I. M. Taranenko, T. A. Kupriyanova

ELECTROTECHNICAL MATERIALS

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MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE
Zhukovsky National Aerospace University
«Kharkiv Aviation Institute»

I. M. Taranenko, T. A. Kupriyanova

ELECTROTECHNICAL MATERIALS

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Запропоновано узагальнений підхід до вивчення властивостей напівпровідникових, провідникових, діелектричних і магнітних матеріалів, методів їх випробувань і основних шляхів керування їхніми властивостями. Подано опис технологій виготовлення матеріалів і конструкцій електротехнічного призначення. Наведено основні механічні, фізико-хімічні, електричні, магнітні, технологічні й експлуатаційні властивості електротехнічних матеріалів.

Для студентів вузів, що вивчають курс електротехнічних матеріалів.

Reviewer: doctor of eng. Science prof. A.A. Plugin,
Ph. D., ass. Prof. O.O. Chuprynin

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Generalized approach to studying properties of semi-conductive, conductive, dielectric and magnetic materials, methods of their testing and main methods of properties governing is suggested. Description of technologies for mentioned materials and structures manufacturing is considered. Basic mechanical, physical-chemical, electrical, magnetic, technological and operational properties are shown.

For students of universities studying electrotechnical materials.

Figs. 22. Table 4. Bibliogr.: 14 sources

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CONTENTS

INTRODUCTION

The science of Material Engineering that includes Electrotechnical Material Engineering too is the system of knowledge about physical-chemical nature, properties, methods of manufacturing and studying of different materials. Success of both theoretical and applied Material Engineering has led to make a step from application of conventional materials to fully new ones with predefined properties.

In different branches of electrotechnical engineering variety of electrotechnical, structural and materials for special application are used. Electrotechnical materials possess definite properties related to their response to electrostatic or electromagnetic field. Structural materials are developed for auxiliary articles and elements of electrical engineering: cases, landing gears, control surfaces and other load-bearing elements. Materials for special application have definite special properties and developed for operation at particular conditions.

Materials used in aerospace engineering besides electrotechnical, mechanical and special properties have to be relatively light. Because taking-off weight of any aerospace vehicle depends on weight of empty structure, fuel, equipment etc. Each auxiliary kilogram of equipment (avionics) leads to increasing of aircraft up to 5 kg and spacecraft – up to 40 kg.

One of the up-to-date branch of electrotechnical engineering is microelectronics. Developing of this branch requires design and manufacturing of very complicated cybernetic systems, increasing durability and life-time of electronic device used in aerospace engineering, biology, medicine. To solve mentioned questions such new electronic elements as semi-conductors, active dielectrics, ferrites, integral schemes based on thin films principles have to be created. Moreover minimization of energetic process in electronic schemes and more functional controlling of material properties are very actual.

The process of novel material creation stimulates appearing of new technical ideas and approaches. From the history of engineering it is known that exactly developing of materials has become final successful chain in multiple engineer solutions at creation of complicated electronic devices.

In accordance with explanatory dictionary the word “**material**” means a substance used for manufacturing of semi-finished articles, articles and ready products. Practically one can consider as a material everything can be converted from animal, plant or mineral raw-materials to organize and support different manufacturing processes.

The history of materials developing relates tightly with the history of humans, the ages of humans growth are called after main materials used: stone, copper etc.

Originally only **natural** material was used it state “as it is”. Further man has started to process materials, combine them between each other creating **artificial** materials. Next step was devoted to invention of **synthetic** materials, i.e. materials created from the raw materials absent in real nature (for example synthetic rubber).

Besides above-mentioned materials division engineers consider following classification of materials:

a) by chemical composition:

– organic – compounds of carbon with hydrogen, oxygen, nitrogen, halogens etc;

– non-organic – contain silicon, oxygen, metals;

– silicon-organic – have a micro-skeleton from atoms of silicon and oxygen bonded consequently to each other and with organic radical;

– element-organic – consist of atoms of elements presented both in arganic and in non-organic materials;

b) by structure (internal arrangement):

– amorphous;

– crystalline (mono- and polycrystalline);

– combined (having both crystalline and amorphous phases);

c) by nature (or chemical composition): metal and non-metal.

Metal materials are divided by ferrous (alloys of iron) and non-ferrous (alloys light metals, low- and high melting metals, noble metals).

Non-metal materials group includes organic materials (polymeric resins, fibrous materials, rubber, varnishes, adhesives etc.), non-organic materials (glasses, sitals, ceramics, mica etc) and semi-conductors.

d) by behavior in electric field: conductors, semi-conductors, dielectrics.

e) by behavior in magnetic field:

– non-magnetic (diamagnetics) or low-magnetic (paramagnetics);

– magnetic.

In accordance with required operational conditions following **requirements** have to be satisfied at materials selection and creation:

1. Materials have to possess high level of functional properties defining material destination. For example at cable manufacturing selected for insulation dielectric has to have high specific resistance; at design of capacitor dielectric has to have high relative dielectric permeability.

2. Properties of materials should be stable at influence of different operational factors: temperature, humidity, field frequency and intensity, chemical substances, irradiation, mechanical loads etc.

3. Materials have to be manufacturable, i.e. cheap and allowable in manufacturing, technology has to be up-to-date, low resource-consuming, repeatable, wasteless, short-term and automizable.

The most critical requirement is lowest cost of materials because its cost takes up to 60% of the cost of total object.

Auxiliary requirements are demanded to materials of aerospace engineering:

a) operation in wide range of temperatures from -200 up to 1500°C;

b) ability to withstand overloading up to 10 g;

c) high specific strength and modulus.

Theme 1. MATERIALS PROPERTIES AND METHODS OF THEIR DETERMI4.NATION

Main properties of materials are mechanical, thermal, physical-chemical, technological and operational.

1.1. Mechanical properties

Mechanical properties characterize materials ability to resist of external loads action. Applied external loads can be **static** (constant and applied for a long period), **dynamic** (applied for relatively short period) and **alternative** (changing sign, absolute value and direction periodically).

Mechanical properties of materials are defined in accordance with state standards by results of experimental testing on standard specimens. Depending on method of loads application all test can be divided into three groups:

– static - tests on tension, compression, bending, torsion, hardness;

– dynamic – impact toughness, wear;

– cyclic – fatigue test.

Loads applied to a specimen cause in it stress σ and strain ε. **Stress** (MPa) is a ratio of applied force P to specimen cross-section F. Absolute deformation Δl is changing of specimen shape and cross-section under influence of applied loads or due to physical-mechanical processes happened in specimen (phase transformations, shrinkage, expansion etc.). **Strain** (relative deformation) is a ratio of absolute specimen deformation Δl to its original length l_0:

$$\varepsilon = \frac{\Delta l}{l_0} = \frac{l_i - l_0}{l_0}. \tag{1.1}$$

Deformations of compression, tension, torsion, shear, bending are considered. Deformations can be **elastic** or reversible (disappearing after external loads removing) and **plastic** (irreversible after external loads removing). At continuous loading of a specimen elastic deformation transfers to plastic one with consequent specimen failure.

Main mechanical properties of materials are: strength, elasticity, ductility, impact toughness, hardness and durability.

Tension strength, elasticity and ductility are defined by means of standard specimens at static testing. Standard specimens have definite dimensions with geometrically similar shapes (flat or cylindrical). The length of operational zone l_0 of cylindrical specimen has to be 5 or 10 times more than specimen diameter. For flat specimens the dependence between operational length and cross-sectional area F_0 is $l_0 = 5.65\sqrt{F_0}$ or $l_0 = 11.3\sqrt{F_0}$. Testing is conducted by universal tearing machines equipped with self-writing devices permitting to draw dependence between applied load P and specimen elongation Δl (Fig. 1.1).

Mechanical properties of specimen material is characterize by specific points on the diagram:

P – **proportional limit**;

1 – **elasticity limit**;

S – **yielding point** $\sigma_s = P_s / F_0$. Phenomenon of yielding is significant specimen elongation without visible load increasing (for ductile materials). Brittle materials have no yielding and their behavior is characterizes by **off-set yielding point**. Position of off-set yielding point corresponds to load P_s at which residual specimen elongation is equal to $0.002l_0$.

B – **ultimate strength** or **margin of strength**;

K – moment of specimen failure. Correspondent stress is call as true failure stress $\sigma_K = P_K / F_f$, where F_f is specimen cross-section at failure.

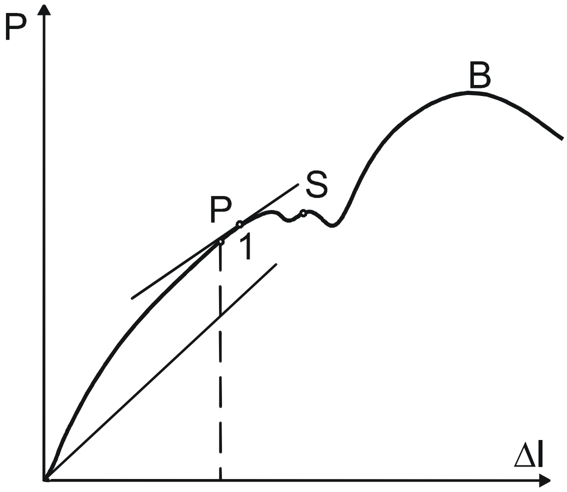


Fig. 1.1. Tension diagram

Strength is ability of a material to resist application of external loads without failure. Strength at tension σ_b, strength at compression σ_c, strength at bending (or flexural strength) σ_{bend} are characterized by ultimate values, i.e. stress which corresponds to specimen failure

$$\sigma_b^{tens} = \frac{P_b^{tens}}{F_0}; \tag{1.2}$$

$$\sigma_b^{comp} = \frac{P_b^{comp}}{F_0}; \tag{1.3}$$

$$\sigma_b^{bend} = 1.5\frac{l \cdot P_b^{bend}}{bh^2}, \tag{1.4}$$

where P_b^{tens}, P_b^{comp}, P_b^{bend} – failure loads at tension, compression, bending, N; F_0 – specimen cross-section , m^2; b, h – width and thickness of specimen, m; l – distance between supports of testing machine.

