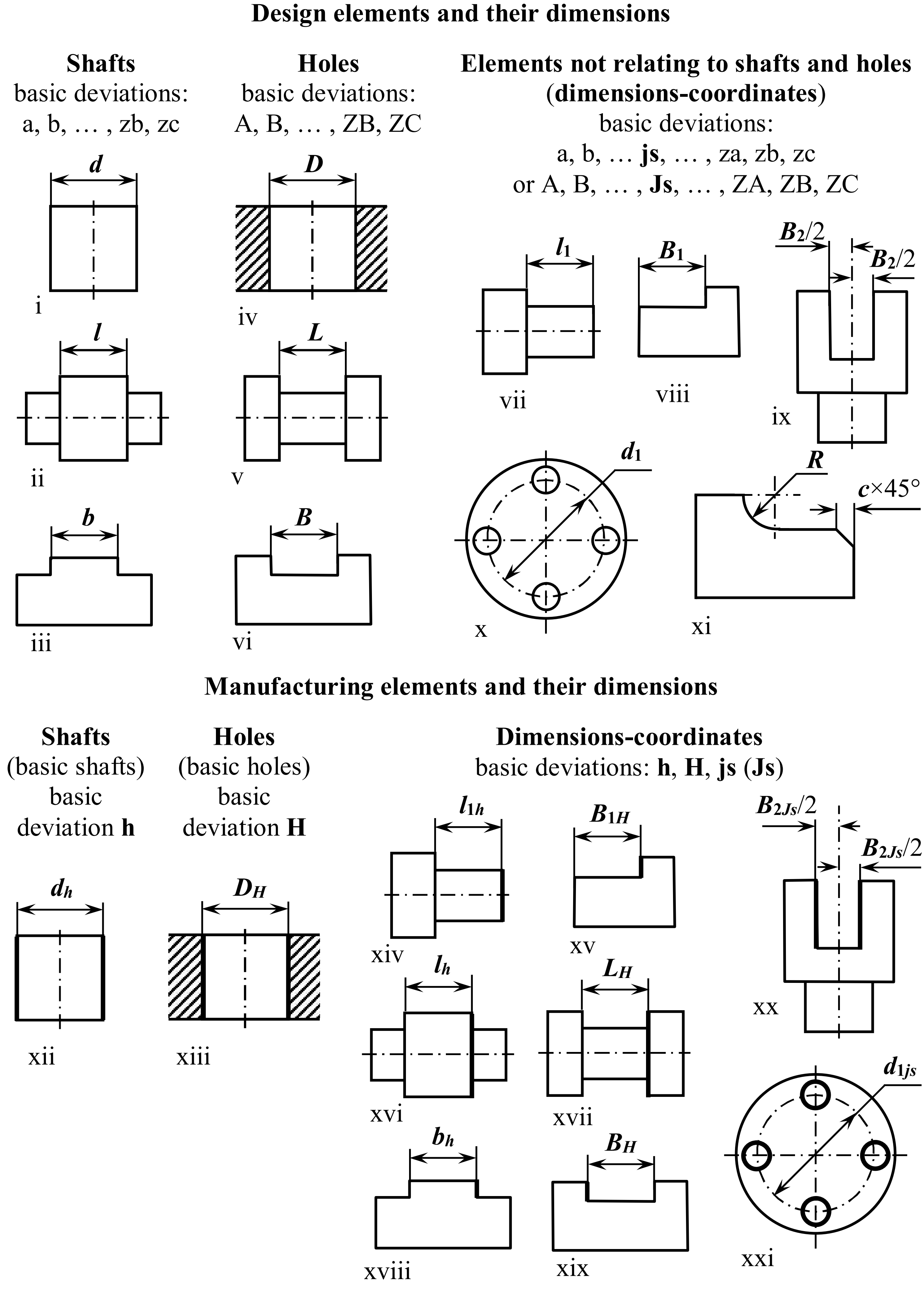


Fig. 1.1. Design and manufacturing elements and their dimensions

However manufacturing engineering does not consider "**shaft**" *created by several surfaces* as one "element of workpiece", but as a combination of surfaces – workpiece features. At that a production engineer should analyse what surface is machined and relative to what surface the machined surface is coordinated in the considered operation. For example, in the sketch of manufacturing operation the manufacturing dimension of shaft l_h (ref. Fig. 1.1-xvi), which corresponds to the design dimension l of "bead" (ref. Fig. 1.1-ii), determines a coordinate of right-hand machined face (shown by thick line) of workpiece relative to the left-hand face. Therefore this manufacturing dimension l_h is a ***dimension-coordinate*** by its functional purpose and it is written in the form of *dimension of basic shaft (dimension-shaft)* in order to the tolerance for this dimension is located in a body of workpiece. Similar considerations are applicable to rectangular shapes with manufacturing dimension b_h (ref. Fig. 1.1-xvi) in comparision with design element "rib" with dimension b (ref. Fig. 1.1-iii).

It is very important to understand that the considered machined surface can be coordinated from any other face, which not included into design element, but convenient and reasonable for mounting in manufacturing operation. In this case manufacture dimension will not coincide with design dimension (Fig. 1.2), and design dimension will be ensured as a result of chain of manufacture dimensions: $[l] = f_h - E_H$. Hence, a production engineer analyses the machining of surfaces included into design element as separate independent sufaces, but with obligatory final performance of design dimension.

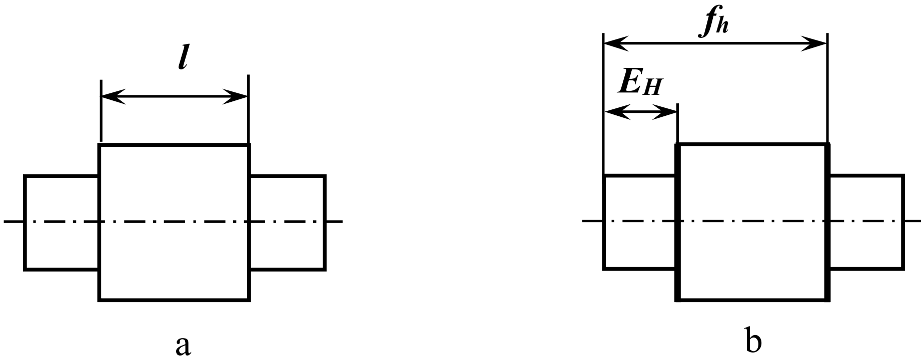


Fig. 1.2. Specifying design and manufacture dimensions in a drawing (a) and operation sketch (b)

Analoguous analysis can be applied also to dimensions of holes and other similar elements of an item.

According to the USTF dimension of hole is a *dimension of any internal element* of part including non-cylindrical elements. In such ***design understanding*** of term "**hole**" an internal element may be created by ***one*** or ***several surfaces***, for example, dimension of internal element – cylindrical surface D (ref. Fig. 1.1-iv). Here the design element is created by segment of one surface having diametrical dimension. In another case – dimension L (ref. Fig. 1.1-v) – the design element "groove" is created by three features: two flat surfaces (faces) and segment of cylindrical surface, located between two faces. In the case of dimension B (ref. Fig. 1.1-vi) the design element "slot" is created by two faces and segement of flat surface located between the faces.

In manufacturing engineering the design element "**hole**" created by only one surface also corresponds to the manufacturing element "hole". Thus manufacturing dimension D_H (Fig. 1.1-xiii) corresponds to design dimension of hole D (Fig. 1.1-iv) with the only difference that design dimension D can be specified with any basic deviation (A, B, C, … , ZB, ZC – 28 letter symbols), and manufacture dimension D_H – only as a *basic hole* with basic deviation **H**.

However manufacturing engineering in respect of design "holes", which are created by several surfaces, should take into account what of the surfaces is machined and relative to what surface the position of machined surface is coordinated. For example, the manufacturing dimension L_H (Fig. 1.1-xvii), which corresponds to design dimension of "hole" (width of groove) L (Fig. 1.1-v), determines a coordinate of right-hand machined face (shown by thick line) of groove relative to the left-hand face. Therefore manufacturing dimension is a ***dimension-coordinate*** by its functional purpose and it is written in the form of *dimension of basic hole (dimension-hole)* in order to the tolerance for this dimension is located in a body of workpiece. Similar considerations are applicable to rectangular shapes with manufacturing dimension B_h (Fig. 1.1-xix) in comparision with design element with slot ("hole") dimension B (Fig. 1.1-vi).

Design elements of the third group (elements not relating to "shafts" and "holes") are: steps, elements of inclined surfaces, rounding radii, chamfers, elements with axes of symmetry, elements with holes axes, etc.

Among design dimensions of the third group there are dimensions, which determine *coordinates of faces*. As a rule, such design elements are created by combination of surfaces. For example, elements of items, which are specified by design dimesions of steps l_1 (Fig. 1.1-vii) and B_1 (Fig. 1.1-viii), are created by two faces and other surfaces located between these faces.

By their essence the design dimensions of the third group are *dimensions-coordinates*, because they determine positions (coordinates) of one features relative to others: one surface relative to another (Fig. 1.1-vii and Fig. 1.1-viii), one or several surfaces relative to axis (Fig. 1.1-xi and Fig. 1.1-ix), several axes relative to another one (Fig. 1.1-x), point of beginning or finish of inclined surface relative to another surface, line or point (Fig. 1.1-xi, dimension c×45°), etc.

Manufacturing dimensions of the third group are ***dimensions-coordinates*** by their essence. In manufacturing metal-cutting engineering the design elements with *coordinates of faces* (ref. Fig. 1.1-vii and Fig. 1.1-viii) are analysed from the point of view of sequence of surfaces machining and, hence, what surface is machined in the considered operation (manufacturing step) and relative to what surface the position of machined surface is determined by coordinate. Based on this analysis, the manufacturing dimension is written in the form of *basic hole* or *basic shaft*. For example, in the Fig. 1.1-xiv the sequence of manufacturing steps provides first machining of left-hand face of workpiece and then maching of right-hand face initiating from left-hand face with performance of *dimension-shaft* l_{1h} that corresponds to design *dimension-coordinate* l_1 (Fig. 1.1-vii).

Similar considerations are related to the manufacture *dimension-hole* B_{1H}

(Fig. 1.1-xv). By its functional purpose it is a *dimension-coordinate* and written in the form of *dimension of basic hole (dimension-hole)* in order to the tolerance for this dimension is located in the body of workpiece. It corresponds to design dimension-coordinate $\boldsymbol{B_1}$ (Fig. 1.1-viii).

Very important here to understand that typical design elements "shafts" (ref. Fig. 1.1-ii and Fig. 1.1-iii) and "holes" (ref. Fig. 1.1-v and Fig. 1.1-vi) created by several surfaces are considered in manufacturing engineering as two flat surfaces connected with a *dimension-coordinate* (ref. Fig. 1.1-xvi, Fig. 1.1-xvii and Fig. 1.1-xviii, Fig. 1.1-xix, respectively), because these two faces are usually machined *separately* and their coordinates can be initiated from the third surfaces (ref. Fig. 1.2-b) in manufacturing operations. Therefore, the design elements shown in Fig. 1.1-ii, Fig. 1.1-iii, Fig. 1.1-v and Fig. 1.1-vi are similar to design elements shown in Fig. 1.1-vii and Fig. 1.1-viii for a production engineer by their coordinate-type dimensions.

Thus, ***selection of initial datum for manufacturing dimensions-coordinates determines the form of writing of operation dimensions of this type: dimension-shaft (basic shaft)*** (ref. Fig. 1.2-b, dimension f_h) ***or dimension-hole (basic hole)*** (ref. Fig. 1.2-b, dimension E_H).

Dimensions of such *design elements of the third group* as dimensions, which specify ***coordinates of positions of axes and symmetry planes***, production engineers transform, if necessary, into dimensions with symmetric limit deviations (basic deviation js, limit deviations ±ITn/2) in order to the tolerance for dimension is in the body of workpiece and is uniformly distributed along the directions of possible deviations of an actual dimension, for example, operation dimension d_{1js} (Fig. 1.1-xxi) in comparison with design dimension d_1 (Fig. 1.1-x) with any basic deviation specified by designer.

Dimensions of such *design elements of the third group* as ***dimensions of rounding radii, fillets, chamfers*** are performed in a manufacturing process by formed cutting tools in universal machines or by standard tools in machines with computer numerical control (CNC machines). Thus, positive and negative deviations from theoretical profile are equiprobable. Therefore such manufacturing operation dimensions are specified, as a rule, with symmetric limit deviations.

1.2.1. Design dimensions

Design dimension specified in the drawing consists of nominal dimension A_{nom} and two limit deviations – upper Δs_A and lower Δi_A. Nominal dimension and upper limit deviation determine maximum limit dimension: $A_{max} = A_{nom} + \Delta s_A$. Nominal dimension and lower limit deviation determine minimum limit dimension: $A_{max} = A_{nom} + \Delta i_A$.

Nominal dimension A_{nom} is determined from functional destination of a part by conducting computations (of accuracy, strength, rigidity, etc.) taking into account other factors of design and manufacture aspects. Computed value of nominal dimension is rounded off to the value from preferred numbers of linear series (R5, R'5, R10, R'10, R"10, etc.) [6]. Nominal dimension determines position of *zero line for limit deviations*.

Upper and lower limit deviations are specified in explicit (numerial) form according to the selected standard level of accuracy, for example, shaft dimension $Ø40^{+0.033}_{+0.017}$.

Limit deviations are also specified in the form of basic deviation (letter) and accuracy grade (number), for example, shaft dimension Ø40n6. The combined form of design dimension is permitted Ø40n6$\binom{+0.033}{+0.017}$.

Deviation is an algebraic difference between dimension (limit dimension, actual dimension) and nominal dimension. ***Deviation is always specified with a sign "+" or "–"***.

Limit deviation is an algebraic difference between limit dimension and nominal dimension. There are upper limit deviation (***es***, ***ES***, ***Δs***) and lower limit deviation (***ei***, ***EI***, ***Δi***). Capital letters ***ES*** and ***EI*** are used in formulas for designation respectively of upper and lower limit deviations of *hole dimensions*, small leters ***es*** and ***ei*** – for *shaft dimensions*, and symbols ***Δs*** and ***Δi*** are used for those elements, which *not relating to shafts and holes*. *Limit deviations determine maximum and minimum limit dimensions*.

Basic deviation is one of two limit deviations (the upper or the lower), which is the nearest to zero line. Basic deviation is used for specifying the position of *tolerance band* relative to zero line. According to the standards [5, 6] small letters (a, b, c, … z, za, zb, zc – 28 in total) are used for designation of basic deviations in shafts dimensions, and capital letters (A, B, C, … Z, ZA, ZB, ZC – 28 in total) – for basic deviations in holes dimensions.

Tolerance band is a range limited by upper and lower limit deviations. It determines tolerance numerical value and its position relative to nominal dimension (zero line) in graphic presentation. Term "tolerance band" has a wider meaning than term "tolerance". Term "tolerance" means only numerical value of tolerance without definit correlation with nominal dimension. Term "tolerance band" includes numerical value and also determines position of upper and lower limit deviations relative to zero line (nominal dimension), and, thereby, limit dimensions (maximum and minimum).

In written presentation the tolerance band is specified by letters (basic deviation) and digits (accuracy grade), for example, tolerance band of shaft dimension f8 and tolerance band of hole dimension F8, where f is basic deviation of shaft dimension, F is basic deviation of hole dimension, 8 is accuracy grade. In combination with nominal dimension the tolerance band allows to find one of limit deviations (es_f for f shaft, EI_F for F hole) and tolerance numerical value (T = IT8), and then – the second limit deviation ($ei_f = es_f - T$, $ES_F = EI_F + T$), and, thereby, maximum and minimum limit dimensions. The *preferred tolerance bands* are submitted in the standards [5] that allow finding numerical values of both limit deviations directly from the tables.

Tolerance (***T***) is a difference between maximum and minimum limit dimensions ($T = A_{max} - A_{min}$) or *algebraic* difference between upper and lower limit deviations ($T = \Delta s - \Delta i$), that *is, tolerance is always positive value*. The tolerance itself specified without one of limit deviations does not allow calculations of maximum and minimum limit dimensions.

Shaft is a term conventionally used in the USTF for designation of external (male) elements of a part including non-cylindrical elements (ref. Fig. 1.1).

Dimension of shaft is a dimension of external element of part, tolerance band (limit deviations ***es***, ***ei***) of which can be over or below zero line of deviations, which position being determined by nominal dimension (***d***, ***l***), for example, $d_{ei_d}^{es_d}$, $l_{ei_l}^{es_l}$ (Fig. 1.3-a), $\varnothing 40^{+0.033}_{+0.017} = \varnothing 40n6$, $96^{-0.036}_{-0.090} = 96f8$, $50^{+0.027}_{+0.002} = 50k7$.

Basic shaft is a shaft with dimension, tolerance band of which is below zero line and upper limit deviation being equal to zero ($es = 0$). Lower limit deviation equals tolerance value with minus ($ei = -T$). The basic deviation **h** is used when specifying the basic shaft dimension with tolerance band. Nominal dimension of basic shaft equals maximum limit dimension ($d_{nom} = d_{max}$) due to $es = 0$ and so dimension of basic shaft is specified in the form $d = d_{max}{}^{0}_{-T}$, for example, $\varnothing 42h6 = \varnothing 42_{-0.016}$.

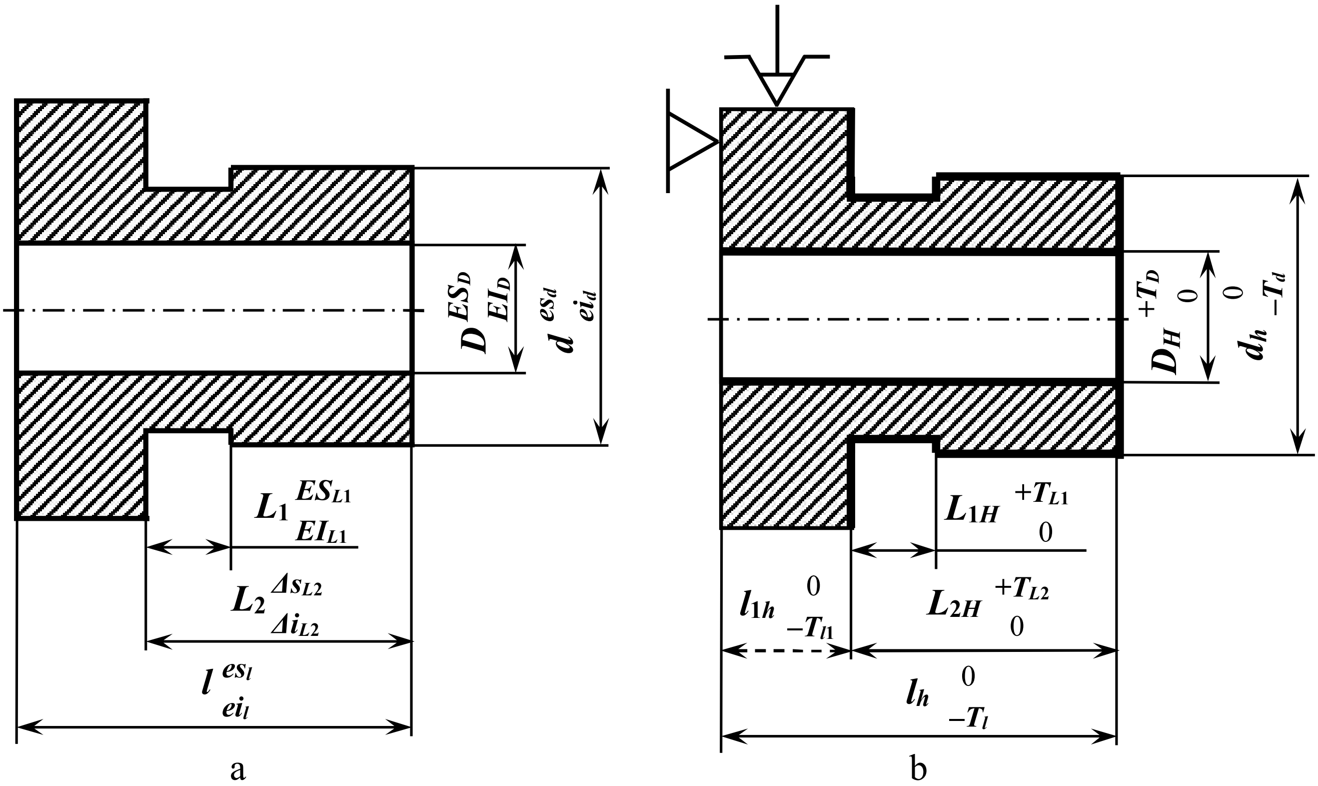


Fig. 1.3. Specifying design dimensions in a drawing for part (a) and manufacture dimensions in a sketch for machining operation of workpiece (b): $d_{ei_d}^{es_d}$, $l_{ei_l}^{es_l}$ – design dimensions of shafts; $d_h{}^{0}_{-T_d}$ – manufacturing dimension of shaft; $D_{EI_D}^{ES_D}$, $L_{1EI_{L1}}^{ES_{L1}}$ – – design dimensions of holes; $D_H{}^{+T_D}_{0}$ – manufacturing dimension of hole; $L_{2\Delta i_{L2}}^{\Delta s_{L2}}$ – design dimension of element not relating to shafts and holes; $l_h{}^{0}_{-T_l}$, $l_{1h}{}^{0}_{-T_{l1}}$ – manufacturing dimensions-coordinates specified in the form of dimension-shaft (basic shaft h); $L_{1H}{}^{+T_{L1}}_{0}$, $L_{2H}{}^{+T_{L2}}_{0}$ – manufacturing dimensions-coordinates specified in the form of dimension-hole (basic hole H). In the sketch (b) machined surfaces are shown by thick lines

Hole is a term conventionally used in the USTF for designation of internal (female) elements of a part including non-cylindrical elements.

Dimension of hole is a dimension of internal element of part, tolerance band (limit deviations ***ES***, ***EI***) of which can be over or below zero line of deviations, which position being determined by nominal dimension (***D***, ***L***), for example, $\boldsymbol{D}_{\boldsymbol{EI_D}}^{\boldsymbol{ES_D}}$, $\boldsymbol{L}_{1\,\boldsymbol{EI}_{L1}}^{\;\boldsymbol{ES}_{L1}}$ (ref. Fig. 1.3-a), $Ø40^{-0.012}_{-0.028}$ = Ø40N6, $96^{+0.090}_{+0.036}$ = 96F8, $50^{+0.007}_{-0.018}$ = 50K7.

Basic hole is a hole with dimension, tolerance band of which is over zero line and lower limit deviation being equal to zero (***EI*** = 0). Upper limit deviation equals tolerance value with plus (***ES*** = + ***T***). The basic deviation **H** is used when specifying the basic hole dimension with tolerance band. Nominal dimension of basic hole equals minimum limit dimension ($\boldsymbol{D_{nom}} = \boldsymbol{D_{min}}$) due to ***EI*** = 0 and so dimension of basic hole is specified in the form $\boldsymbol{D} = \boldsymbol{D_{min}}{}^{+\boldsymbol{T}}_{0}$, for example, Ø42H6 = $Ø42^{+0.016}$.

Dimension of a part element not relating to shafts and holes is specified by nominal dimension (***l***, ***L***), upper ***Δs*** and lower ***Δi*** limit deviations: $\boldsymbol{L}_{2\,\boldsymbol{\Delta i}_{L2}}^{\;\boldsymbol{\Delta s}_{L2}}$ (ref. Fig. 1.3-a). Designers may use any basic deviation, tolerance band and, hence, upper and lower limit deviations from the standard values related to shafts or holes suitable for the geometric parameters of the designed part.

For free surfaces not mating (not contacting) with other surfaces in an assembly unit designers specify dimensions, as a rule, by *nominal dimension and symmetric limit deviations* with js (Js) basic deviation. In this case nominal dimension equals mean (middle) dimension (half-sum of maximum and minimum limit dimensions), and limit deviations – half-tolerance values with "+" and "–" (±ITn/2), for example, 50±0.125 = 50js12 (***T***/2 = IT12/2 = 0.25/2 = 0.125 mm), 80±0.37 = 80Js14 (***T***/2 = IT14/2 = = 0.74/2 = 0.37 mm).

1.2.2. Manufacturing dimensions

Manufacturing dimension is intended for application in the charts of manufacturing processes and other technological documentation. It consists of nominal dimension and upper and lower limit deviations.

Nominal dimension is determined from technological computations of operation dimensions and from other production and economical considerations. Calculated values of nominal dimensions are rounded off according to the standards and recommendations: branch standards (OST), standards of enterprise (STP), rounding off to value divisible by 0.1 mm, rounding off to value divisible by the smallest decimal portion of limit deviations, as well as, rounding off to standard dimensions of cutting tools, by standards for cast, rolled, forged, formed products and other initial blanks. The exceptions are manufacturing dimensions obtained from transformations of design dimensions. For example, the operation dimension-shaft $Ø40.033_{-0,016}$, which is obtained from design dimension of shaft $Ø40^{+0.033}_{+0.017}$, is not subjected to rounding off.

Here it should be taken into account that *preferred numbers of linear series*, stated by the standard for design dimensions, *are not applicable for manufacturing dimensions*.

Limit deviations for operation dimensions of manufacturing metal-cutting processes are determined from technological calculations or accuracy grade ITn assigned for dimension and, hence, tolerance $\boldsymbol{T}$ is determined from the standard using the accuracy grade and nominal dimension. Then limit deviations are assigned using only three basic deviations: **H** (basic hole, lower deviation $\boldsymbol{EI} = 0$), **h** (basic shaft, upper deviation $\boldsymbol{es} = 0$) in order to the tolerance for dimension being located in the body of machined workpiece (tolerance is directed into "metal") or **js** (symmetric limit deviations ±ITn/2).

Limit deviations of initial blanks are assigned by the standards: for steel forgings – from the GOST 7505-89; for steel and non-ferrous forgings – from the branch standard; for castings – from the GOST 26645-85; for the rolled products – from the corresponding standards. *Limit deviations for dimensions of initial blanks in general do not correspond to the limit deviation stated by USTF standards*.

Operation dimension is a manufacturing dimension specified for performance in manufacturing operation. It is written in operation sketches of manufacturing processes and other technological documentation.

Operation dimensions are written in the following forms: ***dimension-shaft (dimension of basic shaft)*, *dimension-hole (dimension of basic hole)*, *and dimension with symmetric deviations***.

Dimension-shaft $\boldsymbol{d_{max}}_{-T_d}$ is a manufacturing dimension of *external element of workpiece created by only one surface* and written in the form of dimension of basic shaft (basic deviation h), that is, nominal dimension equals maximum limit dimension ($\boldsymbol{d_{nom}} = \boldsymbol{d_{max}}$), upper limit deviation $\boldsymbol{es} = 0$, lower limit deviation equals tolerance with minus sign ($\boldsymbol{ei} = -\boldsymbol{T_d}$), for example, dimension of external cylindrical surface in operation sketch $\boldsymbol{d_h}_{-T_d}$ (Fig. 1-b). In technological calculations dimension of non-basic shaft, specified by designer, a production engineer transforms into dimension of basic shaft, for example, design dimension of non-basic shaft $Ø40^{+0.033}_{+0.017}$ is transformed into manufacturing dimension having form of basic shaft $Ø40.033_{-0.016}$. This *transformation does not change maximum and minimum limit dimensions* specified by designer.

Dimension-hole $\boldsymbol{D_{min}}^{+T_D}$ is a manufacturing dimension of a workpiece element – dimension of a basic hole, nominal dimension of which equals minimum limit dimension ($\boldsymbol{D_{nom}} = \boldsymbol{D_{min}}$), lower limit deviation equals zero ($\boldsymbol{EI} = 0$, basic deviation **H**), and upper deviation equals tolerance with plus sign ($\boldsymbol{ES} = +\boldsymbol{T_D}$). *Manufacturing dimension-hole relates to internal elements of workpiece created by only one surface*, for example dimension of internal cylindrical surface $\boldsymbol{D_H}{}^{+T_D}_{0}$ (ref. Fig. 1-b). In technological calculations the dimension of *non-basic hole*, specified by designer, production engineer transforms into the dimension of *basic hole* keeping values of maximum and minimum limit dimensions, for example, design form of non-basic hole dimension $Ø30^{-0.012}_{-0.028}$ is transformed into manufacturing form of basic hole dimension $Ø29.972^{+0.016}$.

Dimension-coordinate is a manufacturing dimension, which determines coordinate of a workpiece feature position (machined surface, line, point) relative to initial datum in the operation sketch (ref. Fig. 1-b). Depending on position of a machined feature and selection of initial datum the dimension-coordinate can be written in various forms: as a *dimension-shaft* $l_{max\ -Tl}$, as a *dimension-hole* L_{min}^{+TL}, *dimension with symmetrical limit deviations* $l_{nom}(\pm T_l/2)$ according to **js** basic deviation (nominal dimension equals middle dimension – half-sum of maximum and minimum limit dimensions, and limit deveations ±ITn/2).

Operation sketch (ref. Fig. 1-b) shows manufacture dimensions-coordinates $l_{h\ -T_l}$, $l_{1h\ -T_{l1}}$ specified in the form of dimension-shaft (basic shaft h) and manufacture dimensions-coordinates $L_{1H}^{+T_{L1}}$, $L_{2H}^{+T_{L2}}$ specified in the form of dimension-hole (basic hole H).

Operation dimensions with symmetrical limit deviations, as a rule, are applied to coordinates of axes, axes of symmetry for slots, rounding radii, chamfers and to other similar elements.

1.3. Datums

Datums are surfaces, lines or points of a part, relative to which positions of other features (surfaces, lines or points) are considered.

Design datum is a surface, line or point, relative to which a coordinate of other surface, line or point is specified by *design dimension* in drawing of a part.

Manufacturing datums are used in manufacturing technology. They are divided into *initial*, *mounting* and *measuring*.

Initial datum is a surface, line or point, relative to which a coordinate of machined surface (feature) of workpiece is specified by *initial dimension* in an operation sketch.

Mounting datum is a workpiece suface (feature), which creates definit position of workpiece in the direction of initial dimension, when mounting a workpiece in workholding device or directly in machine.

Measuring datum is a surface, generating line or point of a workpiece surface, relative to which a position of machined surface (*actual dimension*) is checked.

2. ORGANISATIONAL AND METHODICAL FUNDAMENTALS OF PLANNING OF MANUFACTURING PROCESSES

Development of manufacturing processes is one of main components of technological preproduction preparations (TPP), which is regulated by the unified system (USTPP, GOST 14.001-73). This system of the TPP organisation and control provides application of progressive *typical* manufacturing processes, standardised manufacturing tooling and equipment, means of mechanisation and automation of production processes, engineering, technical and managing works. The TPP should provide complete technological preparedness of an enterprise to produce items of high quality according to with specified technical and economical indexes stated high engineering level, minimal labour and material expenses.

2.1. Technological check of design documentation and technological analysis of production object

Design documentation is subjected to the check, which is directed according to the GOST 2.121-73 to observation of the stated technological norms and requirements in designs of items to be developed, achievement of high level of manufactureability, selection of the most rational methods for production of items taking into account the specified volume of output.

Drawings of parts should contain all necessary information: projections and sections clearly explaining the configuration of an item; dimensions with substantiated accuracy (limit deviations), roughness and permissible deviations of geometric form and relative position of surfaces; method for initial blank production; information about material, heat and diffusion threatments; protective coatings; special methods and equipment of quality check; mass of part, etc. Designs of items, certainly, should meet exploitation requirements and requirements to their most economical production. *The smaller labour-intensiveness and production costs in manufacture of an item are, the higher manufactureability is*.

Production engineer starts from ***analisys of purpose and operation conditions*** of a part (forces and moments applied, wet or dry friction, range of work temperatures, etc.) in order to understand the technical requirements to a part to be produced and selection of material performed by designer.

Analysis of material properties includes chemical composition that determines possibilities for heat treatment, diffusion treatment (carbonization, nitriding, etc.) and mechanical properties (ultimate strength, yield limit, hardness, impact strength, etc.), physical properties (electric conductivity, magnetic properties, resistance to corrosion, etc.), manufacturing properties (castability, forgeability, weldability, machinability).

Analysis of design peculiarities is aimed to develop an estimation of complexity of design elements and preliminary to assign processing methods for their performance taking into account accuracy and roughness paramters. Here, first of all, production engineer reveals such complicated elements like gear rings, splines, threads, which are typically produced by under-productive methods in expensive machines with complicated tools. If necessary, the needed geometric parameters of such elements are calculated and their accuracy and roughness is assigned according to the technological recommendations, for example, holes parameters for spline bushings, holes for internal thread cutting, shaft parameters for external thread cutting, etc. Another type of design elements is surfaces of simple shape (planes, cylinders), but of high accuracy and surface finish. Here production engineer preliminary determines the methods for their performance including possible diffusion treatment, heat and sub-zero treatments taking into account operation conditions of a part and possible application of machining methods with abrasive tools. Surfaces, which can be used as manufacturing datums, are revealed with orientation to design datums (explicit and implicit) taking into account their geometric parameters (length, diameter, area). Also production engineer estimates easiness of access to the machined surfaces with cutting tools including surfaces of relatively low accuracy (free surfaces not mating with other parts in assembly). Finally production engineer should obtain some orientation to typical *structure of manufacturing process* recommended by production experience of an entertprise or in literature sources for the considered part configuration.

Types and indexes of manufactureability of designs are stated by the GOST 14.205-83, general rules and rules for providing the manufactureability of designs of parts – in the GOST 14.202-73 and GOST 14.204-73.

Manufactureability estimation of a design can be of two types: qualitative and quantitative.

Qualitative estimation characterises design in general by the following indexes: good – bad, permissible – not permissible, etc. It is performed for material (cost, machineability, etc.), geometric configuration (differences from cylinder and plane), surface finish (accuracy and roughness), manner for specifying dimensions (how many datums are used) and possible methods for initial blank production.

Quantitative estimation is performed along absolute and relative indexes, main of which are:

- Labour-intensiveness;
- Production cost (determined after development and norm-setting ofmanufacturing process);
- Coefficient of material utilisation (determined after selection of method for initial blank production and calculations of machining allowances.

Additional indexes of quantitative estimation are:

- Coefficient of machining accuracy;
- Coefficient of surfaces roughness, etc.

When making analysis of manufactureability of shafts, the following aspects are considered: possibilities to machine surfaces with straight turning tools; reduction of diametrical dimensions of journals to the ends of shafts; possibilities to change closed keyslots by open ones machined with disk-type milling cutters; shape and dimensions of grooves suitable for cutting tools at the end of work pass; stiffness of shafts that influences machining accuracy, for example, at required accuracy of 6 to 8 accuracy grade the ratio of shaft length to its diameter is not more than 10–12. Besides, other characteristics are analysed: presence of convenient surfaces for locating or possibilities for creation auxiliary manufacturing datums; possibilities for technological agreement of dimensions ensuring the shortest manufacturing dimension chains; possibilities for selection of a rational method for initial blank production ensuring the largest value of material utilisation coefficient and the smallest labour-intensiveness of machining.

Parts with toothed surfaces (gearing – spurs and bevel gears, toothed joints – splines) are considered to be under-manufactureable because of complexity and high cost of equipment and cutting tools (gear and spline milling machines, gear shaping machines, gear grinding machines; worm hobs and grinding wheels, broaches for splines, etc.).

2.2. Types and structures of manufacturing processes

Type of manufacturing process (single, unified, typical, group, etc.) is determined by quantity of produced items (one type of items, group of same-type items or different-type items). Classification of manufacturing processes along types is stated by GOST 3.1109-82.

Typical manufacturing process is characterised by unity of content and sequence of majority of manufacturing operations and steps for a group of items with common design indexes.

By detailing level of description the manufacturing processes are divided into route, operation and route-and-operation.

Route manufacturing processes are performed according to the documentation (MK – route chart), in which contents of operations are described without manufacturing steps and processing conditions.

Opearation manufacturing processes are performed according to the documentation, in which contents of operations are described with manufacturing steps and processing conditions, with operation sheets (OK) and sketch sheets (КЭ) for *all operations* (critical and auxiliary).

Route-and-operation manufacturing processes are performed according to the documentation, in which contents of several operations are described without manufacturing steps and processing conditions (like in route description), and for the critical operations the steps and cutting conditions are specified in operation sheets (OK) and sketch sheets (КЭ) (like in operation description).

Description detailing levels for manufacturing processes are stated by the branch standards and depend on production type.

Manufacturing processes consist of separate *segments*, *stages*, *operations*, *mountings*, *steps* and *passes* (GOST 3.1109-82).

The following segments of unified manufacturing processes are defined.

Blanking segment is providing an initial blank with a preliminary shape before the sequent machining, for example, metalworking – change of shape, dimensions, roughness and material properties by plastic deformation, or dividing the blank material into pieces without chip generation (smith forging, forging in dies, die rolling, etc.).

Machining (metal-cutting) is change of shape, dimensions, surfaces roughness of a workpiece with creation of new surfaces by removal of surface laeyrs (allowances) with chip generation (turning, drilling, milling, broaching, etc.).

Heat and diffusion treatment is change of structure and workpiece material properties due to heat and diffusion effects (normalisation, quenching, annealing, tempering, hardening and tempering, carbonisation, nitriding, etc.) [9]. Definitions and purposes of various types of heat and diffusion treatment are submitted in the Appendix 1.

Deposition of coating is creation of surface layer from the selected other materials on a workpiece (anodization, oxidation, painting, etc.).

Products quality control is check for compliance of products quality indexes to the stated requirements.

By structure a manufacturing process is divided, as a rule, into *three stages*: rough machining, finish machining and fine-finish machining [8].

Manufacturing operation is a complete part of manufacturing process performed at one work place and covering all sequent actions of a worker and a machine for processing of a workpiece. During operation a worker can *mount*, *re-mount* and change *position* of a workpiece.

Manufacturing step is a complete part of manufacturing operation performed by the same technological tooling at permanent technological (cutting) conditions and mounting.

Work pass is a complete part of manufacturing step that changes shape, dimensions and/or roughness by single or several motions of cutting tool along workpiece surfaces.

Auxiliary pass is a complete part of manufacturing step that does not change workpiece characteristics at motion of cutting tool along its surfaces, but necessary for performance of work pass.

Mounting is a part of manufacturing operation performed at permanent clamping of a machined workpiece.

Position is a fixed location occupied by a workpiece clamped in a workholding device relative to cutting tool or steady element of machine, when performing some portion of manufacturing operation.

Setting (*adjustment*) is a preparation of technological equipment and tooling for performance of manufacturing operation.

Re-setting (*tuning*) is an additional adjustment of technological equipment and tooling for restoring the parameters obtained at setting.

2.3. Technical and economical principles of technological development

Three principles are laid into the basis of planning of manufacturing processes: *technical*, *economical* and *organisational*.

According to the ***technical principle*** a planned manufacturing process should entirely ensure performance of all requirements of a drawing and technical conditions for production of a considered item. They are: *accuracy of parts* and accuracy of machines, *surfaces quality* of parts, manufactureability of parts and machines. Parts are characterised by accuracy of dimensions, form and relative position of their design elements. *Accuracy* is a compliance of actual parameters and the pameters specified by a drawing or stated by technical conditions.

Depending on the requirements of *final accuracy* and operation conditions of parts in assembly unit the accuracy for production of separate parts is assigned, that is, mathematical relation between initial link and constituent links in assembly unit is provided. The higher is the required accuracy of initial link, the higher should be accuracy of the parts dimensions – links of a dimension chain. Methods for ensuring the required accuracy of initial links are stated by the GOST 16319-80.

Quality of surfaces of machines parts is determined by geometric, physical and mechanical parameters. The *geometric parameters* are: deviations of form (GOST 24642-81), waviness and roughness (GOST 2789-73). The *physical and mechanical parameters* are: hardness, depth and intensity of hardening, value and character of stresses.

According to the ***economical principle*** items should be produced with minimal labour and production expenses. Main requirements for technological developments according to the economical principle are submitted in the Appendix 2.

According to the ***organisational principle*** production of a part should be realised under conditions providing maximal efficiency, in particular:

- It is necessary that form of manufacturing process organisation corresponds to type of production;
- Layout of equipment along production area (in shop) should provide continuous manufacture of an item and minimal lengths of transportation ways;
- Workplaces should be supplied in time with intial blanks, cutting tools, cutting fluids.

2.4. Initial data and stages for development of manufacturing processes

Most often manufacturing processes are developed at organisation of production of new items at long-term working enterprises. Obligatory minimum of ***initial data*** for planning of manufacturing processes includes: drawings of items; program for production output detailed in years or other calendar terms; description of an item design; technical conditions for manufacture and acceptance of items. Besides it is necessary to have information about available equipment, methods for producing initial blanks, etc.

Program for production output allows to determine type of a planned production and select reasonable structure of a manufacturing process. *Descriptions of items designs* should give right and full submission about their operation, functions of separate constituent parts and their interaction in operation, exploitation purposes of items and constituent parts. *Technical conditions* for manufacture and acceptance of items determine requirements to an item as a whole, as well as to its assembly units and parts. Depending on these requirements the methods for machining of parts and methods for ensuring the accuracy of closing links in dimension chains are selected.

Development stages of manufacturing processes are stated by the GOST 14.102-73: performance specification, draft project, work project.

Performance specification states technical requirements to technological documentation, level of its detailing, executors, funding sources.

Draft project includes preliminary manufacturing process and basic principal engineering and organisational decisions.

Work project includes route-and-operation or operation manufacturing process depending on approved level of detailing in the description.

3. PLANNING OF METAL-CUTTING MANUFACTURING PROCESSES

General rules for planning of manufacturing processes are stated by the standard GOST 14.301-83. They determine a definite sequence in performance of planning works. Thus, the first large section finished with calculations of machining allowances and operation dimensions includes the paragraphs described in this chapter.

3.1. Technological analysis of a part drawing

When analyzing a drawing of part the following is considered: purpose of a part, diagram of loads application, operation conditions; material of a part – chemical composition, mechanical and physical properties, manufacturing properties, methods for hardening treatments; design peculiarities of a part – shapes of surfaces, accuracy, roughness, tolerances for surfaces relative position, methods for meeting the specified requirements; type of initial blank specified by a designer.

For proper planning of manufacturing process it is necessary that a production engineer clearly understands functional *purpose of a part*, its definite role in functioning of mechanism or machine as a whole.

Understanding of *diagram of loads* applied to a part allows a production engineer to take into consideration an importance of introduction of additional manufacturing steps for quality performance of definite design elements, which ensure reliable operation of part at specified loads (static and dynamic forces and moments) during a specified life.

Operation conditions of a part often determine selection of material structure of initial blank (cast, forged, textured, etc.), method for production of initial blank, content and methods of heat treatment, diffusion treatment of a surface layer that a produced part would obtain properties to withstand adverse attacks. Operation conditions include: range of operation temperatures; presence or absence of lubricant; presence of mechanical particles on contact surfaces; presence of static and/or dynamic loads, high contact stresses, etc.

Chemical composition of material determines physical and mechanical characteristics, manufacturing properties, methods of hardening treatment. First of all, a production engineer is interested in *mechanical properties* of work material, its abilities to be processed by various methods of treatment, including non-traditional machining (electroerosion, electronic beam, etc.) and its abilities to withstand high temperatures, corrosion, oxidation, which can appear in the applied processes.

Chemical composition determines *methods of hardening treatment*, for example: heat treatment (HT) (quenching and annealing) for middle- and high-carbon steels; cabornisation (diffusion treatment – DT) of surface layer of parts from low-carbon steels; nitriding for steels containing chromium, molybdenum, aluminium. If impossible to apply HT or DT for hardening of surface layer, othe methods are used: plastic deformation (roll burnishing and other methods), application of hardening coatings, etc.

Manufacturing properties characterise manufacturability by various methods of processing: casting, welding, smithing, die forging, metal-cutting, etc. They determine selection of machining methods for a definite part, selection of equipment type and materials for processing tools (cast moulds, dies, cutting tools).

When analysing *design peculiarities of a part*, a production engineer, first of all, reveals the surfaces of high accuracy and surface finish, which need especial approach and attention when planning a manufacturing process. As a rule, high-presicion surfaces have high accuracy of position relative to other surfaces. Therefore surfaces of high-accuracy relative position are planned to machine in one mounting, if possible, that ensures minimal error.

Important design peculiarities of a part are also such elements as gear rings (external and internal), splines, threads, presice centre holes, presice grooves, etc. Such elements usually need application of special-purpose machines and such machining methods that can ensure the required parameters, but have low productivity that significantly reduces manufacturability of a part.

Accuracy of toothed gear wheels is specified by *accuracy degrees* (they are 12) along 3 *norms of accuracy* (kinematic accuracy, smoothness of operation and contact patch), and requirements for *circumferential backlash* – by types of engagement (they are 6: A (the largest backlash), B, C, D, E, H (the smallest)). For example, the gear wheel can be designated as 7-C, when wheel is of the 7^{th} accuracy degree along all three norms with circumferential backlash in gears engagement C. Surfaces of tip circle diameter for external toothing and surfaces of root circle diameter for internal toothing are machined before teeth-cutting operations with accuracy and roughness specified in a drawing.

Machining of gear rings (toothing) is usually performed in the specialised gear-making shops, because they have large quantity of geometric and accuracy parameters describing involute surfaces of flanks and their relative positions. They are produced in complicated special-purpose equipment with special-purpose cutting tools and so they are very complicated in manufacture. Therefore planning of such gear machining operations is usually performed by a production engineer specilised in manufacture of gear rings.

Involute spline (toothed) joints exceede joints with straight and triangle profiles of teeth by transmitted rotational moment, accuracy of alignment and guiding of teeth, fatigue strength and durability, relative manufacturability.

When centring along flanks of teeth, the GOST 6033-80 introduces the following *accuracy degrees* (in contrast to accuracy grades for slick joints) for spline joint elements determining the tolerances of bushing and shaft: 7; 9; 11 – for a *bushing space width* ***e*** and 7; 8; 9; 10; 11 – *for a shaft tooth thickness* ***s*** along reference circle diameter. The following series of basic deviations are stated: H – for a bushing space width ***e*** and a, c, d, f, g, h, k, n, p, r – for a shaft tooth thickness ***s***. For example, designation of involute spline bushing with alignment along teeth flanks is 50×2×9H, where 50 is nominal diameter of joint D, mm; 2 is module m, mm; 9H is tolerance band for bushing tooth space width ***e***. Here designer does not specify minor diameter of splines and so production engineer should calculate it from the formula $\boldsymbol{D_a} = \boldsymbol{m}\ (\boldsymbol{z} - 0.9)$, where ***m*** is module, mm, and ***z*** is number of splines to be found from the GOST 6063-80. Preparation of hole for a broaching operation should include several manufacturing steps to obtain accuracy grade IT11 and roughness $\boldsymbol{R_z}$10 necessary for alignment of a cutting tool (broach).

Various types of *threads* are often used in designs of aerospace parts. The most applied threads are of metric type for fasterning purpose. Designation of a thread typically contains information about nominal (major) diameter, pitch, accuracy of profile, for example, external metric thread M12-6g (coarse pitch 1.75 mm and tolerance bands 6g of profile along pitch and major diameters, accuracy degree 6, basic deviation g), internal metric thread M16×1.5-7H8G (fine pitch 1.5 mm, tolerance band 7H along pitch diameter, 8G along minor diameter).

Before cutting threads with blade tools the major diameter for external threads (shafts) and minor diameter for internal threads (holes) should be prepared with proper accuracy and surface finish depending on those specified in a drawing. Limit deviations for major external thread diameter are found from the standards (handbooks) by basic deviation (upper deviation $\boldsymbol{es}$) and accuracy degree (tolerance $\boldsymbol{T}$): lower deviation $\boldsymbol{ei} = \boldsymbol{es} - \boldsymbol{T}$. Hole diameter for internal thread is determined from the standard of considered thread. Limit deviations for minor internal thread diameter are found from the standards by basic deviation (lower deviation $\boldsymbol{EI}$) and accuracy degree (tolerance $\boldsymbol{T}$): upper deviation $\boldsymbol{ES} = \boldsymbol{EI} + \boldsymbol{T}$. Then the nearest accuracy grade is selected from the standard USTF by nominal (major) diameter and tolerance smaller than tolerance of thread diameter. It is necessary for planning of manufacturing steps for the considered surface. It is recommended to assign roughness parameter as $\boldsymbol{R_z} = (0.25 \div 0.3) \cdot \boldsymbol{T}$ rounded off to the nearest standardied value.

Any complicated design element needs careful consideration by a production engineer in order to calculate (found) necessary geometric parameters and assign accuracy and roughness parameters for those surfaces, which will be used as preliminary ones in making such complicated design elements. Here the designing and manufacturing handbooks will be extremely helpful.

Also the important question is revealing of design datums, which can be specified in explicit or implicit forms in order to use them as manufacturing datums, if possible.

When analysing the design peculiarities of a part, a production engineer preliminary determines *ways for ensuring the specified requirements*.

Generally *specified requirements for accuracy of form and relative position of surfaces* are ensured by either machining of several high-accuracy surfaces in one operation, or by machining of one high-accuracy surface, when another high-accuracy surface is a datum, or high-accuracy surfaces are machined from permanent mounting datums (for example, in centres) in several operations.

Originating from functional purpose of a part and experience accumulated by a design institution a designer can specify type of initial blank and method for its production in a drawing. Though in many cases selection of initial blank type and production method should be made by a production engineer.

3.2. Analysis of manufacturability of a part

According to the GOST 14.201-83 *manufacturability of item design* is a collection of item properties that determines suitability of its design for obtaining the optimal expenditures of resources in production and exploitation at specified quality indexes, output volume and conditions for works performance. Term "manufacturability of item design" expresses design peculiarities of an item, but not its functional properties.

The paragraph 2.1 describes indexes needed for qualitative estimation of a part manufacturability.