Majority of metals are **isotropic**, i.e. possess the same properties in different directions but such materials like dielectrics, glasses, ceramics, composites are **anisotropic**, i.e. have different properties in different directions. For example quartz glass has σ_b^{tens}=50 MPa, σ_b^{comp}=200 MPa.

Elasticity is ability of material to restore original shape and dimensions after external load removing. Numerically can be characterized by proportional limit σ_p and elasticity limit σ_{el}.

Proportional limit $\sigma_p = P_P / F_0$ is maximum stress for which linear dependence between applied force and specimen elongation is valid.

Elasticity limit $\sigma_{el} = P_1 / F_0$ is maximum stress above which residual deformation can be observed.

Ductility is ability of material to be deform without failure under mechanical load and keep given shape after external load removing. Numerically can be characterized by relative elongation

$$\varepsilon = \frac{l_f - l_0}{l_0} \cdot 100\ \% \tag{1.5}$$

and by reduction in area

$$\psi = \frac{F_0 - F_f}{F_0} \cdot 100\ \%, \tag{1.6}$$

where l_0 – original length; l_0 – length after failure; F_0 – original cross-section area; F_f – cross-section area after failure.

With respect to impact loads **ductile** and **brittle** materials can be considered. **Brittle materials** can be destroyed easily with dynamic loads but can withstand quite high static ones. Their plastic deformation is close to zero so they fail at $\sigma_b = \sigma_{yield}$, also ε, ψ are close to zero. Brittle materials are glass, ceramics, porcelain, chromium, manganese, cobalt, tungsten etc.

Ductility is ability of material to resist dynamic loads. Numerically brittleness and ductility can be estimated by **impact toughness** value. Impact toughness is a ratio of work A of impact load directed to specimen failure to its cross-section F

$$a = A / F. \tag{1.7}$$

The work is equal to the difference between potential energy of a weight before and after impact to specimen. Testing on impact toughness is conducted by means of pendulum machine. The weight of pendulum is P. For testing of brittle materials unnotched specimens are used, for ductile – specimens with notch, having definite shape. The work of pendulum A is equal to $P(h_2 - h_1)$, where h_2 is original pendulum position by height, h_1 - is position of pendulum after impact and specimen failure. Impact toughness of materials varies in wide range and is more for ductile materials: for duralumin D16 a=2 MJ/m^2, for polyethylene and fluoride plastic-4 is near 100 kJ/m^2, for ceramics – 4 kJ/m^2, for glass – 1 kJ/m^2.

For liquid and semi-liquid materials the term “viscosity” is the main operational and technological parameter. **Viscosity** defines property of a material to resist moving of a one part of substance refer another.

Ability of a material to withstand influence of cyclic (or alternative) loads is defined by **fatigue strength** or **endurance**. Fatigue is the process of accumulation of micro-damages in material under variable loads leading to macro-cracks appearing and final specimen failure. Fatigue failure is developing slowly and is stipulated by non-uniform stress distribution at places of non-metal impurities, gas bubbles, sharp shape changes etc. Plastic deformations appearing at above-mentioned places at periodical loading promote occurring of micro-stress leading to fatigue fracture at stress significantly less than ultimate material strength and even yielding strength.

Distinctive feature of fatigue fracture is presence of two zones on the surface of fracture. First zone has smooth structure appeared due to friction of micro-cracks surfaces. Second zone has crystalline visual structure similar to brittle fracture or fiber-like view similar to ductile one.

Fatigue test is conducted on special machines on batch of specimens (6…10 pieces) at bending, tension, compression, torsion and cyclic loading. First specimen is loaded by σ_1 stress (for steel $\sigma_1=0.6\sigma_b$) and quantity of loading cycles N led to specimen failure is read. For second and further specimens stress σ_2, σ_2 etc are reduced. By results of testing **fatigue curve** (Vöhler curve) is drawn (see Fig. 1.2). Fatigue curve is dependence between maximum stress and quantity of loading cycles. **Loading cycle** is total consequence of applied stress through loading period. Maximum and minimum loading stress are designated as σ_{max} and σ_{min}. Their ratio $\sigma_{min}/\sigma_{max}$ is known as **fatigue cycle ratio**. Generally symmetrical, non-symmetrical and pulsating loading cycles are used for materials testing (Fig. 1.3).

Quantity of cycles up to specimens failure is known as **reference cycles number**. For majority of steels this value is near 10^7 cycles, for non-ferrous metal – 10^8 cycles.

The main goal of testing is to find maximum stress (right horizontal side of the curve shown on the Fig. 1.2) which specimen can withstand without failure. This stress σ_R is known ad **endurance limit** or **fatigue limit**.

Next non-destructive method of testing is hardness test. **Hardness** is ability of material to resist penetration to it of special body (indenter). There are many different methods of hardness estimation: by penetration, by scratching, elastic response etc. Mostly the method of penetration is used.

Brinell hardness measuring method is based on penetration of steel ball to testing material (with diameter 2.5; 5.0; 10.0 mm). Thicker and harder material more diameter of a ball, applied load and duration of load application. Numerical value of Brinell hardness number (kg/mm^2 or MPa) is ratio of applied load P to the area of impression F:

$$HB=P/F. \tag{1.8}$$

The main advantages of Brinell method are simplicity and reliability of measuring and high precision of measuring. But at measuring material surface is damaged by impressions, minimal thickness of measuring material is near 2..3 mm and maximum hardness is up to 450 HB.

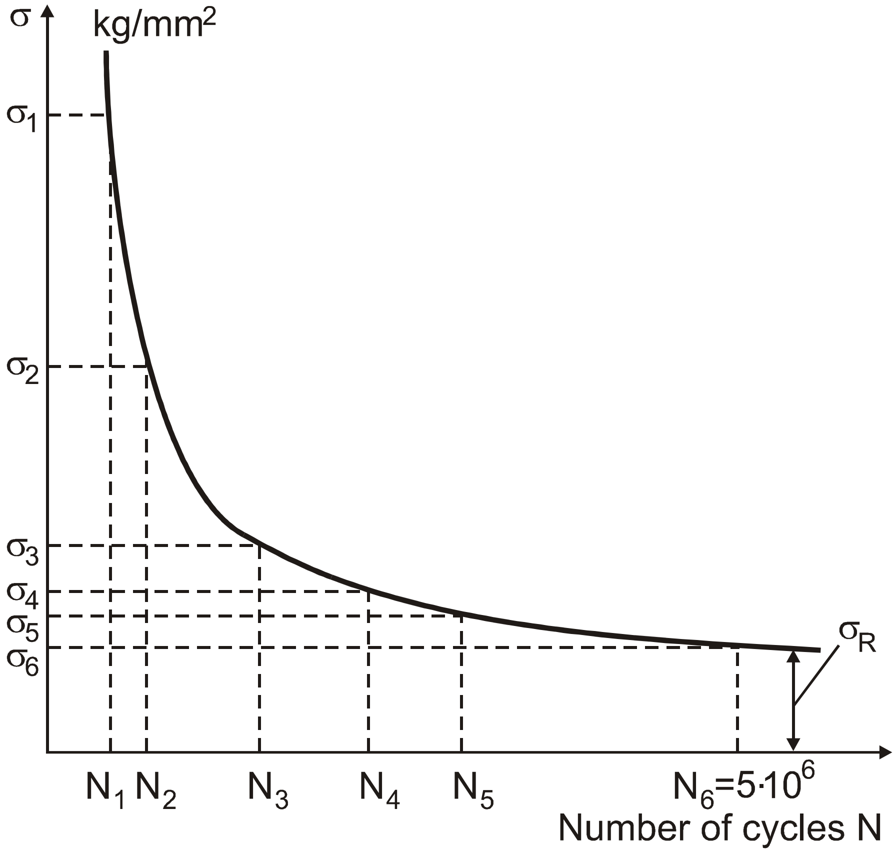


Fig. 1.2. Fatigue curve

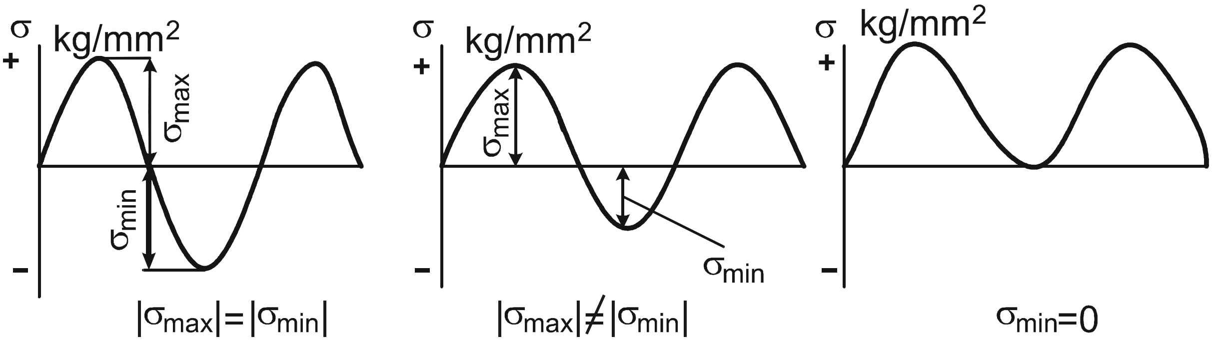


Fig. 1.3. Types of fatigue loading cycles:
a– symmetrical; b– non-symmetrical; c– pulsating

Rockwell hardness measuring method is grounded on penetration of diamond cone (brale) with angle at the vertex 120° or steel quenched ball with diameter 1.6 mm (1/16th of inch) to testing material. Hardness is measured by relative conditional scale in which one unit corresponds to vertical displacement of indenter on 0.0002 mm.