At the stage of technological analysis of a drawing it is rather impossible to give *quantitative estimation* by main absolute and relative indexes (labour-output ratio, production costs, etc.). But it is possible to make quantitative estimation by *coefficient of accuracy* K_T and *coefficient of roughness* K_R along dimensions and surfaces of a considered part from the drawing. These coefficients are calculated from mean accuracy grade IT_m and mean roughness R_{am}:

$$IT_m = \frac{\sum IT_i \cdot n_i}{\sum n_i}, \quad (3.1)$$

$$K_T = 1 - \frac{1}{IT_m}, \quad (3.2)$$

$$R_{am} = \frac{\sum R_{ai} \cdot n_i}{\sum n_i}, \quad (3.3)$$

$$K_R = \frac{1}{R_{am}}, \quad (3.4)$$

where IT_i – accuracy grade of i dimension; n_i – quantity of dimensions of the IT_i accuracy grade in the formula (3.1); R_{ai} – roughness value R_a of i surface; n_i – quantity of surfaces with the R_{ai} roughness in the formula (3.3).

When roughness parameter R_z is specified in a drawing of part, it should be transformed into parameter R_a taking into account that $R_z \approx 4R_a$ (Appendix 3).

The calculated values of coefficients are compared with the normative ones. According to these normatives a part is considered to be manufacturable, if $K_T \geq 0.8$ and $K_R \leq 0.32$ [3].

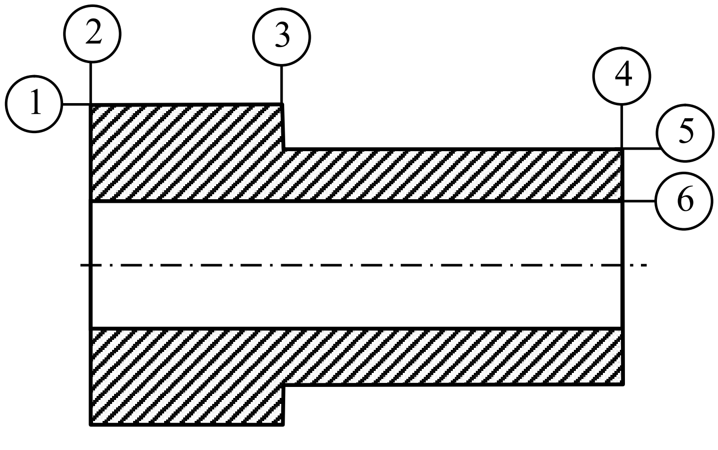


Fig. 3.1. Example of numbering diagram for round part: 1, 5, 6 – cylindrical surfaces; 2, 3, 4 – flat surfaces

Diagram of surfaces numbering of a part is developed for convience of analysis and calculations of the K_R roughness coefficient. Here it is assumed that any part geometric configuration is considered as a collection of elementary surfaces, simple and intricated: flat, cylindrical, conical, involute, helical, etc. (Fig. 3.1).

Components for calculations of the the K_T accuracy coefficient are selected from a drawing of part among main dimensions determining geometric configuration.

In calculations several elements of the same dimensions (holes, slots) are included as single geometric elements. For example, 6 holes Ø12H9, $\boldsymbol{R_z}10$ should be included into the formulas (3.1) and (3.3) as a single accuracy parameter IT9 and a single roughness parameter $\boldsymbol{R_z}10$.

Usually small elements of low accuracy (IT12 and larger) and suface finish ($\boldsymbol{R_z}20$ and larger) such as grooves, slots, chamfers, fillets, rounding radii are not taken into consideration and calculations of both coefficients, because they are very simple in manufacture and do not determine manufacturability of a part.

Also the complicated design elements like toothing, splines, threads are also excluded from consideration in the quantitative analysis because their accuracy is described by accuracy degrees and accuracy classes, but not accuracy grades ITn. Their intricated shapes are described by large amount of geometric and accuracy parameters. Here qualitative analysis shows that these elements are very complicated in manufacture, produced by underproductive methods and so the parts with such elements are considered to be non-manufacturable.

3.3. Selection of method for initial blank production

Main things in selection of method for initial blank production are ensuring the specifed *quality* of a final part at its *minimal production costs*. Selecting a blank a production engineer should take into account purpose and operation conditions of a part, its geometric configuration, type of production, required accuracy of initial blank, quality of surface layers, desired direction of metal fibres, as well as the recommendations [8].

Proper selection of initial blank means proper selection of rational method for its production, determination of machining allowances, its dimensions, their deviations and surfaces roughness.

Principal manufacturing processes for production of initial blank are *metalworking*, *casting* and *welding*. Welding as an independent method for creation of initial blank can be considered only conventionally, because it is applied for permanent joints of separate components of blank produced by other methods.

Selection of principal method for production of initial blank and method for its realisation are determined by the following factors:

- Manufacturing properties of material: its capability to deform plastically at metalworking, or by its castability, or by its weldability;
- Required material mechanical and physical properties: material structures as a result of application some method of intial blank manufacture (orientation of fibres in forgings, size of grains in castings, etc.)
- Design shapes and dimensions of a part (the larger the part is, the more expensive production of dies, metallic moulds, etc.);
- Required accuracy of initial blank and quality of its surfaces (roughness of surfaces, strainhardening, residual stresses, etc.);
- Volume (quantity) of parts output (at large batches the most favourable are the methods, which provide the nearest approach of initial blank shape and dimensions to

shape and dimensions of final part: precise forging, die casting, etc.).

Casting methods typically produce coarse-grain structures with casting defects (porosity, shrinkage cavities and cracks, etc.). These features greatly reduce all mechanical properties of material. Therefore the casting methods are aplicapable for the parts of the specified purpose and intricate shapes.

Welded blanks can reduce material consumption for the part production by joining of simple geometric preforms. But they have similar casting defects in a welded seam and coarse-grain structure in a heat-affected zone.

Rolled products have improved structure in comparision with cast structures due to large plastic deformations. Hot-rolled products have fine-grain structure in surface layers, but coarse grains in a core section that reduces mechanical properties. Structure can be improved by special-purpose heat treatment for refinement of grains size.

Forging in dies is the most suitable technique among metalworking method, due to its capability to generate shapes near to a part shape, fine-grain fiber-like structure with high mechanical properties of material. It's important that the dies cavities form favorable location of fibers equidistant to outer contour of blank.

Forged blanks (forgings) according to the GOST 7505-74 are reasonable for application in those cases, when mass of forging is 12…15 % less than mass of a rolled product blank for the same part [4]. The most progressive methods for forged blanks are forging processes in horizontal upset forging machines and crank hot-forging presses. Forging in crank presses is less productive than in horizontal upset machines, but it is 2–3 times more productive than forging in power hammers and provides 20…35 % smaller machining allowances.

The drawings of forged blanks produced by forging and smithing should include: absence of abrupt changes in cross-section areas, transition from one cross-section area to another is along arch of relatively large radius, enlargements of cross-section areas in places of bending, sharp corners and ribs are rounded. Forgings should have forging drafts for those surfaces, which are perpendicular to parting line of die. Forging drafts are necessary for easy removal of forgings from dies. For dies apllied in crank hot-forging presses forging drafts are assigned for external surfaces 3…5°, for the internal

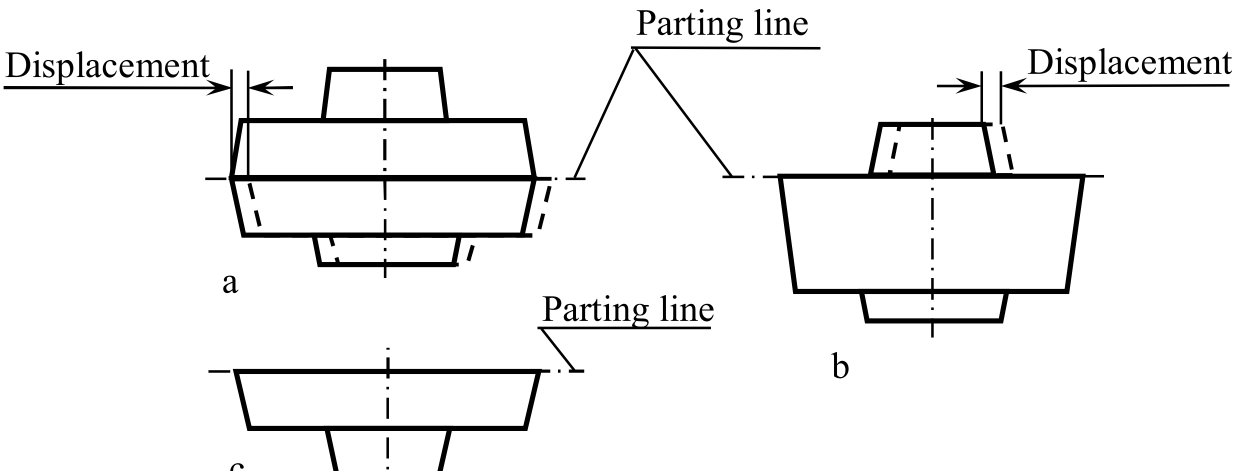


Fig. 3.2. Diagrams for selection of die parting line: a – good; b – bad; c – possible

ones – 5…7°.

Parting line should go through the largest cross section of blank (Fig. 3.2) that facilitate filling the die cavities with metal, provides easy removal of forging from die and check of displacement of upper die (and respective portion of a forging) relative to lower die after the trimming of flash. Veritical position of a blank axis in a die provides more favourable location of metal fibres parallel to outside contour of blank [10].

Tolerances for forging dimensions (expressed in limit deviations) are submitted in the Appendix 4. Initial data for determination of tolerances for forged blank dimensions are: mass of forging $\boldsymbol{m_f}$, group of steel (M1 or M2), complexity level $\boldsymbol{C}$ (C1, C2, C3 or C4). The forging surfaces roughness ($\boldsymbol{R_z}$) is selected from the reference table (ref. Appendix 4) according to the mass $\boldsymbol{m_f}$ value.

Modern ***foundry*** possesses the following main methods for production of cast blanks: sand mould casting, permament mould casting, die casting, investment casting, shell mould casting, centrifugal casting.

Now approximately 80…90 % cast blanks are produced in *sand moulds*.

Castings designs should meet the following requirements [10–12]:

- thickness of cast walls should be without abrupt changes in transition segement from thin wall to thick wall (it is necessary for homogenious structure of casting and reduction of residual stresses);
- simple parting line for moulds and castings;
- those surfaces, which are perpendicular to parting line of pattern, should have casting drafts in order to avoid damage of sand moulds when removing a pattern from them;
- holes of 10 mm diameter and larger can be formed by cores.

When developing a preliminary sketch of casting, approximate dimensions are calculated from the design dimensions by there increase for external elements and their decrease for internal elements by 15…20 %. Deviations for blank dimensions are selected from the GOST 26645-85 and surfaces roughness is assigned according to the handbook [10] (Appendix 5).

For ***initial blanks from rolled products*** the rolled and shaped sections, tubing, bent, extruded and die-rolled sections are applied.

Simple *round sections* of general purpose (GOST 2590-71 “Hot-rolled round steel”) are used for manufacture of smooth and stepped shafts with small steps in diameters, sleeves with diameters up to 50 mm, bushings with diameters up to 25 mm, flanges.

Tubular rolled products are steel seamless hot-rolled, cold-drawn and cold-rolled tubular sections (according to the GOST 8732-78, GOST 8734-75 and other). They are used for manufacture of cylinders, bushings, sleeves, shells, hollow shafts.

Accuracy of hot-rolled sections corresponds approximately to the 12^{th}–14^{th} grades, cold-rolled sections – 9^{th}–12^{th} grades [10].

At this stage of planning the diametrical dimensions of blanks from rolled products are determined *approximetely* from the parameters of respective surfaces of a part. Deviations for these dimensions and rougness are specified by the GOSTs for corresponding types of rolled products (see also Appendix 6). Length dimensions for cutting off (parting) the rolled products in separate pieces are calculated from the total length of a part with respective increase. Deviations for these dimensions and roughness are determined from the handbook [10] (ref. Appendix 6).

Initial blanks are supplied to machine shops after heat treatment (normalisation or annealing) and cleaning (sand or shot blasting).

Development of preliminary sketch of initial blank finishes this stage in development of manufacturing process. Preliminary sketch of initial blank includes *approximate dimensions*, their deviations and surfaces roughness (Fig. 3.3). Blank dimensions are specified in a *similar to design dimensions manner* that ensures coincidence of design and manufacturing datums for blank production. *Final dimensions of initial blank*

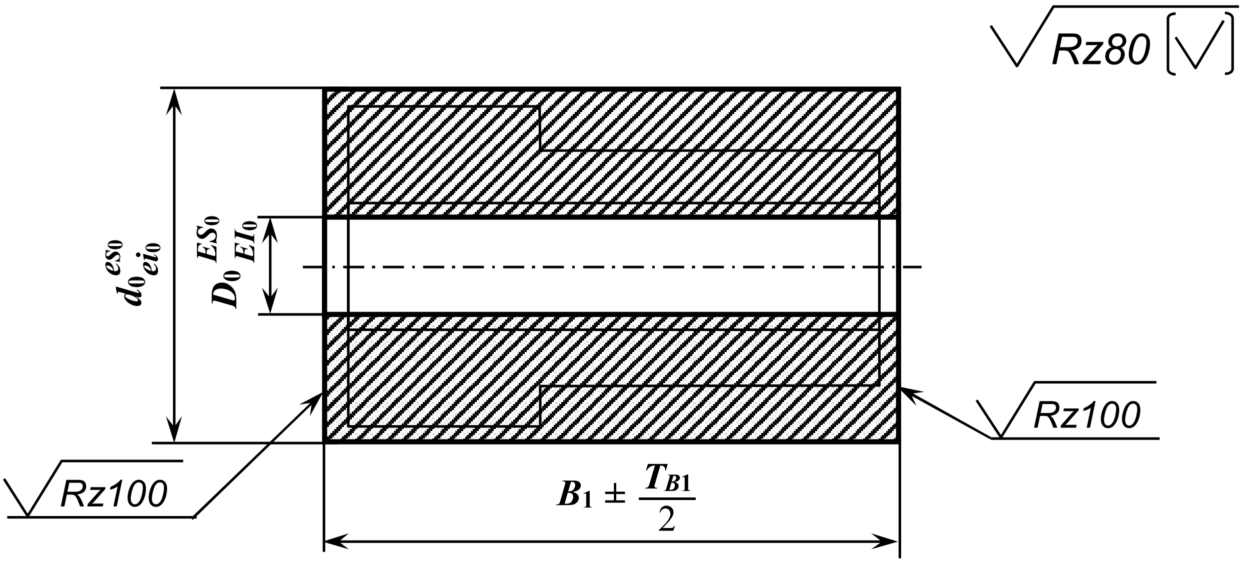


Fig. 3.3. Example of sketch of preliminary initial bank (piece of hot-rolled tube). Contour of final part (ref. Fig. 3.1) is shown by thin line

will be determined as results of calculations of operation dimensions.

3.4. Calculations of number of manufacturing steps and development of routes for machining of main surfaces of part

3.4.1. Calculations of number of manufacturing steps by accuracy and roughness

Quantity of manufacturing steps, necessary for obtaining the specified parameters of elementary surface of a part, is determined by ratio of characteristics of accuracy and roughness of the like surfaces of initial blank and part. These characteristics obtained from preliminary sketch of initial blank and drawing of a part allow to calculate *total accuracy improvement*

$$U_{\Sigma} = \frac{T_b}{T_p},$$

where T_b and T_p are tolerances for initial blank and final part respectively.

Total improvement consists of particular *operation improvements*, that is, each from sequent machining steps provides improvements of the mentioned characteristics in U_i times

$$U_i = \frac{T_{i-1}}{T_i} ,$$

where T_{i-1} and T_i are tolerance for machining of a workpiece at previous (i–1) and current i manufacturing steps respectively.

Character of these changes in improvements is not uniform. They are distributed along the stages of machining in the following manner [8, 13]:

- for steps of *rough machining* the attainable values are $U_i \leq (5\ldots6)$ that corresponds to improvements of accuracy by 3–4 accuracy grades;
- for steps of *finish machining* $U_i = (3\ldots4)$, that is, accuracy improvements are 2–3 accuracy grades;
- for steps of *fine-finish machining* (with required accuracy level of 5–7 accuracy grades) $U_i = (1.5\ldots2)$ accuracy can be improved only by one accuracy grade.

Mean values of improvements corresponding to the machining stages are

$$U_1 = 6.4; \quad U_2 = 4.0; \quad U_3 = 2.5; \quad U_4 = 1.6.$$

These numerical values were rounded off and appeared to be a fragment of basic series of linear numbers R5 (geometric progression with index 1.6).

The analysis results above allow to introduce the conventional value of *average improvement* $U_A \approx (2.5\ldots3.0)$, which is attained in one step of metal-cutting processing. This value is used in the empirical formula for calculations of *number of manufacturing steps* at the condition of obtaining the dimension accuracy specified by a part drawing [14]:

$$n_T = \frac{lg\,U_\Sigma}{lg\,U_A} = \frac{lg\,U_\Sigma}{lg\,2.9} = \frac{lg(T_b/T_p)}{0.46}. \quad (3.5)$$

When the result is a number with decimal fraction up to five tenth not including, the rounding off to a whole number (integer) is performed with decrease, and starting from five tenth – with increase. When the result number is any value between above 0 and 1,5 not including the rounding off is performed to 1.

Similar calculations are performed for roughness, as well as plans for machining of elementary surfaces are developed. At that the experimental relationship between accuracy (tolerance) and roughness is taken into account. The higher the accuracy of surface is, the lower should be hight of microirregularities; otherwise it becomes comparable with a dimension tolerance and in exploitation a part quickly loses accuracy of its dimensions because of crushing of microirregularities peaks. In these cases (surfaces of high accuracy) it is recommended to assign hight of microirregularities R_z depending on a dimension tolerance T from empirical dependence (Fig. 3.4) [13, 15]

$$R_z \leq (0.1\ldots0.25)T. \quad (3.6)$$

Smaller values of roughness are assigned for dimensions above 100 mm, the larger values – for smaller dimensions.

Typical values for a manufacturing step of rough turning are: Ø54h12 with tolerance T = 300 μm and roughness R_z = 50 μm (50/300 ≈ 0.167).

Here should be noticed that this dependence does not exclude specifying the high

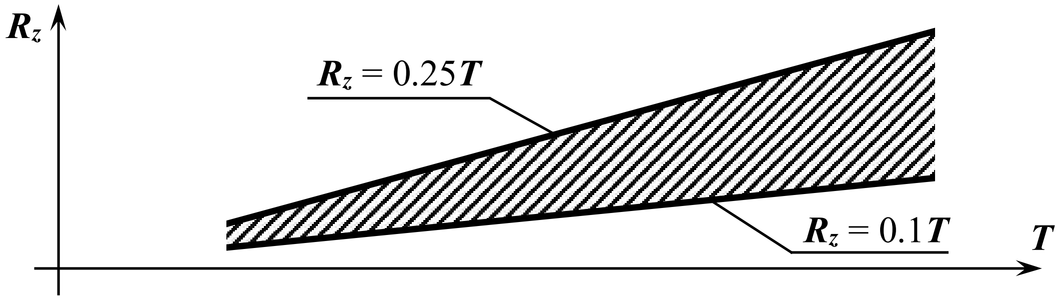


Fig. 3.4. Dependence between roughness and dimension tolerance for a machined surface: the lower line limits roughness values for dimensions above 100 mm; the hatched area and upper line are for dimensions less than 100 mm

surface finish (small roughness value below the lower line) for surfaces of low accuracy (large tolerance of dimension), for example, grinding of face with dimension-coordinate 54h10, $\boldsymbol{T}$ = 120 µm and $\boldsymbol{R_a}$0.63 ($\boldsymbol{R_z}$ = 2.5 µm), 2.5/120 ≈ 0.021.

Tight correlation of dimension tolerance and roughness of a machined surface allows using the dependence similar to the (3.5) for determination of number of manufacturing steps necessary for obtaining the roughness specified in a drawing

$$n_R = \frac{lg\left(R_{zb}/R_{zp}\right)}{lg\,2.5} = \frac{lg\left(R_{zb}/R_{zp}\right)}{0.4}. \qquad (3.7)$$

The values n_T and n_R calculated from the formulas (3.5) and (3.7) are rounded off to integers and the larger of them is adopted (n_A) for further consideration.

Very important to emphasize that flat surfaces (geometric planes) have no thickness dimension. Therefore, for faces of a workpiece only the calculations of number of manufacturing steps by roughness n_R are performed. For these flat surfaces consideration of dimensions-ccordinates and their tolerances (accuracy grades) appears at that stage of planning of manufacturing process, when analysis of dimension chains is performed. And at this stage the dependence (3.6) should be taken into account, when assigning the accuracy grade of a dimension-coordinate between a machined face and another face being an initial datum.

3.4.2. Development of routes for machining of main surfaces of part

According to a purpose various surfaces of a part perform various functions. Therefore, the requirements for these surfaces can be very different: by accuracy of dimension, surface roughness, hardness, position accuracy relative to another surface, etc. These requirements are ensured by application of various machining methods. The methods are selected depending on overall dimensions, nature and accuracy of initial blank, material properties, available equipment in a production shop and other factors. At that, it is taken into account that one or several possible preliminary (less precise) methods procede a considered method of final machining. Thus, preliminary reaming procedes final reaming, and core drilling or drilling procedes preliminary reaming.

It means that in a ***route of surface machining*** (RSM) each sequent method should be more accurate than the previous one. Manufacturing tolerance for a dimension and a surface roughness, obtained at previous manufacturing step, should be in the ranges that ensures normal application of a planned sequent method of machining. For example, one should not apply fnish reaming after rough boring, because the reamer teeth would operate with inadmissible large cutting depth determined by depth of all errors of the previous machining method (rough boring). Or it is not reasonable to apply final grinding of round surface after rough turning, because the grinding step would take very long period of time in order to remove thick layer of machining allowance determined by rough turning errors. When selecting methods for rough, finish and fine-finish machining of a separate surface, production engineer uses reference data (tables) of economical accuracy of various machining methods. As a rule, there are several possible variants of RSM in order to obtain final parameters of a considered surface. And depending on the RSM variant the quantity of manufacturing steps can be different.

It is desirable that *repeatability of the selected machining methods* would be maximal in the routes of machining of different surfaces belonging to the same part. It shortens a variety of necessary cutting tools and allows development of a manufacturing process on the *principle of operations concentration* with maximum combination of manufacturing steps for different surfaces in one operation that reduces quantity of mountings (operations) along manufacturing process, increases productivity and accuracy of machining [4].

The total accuracy improvement is distributed along manufacturing steps (particular operation improvements) for a considered surface according to the geometric progression (see the above paragraph 3.4.1) and this geometric progression is *decreasing* by tolerance and roughness values along several sequent manufacturing steps. It means that each sequent step should have assigned tolerance and roughness of surface smaller than parameters at previous manufacturing step.

Rule of progressive decrease states that values of tolerances and roughness should be distributed according to decreasing geometric progression along several manufacturing steps between the parameters of initial blank surface and the parameters of final part of the like surface. It is convenient to make decreasing distribution of accuracy with use of accuracy grades. Here it is reasonable to mention that according to the standard the tolerances values are distributed by geometric progression along numbers of accuracy grades. Thus, for the range of nominal dimensions from 30 to 50 mm tolerance values for accuracy grades from the 6^{th} to the 16^{th} are: 16, 25, 39, 62, 100, 160, 250, 390, 620, 1000, 1600 μm. These values correspond to geometric progression with index 1.6.

Rule of progressive decrease states that values of tolerances and roughness should decrease very fast at the first manufacturing steps with rough machining and slow at the steps of finish and fine-finish machining.

For example, tolerance (deviations) of initial blank dimension corresponds to the 16^{th} accuracy grade, and like dimension of final part surface (Ø40h6) – to the 6^{th} accuracy grade. Total difference in accuracy equals 10 accuracy grades and it should be distributed, for instance, along four manufacturing steps. According to the recommendations (see the above paragraph 3.4.1) accuracy improvements along stages of manufacturing process with use of accuracy grades can be distributed as: 10 = 4 + 3 + 2 + 1. Hence, accuracy grades of dimensions along four manufacturing steps will be distributed as follows:

IT16 (initial blank) – h12 – h9 – h7 – h6 (part).

Though distribution of 10 accuracy grades looks like arithmetic progression one should take into account geometric progression of tolerances values. Thus, for a considered case, accuracy improvements are: 1600/250 = 6.4 for rough machining step (4 grades' improvement), 250/62 = 4.03 for semi-finish step (3 grades), 62/25 = 2.48 for finish step (2 grades), 25/16 = 1.56 for fine-finish step (1 grade). The values of particular improvements approximately correspond to the decreasing geometric progression with index 1/1.6.

Depending on combination of accuracy and roughness parameters of initial blank and part and number of manufacturing steps the distribution of accuracy grades differences can be a monotonic progression (for example, 6 = 2 + 2 + 2), combined (for instance, 6 = 3 + 1 + 1 + 1). There are also situations, when only one parameter (accuracy or roughness) is changed in a manufacturing step. For example, when applying fine grinding step followed by superfinishing step without changing the accuracy of round surface dimension, but improving only roughness parameter. In this case no accuracy grade change would occur: 6 = 3 + 2 + 1 + 0.

Basic deviation for all manufacturing steps are assigned as for basic item (basic hole H or basic shaft h), that is, a whole tolerance is located in "metal".

According to the rule of progressive decrease a roughness is distributed similar to accuracy. When assigning a roughness along manufacturing steps it changes at the first steps very rapidly (at rough machining in 3–5 times), and then slowly (at fine finish machining in 1.5–2 times). In the considered example the roughness distribution can be as follows:

$\boldsymbol{R_z}$160 (initial blank) – $\boldsymbol{R_z}$40 – $\boldsymbol{R_z}$12.5 – $\boldsymbol{R_z}$5($\boldsymbol{R_a}$1.25) – $\boldsymbol{R_a}$0.80 (part).

Here the roughness improvements are: 4, 3.2, 2.5 and 1.56 times. This series of numbers is a practical realisation of the progressive decrease rule for roughness.

Then the machining methods are selected and assigned according to the accuracy and roughness parameters already distributed along manufacturing steps. When selecting machining methods for manufacturing steps, the *economical limits of accuracy and roughness* of various methods should be taken into account. For the considered example of producing the external round surface, the selected machining methods (route of surface machining) can be as follows:

- rough turning (h12, $\boldsymbol{T}$ = 250 μm, $\boldsymbol{R_z}$40);
- finish turning (h9, $\boldsymbol{T}$ = 62 μm, $\boldsymbol{R_z}$12.5);
- preliminary grinding (h7, $\boldsymbol{T}$ = 25 μm, $\boldsymbol{R_z}$5);
- final grinding (h6, $\boldsymbol{T}$ = 16 μm, $\boldsymbol{R_a}$0.80).

Here the economical limits of accuracy grade IT8 and roughness $\boldsymbol{R_z}$10 for turning machining method are used, and for grinding method – IT6 and $\boldsymbol{R_a}$0.32.

Development of *routes for machining of flat surfaces* (*faces*) differs from RSM of round surfaces. As already mentioned, for faces the calculations of number of manufacturing steps are performed only by roughness parameter. Thus, only the roughness distribution is performed along manufacturing steps. Hence, selected economical machining methods are determined only by roughness parameter. If the considered flat surface is an element of a round part, a production engineer usually selects the same machining methods as for round surfaces. For example, for a face the distribution of roughness along three manufacturing steps is:

$$\boldsymbol{R}_z160 \text{ (initial blank)} - \boldsymbol{R}_z40 - \boldsymbol{R}_z12.5 - \boldsymbol{R}_z5 \text{(part)}.$$

Then the route of surface machining for this face will be as follows:

- rough turning ($\boldsymbol{R}_z40$);
- finish turning ($\boldsymbol{R}_z12.5$);
- grinding ($\boldsymbol{R}_z5$);

Appendix 7 contains tables of economical limits of accuracy and roughness for external and internal cylindrical and flat surfaces at various machining routes as well as for threaded and toothed surfaces.

The calculations of numbers of manufacturing steps and development of machining routes are performed for all significant (main) surfaces (ref. Fig. 3.1) and usually submitted in the form of table.

3.5. Development of preliminary plan of manufacturing process

Development of plan of manufacturing process includes description of structural diagram of manufacturing process, selection and substantiation of manufacturing datums, and itself development of preliminary plan of manufacturing process.

3.5.1. Structure of manufacturing process

Manufacturing metal-cutting processes are divided into three stages: rough machining, finish machining and fine-finish machining [1] (Fig. 3.5).

Rough machining stage consists of rough-machining operations, in which up to 60…70 % total machining allowance is removed. At this stage a uniform distribution of allowances along surfaces are provided for the sequent machining, surface layer defects are removed from a blank, mounting datums are prepared for further machining with higher accuracy. Typical parameters obtained in this stage are accuracy grades IT14–IT12 and surfaces roughness $\boldsymbol{R}_z80$–$\boldsymbol{R}_z50$.

At *finish machining stage* up to 30% total machining allowance is removed and a part gets nearly final geometric shape. Most of surfaces are produced with the specified accuracy of dimensions and roughness: dimensions with accuracy up to 8 grade and roughness not better than $\boldsymbol{R}_z10$. Small design elements of lower accuracy like holes, grooves, slots, fillets, chamfers are performed at the end of this stage. Manufacture of many parts stops at this stage. Machines of improved accuracy are used for finish machining of many surfaces of a part. If necessary, gear-cutting operations are also included into this stage as final operations in order to perform them from carefully prepared mounting datums and avoid damages of teeth at previous operations.

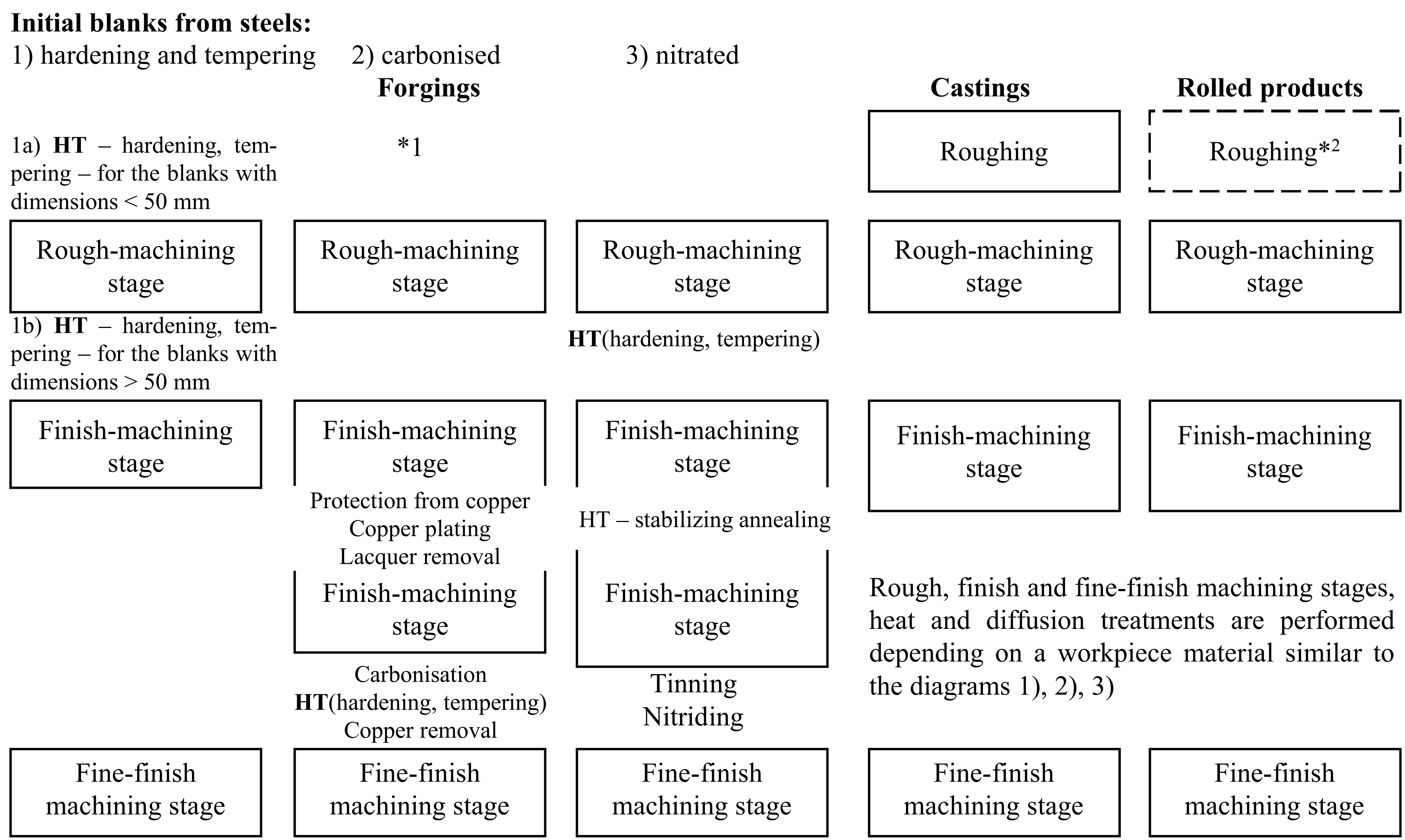


Fig. 3.5. Structure diagrams of manufacturing processes for producing parts from steel blanks: *1 – after hot plastic deformation blanks are heat treated (normalisation); *2 – stage of very rough machining – roughing – is introduced when hot smithing, setting of a rolled product or large floodings are applied to initial blank

Fine-finish machining stage includes manufacturing operations directed only to *several surfaces of the highest accuracy and surface finish* (IT7–IT5, $\boldsymbol{R_a}$1.25–$\boldsymbol{R_a}$0.16 and better) and making such sensitive to damages elements like splines, threads, etc. Also the requirements for accuracy of position of some surfaces relative to other sufaces (axes) are perormed. This stage for gear-type parts is completed by operations of fine-finish machining (gear grinding, gear shaving, burnishing, etc.).

Division of a manufacturing process into stages gives several positive effects: machines of different precision classes are grouped in specialised production sectors; rough machining is performed in worn or normal-precision machines by workers of lower qualification; fine-finish machining is moved to the end of route and, thus, probability of damages of finally machined surfaces is significantly reduced.

Development of *route for machining of a workpiece* gives general plan of machining and determines contents of operations on basis of earlier analised and selected routes for machining of separate surfaces. Sequence of operations on each stage is determined mainly by selection of mounting datums on a workpiece. Usually external and internal cylindrical surfaces and flat surfaces (faces) are selected as datums. For round workpieces a set of datums includes cylindrical surface (external or internal) and adjoining face. In some cases workpieces, for example, gear wheels are mounted on flanks of teeth with use of balls, rolls or toothed sectors. Mounting on gear ring is important for machining of those round and flat surfaces, which will be the datums for further fine-finish machining of the same gear ring.

In manufacturing operation, first of all and obligatory the manufacturing datums (the surfaces selected as datums) are machined. Then all the rest of surfaces are machined with paying attention to the surfaces, which will be of the highest accuracy at the end of manufacturing process. Usually in operation machining of a workpiece starts from the face, from which other flat surfaces can be coordinated. Then outside surfaces are machined starting from the largest diameter, and after that – internal surfaces.

Heat and/or diffusion treatments make significant changes in manufacturing route of a workpiece machining. Heat treatment, as is well known, causes errors in a form of workpiece, in relative positions of surfaces and worsens roughness. Sometime the operations of straightening or repeated machining of some surfaces are introduced into workpiece machining route in order to remove these defects. Besides, heat treatment is often connected with some specific operations such as copper plating of surfaces, which should not be carbonised, and other.

When performing the standardised charts of manufacturing processes, the operations of technical inspection are introduced.

Holes, flats, grooves, slots, fillets and other similar design elements are usually machined in finish-machining stage before hardening (heat treatment). Splines, threads, keyslots and other sensitive elements are produced after hardening to avoid their damages. Anticorrosive coats are applied after final inspection a produced part.

It is recommended to use typical manufacturing processes for development of new machining routes. This approach would shorten period of process development and reduce number of irrational technological decisions.

Sample typical routes for producing gear wheels from carbonised and nitrated nitrated steels are submitted in the Appendix 8. They are similar; the differences are related to type and place of heat and diffusion treatments in structure of manufacturing process [8]. Typical route for gear wheels from hardening and tempering steels is not submitted, because this type of steels is rarely used in aircraft engines technology. This route differs from the route for carbonised gear wheels not so significant: operations of copper plating, carbonisation, hardening and tempering are absent. Heat treatment of wokpieces from hardening and tempering steels with characteristic dimension less than 50 mm is performed before rough-machining stage, with characteristic dimension more than 50 mm – after rough-machining stage in order to provide deep-hardening.

These machining routes for gear wheels are typical and have a general structure for other types of parts by design configurations. And so, they can be used for development of manufacturing processes of other parts except machining of gear rings.

3.5.2. Selection and substantiation of manufacturing datums

One of the most complicated and principal problems in planning of manufacturing processes is determination of manufacturing and measuring datums. Correctness of selection of manufacturing datums mainly determines: actual accuracy of the performed dimensions; accuracy of relative position of machined surfaces; complexity level of workholding devices, cutting and measuring tools; total productivity and production costs. Basic definitions related to the terminology, classification and theory of locating are stated by the standard GOST 21495-76.

Initial data for selection of manufacturing datums are: drawing of a part, technical conditions for its manufacture, type of initial blank and its surfaces quality, desired level of automation.

For round workpieces two sets of datums are usually enough for machining from initial blank to a final part in all operations of manufacturing process. Typically set of datums consists of external or internal cylindrical surface and mating flat surface (face).

When selecting sets of datums for a manufacturing process, two principles should be observed: principle of datums constancy and principle of datums superposition.

Principle of constancy of mounting datums requires that those mounting datums (sets of datums), selected at the beginning of manufacturing process for the first operations, should be kept to its final operation. Observation of constancy priciple for mounting datums ensures smaller variety of workholding devices that reduces production costs. But often, when making a dimensional analysis, the necessity of change of already selected datums appears in order to obtain the dimension chains equations suitable for their solutions.

Principle of superposition of datums means coincidence of manufacturing datums (mounting and initial datums) with design datum and measuring datum. Observation of superposition principle for design, mounting and initial datums ensures shorter dimension chains in dimensional analysis of manufacturing process. In many cases realisation of superposition principle is impossible. And so, production engineers endeavour to arrange at least coincidence of mounting and initial datums in operation sketches when planning a manufacturing process.

Selection of surfaces, which will be used as mounting datums for the sequent operations, procedes selection of datums for the first operation. Such mounting datums for the most of operations are usually main surfaces, from which many dimensions are specified in a drawing (design datums) coordinating positions of other critical surfaces of a part. Deviation from this rule is possible, if a datum surface is rather short and insufficient for reliable mounting of a workpice. As a rule, there are several variants of locating diagrams for the same workpiece. Each variant has positive and negative sides. Only analysis of different variants will allow to determine the better one. Having determined sets of datums for the most of operations, production engineer selects mounting datums for the first operation.

Here there are several recommendations for selection of mounting datums:

1) datum surfaces should have enough length (area) to diminish elastic and surface plastic deformations under clamping force and, thus, to increase accuracy of mounting;

2) in the first operation the surfaces of the largest diameter and the largest length (if possible) are selected as datums for the reliability of clamping;

3) datum surfaces should be smooth for steadiness of locating. It is not recommended to use surfaces with the parting line imprints of forging dies or casting moulds, rests of gating systems and other similar elements;

4) it is recommended to use surfaces of the highest accuracy and surface finish as datums. Datum surfaces are permanently improved from the beginning of manufacturing process to its end, that is, they are machined many times. High-accuracy surfaces also need large quantity of machining steps. Therefore making coincidence of mounting datums with high-accuracy surfaces reduces labour-intensiveness of a part production as a whole;

5) it is necessary that mounting datums ensure access for machining of largest quantity of surfaces (complexes of surfaces);

6) after the first operation the mounting datums should be changed, that is, double use of rough (unmachined) datums are extremely undesirable.

Complex of surfaces is a collection of main surfaces, which should be machined in one mounting in order to provide the specified requirements for their relative positions.

Locating and clamping elements are depicted in operation sketches by special symbols introduced by the GOST 3.1107-81 (Appendix 9) according to the selected mounting diagrams.

3.5.3. Performance of preliminary plan of manufacturing process

Using the recommended routes for typical manufacturing processes (ref. Appendix 7), typical structures (ref. Fig. 3.5) and routes for surfaces machining (paragraph 3.4.2), the preliminary plan of manufacturing process for a considered part is developed. Thus, *rough-machining manufacturing steps* assigned for each surface should be included into operations of *rough-machining stage*, *semi-finish and finish steps* – into operations of *finish-machining stage*, and *high-accuracy manufacturing steps* – into operations of *fine-finish stage* (Fig. 3.6).

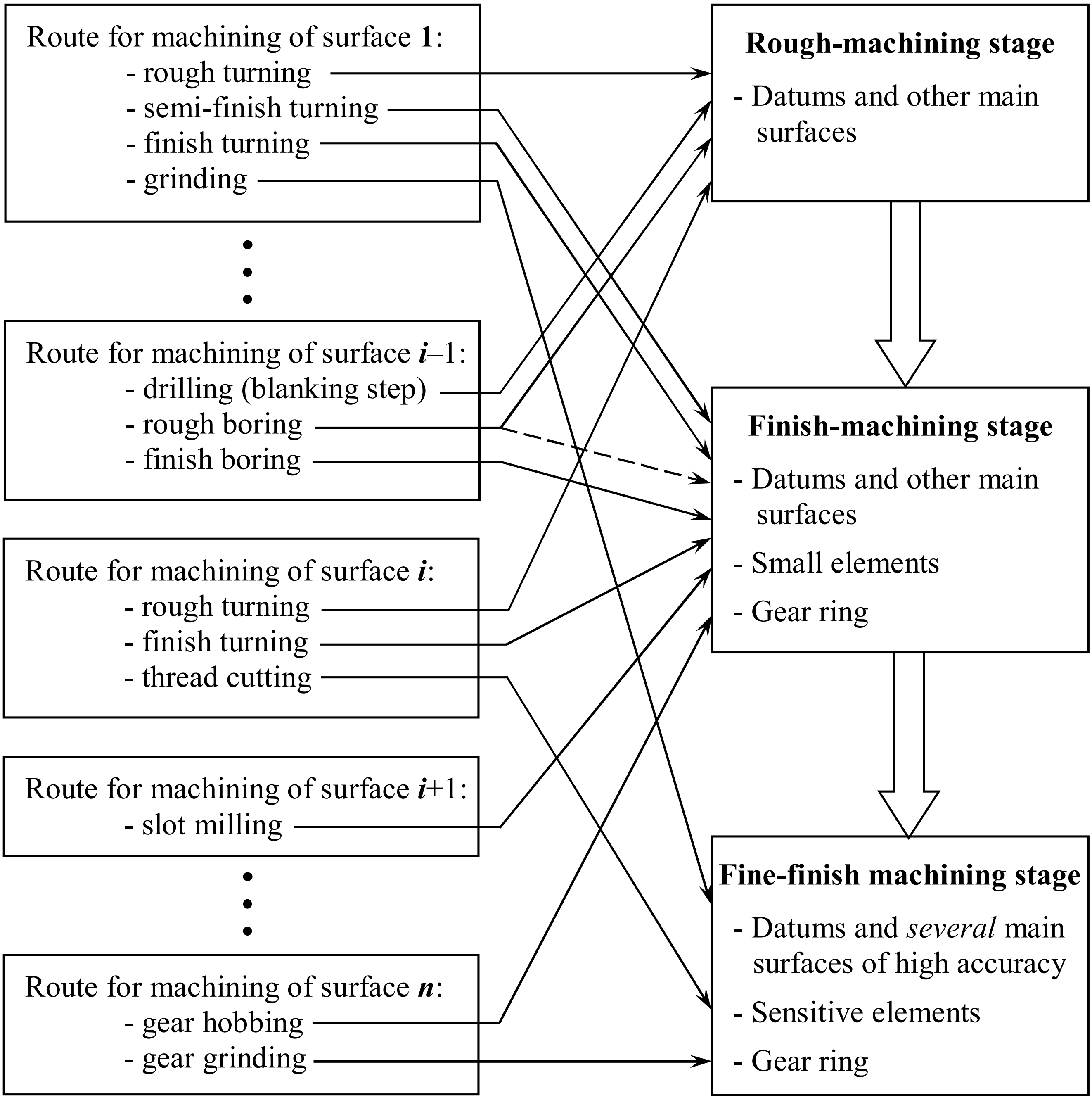


Fig. 3.6. Diagram for planning of manufacturing process based on routes for machining of main surfaces

When developing a preliminary plan of manufacturing process for a round part, the operations are arranged in the following manner in order to transform low accuracy of intial blank into high accuracy of a final product (Fig. 3.7).

When machining in turning lathes, in the first operation 05 the workpiece is mounted in workholding device on rough surfaces of left-hand segment of workpiece (IT18–IT15, R_z320–R_z80). Surfaces 3, 4, 5 of another (right-hand) segment of a workpiece have free access for cutting tools and they are machined with improvement of accuracy and roughness (IT14–IT12, R_z80–R_z20). Then in the next turning operation 10 workpiece is rotated in 180° for mounting on already machined surfaces with higher

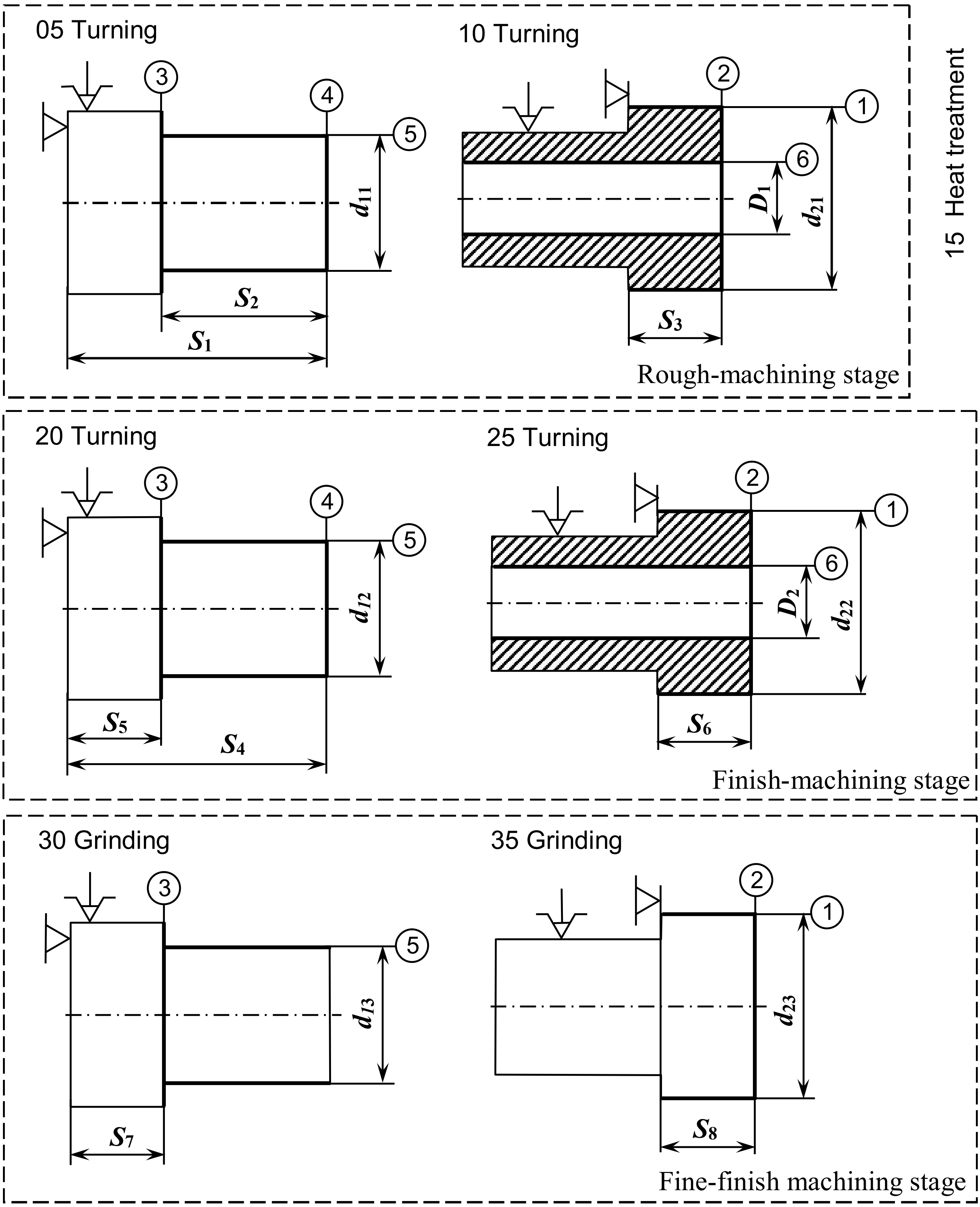


Fig. 3.7. Example of preliminary plan of manufacturing process

accuracy in comparision with the initial blank accuracy. Another (rough) side of workpiece (surfaces 1, 2, 6 with free access for cutting tools) is machined with generation of higher accuracy and better roughness (IT14–IT12, $\boldsymbol{R}_z$80–$\boldsymbol{R}_z$20).

In the third machining operation 20 the workpiece is again rotated and mounted on the improved datum surfaces and from the better datums the surfaces 3, 4, 5 are machined thus making further improvements of accuracy and roughness (IT11–IT10, R_z40–R_z10). And in the forth operation 25 these improved surfaces are used as datums for further turning and improvents of the opposite side surfaces (1, 2, 6). Thus, performing machining of surfaces with free access for cutting tools and making rotations of a workpiece between operations one can gradually improve accuracy and roughness of datum surfaces and other surfaces from rough parameters of initial blank to high accuracy and surface finish of a final part.

Here it is very important to understand that from rough (unmachined) datums (IT18–IT15, R_z320–R_z80) the surfaces of high accuracy cannot be produced, for example, IT14–IT12, R_z80–R_z20, but ***not*** *jump to final high accuracy*, for example, directly to (IT7–IT5, R_a1.25–R_a0.16). Improvements of surfaces accuracy and roughness are performed in smaller steps, gradually, from one operation to another, from the beginning of manufacturing process to its end.

Usually *rough-machining stage* includes 2 or 3 first operations, when all main surfaces are machined at least one time (ref. Fig. 3.7).

The next operations are included into *finish-machining stage* with performance of semi-finish and finish turning steps, hole drilling and slot milling steps, gear-cutting step (if necessary). Most of surfaces are produced with final specified parameters: IT12–IT8, R_z25–R_z10.

As a rule, fine-finish machining stage includes the grinding operations, in order to produce high parameters (IT7–IT5, R_a1.25–R_a0.16) of several surfaces, and finishes with gear ring fine-machining operation (if necessary).

Sets of datums are selected for each operation according to the principles of superposion and constancy, other recommendations (ref. paragraph 3.5.2).

When considering a machining of datum surfaces (flat and cylindrical), the following recommendations should be performed. *For high accuracy of mounting in current operation both datum surfaces are machined in previous operation*. Both datum surfaces should be machined in one mounting of the same operation for their highest accuracy of relative position. *The calculated numbers of manufacturing steps can be exceeded* for flat and cylindrical surfaces in order to machine **both** surfaces included into set of datums.

Sketches for operations are performed in arbitrary scale, but with observation of proportions and accurately. In the sketches a number and name of operation are written in the top left-hand corner, locating and clamping diagram is shown on the image of workpiece, the machined surfaces are marked by thick lines. Dimension lines are shown without operation dimensions (numerical values) – "dumb" dimensions lines.

3.6. Determination of machining allowances

3.6.1. Basic concepts and definitions

Allowance is a layer of material to be removed from a surface of workpiece in process of its machining with aim to obtain specified parameters of a considered surface (shape, dimensions, roughness, etc.).

Value of machining allowance is measured along a normal to the machined surface. Allowances are specified *per dimension* (symmetric or double-side allowance) for round surfaces and some symmetric elements and *per side* (asymmetric allowance) for faces, flat surfaces, contoured surfaces.

Operation allowance is a layer of material removed from a surface at performance of one manufacturing operation.

Intermediate allowance is a layer of material removed from a surface at performance of one manufacturing step. If the allowance is removed in one step of a considered operation, then this intermediate allowance is operation allowance.

Total allowance is a layer of material removed from a workpiece surface as a result of performance of all manufacturing operations (steps). For round surfaces double-side allowance $2\boldsymbol{Z_\Sigma}$ can be calculated as a difference of nominal dimensions of initial blank $\boldsymbol{d_{b\,nom}}$ and final part $\boldsymbol{d_{p\,nom}}$ for shafts

$$2\boldsymbol{Z_\Sigma} = \boldsymbol{d_{bnom}} - \boldsymbol{d_{pnom}},$$

and for holes as a difference of nominal dimensions of final part $\boldsymbol{D_{p\,nom}}$ and initial blank $\boldsymbol{D_{b\,nom}}$

$$2\boldsymbol{Z_\Sigma} = \boldsymbol{D_{pnom}} - \boldsymbol{D_{bnom}}.$$

Total allowance for a considered surface is also equal to sum of nominal values of operation (intermediate) allowances along all manufacturing operations (steps)

$$2\boldsymbol{Z_\Sigma} = \sum_{\boldsymbol{i}=1}^{\boldsymbol{n}} 2\boldsymbol{Z_{i\,nom}},$$

where $2\boldsymbol{Z_{i\,nom}}$ is a nominal operation (intermediate) allowance in the $\boldsymbol{i}$ operation (step); $\boldsymbol{n}$ is a quantity of operations (steps) in machining of a considered surface.

Composition of allowance for current operation should include all errors and defects that appear at previous step of machining and also errors of workpiece mounting in current operation (Fig. 3.8).

Quality of a workpiece surface at any stage of its machining is characterised by *roughness* (height of microirregularities) $\boldsymbol{R_z}$ and by *depth of defective surface layer* $\boldsymbol{h}$. In order to avoid sequent accumulation of material structure defects the value of allowance should ensure removal of microirregularities and surface layer with defective

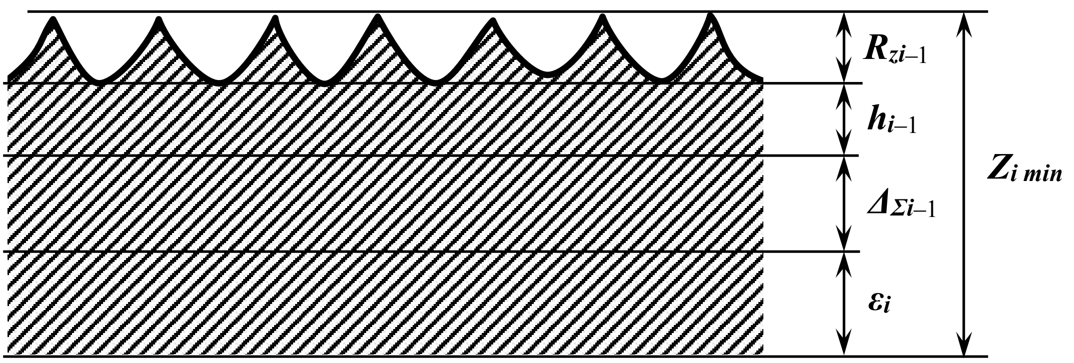


Fig. 3.8. Diagram illustrating components of minimum machining allowance

structure, both obtained from the previous manufacturing step.

Accuracy of a workpiece is characterised by tolerances of dimensions, as well as by deviations of form and surfaces positions. Non-uniformity of allowance distribution is caused by *displacement* (shift) of forging upper die relative to the lower die or one half of casting mould relative to another half Δ_d (ref. Fig. 3.2) and by *warping* Δ_w (form errors: deviation from flatness, axis deviation of round surfaces, etc.). They should be included into the allowance value as a total form deviation Δ_Σ.

Not all deviations of form and positions of blank surfaces are included into allowance, but only those, which are not covered by a dimension tolerance. Such deviations as ovality, barreling, taper, deviations from parallelism of planes are limited by a definite portion of dimension tolerance. Deviations related to the non-straightness of axes or generating lines, displacements of axes and concavity of faces should be obligatory taken into account.

Deviations of form and positions of initial blank surfaces are copied in some extent to the workpiece surfaces at sequent metal-cutting operations because of some elasticity (non-stiffness) of technological machining system, but these deviations are gradually reduced as a result of performance of each manufacturing step.

On the other hand processing in metal-cutting machines causes new deviations of form and positions of workpiece surfaces. These new deviations are generated by *error of workpiece mounting* ε, type of machining method, geometric errors of a machine and workholding device, cutting conditions, diagrams of locating and clamping of a workpiece and by other factors. These technological deviations result in errors of a machined surface and should be compensated by respective increase of allowance value.

So, resulted maching error is a consequence of residual errors of previous machining operation and errors appeared in current operation (ref. Fig. 3.8).

Hence, a minimum value of allowance should guarantee removal of a surface defective layer, compensation of errors of previous machining operation and errors of mounting in current operation in order to obtain specified parameters of a surface. Thus, *observation of concept of minimum machining allowance in manufacturing operations will ensure quality of separate surfaces and a part in the whole*.

3.6.2. Methods for determination of minimum machining allowance

Determination of machining allowances can be considered as the first step in procedures for calculations of operation dimensions. According to the literature sources there are three methods for determination of minimum machining allowance: *analythical*, *normative* and *normative-analythical*.

Professor V. N. Kovan developed ***analythical method*** for calculations of machining allowances based analysis of factors influencing value of allowance. According to the method a calculated value of allowance equals

$$Z_{i\,min} = R_{z\,i-1} + h_{i-1} + \Delta_{\Sigma\,i-1} + \varepsilon_i\,, \qquad (3.8)$$

where $R_{z\,i-1}$, h_{i-1} and $\Delta_{\Sigma\,i-1}$ are roughness, depth of surface defective layer and total form error respectively resulted from previous (i – 1) machining operation; ε_i is a workpiece mounting error in current (i) operation.

Here the assumption is accepted that vectors of displacement $\vec{\Delta}_{di-1}$ and warping $\vec{\Delta}_{wi-1}$ are collinear and unidirectional for faces, and their sum is arithmetical

$$\Delta_{\Sigma\, i-1} = \Delta_{d\, i-1} + \Delta_{w\, i-1}. \qquad (3.9)$$

Displacement value Δ_d is not taken into calculations, when a workpiece face is formed in one half of die or casting mould.

Value of minimum symmetric allowance for machining of *surfaces of revolution* is calculated from

$$2Z_{i\, min} = 2\left(R_{zi-1} + h_{i-1} + \sqrt{\Delta_{\Sigma i-1}^2 + \varepsilon_i^2} \right). \qquad (3.10)$$

Here the vectors $\vec{\Delta}_{\Sigma\, i-1}$ and $\vec{\varepsilon}_i$ can hold any angular position, and so their most probable resultant value can be obtained by geometric summation (probabilistic approach).

Total form error of a workpiece $\Delta_{\Sigma\, i-1}$ is also determined by formula of geometric summation, because vectors $\vec{\Delta}_{di-1}$ and $\vec{\Delta}_{wi-1}$ can occupy any angular positions

$$\Delta_{\Sigma\, i-1} = \sqrt{\Delta_{di-1}^2 + \Delta_{wi-1}^2}\,. \qquad (3.11)$$

According to the analythical method the components of minimum allowance are analysed and necessary data are selected from technological handbooks [10]. The calculations results are the most exact values in comparision with other methods.

Normative method is based on fixed values of *minimum* allowance Z_{minN} for flat surfaces and $2Z_{minN}$ for round surfaces stated by normatives (data tables) for various methods of machining (rough turning of round surfaces, finish turning of round surfaces, preliminary grinding of faces, final grinding, etc.). A minimum allowance value depends on type of material (steels, cast irons, non-ferrous metals), type of initial blank (forgings, castings, rolled products), heat treatment, diameter and length of a machined surface (Appendix 10). Normative minimum allowance values are just selected from the data tables without analysis of factors described above for the analythical method.

Nomative method is easier than the analythical method, but gives the values of minimum allowance typically larger than the values calculated by analythical method. This feature ensures quality of a machined surface, but increases production expenses in some extent.

It is very important that using the normative value Z_{minN} ensures quality of a machined surface.

Normative-analythical method is based on fixed values of *nominal* allowance Z_{nomN} for flat surfaces and $2Z_{nomN}$ for round surfaces stated by normatives (branch standards) for various methods of machining [2]. Application of a normative nominal allowance instead of minimum normative makes the normative-analythical method even easier than the normative method. But there is one significant imperfection. In order to estimate quality of a machined surface a minimum value of allowance $\boldsymbol{Z_{imin}}$ should be calculated from the formula

$$\boldsymbol{Z_{i\,min}} = \boldsymbol{Z_{i\,nomN}} - \boldsymbol{T_{i-1}}, \qquad (3.12)$$

where $\boldsymbol{T_{i-1}}$ is a tolerance for dimension at previous ($\boldsymbol{i}$–1) manufacturing operation.

At previous rough-machining operation a dimension tolerance is usually large, and so often the $\boldsymbol{Z_{imin}}$ value can appear to be very small and even negative, that will not ensure quality of a machined surface [1]. Also this calculated $\boldsymbol{Z_{imin}}$ should be compared with normative $\boldsymbol{Z_{iminN}}$ used in the normative method that makes application of normative-analythical method not reasonable in many cases.

In general, the allowances are such elements of manufacturing process, which are not obligatory for performance. Indeed ***operation dimensions are obligatory for performance***. But *determination of allowances is an obligatory step* in calculations of operation dimensions.

3.7. Dimension analysis of manufacturing process and calculations of operation dimensions-coordinates between faces

Dimension analysis is based on *preliminary plan* of manufacturing process. Main tasks of dimension analysis are agreement of all operation dimensions-coordinates and their initial datums in order to organise rational dimension chains suitable for solutions. And final task is determination of intermediate (operation) dimensions between faces of a workpiece, as well as exact dimensions of initial blank.

Work on machines set for operations needs careful analysis and corrections of all intermediate dimensions in order to obtain final dimensions of a part automatically in final operations. Right solution of this task is based on the theory of dimension chains.

Dimension analysis of manufacturing process consists of several stages: development of dimension diagram of manufacturing process; detection of manufacturing dimension chains and their optimisations; compiling and solutions of equations of dimension chains [3].

When selecting mounting datums and making optimisations of dimension chains between faces, additional manufacturing steps can be also assigned to round surfaces in order to keep sets of mounting datums by the machining of datum face and datum round surface in the same operations.

3.7.1. Dimensions relations in machining processes

Dimensions of part specified in a drawing frequently can not be performed directly at machining.

Design dimension for a round surface is usually performed in result of definite sequence of operation dimensions from initial blank to the final part, and these operation dimensions are related to the same round element from one manufacturing operation to another.

But *design dimension-coordinate between two faces* typically appears as a result of performance of intermediate (operation) dimensions coordinated from other faces (initial datums). And so final design dimension is usually obtained indirectly via several operation dimensions located in some contour.

Two variants of turning operation are shown in Figure 3.9 (b and c). In the variant (b) both design dimensions [A_1] and [A_2] are performed *directly*, because respective manufacturing dimensions $\boldsymbol{S_1}$ and $\boldsymbol{S_2}$ are specified just so as design dimensions in the sketch (see Fig. 3.9-a and Fig. 3.9-b, dimension chains (1) and (2)). But such manner of specifying the $\boldsymbol{S_2}$ dimension does not allow automatic performance of this dimension, when applying the method of machines set for dimensions: initial datum of the $\boldsymbol{S_2}$ dimension does not coincide with mounting datum.

Superposition of initial and mounting datums in the variant (c) eliminates this limitation, but initial dimension [A_2] cannot be performed directly; it is determined by combination of two operation dimensions, that is, it is performed *indirectly* (see Fig. 3.9-c, diagram of dimension chain (2)):

$$[A_2] = \boldsymbol{S_1} - \boldsymbol{S_3}\,.$$

In this case error [$\boldsymbol{T_{A2}}$] of design dimension [A_2] is determined by errors of operation dimensions $\boldsymbol{T_{S1}}$ and $\boldsymbol{T_{S3}}$ performance:

$$[A_{2max}] = \boldsymbol{S_{1max}} - \boldsymbol{S_{3min}},$$

$$[A_{2min}] = \boldsymbol{S_{1min}} - \boldsymbol{S_{3max}}$$

and, hence, the difference of two equations is

$$[\boldsymbol{T_{A2}}] = \boldsymbol{T_{S1}} + \boldsymbol{T_{S3}}.$$

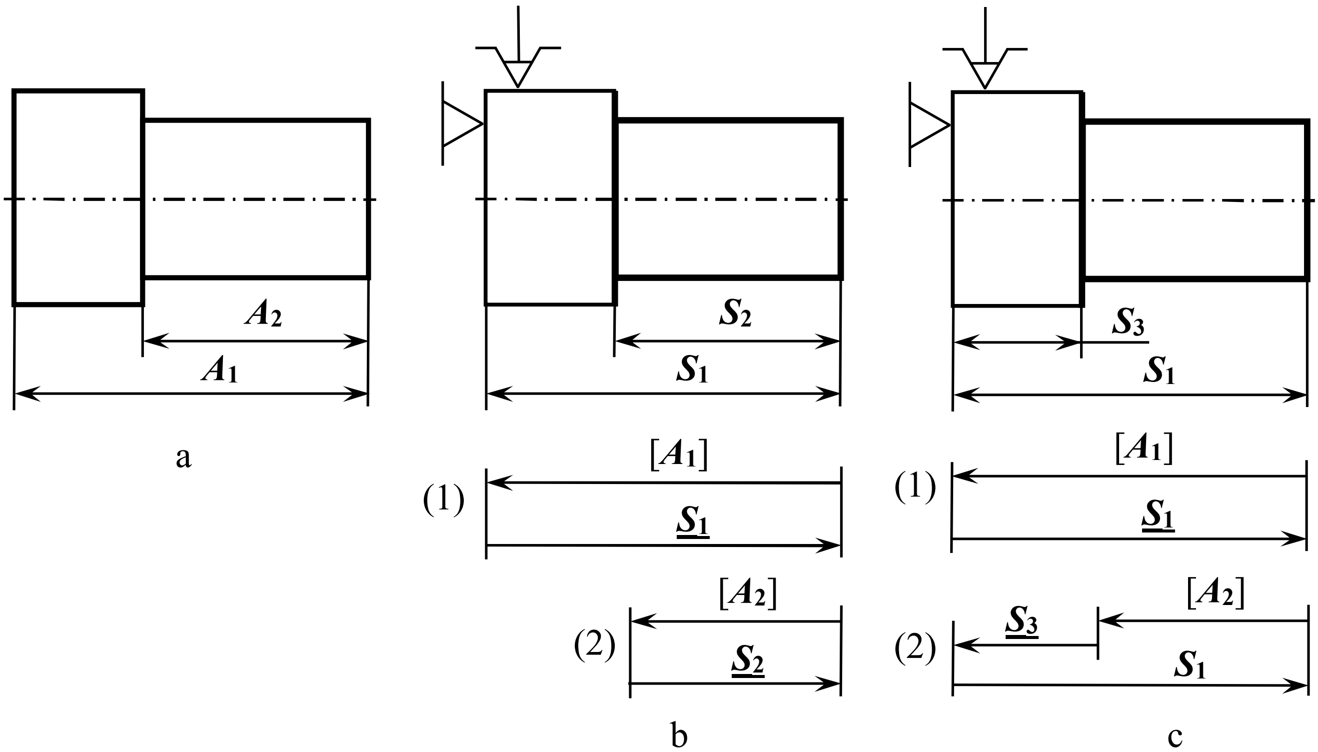


Fig. 3.9. Sketch of part (a), direct (b) and indirect (c) performance of design dimensions in manufacturing operations. Initial links are shown by square brackets and sought operation dimensions are underlined in the diagrams

Thus, *error (tolerance) of an initial link equals sum of errors (tolerances) of constituent links*.

In these cases the dimension chains are plotted in order to provide a specified accuracy of design dimensions.

Dimension chain is a combination of dimensions creating a closed contour and directly participating in solving a given task.

Manufacturing dimension chain is a dimension chain, with aid of which the parameters of a sought manufacturing dimension are found (nominal dimension and limit deviations).

Dimensions, which create a dimension chain, are *links* of dimension chain. Each dimension chain contains *only one initial link* (or closing link) and one or *several constituent links*.

By their influence on initial (closing) link the constituent links are divided into two types: *increasing* and *decreasing*. The increasing is a link, increasing of which increases initial (closing) link. The decreasing is a link, increasing of which decreases initial (closing) link.

Initial or *closing link* is a dimension directly connecting two surfaces, distance between which is necessary to provide (or determine) in a given task. *Initial link* is considered at solving a *direct task* of calculating the value of one of constituent links. And *closing link* appears as a result of solving an *inverse task*, when values of all constituent links are known.

Each dimension chain gives solution of only one task and may have only one initial (closing) link.

Dimensions of a workpiece, which are performed in manufacturing operations, are constituent links of a dimension chain. They are operation dimensions.

Dimension of a workpiece, which appears as a result of performance of constituent links (operation dimensions), is initial (closing) link of a dimension chain. Design dimensions and allowances are used as initial (closing) links.

Thus, at performance of technological dimensional calculations a complex problem is solved: operation dimensions and their tolerances are determined to ensure specified values of *design dimensions* and sufficient values of *allowances*.

At that, for initial link – allowance [$\boldsymbol{Z}$] – the minimum value is known, and for design dimension [$\boldsymbol{A}$] – nominal value, limit deviations and tolerance, when solving a direct task. For constituent links – operation dimensions – nominal values are unknown, but tolerances can be calculated or assigned.

In the general form the *original equation of dimension chain* (equation of closeness of dimension chain) is written as follows:

$$\boldsymbol{L} = \sum_{j=1}^{n_j} \boldsymbol{C}_j - \sum_{q=1}^{n_q} \boldsymbol{C}_q \,, \tag{3.13}$$

where $\boldsymbol{L}$ is a value of initial [$\boldsymbol{L}$] or closing $\boldsymbol{L}$ link; $\boldsymbol{C}_j$ are values of increasing constituent links; $\boldsymbol{C}_q$ – are values of decreasing constituent links; $\boldsymbol{n}_j$ and $\boldsymbol{n}_q$ are numbers of increasing and decreasing links, respectively.

In this case an *expected error (tolerance) of initial link* [$\boldsymbol{T}_L$] should not be less than sum of tolerances of constituent links T_{Sk}:

$$[T_L] \geq \sum_{k=1}^{n_j+n_q} T_{Cp} , \qquad (3.14)$$

where $\sum_{k=1}^{n_j+n_q} T_{Cp} = T_L$ – tolerance of closing link.

Analysis of the formula (3.14) gives the conclusion: it is necessary to compile dimension chains as short as possible (smaller number of constituent links). It allows to enlarge tolerances for constituent links (operation dimensions) that, in its turn, reduces production costs.

The formula (3.14) is usually used with sign " = " (instead of " ≥ ") in order to simplify solutions of dimension chains.

In comparision with a design dimension chain, manufacturing dimension chain contains only one unknown link.

Detection of manufacturing dimension chains is performed in a dimension diagram of manufacturing process, which includes all final and intermediate flat surfaces (faces) appeared after each manufacturing step, all design and manufacturing dimensions connecting these faces. Diagram gives an opportunity to reveal (detect) closed contours, which create dimension chains for each design dimension and allowance.

3.7.2. Development and optimisation of dimension diagram of manufacturing process

Dimension diagram of manufacturing process is plotted according to the following procedure (Fig. 3.10). Sketch of a part is developed in one or two (three) projections depending on its geometric configuration. For bodies of revolution one projection (view) is enough. The length dimensions with tolerance bands, specified in a drawing, are shown in the sketch. Design dimensions are designated by capital letter A_i, where i is a number of design dimension. Faces of a part in the sketch are covered with allowances Z_m, where m is a number of intermediate or final surface, from which this allowance is removed. Quantity of allowances attached to the faces of a part is determined from preliminary manufacturing process. Vertical straight lines are plotted from all flat surfaces of part and allowances. Surfaces (vertical lines) are numbered from left to right.

Lines of operation dimensions are plotted between *respective* vertical lines (faces) with applying the pictures of removed allowances. It is convenient to reveal length dimensions in the preliminary plan starting from final operation and moving back to the first operation. These revealed operation dimensions are sequentially plotted *top-down* in the dimension diagram. Operation dimensions are designated by capital letter S_k, where k is a number of dimension. Numeration of operation dimensions is performed in *bottom-up* direction (starting from the first operation dimension and going to the final). Initial blank dimensions are designated by capital letter B_r, where r is a number of dimension. They are plotted between vertical lines, symbolizing butt surfaces of initial blank, below operation dimensions. In the Fig. 3.10 dimension B_2 has no sense, because shape of initial blank has no step along external round surface (ref. Fig. 3.3).

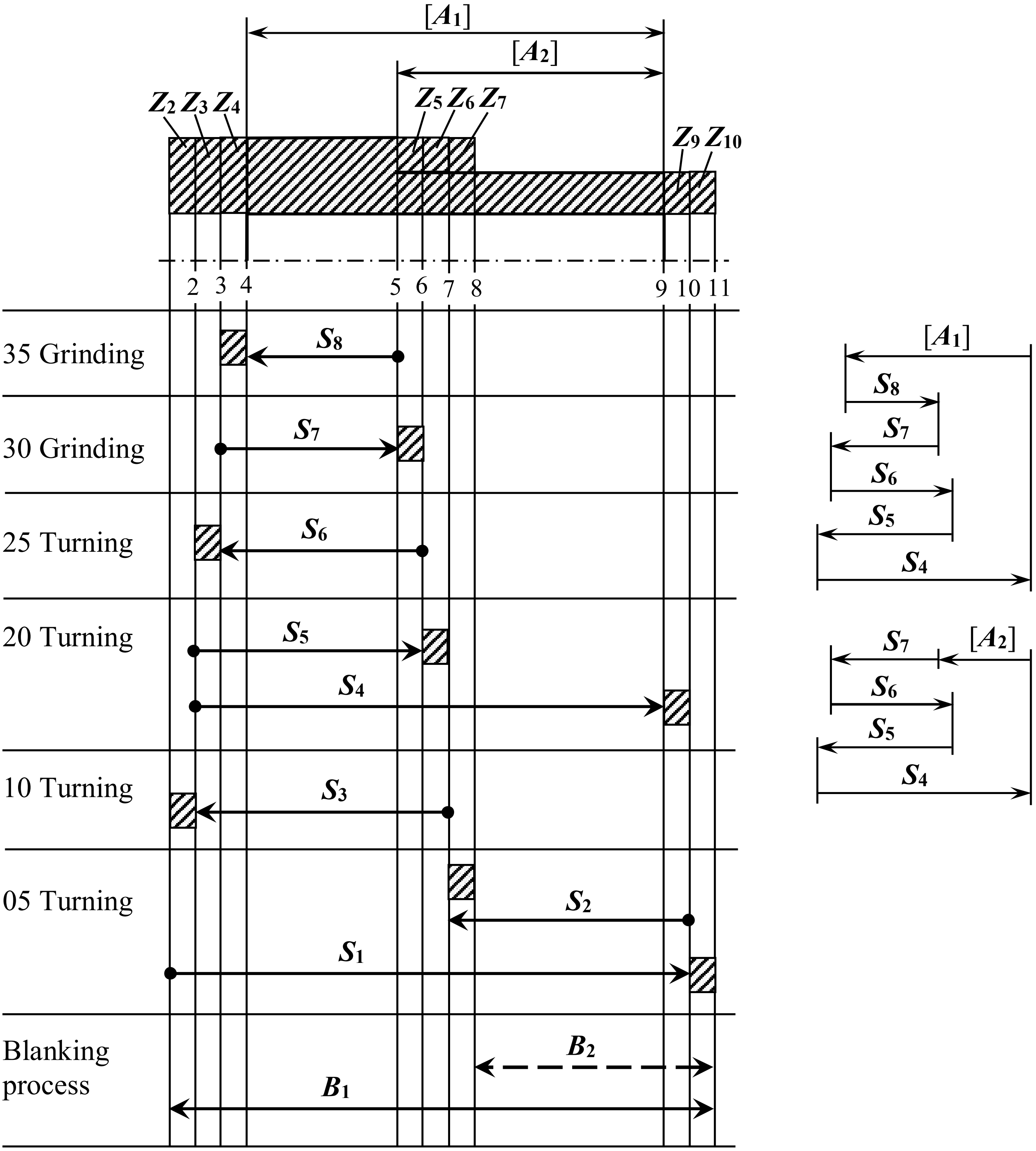


Fig. 3.10. Example of preliminary dimension diagram of manufacturing process (ref. Fig. 3.7) with two detected dimension chains with design dimensions as initial links

In the diagram dimension lines of design dimensions $\boldsymbol{A_i}$ and initial blank dimensions $\boldsymbol{B_r}$ have arrows on both ends. Dimension lines of operation dimensions (dimensions-coordinates) $\boldsymbol{S_k}$ are vectors directed from initial datum (respective vertical line) to the machined surface (another vertical line) after removal of allowance. Initial datum is specified by black bold point on a dimension line. Another end of dimension line is finished with arrow attaching to the machined surface (vertical line).

Operation dimensions S_k and initial blank dimensions B_r are unknown values. Quantity of equations necessary for finding these unknown values should be equal to the total quantity of the S_k and B_r links. Design dimensions A_i and allowances Z_m are considered as known values. They are used in equations of dimension chains as initial links. Therefore, as a rule, total quantity of known links (A_i and Z_m) should be equal to total quantity of unknown links (S_k and B_r). Deviations from this rule appear, when quantity of intial blank dimensions is less than quantity of design dimensions (ref. Fig. 3.10), because of simplified shape of initial blank (ref. Fig. 3.3).

Schemes of manufacturing dimension chains are revealed and composed for each operation dimension S_k and initial blank dimension B_r.

Detection of manufacturing dimension chains in dimensional diagram is begun from the last dimension (last operation), that is, by the *top-down* scheme. In the same sequence the equations of dimension chains are solved. Typically the first dimension chains are based on design dimensions as initial links (ref. Fig. 3.10).

Dimension chains and their equations are composed in such a manner that *each dimension chain contains only one unknown dimension* (link).

Difficulties in detection of dimension chains in dimensional diagram of manufacturing process are explained by their implicit character. In many cases dimension chains are not explicit and evident. So, some efforts should be applied to find them.

Detection of a dimension chain is started from the initial datum (bold point) on dimension line of unknown link. Motion is made along the dimension line to its end on vertical line (face line). Then search of dimension lines (links) connected to this vertical line at any level (operation) is performed, that is, above (mainly) the unknown link or below. The best link is selected from several attached links and then motion is made horizontally along the selected link till its end on another vertical line. Then again the search of dimension lines (links) connected to this vertical line at any level is performed and the best link is selected. This sequence of actions is repeated till the moment, when motion along links finishes in the initial point of the unknown link (contour of links becomes closed). The best links from many possible variants are considered those, which ensure the shortest contour, that is, the chain with the smallest quantity of links. And at the same time, the principle that each dimension chain includes *only one* initial link and *only one* unknown link should be observed.

Here also it is important to observe the *rule*: dimension chains with design dimensions as initial links [A_i] should include *only* operation dimensions S_k as constituent links. Application of other design dimensions A_i and allowances Z_m as constituent links is not permitted. When solving the equations of such dimension chains, it is often necessary to reduce tolerances of constituent links. But production engineer has no right to change tolerance of a design dimension, and allowance appears as a result of performance of operation dimensions.

Another *rule* is related to allowances. Allowance (minimum allowance) is usually applied as an initial link [Z_m]. Also allowance can be used as a constituent link, but *only after* its application as initial link. But that equation with allowance as constituent link should not include those links S_k used in the previous equation with a considered allowance as initial link. Otherwise that equation with considered allowance as constituent link would use double tolerances of the $\boldsymbol{S_k}$ links.

Detection of manufacturing dimension chains can be facilitated by application of theory of graphs.

Plotting of scheme of detected dimension chain is started from the image of *unknown link*, which is limited by two vertical lines. Then all other chain's links are added in a sequence, including initial link, with orientation to level of each link in dimensional diagram in order to create a closed contour. It is allowed to displace the links in vertical direction to avoid crossing of vertical lines by the links lines.

In the plotted scheme the directions of links are shown by vectors (one-end arrows). Arrows directions are determined by direction of going along the contour around. Travel along the contour around starts from initial link. At that, initial link line is supplied with the arrow symbolising negative direction of initial link. Any initial link is always decreasing link and so negative (with minus) in equation of dimension chain. It is recommended to select negative direction from right to left, that is, the left-hand end of initial link is supplied with arrow. *Using the selected direction of initial link, all constituent links are supplied with arrows in sequence, when going along the contour around*. Here, in the scheme of dimension chain, the obtained directions (arrows) of constituent links $\boldsymbol{S_k}$ has **no** correlation with their directions in the dimensional diagram of manufacturing process.

When analysing the plotted dimension chain scheme with arrows, the decreasing and increasing links are detected. Those links, which coincide with initial link by direction (from right to left), are decreasing links like each initial link and they will be written in equation with minus symbol. And those links, which are opposite to initial link by direction (from left to right), are increasing links and will be written in equation with plus symbol.

If constituent link $\boldsymbol{S}$ coincides with initial link (design dimension) [$\boldsymbol{A}$] by dimension (length), the simplest two-link chain is compiled.

Initial links (design dimensions [$\boldsymbol{A_i}$] and allowances [$\boldsymbol{Z_m}$]) in all schemes of dimension chains are placed into *square brackets*.

Each design dimension should be used in schemes and equations of dimension chains only as an initial (closing) link and only one time. In such equations use of allowances and other design dimensions as constituent links is not permitted.

Allowance also should be used only one time as an initial (closing) link. After application of allowance as initial and closing link, it can be used as constituent link in other schemes and equations with other allowances as initial links.

Dimensions of unknown (sought) constituent links are underlined in schemes and equations of dimension chains.

On the basis of detected and optimised schemes of dimension chains the original equations are compiled and solved.

Optimisation of manufacturing dimension chains and dimension diagram of manufacturing process is based on dimensional analysis of preliminary dimensional diagram (ref. Fig. 3.10) of preliminary plan of manufacturing process.

Corrections of dimensional diagram and preliminary plan of manufacturing process are necessary, when: 1) dimension chains contain more than one unknown link and so their equations cannot be solved (ref. Fig. 3.10); 2) dimension chains contain more than six links that requires increasing the accuracy of constituent links up to unreasonable level.

In general, planning of manufacturing process is an *iteration procedure* including dimension diagram.

The first iteration is made from the principle of datums superposition and, first of all, with coincidence of initial and mounting datums (ref. paragraph 3.5.2), realised in preliminary plan of manufacturing process and its dimension diagram. Usually the mentioned problem 1) appears in final operations of manufacturing process with inderect performance of design dimensions, for example, the dimension chains for $[\boldsymbol{A}_1]$ and $[\boldsymbol{A}_2]$ shown in Fig. 3.10. In this case a dimension chain with initial link $[\boldsymbol{A}_i]$ includes several *unknown* constituent links $\boldsymbol{S}_k$ operation dimensions that makes equation of dimension chain unsolvable. To resolve this problem it is recommended to move initial datum of operation dimension from mounting datum to design datum in such a manner that a considered operation dimension would coincide with design dimension, for example, the dimension chain (1) with initial link $[\boldsymbol{A}_2]$ and *one unknown* constituent link $\underline{\boldsymbol{S}_7}$ shown in Fig. 3.11. The next dimension chain (2) with initial link $[\boldsymbol{A}_1]$ contains the known constituent link $\boldsymbol{S}_7$ (found from the previous chain (1)) and *one unknown* link $\underline{\boldsymbol{S}_8}$. If possible, mounting datum should be also moved to design datum, but it is not critical for final operations. Operations of fine-finish machining stage are usually performed by abrasive tools, subjected to intensive wear, and so these operations are produced with *hand adjusting/tuning* of abrasive tool position after one or several passes. And so, coincidence of initial datum with mounting datum is not so important for such operations.

In some cases dimension chains are very complicated with quantity of links more than six (the mentioned problem 2)). Solutions of such equations can give extremely high accuracy of constituent links (operation dimensions) that would greatly raise production costs. It is recommended to optimise a scheme of operation dimensions in dimensional diagram and preliminary plan of manufacturing process with changes of their initial datums and, if necessary, mounting datums in operations. These changes for faces can cause also changes (enlargements) in quantities of manufacturing steps for *cylindrical surfaces* included into sets of datums.

All the developed *corrections* in mounting and initial datums positions, quantities of manufacturing steps for flat and round surfaces, positions of operation dimensions are introduced into preliminary plan and dimension diagram of manufacturing process, and optimised schemes of dimension chains are composed in a proper sequence. *This second iteration* results in *optimised dimension diagram* (ref. Fig. 3.11) and *optimised preliminary plan* of manufacturing process (Fig. 3.12).

In the operations of rough and finish machining stages the most of initial datums of operation dimensions should coincide with mounting datums. Thus, in the optimised preliminary plan of manufacturing process change of initial datum for dimension $\boldsymbol{S}_6$ caused change of mounting datum in turning operation 25 (compare Fig. 3.12 and

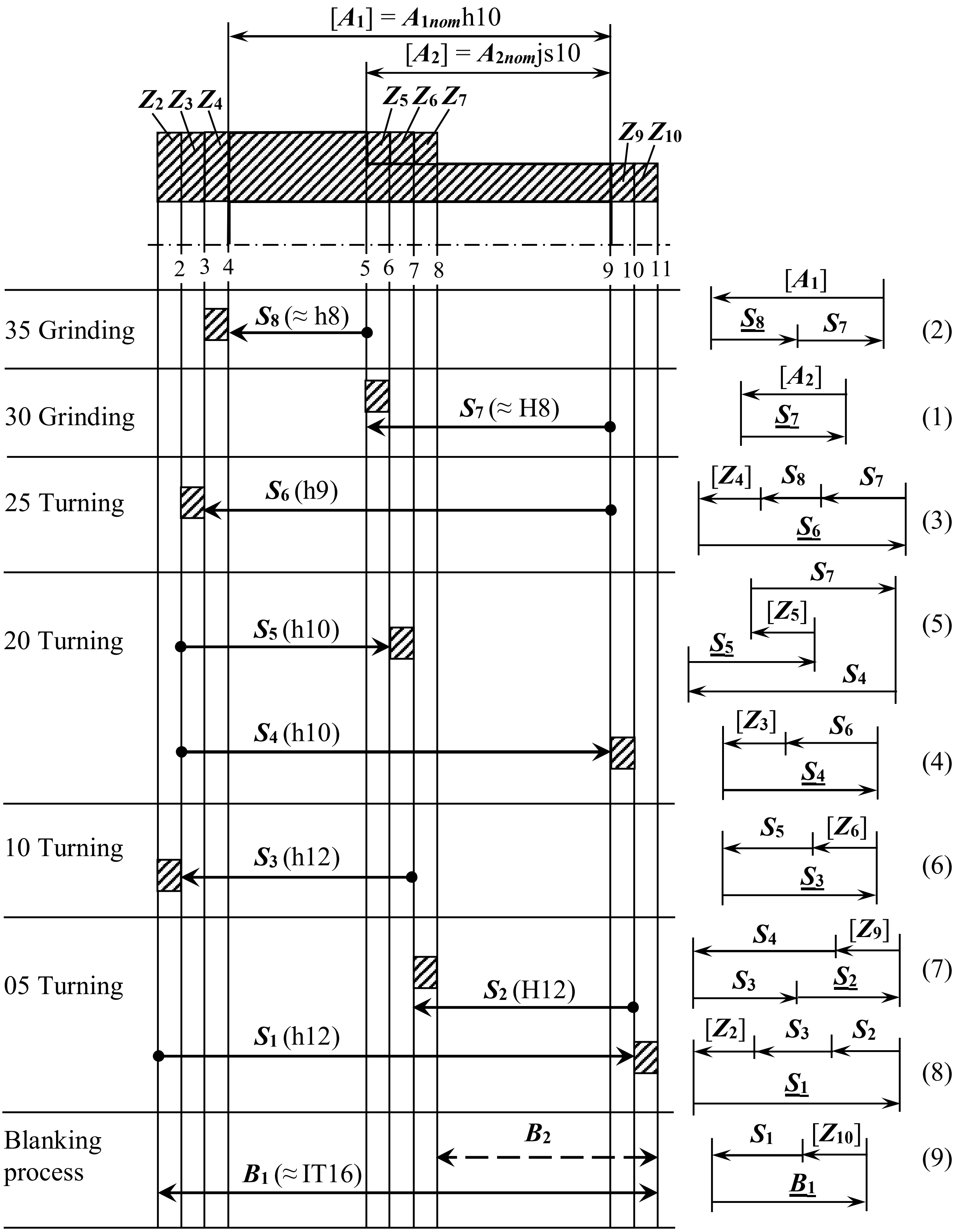


Fig. 3.11. Example of optimised dimension diagram of manufacturing process with detected dimension chains

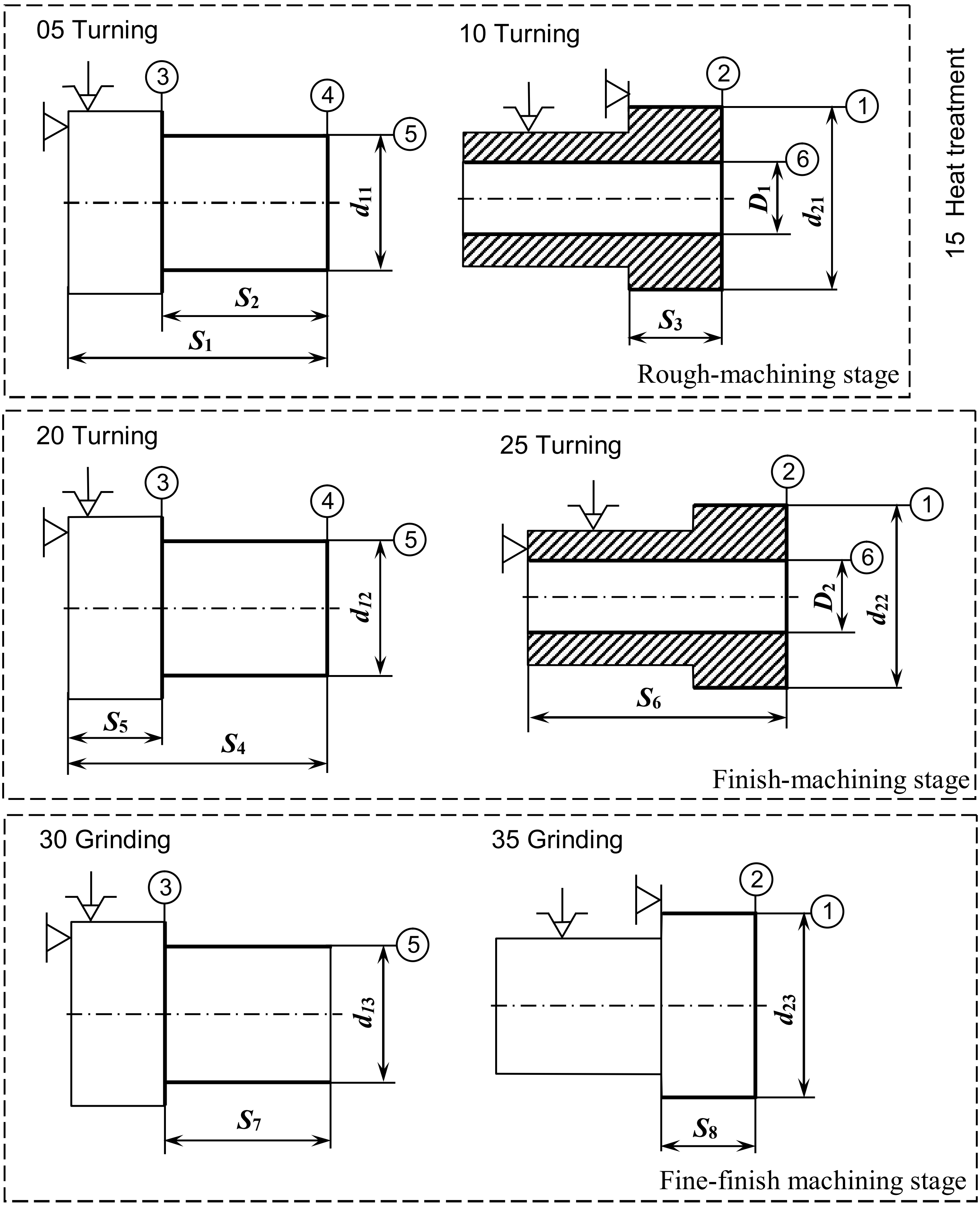


Fig. 3.12. Example of optimised preliminary plan of manufacturing process

Fig. 3.7). This is rather deviation from the principle of constancy of mounting datums, but this deviation is necessary for solubility of dimension chains. The change of mounting datum in operation 25 is prepared in turning operation 20: both datum surfaces (cylindrical 5 and flat 4) are machined at one mounting for the sake of high accuracy of their relative position (ref. Fig. 3.12).

The next iterations are possible, if further improvements are necessary.

Original equation of manufacturing dimension chain is written relative to initial link, that is, symbol of initial link is written in the left part of equation, and algebraic sum of constituent links including a sought link – in the right part. Increasing and decreasing links should be gathered into groups (see the formula (3.13)).

Increasing links have sign "plus" and decreasing links – "minus". Signs of links are determined from a scheme of dimension chain (ref. Fig. 3.11). Those links, which have the same direction as initial link (from right to left), are supplied with sign "minus", and those links directed to opposite side (from left to right) – with sign "plus":

$$[A_2] = \underline{S_7}; \qquad (1)$$
$$[A_1] = \underline{S_8} + S_7; \qquad (2)$$
$$[Z_4] = \underline{S_6} - S_7 - S_8; \qquad (3)$$
$$[Z_3] = \underline{S_4} - S_6; \qquad (4)$$
$$[Z_5] = \underline{S_5} + S_7 - S_4; \qquad (5)$$
$$[Z_6] = \underline{S_3} - S_5; \qquad (6)$$
$$[Z_9] = S_3 + \underline{S_2} - S_4; \qquad (7)$$
$$[Z_2] = \underline{S_1} - S_2 - S_3; \qquad (8)$$
$$[Z_{10}] = \underline{B_1} - S_1. \qquad (9)$$

In different equations of dimension chains the same constituent links can be both increasing and decreasing.

Assigning accuracy grades to operation dimensions-coordinates is necessary for further solutions of equations of dimension chains. This is a logical phase in development of dimension diagram of manufacturing process. In comparison with round surfaces, for flat surfaces (faces) the distribution of accuracy grades among dimensions-coordinates has not been developed yet, because there were no dimensions-coordinates at the stage of development of machining routes for main surfaces (ref. paragraph 3.4.2). By the same reason the quatities of manufacturing steps for faces were calculated only from roughness parameter (ref. paragraph 3.4.1).

There are several factors, which influence the assigning accuracy grades for dimensions-coordinates:

- Accuracy levels typical for three stages in structure of manufacturing process;
- Accuracy of design dimensions of a part;
- Accuracy conditions of dimension chains with design dimensions as initial links;
- Accuracy of initial bank dimensions.

According to the purposes of stages of manufacturing process the typical accuracy levels are: for rough-machining stage IT14–IT12, for finish-machining stage IT12–IT8, for fine-finish machining stage IT7–IT5 (ref. paragraph 3.5.1).

But design dimensions-coordinates are often specified with relatively low accuracy (IT12–IT8) (ref. Fig. 3.11) and so there is no need to assign high accuracy grades (IT7–IT5) to final operation dimensions-coordinates. Assigning the high accuracy greatly increases production costs. Application of high-precision methods (grinding, lapping, etc.) in final fine-finish operations is often determined by high roughness requirements: R_a1.25–R_a0.16.

Accuracy condition of a dimension chain with design dimension as initial link originates from the formula (3.14): tolerance of *one* initial link should include tolerances of *all* constituent links, from which the dimension chain is compiled. It results in the increased accuracy (smaller tolerances) of operation dimensions in comparison with accuracy of design dimensions. Thus, dimension chains (1) and (2) in Fig, 3.11 and respective equations are based on initial links [A_2] and [A_1] design dimensions. Though equation (1) allows to assign the same accuracy grade for operation dimension S_7 as for design dimension [A_2], the equation (2) requires increase of accuracy for both constituent links S_7 and S_8 in comparison with accuracy of design dimension [A_1].

It becomes more obvious from the following example. If design dimensions are [A_1] = 100h9($_{-0.087}$) and [A_2] = 65js9(±0.037), the nominal dimensions of operation dimensions are S_{7nom} = 65 and S_{8nom} = 35:

$$[A_1] = \underline{S_8} + S_7; \quad [A_{1nom}] = \underline{S_{8nom}} + S_{7nom}; \quad 100 = 35 + 65.$$

At this stage of planning of manufacturing process the nominal values of operation dimensions S_k can be determined *approximately* by using nominal values of design dimensions and minimum allowances values. In the standards [5] tolerances are stated for wide ranges of nominal dimensions (ref. Appendix 3).

In the considered example, if we would use equation (1) and determine tolerance for operation dimension T_{S7} equalling the tolerance of intial link [T_{A2}]

$$T_{S7} = [T_{A2}] = 0.074 \text{ (IT9)},$$

accuracy of operation dimension T_{S8} deternined from the equations (2) and (3.14) would be too high :

$$[T_{A1}] = T_{S7} + T_{S8}; \quad 0.087 = 0.074 + T_{S8}; \quad T_{S8} = 0.087 - 0.074 = 0.013$$

that corresponds to the 5th accuracy grade (IT5 = 0.011 mm for 30–50 mm range).

Therefore, first of all, the equation (2) should be analysed. According to the formula (3.14) the tolerance [T_{A1}] should include tolerances of operation dimensions:

$$[T_{A1}] = T_{S7} + T_{S8}; \quad 0.087 = T_{S7} + T_{S8}; \quad 0.087 = 0.047 + 0.040.$$

Thus, the *assigned tolerances* of operation dimensions are: T_{S7} = 0.047 mm (IT8 = = 0.046 mm for 50–80 mm range) and T_{S8} = 0.040 mm (IT8 = 0.039 mm for 30–50 mm range). Regard to nominal dimensions both tolerances *approximately* correspond to the 8th *accuracy grade* (ref. Appendix 3).

When selecting accuracy grade by calculated tolerance for operation dimension, the *smaller* number of grade is usually chosen (in this example: not IT9, but IT8). Tolerances of manufacturing dimensions *do not obey* to the USTF system [5], and so they can be of any non-standardised value, but they are estimated by accuracy grades from this system.

Further corrections of tolerances for operation dimensions (and their accuracy grades) can be performed at solving the equations of dimension chains with design dimension as initial link and at their rounding-off, when *exact* nominal values of operation dimensions are calculated.

Assigning of accuracy grades for the rest of operation dimensions is performed on the basis of final dimensions (for example, S_7 and S_8) taking into account stages of manufacturing process and typical accuracy levels (ref. Fig. 3.11).

Accuracy grades for initial blank dimensions are selected from the nearest *larger* numbers [5]. Initial blanks are produced in a wide range of tolerances for dimensions: from IT8 (for calibrated rolled bars) to IT20 (cast blanks). Naturally accuracy of initial blank dimensions will influence assigning the accuracy grades along stages and operation dimensions of manufacturing process.