Loading used at testing is 60, 100, 150 kg. Hardness is reading from the dial indicator by scales A (HRA), B (HRB) and C (HRC).

Vickers hardness measuring method is based on penetration of four-faced diamond pyramid with angle between vertex faces 136° to testing materials. Numerical value of hardness HV is defined by

$$HV=P/d^2. \tag{1.9}$$

where P– load, applied to pyramid, N (generally from 50 up to 1000 N); d– average value of impression diagonals, mm.

This method permits to measure hardness of thin coatings with high hardness.

To measure hardness of microscopic objects (for example, grains) relatively small load (from 0.05 up to 5 N) is applied to diamond pyramid.

Hardness of very hard materials (glass, ceramics, sitalls, mineral dielectrics) is conducted by **Moose scratching method**. This method used ten digit relative scale. Zero value corresponds to talc hardness, maximum 10th grade corresponds to hardness of natural diamond.

Also hardness of hard materials and films is defined by **Kuznetsov's method of elastic response**. The essence of method is application of pendulum, i.e. light frame with weight and pointer supported on steel quenched ball. The hardness is defined by duration pendulum damping. More material hardness longer pendulum duration.

1.2. Thermal properties

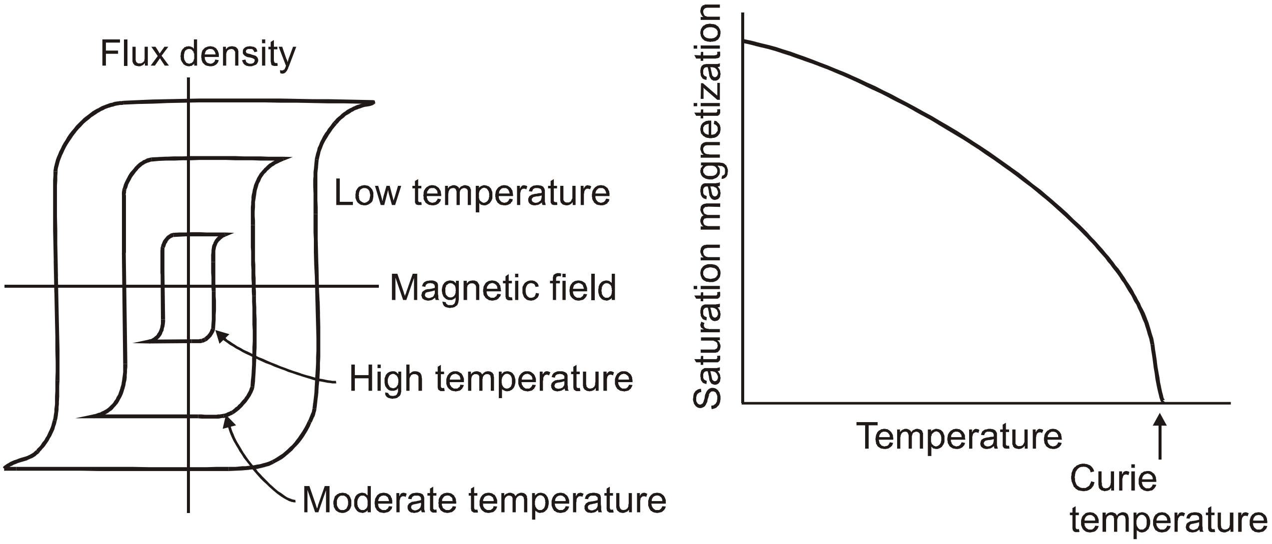
Thermal properties of materials are defined by thermal resistance, cold resistance (low-temperature resistance), thermal conductivity, thermal coefficients.

Thermal resistance is ability of material to keep required level of operational properties at elevated temperatures. Numerically thermal resistance is estimated by temperature (in °C) at which significant material properties changes occur. For example, heat resistance of liquid materials is restricted by temperature of boiling, deterioration, flashing or burning. Thermal resistance of solid materials is defined by point of melting, softening, oxidizing, self-burning, Curie point (i.e. by temperatures at which material looses magnetic, ferroelectric or super-conductive properties (Fig. 1.4)).

Thermal resistance belongs to quite wide temperature range and depends on operational conditions. For example, thermal resistance of tungsten (refractory metal) in vacuum or in inert medium is 2800°C (restricted by softening temperature), but at open air – is near 700°C (restricted by oxidation temperature).

In accordance with GOST 8865-70 electrotechnical materials are divided by 7 grades of thermal resistance (Table 1.1).

Cold resistance (low-temperature resistance) is ability of material to operate at low temperatures without properties worsening. Generally electrical properties of materials at low temperatures become better, but rigidity and brittleness decrease. Application of liquids is restricted by their viscosity increasing at low temperatures or by crystallization temperature. Restriction on gases application is their liquidizing at low temperatures.



a b

Fig. 1.4. Influence of temperature on properties of a conductor:
a – changing of magnetic field; b – decreasing of saturation magnetization at heating up to Curie point

Table 1.1. Grades of electrotechnical material thermal resistance

Thermal resistance grade	У	A	E	B	F	H	C
Allowable operational temperature	90°	105°	120°	130°	155°	180°	>180°
Materials	Fibrous non-impregnated	Fibrous impregnated, polyamide resins	Plastics with organic filler	Plastics with non-organic filler	Based on mica, glass-fiber	Based on silicon-organic resins	Mica, asbestos, ceramics

Thermal conductivity is ability of material to conduct heat. Numerically is characterized by specific thermal conductivity λ showing the value of heat flow (in Watts) passing through unit area of a surface at difference of temperatures of two sides of a material on 1°C. More thermal conductivity of material is better cooling properties of device and more operational temperature. High thermal conductivity of material permits to reduce overall dimensions of object and increase operational stress.

Thermal coefficients are indicators of relative changing of any parameter x of material at changing temperature on 1 °C:

$$TKx = \alpha_x = \frac{x_2 - x_1}{x_1 \Delta T}. \qquad (1.10)$$

Mostly thermal coefficients of volumetric expansion α_v, linear expansion α_{lin}, specific magnetic permeability α_μ and dielectric permeability α_ε are used.

1.3. Physical-chemical properties

The most important physical-chemical properties of materials are moisture resistance, tropical resistance, altitude resistance, radiation resistance, chemical activity, chemical resistance, solubility, acidity.

Moisture resistance is ability of material to operate in atmosphere close to state saturated with water steam. Moisture resistance is characterizes by hydroscopicity, moisture saturation, moisture permeability, wettability.

Hydroscopicity is ability of material to absorb moisture from ambient medium. Numerically is defined as ratio $\bar{G} = ((G_1 - G_0)/G_0)100\ \%$, where G_1 – weight of material after presence during 24 or 48 hrs at conditions of 97% relative air humidity, G_0 – weight of dry material.

Moisture saturation is ability of material to absorb moisture at immersing in water. Numerically is defined by similar way as hydroscopicity.

Moisture permeability is ability of material to pass water steam through itself. Numerically can be estimated by moisture permeability coefficient A which is equal to quantity of moisture m passing per unit time τ through unit area s of material with unit thickness h under difference of unit steam pressure P_1 and P_2 applied to sides of a layer

$$A = \alpha_x = \frac{mh}{(P_1 - P_2)s\tau}, \ \frac{kg}{Pa \cdot m \cdot s}. \qquad (1.11)$$

Wettability is ability of material to attract molecules of liquid and keep them on the surface. Numerically is characterized with edge angle of wettability θ of water drop laid over body surface. Less θ more wettability. For wettable surfaces $\theta<90°$, for non-wettable - $\theta>90°$. Generally neutral and low polar materials are non-wettable, high polar and ionic are well wettable.

Tropical resistance is ability of material to withstand influence of tropical conditions: intensive solar radiation, high and low humidity, high temperature, fungi, micro-organisms without significant properties reduction.

Materials containing oils, oil acids, cellulose possess minimal tropical resistance because such substances serve as food solutions for micro-organisms. The most resistant are non-organic element-organic materials like non-polar hydrocarbons, polyamides, epoxy resins etc.

Tropical resistance can be increased by application of protective coatings, saturation with water-proof substances, mechanical tightening etc.

Altitude resistance is ability of materials to operate at high altitudes without significant properties reduction.

It is known that higher the altitude changes of pressure and temperature, atmosphere composition, radiation intensity occur. All mentioned factors influence on material properties. As a result discharge and breakdown voltage decreases, heat removing and efficiency of air cooling become less, intensive evaporation and boiling of impregnating materials and capacitors electrolytes happen.

Radiation resistance of materials is degree of saving their properties after influence of corpuscular (slow neutrons, nuclear fragments, α-particle, β-rays) and wave (γ-rays, hard and low X-radiation) irradiation of high energy.

Effect of irradiation leads to molecular transformations (chemical bonding tearing, appearing and disappearing of double- and cross links and free radicals). The most resistant to radiation is material which can absorb energy without significant ionization and creation of double linking.

Degree of radiation absorbing depends on radiation type and material nature. Majority of organic materials deteriorate at radiation, majority of non-organic materials slightly loose in density and elasticity modulus. The most resistant to radiation are polystyrene, aniline-formaldehyde resins, polyethylene, fluoride rubber, silicon organic rubber, polycarbonates, polyamide film etc.

Chemical properties of materials are quite important for estimation their reliability in operation and developing manufacturing processes. Materials shouldn’t react with ambient medium, cause corrosion and evaporate auxiliary products of chemical reactions. Moreover following properties are quite important: manufacturability, solubility, degree of adhesion to other materials etc. All these properties depend on material chemical activity, solubility, ability to dissolve materials, acidity.

Chemical activity is ability of substance to interact with other substances with creation of chemical compounds. For example, metals possess high chemical activity with respect to oxygen, they can replace hydrogen from molecules of acids and ions of metals in molecules of salts.

Chemical resistance is resistance of materials under influence of chemically active mediums (humid air, water, solvents, salts etc). It depends on composition and arrangement of dielectric.