3.7.3. Solution of equation of manufacturing dimension chain with design dimension as initial link

When calculating the equations of dimension chains, two types of tasks are solved: the *direct* and the *inverse* (GOST 16320-80).

Solution of direct task gives nominal value of a sought (unknown) link and its limit deviations. Initial data for direct task are: parameters (nominal dimensions and limit deviations) of initial link and parameters of known constituent links excluding the sought (unknown) link.

Solution of inverse task is parameters of a closing link: nominal dimension and limit deviations. Initial data for inverse task are: parameters of all constituent links. Solution of inverse task is usually used for check of correctness of direct task solution, as well as for determination of allowance nominal dimension and limit deviations.

In manufacturing dimension chains quantity of constituent links is rarely more than six. Therefore, their solutions, as a rule, are performed by ***maximum-minimum method***. In those cases, when number of constituent links is more than six, *probabilistic method* is used. It can be used also at smaller number of constituent links, when the necessity of increased tolerances for constituent links appears.

Procedures for solutions of manufacturing dimension chains depend on type of initial link: design dimension or allowance.

Equation of dimension chain with *initial link* [*A*] ***design dimension*** is solved along the following procedure.

In comparision with general view of formula (3.13) the full form of *original equation* has the view

$$\left[\boldsymbol{A}_{nom}{}^{\Delta s_A}_{\Delta i_A}\right] = \sum_{j=1}^{n_j} \boldsymbol{S}_{jnom}{}^{\Delta s_j}_{\Delta i_j} - \sum_{q=1}^{n_q} \boldsymbol{S}_{qnom}{}^{\Delta s_q}_{\Delta i_j}, \qquad (3.15)$$

where $\boldsymbol{S}_{jnom}$ and $\boldsymbol{S}_{qnom}$ are nominal values of increasing and decreasing links, respectively; $\boldsymbol{\Delta s}$ and $\boldsymbol{\Delta i}$ are upper and lower limit deviations, respectively; $\boldsymbol{n}_j$ and $\boldsymbol{n}_q$ are quantities of increasing and decreasing links, respectively.

In the function of a constituent link only operation dimensions $\boldsymbol{S}_k$ and initial blank dimensions $\boldsymbol{B}_r$ can be used. Applications of allowances values $\boldsymbol{Z}_m$ and other design dimensions $\boldsymbol{A}_i$ are not permitted.

In the equation (3.15) one of constituent links $\boldsymbol{S}_{jX}$ (increasing) or $\boldsymbol{S}_{qX}$ (decreasing) is unknown.

Tolerance of initial link [$\boldsymbol{T}_A$] design dimension should include tolerances of all constituent links $\boldsymbol{T}_{Si}$ (adequacy of initial link tolerance)

$$[T_A] = \sum_{i=1}^{n_j+n_q} T_{Si} . \qquad (3.16)$$

The formula (3.16) allows calculating tolerance T_{SX} of unknown constituent link

$$T_{SX} = [T_A] - \sum_{i=1}^{n_j+n_q-1} T_{Si} .$$

If the tolerance T_{SX} is a negative value or positive value, but very small for the link S_{jX} or S_{qX} at a certain stage of manufacturing process, then *new smaller tolerances* should be assigned *to other constituent links* to satisfy the condition (3.16). Assigning of new tolerances is made taking into account nominal dimensions of constituent links and admissible accuracy grade for each constituent link at a certain stage of manufacturing process. *New deviations* are assigned to the known constituent links depending on type of dimension: shaft or hole. Then the original equation is solved along the ordinary algorithm. *But in this case the solutions of previous equations should be repeated with new-assigned deviations of the constituent links*. Application of the procedure for assigning accuracy grades to operation dimensions-coordinates, described in the paragraph 3.7.2 above, allows avoiding the repeated calculations in the most of cases, though sometime corrections of tolerances T_{SX} can be necessary.

Estimation of satisfactory value of tolerance T_{SX} is made by determination of accuracy grade from the standard [5] and its comparison with admissible accuracy grade recommended for a certain stage of manufacturing process (ref. paragraph 3.5.1). For manufacturing dimensions the tolerances can be of non-standardised values, therefore respective accuracy grades are determined approximately.

If the tolerance T_{SX} is a positive value and large enough for the link S_{jX} or S_{qX} at the certain stage of manufacturing process, the ordinary algorithm continues.

Original equation (3.15) is decomposed into three linear equations with one unknown value in each equation:

1) $[A_{nom}] = \sum_{j=1}^{n_j} S_{jnom} - \sum_{q=1}^{n_q} S_{qnom}$ is equation written down in nominal values of links. Unknown nominal value S_{jXnom} or S_{qXnom} is found;

2) $[\Delta s_A] = \sum_{j=1}^{n_j} \Delta s_j - \sum_{q=1}^{n_q} \Delta i_q$ is equation compiled for upper deviation of initial link. The upper deviation Δs_{jX} or lower deviation Δi_{qX} of unknown link is determined from this equation;

3) $[\Delta i_A] = \sum_{j=1}^{n_j} \Delta i_j - \sum_{q=1}^{n_q} \Delta s_q$ is equation compiled for lower deviation of initial link. The lower deviation Δi_{qX} or upper deviation Δs_{jX} of unknown link is determined from this equation.

The equations 2) and 3) in a mathematical form realize “crosswise (criss-cross) scheme” suitable for calculations from the original equation (3.15). This scheme operates when view of original equation (3.15) is observed: increasing and decreasing links are gathered into two separate groups and devided by the minus sign.

Operation dimension-coordinate is written using the found parameters: nominal dimension, upper and lower limit deviations

$$S_{jX} = S_{jXnom}{}^{\Delta s_j}_{\Delta i_j}.$$

Then operation dimension-coordinate should be written in a proper form: as a basic hole with basic deviation H, as a basic shaft with basic deviation h or as a dimension with symmetrical deviations Js (ref. paragraph 1.2.2). Calculated parameters of a found dimension-coordinate are transformed into proper form in order to the tolerance is located in the "body" of workpiece (in metal). Type of dimension-coordinate is determined from the dimensional diagram (ref. Fig. 3.11) or optimised plan of manufacturing process (ref. Fig. 3.12).

If dimension-coordinate S_{jX} of increasing link has form of *dimension-hole* the minimum limit dimension is calculated in order to use it as nominal dimension (for a basic hole nominal dimension equals the minimum)

$$S_{jXmin} = S_{jXnom} + \Delta i_j.$$

Then, after transformation, the operation dimension-coordinate is written in the form of dimension-hole

$$S_{jX} = S_{jXnom}{}^{\Delta s_j}_{\Delta i_j} = S_{jXmin}{}^{+T_{SX}},$$

where $+T_X$ is upper deviation of operation dimension-hole, $T_{SX} = (\Delta s_j - \Delta i_j)$; 0 is lower deviation.

In Fig. 3.11 the dimensions-coordinates S_2 and S_7 are dimensions-holes.

If dimension-coordinate S_{jX} of increasing link has form of *dimension-shaft* the maximum limit dimension is calculated in order to use it as nominal dimension (for a basic shaft nominal dimension equals the maximum)

$$S_{jXmax} = S_{jXnom} + \Delta s_j.$$

Then operation dimension-shaft will be

$$S_{jX} = S_{jXnom}{}^{\Delta s_j}_{\Delta i_j} = S_{jXmax}{}_{-T_{SX}}.$$

In Fig. 3.11 the dimensions-coordinates S_1, S_3, S_4, S_5, S_6, S_8 are dimensions-shafts.

If dimension-coordinate S_{jX} has form of *dimension with symmetric deviations* (basic deviation Js) the mean dimension is calculated in order to use it as nominal dimension (in this case nominal dimension equals the mean)

$$S_{jXmean} = \frac{S_{jX\,max} - S_{jX\,min}}{2}.$$

Then operation dimension will be with symmetric deviations

$$S_{jX} = S_{jXnom}{}^{\Delta s_j}_{\Delta i_j} = S_{jXmean} \pm \frac{T_{SX}}{2}.$$

The procedure described above for writing the operation dimension S_{jX} of increasing link is totally suitable for the operation dimension S_{qX} of decreasing link.

In general the described algorithm with (3.15), (3.16) and other formulas is an algorithm for solution of *direct task* for finding the parameters of unknown constituent link S_{jX} or S_{qX}.

Rounding of a dimension-coordinate (constituent link) found from a dimension chain with *initial link* [A] ***design dimension*** is performed depending on type of dimension writing under condition of tolerance limits. Correctness of rounding-off is checked by solution of *inverse task*, that is, value of *closing link* A is calculated from known values of constituent links.

Rounding of a calculated dimension-coordinate S_{Xmin} or S_{Xmax} is performed, as a rule, with accuracy of tenths millimeter for operations of rough and finish machining stages and hundredths or tenths millimeter for operations of fine-machining stage.

For operation dimension-coordinate in the form of ***dimension-hole*** the minimum value S_{Xmin} is rounded off ***with increase*** (Fig. 3.13-a). At that the dimension tolerance T_{SX} is reduced by value of rounding-off ΔS_X in order to avoid the closing link A_{max} exceeding the maximum limit of initial link [A_{max}], when constuient link S_{jXmin} is increasing, and the A_{min} reducing smaller than the minimum limit [A_{min}], when constuient link S_{qXmin} is decreasing:

$$\Delta S_X = S_{XminR} - S_{Xmin}; \qquad T_{SXR} = T_{SX} - \Delta S_X. \tag{3.17}$$

After calculations by the (3.16) formulas the rounded-off dimension-coordinate in the form of a *dimension-hole* will be written

$$S_{XR} = S_{XminR}^{+T_{SXR}}. \tag{3.18}$$

Formulas (3.17) and (3.18) are applicable for *dimensions-holes* with no relation to the type of constituent link S_X, increasing or decreasing, for example, dimension S_7 in the Fig. 3.11.

For operation dimension-coordinate in the form of ***dimension-shaft*** the maximum value S_{Xmax} is rounded off ***with decrease*** (Fig. 3.13-b). At that the dimension tolerance T_{SX} is reduced by value of rounding-off ΔS_X in order to avoid the closing link A_{min} reducing smaller than the minimum limit of initial link [A_{min}], when constuient link S_{jXmax} is increasing, and the A_{max} exceeding the maximum limit [A_{max}], when constuient link S_{qXmax} is decreasing:

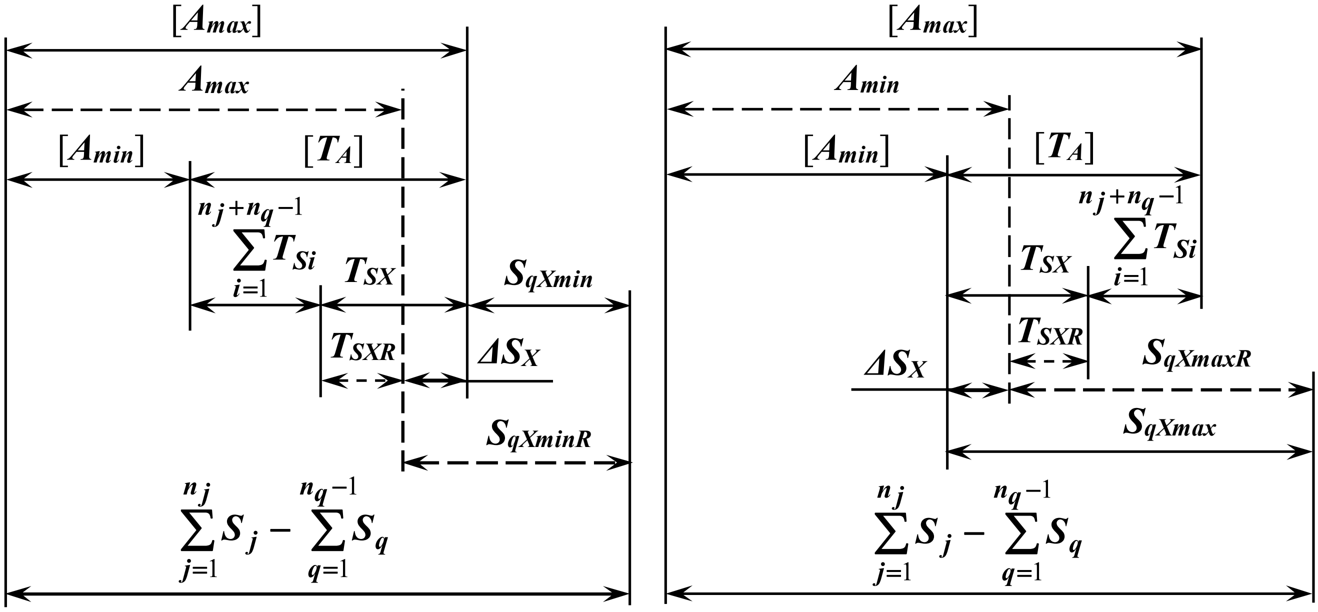
$$\Delta S_X = S_{Xmax} - S_{XmaxR}; \qquad T_{SXR} = T_{SX} - \Delta S_X. \tag{3.19}$$

After calculations by the (3.18) formulas the rounded-off dimension-coordinate in the form of a *dimension-shaft* will be written

$$S_{XR} = S_{XmaxR\,-T_{SXR}}. \tag{3.20}$$

Formulas (3.19) and (3.20) are applicable for *dimensions-shafts* with no relation to the type of constituent link S_X, increasing or decreasing, for example, dimension S_8 in the Fig. 3.11.

Formulas (3.17) and (3.19) are derived from the diagrams submitted in the Fig. 3.13 for rounding off a decreasing link. The similar diagrams have been plotted al-



a b

Fig. 3.13. Diagrams for procedures of rounding off the operation dimensions-coordinates between faces of a workpiece: for dimensions-holes (a); for dimensions-shafts (b)

so for an increasing link (not submitted) and they confirmed correctness of the formulas (3.17) and (3.19).

When rounding off operation dimension-coordinate, *check for satisfactory value of rounded (reduced) tolerance* $\boldsymbol{T_{SXR}}$ should be performed in order that accuracy of rounded dimension $\boldsymbol{S_{XR}}$ fits a respective stage of manufacturing process. Using nominal value of operation dimension $\boldsymbol{S_{XR}}$ and its tolerance $\boldsymbol{T_{SXR}}$, the accuracy grade ITn_X is determined from the standard [5] (approximately). The accuracy grade ITn_X of operation dimension should correspond to typical machining accuracy levels of manufacturing process stages: rough – IT14–IT12; finish – IT12–IT8; fine-finish – IT7–IT6. Otherwise a rounding-off procedure for calculated operation dimension is not performed.

Solution of inverse task from the original equation (3.15) gives maximum and minimum values of *closing link **A*** after rounding-off procedures:

$$A_{max} = \sum_{j=1}^{n_j} S_{j\,max} - \sum_{q=1}^{n_q} S_{q\,min}\,; \qquad A_{min} = \sum_{j=1}^{n_j} S_{j\,min} - \sum_{q=1}^{n_q} S_{q\,max}\,, \qquad (3.21)$$

where $\boldsymbol{S_{jmax}}$ and $\boldsymbol{S_{jmin}}$ are maximum and minimum values of increasing links, respectively; $\boldsymbol{S_{qmax}}$ and $\boldsymbol{S_{qmin}}$ are maximum and minimum values of decreasing links, respectively.

Calculated limit values of closing link are compared with limit values of initial link in order to check *meeting the requirements for initial link* specified by designer

$$A_{max} \le [A_{max}]; \qquad A_{min} \ge [A_{min}]. \qquad (3.22)$$

It is evident from the Fig. 3.13-a that $A_{min} = [A_{min}]$ and $A_{max} < [A_{max}]$ and the difference $[A_{max}] - A_{max} = \Delta S_X$ (value of rounding-off).

Similar from the Fig. 3.13-b follows that $A_{max} = [A_{max}]$ and $A_{min} > [A_{min}]$ and the difference $A_{min} - [A_{min}] = \Delta S_X$.

In both cases the closing link A will be in the range of tolerance $[T_A]$ of initial link $[A]$ and tolerance for closing link becomes smaller: $T_A = [T_A] - \Delta S_X$.

Operation ***dimensions-coordinates with symmetrical deviations***, as a rule, are not rounded off, because they usually coincide with design dimensions-coordinates with Js basic deviation. Such dimensions are specified to coordinate positions of holes axes, axes of slots symmetry, fillets, chamfers and other similar elements (ref. Fig. 1.1). If a designer uses other basic deviations (a, b, … , zb, zc or A, B, … , ZB, ZC, except Js), a production engineer makes transformation of such a design dimension into operation *dimension-coordinate with symmetrical limit deviations* according to Js basic deviation (nominal dimension equals half-sum of maximum and minimum limit dimensions, and limit deviations are ±ITn/2) usually without rounding-off.

3.7.4. Solution of equation of manufacturing dimension chain with allowance as initial link

Original equation with initial link $[Z]$ *allowance* looks like the equation (3.15) with initial link $[A]$ design dimension

$$\left[Z_{nom}{}^{\Delta s_Z}_{\Delta i_Z}\right] = \sum_{j=1}^{n_j} S_{jnom}{}^{\Delta s_j}_{\Delta i_j} - \sum_{q=1}^{n_q} S_{qnom}{}^{\Delta s_q}_{\Delta i_j} . \qquad (3.23)$$

But solution of this equation according to the described algorithm for $[A]$ is rather impossible. In contrast to design dimension $[A]$, parameters of allowance $[Z]$ (nominal dimension, upper and lower deviations) are not known.

The only characteristic of allowance, which can be determined before solution of equation (3.23), is its minimum limit value $[Z_{min}]$. The paragraph 3.6.2 describes three methods for determination of minimum machining allowance.

Therefore, the original equation is transformed relative to minimum allowance

$$[Z_{min}] = \sum_{j=1}^{n_j} S_{j\,min} - \sum_{q=1}^{n_q} S_{q\,max} , \qquad (3.24)$$

where S_{jmin} are minimum values of increasing links; S_{qmax} are maximum values of decreasing links.

So as each manufacturing dimension chain contains only one unknown link, therefore the task is to solve the equation (3.24) in order to find the minimum value S_{jXmin} of increasing link or maximum value S_{qXmax} of decreasing link (*direct task*).

Constituent links for this type dimension chains are: operation dimensions S_k, initial blank dimensions B_r and those allowances values Z_m, which were earlier used as initial links $[Z_m]$ in other equations.

If a sought dimension S_X is decreasing link, then

$$S_{qX\,max} = \sum_{j=1}^{n_j} S_{j\,min} - \sum_{q=1}^{n_q-1} S_{q\,max} - [Z_{min}]. \qquad (3.25)$$

If a sought dimension S_X is increasing link, then

$$S_{jX\,min} = \sum_{q=1}^{n_q} S_{q\,max} - \sum_{j=1}^{n_j-1} S_{j\,min} + [Z_{min}]. \quad (3.26)$$

Accuracy grade ITn is assigned to S_{qXmax} or S_{jXmin} value according to the stage of manufacturing process, in which the sought dimension S_X is used, and tolerance T_{SX} is determined from the standard [5]. Assigning the accuracy grades (tolerances) to operation dimensions is performed at the stage of development and optimisation of dimension diagram (ref. paragraph 3.7.2). The results are shown in the optimised dimension diagram (ref. Fig. 3.11).

Assigning the accuracy grades is made depending on place of manufacturing step with dimension S_X in a structure of manufacturing process: IT12 – IT14 accuracy grades at rough-machining stage, IT8 – IT12 – at finish-machining stage, and IT6 – IT7 – at fine-finish machining stage that corresponds to the *rule of progressive decrease* (ref. paragraph 3.4.2). Also other factors are included into consideration at assigning (ref. paragraph 3.7.2)

Operation dimension-coordinates are written in the forms of *dimension-hole* (with basic deviation H), *dimension-shaft* (with basic deviation h) or dimension with symmetric deviations (with basic deviation Js).

With this purpose calculation of another limit dimension of S_X link is performed, if necessary.

Thus, if a sought dimension S_{qX} of ***decreasing link*** has form of *dimension-hole* (nominal dimension of basic hole equals minimum limit dimension), the minimum limit dimension is calculated from the formula

$$S_{qX\,min} = S_{qXmax} - T_{SX}.$$

Then operation dimension is

$$S_{qX} = S_{qXmin}{}^{+T_{SX}}.$$

If a sought dimension S_{qX} has form of *dimension-shaft* (nominal dimension of basic shaft equals maximum limit dimension), the operation dimension is

$$S_{qX} = S_{qXmax}{}_{-T_{SX}}.$$

If a sought dimension S_{qX} has form of *dimension with symmetric deviations* (nominal dimension equals mean dimension), the mean dimension is calculated from

$$S_{qX\,mean} = \frac{S_{qX\,max} + S_{qX\,min}}{2}.$$

The operation dimension is

$$S_{qX} = S_{qXmean} \pm \frac{T_{SX}}{2}.$$

Thus, if a sought dimension S_{jX} of ***increasing link*** has form of *dimension-hole* (nominal dimension of basic hole equals minimum limit dimension), the operation dimension is

$$S_{jX} = S_{jXmin}{}^{+T_{SX}}.$$

If a sought dimension S_{jX} has form of *dimension-shaft* (nominal dimension of basic shaft equals maximum limit dimension), the maximum limit dimension is calculated from the formula

$$S_{jXmax} = S_{jXmin} + T_{SX}.$$

Then operation dimension is

$$S_{jX} = S_{jXmax\,-T_{SX}}.$$

If a sought dimension S_{jX} has form of *dimension with symmetric deviations* (nominal dimension equals mean dimension), the mean dimension is calculated from

$$S_{jX\,mean} = \frac{S_{jX\,max} + S_{jX\,min}}{2}.$$

The operation dimension is

$$S_{jX} = S_{jXmean} \pm \frac{T_{SX}}{2}.$$

Dimensions of initial blanks are usually written in two forms: dimensions with symmetric deviations and dimensions with non-symmetric deviations.

Dimensions with symmetric deviations are typical for initial blanks produced by casting methods or by cutting-off (parting) of long rolled products:

$$B_X = B_{Xmean} \pm \frac{T_{BX}}{2},$$

where $+T_{BX}/2$ and $-T_{BX}/2$ are upper Δs_B and lower Δi_B limit deviations, respectively; B_{Xmean} is nominal dimension, which equals mean dimension.

Depending on calculated value B_{Xmin} or B_{Xmax}, the mean dimension is determined from the formulas

$$B_{Xmean} = B_{Xmin} + T_{BX}/2 \;\; (B_{Xmean} = B_{Xmin} - \Delta i_B)$$

or from the formulas

$$B_{Xmean} = B_{Xmax} - T_{BX}/2 \;\; (B_{Xmean} = B_{Xmax} - \Delta s_B).$$

Initial blanks produced by forging, rolling and other metalworking processes have *dimensions* $B_{nom\,\Delta i_B}^{\;\;\;\;\Delta s_B}$ *with non-symmetrical deviations* (Δs_B, Δi_B) stated by corresponding standards. In this case the tolerance T_{BX} of blank dimension is divided in two portions: the upper portion $T_{BX\Delta s}$ determined by upper limit deviation Δs_B ($T_{BX\Delta s} = |\Delta s_B|$) and the lower portion $T_{BX\Delta i}$ determined by lower limit deviation Δi_B ($T_{BX\Delta i} = |\Delta i_B|$).

Depending on the calculated value of dimension B_X, the nominal value B_{Xnom} is determined from the formulas

$$B_{Xnom} = B_{Xmin} + T_{BX\Delta i} \;\; (B_{Xnom} = B_{Xmin} - \Delta i_B)$$

or from the formulas

$$B_{Xnom} = B_{Xmax} - T_{BX\Delta s} \;\; (B_{Xnom} = B_{Xmax} - \Delta s_B).$$

Rounding off the operation dimensions S_X, calculated from equations of dimension chains with initial link [Z] allowance, is performed in such a manner that *increase of allowance as a closing link* occurs. Here the type of calculated constituent link and its influence on closing link is taken into account (ref. paragraph 3.7.1, formulas 3.13 and 3.23).

If calculated dimension S_{jX} is an ***increasing link***, its *rounding is performed with increase of its nominal dimension*: increase of S_{jXmin} in hole-type dimensions, increase of S_{jXmax} in shaft-type dimensions and increase of S_{jXmean} in dimensions with symmetrical deviations. It is evedent from the formula (3.23) that *enlargement of S_j increasing link* will cause *increase of **Z** allowance.*

If calculated dimension S_{qX} is an ***decreasing link***, its *rounding is performed with decrease of its nominal dimension:* decrease of S_{jXmin} in hole-type dimensions, decrease of S_{jXmax} in shaft-type dimensions and decrease of S_{jXmean} in dimensions with symmetrical deviations. It is evedent from the formula (3.23) that *decrease of S_q decreasing link* will cause *increase of **Z** allowance.*

Rounding of a calculated dimension-coordinate S_X is performed, as a rule, with accuracy of tenths millimeter for operations of rough and finish machining stages and hundredths or tenths millimeter for operations of fine-machining stage.

Rounding of a calculated dimension-coordinate B_X of initial blank is performed with accuracy of tenths millimeter for forged and cast blanks or by selection of the nearest standard nominal dimension of a rolled product (the larger standard dimension for shaft elements of initial blank and the smaller – for hole elements).

Tolerances T_{SX} and T_{BX} of the rounded dimensions S_{XR} and B_{XR} are not changed in the rounding-off procedure, when allowance [Z] is used as an initial link.

After rounding-off, the ***nominal value of allowance and its deviations*** are calculated by solution of three linear equations. In this case an *inverse task* is solved in order to find *closing link **Z***

$$Z_{nom}{}_{\Delta i_Z}^{\Delta s_Z} = \sum_{j=1}^{n_j} S_{jnom}{}_{\Delta i_j}^{\Delta s_j} - \sum_{q=1}^{n_q} S_{qnom}{}_{\Delta i_j}^{\Delta s_q} . \tag{3.27}$$

The equation (3.27) is decomposed into three linear equations with one unknown value in each equation (nominal dimension Z_{nom}, upper limit deviation Δs_Z and lower limit deviation Δi_Z):

1) $Z_{nom} = \sum_{j=1}^{n_j} S_{jnom} - \sum_{q=1}^{n_q} S_{qnom}$;

2) $\Delta s_Z = \sum_{j=1}^{n_j} \Delta s_j - \sum_{q=1}^{n_q} \Delta i_q$;

3) $\Delta i_Z = \sum_{j=1}^{n_j} \Delta i_j - \sum_{q=1}^{n_q} \Delta s_q$.

The equations 2) and 3) in a mathematical form realise the crosswise (criss-cross) scheme suitable for calculations from the original equation (3.27). This scheme operates when view of original equation (3.27) is observed: increasing and decreasing links are gathered into two separate groups and devided by the minus sign.

Correctness of S_{XR} (or B_{XR}) rounding-off is checked by solution of inverse task $Z_{nom}{}_{\Delta i_Z}^{\Delta s_Z}$. Minimum value of *closing link Z_{min}* should not be less than minimum value of *initial link* [Z_{min}]

$$Z_{min} \geq [Z_{min}]. \tag{3.28}$$

where $Z_{min} = Z_{nom} + \Delta i_Z$.

Also the maximum value of closing link Z_{max} is determined for its application in further calculations of *cutting conditions* of a respective operation, in which this allowance is removed:

$$Z_{max} = Z_{nom} + \Delta s_Z.$$

The obtained value of allowance $Z_{nom}{}_{\Delta i_Z}^{\Delta s_Z}$ *can be used as a constituent link* (like operation dimensions S_k) *in further dimension chains* with other allowances $[Z_m]$ as initial links. But those further dimension chains should not include the S_k links used in a considered chain with this $[Z]$ initial link.

Form of writing the operation dimension-coordinate depends on selection of initial datum. In most cases the operation dimensions have basic deviation equal zero, another deviation numerically equal tolerance, and tolerance located in "body" of a workpiece (in metal, not in air): *dimension-hole* $S_{Xmin}{}^{+T_{SX}}$ or *dimension-shaft* $S_{Xmax}{}_{-T_{SX}}$. For example, operation dimension S_1 in Fig. 3.14 is started from left-hand face of the workpiece (initial datum ID_{S1} coinciding with mounting datum). Considering the positions of machined surface and removed allowance relative to the initial datum, it becomes obvious that the operation dimension is performed with reducing, that is, from larger value ($S_1 + Z_{S1}$) to the samller S_1 with removal of allowance Z_{S1}. This position of machined surface relative to initial datum, and position of body of workpiece relative to machined surface stipulate assigning of basic-shaft dimension $S_{1max}{}_{-T_{S1}}$. The same consideration can be applied also to the dimension S_3 (see Fig. 3.14): $S_{3max}{}_{-T_{S3}}$. The dimension S_3 is shown by dotted line as a variant for operation dimension S_2. Analysis of manufacturing process plan (ref. Fig. 3.12) and dimension diagram (ref. Fig. 3.11) shows that dimensions S_8, S_6, S_5, S_4, S_3, S_1 are dimensions-shafts specified with basic deviation h.

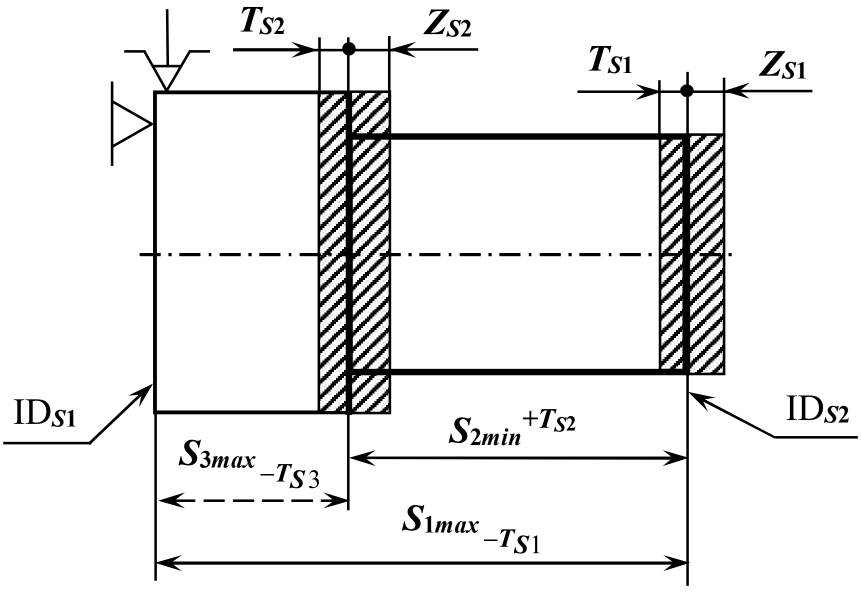


Fig. 3.14. Diagram from manufacturing operation for determination of dimensions-shafts and dimensions-holes: ID_{S1} and ID_{S2} are initial datums for S_1 and S_2 operation dimensions, respectively

On the other hand, when operation dimension goes into metal from smaller value ($S_2 - Z_{S2}$) to larger one S_2 (after removal of allowance $\boldsymbol{Z_{S2}}$ from machined surface), assigning of basic-hole dimension $\boldsymbol{S_{2min}}^{+T_{S2}}$ (see Fig. 3.14) places the tolerance $\boldsymbol{T_{S2}}$ into metal. In this case the dimension $\boldsymbol{S_2}$ starts from the right-hand face of the workpiece – initial datum ID_{S2} not coinciding with mounting datum (see also dimension $\boldsymbol{S_3}$ for comparison, Fig. 3.14). In the manufacturing process plan (ref. Fig. 3.12) and dimension diagram (ref. Fig. 3.11) dimensions $\boldsymbol{S_7}$ and $\boldsymbol{S_2}$ are dimensions-holes specified with basic deviation H.

Calculated and rounded operation dimensions are written into operation sketches of preliminary plan of manufacturing process that gradually transforms it into final plan. Calculated and rounded dimensions of initial blank are specified in preliminary sketch of initial blank to make it a drawing with final dimensions.

3.8. Calculations of operation dimensions for round surfaces

Round surfaces are usually machined several times in operations of manufacturing process. Quantity of manufacturing steps for a definite round surface is determined by its accuracy and roughness parameters (ref. paragraph 3.4). This quantity of steps can be increased, when optimising the dimension chains and selection of datums (ref. paragraph 3.7.2). Therefore, the final quantity of manufacturing steps and route for machining of a definite round surface is determined from the optimised plan of manufacturing process (ref. Fig. 3.12).

Operation dimensions for round surfaces are calculated by ***maximum-minimum methods***, but algorithm for its application differs from the algorithms used for solutions of equations of dimension chains.

The algorithms for round surfaces are easier in comparison with dimension chains algorithms. It is explained by consideration of only one round surface, while dimension chains involve several flat surfaces machined several times in a complicated sequence.

There are differences in formulas for shaft-type and hole-type elements and, respectively, dimensions and peculiarities in calculations of initial blank dimensions.

Initial data for calculations are the parameters of final dimension $\boldsymbol{d}$ ($\boldsymbol{D}$) of a part (nominal dimension $\boldsymbol{d_{nom}}$ ($\boldsymbol{D_{nom}}$), upper $\boldsymbol{es}$ ($\boldsymbol{ES}$) and lower $\boldsymbol{ei}$ ($\boldsymbol{EI}$) limit deviations), parameters of initial blank dimension (upper $\boldsymbol{es_0}$ ($\boldsymbol{ES_0}$) and lower $\boldsymbol{ei_0}$ ($\boldsymbol{EI_0}$) limit deviations), values of minimum allowances $2\boldsymbol{Z_{minN}}$ for all manufacturing steps and tolerances $\boldsymbol{T}$ for all operation dimensions.

Design dimension is specified in a drawing of part, upper and lower limit deviations of blank dimension – in preliminary sketch of initial blank (ref. paragraph 3.3). Tolerances $\boldsymbol{T}$ are assigned for all operation dimensions, when distributing the parameters along manufacturing steps at development of machining routes for main surfaces (ref. paragraph 3.4.2). Values of minimum allowances $2\boldsymbol{Z_{minN}}$ are determined from analythical or normative (ref. Appendix 10) method depending on definite conditions of manufacturing steps (ref. paragraph 3.6.2).

3.8.1. Calculations of operation dimensions-shafts

Calculated dimension $\boldsymbol{d_{ic}}$ for shafts equals nominal dimension $\boldsymbol{d_{inom}}$ that, in its turn, equals *maximum* limit dimension $\boldsymbol{d_{imax}}$ (before rounding-off):

$$d_{ic} = d_{inom} = d_{imax}.$$

But for intial blank dimensions there is a peculiarity (Fig. 3.15):

$$d_{0c} = d_{0nom} \neq d_{0max}.$$

Calculated nominal dimension d_{i-1c} of a workpiece round external surface (shaft) at previous (i–1) manufacturing step (operation) is *larger* than nominal dimension d_{ic} at current i operation by the value of nominal allowance $2Z_{inom}$ determined for current operation. Nominal allowance $2Z_{inom}$ is calculated from values of minimum allowance for current operation $2Z_{iminN}$ and tolerance T_{i-1} of dimension at previous operation (ref. Fig. 3.15):

$$2Z_{inom} = 2Z_{iminN} + T_{i-1}, \tag{3.29}$$

$$d_{i-1c} = d_{ic} + 2Z_{inom}. \tag{3.30}$$

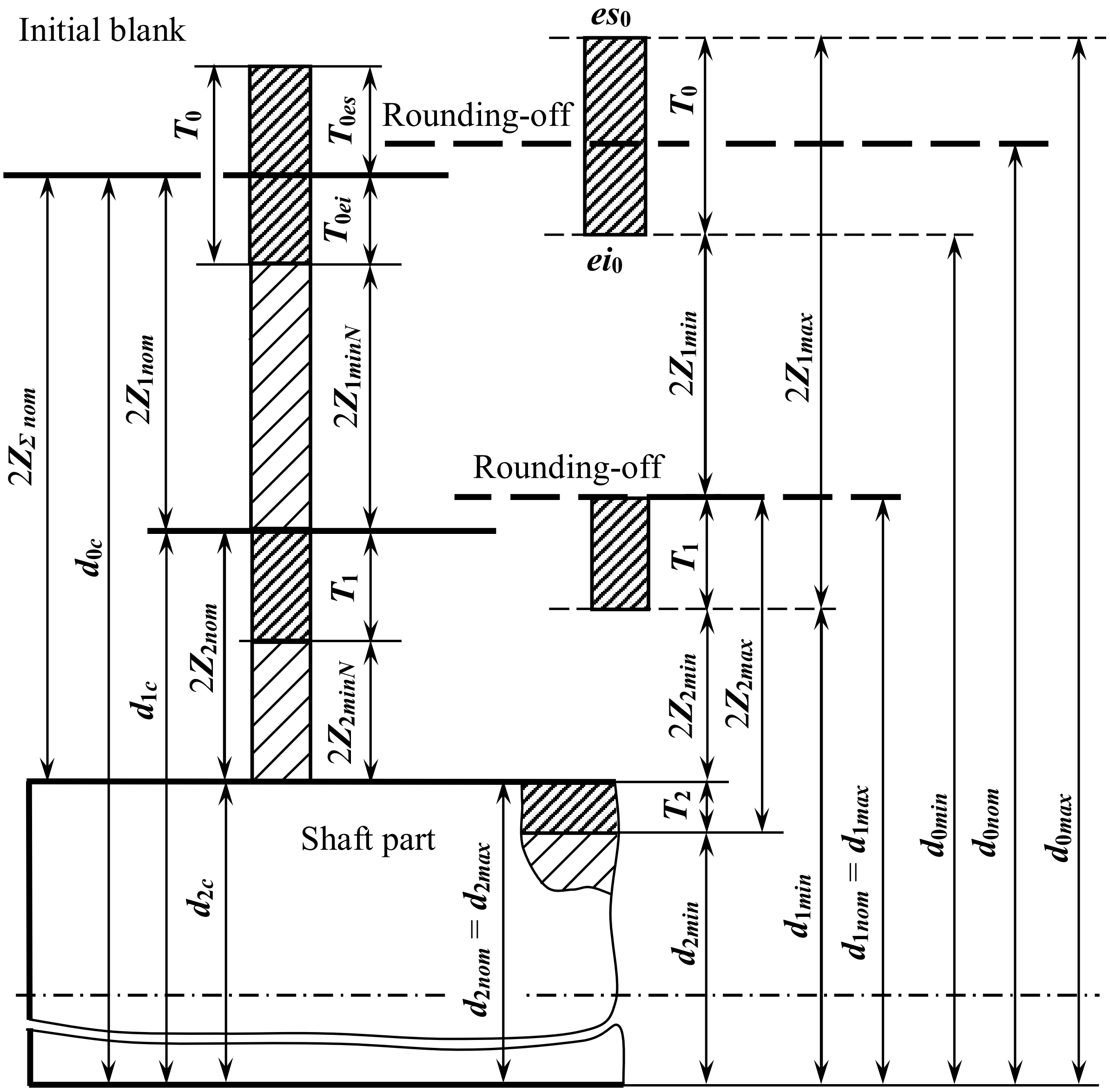


Fig. 3.15. Diagram of allowances, tolerance bands and operation dimensions along manufacturing steps for shaft-type parts

Here it is worth to remember that allowance belongs to the surface, from which it is removed, and so number $\boldsymbol{i}$ shows that surface $\boldsymbol{i}$ has diameter $\boldsymbol{d_i}$ and allowance $2\boldsymbol{Z_i}$ covers this surface.

Number $\boldsymbol{i}$ also means number of a manufacturing step in sequence of several steps assigned for a considered round surface, when developing a machining route (ref. paragraph 3.4.2). Number $\boldsymbol{i}$ can possess values from 1 to $\boldsymbol{n_A}$. Number $\boldsymbol{n_A}$ is a quantity of manufacturing steps calculated and adopted for a considered surface. This number can be corrected (enlarged), when making optimisation of manufacturing dimension chains (ref. paragraph 3.7.2).

Manufacturing operation dimensions of shaft-type elements are written in the form of *dimension-shaft* with basic deviation h (basic shaft) $\boldsymbol{d_i} = \boldsymbol{d_{imax}}{}^{\,0}_{-\boldsymbol{T_i}}$. Nominal dimension of basic shaft equals maximum limit dimension: $\boldsymbol{d_{inom}} = \boldsymbol{d_{imax}}$, $\boldsymbol{d_{i-1nom}} = \boldsymbol{d_{i-1max}}$.

Design dimension, as initial data for calculations of operation dimensions, can be specified not with h basic deviation, but with any other one from 28 small letter symbols (a, b, c, … , zb, zc). In this case a production engineer makes transformation of design dimension into *dimension-shaft* with h basic deviation *without rounding-off*, for example,

$$\varnothing 40\text{n}6\binom{+0.033}{+0.017} = \varnothing 40.033\text{h}6(_{-0.016}).$$

Initial blank dimensions have another form of writing $\left(\boldsymbol{d}_{0nom}{}^{\boldsymbol{es}_0}_{\boldsymbol{ei}_0}\right)$ than *dimension-shaft* typical for metal-cutting operation, because initial blank is produced by casting, forging, rolling and other methods under special standards. Neither upper $\boldsymbol{es_0}$ nor lower $\boldsymbol{ei_0}$ limit deviation equals zero. Therefore nominal dimension $\boldsymbol{d_{0nom}}$ does not equal maximum limit dimension $\boldsymbol{d_{0max}}$ (ref. Fig. 3.15).

Nominal allowance for the first manufacturing step $2\boldsymbol{Z_{1nom}}$ and nominal dimension of initial blank (as previous step $(\boldsymbol{i}-1) = 0$) are obtained from the formulas:

$$2\boldsymbol{Z_{1nom}} = 2\boldsymbol{Z_{1minN}} + \boldsymbol{T_{0ei}}, \tag{3.31}$$

$$\boldsymbol{d_{0c}} = \boldsymbol{d_{1c}} + 2\boldsymbol{Z_{1nom}}, \tag{3.32}$$

where $\boldsymbol{T_{0ei}}$ is the lower portion of blank dimension tolerance.

The calculated nominal dimensions $\boldsymbol{d_{ic}}$ and blank dimension $\boldsymbol{d_{0c}}$ are rounded off with their *increases* except design dimensions:

$$\boldsymbol{d_{ic}} \approx \boldsymbol{d_{imax}}, \quad \boldsymbol{d_{0c}} \approx \boldsymbol{d_{0nom}}.$$

Rounding-off is usually made with accuracy of 0.1 mm for blank dimensions, for operation dimensions of rough and finish machining stages, and with accuracy of 0.1 mm and 0.01 mm for operation dimensions of fine-finish machining stage depending on tolerance.

Then, the *adopted* limit dimensions are calculated from the formulas with rounded values:

- For operation dimensions

$$\boldsymbol{d_{imin}} = \boldsymbol{d_{imax}} - \boldsymbol{T_i}; \tag{3.33}$$

- For initial blank dimensions:

$$d_{0min} = d_{0nom} + ei_0; \tag{3.34}$$

$$d_{0max} = d_{0nom} + es_0. \tag{3.35}$$

Usually the increases of nominal dimensions at their rounding-off result in increase of allowance. But in sequence of several manufacturing steps and dimensions some decrease of allowance can happen and, in particular, decrease of minimum allowance. Minimum value of *adopted* allowance $2Z_{imin}$ is the smallest layer of material that provides quality of a part, and so it must not be less than *normative* minimum allowance $2Z_{iminN}$ at each manufacturing step:

$$2Z_{imin} \geq 2Z_{iminN}. \tag{3.36}$$

Therefore, after rounding of operation and blank dimensions the adopted values of minimum allowances are calculated from the formulas (ref. Fig. 3.15):

$$2Z_{imin} = d_{i-1min} - d_{imax}, \tag{3.37}$$

$$2Z_{1min} = d_{0min} - d_{1max}, \tag{3.38}$$

where d_{i-1min} is minimum limit of operation dimension at previous manufacturing step; d_{imax} is maximum limit of operation dimension at current manufacturing step; d_{0min} is minimum limit of initial blank dimension; d_{1max} is maximum limit of operation dimension at the first manufacturing step (operation).

Corrections of the adopted limit dimensions are made, if necessary, in order to fit the condition (3.36).

Maximum value of *adopted* allowance is necessary for application as initial data for calculations of cutting conditions for respective operation. It is determined from the formulas (ref. Fig. 3.15):

$$2Z_{imax} = d_{i-1max} - d_{imin}, \tag{3.39}$$

$$2Z_{1max} = d_{0max} - d_{1min}, \tag{3.40}$$

where d_{i-1max} is maximum limit of operation dimension at previous manufacturing step; d_{imin} is minimum limit of operation dimension at current manufacturing step; d_{0max} is maximum limit of initial blank dimension; d_{1min} is minimum limit of operation dimension at the first manufacturing step (operation).

If necessary, some corrections of rounded values d_{imax} and d_{0nom} made and calculations are repeated by formulas (3.33) – (3.40) in order to fit condition (3.36). It is recommended to tune, first of all, values of minimum adopted allowances $2Z_{imin}$ and then calculate values $2Z_{imax}$.

Then operation dimensions-shafts are written in the form of basic shaft $d_i = d_{imax}{}^{0}_{-T_i}$, and initial blank dimensions – in the form $d_0 = d_{0nom}{}^{es_0}_{ei_0}$ stated by a respective standard.

It is convenient to conduct calculations in a table, which includes initial data, intermediate and final results.

3.8.2. Calculations of operation dimensions-holes

Calculation procedure (algorithm) for operation dimensions-holes is very similar to dimensions-shafts (ref. paragraph 3.8.1), but with several peculiarities.

First of all, calculated dimension $\boldsymbol{D_{ic}}$ for holes equals nominal dimension $\boldsymbol{D_{inom}}$ that, in its turn, equals *minimum* limit dimension $\boldsymbol{D_{imin}}$ (before rounding-off):

$$D_{ic} = D_{inom} = D_{imin}.$$

But intial blank dimensions differ from operation dimensions (Fig. 3.16):

$$D_{0c} = D_{0nom} \neq D_{0min}.$$

Calculated nominal dimension $\boldsymbol{D_{i-1c}}$ of a workpiece round internal surface (hole) at

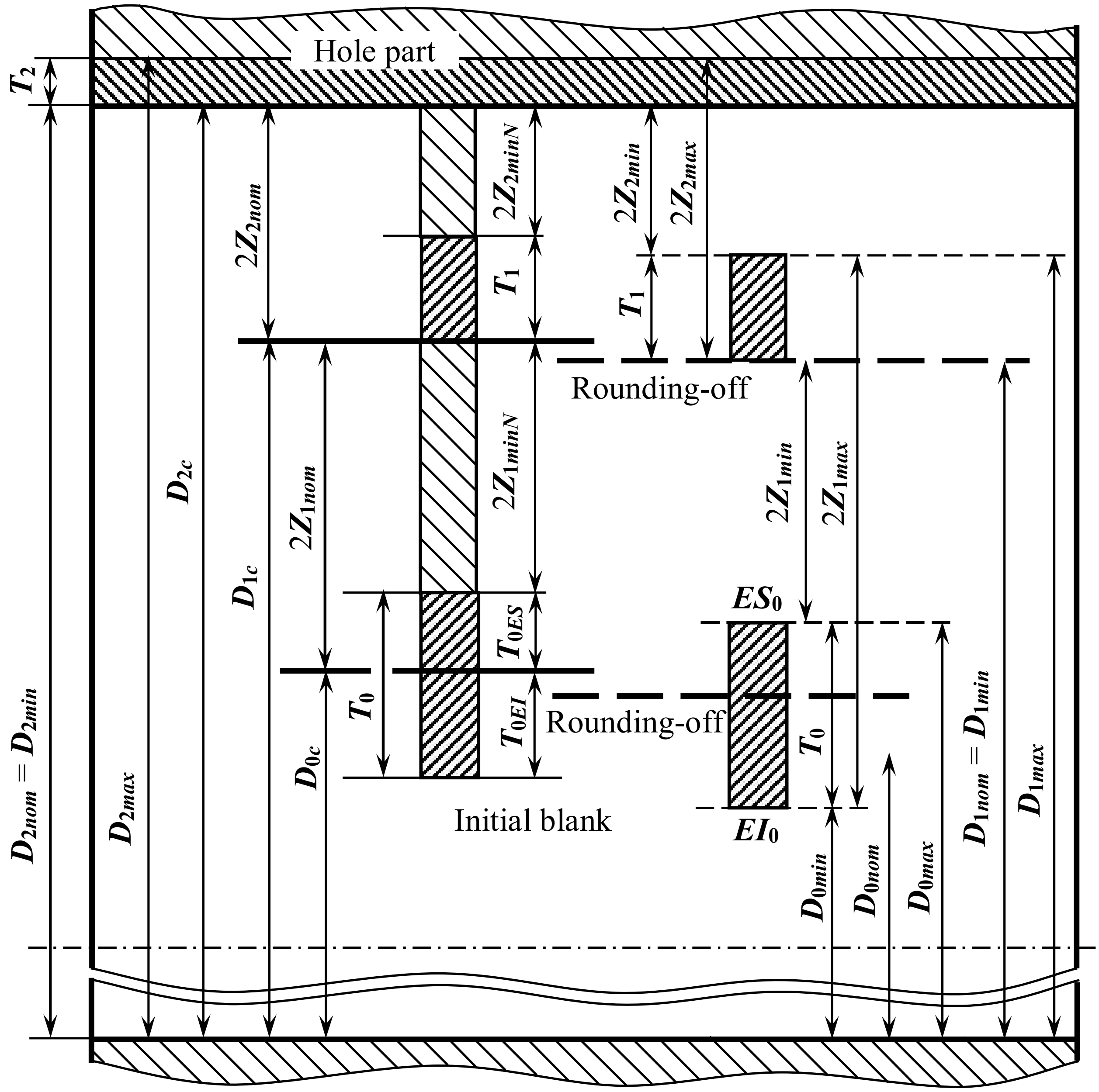


Fig. 3.16. Diagram of allowances, tolerance bands and operation dimensions along manufacturing steps for hole-type parts

previous ($\boldsymbol{i}$–1) manufacturing step (operation) is *smaller* than nominal dimension $\boldsymbol{D_{ic}}$ at current $\boldsymbol{i}$ operation by the value of nominal allowance $2\boldsymbol{Z_{inom}}$ determined for current operation. Nominal allowance $2\boldsymbol{Z_{inom}}$ is calculated from values of minimum allowance for current operation $2\boldsymbol{Z_{iminN}}$ and tolerance $\boldsymbol{T_{i-1}}$ of dimension at previous operation (ref. Fig. 3.16):

$$2Z_{inom} = 2Z_{iminN} + T_{i-1},$$

$$D_{i-1c} = D_{ic} - 2Z_{inom}. \qquad (3.41)$$

Manufacturing operation dimensions of hole-type elements are written in the form of *dimension-hole* with basic deviation H (basic hole) $D_i = D_{imin}{}^{+T_i}_{0}$. Nominal dimension of basic hole equals minimum limit dimension: $D_{inom} = D_{imin}$, $D_{i-1nom} = D_{i-1min}$.

Design dimension, as initial data for calculations of operation dimensions, can be specified not with H basic deviation, but with any other one from 28 capital letter symbols (A, B, C, … , ZB, ZC). In this case a production engineer makes transformation of a design dimension into *dimension-hole* with H basic deviation *without rounding-off*, for example,

$$\varnothing 40\mathrm{N7}\left({}^{-0.008}_{-0.033}\right) = \varnothing 39.967\mathrm{H7}\left({}^{+0.025}\right).$$

Initial blank dimensions of hole type elements have another form of writing $\left(D_{0nom}{}^{ES_0}_{EI_0}\right)$ than *dimension-hole* typical for metal-cutting operation, because initial blank is produced by casting, forging, rolling and other methods under special standards. Neither upper $\boldsymbol{ES_0}$ nor lower $\boldsymbol{EI_0}$ limit deviation equals zero. Therefore nominal dimension $\boldsymbol{D_{0nom}}$ does not equal minimum limit dimension $\boldsymbol{D_{0min}}$ (ref. Fig. 3.16).

Nominal allowance for the first manufacturing step $2\boldsymbol{Z_{1nom}}$ and nominal dimension of initial blank (as previous step ($\boldsymbol{i}$–1) = 0) are obtained from the formulas:

$$2Z_{1nom} = 2Z_{1minN} + T_{0ES}, \qquad (3.42)$$

$$D_{0c} = D_{1c} - 2Z_{1nom}, \qquad (3.43)$$

where $\boldsymbol{T_{0ES}}$ is the upper portion of blank dimension tolerance.

The calculated nominal dimensions $\boldsymbol{D_{ic}}$ and blank dimension $\boldsymbol{D_{0c}}$ are rounded off with their *decreases* except design dimensions:

$$D_{ic} \approx D_{imin}, \quad D_{0c} \approx D_{0nom}.$$

Rounding-off is usually made with accuracy of 0.1 mm for blank dimensions, for operation dimensions of rough and finish machining stages, and with accuracy of 0.1 mm and 0.01 mm for operation dimensions of fine-finish machining stage depending on tolerance.

Then, the *adopted* limit dimensions are calculated from the formulas with rounded values:

- For operation dimensions

$$D_{imax} = D_{imin} + T_i; \qquad (3.44)$$

- For initial blank dimensions:

$$D_{0min} = D_{0nom} + EI_0; \tag{3.45}$$

$$D_{0max} = D_{0nom} + ES_0. \tag{3.46}$$

Usually the decreases of nominal dimensions at their rounding-off result in increase of allowance. But in sequence of several manufacturing steps and dimensions some decrease of allowance can happen and, in particular, decrease of minimum allowance. Minimum value of *adopted* allowance $2Z_{imin}$ is the smallest layer of material that provides quality of a part, and so it must be no less than *normative* minimum allowance $2Z_{iminN}$ at each manufacturing step (see the formula (3.36)).

Therefore, after rounding of operation and blank dimensions the adopted values of minimum allowances are calculated from the formulas (ref. Fig. 3.10):

$$2Z_{imin} = D_{imin} - D_{i-1max}, \tag{3.47}$$

$$2Z_{1min} = D_{1min} - D_{0max}, \tag{3.48}$$

where D_{imin} is minimum limit of operation dimension at current manufacturing step; D_{i-1max} is maximum limit of operation dimension at previous manufacturing step; D_{1min} is minimum limit of operation dimension at the first manufacturing step (operation); D_{0max} is maximum limit of initial blank dimension.

Maximum value of *adopted* allowance is necessary for application as initial data for calculations of cutting conditions for respective operation. It is determined from the formulas (ref. Fig. 3.16):

$$2Z_{imax} = D_{imax} - D_{i-1min}, \tag{3.49}$$

$$2Z_{1max} = D_{1max} - D_{0min}, \tag{3.50}$$

where D_{imax} is maximum limit of operation dimension at current manufacturing step; D_{i-1min} is minimum limit of operation dimension at previous manufacturing step; D_{1max} is maximum limit of operation dimension at the first manufacturing step (operation); D_{0min} is minimum limit of initial blank dimension.

If necessary, some corrections of rounded values D_{imin} and D_{0nom} are made and calculations are repeated by formulas (3.44) – (3.50) in order to fit condition (3.36). It is recommended to tune, first of all, values of minimum adopted allowances $2Z_{imin}$ and then calculate values $2Z_{imax}$.

Finally the operation dimensions-holes are written in the form of basic hole $D_i = D_{imin}{}^{+T_i}_{0}$, and initial blank dimensions – in the form $D_0 = D_{0nom}{}^{ES_0}_{EI_0}$ stated by a respective standard.

It is convenient to conduct calculations in a table, which includes initial data, intermediate and final results.

3.9. Performance of final plan of manufacturing process

The optimised preliminary plan, the calculated and adopted operation dimensions-coordinates for faces and operation dimensions for round surfaces are enough information for performance of final plan of manufacturing process.

In comparision with preliminary plan the optimised plan of manufacturing process includes all changes in schemes of locating and clamping in separate operations related to changes of initial datums at optimisation of dimension chains, as well as changes related to increases of quantities of manufacturing steps for separate round and flat surfaces made for ensuring the accuracy of relative positions of datums and combinations of surfaces.

In comparision with optimised plan the final plan of manufacturing process contains operation dimensions and roughness parameters in all machining operations.

Operation sketches are performed in the arbitrary scale, but accurately and with observance of proportions. In a sketch sheet the number and title of operation is written in the upper left corner, schemes of locating and clamping are shown on the picture of workpiece, and machined surfaces are shown by thick lines, the rest of lines being thin. The machined surfaces are numbered. According to the standard GOST 3.1104-84 the numbering should start from number "1" and the following numbers are applied to machined surfaces in sequence, when going around the surfaces clockwise. With educational purpose it is recommended to use the same numbers of main surfaces, assigned at calculations of manufacturability indexes (ref. paragraph 3.2), for numbering the machined surfaces in operation sketches.

Roughness values are specified *only* for machined surafaces. Roughness symbols are shown, as a rule, in the upper right corner of sketch sheet and on the lines (surfaces) of a workpiece picture.

Adopted operation dimensions for flat and round surfaces are specified over dimension lines in all machining operation sketches.

At the foot of the sketch sheet on righ-hand side the *manufacturing steps are written in a definite sequence*. For round workpieces the following sequence of steps is recommended at machining in turning machines. The first surface to be machined is the face, which is used as an initial datum for dimensions-coordinates of other machined faces. Then the face mating with an axial hole is machined. After that the axial hole and mating internal face (if any) are machined. Finally the outside round surfaces with mating faces are processed. Special attention is paid to the surfaces, which serve as set of datums (round surface and mating face) for the next operation or for the several following operations. Such datum surfaces should be *obligatory* machined and it is advisable to machine at one mounting in order to provide the highest level of accuracy of their relative position.

Manufacturing steps are numbered starting from number "1". In the operation sketch sheet the texts of manufacturing steps are written in the imperative mood, for example, "3. Turn surface 14.", "1. Mill slot 6", "4. Bore hole 8 and turn face 7".

The example of final plan of manufacturing process is submitted in the Chapter 4.

4. PLANNING OF ROUTE MANUFACTURING PROCESS FOR PRODUCTION OF BATCH OF PARTS

This chapter is based on the theoretical basis submitted in the Chapter 3.

Initial data for the planning are the drawing of the part with specified parameters of accuracy, surface roughness, technical requirements, type of blank, material (Fig. 4.1) and type of production conditions (small-batch).

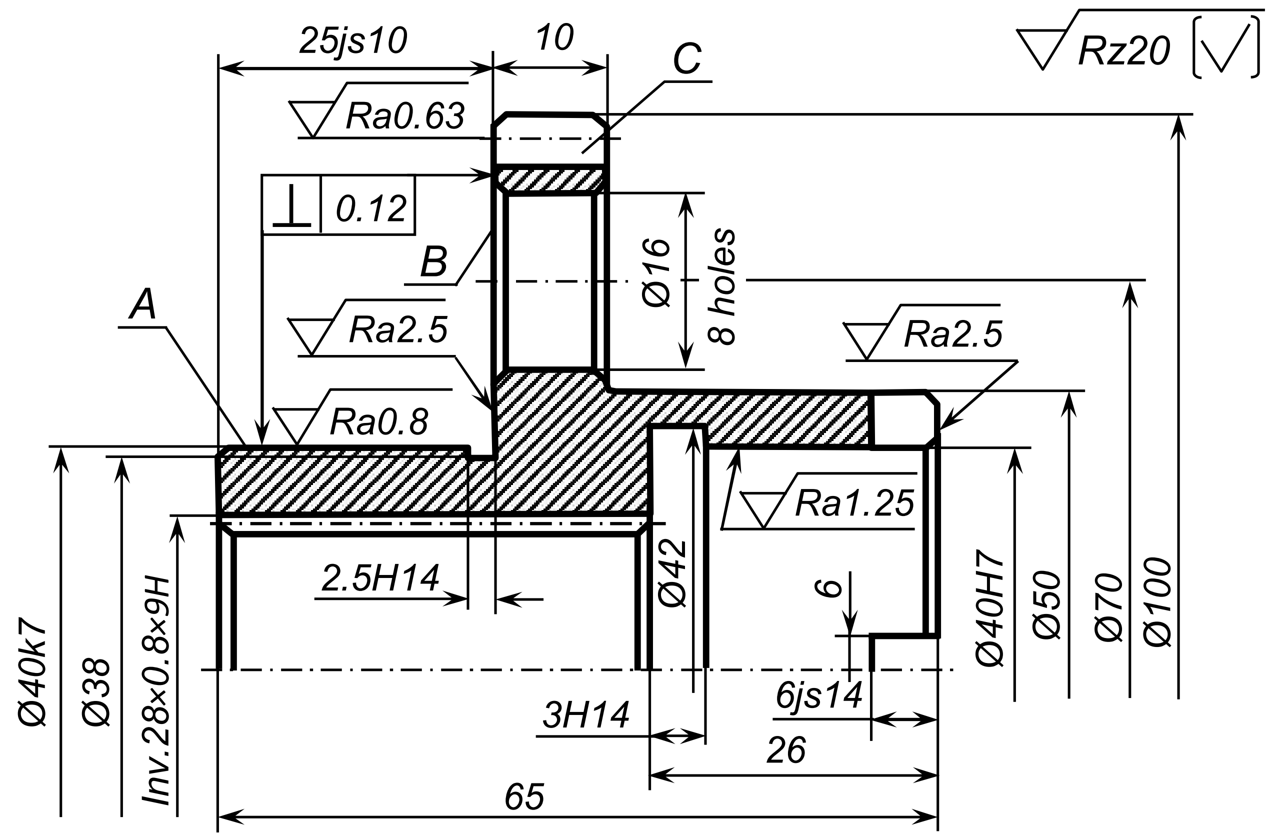


Fig. 4.1. Sketch of the shaft-gear part from 20X2H4A (20H2N4A) carbonized steel with the following technical requirements. 1. Blank is a forging. 2. Unspecified limit deviations of dimensions: H12, h12, ±IT12/2, ±AT12/2, ±AT13/2. 3. Relative geometric accuracy C. 4. Total face runout of surface B relative to the axis is not more than 0.05 mm. 5. Carbonize surfaces A, B and gear ring C at depth ***h*** = 0.4…0.7 mm with hardness HRC 56…63, the rest material HB 321…420, inspection group 3-1Ts OST 1.00021-78. Gear ring C parameters are: module ***m*** = 2.5 mm, number of teeth *z* = 38, accuracy 7-6-6-C GOST 1643-81

4.1. Technological analysis of the drawing

4.1.1. Purpose of part, diagram of loads application, operation conditions

The part is designed for transmission of torque from accessory drive box to the electric generator of aviation turbine engine.

Load is transmitted from the gear ring to the involute splines and then to the splined shaft of the generator.

Gear wheels of aircraft engines operate under the load up to 700÷800 N per 1 mm of a tooth length. They should be lightweight and reliable; therefore they are made with holes to reduce mass, but with sufficient safety factor.

Operating temperature of the part is from –60°C to +200°C. Oil lubricant is applied in drive box, and so friction of teeth flanks is wet.

Operation conditions of the part are: high contact stresses, cyclic and impact character of load. These conditions determined selection of a material – alloy high-quality steel 20X2H4A (20H2N4A) with ability of hardening of teeth flank surfaces by carbonization.

4.1.2. Properties of material

Carbonized steel 20X2H4A (20H2N4A) was selected from the steels [16] recommended for production of gear wheels taking into account the operation conditions and high requirements to the part purpose.

Chromium and nickel improve strength, toughness and impact strength of the steel (Table 4.1). Low carbon content does not allow to obtain high hardness by quenching. Therefore the carbonization of the specified surfaces is recommended to saturate them with carbon. The sequent heat treatment produces high Rockwell hardness number HRC 56…63 of carbonized surfaces.

Table 4.1. Chemical composition of steel 20X2H4A (20H2N4A), mass %

C	S_i	Mn	Cr	Ni	Cu	Fe	S	P
							Not more than	
0,16– –0,22	0,17– –0,37	0,30– –0,60	1.25– –1.65	3.25– –3.65	≤ 0.30	basis	0,025	0,030

Mechanical characteristics after diffusion heat treatment and heat treatment are submitted in the Table 4.2.

Table 4.2. Mechanical properties of steel 20X2H4A (20H2N4A)

Heat treatment			$\sigma_{0.2}$, MPa	σ_u, MPa	δ, %	ψ, %	***KCU***, kJ/m^2	HRC	HB
Operation	***T***, °C	Cooling medium	Not less than						
Carbonisation Normalisation or quenching Tempering Quenching Tempering	920-950 900-920 880-920 630-660 780-820 150-200	 Air Oil Air Oil Air	835	1080	9	35	780	Surface 56-63	Core 321-420

Carbonization (ref. Appendix 1) followed by heat treatment provides high contact strength and wear resistance of teeth surfaces and large impact toughness of core material that prevents generation of cracks and premature failure under impact loads.

Density of the steel is ρ = 7850 kg/m^3 at 20°C.

Manufacturing properties are characterized by forgeability, weldability, machinability.

Forging temperature range is from 1200°C (start) down to 800°C (finish).

Weldability is not good. Recommended methods are: hand arc welding, hand argon-arc welding with non-consumable electrode, automatic submerged-arc welding, electroslag welding and resistance welding. Preheating and sequent heat treatment of welded parts is necessary.

Machinability is worse in comparison with steel 45. It is characterised by coefficient K_V = 0.72, when machining with cemented carbide cutting tools and K_V = 0.63, when machining with high-speed steels. These values are given for the steel condition after normalisation and tempering at HB 256 and σ_u = 880 MPa.

The steel is very sensitive to flakes and has low tendency to temper brittleness.

4.1.3. Design features of part

In the longwise section the part has no curvilinear segments (ref. Fig. 4.1); diameters of left-hand and right-hand hubs (shafts) are straigt and smaller than diameter of gear ring that allows to machine outside and internal surfaces with turning and facing cutting tools. Sufaces of high accuracy are mating with grooves that facilitate machining with grinding wheels. Ratio of the part length to its diameter is not large that results in its high stiffness and exclude application of special-purpose mandrels for a stiffness improvement.

The part has gear ring of relatively high accuracy 7-6-6-C GOST 1643-81: 7th degree by kinematic accuracy, 6th degree by operation smoothness and 6th degree by teeth contact patch with backlash by C type engagement. These parameters and geometric position dictate the following route for machining of gear ring [8, 17]: gear hobbing due to free access of a milling cutter, diffusion heat treatment, heat treatment, single gear grinding.

The part also includes spline bushing 25×0.8×9H GOST 6033-80 (ref. Fig. 4.1): 25 – nominal (major) diameter of joint, mm; 0.8 – module, mm; 9 – accuracy degree; H – basic deviation of teeth space; z = 30 – number of teeth. Minor diameter of spline bushing is calculated from the formula [18]: $D_a = m\,(z - 0.9)$ = 23.28 mm.

Taking into account geometric dimensions, accuracy and internal location of splines, it is reasonable to produce them with broaching [18]. Preparation of hole of 23.28-mm diameter for a broaching operation should include several manufacturing steps to obtain accuracy grade IT11 and roughness R_z10 necessary for alignment of a cutting tool (broach).

The surfaces of the highest accuracy are outer cylindrical surface Ø40k7 and inner cylindrical surface Ø40H7 (ref. Fig. 4.1). The 7th accuracy grade needs application of grinding operation at fine-finishing stage of manufacturing process.

Most surfaces are non-mating with other parts and so they are produced by the 12th accuracy grade.

Accuracy of relative position of surfaces A and B shown by special symbols in the drawing (ref. Fig. 4.1) is important for a designer. It is recommended to machine both surfaces at one mounting (in one operation) that ensures the highest accuracy of relative position.

For other surfaces the accuracy of form and position are specified by accuracy grade IT12 and relative geometric accuracy C. These requirements are provided by increasing accuracy level of datum surfaces and by use of the same mounting datums along operations of manufacturing process.

Roughness of the most of surfaces is $\boldsymbol{R_z} = 20$ µm (ref. Fig. 4.1). Several surfaces have better surface finish: surface A ($\boldsymbol{R_a}$0.8) and adjacent face B ($\boldsymbol{R_a}$2.5); hole Ø40H7 ($\boldsymbol{R_a}$1.25) and adjacent face ($\boldsymbol{R_a}$2.5); flanks of theeth C ($\boldsymbol{R_a}$0.63). Surface roughness of less than $\boldsymbol{R_a}$2.5 will be produced by grinding machining methods.

4.2. Estimation of manufacturability

Additional indexes of quantitative estimation of manufacturability are calculated for the main surfaces of the part (Fig. 4.2). Any part can be presented as a combination of simple or complicated geometric surfaces (planes, cylinders, cones, involute surfaces, etc.).

Mean accuracy grade is calculated for the main dimensions (ref. Fig. 4.1) from the formula (3.1)

$$\boldsymbol{IT_m} = \frac{\sum \boldsymbol{IT_i} \cdot \boldsymbol{n_i}}{\sum \boldsymbol{n_i}} = \frac{7 \cdot 2 + 10 \cdot 1 + 11 \cdot 1 + 12 \cdot 7 + 14 \cdot 1}{2 + 1 + 1 + 7 + 1} = 11.08,$$

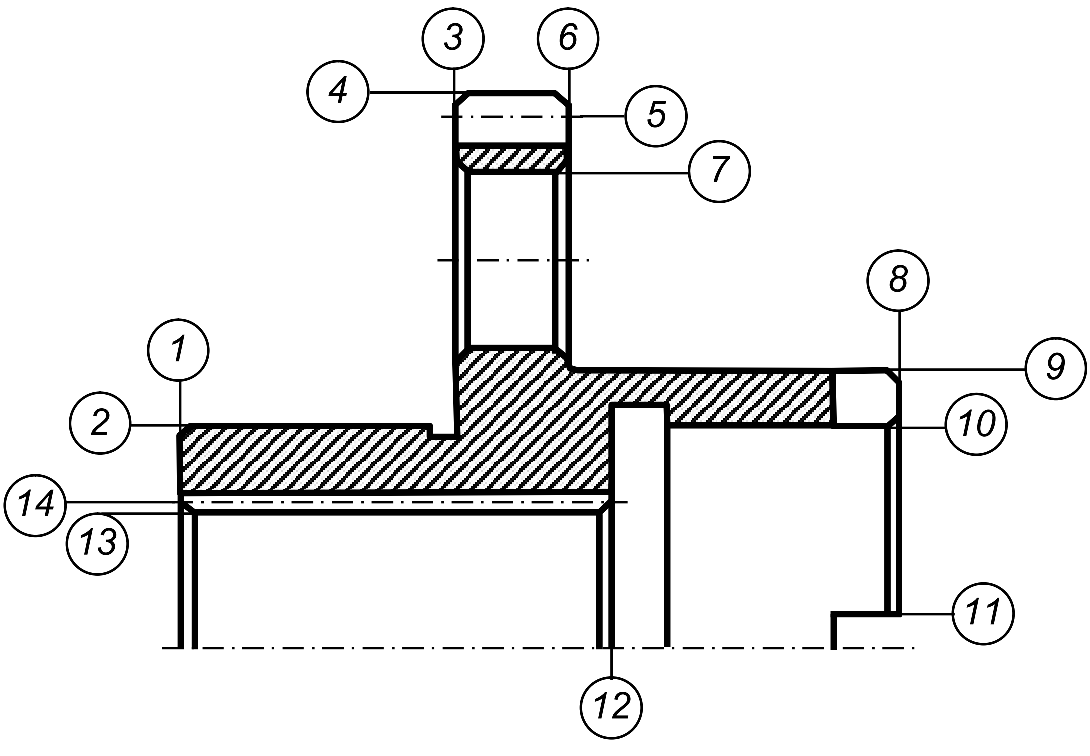


Fig. 4.2. Diagram of numbering of main surfaces of the part

and coefficient of machining accuracy – from the formula (3.2)

$$K_T = 1 - \frac{1}{IT_m} = 1 - \frac{1}{11.08} = 0.91.$$

Since $K_T > 0.8$, the part is manufacturable by this index.

Mean roughness of main surfaces (ref. Fig. 4.2 and Fig. 4.1) is calculated from the formula (3.3)

$$R_{am} = \frac{\sum R_{ai} \cdot n_i}{\sum n_i} = \frac{0.8 \cdot 1 + 1.25 \cdot 1 + 2.5 \cdot 3 + 5 \cdot 7}{1 + 1 + 3 + 7} = 3.71,$$

and coefficient of surfaces roughness – from the formula (3.4)

$$K_R = \frac{1}{R_{am}} = \frac{1}{3.71} = 0.269.$$

Since $K_R < 0.32$, the part is manufacturable by this index.

Coefficients K_T and K_R do not include parameters of accuracy and roughness of surfaces 5 and 14.

Coefficient of material utilisation is calculated after selection of the method for initial blank production and calculations of its exact dimensions

$$C_{MU} = \frac{m_p}{m_b} = \frac{0.723}{1.889} = 0.383,$$

where m_p and m_b – masses of the part and initial blank respectively, kg.

Qualitative analysis of manufacturability shows that machining of toothed surfaces is performed by underproductive methods in complicated and expensive equipment and with complicated and expensive cutting tools.

4.3. Selection of method for initial blank production and development of its sketch

Selection of method for production of initial blank is determined by several factors: purpose and operating conditions of the part, its geometric configuration, properties of material and type of production.

There are three groups of fundamental methods for blank manufacture: foundry, metalworking and welding.

Casting methods typically produce coarse-grain structures with casting defects (porosity, shrinkage cavities and cracks, etc.). These features greatly reduce all mechanical properties of material. Therefore the casting methods are applicapable for the gears of the specified purpose.

Welded blanks can reduce material consumption for the part production by joining of simple geometric preforms. But they have similar casting defects in a welded seam and coarse-grain structure in a heat-affected zone.

Forging in dies is the most suitable technique among metalworking method, due to its capability to generate fine-grain fiber-like structure with high mechanical properties of material. It's important that the dies cavities form favourable location of fibers equidistant to outer contour of blank.

Taking into account this consideration and recommendations given in the literature [8, 10, 12], it is reasonable to select hot-forging process in open dies on a crank hot-forging press. Parting line of the dies goes through the largest cross-section of the part that facilitates filling the dies cavities with metal and provides easy check of dies displacement [10]. The forging drafts are specified for those surfaces, which are perpendicular to the parting plane. When forming in a crank hot-forging press the drafts for outer surfaces equal 5° and for inner surfaces – 7°.

At this stage of manufacturing process planning the dimensions of initial blank are determined approximately, by increasing of shaft-type dimensions by 10–20 % and decreasing of hole-type dimensions by 10–20 %. *Approximate* dimensions in the sketch of blank (Fig. 4.3) are specified like in the drawing of part (ref. Fig. 4.1). This approach ensures coincidence of design and manufacturing (forging) datums.

Rounding radii of forging corners are selected from the standardised series [10] (ref. Appendix 4): the internal corners are of 8 mm, the external ones – 3 mm. Permissible displacement of dies is 0.4 mm.

Initial data for determination of limit deviations of forging dimensions according to the GOST 7505-74 are: forged blank mass, group of steel and complexity level (ref. Appendix 4).

Approximately the forging volume V_f is calculated as an algebraic sum of cylin-

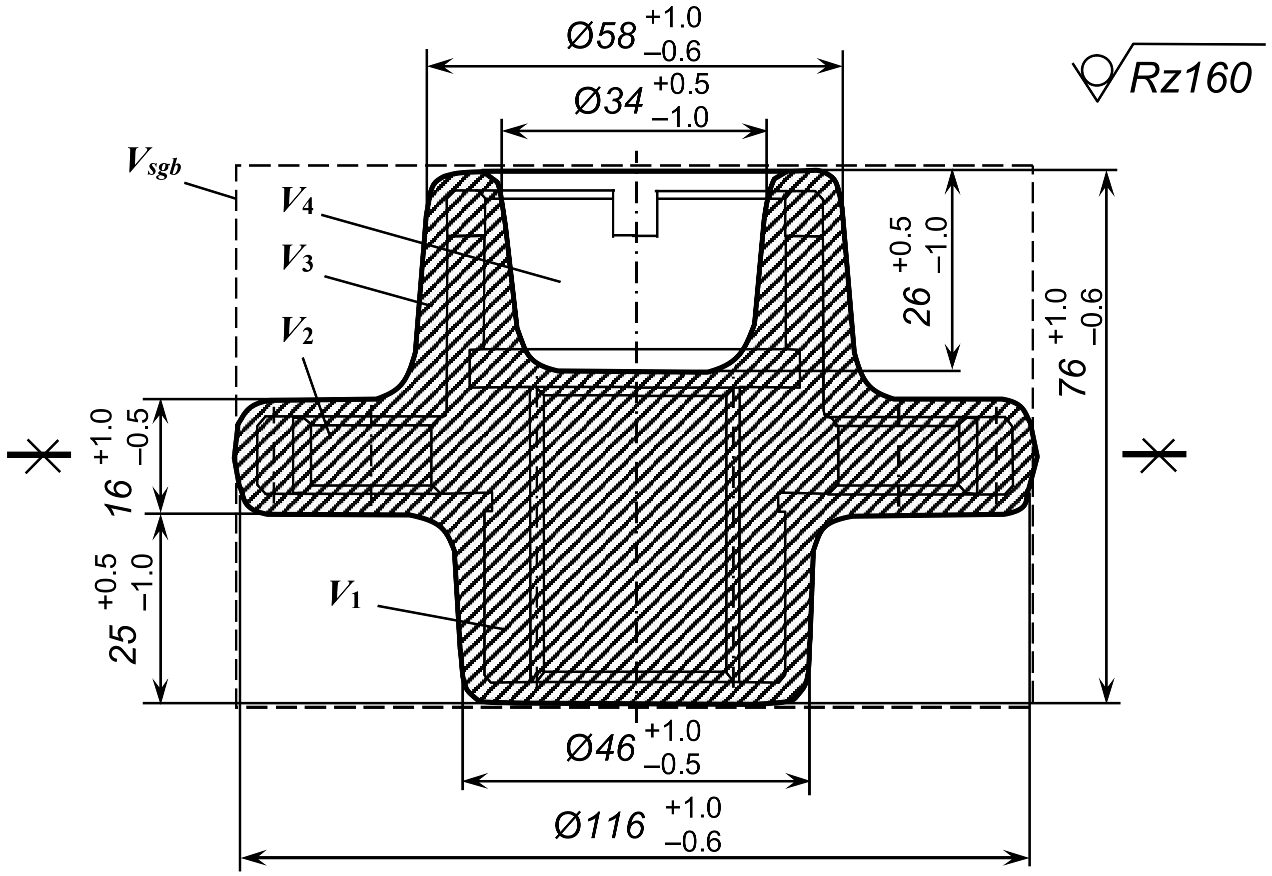


Fig. 4.3. Preliminary sketch of forging of shaft-gear

ders volumes, from which the forging configuration can be compiled (ref. Fig. 4.3)

$$V_f = V_1 + V_2 + V_3 - V_4 = \frac{\pi}{4}\left(d_1^2 \cdot l_1 + d_2^2 \cdot l_2 + d_3^2 \cdot l_3 - D_4^2 \cdot l_4\right);$$

$$V_f = \frac{\pi}{4}\left(46^2 \cdot 25 + 116^2 \cdot 16 + 58^2 \cdot 35 - 34^2 \cdot 26\right) = 277957 \text{ mm}^3 = 2.77957 \cdot 10^{-4} \text{ m}^3.$$

At this stage of planning the forging drafts and radii are not included into values of volume, because exact mass value is not necessary due to wide ranges of a forging mass used for selection of dimensions deviations (ref. Appendix 4).

Mass of forging is determined by its volume V_f and density of material ρ

$$m_f = \rho \cdot V_f = 7850 \cdot 2.77957 \cdot 10^{-4} \approx 2.18 \text{ kg}.$$

Alloy steel 20X2H4A (20H2N4A) belongs to the group M2, because it contains more than 2 % alloying elements except carbon (ref. Table 4.1).

Volum of simple geometric body (cylinder) V_{sgb}, in which the forging configuration can be inscribed, is calculated

$$V_{sgb} = \frac{\pi d_{max}^2}{4} \cdot l = \frac{3.14 \cdot 116^2}{4} \cdot 76 = 802785 \text{ mm}^3 = 8.02785 \cdot 10^{-4} \text{ m}^3,$$

where d_{max} is diameter of cylinder equals the maximum diameter of forging, mm; l is height of cylinder equals height of forging, mm.

Complexity level of forging is calculated from the formula

$$C = \frac{V_f}{V_{sgb}} = \frac{2.77957 \cdot 10^{-4}}{8.02785 \cdot 10^{-4}} = 0.346.$$

This value corresponds to the C2 (C = 0.32–0.63) complexity index.

For forgings of the higher accuracy class (ref. Appendix 4) the limit deviations of dimensions are selected according to m_f, M2, C2:

- For dimensions interval from 0 to 50 mm: for shaft-type elements: upper limit deviation es = + 1.0; lower limit deviation ei = – 0.5 mm; for hole-type elements: ES = + 0.5, EI = – 1.0 mm;

- For dimensions interval from 50 to 120 mm: for shaft-type elements: es = + 1.0, ei = – 0.6 mm; for hole-type elements: ES = + 0.6, EI = – 1.0 mm.

The forging surfaces roughness R_z = 160 μm is selected from the reference table (ref. Appendix 4) according to the mass value.

4.4. Calculations of number of manufacturing steps and development of routes for machining of main surfaces

Quantity of manufacturing steps for main surfaces is determined by ratio of parameters of dimensions accuracy and roughness of the same-number surfaces of initial blank and final part, that is, by their total improvement.

For example, for surface 2 (ref. Fig. 4.2) parameters of the final part are Ø40k7$\left(^{+0.027}_{+0.002}\right)$, T_p = 25 μm, R_a0.8 (R_z3.2) (ref. Fig. 4.1), and parameters of the initial blank are Ø$46^{+1.0}_{-0.5}$, T_b = 1500 μm (that approximately corresponds to ≈ IT16), R_z160 (ref. Fig. 4.3).

Number of steps by accuracy (tolerance) is calculated from the formula (3.5):

$$n_T = \frac{lg(T_b/T_p)}{lg\,2.9} = \frac{lg(1500/25)}{0.46} = 3.865 \approx 4.$$

Number of steps by surface roughness is calculated from the formula (3.7):

$$n_R = \frac{lg(R_{zb}/R_{zp})}{lg\,2.5} = \frac{lg(160/3.2)}{0.4} = 4.247 \approx 4.$$

Adopted number of manufacturing steps is n_A = 4. This number is a minimum quantity of manufacturing steps in order to obtain the specified accuracy of dimension and surface roughness. When planning manufacturing process, this number may be enlarged in order to meet requirements on datums selection.

Improvements of accuracy from initial blank IT16 to final part IT7 (9 accuracy grades) are distributed among 4 manufacturing steps according to the rule of progressive decrease (ref. paragraph 3.4.2):

$$9 = 4 + 3 + 1 + 1.$$

Improvements of surface finish from initial blank R_z160 to final part R_a0.63 (R_z3.15) are distributed in a similar manner.

Basic deviation h (basic shaft) is selected due to the element under consideration is of shaft type.

Finally the distribution of accuracy and roughness parameters among 4 manufacturing steps is the following:

- 1st step: 16 – 4 = h12, T = 250 μm, R_z50;
- 2nd step: 12 – 3 = h9, T = 62 μm, R_z20;
- 3rd step: 9 – 1 = h8, T = 39 μm, R_z10 (R_a2.5);
- 4th step: 8 – 1 = k7(h7), T = 25 μm, R_z3.2 (R_a0.8).

The final dimension of part specified by the drawing is converted into executive (manufacturing) dimension with one-side tolerance directed into metal:

$$Ø40k7\binom{+0.027}{+0.002} = Ø40.027h7(_{-0.025}).$$

Taking into account distribution of accuracy and roughness among manufacturing steps and recommendations [4] (ref. Appendix 7) the route for machining of surface 2 is developed:

- 1st step – rough turning: h12, R_z50;
- 2nd step – semi-finish turning: h9, R_z20;
- 3rd step – finish turning: h8, R_z10 (R_a2.5);
- 4th step – grinding: k7(h7), R_z3.2 (R_a0.8).

Results of calculations and machining routes for the rest of main surfaces are submitted in the Table 4.3.

Table 4.3. Distribution of accuracy and roughness along manufacturing steps and routes for machining of main surfaces

Surface No.	Parameters of part	Parameters of blank	Number of step n_T	Number of step n_R	Number of step n_A	Parameters along steps: IT/T, mm, R_z, µm — 1	2	3	4	Machining route
1	R_z20	R_z160	–	2.26	2	R_z50				Rough turning
							R_z20			Finish turning
2	Ø40k7$\left(^{+0.027}_{+0.002}\right)$ R_a0.8	Ø46$^{+1.0}_{-0.5}$ ≈ IT16 R_z160	3.87	4.26	4	h12/0.25 R_z50				Rough turning
							h9/0.062 R_z20			Semi-finish turning
								h8/0.039 R_z10		Finish turning
									h7/0.025 R_z3.2	Grinding
3	R_a2.5 (R_z10)	R_z160	–	3.01	3	R_z50				Rough turning
							R_z20			Semi-finish turning
								R_z10		Finish turning
4	Ø100h12($_{-0.35}$) R_z20	Ø116$^{+1.0}_{-0.6}$ ≈ IT16 R_z160	1.43	2.26	2	h14/0.87 R_z50				Rough turning
							h12/0.35 R_z20			Finish turning
5	Gear ring 7-6-6-C, R_a0.63	–								Gear hobbing
										Gear grinding
6	R_z20	R_z160	–	2.26	2	R_z50				Rough turning
							R_z20			Finish turning
7	Ø16H12($^{+0.18}$) R_z20	Blanking step – drilling Ø14H14($^{+0.43}$) R_z50	0.82	0.75	1	H14/0.43 R_z50				Drilling (blanking step)
							H12/0.18 R_z20			Core drilling

Table 4.3, continued

Surface No.	Parameters of: part	Parameters of: blank	Number of step: n_T	Number of step: n_R	Number of step: n_A	Parameters along steps: IT/$\boldsymbol{T}$, mm, $\boldsymbol{R_z}$, µm: 1	2	3	4	Machining route
8	R_a2.5 (R_z10)	R_z160	–	3.01	3	R_z50				Rough turning
							R_z20			Semi-finish turning
								R_z10		Finish turning
9	Ø50h12($_{-0.25}$) R_z20	Ø$58^{+1.0}_{-0.6}$ ≈ IT16 R_z160	1.75	2.26	2	h14/0.74 R_z50				Rough turning
							h12/0.25 R_z20			Finish turning
10	Ø40H7($^{+0.25}$) R_a1.25 (R_z5)	Ø$34^{+0.5}_{-1.0}$ ≈ IT16 R_z160	3.86	3.76	4	H12/0.25 R_z50				Rough boring
							H9/0.062 R_z20			Semi-finish boring
								H8/0.039 R_z10		Finish boring
									H7/0.025 R_z5	Internal grinding
11	Slot 6H12($^{+0.12}$), R_z20	–								Milling
12	R_z20	R_z160	–	2.26	2	R_z50				Rough turning
							R_z20			Finish turning
13	Ø23.28H11($^{+0.13}$) R_z10	Blanking step – drilling Ø20H14($^{+0.52}$) R_z50	1.31	1.75	2	H14/0.52 R_z50				Drilling (blanking step)
							H12/0.21 R_z20			Rough boring
								H11/0.13 R_z10		Finish boring
14	Spline bushing 25×0.8×9H	–								Broaching

4.5. Development of preliminary plan of manufacturing process

4.5.1. Structure of manufacturing process

Manufacturing steps assigned in previous paragraph in the routes for machining of main surfaces (ref. Table 4.3) are included into operations of three stages of manufacturing process: rough-machining, finish-machining and fine-machining stages.

Respectively rough-turning steps for all main surfaces, drilling of axial hole to complete shape of initial blank are included into operations of *rough-machining stage* (ref. paragraph 3.5.3). At rough-machining stage of metal-cutting manufacturing process usually 60–70 % total machining allowance is removed from the surfaces of initial blank. This stage has tasks to remove defective layer of material resulted from blanking processes (casting processes, forging, rolling, etc.) and to make more uniform distribution of allowance thickness along workpiece surfaces. It will make further machining more precise. In the preliminary plan (Fig. 4.4) the rough-machining stage includes 2 turning operations (05 and 10), when all main surfaces are machined at least one time.

Semi-finish and finish turning steps are included into operations of *finish-machining stage*. At this stage a workpiece acquires nearly final shape. Final operations of finish-machining stage typically include machining of small elements (holes, grooves, slots, etc.), galvanic treatment, diffusion treatment, cutting of gear rings and heat treatment. In the preliminary plan (ref. Fig. 4.4) the finish-machining stage includes operations with numbers from 15 to 75.

At *fine-machining stage* only several surfaces of high accuracy are machined with grinding and other high-precision methods. Also small elements (threads, splines, keyways), which can be easily damaged, are machined. The final operation of this stage is grinding of gear ring. In the preliminary plan (ref. Fig. 4.4) the fine-machining stage includes operations with numbers from 80 to 100.

4.5.2. Selection and substantiation of manufacturing datums

When selecting manufacturing datums, the recommendations submitted in the paragraph 3.5.2, are taken into account. Basic recommendations are the following:

- Reliability of a workpiece mounting in a machine-tool;
- Machining of datum surfaces (sets of datums) and complexes of surfaces with high requirements for accuracy of their relative position in one mounting;
- Observation of superposition principle for design and manufacturing (mounting and initial) datums that ensures shorter dimension chains in dimensional analysis of manufacturing process;
- Observation of constancy principle for mounting datums that ensures smaller variety of workholding devices.

At the rough-machining stage in the first operation (ref. Fig. 4.4, operation 05) the surfaces 9 and 6 are selected as datums in order to ensure high realiability of mounting – though cylindrical surface 9 is not of the largest diameter, it has the largest length that prevents falling-down of workpiece, if its sliding-out occurs. Only one dimension is specified from the rough (unmachined) datum (face 6) in order to avoid copying of the datum surface imperfectness to other dimensions and surfaces.

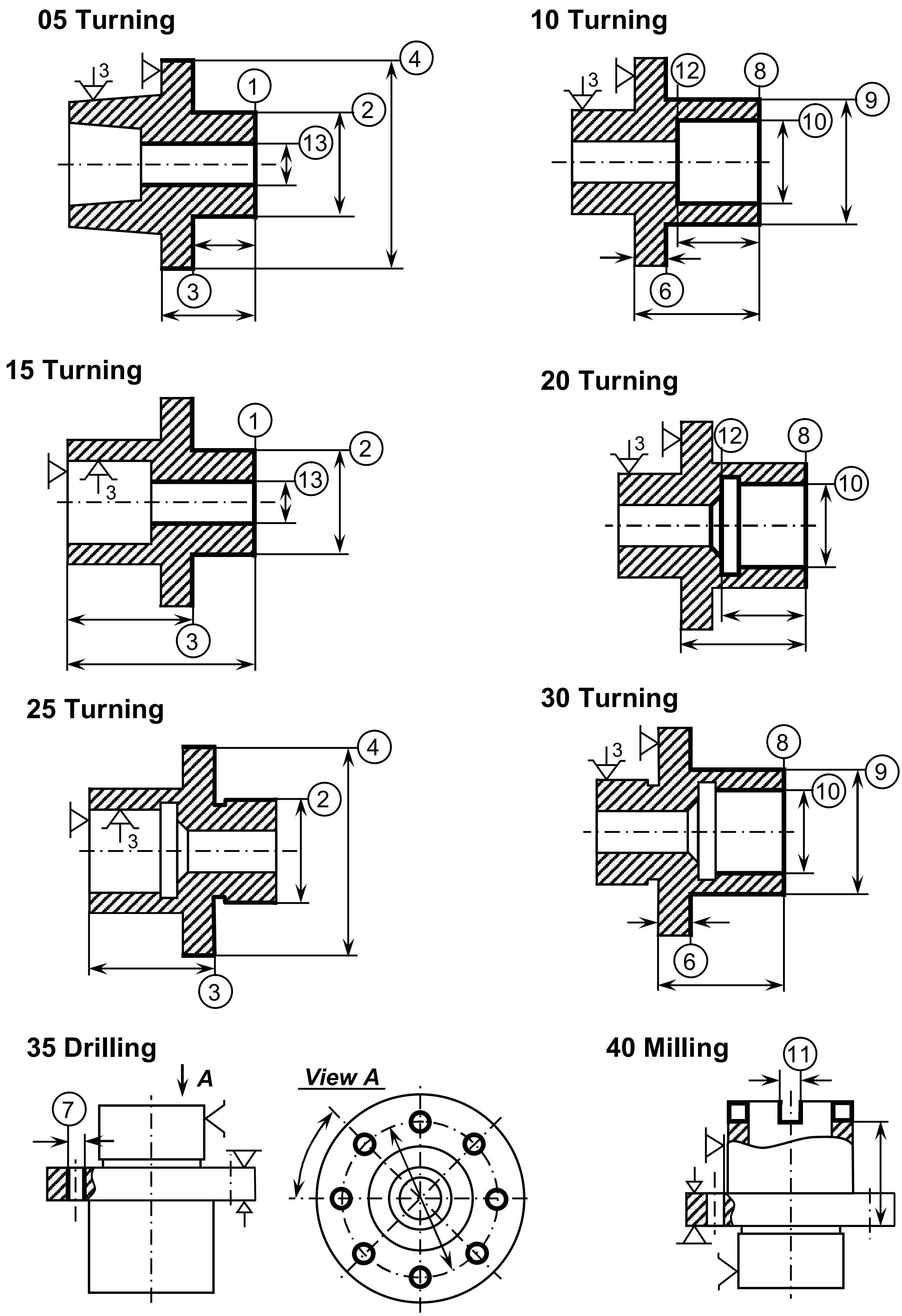


Fig. 4.4. Preliminary plan of manufacturing process for production of gear-shaft

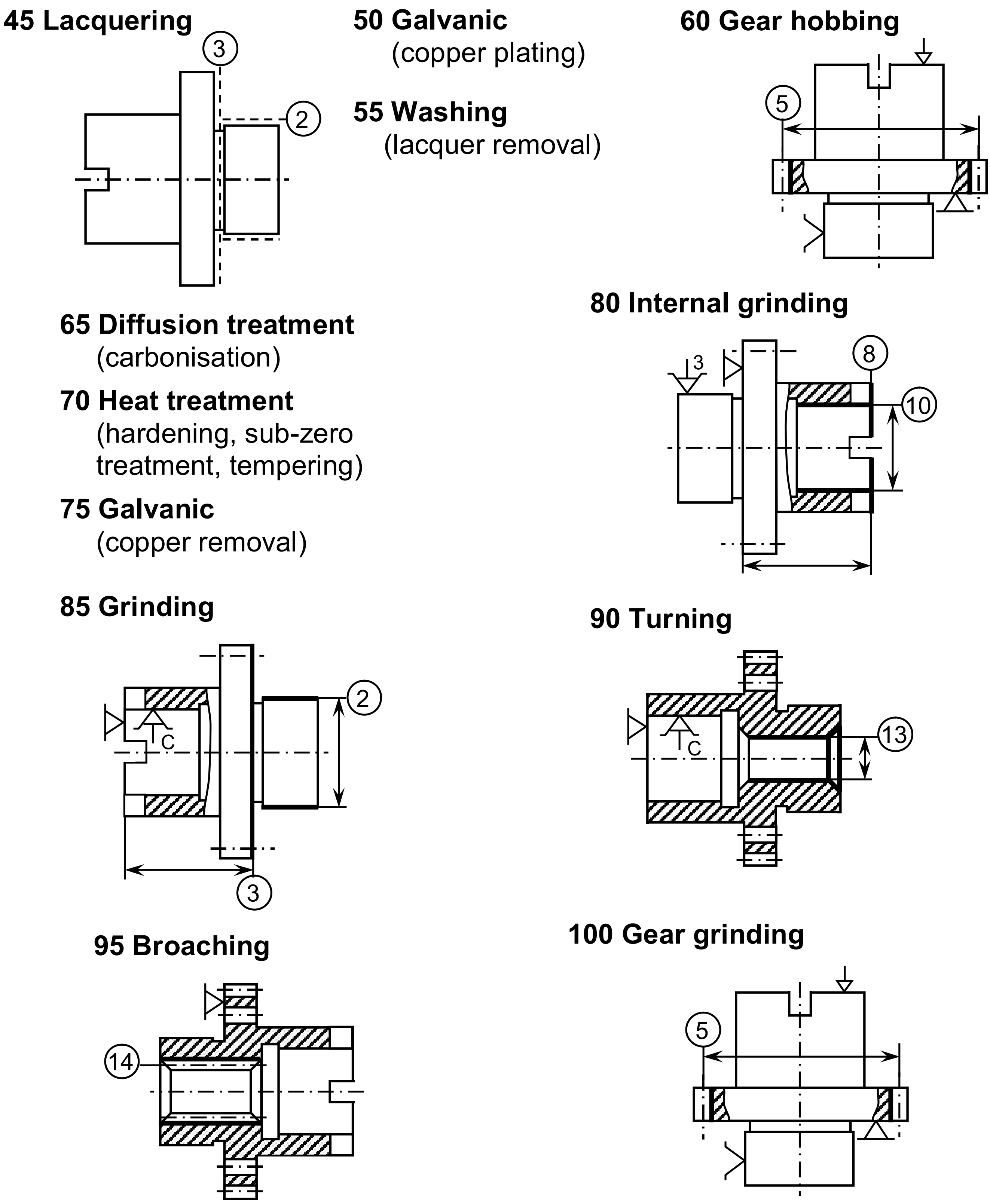


Fig. 4.4, continued

In the next operations two sets of datums are applied. The first set includes external cylindrical surface 2 and adjoining face 3 (ref. Fig. 4.4, operations 10, 20, 30, 35, 40, 60, 80, 100). These datums are also a complex of surfaces with high requirement for relative position – perpendicularity specified by the drawing (ref. Fig. 4.1). The surfaces possess higher accuracy and surface finish that needs larger number of manufacturing steps (ref. Table 4.3). They have also large areas that ensure reliable and precise mounting.

The second selected set of datums includes internal cylindrical surface 10 and adjoining face 8 (ref. Fig. 4.4, operations 15, 25, 85, 90). They possess sufficient areas, higher accuracy and surface finish that need a larger number of manufacturing steps (ref. Table 4.3).

Datum surfaces that establish set of datums should be machined each time in a previous operation in order to prepare datums for a current operation, and so large number of steps for providing high accuracy is also used for preparation of datums that reduces production costs.

Results of calculations submitted in the Table 4.3 shows 3 machining steps for the surface 8. But it is necessary to add one more machining step for the face 8 (in grinding operation 80) in order to ensure accuracy of relative position of surfaces 10 and 8 (to keep the datums set) used for a workpiece mounting in operation 85 (ref. Fig. 4.4).

The same approach is used for the face 3 in grinding operation 85 in order to keep set of datums (sufaces 2 and 3) to ensure machining accuracy in the operation 100 (gear grinding).

Faces 3 and 8 can be considered as design datums (ref. Fig. 4.1). Almost all linear dimensions-coordinates between faces are specified from mounting datums (ref. Fig. 4.4). These features ensure coincidence of initial datum with mounting and design datums (*observation of superposition principle*) or, at least, with design datum.

Two sets of manufacturing datums are kept from the beginning of manufacturing process (except the first operation 05) to the end (ref. Fig. 4.4) that provides *observation of constancy principle*.