Solubility is ability of material to be dissolved in solvent. It is estimated by quantity of material transferring to solvent per unit time from unit surface area being in contact with solvent.

Ability to dissolve materials is ability of liquids to dissolve other materials. Solubility and ability to dissolve materials depend on chemical nativity of materials. For example, dipole substances easily dissolve in dipole liquids, neutral substances – in neutral liquids. Solubility decreases with increasing degree of polarization and at transferring from linear to special molecular arrangement.

Acidity is characterized by acidity number showing quantity of alkali (in milligrams) necessary for neutralizing of chemically free acids in one gram of given material. Materials with high acidity number have low electrical properties and cause corrosion of materials being in contact.

1.4. Technological and operational properties

Technological properties characterize ability of material to be machined by different technological methods, i.e. give qualitative estimation of material suitability to methods of treatment. Main technological properties are: weldability, forgeability, cutability, castability etc.

Weldability is ability of material to create welded joint having properties close to properties of joining materials.

Forgeability is ability of material to be processed by pressure in cold or hot state with failure features (cracks).

Cutability is ability of materials to create smooth machined surface at low heating and cutting tool wear. Generally machining of ductile materials leads to rough surface with scuffing. Machining of hard materials leads to heating and significant cutting tool wear.

Castability is total series of properties characterizing ability of material to create ingots without defects (cracks, porosities). Main casting properties are fluidity, shrinkage and liquation.

Fluidity is ability of material to fill volume of casting mould and especially narrow channels with complicated shape.

Shrinkage is reduction volume of a material at transition from liquid to solid state. Shrinkage is the main reason of appearing shrinkage porosities and cavities.

Liquation is non-uniform chemical composition of an alloy appearing at crystallization and stipulated by saturation of liquid phase with elements solubility of which in liquid phase is more than in solid. For example, sulphur, oxygen, phosphorus, carbon is mostly liquate in steel.

Operational properties are ones defining required operation of articles in necessary conditions. Operational properties are wear resistance, heat resistance, corrosion resistance etc.

Wear resistance is ability of materials is to resist material wearing, i.e. changing of body shape and dimensions due to destruction of superficial layers at friction.

Heat resistance is ability of materials to resist oxidation in gas medium at elevated temperature.

Corrosion resistance is ability of materials to resist action of aggressive acid and alkali mediums.

Theme 2. BASICS OF MATERIAL ENGINEERING

2.1. Fundamentals of materials atomic structure arrangement

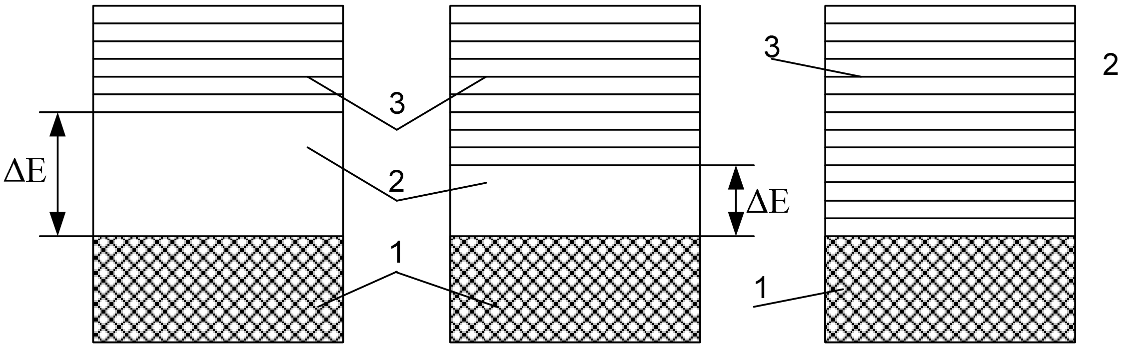
Substances micro-structure defines their macro-properties that is why such parameters as type of chemical bonding, aggregate state, micro-arrangement, energy of particles interaction permit to distinguish materials from each other.

It is known from the course of conventional physics that all substances consist of atoms, molecules and ions and it doesn't depend on a substance aggregate state. Atom is complicated system consisting on nuclear and electrons rotating over it by orbitals.

Electrons disposed at orbitals nearest to the nuclear possess low energy level. More radius of electron orbit more energy level of electrons.

Energy state of an atom can be demonstrated by energy diagram (Fig. 2.1). On this diagram allowed discrete levels of energy are shown by horizontal lines separated by forbidden bands.

Splitting and translation of energy levels with consequent creation of allowed and forbidden energy zones occurs in process of joining atoms to molecule.



a b c

Fig. 2.1. Energy diagram for dielectrics at absolute zero temperature:
a – for dielectrics; b – for semi-conductors; c – for conductors

Allowed zone created by energy levels of valent electrons is known as **valent allowed zone** (item 1 on the Fig. 1.1). Zone in which energy level of electrons is higher than in valent shell of an atom is known as **conduction zone** (item 3 on the Fig. 1.1). Item 2 on the Fig. 2.1 shows **forbidden zone**.

In accordance with **zone theory of solids** all materials can be divided on conductors, semi-conductors and dielectrics. Group of **conductors** include materials in valent energy zones of which quantity of allowed levels is more than quantity of electrons. In conductors the valent zone is overlapped with conduction zone, i.e. forbidden zone is absent. Main distinctive feature of conductors – high electrical and thermal conductivity.

Substances having valent zone fully filled with electrons and zone of conduction separated from valent zone by relatively wide forbidden zone (from 2 up to 10 eV) are known as **dielectrics**.

Semi-conductors like dielectrics have forbidden zone between conduction zone and valent zone but the width of this band is quite narrower – from doles up to 2…3 eV.

2.2. Type of atomic bonding of atoms and molecules

Final engineering properties of materials depend on types of bonding of atoms in molecules and on their reciprocal influence.

Ability of an atom to chemical interaction is characterized by **valence**. **Valence** is ability of atoms to attach to it or replace in molecules of complex substances definite atoms of another elements.

Depending on arrangement of valent electron layers following types of bonding can be observed:

- covalent;
- ionic;
- metal;
- polarized (Van der Waals bonding);
- donor-acceptor.

Covalent bonding appears between atoms of one or several electronegative chemical elements with close ionization energy having the half or more quantity of electrons in outer electronic shells.

Electro-negativity of an element is equal to the sum of **electron affinity energy** and **ionization energy**. Energy of ionization is one spending on removing of a single outer electron from atom staying in basic energy state. Ionization energy is one releasing in process of joining electron to atom.

Covalent bonding is observed in some gases (hydrogen, oxygen, chlorine, fluoride, nitrogen etc.), solid crystals (diamond, silicon, germanium, stibium, bismuth etc.) and in majority of organic compounds.

Molecules with covalent bonding can be neutral, low polar and polar. Covalent bonding have relatively high level of bonding (600…2000 kJ/mole), substances having such type of bonding possess high melting point, hardness, chemical inert, low electronic conduction and negative specific electrical conductivity.

Ionic bonding occurs due attraction of atom of first element the electron of another atom. Ionic bonding has no definite spatial direction but is quite saturated because the sum of negative and positive ions is the same. Substances with ionic bonding are mainly polar. In solid state they are brittle and possess semi-conductive and dielectric properties, in liquid state – have properties of conductors of the second type. By mechanical properties substances with ionic bonding are less strong (energy of bonding is 600…1000 kJ/mole), have high melting point and hardness, low ductility.

Metal bonding is typical for metals and alloys and can be considered as array of positive ions surrounded by moving electrons (so-called “electronic gas”), i.e.

metal bonding is based on interaction of positive ions and “electronic gas”.

Metal bonding has no spatial direction and saturation and possesses intermediate position between covalent bonding (the same electrons belong to neighboring atoms) and ionic (electrons bond together positive ions). Materials with metal bonding have high ductility, thermal- and electrical conductivity.

Polarizing or **Van der Waals bonding** can be explain by electrostatic interaction of dipole molecules or by induction influence of polar molecule to neutral one. Dipole molecule induces an electrical moment in neutral molecule.

Polarizing bonding is the weakest (bonding energy is up to several kJ/mole) has no dominant direction and saturation. Materials with polarizing bonding have low melting point and low strength. Such bonding can be observed in noble gases, graphite, some organic compounds.

Donor-acceptor bonding appears between atoms, moleculas and radicals which have no unpaired electrons. One particle has free pair of electrons and serves as donor, another particle have ability to take mentioned free electron is acceptor. When donor-acceptor bonding is created it is practically very close to covalent one.

Above-mentioned types of ponding in their pure state can be observed practically very rarely. In real materials several different types of bonding occur and engineering properties of materials are defined by major types of atoms and molecules.

2.3. Fundamentals of crystallography

Crystallography is the science about arrangement, properties, creation and growth of crystals.

Particles in solids tend to arrange in space to minimize energy of interaction. This spatial state of particle reciprocal arrangement is called as **crystalline lattice**. For crystalline lattice description following terms are used: elementary unit cell, type and period of lattice, crystallographic axes, interatomic distance, coordination number.

Crystalline lattice is imaginary spatial grid at nodes of which atoms or particles creating crystalline body are located. Crystalline body can be obtained by multiple repeating in three different directions of the same structural element (known as **elementary unit cell**). Unit cell is parallelepiped composed by three vectors $\bar{a}$, $\bar{b}$, $\bar{c}$ (Fig. 2.2) modules of which are known as **crystalline lattice period**.

Periods of crystalline lattice are lengths of unit cells along crystallographic axes and equal to distance between nodes of crystalline lattice. Periods are measured in angstroms ($1Å=10^{-10}$ м) in metals and up to 10^3 Å in biological crystals.

Type of crystalline lattice is characterized by rib a, b, c and angles between axes α, β, γ. Generally 14 different types of crystalline lattices are known and they can be united to seven crystallographic systems:

1. **Triclinic** – a≠b≠c and α≠β≠γ, its unit cell has shape of oblique-angled parallelepiped.