At finish-machining stage the operation 50 of copper plating is applied in order to protect other surfaces from carbonization. Only surfaces A, B and C (ref. Fig. 4.1) are specified for carbonization (diffusion treatment). Surfaces A and B are protected from copper galvanic coating by application of lacquer in operation 45. Flanks of theeth (gear ring C) appear and open for carbonization after gear hobbing operation 60 (ref. Fig. 4.4). Heat treatment provides the specified hardness of the mentioned surfaces after diffusion treatment.

At fine-machining stage the broaching of splines is performed in operation 95. Locating of workpiece in this case is incomplete, only rest on datum face 3 is used, due to self-centring capability of cutting tool – round splined broach. The hole for spline cutting is bored directrly before the broaching in turning operation 90 (ref. Fig. 4.4). High accuracy of the hole axial position is ensured by careful preparation of datums in the internal grinding operation 80.

4.5.3. Drawing-up the preliminary plan of manufacturing process

Preliminary plan of manufacturing process is compiled in the form of sequence of operation sketches. Such plan is a solution of main technological tasks. It realizes previously made decisions including routes for machining of main surfaces (ref. Table

4.3). It sets boundaries between operations, sequence of operations in a manufacturing process, degree of concentration of operations, mounting and clamping diagrams, places for diffusion heat treatment and heat treatment, etc. (ref. Fig. 4.4).

The following features are specified in operation sketches of preliminary plan: number and name of operation; workpiece is shown in that position, in which it is machined; machined surfaces are emphasized with thick lines, dimension lines are shown without dimension values ("dumb dimensions"); mounting and clamping diagrams are depicted with special symbols (ref. Appendix 9).

Plan of manufacturing process does not include auxiliary operations (check, inspection, washing, workbench operations, etc.), and operations do not include manufacturing steps for machining of minor (non-main) elements (chamfers, fillets, rounding radii, etc.) and auxiliary steps (mounting of workpiece, removal of workpiece, etc.)

4.6. Calculations of operation dimensions-coordinates between faces of part

These calculations differ from calculations of diametrical dimensions. Values of operation dimensions, nominal and maximal allowances are determined as results of solutions of equations of manufacturing dimension chains with the maximum-minimum method, when initial link is a design dimension or minimum allowance.

In this work the values of minimum allowances are determined from normatives (ref. Appendix 10) – normative method.

Calculations of operation dimensions-coordinates between faces of part is a special procedure, which includes the following steps: development of dimension diagram of manufacturing process, revealing dimension chains, compiling original equations and solutions of equations of manufacturing dimension chains. Calculated operation dimensions are recommended to round off according to the special rules (ref. paragragh 3.7).

4.6.1. Development of dimension diagram of manufacturing process, revealing dimension chains, compiling original equations

Development of dimension diagram is based on the preliminary plan of manufacturing process (ref. Fig. 4.4) and procedure described in the paragragh 3.7.2. Linear dimensions-coordinates are selected from operations sketches and plotted between vertical lines symbolising faces of final part, intermediate butt surfaces of workpiece and faces of initial blank (Fig. 4.5). Operation dimensions are shown by lines with arrow at one end and dot on the other end. The dot symbolises position of initial datum, and arrow shows a machined surface.

Analysis of the dimension diagram allows to reveal dimension chains (Fig. 4.6). Dimension chain is a collection of dimensions located along closed contour. Manufacturing dimension chain should include only one unknown link (dimension).

But further analysis of dimension chains (ref. Fig. 4.6) shows that the chains contain not one, but several unknown links and equations compiled from these dimension chains cannot be solved. The first problem here is the dimension chains with initial links [$\boldsymbol{A_1}$], [$\boldsymbol{A_2}$], [$\boldsymbol{A_3}$] design dimensions. They contain many links and all of them are unknown, and so they cannot be solved. Respectively, the next chains are also unsolvable.

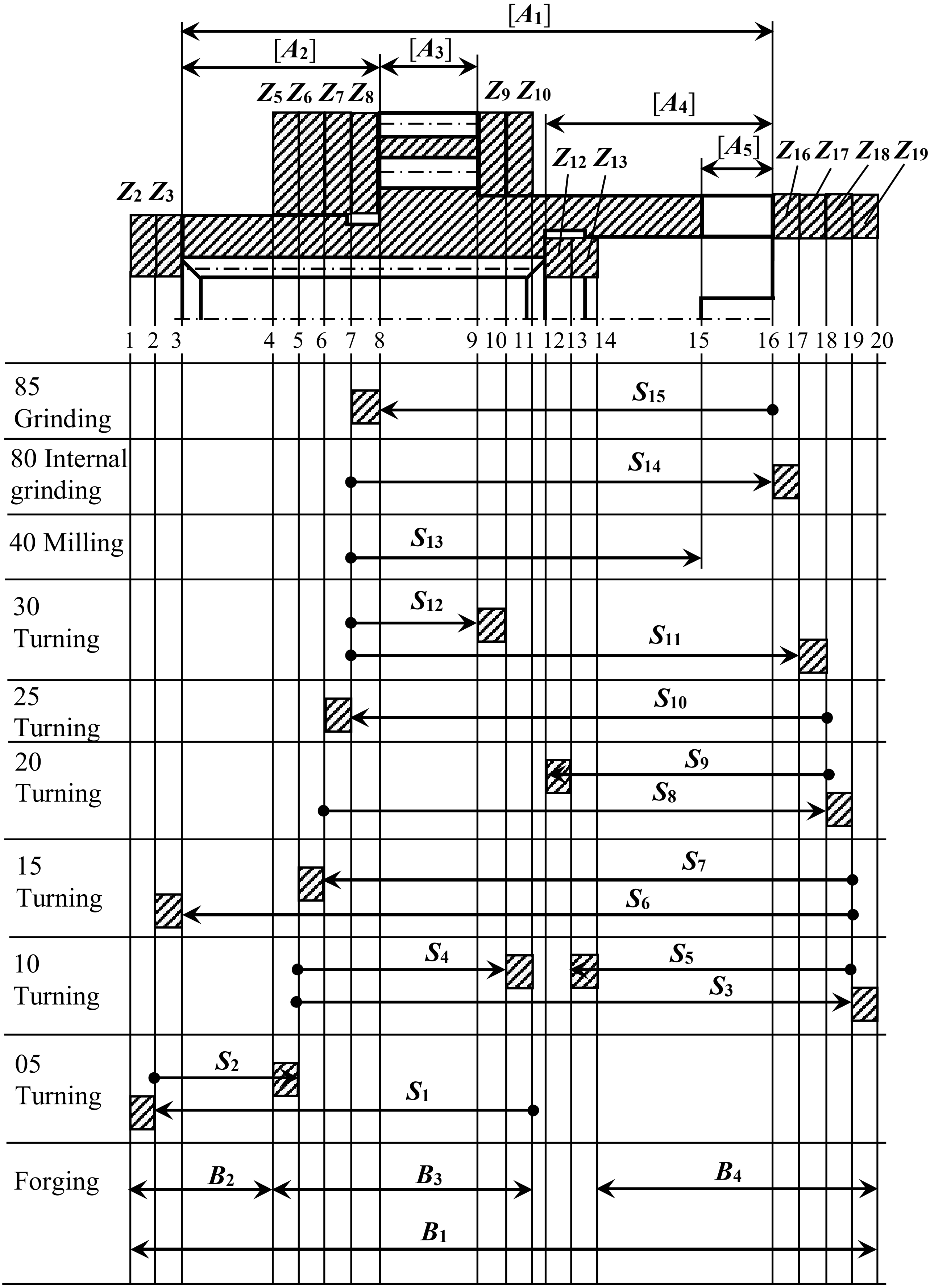


Fig. 4.5. Preliminary dimension diagram of manufacturing process

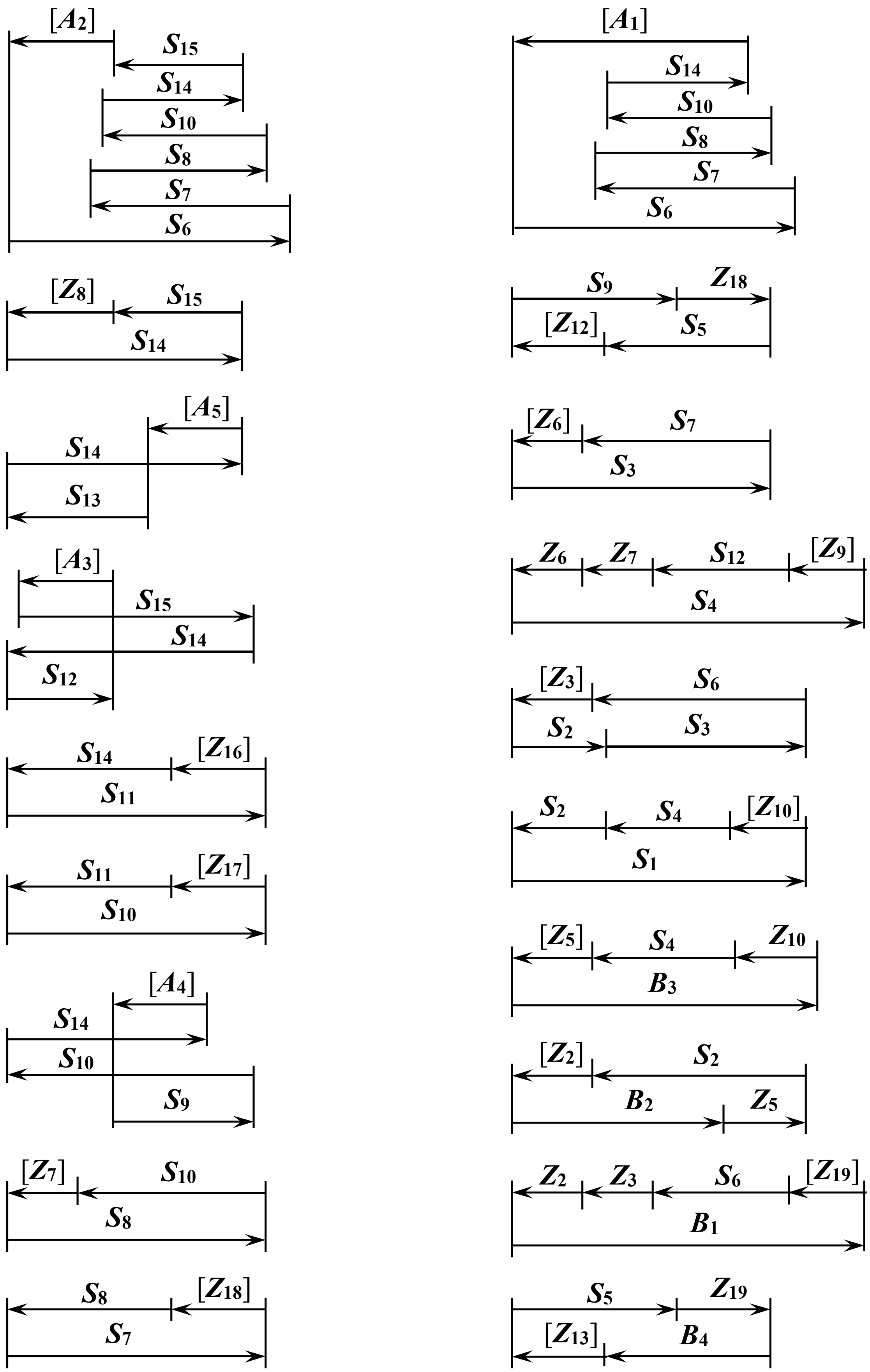


Fig. 4.6. Dimension chains revealed in preliminary dimension diagram of manufacturing process

This situation is not unusual, even when initial datums coincide with mounting datums nearly for all operation dimensions (ref. Fig. 4.4). Planning of manufacturing process is an *iteration procedure*. The first iteration (dimension diagram based on the preliminary plan) in this case showed unsatisfactory combinations of links in dimension chains. Therefore the dimension diagram needs optimization – the second iteration.

For the second iteration it is recommended that the final operation dimensions coincide with design dimensions, that is, initial datums coincide with design datums (Fig. 4.7 and 4.8).

Indeed, even small changes (Fig. 4.9) in dimensions positions (changes of initial datums) significantly improve the dimension chains (smaller quantity of constituent links) in operations 85, 80, 40 (ref. Fig. 4.7) and their solvability – chains (1), (2), (3) with initial links [A_2], [A_1], [A_5] design dimensions respectively (ref. Fig. 4.8).

Thus, dimension S_{15} is specified not from mounting datum (see the grinding operation 85 in preliminary plan (ref. Fig. 4.4) and in preliminary dimension diagram (ref. Fig. 4.5)), but from design datum (see operation 85 in optimised plan (ref. Fig. 4.9) and in optimised dimension diagram (ref. Fig. 4.7)). This allows to reduce quantity of constituent links in dimension chain (1) to single unknown dimension S_{15} with initial link [A_2] (see Fig. 4.8 in comparision with Fig. 4.6).

Dimension S_{14} in the internal grinding operation 80 is also specified from design datum in order to reduce quantity of links in dimension chain (2) with initial link [A_1] (see Fig. 4.8 in comparision with Fig. 4.6). Mounting datum is moved to the design datum like in operation 30.

Usually organisation of batch-type production requires coincidence of initial datums with mounting datums in all operations to make possible a work on the machines set for operations. The only exception is made for grinding operations because they are performed with hand setting for each workpiece in the batch. This feature is explained by intensive "dimensional wear" of a cutting tool (grinding wheel).

Therefore two changes in grinding operations 85 and 80 are quite possible, on the one hand, and quite reasonable, on the other hand, for compiling the optimised dimension chains for the sake of solutions of their equations.

Other change is proposed in milling operation 40 in order to simplify dimension chain (3) for finding the operation dimension S_{13}. This improvement is accompanied with change of set of datums (ref. Fig. 4.9). This is a deviation from principle of datums constancy, but it is possible when new datums are carefully prepared – see operation 25 in the optimised plan.

Changes in grinding operations and turning operation 30 improved finding of dimension S_{13} in the chain and equation (3) and finding of dimension S_{12} in the chain and equation (4) with initial link [A_3].

There are two improvements in turning operation 30 agreed with change of dimension S_{15}. Both initial and mounting datums are displaced from one design datum (line 7 in Fig. 4.5) to another datum (line 3 in Fig. 4.7) in order to compile shorter dimension chain (4) with initial link [A_3] and one unknown link S_{12}, while dimension S_{15} is found from the chain (1) (ref. Fig. 4.8). The deviation from principle of datums constancy – change of datums set in this operation – is prepared in the operation 25 (also

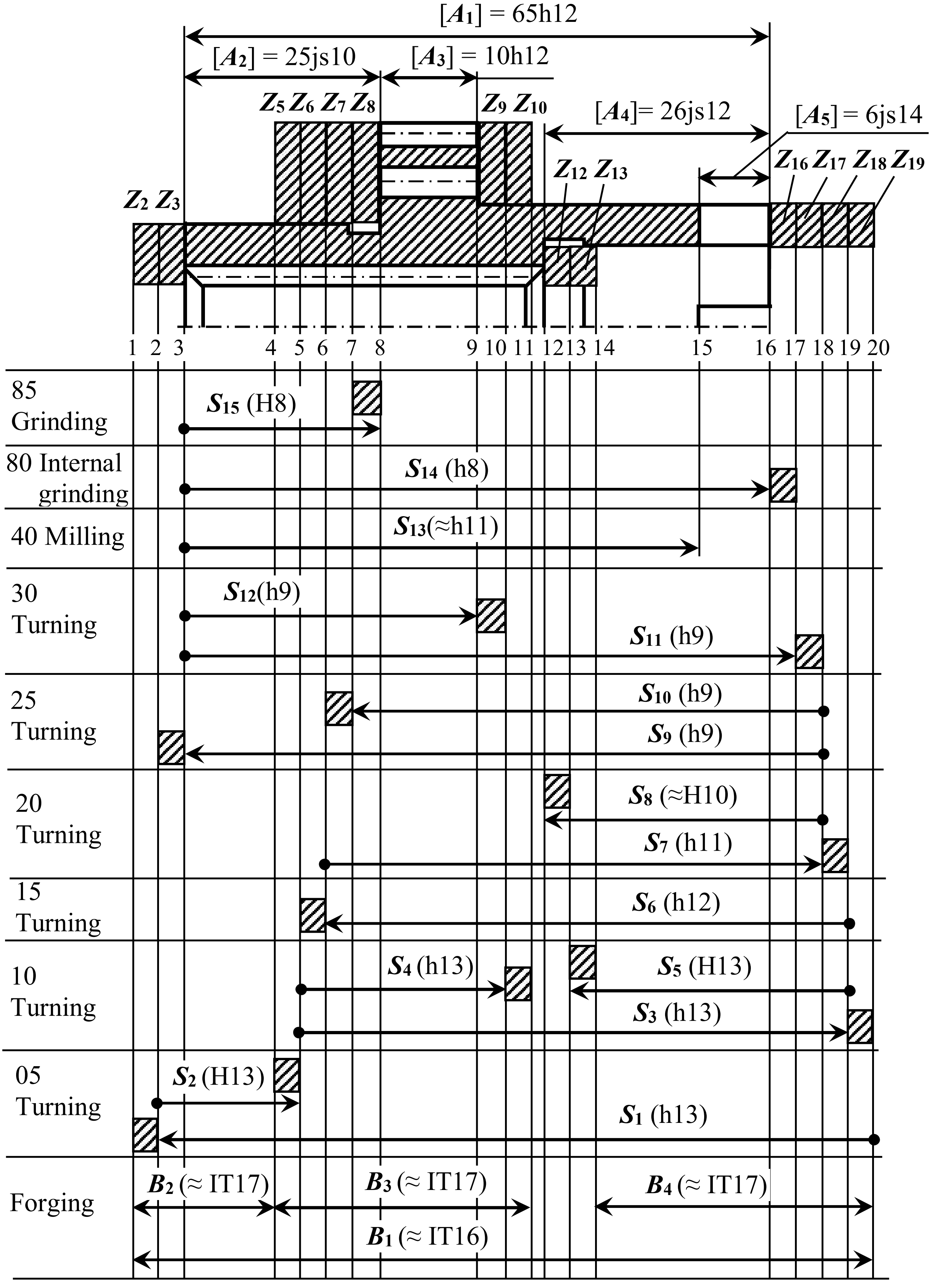


Fig. 4.7. Optimised dimension diagram of manufacturing process

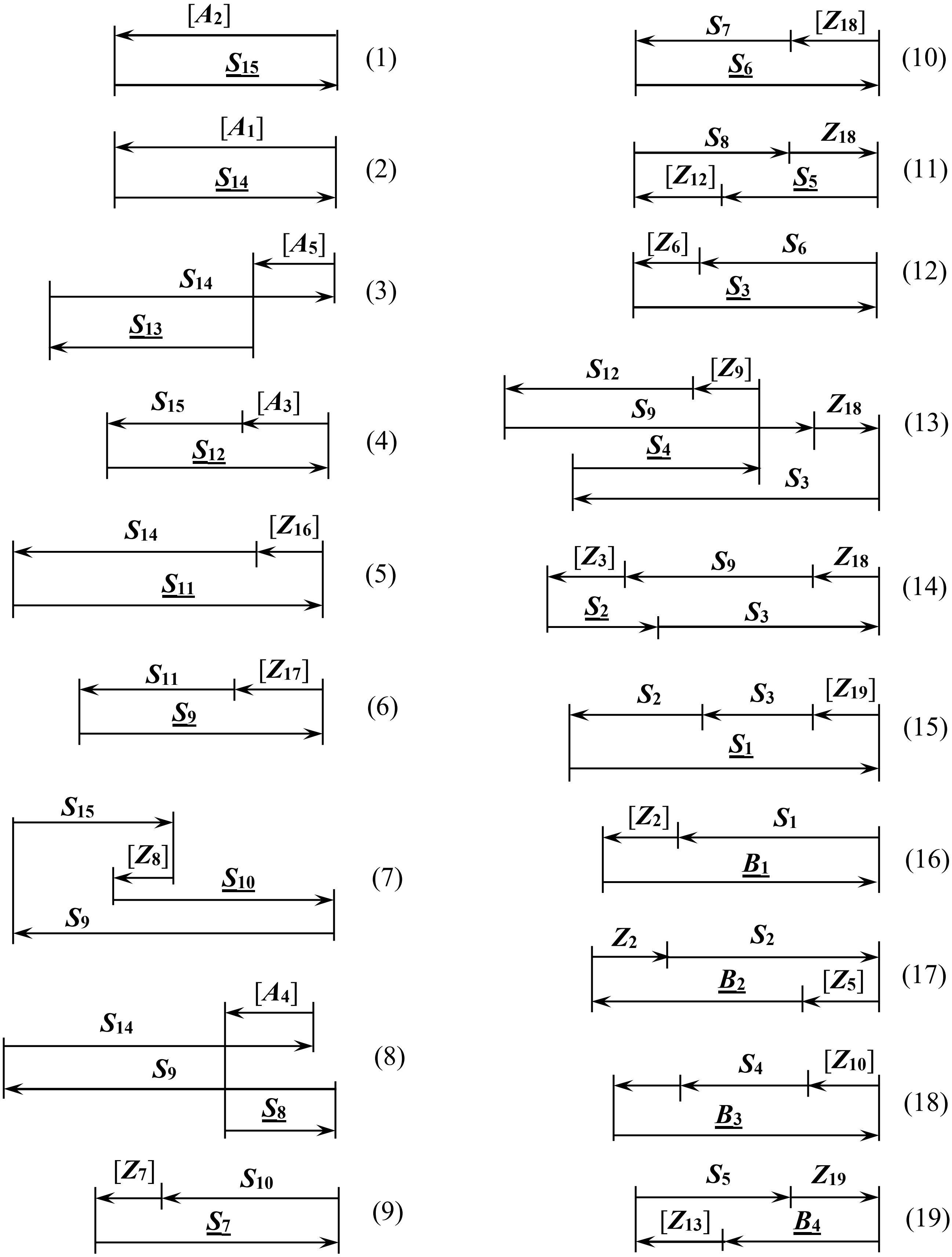


Fig. 4.8. Dimension chains revealed in the optimised dimension diagram

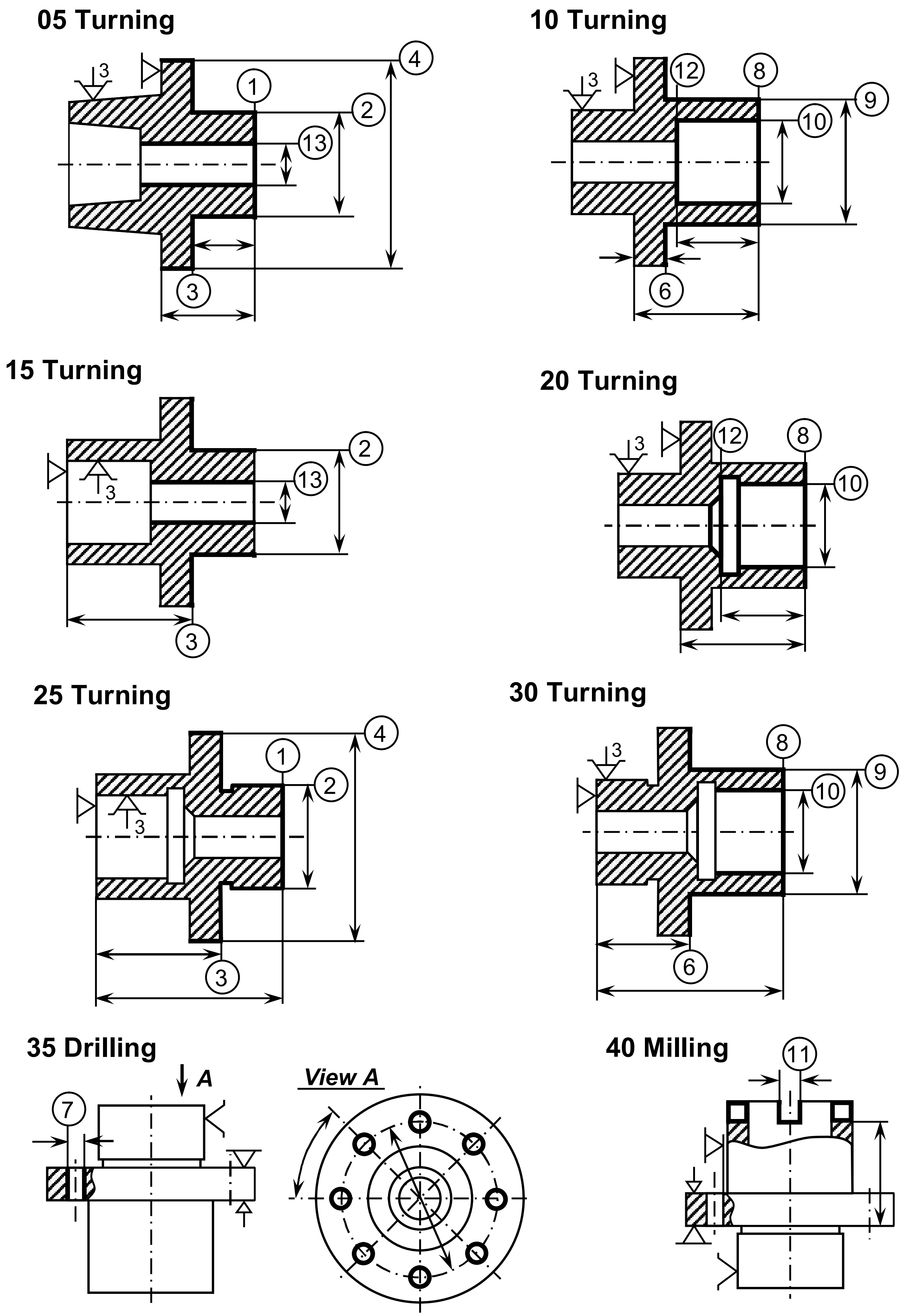
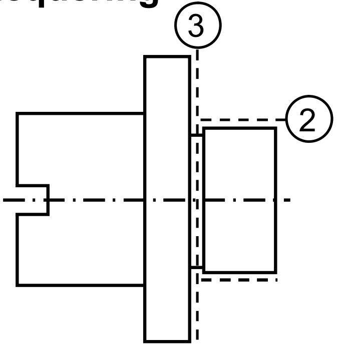


Fig. 4.9. Optimised preliminary plan of manufacturing process

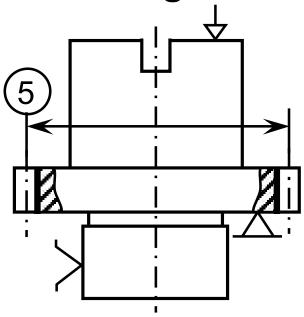
45 Lacquering



50 Galvanic
(copper plating)

55 Washing
(lacquer removal)

60 Gear hobbing

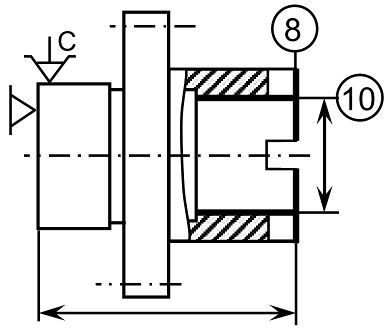


65 Diffusion treatment
(carbonisation)

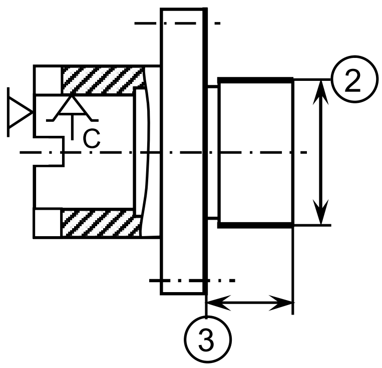
70 Heat treatment
(hardening, sub-zero treatment, tempering)

75 Galvanic
(copper removal)

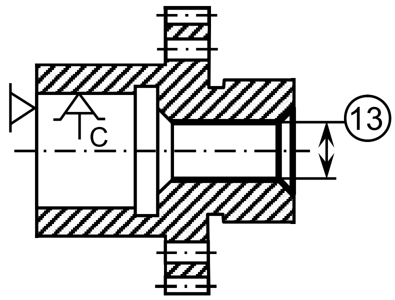
80 Internal grinding



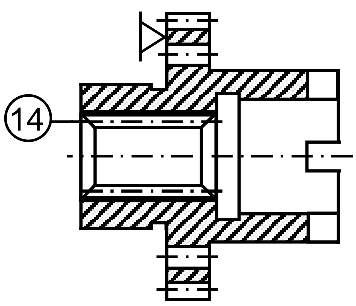
85 Grinding



90 Turning



95 Broaching



100 Gear grinding

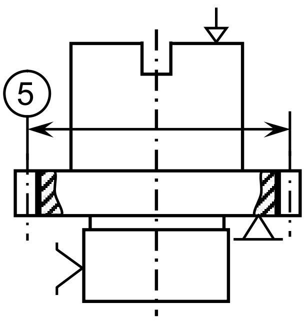


Fig. 4.9, continued

used in the milling operation).

One more improvement, related with the datums preparation for the operation 30, is the displacement of dimension $\boldsymbol{S_6}$ from turning operation 15 (ref. Fig. 4.4 and 4.5) to another turning operation 25 with the same position of initial datum (dimension $\boldsymbol{S_9}$ in Fig. 4.7) in order to compile short chain (6) based on dimension $\boldsymbol{S_{11}}$ earlier improved in operation 30 and found from the chain (5).

Dimension S_{10} is found not in the order of numbering the operation dimensions S_k, but only after determination of dimension S_9, because the chain (7) with initial link $[Z_8]$ includes constituent link S_9.

Dimension S_8 in turning operation 20 can be found only after calculations of dimensions S_{14} and S_9, from dimension chain (8) with initial link $[A_4]$ design dimension. This chain contains three constituent links, and design dimension $[A_4]$ is relatively small (in comparison with dimensions S_{14} and S_9) with respective small tolerance $[T_4]$. Small tolerance of initial link can be a problem, when solving equations of long dimension chains.

Other dimension chains are revealed from the optimised dimension diagram (ref. Fig. 4.7) to find unknown values – operation dimensions S_k and blank dimensions B_r. The sequence of chains is determined by principle: one chain contains only one unknown value. Typically quantity of unknown values (S_k and B_r) coincides with quantity of known values (design dimensions A_i and allowances Z_m). Exceptions appear when initial blank has a simplified shape and quantity of blank dimensions is smaller than quantity of design dimensions. At least, quantity of dimension chains (and their equations) must be equal to quantity of unknown values.

Equations are compiled from the optimised dimension diagram and revealed dimension chains (ref. Fig. 4.8). They should be solved in the sequence specified by numbers, which realises conditions that each equation contains only one unknown link (underlined) and other constituent links (dimensions) are known values, found from previous equations:

$[A_2] = \underline{S_{15}};$ (1)

$[A_1] = \underline{S_{14}};$ (2)

$[A_5] = S_{14} - \underline{S_{13}};$ (3)

$[A_3] = \underline{S_{12}} - S_{15};$ (4)

$[Z_{16}] = \underline{S_{11}} - S_{14};$ (5)

$[Z_{17}] = \underline{S_9} - S_{11};$ (6)

$[Z_8] = S_{15} + \underline{S_{10}} - S_9;$ (7)

$[A_4] = S_{14} + \underline{S_8} - S_9;$ (8)

$[Z_7] = \underline{S_7} - S_{10};$ (9)

$[Z_{18}] = \underline{S_6} - S_7;$ (10)

$[Z_6] = \underline{S_3} - S_6;$ (11)

$[Z_{12}] = S_8 + Z_{18} - \underline{S_5};$ (12)

$[Z_{12}] = S_8 + (S_6 - S_7) - \underline{S_5};$ (12a)

$[Z_9] = S_9 + \underline{S_4} + Z_{18} - S_{12} - S_3;$ (13)

$[Z_3] = \underline{S_2} + S_3 - S_9 - Z_{18};$ (14)

$[Z_{19}] = \underline{S_1} - S_2 - S_3;$ (15)

$[Z_2] = \underline{B_1} - S_1;$ (16)

$[Z_5] = S_2 + Z_2 - \underline{B_2};$ (17)

$[Z_{10}] = \underline{B_3} - S_4 - Z_5;$ (18)

$[Z_{13}] = S_5 + Z_{19} - \underline{B_4}.$ (19)

The equations (12) and (12a) are similar and illustrate the possibility to use allowance as a constituent link after its application as an initial link in previous equation. In this example allowance Z_{18} was used as the initial link in equation (10). But equation for allowance Z_m should not contain constituent links (S_k and B_r) used in the considered equation – compare (12), (12a) and (10). Otherwise allowance as an initial link would include double tolerances of links used two times in a considered equation while nominal dimension of allowance will be the same.

All the improvements made in the optimised dimension diagram (ref. Fig. 4.7) are reflected in the optimised preliminary plan of manufacturing process (ref. Fig. 4.9) – – the second and final iteration of preliminary plan.

Assigning accuracy grades to operation dimensions-coordinates is necessary for further solutions of equations of dimension chains (ref. paragraph 3.7.2). Equations (1), (2), (3), (4), (8) have design dimensions as initial links. This feature lays down condition of tolerances limitations for constituent links (formula (3.14)). Equations (1) and (2) describe the simplest two-link chains without severe requirements for accuracy of operation dimensions $\boldsymbol{S}_{15}$ and $\boldsymbol{S}_{14}$. Therefore other equations, which include more constituent links, should be analysed first of all (Table 4.4).

Table 4.4. Assigned accuracy parameters for constituent links in equations with design dimensions as initial links

Equation No.	Equation	$[A_i]$	$\boldsymbol{S}_{15}$	$\boldsymbol{S}_{14}$	$\boldsymbol{S}_{13}$	$\boldsymbol{S}_{12}$	$\boldsymbol{S}_{9}$	$\boldsymbol{S}_{8}$	$\boldsymbol{T}_{Ai}$
(3)	$[A_5] = \boldsymbol{S}_{14} - \underline{\boldsymbol{S}_{13}}$	6		65	59				
	$[\boldsymbol{T}_{A5}] = \boldsymbol{T}_{S14} + \boldsymbol{T}_{S13}$	0.300		0.046	0.254				0.300
	ITn	js14		IT8	≈IT11				
(4)	$[A_3] = \underline{\boldsymbol{S}_{12}} - \boldsymbol{S}_{15}$	10	25			35			
	$[\boldsymbol{T}_{A3}] = \boldsymbol{T}_{S12} + \boldsymbol{T}_{S15}$	0.150	0.033			0.062			0.095
	ITn	h12	IT8			IT9			
(8)	$[A_4] = \boldsymbol{S}_{14} + \underline{\boldsymbol{S}_{8}} - \boldsymbol{S}_{9}$	26		65			≈67	≈28	
	$[\boldsymbol{T}_{A4}] = \boldsymbol{T}_{S14} + \boldsymbol{T}_{S8} + \boldsymbol{T}_{S9}$	0.210		0.046			0.074	0.090	0.210
	ITn	js12		IT8			IT9	≈IT10	
(1)	$[A_2] = \underline{\boldsymbol{S}_{15}}$	25	25						
	$[\boldsymbol{T}_{A2}] = \boldsymbol{T}_{S15}$	0.084	0.033						0.033
	ITn	js10	IT8						
(2)	$[A_1] = \underline{\boldsymbol{S}_{14}}$	65		65					
	$[\boldsymbol{T}_{A1}] = \boldsymbol{T}_{S14}$	0.300		0.046					0.046
	ITn	h12		IT8					

Nominal values of dimensions $\boldsymbol{S}_{13}$ and $\boldsymbol{S}_{12}$ are calculated: $\boldsymbol{S}_{13nom} = \boldsymbol{S}_{14nom} - [A_{5nom}]$, $\boldsymbol{S}_{12nom} = \boldsymbol{S}_{15nom} + [A_{3nom}]$. Nominal values of dimensions $\boldsymbol{S}_{9}$ and $\boldsymbol{S}_{8}$ are determined approximately from the known design dimensions and approximate values of allowances.

Approximate accuracy grade symbols "≈ITn" mean that assigned tolerance $\boldsymbol{T}_{Sk}$ is larger than the tolerance of the ITn grade, but smaller than the tolerance of the next ITn+1 grade.

Distibutions of tolerances $\boldsymbol{T}_{Si}$ and accuracy grades ITn among constituent links (operation dimensions) $\boldsymbol{S}_{k}$ are made from the following principles:

- Principle of progressive decrease (ref. paragraph 3.4.2): fast increase of accuracy in the first (rough) manufacturing steps (operations) and slow accuracy improvements in the finish and fine-finish steps (ref. Fig. 4.7);
- Accuracy of operation dimensions in fine-finish operations (grinding) is determined by accuracy of design dimensions, quantity of constituent links and their nominal dimensions;
- Tolerance of closing link $\boldsymbol{T}_{Ai}$ should not exceed tolerance of initial link $[\boldsymbol{T}_{Ai}]$ (ref.

formula 3.14)

$$[\boldsymbol{T_{Ai}}] \geq \boldsymbol{T_{Ai}}, \quad \boldsymbol{T_{Ai}} = \sum_{k=1}^{n_j+n_q} \boldsymbol{T_{Sk}}\ .$$

These distibutions of tolerances (ref. Table 4.4) and accuracy grades (ref. Fig. 4.7) among operation dimensions can be corrected in further calculations.

4.6.2. Solutions of equations of manufacturing dimension chains

There are two types of dimension chains and, hence, two types of equations that differ by type of initial link: 1) design dimension and 2) allowance. Both types of equations are solved by one method – ***maximum-minimum method***, but algorithms for their solutions are different.

Equation of dimension chain with initial link [***A***] design dimension is solved along the following procedure (ref. paragraph 3.7.3). First of all, the full form of *original equation* (3.15) is written down

$$\left[\boldsymbol{A}_{nom}{}_{\Delta i_A}^{\Delta s_A}\right] = \sum_{j=1}^{n_j} \boldsymbol{S}_{jnom}{}_{\Delta i_j}^{\Delta s_j} - \sum_{q=1}^{n_q} \boldsymbol{S}_{qnom}{}_{\Delta i_j}^{\Delta s_q}\ ,$$

where $\boldsymbol{S_j}$ and $\boldsymbol{S_q}$ are increasing and decreasing links, respectively; $\boldsymbol{n_j}$ and $\boldsymbol{n_q}$ are quantities of increasing and decreasing links, respectively.

In the equation one of constituent links $\boldsymbol{S_{jX}}$ or $\boldsymbol{S_{qX}}$ is unknown.

Then the check for adequacy (sufficient value) of initial link tolerance is made from the formula (3.16)

$$[\boldsymbol{T_A}] = \sum_{i=1}^{n_j+n_q} \boldsymbol{T_{Si}}\ .$$

The formula allows calculating tolerance $\boldsymbol{T_{SX}}$ of unknown constituent link

$$\boldsymbol{T_{SX}} = [\boldsymbol{T_A}] - \sum_{i=1}^{n_j+n_q-1} \boldsymbol{T_{Si}}\ .$$

If the tolerance $\boldsymbol{T_{SX}}$ is a negative value or positive value, but very small for the link $\boldsymbol{S_{jX}}$ or $\boldsymbol{S_{qX}}$ at the certain stage of manufacturing process, then *new smaller tolerances* should be assigned to other constituent links to satisfy the condition (3.16). Assigning of new tolerances is made taking into account nominal dimensions of constituent links and admissible accuracy grade for each constituent link at a certain stage of manufacturing process. *New deviations* are assigned to the known constituent links. Then the original equation is solved along the ordinary algorithm. *But in this case the solutions of previous equations should be repeated with new-assigned deviations of the constituent links.*

If the tolerance $\boldsymbol{T_{SX}}$ is a positive value and large enough for the link $\boldsymbol{S_{jX}}$ or $\boldsymbol{S_{qX}}$ at the certain stage of manufacturing process, the ordinary algorithm continues. Estimation of satisfactory value of tolerance for a certain stage of manufacturing process is made by comparison of the calculated tolerance and standardised tolerance according to the accuracy grade of unknown link suitable for a certain stage of manufacturing process.

Original equation (3.15) is decomposed into 3 linear equations with one unknown value in each equation:

1) $\left[A_{nom}\right]=\sum_{j=1}^{n_j} S_{jnom}-\sum_{q=1}^{n_q} S_{qnom}$ is equation written down in nominal values of links. Unknown nominal value S_{jXnom} or S_{qXnom} is found;

2) $\left[\Delta s_A\right]=\sum_{j=1}^{n_j} \Delta s_j-\sum_{q=1}^{n_q} \Delta i_q$ is equation compiled for upper deviation of initial link. The upper deviation Δs_{jX} or lower deviation Δi_{qX} of unknown link is determined from this equation;

3) $\left[\Delta i_A\right]=\sum_{j=1}^{n_j} \Delta i_j-\sum_{q=1}^{n_q} \Delta s_q$ is equation compiled for lower deviation of initial link.

The lower deviation Δi_{qX} or upper deviation Δs_{jX} of unknown link is determined from this equation.

In the **equation (1)** *initial link* is design dimension $[A_2]$ = 25js10(±0.042) with limit dimensions: $[A_{2min}]$ = 24.958 and $[A_{2max}]$ = 25.042.

The equation (1) is the simplest two-link, and so the solution is simple

$$[A_2] = \underline{S_{15}};\quad 25\pm0.042 = S_{15};\quad S_{15} = 24.958^{+0.084}.$$

Taking into account the assigned accuracy grade IT8 = 0.033 mm (ref. Table 4.4) the *operation dimension* S_{15} is

$$S_{15} = 24.958^{+0.033}.$$

The design dimension $[A_2]$ is of neither shaft, nor hole type (ref. Fig. 4.1 and 4.7). Operation dimension S_{15} is a hole-type dimension (ref. Fig. 4.7 and 4.9), and so transformation is necessary and performed.

Rounding off the dimension-hole (ref. paragraph 3.7.3) is performed with increase of nominal (minimum) dimension

$$S_{15R} = 25^{+0.033}.$$

Reduction of tolerance is not applied, because of assigning much smaller tolerance (IT8) for constituent link in comparision with initial link tolerance (IT10).

Value of *closing link* A_2 will be

$$A_2 = S_{15} = 25^{+0.033},$$

and limit dimensions are: A_{2max} = 25.033 and A_{2min} = 25.0.

Calculated limit values of closing link are compared with limit values of initial link in order to check *meeting the requirements for initial link* specified by designer (ref. conditions (3.22)):

$$[A_{2min}] \le A_{2min};\qquad A_{2max} \le [A_{2max}];$$

$$24.958 < 25.0;\qquad 25.033 < 25.042.$$

The **equation (2)** with initial link $[A_1]$ is similar to the equation (1), and so it has the similar solution:

$$[A_1] = 65h12(_{-0.3}); \quad [A_{1min}] = 64.7; \quad [A_{1max}] = 65;$$

$$[A_1] = \underline{S_{14}}; \quad 65_{-0.3} = \underline{S_{14}}.$$

Taking into account the assigned accuracy grade IT8 (ref. Table 4.4) the *operation dimension* S_{14} (ref. Fig. 4.7 and 4.9) is

$$S_{14} = 65_{-0.046}.$$

The design dimension $[A_1]$ is of shaft type (basic shaft h12). Operation dimension S_{14} is a shaft-type dimension (ref. Fig. 4.7 and 4.9), and so transformation is not needed.

Value of *closing link* A_1 will be

$$A_1 = S_{14} = 65_{-0.046},$$

and limit dimensions are: $A_{1min} = 64.954$ and $A_{1max} = 65$.

The conditions (3.22) are:

$$[A_{1min}] \leq A_{1min}; \qquad A_{1max} \leq [A_{1max}];$$

$$64.7 < 64.954; \qquad 65 = 65.$$

The **equation (3)** with initial link $[A_5]$ design dimension of the 14th accuracy grade has two constituent links. The solution is performed according to the described procedure.

Parameters of initial link are: $[A_5] = 6js14(\pm 0.15)$, $[A_{1min}] = 5.85$, $[A_{1max}] = 6.15$.

Original equation is

$$[A_5] = S_{14} - \underline{S_{13}}; \quad 6\pm 0.15 = 65_{-0.046} - S_{13nom}{}^{es}_{ei}.$$

Tolerance of unknown link S_{13} is calculated from the formula (3.16):

$$[T_{A5}] = T_{S14} + \underline{T_{S13}}; \quad 0.300 = 0.046 + T_{S13}; \quad T_{S13} = 0.300 - 0.046 = 0.254.$$

Tolerance $T_{S13} = 0.254$ mm is of approximately IT11 accuracy grade (IT11 = 0.19 mm, IT12 = 0.3 mm) and good for milling operation 40.

According to the algorithm the nominal value of dimension S_{13} and its deviations are calculated:

1) $6 = 65 - S_{13nom}$, $S_{13nom} = 59$;
2) $+0.15 = 0 - ei$, $ei = -0.15$;
3) $-0.15 = (-0.046) - es$, $es = +0.104$.

Respectively, the operation dimension is $S_{13} = 59^{+0.104}_{-0.150}$.

It should be of basic shaft type (ref. Fig. 4.7 and 4.9), and so transformation is performed:

$$S_{13} = 59.104_{-0.254}.$$

Rounding off the dimension-shaft (ref. paragraph 3.7.3) is performed with decrease of nominal dimension, which equals maximum limit dimension,

$$S_{13R} = 59.1_{-0.25}.$$

Tolerance for the rounded dimension is decreased by value of rounding-off:

$$\Delta S_{13} = S_{13max} - S_{13maxR} = 59.104 - 59.100 = 0.004;$$

$$T_{S13R} = T_{S13} - \Delta S_{13} = 0.254 - 0.004 = 0.25 \ (\approx \text{IT11}).$$

Value of *closing link* A_5 is calculated according to the "criss-cross scheme" (ref. paragraph 3.7.3):

$$A_5 = S_{14} - S_{13R} = 65_{-0.046} - 59.1_{-0.25} = 5.9^{+0.250}_{-0.046}.$$

The limit dimensions are: $A_{5min} = 5.854$ and $A_{5max} = 6.15$.

The conditions (3.22) are observed:

$$[A_{5min}] \le A_{5min}; \qquad A_{5max} \le [A_{5max}];$$

$$5.85 < 5.854; \qquad 6.15 = 6.15.$$

Solution of the **equation (4)** with initial link $[A_3]$ is similar to the solution of equation (3). The results of calculations are submitted in the Table 4.5.

Equation of dimension chain with **initial link** $[Z]$ machining **allowance** is solved along the following procedure (ref. paragraph 3.7.4). First of all, the full form of original equation (3.23) is transformed relative to the minimum allowance value (3.24)

$$\left[Z^{\Delta s_Z}_{\Delta i_Z}\right] = \sum_{j=1}^{n_j} S_j{}^{\Delta s_j}_{\Delta i_j} - \sum_{q=1}^{n_q} S_q{}^{\Delta s_q}_{\Delta i_j}, \qquad [Z_{min}] = \sum_{j=1}^{n_j} S_{j\,min} - \sum_{q=1}^{n_q} S_{q\,max}.$$

According to the normative method the $[Z_{min}]$ minimum value is selected from the reference tables (ref. Appendix 10).

Then the minimum S_{jXmin} or maximum S_{qXmax} unknown value is calculated. Accuracy grade ITn is assigned according to the stage of manufacturing process (ref. Fig. 4.11) and tolerance T_X is determined from the standard. Calculation of another limit dimension is performed, if necessary, and operation dimension S_X is written down according to its type (basic shaft or basic hole).

Rounding off the operation dimension is performed (ref. paragraph 3.7.4) according to the type of considered link: increasing or decreasing.

Then the nominal value of allowance and its deviations are calculated from the original equation (3.27) by decomposing and solution of three linear equations. In this case an *inverse task* is solved in order to find *closing link* Z.

The selected normative values of minimum allowances (ref. Appendix 10) are:

- For rough turning: $[Z_{2min}] = [Z_{5min}] = [Z_{10min}] = [Z_{13min}] = [Z_{19min}] = 1.0$ mm;
- For semi-finish turning: $[Z_{6min}] = [Z_{18min}] = 0.7$ mm;
- For finish turning: $[Z_{3min}] = [Z_{7min}] = [Z_{9min}] = [Z_{12min}] = [Z_{17min}] = 0.4$ mm;
- For grinding: $[Z_{8min}] = [Z_{16min}] = 0.2$ mm.

Minimum allowances for semi-finish face turning are determined from linear interpolation between the values for rough and finish facing

$$(1.0 + 0.4)/2 = 0.7 \text{ mm}.$$

Thus, **equation (5)** with initial link $[Z_{16}]$ allowance is solved according to the described procedure:

$$[\boldsymbol{Z}_{16}] = \underline{\boldsymbol{S}_{11}} - \boldsymbol{S}_{14}; \qquad [\boldsymbol{Z}_{16min}] = \underline{\boldsymbol{S}_{11min}} - \boldsymbol{S}_{14max};$$

$$\underline{\boldsymbol{S}_{11min}} = \boldsymbol{S}_{14max} + [\boldsymbol{Z}_{16min}] = 65 + 0.2 = 65.2.$$

Minimum normative allowance value $[\boldsymbol{Z}_{16min}]$ for the single face grinding after heat treatment is determined from the Appendix 10.

According to the optimised dimension diagram (ref. Fig. 4.7) the assigned accuracy (tolerance band) for dimension $\boldsymbol{S}_{11}$ is h9 (tolerance $\boldsymbol{T}_{S11} = 0.074$).

The $\boldsymbol{S}_{11}$ operation dimension is dimension-shaft and so maximum value $\boldsymbol{S}_{11max}$ is calculated:

$$\boldsymbol{S}_{11max} = \boldsymbol{S}_{11min} + \boldsymbol{T}_{S11} = 65.2 + 0.074 = 65.274.$$

Hence, the operation dimension is $\boldsymbol{S}_{11} = 65.274_{-0.074}$.