2. **Monoclinic** – a≠b≠c, has two right angles угла α=γ=90°, the third is different from the right β≠90°. Unit cell has the shape of right-angle prism with parallelogram basement.

3. **Rhombic** – all angle are right α=β=γ=90°, but ribs are different a≠b≠c. unit cell has the shape of right-angled parallelepiped.

4. **Tetragonal** – unit cell has the shape of right-angle prism with square basement, i. e. a=b ≠ c и α=β=γ= 90°.

5. **Rhombohedral** (or trigonal) has the same ribs (a=b=c) and angles different from the right α=β=γ≠90°, unit cell is a cube deformed by tension and compression in diagonal direction.

6. **Hexagonal** has the shape of hexagonal prism with parameters a=b≠c, α=β =90°, γ =120°.

7. **Cubic** unit cell has the shape of cube with the same ribs length and right angles a = b = c, α = β = γ = 90°.

Crystalline lattices having atoms at nodes only are known as simple, but if atoms are presented inside cells or on the faces that such lattice is considered as complicated. Therefore simple, base-centered, body-centered anf face-centered lattices are known.

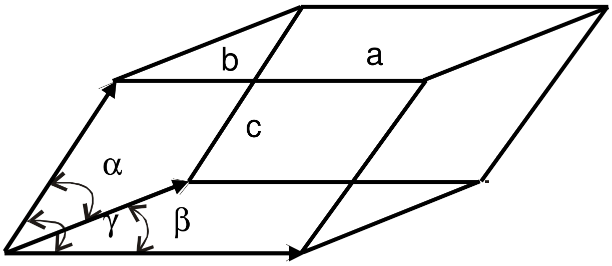


Fig. 2.2. Model of crystalline lattice

2.4. Defects in crystals

Above-mentioned model of crystalline lattices correspond to ideal crystals at temperature close to absolute zero/ At this conditions all particles can be considered as unmovable and staying at position of minimal potential energy.

Real crystals are effected by thermal, mechanical and electrical, radiation influence and contain impurities therefore particles are not arranged in ideal order with neighboring ones. The ideal order can be observed in real crystals in relatively small areas known as **crystallite** or **grain**. Grain is not monolithic object, it consists of several blocks having crystallographic planes rotated refer each other by small angle.

All irregularities of material atomic arrangement are known as **defects** or **imperfections**. They can be **point** (zero-dimensional), **linear** (one-dimensional), **su-**

perficial (two-dimensional) and **volumetric** (three-dimensional).

Point defects have are very small (several atomic diameters) and have dimensions of the same order. Point defects are vacancies, interstitial atoms, interstitial and substitution impurity atoms and violations of stoichiometric composition. Main reason of such defects appearing is transferring of atoms due to thermal oscillations of crystalline lattice at nodes. Point defects are also presented in any crystals.

Vacancies or “holes” are nodes of crystalline lattice with absent atoms (Fig. 2.3, a). Vacancies (Schottky defect) appear due to transition of particles having kinetic energy more than average at current temperature to the boundary of grain of irregularity (porosity, micro-crack etc) also due to particle evaporation from the crystal surface or due to transition to interstitial zone. Vacancies pass through lattice from particle to particle leaving node to be free, creating visibility of vacancy movement.

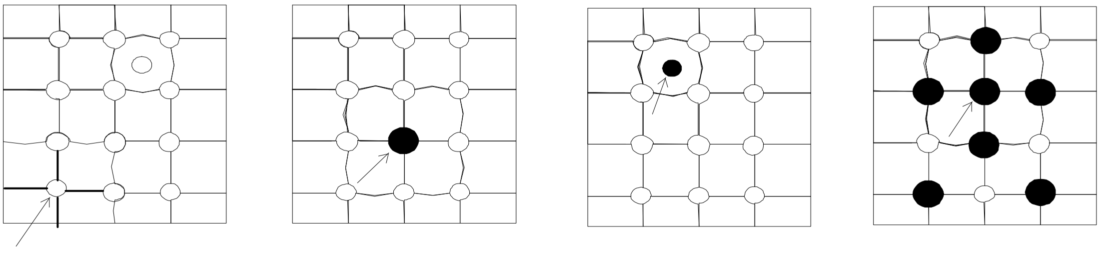


Fig. 2.3. Main types of point defects:
a – vacancy; b – substitution atom; c – interstitial atom;
d – violation of stoichiometric composition

Impurity substitution atoms are located between nodes of lattice and create interstitial solid solution (Fig. 2.3, c). Impurity atoms located at the nodes of main substance lattice create substitution solid solution (Fig. 2.3, b). In crystals of chemical compounds the excess of one of components leads to violation of stoichiometric composition of a compound (see Fig. 2.3, c).

Point defects lead to appearing of irregularities prolonged on several periods of crystalline lattice.

Vacancies play important role in analysis of diffusion processes in metals and alloys. At room temperature the density of vacancies is approximately one per 10^{10} atoms. But density of vacancies increases significantly at heating (up to one vacancy per 10^4 atoms) especially near melting point.

Main linear defects in crystal are dislocations. The simplest dislocations are **edge** and **screw dislocations**.

Screw dislocation is stipulated by presence of excess crystalline semi-plane created between neighboring layers of atoms perpendicular to the drawing plane (Fig. 2.4, a). Edge A-A of this semi-plane creates linear defect of crystalline lattice which is called **edge dislocation**. If extra-plane is located over the plane of crystals sliding the dislocation is considered as positive and designated as ⊥, if dislocation is below the sliding plane it is negative and designated as T.

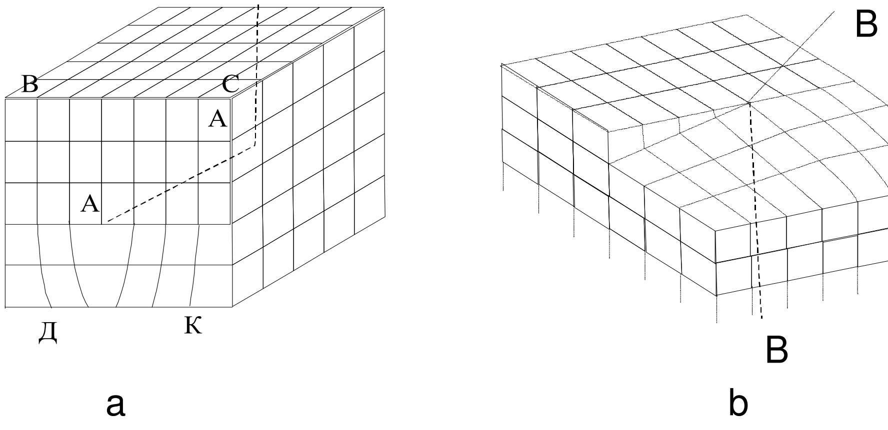


Fig. 2.4. Edge and screw dislocations

The length of edge dislocation can be up to several thousands of unit cell parameters, the shape of dislocation can be straight and curved.

Screw dislocation is considered as a result of a crystal cutting through semi-plane and consequent sliding of crystalline lattice parts refer each other by one interatomic distance (Fig. 2.4, b). Inner edge B-B of a cut is exactly screw dislocation.

Crystal with screw dislocation consists of one crystalline plane bent over helical surface. Dislocation line coincides with the axis of a screw. Each one pass over this line means movement of crystalline plane on one period.

Unit cells enveloping screw dislocation are distorted, the energy of this distorted field is characterized Burgers vector.

Screw dislocation can move inside lattice under the influence cleavage (sliding) force or by the gathering of free dislocations.

Quantative characteristic of dislocations in crystals is the notion of **dislocation density**, i.e. total length of all dislocations per one cubic centimeter. For metals dislocation density belongs to the range $10^{8}\ldots10^{13}$ см$^{-3}$ (or one million kilometers of dislocations length in one cubic centimeter).

Superficial defects have only one dimension of low order. Generally as such defects one can consider boundaries of blocks, grains, defects of agrains arrangement, domains boundaries etc.

Point, linear and superficial defects are microscopic ones because the is absolute length have the order of atomic diameters in one direction. But **volumetric defects** are considered as macro-objects (can be seen with naked eye) because they have relatively large dimensions in all three dimensions significantly more than atomic diameter. Porosities, cracks and scratches are volumetric defects.

2.5. Methods of materials arrangement research

There are several main up-to-date methods of studying structure of materials, determination their defects and estimation quality of articles. Methods of materials structure analysis can be **destructive** and **non-destructive** (without material failure). Destructive methods include macro-structural analysis and micro-structural analysis based on optical microscopy.

Macrostructure is crystalline structure of a material observed naked-eye or at relatively low magnifications (up to 1000 times).

Microstructure means crystalline arrangement of a material which can be observed by naked eye (or at low magnification – up to 10…30 times). Typical studying includes observation of specimen after failure, analysis of its fracture or macrosection. Mostly attention has to be drawn to defects, irregularities of specimen (cracks, porosities, cavities etc).

Typically three main types of fracture can be determined, i.e. **ductile**, **brittle** and **fatigue**. **Ductile** fracture is characterized by fiber-like fracture because failure occurs through grain bodies by shear mode (so-called “cup-cone”). Exactly before failure **neck** appearance can be observed. Neck is local plastic deformation of a material near zone of failure.

Brittle fracture appears at relatively low work of failure spent only to elastic deformation. It happens without plastic deformation (neck is absent) by tearing or cleavage mode. The surface has crystalline view and metal glazing.

Fatigue fracture is developed under cyclic loading (with variable amplitude and sign). It is characterized by presence of two different zones: zone of micro-cracks developing (has very smooth surface) and zone of final catastrophic brittle failure (mainly has rough crystalline surface).

Macrosection is specimen (cross-section of an article or its fragments) prepared by cutting, filing and consequent polishing. Macro analysis can be conducted with application of **etching agents** or by means of them.