The $\boldsymbol{S}_{11}$ operation dimension is increasing link in the equation (5), and so rounding off is performed with increase of nominal dimension:

$$\boldsymbol{S}_{11R} = 65.3_{-0.074}.$$

Nominal value of allowance $\boldsymbol{Z}_{16nom}$ and its deviations are calculated from the original equation (5) (solution of the *inverse task* – $\boldsymbol{Z}_{16}$ is a *closing link*):

$$\boldsymbol{Z}_{16nom}{}^{\Delta sz}_{\Delta iz} = \boldsymbol{S}_{11R} - \boldsymbol{S}_{14} = 65.3_{-0.074} - 65_{-0.046} = 0.3^{+0.046}_{-0.074};$$

1) $\boldsymbol{Z}_{16nom} = 65.3 - 65 = 0.3$;
2) $\boldsymbol{\Delta s_Z} = 0 - (-0.046) = +0.046$;
3) $\boldsymbol{\Delta i_Z} = (-0.074) - 0 = -0.074$.

Minimum allowance is calculated

$$\boldsymbol{Z}_{16min} = \boldsymbol{Z}_{16nom} + \boldsymbol{\Delta i_Z} = 0.3 + (-0.074) = 0.226.$$

Minimum value of *closing link* $\boldsymbol{Z}_{16min}$ should not be less than the minimum normative value of *initial link* $[\boldsymbol{Z}_{16min}]$ in order to ensure quality of machined surface (see the condition (3.28)):

$$\boldsymbol{Z}_{16min} \geq [\boldsymbol{Z}_{16min}];$$

$$0.226 > 0.2.$$

The maximum value $\boldsymbol{Z}_{16max}$ of closing link is determined for its application in further calculations of *cutting conditions* for internal grinding operation 80 (ref. Fig. 4.7):

$$\boldsymbol{Z}_{16max} = \boldsymbol{Z}_{16nom} + \boldsymbol{\Delta s_Z} = 0.3 + (+0.046) = 0.346.$$

Calculations of operation dimensions-coordinates are performed with assigned accuracy grades (ref. Fig. 4.7) and results are submitted in the Table 4.5.

Table 4.5. Results of calculations of operation dimensions-coordinates between the workpiece faces, mm

No.	Initial link value	Original equation and its solution	Grade / Tolerance	Operation dimension	Closing link and tolerance calculations
1	$[A_2] = 25\pm0.042$ $[A_{2max}] = 25.042$ $[A_{2min}] = 24.958$	$[A_2] = \underline{S_{15}}$, $S_{15} = 25\pm0.042 = 24.958^{+0.084}$	$\frac{H10}{0.084}$	–	–
		$S_{15} = 24.958^{+0.033}$	Assigned $\frac{H8}{0.033}$	Hole $S_{15} =$ $= 24.958^{+0.033}$ Rounding off: $S_{15R} =$ $= 25^{+0.033}$	$A_{2max} = S_{15Rmax} = 25.033 < [A_{2max}]$ $A_{2min} = S_{15Rmin} = 25.0 > [A_{2min}]$
2	$[A_1] = 65_{-0.3}$ $[A_{1max}] = 65.0$ $[A_{1min}] = 64.7$	$[A_1] = \underline{S_{14}}$, $S_{14} = 65_{-0.3}$	$\frac{h12}{0.3}$	–	–
		$S_{14} = 65_{-0.046}$	Assigned $\frac{h8}{0.046}$	Shaft $S_{14} = 65_{-0.046}$	$A_{1max} = S_{14max} = 65.0 = [A_{1max}]$ $A_{1min} = S_{14min} = 64.954 > [A_{1min}]$
3	$[A_5] = 6\pm0.15$ $[A_{5max}] = 6.15$ $[A_{5min}] = 5.85$	$[A_5] = S_{14} - \underline{S_{13}}$; $6\pm0.15 = 65_{-0.046} - \underline{S_{13nom}{}^{es}_{ei}}$ 1) $6 = 65 - S_{13nom}$, $S_{13nom} = 59$ 2) $+0.15 = 0 - ei$, $ei = -0.15$ 3) $-0.15 = (-0.046) - es$, $es = +0.104$ $S_{13} = 59^{+0.104}_{-0.150} = 59.104_{-0.254}$	$\frac{\approx h11}{0.254}$	Shaft $S_{13} =$ $= 59.104_{-0.254}$	$[T_{A5}] = T_{S14} + \underline{T_{S13}}$; $0.3 = 0.046 + \underline{T_{S13}}$; $\underline{T_{S13}} = 0.3 - 0.046 = 0.254$
			$\frac{\approx h11}{0.25}$	Rounding off: $S_{13R} =$ $= 59.1_{-0.25}$	$\Delta S_{13} = S_{13nom} - S_{13Rnom} =$ $= 59.104 - 59.1 = 0.004$ $T_{S13R} = T_{S13} - \Delta S_{13} =$ $= 0.254 - 0.004 = 0.25$ $A_5 = S_{14} - S_{13R} =$ $= 65_{-0.046} - 59.1_{-0.25} = 5.9^{+0.250}_{-0.046}$ $A_{5max} = 6.15 = [A_{5max}]$ $A_{5min} = 5.854 > [A_{5min}]$

Table 4.5, continued

No.	Initial link value	Original equation and its solution	Grade / Tolerance	Operation dimension	Closing link and tolerance calculations
4	$[A_3] = 10_{-0.15}$ $[A_{3max}] = 10.0$ $[A_{3min}] = 9.85$	$[A_3] = \underline{S_{12}} - S_{15}$ $10_{-0.15} = S_{12nom}{}^{es}_{ei} - 25^{+0.033}$ 1) $10 = S_{12nom} - 25$, $S_{12nom} = 35$ 2) $0 = es - 0$, $es = 0$ 3) $-0.150 = ei - (+0.033)$, $ei = -0.117$ $S_{12} = 35_{-0.117}$	Assigned h9 0.062	Shaft $S_{12} =$ $= 35_{-0.062}$	$[T_{A3}] \geq \underline{T_{S12}} + T_{S15}$ $0.15 > (0.062 + 0.033) = 0.095$ $A_3 = S_{12} - S_{15} =$ $= 35_{-0.062} - 25^{+0.033} = 10_{-0.095}$ $A_{3max} = 10.0 = [A_{3max}]$ $A_{3min} = 9.905 > [A_{3min}]$
5	$[Z_{16min}] = 0.2$	$[Z_{16}] = \underline{S_{11}} - S_{14}$ $[Z_{16min}] = \underline{S_{11min}} - S_{14max}$ $\underline{S_{11min}} = S_{14max} + [Z_{16min}] = 65 + 0.2 =$ $= 65.2$ $S_{11max} = S_{11min} + T_{S11} = 65.2 + 0.074 =$ $= 65.274$	h9 0.074	Shaft $S_{11} =$ $= 65.274_{-0.074}$ Rounding off: $S_{11R} =$ $= 65.3_{-0.074}$	$Z_{16} = S_{11R} - S_{14} =$ $= 65.3_{-0.074} - 65_{-0.046} =$ $= 0.3^{+0.046}_{-0.074}$ $Z_{16min} = 0.226 > [Z_{16min}]$
6	$[Z_{17min}] = 0.4$	$[Z_{17}] = \underline{S_9} - S_{11}$ $[Z_{17min}] = \underline{S_{9min}} - S_{11max}$ $\underline{S_{9min}} = S_{11max} + [Z_{17min}] = 65.3 + 0.4 =$ $= 65.7$ $S_{9max} = S_{9min} + T_{S9} = 65.7 + 0.074 =$ $= 65.774$	h9 0.074	Shaft $S_9 =$ $= 65.774_{-0.074}$ $S_{9R} = 65.8_{-0.074}$	$Z_{17} = S_{9R} - S_{11} =$ $= 65.8_{-0.074} - 65.3_{-0.074} =$ $= 0.5 \pm 0.074$ $Z_{17min} = 0.426 > [Z_{17min}]$
7	$[Z_{8min}] = 0.2$	$[Z_8] = S_{15} + \underline{S_{10}} - S_9$ $[Z_{8min}] = S_{15min} + \underline{S_{10min}} - S_{9max}$ $\underline{S_{10min}} = S_{9max} + [Z_{8min}] - S_{15min} =$ $= 65.8 + 0.2 - 25 = 41.0$ $S_{10max} = S_{10min} + T_{S10} = 41.0 + 0.062 =$ $= 41.062 \approx 41.1$	h9 0.062	Shaft $S_{10} =$ $= 41.1_{-0.062}$	$Z_8 = S_{15} + S_{10} - S_9 =$ $= 25^{+0.033} + 41.1_{-0.062} -$ $- 65.8_{-0.074} = 0.3^{+0.107}_{-0.062}$ $Z_{8min} = 0.238 > [Z_{8min}]$

Table 4.5, continued

No.	Initial link value	Original equation and its solution	Grade Tolerance	Operation dimension	Closing link and tolerance calculations
8	$[A_4] = 26\pm0.105$ $[A_{4max}] = 26.105$ $[A_{4min}] = 25.895$	$[A_4] = S_{14} + \underline{S_8} - S_9$ $26\pm0.105 = 65_{-0.046} + S_{8nom}{}^{ES}_{EI} - 65.8_{-0.074}$ 1) $26 = 65 + S_{8nom} - 65.8$, $S_{8nom} = 26.8$ 2) $+0.105 = 0 + ES - (-0.074)$, $ES = +0.031$; 3) $-0.105 = (-0.046) + EI - 0$, $EI = -0.059$ $S_8 = 26.8^{+0.031}_{-0.059} = 26.741^{+0.090}$	≈ H10 0.090 ≈ H9 0.081 permissible for operation 20 (ref. Fig. 4.7) (IT10 = = 0.084)	Hole $S_8 =$ $= 26.741^{+0.090}$ $S_{8R} =$ $= 26.75^{+0.081}$	$[T_{A4}] = T_{S14} + \underline{T_{S8}} + T_{S9}$ $0.21 = 0.046 + 0.090 + 0.074$ $\Delta S_8 = S_{8Rnom} - S_{8nom} =$ $= 26.75 - 26.741 = 0.009$ $T_{S8R} = T_{S8} - \Delta S_8 =$ $= 0.090 - 0.009 = 0.081$ $A_4 = S_{14} + S_{8R} - S_9 = 65_{-0.046} +$ $+ 26.75^{+0.081} - 65.8_{-0.074} =$ $= 25.95^{+0.155}_{-0.046}$ $A_{4max} = 26.105 = [A_{4max}]$ $A_{4min} = 25.904 > [A_{4min}]$
9	$[Z_{7min}] = 0.4$	$[Z_7] = \underline{S_7} - S_{10}$ $[Z_{7min}] = \underline{S_{7min}} - S_{10max}$ $S_{7min} = S_{10max} + [Z_{7min}] = 41.1 + 0.4 = 41.5$ $S_{7max} = S_{7min} + T_{S7} = 41.5 + 0.16 = 41.66$	h11 0.16	Shaft $S_7 =$ $= 41.66_{-0.16} \approx$ $\approx 41.7_{-0.16}$	$Z_7 = 41.7_{-0.16} - 41.1_{-0.062} =$ $= 0.6^{+0.062}_{-0.160}$ $Z_{7min} = 0.44 > [Z_{7min}]$
10	$[Z_{18min}] = 0.7$	$[Z_{18}] = \underline{S_6} - S_7$ $[Z_{18min}] = \underline{S_{6min}} - S_{7max}$ $S_{6min} = S_{7max} + [Z_{18min}] = 41.7 + 0.7 = 42.4$ $S_{6max} = S_{6min} + T_{S6} = 42.4 + 0.25 = 42.65$	h12 0.25	Shaft $S_6 =$ $= 42.65_{-0.25} \approx$ $\approx 42.7_{-0.25}$	$Z_{18} = 42.7_{-0.25} - 41.7_{-0.16} =$ $= 1.0^{+0.16}_{-0.25}$ $Z_{18min} = 0.75 > [Z_{18min}]$
11	$[Z_{6min}] = 0.7$	$[Z_6] = \underline{S_3} - S_6$ $[Z_{6min}] = \underline{S_{3min}} - S_{6max}$ $S_{3min} = S_{6max} + [Z_{6min}] = 42.7 + 0.7 = 43.4$ $S_{3max} = S_{3min} + T_{S3} = 43.4 + 0.39 = 43.79$	h13 0.39	Shaft $S_3 =$ $= 43.79_{-0.39} \approx$ $\approx 43.8_{-0.39}$	$Z_6 = 43.8_{-0.39} - 42.7_{-0.25} =$ $= 1.1^{+0.25}_{-0.39}$ $Z_{6min} = 0.71 > [Z_{6min}]$

Table 4.5, continued

No.	Initial link value	Original equation and its solution	Grade / Tolerance	Operation dimension	Closing link and tolerance calculations
12	$[Z_{12min}] = 0.4$	$[Z_{12}] = S_8 + Z_{18} - \underline{S_5}$ $[Z_{12min}] = S_{8min} + Z_{18min} - \underline{S_{5max}}$ $S_{5max} = S_{8min} + Z_{18min} - [Z_{12min}] =$ $= 26.75 + 0.75 - 0.4 = 27.1$ $S_{5min} = S_{5max} - T_{S5} = 27.1 - 0.33 = 26.77$	$\frac{\text{H13}}{0.33}$	Hole $S_5 =$ $= 26.77^{+0.33} \approx$ $\approx 26.7^{+0.33}$	$Z_{12} = 26.75^{+0.081} + 1.0^{+0.16}_{-0.25} -$ $- 26.7^{+0.33} = 1.05^{+0.241}_{-0.580}$ $Z_{12min} = 0.47 > [Z_{12min}]$
13	$[Z_{9min}] = 0.4$	$[Z_9] = S_9 + \underline{S_4} + Z_{18} - S_{12} - S_3$ $[Z_{9min}] = S_{9min} + \underline{S_{4min}} + Z_{18min} -$ $- S_{12max} - S_{3max}$ $S_{4min} = S_{12max} + S_{3max} + [Z_{9min}] - S_{9min} -$ $- Z_{18min} = 35 + 43.8 + 0.4 - 65.726 -$ $- 0.75 = 12.724$ $S_{4max} = S_{4min} + T_{S2} = 12.724 + 0.27 =$ $= 12.994$	$\frac{\text{h13}}{0.27}$	Shaft $S_4 =$ $= 12.994_{-0.27} \approx$ $\approx 13_{-0.27}$	$Z_9 = 65.8_{-0.074} + 13_{-0.27} +$ $+ 1.0^{+0.16}_{-0.25} - 35_{-0.062} - 43.8_{-0.39} =$ $= 1^{+0.612}_{-0.594}$ $Z_{9min} = 0.406 > [Z_{9min}]$
14	$[Z_{3min}] = 0.4$	$[Z_3] = \underline{S_2} + S_3 - S_9 - Z_{18}$ $[Z_{3min}] = \underline{S_{2min}} + S_{3min} - S_{9max} - Z_{18max}$ $S_{2min} = S_{9max} + Z_{18max} + [Z_{3min}] - S_{3min} =$ $= 65.8 + 1.16 + 0.4 - 43.41 = 23.95$	$\frac{\text{H13}}{0.33}$	Hole $S_2 =$ $= 23.95^{+0.33} \approx$ $\approx 24^{+0.33}$	$Z_3 = 24^{+0.33} + 43.8_{-0.39} -$ $- 65.8_{-0.074} - 1.0^{+0.16}_{-0.25} = 1.0^{+0.654}_{-0.550}$ $Z_{3min} = 0.45 > [Z_{3min}]$
15	$[Z_{19min}] = 1.0$	$[Z_{19}] = \underline{S_1} - S_2 - S_3$ $[Z_{19min}] = \underline{S_{1min}} - S_{2max} - S_{3max}$ $S_{1min} = S_{2max} + S_{3max} + [Z_{19min}] =$ $= 24.33 + 43.8 + 1.0 = 69.13$ $S_{1max} = S_{1min} + T_{S1} = 69.13 + 0.46 = 69.59$	$\frac{\text{IT13}}{0.46}$	Shaft $S_1 =$ $= 69.59_{-0.46} \approx$ $\approx 69.6_{-0.46}$	$Z_{19} = 69.6_{-0.46} - 24^{+0.33} -$ $- 43.8_{-0.39} = 1.8^{+0.39}_{-0.79}$ $Z_{19min} = 1.01 > [Z_{19min}]$

Table 4.5, continued

No.	Initial link value	Original equation and its solution	Grade / Tolerance	Operation dimension	Closing link and tolerance calculations
16	$[Z_{2min}] = 1.0$	$[Z_2] = \underline{B_1} - S_1$ $[Z_{2min}] = \underline{B_{1min}} - S_{1max}$ $B_{1min} = S_{1max} + [Z_{2min}] = 69.6 + 1.0 = 70.6$ $B_{1nom} = B_{1min} - ei = 70.6 - (-0.6) = 71.2$	$\approx$ IT16 / $1.6\left(^{+1.0}_{-0.6}\right)$	Shaft $B_1 =$ $= 71.2^{+1.0}_{-0.6}$	$Z_2 = 71.2^{+1.0}_{-0.6} - 69.6_{-0.46} =$ $= 1.6^{+1.46}_{-0.60}$ $Z_{2min} = 1.0 = [Z_{2min}]$
17	$[Z_{5min}] = 1.0$	$[Z_5] = S_2 + Z_2 - \underline{B_2}$ $[Z_{5min}] = S_{2min} + Z_{2min} - \underline{B_{2max}}$ $B_{2max} = S_{2min} + Z_{2min} - [Z_{5min}] =$ $= 24 + 1.0 - 1.0 = 24$ $B_{2nom} = B_{2max} - ES = 24 - (+0.5) = 23.5$	$\approx$ IT17 / $1.5\left(^{+0.5}_{-1.0}\right)$	Hole $B_2 =$ $= 23.5^{+0.5}_{-1.0}$	$Z_5 = 24^{+0.33} + 1.6^{+1.46}_{-0.60} -$ $- 23.5^{+0.5}_{-1.0} = 2.1^{+2.79}_{-1.10}$ $Z_{5min} = 1.0 = [Z_{5min}]$
18	$[Z_{10min}] = 1.0$	$[Z_{10}] = \underline{B_3} - S_4 - Z_5$ $[Z_{10min}] = \underline{B_{3min}} - S_{4max} - Z_{5max}$ $B_{3min} = S_{4max} + Z_{5max} + [Z_{10min}] =$ $= 13 + 4.89 + 1.0 = 18.89$ $B_{3nom} = B_{3min} - ei = 18.89 - (-0.5) = 19.39$	$\approx$ IT17 / $1.5\left(^{+1.0}_{-0.5}\right)$	Shaft $B_3 =$ $= 19.39^{+1.0}_{-0.5} \approx$ $\approx 19.4^{+1.0}_{-0.5}$	$Z_{10} = 19.4^{+1.0}_{-0.5} - 13_{-0.27} -$ $- 2.1^{+2.79}_{-1.10} = 4.3^{+2.37}_{-3.29}$ $Z_{10min} = 1.01 > [Z_{10min}]$
19	$[Z_{13min}] = 1.0$	$[Z_{13}] = S_5 + Z_{19} - \underline{B_4}$ $[Z_{13min}] = S_{5min} + Z_{19min} - \underline{B_{4max}}$ $B_{4max} = S_{5min} + Z_{19min} - [Z_{13min}] =$ $= 26.7 + 1.01 - 1.0 = 26.71$ $B_{4nom} = B_{4max} - ES = 26.71 - (+0.5) =$ $= 26.21$	$\approx$ IT17 / $1.5\left(^{+0.5}_{-1.0}\right)$	Hole $B_4 =$ $= 26.21^{+0.5}_{-1.0} \approx$ $\approx 26.2^{+0.5}_{-1.0} \approx$	$Z_{13} = 26.7^{+0.33} + 1.8^{+0.39}_{-0.79} -$ $- 26.2^{+0.5}_{-1.0} = 2.3^{+1.69}_{-1.29}$ $Z_{13min} = 1.01 > [Z_{13min}]$

4.7. Calculations of operation dimensions for round surfaces

The algorithms for calculations of operation dimensions for round surfaces are described in the paragraph 3.8.

When starting the calculations, a considered surface should be identified as a basic part in order to specifiy proper position of tolerance band: for *basic shaft* with basic deviation **h** – upper deviation equals zero; for *basic hole* with basic deviation **H** – lower deviation equals zero. That is a whole tolerance band should be located in the workpiece body (in a metal).

Initial data for calculations are values of normative minimum allowance $2\boldsymbol{Z}_{iminN}$, distribution of accuracy grades ITn and tolerances $\boldsymbol{T}_i$ for each manufacturing step made in Table 4.3 with possible corrections made in the optimised preliminary plan (ref. Fig. 4.9).

In this paragraph a minimum limit value of allowance $2\boldsymbol{Z}_{minN}$ for each manufacturing step is determined by *normative method* (ref. paragraph 3.6.2), that is, from the normatives given in the reference literature in a form of tables [13] (ref. Appendix 10).

Surface 2 with design dimension ø40k7$\left(^{+0.027}_{+0.002}\right)$ is used as an example for calculations of operation dimensions for shaft-type element of the part. Surface parameters specified by the drawing (ref. Fig. 4.1) are obtained as a result of four metal-cutting steps, diffusion and heat treatments performed at the end of finish-machining stage (ref. Fig. 4.9).

First of all, the final dimension of part specified by the drawing is converted into executive (manufacturing) dimension with **h** basic deviation: Ø40k7$\left(^{+0.027}_{+0.002}\right)$ = = Ø40.027h7($_{-0.025}$).

Values of minimum allowance $2\boldsymbol{Z}_{iminN}$ determined from the Appendix 10 and tolerances along manufacturing steps $\boldsymbol{T}_i$ (ref. Table 4.3) are the following:

- For grinding: $2\boldsymbol{Z}_{4minN}$ = 0.2 mm (for hardened workpieces), $\boldsymbol{T}_4$ = 0.025 mm;
- For finish turning: $2\boldsymbol{Z}_{3minN}$ = 0.5 mm, $\boldsymbol{T}_3$ = 0.039 mm;
- For semi-finish turning: $2\boldsymbol{Z}_{2minN}$ = (1.7 + 0.5)/2 = 1.1 mm (linear interpolation between normative minimum allowances for rough and finish turning), $\boldsymbol{T}_2$ = 0.062 mm;
- For rough turning: $2\boldsymbol{Z}_{1minN}$ = 1.7 mm, $\boldsymbol{T}_1$ = 0.250 mm;
- Tolerance for initial blank (forging): $\boldsymbol{T}_0$ = 1.5 mm, deviations $\left(^{+1.0}_{-0.5}\right)$, upper portion of tolerance $\boldsymbol{T}_{0es}$ = 1.0 mm, lower portion of tolerance $\boldsymbol{T}_{0ei}$ = 0.5 mm.

Nominal value of *allowance* is equal to sum of minimum allowance for current manufacturing step $\boldsymbol{i}$ and tolerance of dimension at previous step ($\boldsymbol{i}$–1)

$$2\boldsymbol{Z}_{inom} = 2\boldsymbol{Z}_{iminN} + \boldsymbol{T}_{i-1}.$$

Nominal allowances along manufacturing steps are:

- For grinding: $2\boldsymbol{Z}_{4nom}$ = 0.2 + 0.039 = 0.239 mm;
- For finish turning: $2\boldsymbol{Z}_{3nom}$ = 0.5 + 0.062 = 0.562 mm;
- For semi-finish turning: $2\boldsymbol{Z}_{2nom}$ = 1.1 + 0.25 = 1.35 mm;

- For rough turning: $2Z_{1nom} = 2Z_{1min} + T_{0ei} = 1.7 + 0.5 = 2.2$ mm, where only the lower portion of forging tolerance T_{0ei} located in metal is used.

Calculated dimension for the last manufacturing step is equal to the maximum specified dimension of the part $d_c = d_{max}$. *Calculated dimensions* for previous steps are equal to *maximum* dimensions, which equal to *nominal* dimensions for *shaft* type elements (basic shafts), except the blank dimensions.

Calculated dimension for previous step (i–1) equals to sum of calculated (maximum, nominal) dimension and nominal allowance at the current step i

$$d_{i-1c} = d_{ic} + 2Z_{inom}\,.$$

Calculated dimensions along manufacturing steps are determined, except the part dimension specified in the drawing:

- For grinding: $d_{4c} = d_{4max} = 40.027$ mm;
- For finish turning: $d_{3c} = 40.027 + 0.239 = 40.266$ mm;
- For semi-finish turning: $d_{2c} = 40.266 + 0.562 = 40.828$ mm;
- For rough turning: $d_{1c} = 40.828 + 1.35 = 42.178$ mm;
- For initial blank (forging): $d_{0c} = d_{0nom} = 42.178 + 2.2 = 44.378$ mm.

Rounding off the shaft-type dimensions is made for the "favour of allowance", that is, with increase of calculated dimensions that result in increase of allowance. *Adopted maximum (nominal) dimensions* are rounded to the values divisible by 0.1 mm.

Minimum adopted dimensions are calculated from the famous formula

$$d_{imin} = d_{imax} - T_i\,.$$

Maximum and minimum dimensions of initial blank are calculated from the famous formulas with use of adopted nominal dimension and its deviations:

$$d_{0max} = d_{0nom} + es_0; \quad d_{0min} = d_{0nom} + ei_0,$$

where es_0 and ei_0 are upper and lower deviations of blank nominal dimension, respectively.

Thus, along manufacturing steps the rounded-off adopted maximum dimensions and calculated minimum dimensions are:

- For grinding: $d_{4max} = 40.027$ mm, $d_{4min} = 40.002$ mm (both values are specified in the drawing);
- For finish turning: $d_{3max} = 40.3$ mm, $d_{3min} = 40.3 - 0.039 = 40.261$ mm;
- For semi-finish turning: $d_{2max} = 40.9$ mm, $d_{2min} = 40.9 - 0.062 = 40.838$ mm;
- For rough turning: $d_{1max} = 42.3$ mm, $d_{1min} = 42.3 - 0.25 = 42.05$ mm;
- For initial blank (forging): $d_{0nom} = 44.5$ mm, $d_{0max} = 44.5 + (+1.0) = 45.5$ mm, $d_{0min} = 44.5 + (-0.5) = 44.0$ mm.

Dimensions for rough turning and initial blank are increased by 0.1 mm in order to satisfy the condition (3.36) related to minimum value of allowance considered below.

Adopted maximum and minimum values of allowances are calculated with use of adopted maximum and minimum values of dimensions from the formulas:

$$2\boldsymbol{Z}_{imax} = \boldsymbol{d}_{i-1max} - \boldsymbol{d}_{imin}; \quad 2\boldsymbol{Z}_{imin} = \boldsymbol{d}_{i-1min} - \boldsymbol{d}_{imax}.$$

Adopted minimum allowances should be not less than the normative minimum allowances

$$2\boldsymbol{Z}_{imin} \geq 2\boldsymbol{Z}_{iminN}.$$

Adopted maximum and minimum values of allowances are the following:

- For grinding:

$$2\boldsymbol{Z}_{4max} = 40.3 - 40.002 = 0.298 \text{ mm},$$

$$2\boldsymbol{Z}_{4min} = 40.261 - 40.027 = 0.234 \text{ mm} \geq (2\boldsymbol{Z}_{4minN} = 0.2 \text{ mm});$$

- For finish turning:

$$2\boldsymbol{Z}_{3max} = 40.9 - 40.261 = 0.639 \text{ mm},$$

$$2\boldsymbol{Z}_{3min} = 40.838 - 40.3 = 0.538 \text{ mm} \geq (2\boldsymbol{Z}_{3minN} = 0.5 \text{ mm});$$

- For semi-finish turning:

$$2\boldsymbol{Z}_{2max} = 42.3 - 40.838 = 1.462 \text{ mm},$$

$$2\boldsymbol{Z}_{2min} = 42.05 - 40.9 = 1.15 \text{ mm} \geq (2\boldsymbol{Z}_{2minN} = 1.1 \text{ mm});$$

- For rough turning:

$$2\boldsymbol{Z}_{1max} = 45.5 - 42.05 = 3.45 \text{ mm},$$

$$2\boldsymbol{Z}_{1min} = 44.0 - 42.3 = 1.7 \text{ mm} \geq (2\boldsymbol{Z}_{1minN} = 1.7 \text{ mm}).$$

Operation dimensions are written down with basic deviation h (basic shaft): nominal dimension equals maximum adopted dimension, upper deviation equals zero, and lower deviation equals tolerance with minus (dimension with tolerance located in metal) $\boldsymbol{d}_i = \boldsymbol{d}_{imax}{}^{0}_{-\boldsymbol{T}_i}$,:

- For grinding: $\boldsymbol{d}_4 = 40.027_{-0.025}$;
- For finish turning: $\boldsymbol{d}_3 = 40.3_{-0.039}$;
- For semi-finish turning: $\boldsymbol{d}_2 = 40.9_{-0.062}$;
- For rough turning: $\boldsymbol{d}_1 = 42.3_{-0.25}$;
- For initial blank (forging): nominal adopted dimension with deviations determined in paragraph 4.2 (ref. Fig. 4.3): $\boldsymbol{d}_0 = 44.5^{+1.0}_{-0.5}$.

Results of calculations of operation dimensions for this and other round surfaces are submitted in the Table 4.6.

Algorithm for calculations of operation dimensions for hole-type elements of the part is similar to the algorithm for shafts. The main difference is that at machining of a hole its dimension increases. Operation dimensions are determined by **H** basic deviations, that is, *nominal dimension equals minimum limit dimension*, lower deviation equals zero, and upper deviation equals tolerance with plus $\boldsymbol{D}_i = \boldsymbol{D}_{imin}{}^{+\boldsymbol{T}_i}_{0}$.

Suface 13 with design dimension – minor diameter of spline bushing

Ø23.28H11($^{+0.13}$) calculated in the paragraph 4.1.3 – is used for the example (ref. Table 4.6). Accuracy and surface finish of the hole before broaching are determined from the recommendations [18]. The specified parameters of the hole are produced by 3 steps: drilling (blanking step), rough boring and finish boring (ref. Table 4.3). Drilling is necessary to complete initial blank shape and to form initial surface of hole, because the forging has no hole in this segment.

Values of normative minimum allowance $2\boldsymbol{Z_{iminN}}$ determined from the Appendix 10 and tolerances along manufacturing steps $\boldsymbol{T_i}$ (ref. Table 4.3) are the following:

- For finish boring: $2\boldsymbol{Z_{2minN}}$ = 0.5 mm, $\boldsymbol{T_2}$ = 0.13 mm;
- For rough boring: $2\boldsymbol{Z_{1minN}}$ = 1.7 mm, $\boldsymbol{T_1}$ = 0.21 mm;
- Tolerance for the drilled hole: $\boldsymbol{T_0}$ = 0.52 mm.

Nominal value of allowance is calculated from the formula

$$2\boldsymbol{Z_{inom}} = 2\boldsymbol{Z_{iminN}} + \boldsymbol{T_{i-1}}.$$

Nominal allowances along manufacturing steps are:

- For finish boring: $2\boldsymbol{Z_{2nom}}$ = 0.5 + 0.21 = 0.71 mm;
- For rough boring: $2\boldsymbol{Z_{1nom}}$ = 1.7 + 0.52 = 2.22 mm.

Calculated dimension for previous step ($\boldsymbol{i}$–1) equals to *difference* of calculated (minimum, nominal) dimension and nominal allowance at the current step $\boldsymbol{i}$

$$\boldsymbol{D_{i-1c}} = \boldsymbol{D_{ic}} - 2\boldsymbol{Z_{inom}}.$$

Calculated dimensions along manufacturing steps are determined, except the part dimension specified in the drawing:

- For finish boring: $\boldsymbol{D_{2c}} = \boldsymbol{D_{min}}$ = 23.28 mm;
- For rough boring: $\boldsymbol{D_{1c}}$ = 23.28 – 0.71 = 22.57 mm;
- For drilling: $\boldsymbol{D_{0c}}$ = 22.57 – 2.22 = 20.35 mm.

Rounding off the hole-type dimensions is made for the "favour of allowance", that is, with decrease of calculated dimensions that result in increase of allowance. *Adopted minimum (nominal) dimensions* are rounded to the values divisible by 0.1 mm. Dimension of the drilled hole is agreed with the standard diameter of drill.

Maximum adopted dimensions are calculated from the famous formula

$$\boldsymbol{D_{imax}} = \boldsymbol{D_{imin}} + \boldsymbol{T_i}.$$

Thus, along manufacturing steps the rounded-off adopted minimum dimensions and calculated maximum dimensions are:

- For finish boring: $\boldsymbol{D_{2min}}$ = 23.28 mm, $\boldsymbol{D_{2max}}$ = 23.28 + 0.13 = 23.41 mm (both values are specified in the drawing);
- For rough boring: $\boldsymbol{D_{1min}}$ = 22.5 mm, $\boldsymbol{D_{1max}}$ = 22.5 + 0.21 = 22.71 mm;
- For drilling: $\boldsymbol{D_{0min}}$ = 20.25 mm, $\boldsymbol{D_{0max}}$ = 20.25 + 0.52 = 20.77 mm.

Adopted maximum and minimum values of allowances are calculated with use of

Table 4.6. Results of calculations of operation dimensions for round surfaces, mm

Route for surface machining	Normative minimum allowance $2Z_{minN}$	Toler-ance T	Calculated nominal allowance $2Z_{nom}$	Calculated nominal dimension D_c, d_c	Adopted dimension		Adopted allowance		Operation dimension D, d
					D_{max}, d_{max}	D_{min}, d_{min}	$2Z_{max}$	$2Z_{min}$	
Surface 2 Ø40k7$\left(^{+0.027}_{+0.002}\right)$ = Ø40.027h7$(_{-0.025})$ – **shaft**									
Forging	–	$1.5\left(^{+1.0}_{-0.5}\right)$	–	44.378	45.5	44.0	–	–	$44.5^{+1.0}_{-0.5}$
Rough turning	1.7	0.250	2.200	42.178	42.3	42.050	3.450	1.700	$42.3_{-0.25}$
Semi-finish turning	1.1	0.062	1.350	40.828	40.9	40.838	1.462	1.150	$40.9_{-0.062}$
Finish turning	0.5	0.039	0.562	40.266	40.3	40.261	0.639	0.538	$40.3_{-0.039}$
Heat treatment									
Grinding	0.2	0.025	0.239	40.027	40.027	40.002	0.298	0.234	$40.027_{-0.025}$
Surface 4 Ø100h12$(_{-0.35})$ – **shaft**									
Forging	–	$1.6\left(^{+1.0}_{-0.6}\right)$	–	104.07	105.1	103.5	–	–	$104.1^{+1.0}_{-0.6}$
Rough turning	2.0	0.87	2.6	101.47	101.5	100.63	4.47	2.0	$101.5_{-0.87}$
Finish turning	0.6	0.35	1.47	100.0	100.0	99.65	1.85	0.63	$100_{-0.35}$
Surface 7 Ø16H12$(^{+0.18})$ – **hole**									
Drilling	–	0.43	–	15.07	15.43	15.0	–	–	$15^{+0.43}$
Core drilling	0.5	0.18	0.93	16.0	16.18	16.0	1.18	0.57	$16^{+0.18}$

Table 4.6, continued

Route for surface machining	Normative minimum allowance $2Z_{minN}$	Toler-ance T	Calculated nominal allowance $2Z_{nom}$	Calculated nominal dimension D_c, d_c	Adopted dimension		Adopted allowance		Operation dimension D, d
					D_{max}, d_{max}	D_{min}, d_{min}	$2Z_{max}$	$2Z_{min}$	
Surface 9 Ø50h12($_{-0.25}$) – **shaft**									
Forging	–	$1.6\left(^{+1.0}_{-0.6}\right)$	–	53.94	55.0	53.4	–	–	$54^{+1.0}_{-0.6}$
Rough turning	2.0	0.74	2.6	51.34	51.4	50.66	4.34	2.0	$51.4_{-0.74}$
Finish turning	0.6	0.25	1.34	50.0	50.0	49.75	1.65	0.66	$50_{-0.25}$
Surface 10 Ø40H7($^{+0.025}$) – **hole**									
Forging	–	$1.5^{+0.5}_{-1.0}$	–	35.449	35.8	34.3	–	–	$35.3^{+0.5}_{-1.0}$
Rough boring	1.7	0.250	2.200	37.649	37.750	37.5	3.450	1.7	$37.5^{+0.25}$
Semi-finish boring	1.2	0.062	1.450	39.099	39.062	39.0	1.562	1.250	$39^{+0.062}$
Finish boring	0.6	0.039	0.662	39.761	39.739	39.7	0.739	0.638	$39.7^{+0.039}$
Heat treatment									
Internal grinding	0.2	0.025	0.239	40.0	40.025	40.0	0.325	0.261	$40^{+0.025}$
Surface 13 Ø23.28H11($^{+0.13}$) – **hole**									
Drilling	–	0.52	–	20.35	20.77	20.25	–	–	$20.25^{+0.52}$
Rough boring	1.7	0.21	2.22	22.57	22.71	22.5	2.46	1.73	$22.5^{+0.21}$
Finish boring	0.5	0.13	0.71	23.28	23.41	23.28	0.91	0.57	$23.28^{+0.13}$

adopted maximum and minimum values of dimensions from the formulas:

$$2\boldsymbol{Z}_{imax} = \boldsymbol{D}_{imax} - \boldsymbol{D}_{i-1min}; \quad 2\boldsymbol{Z}_{imin} = \boldsymbol{D}_{imin} - \boldsymbol{D}_{i-1max}.$$

Adopted minimum allowances should be not less than the normative minimum allowances

$$2\boldsymbol{Z}_{imin} \geq 2\boldsymbol{Z}_{iminN}.$$

Adopted maximum and minimum values of allowances are the following:

- For finish boring:

$$2\boldsymbol{Z}_{2max} = 23.41 - 22.5 = 0.91 \text{ mm},$$

$$2\boldsymbol{Z}_{2min} = 23.28 - 22.71 = 0.57 \text{ mm} \geq (2\boldsymbol{Z}_{2minN} = 0.5 \text{ mm});$$

- For rough boring:

$$2\boldsymbol{Z}_{1max} = 22.71 - 20.25 = 2.46 \text{ mm},$$

$$2\boldsymbol{Z}_{1min} = 22.5 - 20.77 = 1.73 \text{ mm} \geq (2\boldsymbol{Z}_{1minN} = 1.7 \text{ mm}).$$

Operation dimensions are written down with basic deviation H (basic hole):

- For finish boring: $\boldsymbol{D}_2 = 23.28^{+0.13}$;
- For rough boring: $\boldsymbol{D}_1 = 22.5^{+0.21}$;
- For drilling: $\boldsymbol{D}_0 = 20.25^{+0.52}$.

4.8. Performance of final plan of manufacturing process

Performance of final plan is based on the optimised preliminary plan of manufacturing process (ref. Fig. 4.9) with improvements made in several operations.

Operation dimensions calculated for faces (ref. Table 4.5) and round surfaces (ref. Table 4.6) are specified in the operation sketches (Fig. 4.10) according to the stages of manufacturing process. Machined surfaces are numbered.

Roughness of machined surfaces is shown in operation sketches according to the distribution made in the Table 4.3 and possible changes. Roughness symbols are specified in the upper right-hand corner of the sketch field for the most of machined surfaces. Roughness of a surface with different value is shown directly at this surface.

List of manufacturing steps is written in lower right-hand corner of the sketch field. The list states a sequence for performance of manufacturing steps in a considered operation. Usually a turning operation starts from the machining of the face, from which other faces (external and internal) are coordinated. Then the round surface of the largest diameter is machined followed by other external surfaces. Here combined steps are possible: combination of machining the round and butt surfaces. Internal surfaces are usually machined in the last steps. The sets of datum surfaces (round surface and mating face) should be obligatory machined in one mounting.

Dimensions of initial blank calculated for faces (ref. Table 4.5) and round surfaces (ref. Table 4.6) are specified in the blank sketch (ref. Fig. 4.3). The drawing of blank is developed with specifying the technical requirements (Fig. 4.11). Exact mass of forging $\boldsymbol{m}_b$ = 1.889 kg is calculated from exact dimension of initial blank and then coefficient of material utilisation $\boldsymbol{C}_{MU}$ is determined (ref. paragragh. 4.2)

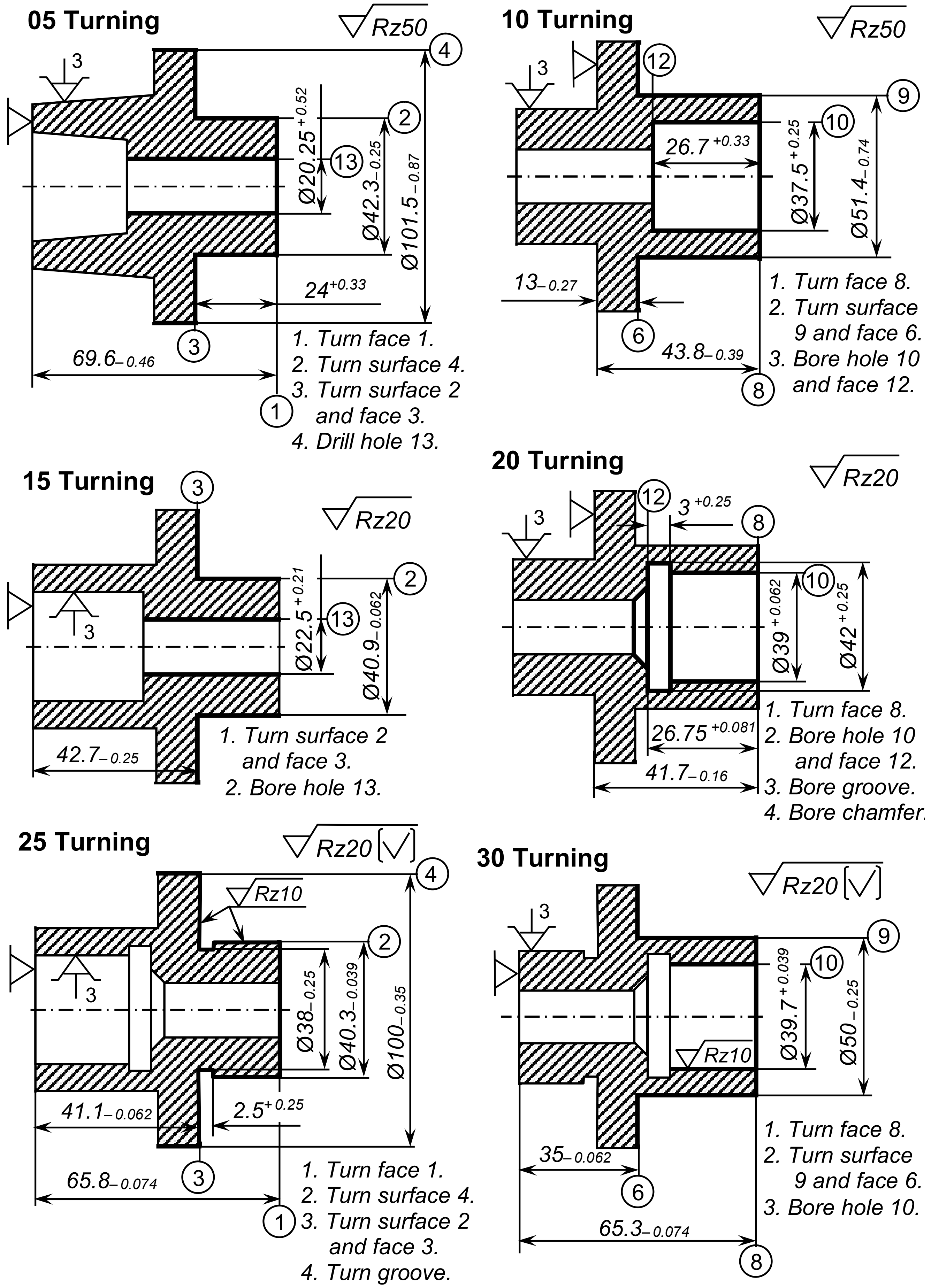
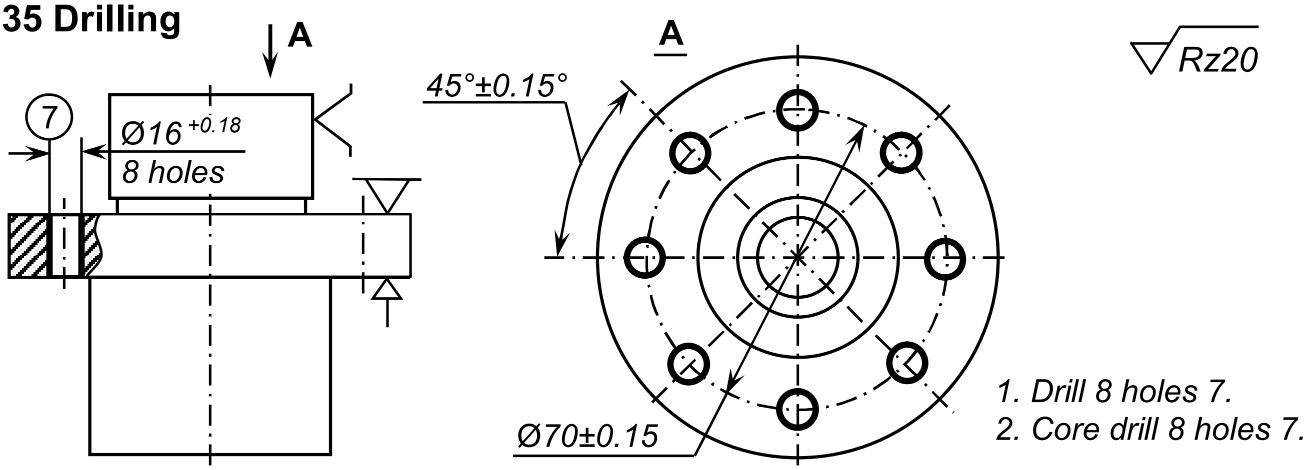
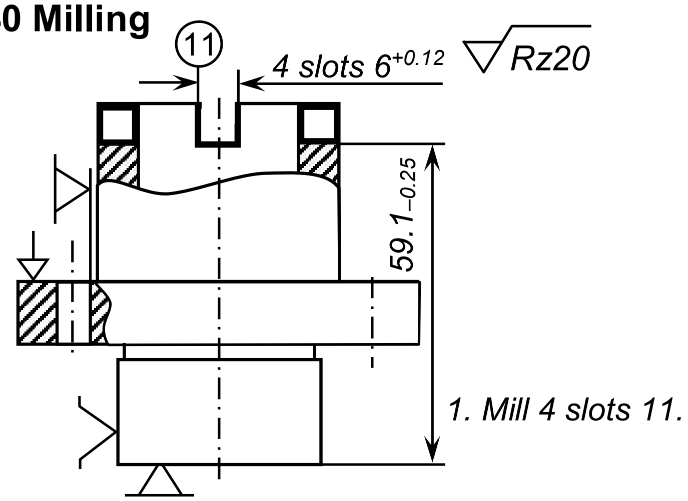


Fig. 4.10. Final plan of manufacturing process for production of shaft-gear

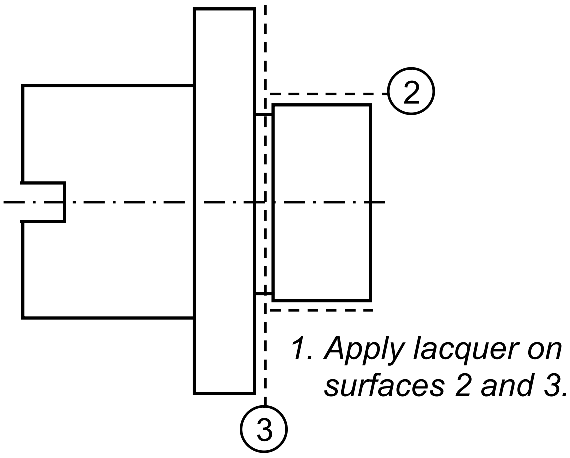
35 Drilling



40 Milling



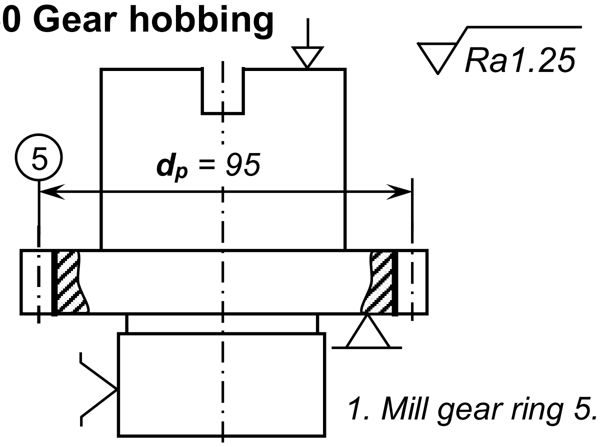
45 Lacquering



50 Galvanic (copper plating)

55 Lacquer washing

60 Gear hobbing



65 Diffusion heat treatment (carbonisation)

70 Heat treatment (hardening, sub-zero treatment, tempering)

75 Galvanic (copper removal)

80 Internal grinding

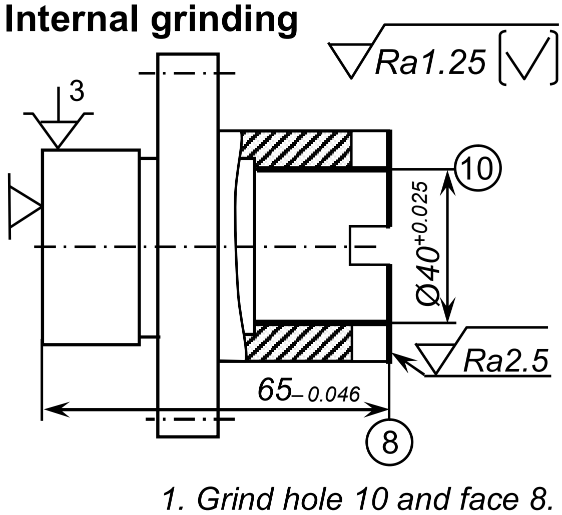


Fig. 4.10, continued

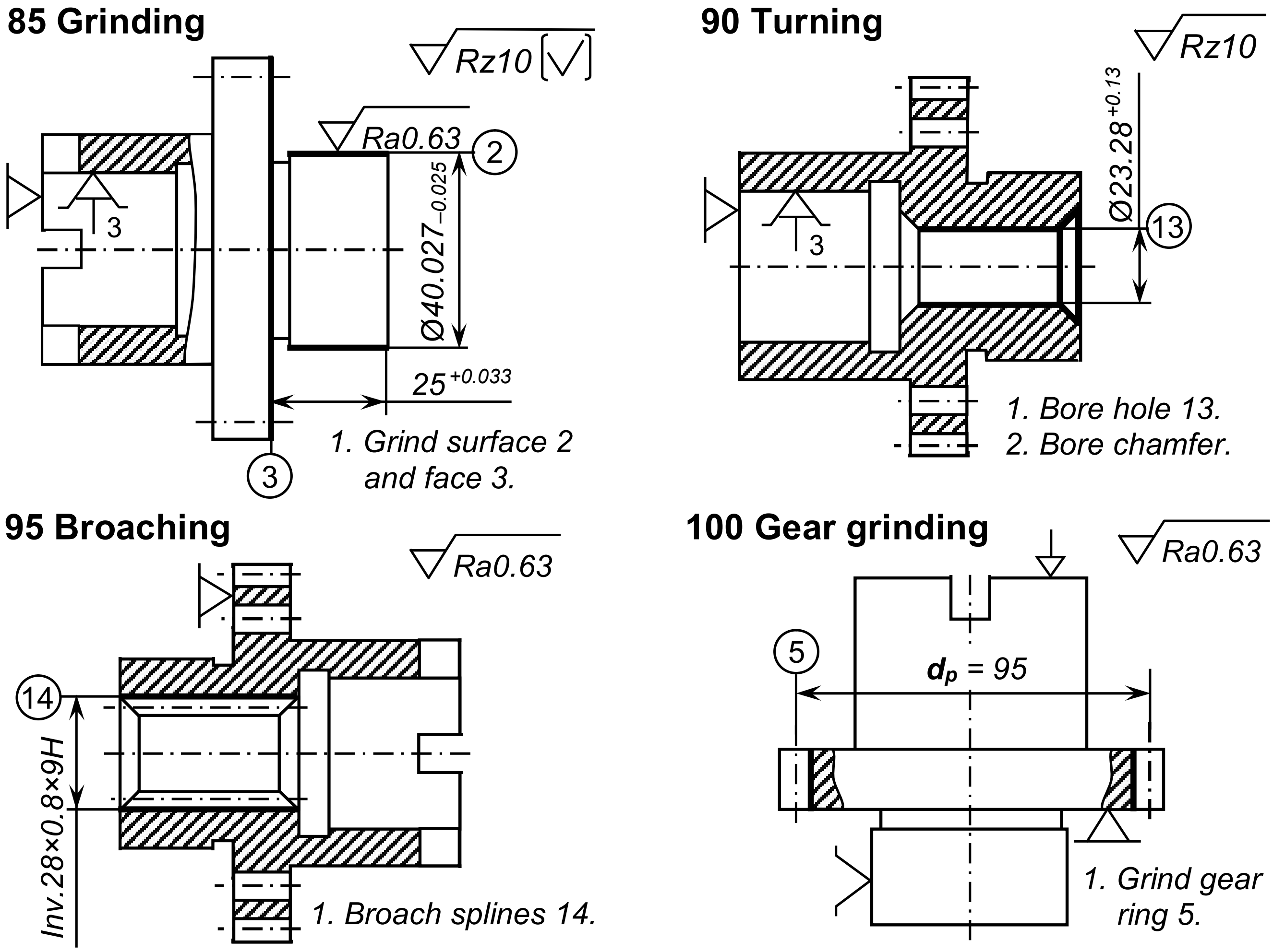


Fig. 4.10, continued

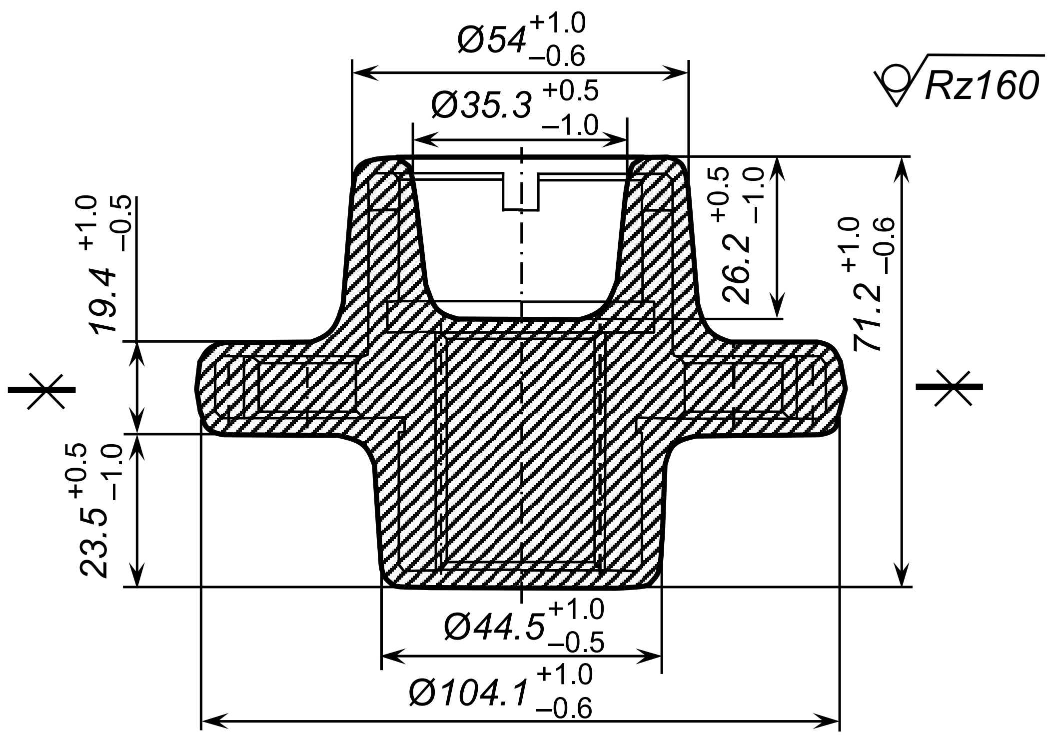


Fig. 4.11. Final sketch of forging of shaft-gear: forging drafts of outer surfaces 5º, inner surface – 7º; inner radii 8 mm, outer radii 6 mm; dies displacement 0.4 mm

Appendix 1

Heat treatment and diffusion heat treatment (case hardening) of steel

The following information is compiled from the source [15].