Superficial and **deep etching** can be used for macro-analysis. **Weak etching agents** (5…10 % solutions of chemicals in water) are used to remove oxidized layer from macro-section but don’t lead to sharp relief appearing. Typically etching duration at room temperature is 20..40 seconds.

Superficial etching permits to reveal chemical and structural inhomogeneity of articles, to study structure and quality of welded joins, to estimate distribution of sulphur and phosphorus in steels and depth of p-n band location in semi-conductors.

Deep etching creates well-defined relief of material structure. Due to different orientation grains in metal the degree of their etching is different too and all presented inclusions can be seen sharply. Relief permits to make conclusion about grain shape, arrangement, dimensions in forging, castings and drawn articles.

Microstructure is material arrangement can be observed at significant magnification (up to 3000 times and more). Microstructural analysis means studying of **micro-sections** structure by metallographic optical and electronic microscopes. **Micro-section** is sections of material specimen previously polished and finished up to lowest roughness. **Micro-sections** are studied in reflected light of optical and electronic beams of raster microscope.

Typically optical microscope reaches 6000 Å, electronic – 5…10 Å that corresponds to magnification of 3000 and $10^5…10^6$ times.

Following irregularities of micro-structure can be found by methods of micro-analysis: shape and size of grains, shape and location of non-metal impurities (carbides, sulphides, silicides, oxides, nitrides etc.), micro-defects of metals and allows (micro-flaws, micro-porosities etc), depth and structure of superficial layers after diffusion, superficial hardening, cladding etc.

Such non-destructive methods as X-ray, acoustic, ultrasonic, magnetic, luminescent, radioactive isotopes are also used for analysis of materials structure. These methods permit to reveal internal and superficial defects .

X-ray methods include X-ray defectoscopy, X-ray spectrum, X-ray structural, X-ray topographic analysis.

Theme 3. CONDUCTIVE MATERIALS

3.1. Classification of conductors

Nowadays classification of semi-conductors can be done by following features: by value of **specific resistance** ρ (low- and high-resistant); by **nature of semi-conductor** (metal and non-metal); by **spatial shape of conductive article** (wired, filmed, volumetric) etc.

Both **solid**, **liquid** and **gas** substances are used as conductors. Solid conductors are metals and alloys, some non-metal materials. Liquid conductors are molten metals and alloys, electrolytes (solutions of acids, alkali, salts, molten ionic compounds). Gas conductors are vapors of substances and gases in ionized state.

Metals and alloys in solid and liquid state and non-metals materials are conductors of the firs type (with electronic conduction). Conductors of the second type (electrolytes) have ionic conduction.

Solid conductors are classified by following groups:

1. Materials with high conduction (low-resistant).
2. Materials with high resistance (high-resistant).
3. Materials and alloys of different application.
4. Non-metal conductors.
5. Super conductors.

3.2. Electrical conductivity of conductors

Conventional electronic theory of metals considers conductor as a system of nodes of crystalline ionic lattice with medium of free electrons inside (so-called “electronic gas”).

Behavior of “electronic gas” (with some assumptions) can be analyzed by means of physical notions and laws of ideal gas, i.e. electrons movement can be described by classical statistics laws according to which electrons exist in the state of continuous random movement with average velocity $\overline{v} \sim 10^5$ m/s at temperature T=300 K.

In electrical field electrons pass in direction of field force lines creating the electrical current with density

$$I = e \cdot n \cdot \overline{v}, \tag{3.1}$$

where I is amperage, A; n– electrons concentration, m^{-3}; $\overline{v}$– average electrons velocity; m/s; e– electron charge, $e=1.6 \cdot 10^{-19}$ C.

Average electrons velocity $\overline{v}$ can be calculated as

$$\overline{v} = \frac{eE\ell_{av}}{2m_0\overline{u}}, \tag{3.2}$$

where E– intensity of electrical field V/m; ℓ_{av}– average length of electrons pass, m; m_0– rest mass of electron, $m_0=9.1 \cdot 10^{-31}$ kg; $\overline{u}$– average velocity of electrons thermal movement.

Inserting of (3.2) to (3.1) permits to obtain Ohm's law, i.e. dependence between current strength I (amperage) and intensity of electrical field E:

$$I = \frac{e^2 n \ell_{av}}{2m_0 \bar{u}} E = \gamma E. \tag{3.3}$$

Coefficient $\gamma = \frac{e^2 n \ell_{av}}{2m_0 \bar{u}}$ is known as **specific electrical conduction**. The value inversed to γ is known as **specific electrical resistance**.

Classical theory of "electronic gas" can't explain properly such processes happen in conductors as low thermal conductivity of "electronic gas", phenomenon of "superconduction" in some conductors etc. This is why nowadays the most exact explanation of physical processes in conductors can be given by "zone theory" of solids based on quantum wave mechanics. According to quantum wave mechanics electrons possess both properties of particles and waves. Moreover analytical parameters are not only mass, velocity and energy of electrons but also wave length correspondent to given energy level.

Statements of quantum mechanics permit to write expression for γ as

$$\gamma = ke^2 n^{2/3} \ell_{av} h^{-1}, \tag{3.4}$$

where k – coefficient; h– Planck's constant, $h=6.6 \cdot 10^{-34}$ J·s.

3.3. Main properties of conductors

Main numerical parameters of conductors are:

1. Specific electrical conduction γ and value reversed to it – specific electrical resistance ρ.
2. Thermal coefficient of specific resistance TK_ρ or α_ρ .
3. Thermal conductivity λ_T.
4. Thermal electromotive force (thermoEMF).
5. Ultimate strength at tension σ_b and relative elongation $\varepsilon(\delta)$.

3.3.1. Specific electrical conduction

For conductor with length l (m), cross-section area S (cm^2) and absolute (total) resistance R (Ohm) specific resistance ρ can be found as

$$\rho = RS / l. \tag{3.5}$$

The range of specific resistance value of metal conductors is quite narrow: from 0.016 (for silver) up to 10 μOhm·m (for iron-chromium-aluminum alloys).

Example 3.1

Calculate the loss of power in a copper transmission line l=1500 m long when a current of 50 A is flowing. The copper wire has a diameter d of 0.1 cm and the electrical resistivity ρ is $1.67\cdot10^{-6}$ Ohm·cm.

$R=\rho l/A=\rho l/(\pi d^2/4)=1.67\cdot10^{-6}\cdot1500\cdot100(cm/m)/(\pi\cdot0.1^2/4)=31.9$ Ohm.

The power loss P in the form of heating of the wire is

$P=UI=I^2R=50^2\cdot31.9=79.8$ kW.

Experimental researches have shown that the velocity of electrons random thermal movement $\bar{u}$ and concentration of electrons n are approximately the same for majority of conductors. Therefore specific resistance depends mainly on the length of free pass of electrons which is defined by structure and composition of a conductor material.

Also ρ depends on presence of impurities, structural defects, temperature, load, frequency of a current etc (Fig. 3.1).

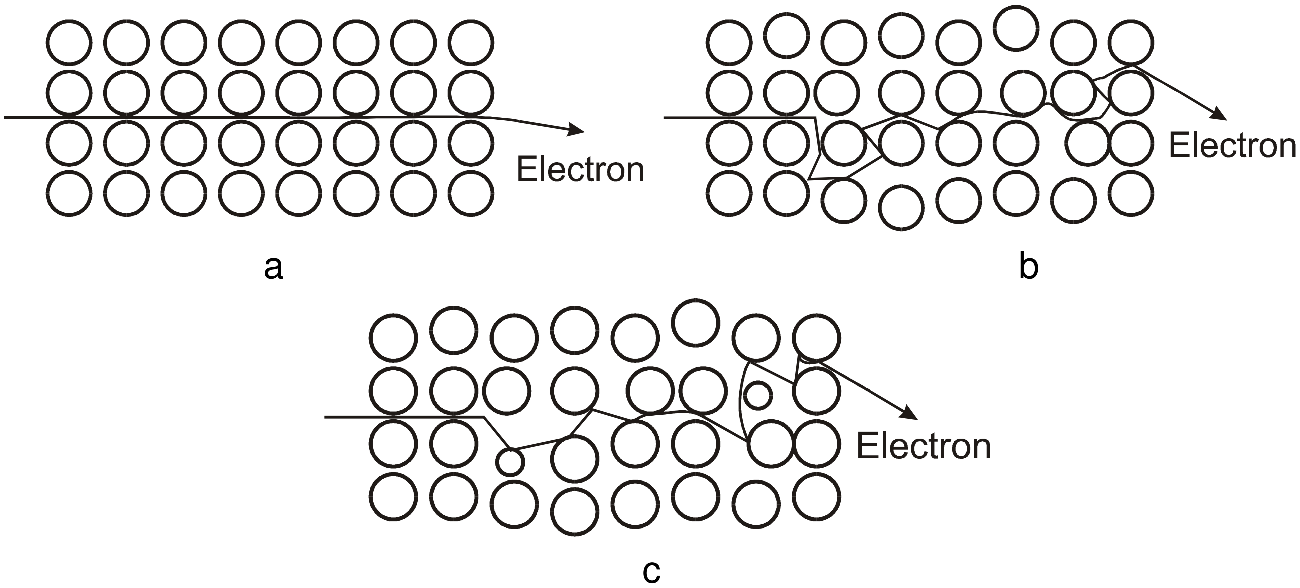


Fig. 3.1. Movement of an electron through (a) perfect crystalline lattice; heated lattice (b); lattice containing impurities and defects

Influence of impurities and defects. Ideal crystalline lattice without distortions doesn't lead to electron pass deviation (Fig. 3.1, a), therefore ℓ_{av} is close to infinity and ρ is close to zero. Any distortions of crystalline lattice (impurities, vacancies, deformations) cause ℓ_{av} decreasing and growth of specific resistance. This is why low-resistance conductors are made of allows with fine-grain structure and large amount of defects existing in stressed state (after machining and thermal treatment).

It was established experimentally by Mattissen in 1864 (so-called **rule about additivity of specific resistance**) that total resistance of a metal is sum of resistance ρ_T stipulated by electrons scattering on thermal oscillations of crystalline lattice nodes and ρ_{res} – residual resistance due to electrons energy scattering on static defects of crystalline lattice, i. e.

$$\rho=\rho_T+\rho_{res}\,. \tag{3.6}$$

Residual resistance depends on presence of impurities, alloying elements etc. Efficiency of impurity dispersion depends mainly on difference of valances of impurity atoms and metal-dissolver.

Influence of temperature (Fig. 3.1, b). The single reason that can restrict the electrons free pass ℓ_{av} in ideal lattice is thermal oscillations of node atoms. Amplitude of atoms oscillations increases with temperature that leads to electrons scattering and specific resistance ρ_T growths.

Relative changing of specific resistance at changing temperature on 1°C is known as thermal **coefficient of specific resistance**, 1/°C:

$$\alpha_\rho = \frac{1}{\rho_0}\frac{\rho_T - \rho_0}{T - T_0}, \tag{3.7}$$

where ρ_0, ρ_T – values of specific resistance at original temperature T_0 and current temperature T, Ohm·m.

Relationship (3.7) is written in differential form characterizes the rate of specific temperature changing in temperature field. Practically mentioned dependence is used for determination of ρ_T at known temperature, ρ_0 and α_ρ (last two values are tabulated).

For majority of metals $\alpha_\rho = 4 \cdot 10^{-3}$ 1/°C at room temperature. Several ferromagnetic metals (Fe, Ni, Co) have $\alpha_\rho = (6.0 \ldots 6.5) \cdot 10^{-3}$ 1/°C.

Typical dependence of specific resistance on temperature for metal conductor is shown on the Fig. 3.2. Generally three main zones can be selected on the graph. For some metals phenomenon of super-conduction occurs at temperature T_{sc} in the zone I (curve 3). When temperature goes to zero pure metals specific resistance comes to zero too (curve 2). Definite metals change their resistance according to curve 1. For majority of metals dependence $\rho(T)$ above T_{sc} is close to linear up to melting point T_m (zone II). After transition from solid state to liquid state (zone III) specific resistance increases 1.5…2.0 times (curves a and c). For several metals like bismuth and gallium melting leads to ρ decreasing (curve b).

Influence of mechanical stress. Distortions of crystalline lattice caused by mechanical or thermal stress also influence on ρ value. At three-axis compression ρ decreases that can be explained by atoms approaching and decreasing amplitude of thermal oscillations.

At elastic tension or torsion interatomic spacing increase then electrons dispersion an also ρ increase. Influence of elastic deformation can be estimated by formula

$$\rho = \rho_0(1 \pm \varphi\sigma), \tag{3.8}$$

where $\varphi = \frac{1}{\rho}\frac{\partial\rho}{\partial\sigma}$ – coefficient of specific resistance by stress σ.

Sign "+" in (3.8) corresponds to deformations of tension, sign "-" – to compression deformations. For engineering analysis φ can be assumed to equal to $(1 \ldots 5) \cdot 10^{-11}$ Pa^{-1}.

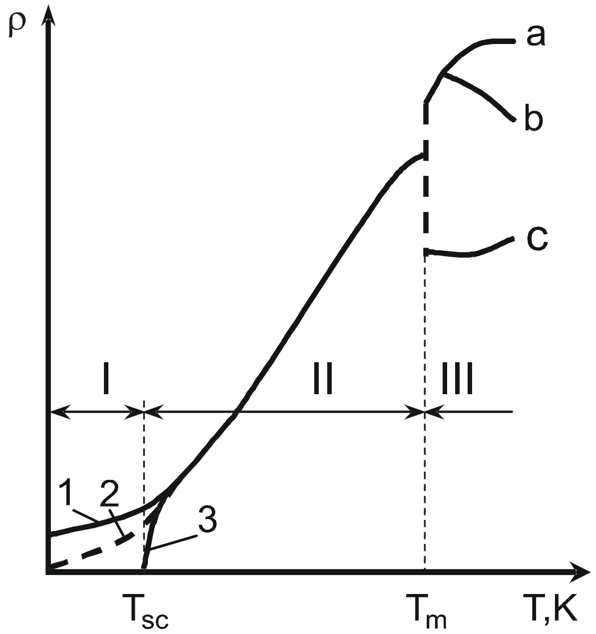


Fig. 3.2. Dependence of specific resistance on temperature:
a, b, c – character of resistance behavior after melting point

Influence of electrical current frequency. It is established experimentally that electrical resistance of a conductor to alternative current is more than to direct one. This phenomenon is known as "**skin-effect**": density of electrical current in a conductor has maximum at the outer surface and decreased to its center because inner layers intersect with large amount of magnetic lines, have more induction and reactive resistance. The depth of electrical field penetration becomes less.

Ratio of active resistances of a conductor to alternative R_{alt} and direct R_{dir} currents is known as **coefficient of resistance increasing**:

$$K_R = \frac{R_{alt}}{R_{dir}} = \frac{d}{4\Delta}, \tag{3.9}$$

where d– conductor diameter, m; Δ– depth of electrical field penetration (numerically equal to the depth at which amplitude of field intensity and density of a current decrease in e times.)

Occurring of skin-effect requires analysis of a conductor surface quality (presence of roughness, cracks, corrosion products etc). Therefore very responsible conductors cover with golden or silver coatings with consequent polishing. Moreover "net" conductive cross-section of a conductor is increased by combination it from multiple thin copper wires (with diameter 0.02…0.2 mm).

Influence of conductor dimensions. Film conductors are widely used in different articles (plates of a capacitor, electrodes, micro-chips). Electrical properties of films differ from properties of macro-conductors due to appearing of **superficial** and **dimensional effects**.

Superficial effect can be explained by "island" structure of a film: particles of deposited metals are located on substrate as separate grains ("islands") having local defects. If thickness of a film is comparable with average free path od electrons the **dimensional effect** can be observed: the pass of electrone movement becomes less due to reflection of electrons from film outer surface.

3.3.2. Thermal electromotive force of conductors

The contact difference of potentials occurs at joining two different metal conductors or semi-conductors due to different work function of electrons (Fermi energy). This phenomenon was discovered in 1797 by Italian engineer A.Volt.

At contact of different materials intensive electrons transition from level with high Fermi energy to level with lower one occurs. As a result one metal obtain positive charges, another one – negative and difference of potentials occurs

$$U_{AB} = U_B - U_A + \frac{kT}{e} \ln \frac{n_A}{n_B}, \tag{3.10}$$

where U_A, U_B– potentials of touching metals A and B, m; n_A, n_B– concentrations of electrons in metals A and B; k– Boltzmann constant, $k=1.38 \cdot 10^{-23}$ J/K; e– electron charge; T– thermodynamic temperature, K.

Thermoelement composed of two different conductors creating closed circuit is known as **thermocouple** (**thermopair**) and is used for temperature measuring. If the circuit is broken the **thermal electromotive force** (TEF) E_T occurs between contacts

$$E_T = U_{AB} + U_{BA} = \frac{k}{e} \ln \frac{n_A}{n_B} (T_1 - T_2) = \alpha_T (T_1 - T_2), \tag{3.11}$$

where α_T– coefficient of thermal electromotive force, μV/K.

Conductors having high and stable coefficients of TEF are used for thermocouples manufacturing. Conductors having smallest α_T are used for measuring devices and standard resistors (to minimize parasitic TEF reducing precision of measuring). Thermocouples are used for measuring relatively high temperature of combustion chamber elements in aviation engines.

Materials used for thermocouples manufacturing and dependence of TEF on heating temperature are shown on the Fig. 3.3.

3.4. Conductors with high conductivity

To this group of materials conductors with specific resistance ρ not more than 0.1 μOhm·m are related, i.e. copper and its alloys, aluminum and its alloys, noble metals (Au, Ag, Pt, Ir, Os, Pd, Rh, Ru) and their alloys.

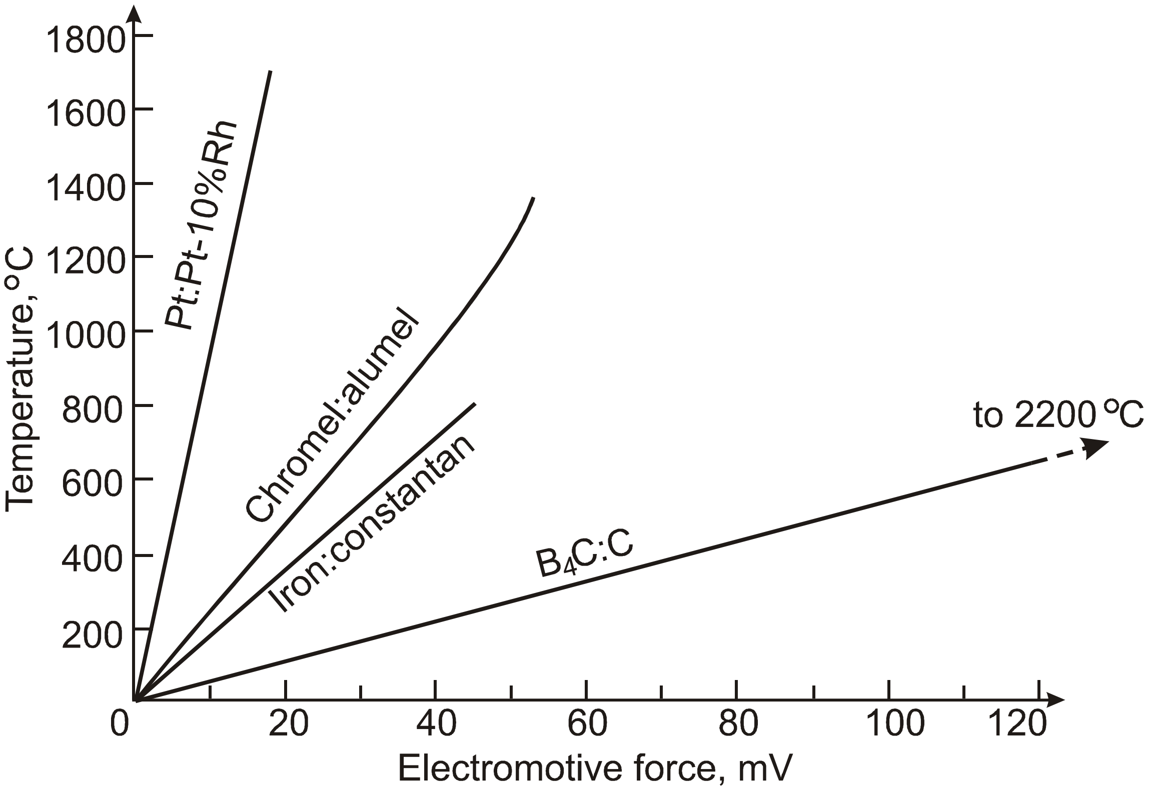


Fig. 3.3. Relationship between TEF (voltage) and temperature for several different thermocouples

3.4.1. Copper and its alloys

Such metals as copper, silver, iron, tin, lead and mercury were known from ancient times. Quantity of copper in Earth crust is very low (0.007%). Main natural copper compounds are Cu_2S, Cu_2O, Cu_2As (generally 250 compounds are known). Typically copper ore is reached by floating, remelted in furnace and refined.