Annealing is a heating of steel above a phase transformation temperature, soaking at this temperature, followed by slow cooling (usually with a furnace). Annealing purposes are: recrystallisation of steel, change of grains size, decrease of internal stresses, reduction of hardness and improvement of metal-cutting ability (machinability).

Normalising is a heating of hypoeutectoid steel above the A_3 temperature line, and hypereutectoid steel – above the A_{Cm} by 50–60°C (austenitizing), followed by cooling in open air. Recrystallisation of steel eliminates course-grain structure resulted from casting or forging processes. Normalisation is applied for medium-carbon steels instead of hardening and high-temperature tempering. Normalisation with high-temperature tempering (600–650°C) is often applied for improvement of carbon steel structure.

Hardening is a heating of steel above a phase transformation temperature, soaking at this temperature, followed by fast cooling (quenching) with velocity more than the critical (the minimum cooling velocity, at which austenite transforms into martensite without perlite structures). Ability of steel to acquire high hardness as a result of hardening (martensite structure) is mainly determined by carbon content. Thus, with carbon content increase from 0.3 to 0.7 % the steel hardness number rises from 30 to the limit HRC 65 after hardening procedure.

Tempering is a heating of steel to the temperature below A_1 (727°C), soaking at this temperature, followed by cooling with the determined velocity (typically in air). Tempering (final operation of heat treatment) is conducted after hardening for reducing the internal stresses (stress relieving) and obtaining the more equilibrium structure. Three types of tempering are defined:

- Low-temperature tempering is realized at the temperature of 80–200°C;
- medium-temperature tempering – at the temperature of 350–500°C;
- High-temperature tempering – at the temperature of 350–500°C, when entire relief of internal stresses occurs.

Tempering results in insignificant hardness decrease of the hardened steel, but greatly increases plasticity and toughness.

Aging is a process of change of alloy properties without noticeable temperature rise. It results in increase of hardness and strength, but characteristics of plasticity and toughness slightly decrease.

Sub-zero treatment is determined by temperature of martensite transformation finish (M_f) below 0°C. The structure contains residual austenite after hardening by quenching. In order to reduce its quantity, quenched steel is cooled (for example, in liquid nitrogen) down to sub-zero temperatures. Increase of martensite quantity at the expense of austenite results in a rise of hardness, stabilisation of dimensions and small increase of a workpiece volume (dimensions).

Carbonisation (carburisation, carburising) is a process of saturation of surface layer with carbon of low-carbon steel workpieces (up to 0.25 % carbon). The purpose is to obtain the high hardness (HRC 60–65) on the workpiece surface after hardening and tempering at keeping the high toughness of core material, that improves wear resistance and endurance limit. Carbonisation temperature (900–950°C) is above the A_3 temperature; depth of carburised layer is 0.8–1.4 mm for the most of steels, though up to 3-mm depth is possible; soaking time in a furnace is 0.8–1.4 hours; carbon content in a surface layer is 0.8–1.0 %. Higher carbon content causes embrittlement of a carburised layer. The segments of a workpiece not to be carbonised are protected mostly by a thin layer of copper (0.02–0.04 mm – galvanic operation).

Nitriding is a process of saturation of surface layer of alloy medium-carbon steels (containing Cr, W, Mo, V, Al alloying elements) with nitrogen atoms in the ammonia medium. Hardness of a workpiece after hardening and tempering is HRC 62–68; temperature of nitriding process is 480–650°C; depth of nitrated layer up to 0.5 mm is obtained during 24 and more hours; at a liquid nitriding process the nitrated case of 0.1–0.2 mm thickness is produced during 1.5–2 hours. The segments of workpiece not to be nitrated are mostly protected by thin layer (0.001–0.005 mm) of tin applied by electroplating method.

Cyaniding and ***carbonitriding*** is a process of simultaneous saturation of steel surfaces (containing 0.3–0.4 % carbon) with carbon and nitrogen. There are liquid and gaseous cyaniding processes. *Liquid cyaniding* is conducted in molten salts containing cyanic natrium. Hardness of workpiece surfaces after hardening and tempering is HRC 59–62; process temperature is 820–850°C (allows hardening (quenching) directly from a salt bath); thickness of cyanided case of 0.15–0.35 mm is obtained during 0.5–1.5 hours. Deep cyaniding (case thickness of 0.5–2 mm, temperature of 900–950°C, duration of 1.5–6 hours) has the advantages in comparison with carburising: shorter process duration, smaller distortions, higher wear resistance and improved fatigue strength. Cooling, hardening and tempering are applied to a workpiece after cyaniding. The disadvantage is a toxicity of cyanide salts (prussiates).

Gaseous cyaniding is also called a *carbonitriding*, conducted in a gaseous mixture of carburising gas and ammonia. Treatment temperature is 840–860°C; case thickness of 0.1–1.0 mm is produced during 1–10 hours.

Appendix 2

Main requirements for planning of manufacturing processes in accordance with economical principle

1. Initial blanks by shape and dimensions should approach to ready-made parts. Degree of similarity of blank with part depends on production output; at large production run approach should be maximum one. In this case machining allowances and the sequent volume of machining will be minimal.

2. Locating diagrams of a workpiece should provide maximum simplicity and reliability of workholding devices.

3. Allowances for rough, finish and fine-finish machining should be rationally distributed.

4. Sequence and structure of operations should be selected in such a manner that

manufacture of quality parts occurs at the shortest time and least materials costs. For this it is necessary to introduce modern methods and types of machining.

5. Equipment should be high-productive and powerful to allow concentration of large number of manufacturing steps, simultaneous application of several cutting tools and automation of auxiliary steps.

6. Production tooling should be high-productive, effective, and precise, with minimum time for mounting and removal of workpieces.

7. Cutting and measuring tools should be standardised, of wide applications and lower cost.

8. Cutting conditions should be optimised, that is, a machine's power and endurance of cutting tools are used in a full volume.

9. Time norms are technically substantiated.

Appendix 3

Standard accuracy and roughness parameters

Table A.3.1. Accuracy grades and tolerances for dimensions up to 500 mm [10]

Dimension, mm (above – up to)	Accuracy grade															
	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	micrometer												mm			
Up to 3	4	6	10	14	25	40	60	100	140	250	400	600	1.0	–	–	–
3 … 6	5	8	12	18	30	48	75	120	180	300	480	750	1.2	1.8	3.0	4.8
6 … 10	6	9	15	22	36	58	90	150	220	360	580	900	1.5	2.2	3.6	5.8
10 … 18	8	11	18	27	43	70	110	180	270	430	700	1100	1.8	2.7	4.3	7.0
18 … 30	9	13	21	33	52	84	130	210	330	520	840	1300	2.1	3.3	5.2	8.4
30 … 50	11	16	25	39	62	100	160	250	390	620	1000	1600	2.5	3.9	6.2	10.0
50… 80	13	19	30	46	74	120	190	300	460	740	1200	1900	3.0	4.6	7.4	12.0
80…120	15	22	35	54	87	140	220	350	540	870	1400	2200	3.5	5.4	8.7	14.0
120…180	18	25	40	63	100	160	250	400	630	1000	1600	2500	4.0	6.3	10.0	16.0
180…250	20	29	46	72	115	185	290	460	720	1150	1850	2900	4.6	7.2	11.5	18.5
250…315	23	35	52	81	130	210	320	520	810	1300	2100	3200	5.2	8.1	13.0	21.0
315…400	25	36	57	89	140	230	360	570	890	1400	2300	3600	5.7	8.9	14.0	23.0
400…500	27	40	63	97	155	250	400	630	970	1550	2500	4000	6.3	9.7	15.5	25.0

Note. Tolerance values for accuracy grades 18, 19 and 20 are determined from extrapolation method

Table A.3.2. Mean arithmetic deviation of profile R_a, ten-point height of profile irregularities R_z and maximum height of profile R_{max} according to the GOST 2789-73, μm

R_a	400	320	250	200	160	125	100	80	63	50	40	32	25
R_z, R_{max}	1600	1250	1000	800	630	500	400	320	250	200	160	125	100
R_a	20	16	12.5	10.0	8.0	6.3	5.0	4.0	3.2	2.5	2.0	1.6	1.25
R_z, R_{max}	80	63	50	40	32	25	20	16.0	12.5	10.0	8.0	6.3	5.0
R_a	1.00	0.8	0.63	0.50	0.4	0.32	0.25	0.20	0.160	0.125	0.100	0.080	0.063
R_z, R_{max}	4.0	3.2	2.5	2.0	1.60	1.25	1.00	0.8	0.63	0.50	0.40	0.32	0.25
R_a	0.050	0.040	0.032	0.025	0.020	0.016	0.012	0.010	0.008	–	–	–	–
R_z, R_{max}	0.20	0.160	0.125	0.100	0.080	0.063	0.050	0.040	0.032	0.025	–	–	–

Notes. 1. Parameter $\boldsymbol{R_a}$ is preferred relative to the parameters $\boldsymbol{R_z}$ and $\boldsymbol{R_{max}}$. 2. Preferred values of roughness parameters are shown in frames.

Appendix 4

Limit deviations for dimensions and surface roughness of die-forged blanks

Parting line of a forging die is usually selected in such a manner that it would coincide with the largest dimension of blank. Parting line should provide easy removal of blank from die and control of displacement of upper die relative to the lower die after trimming of forging. When forging in mechanical hammers, deeper cavities are located in upper dies.

Forging floodings are stated by GOST 7505-74 for rounding radii and drafts; for holes of diameters less than 30 mm; for cavities for holes' piercing.

Rounding radii are specified by GOST 7505-74 in the ranges of 1 to 8 mm and should be 0.5–1.0 mm more than machining allowance. Internal radii should be 3–4 times more than the external radii. Rounding radii should be unificated. When forging in closed dies, external radii in the die cavity are specified as $\boldsymbol{r} \geq 0.1\boldsymbol{h}$ ($\boldsymbol{h}$ – depth of mating cavity); internal radii in the die cavity $\boldsymbol{R} = (2.5–4)\boldsymbol{r}$. For making through holes the cavities with conical lateral walls are performed from two sides, sometime blind cavity is formed on one side of a forging.

Accuracy of dimensions of forgings of the 1^{st} (higher) accuracy class produced in various press-forging equipment is given in the Table A.4.1. Different accuracy classes are permissible for different dimensions of the same forging. Initial data for determination of deviations are group of steel M, mass $\boldsymbol{m_f}$ and complexity level C.

Table A.4.1. Deviations of forgings dimensions, mm (fragment)

Displacement	Flash, mm	Parting line		Complexity level		Mass, kg (above – – up to)	Group of steel		Complexity level				Dimensions, mm (above – up to)					
		Non-straight	Straight	C3, C4	C1, C2		M1	M2	C1	C2	C3	C4	Up to 50	50–120	120–180	180–260	260–360	360–500
0.3	0.3					Up to 0.25							+0.5 –0.2	+0.5 –0.3	+0.6 –0.3	+0.7 –0.3	+0.7 –0.4	+0.7 –0.5
0.3	0.3					0.25 – 0.40							+0.5 –0.3	+0.6 –0.3	+0.7 –0.3	+0.7 –0.4	+0.7 –0.5	+0.7 –0.6
0.3	0.4					0.40 – 0.63							+0.6 –0.3	+0.7 –0.3	+0.7 –0.4	+0.8 –0.4	+0.8 –0.5	+0.9 –0.6
0.4	0.5					0.63 – 1.00							+0.7 –0.3	+0.7 –0.4	+0.8 –0.4	+0.9 –0.4	+0.9 –0.5	+0.9 –0.6
0.4	0.5					1.00 – 1.60							+0.8 –0.4	+0.8 –0.4	+0.9 –0.4	+0.9 –0.5	+1.0 –0.5	+1.0 –0.6
0.4	0.6					1.60 – 2.50							+0.8 –0.4	+0.9 –0.4	+1.0 –0.4	+1.0 –0.5	+1.0 –0.6	+1.1 –0.7
0.5	0.8					2.50 – 4.00							+0.9 –0.4	+1.0 –0.4	+1.0 –0.5	+1.0 –0.6	+1.1 –0.7	+1.2 –0.8
0.6	1.0					4.00 – 6.30							+1.0 –0.4	+1.0 –0.5	+1.0 –0.6	+1.1 –0.7	+1.2 –0.8	+1.3 –0.9
0.7	1.2					6.30 – 10.0							+1.0 –0.5	+1.0 –0.6	+1.2 –0.6	+1.3 –0.7	+1.4 –0.8	+1.5 –1.0
0.8	1.5					10 – 16							+1.0 –0.6	+1.2 –0.6	+1.3 –0.7	+1.4 –0.8	+1.5 –1.0	+1.8 –1.0
0.9	1.7					16 – 25							+1.2 –0.6	+1.3 –0.7	+1.4 –0.8	+1.5 –1.0	+1.8 –1.0	+1.8 –1.2

When using Table A.4.1 it is necessary to take into account the following.

1. Carbon steel of M1 group contains up to 0.45 % carbon and up to 2 % alloying elements. Exceeding of even one of two conditions indicates group M2.

2. Deviations for internal surfaces of forgings (including holes) are to be specified with opposite signs.

3. There are four levels of forgings' complexity C1, C2, C3, C4 determined by the ratio $\boldsymbol{C} = \boldsymbol{m_f}/\boldsymbol{m_{sgb}}$, where $\boldsymbol{m_f}$ – mass of forging; $\boldsymbol{m_{sgb}}$ – mass of simple geometric body, in which the forging can be inserted. For forgings of group C1 the ratio $\boldsymbol{C}$ = 0.63–1.0; for forgings of group C2 the ratio $\boldsymbol{C}$ = 0.32–0.63; for forgings of group C3 the ratio $\boldsymbol{C}$ = 0.16–0.32; for forgings of group C4 the ratio $\boldsymbol{C} < 0.16$.

For determination of deviations in the column "Mass" select the corresponding line and, moving right-hand, in the column for required dimension of forging choose the determining deviations for forgings of M1 group of steels with complexity level C1. For forgings of M2 group of steels move down along inclined line and, moving in horizontal direction to the right-hand side to the required dimension, found the deviations for a forging of C1 complexity level. Analogous motions down by one, two and three lines are performed for forgings of C2, C3, C4 complexity levels along inclined lines located in the column "Complexity level". Permissible values of flash and displacement along parting line of die are determined in analogous manner, on the left-hand side from column "Mass" with motion along inclined line taking into account complexity level of forging and type of parting line.

Table A.4.2. Surface quality of forgings produced by metalworking

Mass of forging, kg (above – up to)	$\boldsymbol{R_z}$	$\boldsymbol{h}$
	micrometer	
Up to 0.25	80	150
0.25 … 4	160	200
4 … 25	200	250
25 … 40	250	300
40 … 100	320	350
100 … 200	400	400

Note. The $\boldsymbol{Rz}$ values are given after sand-blasting or pickling. After shot-blasting $\boldsymbol{Rz}$ is equal to 400 micrometers regardless of forging mass.

Appendix 5

Normative materials for cast blanks

Table A.5.1. Accuracy classes of dimensions and series of machining allowances for castings at various casting methods (GOST 26645-85)

Casting method	Largest overall dimension of casting, mm	Type of alloy		
		Non-ferrous with melting point up to 700 °C	**Non-ferrous** with melting point up to 700 °C, grey **cast iron**	Malleable, high-duty and alloyed **cast iron, steel**
		Accuracy classes of casting dimensions and series of allowances		
Die casting	Up to 100	$\frac{3\text{т}-5}{1}$	$\frac{3-6}{1}$	$\frac{4-7\text{т}}{1}$
	Above 100	$\frac{3-6}{1}$	$\frac{4-7\text{т}}{1-2}$	$\frac{5\text{т}-7}{1}$
Ceramic mould casting, investment and lost-foam casting	Up to 100	$\frac{3-6}{1}$	$\frac{4-7\text{т}}{1-2}$	$\frac{5\text{т}-7}{1-2}$
	Above 100	$\frac{4-7}{1-2}$	$\frac{5\text{т}-7}{1-2}$	$\frac{5-8}{1-2}$
Permanent mould and low-pressure casting without cores and with sand cores; sand moulds polymerised in contact with tooling	Up to 100	$\frac{4-9}{1-2}$	$\frac{5\text{т}-10}{1-3}$	$\frac{5-11\text{т}}{1-3}$
	100 ... 630	$\frac{5\text{т}-10}{1-3}$	$\frac{5\text{т}-11}{1-3}$	$\frac{6-11}{2-4}$
Permanent mould and low-pressure casting without cores and with sand cores; sand moulds polymerised in contact with tooling	Up to 630	$\frac{6-11}{2-4}$	$\frac{7\text{т}-12}{2-4}$	$\frac{7-13\text{т}}{2-5}$

Note. Nominators show accuracy classes, denominators – series of allowances. The smaller values are related to simple cast shapes and conditions of mass automated production, the mean – to castings of middle complexity under conditions of mechanized batch production, the large values – to the complicated castings of intricate shapes under small-batch and individual production conditions

Table A.5.2. Tolerances for casting dimensions, mm

Intervals of nominal dimensions (above – – up to)	Tolerances for accuracy classes of casting dimensions															
	3т	3	4	5т	5	6	7т	7	8	9т	9	10	11т	11	12	13т
up to 4	0.10	0.12	0.16	0.20	0.24	0.32	0.40	0.50	0.64	0.8	1.0	1.2	1.6	2.0	–	–
4 … 6	0.11	0.14	0.18	0.22	0.28	0.36	0.44	0.56	0.70	0.9	1.1	1.4	1.8	2.2	2.8	–
6 ... 10	0.12	0.16	0.20	0.24	0.32	0.40	0.50	0.64	0.80	1.0	1.2	1.6	2.0	2.4	3.2	4.0
10 … 16	0.14	0.18	0.22	0.28	0.36	0.44	0.56	0.70	0.90	1.1	1.4	1.8	2.2	2.8	3.6	4.4
16 … 25	0.16	0.20	0.24	0.32	0.40	0.50	0.64	0.80	1.00	1.2	1.6	2.0	2.4	3.2	4.0	5.0
25 … 40	0.18	0.22	0.28	0.36	0.44	0.56	0.70	0.90	1.10	1.4	1.8	2.2	2.8	3.6	4.4	5.6
40 … 63	0.20	0.24	0.32	0.40	0.50	0.64	0.80	1.00	1.20	1.6	2.0	2.4	3.2	4.0	5.0	6.4
63…100	0.22	0.28	0.36	0.44	0.56	0.70	0.90	1.10	1.40	1.8	2.2	2.8	3.6	4.4	5.6	7.0
100…160	0.24	0.32	0.40	0.50	0.64	0.80	1.00	1.20	1.60	2.0	2.4	3.2	4.0	5.0	6.4	8.0
160…250	0.28	0.36	0.44	0.56	0.70	0.90	1.10	1.40	1.80	22	2.8	3.6	4.4	5.6	7.0	9.0
250…400	0.32	0.40	0.50	0.64	0.80	1.00	1.20	1.60	2.00	2.4	3.2	4.0	5.0	6.4	8.0	10.0
400…630	–	–	0.56	0.70	0.90	1.10	1.40	1.80	2.20	2.8	3.6	4.4	5.6	7.0	9.0	11.0

Note. Deviations for casting dimensions are usually assigned symmetrically ±T/2.

Table A.5.3. Surface quality of castings produced by various methods [10]

Casting method		$\boldsymbol{R_z} + \boldsymbol{h}$, μm	$\boldsymbol{R_z}$, μm
Sand mould casting with hand hammering around wood patterns	Cast iron	600	–
	Steel	500	–
	Non-ferrous metals	400	–
Permanent mould casting		–	200
Centrifugal casting		–	200
Shell-mould casting		–	40
Investment casting		–	32

Note. For technological calculations the components $\boldsymbol{R_z}$ and $\boldsymbol{h}$ can be determined approximately from the assumption $\boldsymbol{h} \approx (1,0...2,0)\boldsymbol{R_z}$.

Appendix 6

Normative materials for initial blanks from rolled products

Table A.6.1. Diameter deviations for round hot-rolled steel bars (GOST 2590–71)

Diameter, mm	Limit deviations, mm, per diameter at rolling accuracy					
	high		improved		normal	
	+	–	+	–	+	–
5; 5.5; 6; 6.3; 6.5; 7…9	0.1	0.2	0.2	0.5	0.3	0.5
10…19	0.1	0.3	0.2	0.5	0.3	0.5
20…25	0.2	0.3	0.2	0.5	0.4	0.5
26…48	0.2	0.5	0.2	0.7	0.4	0.7
50; 52…58	0.2	0.8	0.2	1	0.4	1
60; 62; 63; 65; 67; 68; 70; 72; 75; 78	0.3	0.9	0.3	1.1	0.5	1.1
80; 82; 85; 90; 95	0.3	1.1	0.3	1.3	0.5	1.3
100; 105; 110; 115	–	–	0.4	1.7	0.6	1.7
120; 125; 130; 135; 140; 150	–	–	0.6	2.0	0.8	2.0
160; 170; 180; 190; 200	–	–	–	–	0.9	2.5
210; 220; 230; 240; 250	–	–	–	–	1.2	3

Note. Curvature of a bar should not exceed 0.5 % length; by a customer's order bars should be supplied with a curvature not more than 0.2 % length.

Table A.6.2. Surface roughness of rolled sections, micrometer

Diameter of rolled section, mm (above – up to)	Rolling accuracy					
	high		improved		normal	
	R_z	h	R_z	h	R_z	h
Up to 30	63	50	80	100	125	150
30 … 80	100	75	125	150	160	250
80 … 180	125	100	160	200	200	300
180 … 250	200	200	250	300	320	400

Table A.6.3. Accuracy and surface roughness of blanks after rolled sections cutting-off

Cutting-off method	Accuracy grade	$R_z + h$, μm
In shears	17	300
By power hack-saws, disk milling cutters in milling machines	14	200
By cutting-off tools in turning machines	13	200
Parting in presses	17	R_z = 150 ... 300 h = 1000 ... 1600

Notes. 1. For technological calculations the components R_z and h can be determined approximately from the assumption $h \approx (1{,}0...2{,}0)R_z$. 2. Deviations for cutting-off operations are usually assigned symmetrically ± ITn/2.

Appendix 7

Recommendations for selection of machining routes for various surfaces based on economical principle

Table A.7.1. Economical accuracy and roughness of external cylindrical surfaces at various machining routes

Step No.	Surface machining route	Accuracy grade	Roughness
1	Turning	12	R_a = 10÷5
1 2	Rough turning Finish turning	11–10	R_a = 5÷2.5
1 2	Turning Grinding	10–9	R_a = 2.5÷0.63
1 2 3	Rough turning Finish turning Grinding	9–7	R_a = 1.25÷0.63
1 2 3	Rough turning Finish turning Fine grinding	8–7	R_a = 0.63÷0.32
1 2 3	Turning Preliminary grinding Finish grinding	8–6	R_a = 0.63÷0.32
1 2 3 4	Rough turning Finish turning Preliminary grinding Finish grinding	6	R_a = 0.63÷0.32

Table A.7.1, continued

Step No.	Surface machining route	Accuracy grade	Roughness
1 2 3 4	Rough turning Finish turning Preliminary grinding Fine grinding	7–5	R_a = 0.32÷0.16
1 2 3 4 5	Rough turning Finish turning Preliminary grinding Finish grinding Fine grinding	5	R_a = 0.32÷0.08

Table A.7.2. Economical accuracy and roughness of internal cylindrical surfaces at various machining routes

Machining route	Accuracy grade	Roughness
In solid material		
Drilling	12	R_a = 40÷20
Drilling and core drilling	11	R_a = 10÷2.5
Drilling and reaming	9	R_a = 5÷1.25
Drilling and broaching	9	R_a = 2.5÷0.32
Drilling, core drilling and reaming	9	R_a = 2.5÷0.63
Drilling and double reaming	8–7	R_a = 2.5÷0.32
Drilling, core drilling and double reaming	8–7	R_a = 1.25÷0.32
Drilling, core drilling and grinding	8–7	R_a = 1.25÷0.32
Drilling, broaching and sizing	8–7	R_a = 1.25÷0.32
In blanks with hole		
Core drilling or boring	12	R_a = 10÷2.5
Drilling-out	12	R_a = 40÷5
Double core drilling or double boring	11	R_a = 20÷5
Core drilling or boring and reaming	9	R_a = 5÷1.25
Core drilling and boring	9	R_a = 10÷2.5

Table A.7.2, continued

Machining route	Accuracy grade	Roughness
Double core drilling and reaming or double boring and reaming	9	R_a = 2.5÷0.63
Core drilling or boring and double reaming	8–7	R_a = 1.25÷0.32
Core drilling or double boring and double reaming or fine boring	8–7	R_a = 1.25÷0.15
Progressive-type broaching and grinding	8–7	R_a = 1.25÷0.15
Core drilling or double boring and honing	8–7	R_a = 0.32÷0.04
Core drilling or boring, fine boring and honing	8–7	R_a = 0.16÷0.02

Table A.7.3. Economical accuracy and roughness of flat surfaces at various machining routes

Machining route	Accuracy grade	Roughness
Planing and milling by cylindrical and face cutters: - rough - semi-finish and single - finish - fine-finish	 14–11 12–11 10 9–7	 R_a = 20÷1.25 R_a = 5÷1.25 R_a = 2.5÷0.63 R_a = 2.5÷0.15
Broaching: - rough of cast and forged surfaces - finish	 11–10 9–7	 R_a = 5÷0.63 R_a = 2.5÷0.32
Grinding: - single - preliminary - finish - fine-finish	 9–8 9 8 7	 R_a = 2.5÷0.15 R_a = 2.5÷0.32 R_a = 0.63÷0.08 R_a = 0.32÷0.04

Notes:

1. The data are referred to machining of rigid workpieces with overall dimensions not more than 1 m at locating on a finish-machined surface and using it as a measuring datum.
2. Under the similar conditions the accuracy of machining by face milling cutters is approximately one accuracy grade higher than by the cylindrical cutters.
3. Fine-finish milling is produced only by face milling cutters.

Table A.7.4. Economical accuracy and roughness of threaded surfaces machining

Machining method	Tolerance band for		Roughness
	external thread	internal thread	
Solid threading dies	8g	–	R_a = 20÷5
Taps	–	6H	R_a = 10÷2.5
Milling by: - disk cutters - chaser cutters	 6g 6g	 – –	 R_a = 10÷1.25 R_a = 10÷2.5
Turning by: - single-point cutting tools - chasers	 4h 6g	 4H, 5H –	 R_a = 5÷0.63 R_a = 10÷0.63
Rotating single-point cutting tools	6g	6H	R_a = 5÷1.25
Self-opening threading die heads	4h	–	R_a = 10÷1.25
Rolling by: - flat dies - threading rolls	 6g 6g÷4g	 – –	 R_a = 1.25÷0.32 R_a = 1.25÷0.16

Table A.7.5. Economical accuracy and roughness of gear wheel teeth

Machining method	Accuracy degree	Roughness
Milling: - preliminary - finish by disk milling cutter - finish by hob	 9–10 8–9 7–8	 R_a = 20÷2.5 R_a = 10÷5 R_a = 10÷5
Finish shaping	6–8	R_a = 5÷0.63
Broaching	6–7	R_a = 5÷0.63
Finish planing	5–7	R_a = 5÷0.63
Shaving	6–7	R_a = 2.5÷0.32
Grinding	4–5	R_a = 1.25÷0.15

Appendix 8

Typical routes for production of gear wheels from steels

Gear wheels from carbonised steels

1. Heat treatment of initial blank – normalisation.
2. *Rough-machining stage*: cross turning of a face and a hole boring, cross turning of another face and turning of outside surfaces.
3. *Finish-machining stage*: cross turning of a face and a hole boring, finish boring or grinding of hole and datum face at one mounting, grinding of another face, turning of outside surfaces, wheel hub and rim along inner surfaces, machining of light-weight holes and recesses, gear teeth machining and their deburring.
4. Copper plating of surfaces not subjected to carbonisation.
5. Carbonisation, quench hardening and tempering.
6. *Fine-finish machining stage*: grinding of hole or surface of stem, fine-finish turning of surfaces for splines or thread, machining of splines, machining of thread, gear teeth grinding, workbench deburring.
7. Final inspection.

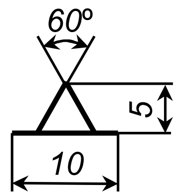
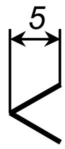
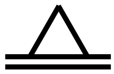
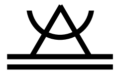
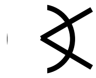
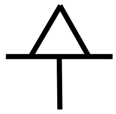
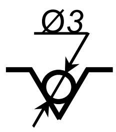
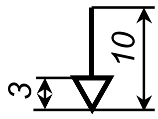
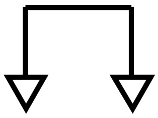
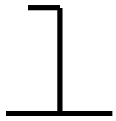
Sometime low-temperature tempering with aim to reduce residual stresses appeared at machining is applied before final inspection.

Gear wheels from nitrated steels

1. Heat treatment – normalisation.
2. *Rough-machining stage*: cross turning of a face and a hole boring, cross turning of another face and turning of outside surfaces
3. Heat treatment – quench hardening and tempering.
4. *Finish-machining stage*: cross turning of a face and a hole boring, finish boring or grinding of hole and datum face at one mounting, grinding of another face, turning of outside surfaces, wheel hub and rim along inner surfaces, machining of light-weight holes and recesses, gear teeth machining and their deburring.
5. Heat treatment – stabilisation tempering.
6. Machining before nitriding: grinding of datum cylindrical surfaces and datum face, preliminary grinding (or shaving) of teeth with providing an allowance for final grinding, tinning of surfaces, which are not to be nitrated.
7. Nitriding.
8. *Fine-finish machining stage*: grinding of hole or surface of stem, fine-finish turning of surfaces for splines or thread, machining of splines, machining of thread, gear teeth grinding, workbench deburring.
9. Final inspection.

The best results are obtained at isothermal nitriding at temperature of 520-540°C and soaking during 35-40 hours.

Symbols for rests, clamping and mounting devices by the GOST 3.1107-81

Name of element	Graphic symbol	Name of element	Graphic symbol
Rests		***Mounting devices***	
Steady		Dead centre	
Movable		Live centre	
Floating		Floating centre	
Adjustable		Cylindrical mandrel	
Clamping elements		Ball mandrel	
Single			
Double		Drive chuck	

Clamping devices

P – pneumatic, H – hydraulic, E – electric, M – magnetic, EM – electromagnetic.

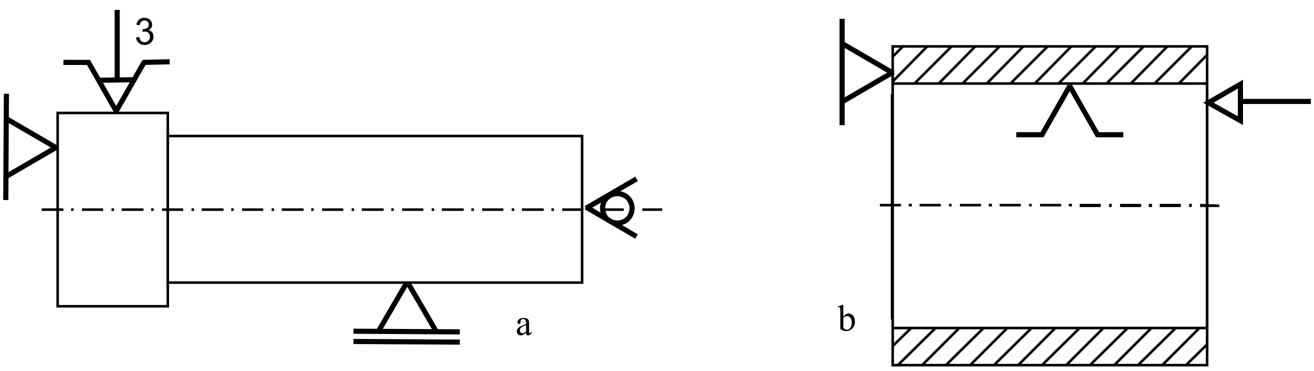


Fig. A.9.1. Examples of mounting diagrams for workpieces in work zone of machine: a – in three-jaw chuck with mechanical clamping with steady rest on face with support by live centre and follow rest; b – on cylindrical mandrel with steady rest and clamping on face

Appendix 10

Minimum operation allowances

Allowances for rough turning and boring, rough milling and planing of blanks produced by hot forging and casting should be specified depending on maximal overall dimension of a blank.

Allowances for rough turning of blanks produced by rolling, as well as for finish turning, boring and grinding, should be specified depending on diameter of work surface and calculated length.

For determination of calculated length use Table A.10.1.

Minimum operation allowances for main types of machining are submitted in the Tables A.10.2 – A.10.13.

Table A.10.1. Calculated length for specifying allowance for rough turning of rolled products, finish turning and grinding of **shafts**

Type of workpiece mounting at machining	Calculated length	
	For middle segments	For end segments of shaft
In centres or in chuck with support of tailstock centre	Full length of shaft	Length is equal to double maximal distance from shaft butt to the work surface of end segment
In chuck without support of tailstock centre	Length is equal to the double maximal distance from the work surface of segment to chuck's jaws	

Table A.10.2. Minimum allowances for **rough turning** and **boring** of workpieces produced by **hot forging** from rolled sections, mm

Workpiece diameter, mm	Rough turning and boring of hot-forged workpieces from steels and titanium alloys				Rough turning of workpieces from ferrous rolled sections of normal accuracy			
	Allowance $2Z_{min}$ per diameter at the length of, mm							
	up to 120	120 – – 260	260 – – 500	500 – – 800	up to 120	120 – – 260	260 – – 500	500 – – 800
Up to 50	1.7	2.0	2.4	2.8	1.3	1.5	2.0	2.5
50 – 120	2.0	2.2	2.6	2.9	1.5	1.8	2.2	2.6
120 – 260	2.2	2.4	2.7	3.0	1.8	2.2	2.4	2.8
260 – 500	2.5	2.7	2.8	3.1	–	–	–	–

***Notes*.**
1. Values of allowances should be multiplied by 0.8 for forgings from aluminium, magnesium and copper alloys.
2. Machining allowance for a forging surface is specified depend on its maximum overall dimension (diameter or length).
3. Values of allowances should be multiplied by 0.8 for ferrous rolled products of improved accuracy.
4. For determination of calculated length for ferrous rolled products see Table A.10.1.

Table A.10.3. Minimum allowances for **rough turning** and **boring** of round surfaces of **castings**, mm

Maximal overall dimension of casting, mm	Sand casting	Permanent-mould and shell-mould casting
	Allowance $2Z_{min}$ per diameter, mm	
Up to 50	2.2	1.4
50 – 120	2.6	1.6
120 – 260	3.3	1.8
260 – 500	4.1	2.0

***Note*.** Machining allowances for all surfaces of a casting are specified depend on its maximal overall dimension (diameter or length).

Table A.10.4. Minimum allowances for **finish turning** after rough turning or of calibrated rolled products, mm

Diameter, mm	**Finish turning after rough turning**					Finish turning after rough turning and heat treatment. Finish turning of calibrated rolled products				
	Allowance $2Z_{min}$ per diameter at the calculated length of, mm									
	Up to 120	120 – – 260	260 – – 500	500 – – 800	800 – – 1250	Up to 120	120 – – 260	260 – – 500	500 – – 800	800 – – 1250
Up to 50	0.5	0.6	0.8	1.0	–	0.8	1.0	1.2	1.4	–
50 – 120	0.6	0.7	0.9	1.1	1.3	0.85	1.1	1.2	1.5	1.8
120 – 500	0.7	0.8	1.0	1.2	1.4	0.9	1.1	1.3	1.6	1.9

***Note*.** For determination of calculated length see Table A.10.1.

Table A.10.5. Minimum allowances for **external grinding** of workpieces (in centres and centreless)

Diameter, mm	Workpieces without heat treatment					Heat-treated workpieces				
	Allowance $2Z_{min}$ per diameter at length of, mm									
	Up to 120	120 – – 260	260 – – 500	500 – – 800	800 – – 1250	Up to 120	120 – – 260	260 – – 500	500 – – 800	800 – – 1250
Up to 18	0.15	0.18	0.25	–	–	0.18	0.22	0.30	–	–
18 – 50	0.18	0.22	0.28	0.35	–	0.20	0.28	0.35	0.5	–
50 – 120	0.20	0.25	0.30	0.4	0.5	0.25	0.35	0.40	0.55	0.7
120 – 500	0.25	0.30	0.35	0.45	0.6	0.3	0.4	0.50	0.65	0.8

Notes:

1. When specifying allowances the heat-treated workpieces are considered those subjected to heat treatment after finish turning before grinding.
2. If grinding is performed in two operations, but in one stage of manufacturing process, then for preliminary grinding 2/3 allowance is specified, and for final grinding – 1/3 allowance.
3. If grinding operations are performed at different stages of manufacturing process (preliminary grinding before heat treatment, final grinding after heat treatment), then allowances for each operation are specified separately, independently.
4. For determination of length value see Table A.10.1.

Table A.10.6. Minimum allowances for **finish boring**, core drilling and reaming of **holes**

Hole diameter, mm	Finish boring, core drilling	Reaming
	Allowance $2Z_{min}$ per diameter, mm	
Up to 10	–	0.12
10 – 30	0.5	0.16
30 – 50	0.6	0.20
50 – 120	0.9	–
120 – 500	1.2	–

Note. If reaming is performed in two operations or steps, then for preliminary reaming 2/3 allowance is specified, and for final reaming – 1/3 allowance.

Table A.10.7. Minimum allowances for **finish grinding** of **holes** after finish boring

Hole diameter, mm	For workpieces without heat treatment of all shapes and for heat-treated rigid (thick-walled) workpieces	For heat-treated non-rigid (thin-walled) workpieces
	Allowance $2\boldsymbol{Z_{min}}$ per diameter, mm	
Up to 30	0.20	0.25
30 – 120	0.25	0.35
120 – 260	0.35	0.50
260 – 500	0.40	0.70

Notes:
1. When specifying allowances the heat-treated workpieces are considered those subjected to heat treatment after finish boring before grinding.
2. If grinding is performed in two operations, but in one stage of manufacturing process, then for preliminary grinding 2/3 allowance is specified, and for final grinding – 1/3 allowance.
3. If grinding operations are performed at different stages of manufacturing process (preliminary grinding before heat treatment, final grinding after heat treatment), then allowances for each operation are specified separately, independently.
4. The data given in this table is used for determination of allowances for grinding of holes in the part types of shafts, cylinders, bushings, etc. For grinding of holes in body-type and eccentric parts the allowance is calculated with application of dimension chains.
5. It is not recommended to use the table data for specifying the allowances for grinding of holes after heat-treatment hardening operations (carbonisation with quenching, cyanidation, nitration), when it is necessary to provide the specified depth of hardened layer.

Table A.10.8. Minimum allowances for **broaching** of holes

Hole diameter, mm	For holes after finish boring, core drilling according to 8–11 accuracy grades	For holes after drilling, rough boring according to 12–13 accuracy grades
	Allowance $2\boldsymbol{Z_{min}}$ per diameter, mm	
Up to 30	0.35	0.45
30 – 50	0.40	0.55
50 – 80	0.50	0.70

Note. The table contains allowances for broaching of holes with length-to-diameter ratio $\boldsymbol{l/d} < 1.5$.

Table A.10.9. Minimum allowances for **fine** (diamond) **boring** of **holes**

Hole diameter, mm	Preliminary fine boring, single boring according to 8 accuracy grade				Final fine boring, all materials
	Light alloys	Babbitt	Bronze and cast iron	Steel	
	Allowance $2Z_{min}$ per diameter, mm				
Up to 50	0.2	0.25	0.15	0.12	0.05
Above 50 up to 500	0.3	0.35	0.25	0.15	0.08

Note. The values of allowances for final boring are given for the case, when final boring is performed after preliminary one at the same mounting.

Table A.10.10. Minimum allowances for **rough facing**, milling and planing

Maximal overall dimension of workpiece, mm	Rough facing, milling and planing of workpieces			
	from steel produced by hot forging	from non-ferrous and titanium alloys produced by hot forging	produced by sand casting	produced by permanent-mould and shell-mould casting
	Allowance Z_{min} per side, mm			
Up to 30	0.9	0.7		
30 – 120	1.0	0.8		
120 – 260	1.2	0.9		
260 – 500	1.5	1.1		

Table A.10.11. Minimum allowances for **finish facing**, finish milling of planes

Overall dimension, face diameter or plane length, mm	Allowance Z_{min} per side, mm
Up to 30	0.30
30 – 120	0.40
120 – 260	0.55
260 – 500	0.70

Note. Allowance value Z_{min} is determined independently of value of specified dimension (shaft length or thickness-height of body-type part).

Table A.10.12. Minimum allowances for **grinding** and fine milling of **faces** and planes after finish turning and milling

Overall dimension: face diameter or plane length, mm	1st variant	2nd variant	3rd variant		4th variant	
	Single grinding and fine milling of workpieces without heat treatment	Single grinding of heat-treated workpieces	Preliminary grinding before heat treatment	Final grinding after heat treatment	Grinding after heat treatment	
					Preliminary	Final
	Allowance Z_{min} per side, mm					
Up to 30	0.10	0.15	0.10	0.07	0.10	0.05
30 – 120	0.15	0.20	0.15	0.15	0.15	0.07
120 – 260	0.20	0.30	0.20	0.25	0.20	0.1
260 – 500	0.30	0.45	0.30	0.35	0.30	0.15

Note. Allowance value Z_{min} is determined independently of value of specified dimension (shaft length or thickness-height of body-type part).

Table A.10.13. Minimum allowances for machining of spurs (straight-toothed gears)

Module, mm	Finish hobbing, shaping, planing	Grinding	Shaving
	Allowance Z_{min} per tooth thickness, mm		
Up to 2	0.25	0.2	0.05
2 – 3	0.4	0.25	0.07
3 – 5	0.5	0.3	0.10
5 – 7	0.6	0.35	0.12
7 – 10	0.7	0.4	0.15

Note. When selecting allowance values one should take into account possible deformations and their character (constriction, expansion, warping) during heat treatment depend on steel grade, shape of spur and number of teeth.

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Content

Навчальне видання

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ПРОЕКТУВАННЯ ТЕХНОЛОГІЧНИХ ПРОЦЕСІВ МЕХАНІЧНОЇ ОБРОБКИ. РОЗРАХУНКИ ОПЕРАЦІЙНИХ РОЗМІРІВ

(Англійською мовою)

Редактор В. А. Булавіна

Технічний редактор Л. О. Кузьменко

Зв. план, 2016
Підписано до друку 04.03.2016
Формат 60×84 1/16. Папір офс. № 2. Офс. друк
Ум. друк. арк. 8. Обл.-вид. арк. 9. Наклад 100 пр. Замовлення 66. Ціна вільна

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Свідоцтво про внесення суб’єкта видавничої справи
до Державного реєстру видавців, виготовлювачів і розповсюджувачів
видавничої продукції сер. ДК № 391 від 30.03.2001