In accordance with GOST fine grades of commercially pure copper is known: form M0 (99.95 %) to M4 (99.99 %).

Pure copper has face-centered cubic crystalline lattice, melting point is 1083°C, density is 8940 kg/m^3, ultimate strength of pure copper is 160 MPa, relative elongation δ=25 %, specific electrical conductivity ρ=0.0168 μOhm·m. Copper can be machined easily by pressure, but has poor cutting properties.

Copper is main electrotechnical material. In radiotechnical engineering such copper alloys as brass, bronze, Cu-Ni alloys supplied as round, square, rectangular, complicated section, bands, sheets, foils, tubes, powders.

Soft copper is used for coils and contact wires, cables, antennas, screens, films of micro-chips etc.

Hard copper is used for wires of external power lines, foiled materials, collectors of electrical machines, current conducting buses, contact wires etc.

Copper powder is used for brushes of electrical machines and metaloceramic materials.

Pure copper is not strong enough for many structural applications, has low cutability therefore copper alloys (brasses and bronzes) are widely used. Generally embedding of alloying elements to pure copper increases specific resistance.

Brasses have less conductivity comparing with pure copper (10…40 % of γ_{Cu}) and used for joining elements, socket elements, wire (dia 0.1…12.0 mm), antimagnetic bands for feeders, buses etc.

Bronzes are stronger than copper, have better thermal and anti-corrosion properties but less electrical conductivity (6…80 % of γ_{Cu}) and used for manufacturing of contacts, trolley wires, collector plates, springs, brush-keepers, sliding contacts, electrodes, clamps, tubes of measuring devices, cables and wires of elevated durability.

3.4.2. Aluminum and its alloys

Pure aluminum was obtained in 1825 and for further 60 year was considered as noble metal. In 1886 French and American engineers were developed main industrial method of pure aluminum manufacturing, i.e. **electrolysis**.

The cost of Al manufacturing is relatively expensive comparing with steel because for getting 1 ton of Al 16 MWatt·hr of electricity and 2 tons of aluminum ore – boxite $(Al_2O_3 \cdot H_2O)$ is required.

Al occupies the third place in Earth crust by mass (8.8 %), there are more then 250 types of Al ore is mined.

There are 13 grades of commercially pure Al – from A999 (quantity of impurities ≤0.001 %) up to A (quantity of impurities ≤1 %). Supplying shapes are wires, sheets, tapes, foil, buses, tubes etc.

Melting point of pure Al is 660°C, FCC crystalline lattice, σ_b=80 MPa, δ=35…40 %. Al has high anti-corrosion properties (higher than copper has) because of appearing of Al_2O_3 (alumina) film on surface of pure Al at oxidation. The thickness of alumina film is near 1 nano-meter, specific resistance $\rho=10^{14}$ Oh·m, discharge voltage is 200…300 V. Therefore Al_2O_3 film is used in capacitors, rectifiers and dischargers.

Electrical conductivity of Al is 63 % of γ_{Cu}, hardness and strength is less than copper has, thermal conductivity is 57 % of copper. At the same length and cross-section the resistance of Al conductor is 1.63 times more than copper one.

High purity Al is used for cases of electrolytic capacitors, foil, contact and coil wires, air power lines, feeders.

Al alloys of less purity are used for antennas, screens, cases of semiconducting devices, fingers of measuring devices, wave guides.

Following **deformable** and **casting** Al alloys are used in electrical engineering:

– duralumins – for load-carrying articles of devices and apparatus, antennas elements;

– АД31 (Al+0.4…0.9 % Mg+0.3…0.7 % Si) – for formed buses, sections, tubes of electrical engineering;

– АМц (Al+1.0…1.5 % Mn) and АМг (Al+0.2…0.5 % Mg+1.0…1.4 % Mn) – for manufacturing of electrotechnical bands and tapes;

– silumins (alloys of Al+Si) – for cases and gears of devices, front panels, screens etc;

– aldrey (Al+0.3…0.5 % Mg+0.4…0.7 % Si+0.2…0.3 % Fe) for air power and communication lines;

– magnalium – (Al+9.5…11.5 Mg) – for pointers and scales of measuring devices.

3.4.3. Noble metals

Main **noble metals** used in electrical engineering are gold, silver, metals of platinum group. Such name originates to their high corrosion resistance, acid resistance, high melting point, forgingability, high esthetic appearance. Quantity of noble metals in pure and ore state is very low and technology of commercial pure metal refining is very expansive.

3.4.3.1. Gold and its alloys

Gold is known from ancient times, quantity of gold in Earth crust is very low $5 \cdot 10^{-8}$ %, gold exists mainly in pure state, minerals happen very rarely.

Gold is glazing metals of yellow color with FCC lattice, melting point is 1063°C, elasticity modulus 211 GPa, σ_b=150 MPa, δ=40 %, density is 19.3 g/cm^3. Electrical and thermal conductivity of a gold is less than copper and silver have (ρ_{Au}=0.0225 µOhm·m). Gold semi-finished products are foils, rods, wires, powders of different purity.

In pure state and in alloys gold is used in economics, engineering and medicine. In medicine gold is used in X-rays, radio-therapy devices and dental prosthetics. Also gold is used in aviation, space and nuclear engineering, oil, chemical and glass-making industries, photography. Coating with gold is used in manufacturing of reflectors, wave guides, resonators, electrical contacts, semi-conductors, micro-chips, photo-resistors, solders.

Main alloying elements for gold is silver, copper, zinc, cadmium, nickel. Alloys of Au+Ag are soft, machined easily, alloys Au+Cu are hard and have high elasticity. Adding of zinc increases an alloy castability.

3.4.3.2. Silver and its alloys

Silver is one of the most electrical and thermal conductive metal with specific resistance ρ_{Ag}=0.016 μOhm·m, melting point T_{melt}=961°C, has FCC crystalline lattice, σ_b=200 MPa, δ=50 %, elasticity modulus E=80 GPa, density 10.5 g/cm^3. Quantity of silver in Earth crust is $1\cdot10^{-5}$ %. Majority of silver is obtained from lead-zinc, gold and copper containing ores.

Silver as structural and electrotechnical material is used both in pure and alloyed state for silvering of metal and non-metal materials by chemical and galvanic methods, deposition and condensation from vacuum medium. Silvering is used in manufacturing of projectors, lightings, wires, wave guides, electrodes of capacitors, micro-chips, as anti-corrosion coatings.

Also silver is used in photography, electrical engineering, electronics, jewelry, coinage.

High light-sensitivity of silver bromine is used in manufacturing of photographic paper, films for movies, protective glasses, solders and brazes (contain 10…30 % of silver), electrical silver-zinc cells (their weight is 3…5 times lighter then lead-based ones). Silver alloyed with bismuth can serve as neutrons moderator. Silver-ceramic and silver-metal oxide electrical contacts produced by methods of powder metallurgy can withstand millions of switching cycles and high amperage without destruction.

3.4.3.3. Metals of platinum group

Metals of so-called **platinum group** are platinum, osmium, palladium, ruthenium, rhodium. They have high melting point, their portion in Earth crust is very small and cost is very high (Table 3.1).

Ruthenium is hard and brittle metal with silver color and high corrosion resistance, presented in sulfide copper-nickel ores. Pure ruthenium is manufactured as powder and sintered rods. As alloying element ruthenium increases strength, hardness, electrical resistance and corrosion resistance of other alloys. Pt+Ru and Ru+Ir alloys are used for wear-resistant articles of measuring devices, electrical contacts, jewelry. Alloys of Ru+Ir can be met in thermocouples (with upper limit of measuring 2000°C), alloys Ru+Pt – in fuel elements. Ru alloys are also used as catalysts at synthesis of organic and non-organic products (hydrocarbons, polyethylene etc), super-conductors, external coatings of articles and colorizing agents in manufacturing od glasses, porcelain, enamels.

Rhodium is rare and dispersed in Earth crust metal. Generally Rh is presented as a impurity in ores of platinum, iridium and copper-nickel ores (from 3 up to 12%). Rh alloys possess high catalytic activity and are used in manufacturing of glass as filters, capacities for glass melting, thermocouples (up to 1800°C).

Pure Rh has high reflective ability in different mediums therefore Rh alloys are used for manufacturing reflectors, projectors, technical mirrors, jewelry.

Table 3.1. Properties of metals of platinum group

Metal	Percentage in Earth crust	Melting point, °C	Type of lattice	Specific resistance, μOhm·m	Cost with respect to gold	Density, g/cm^3	Ultimate strength, MPa	Elasticity modulus, GPa	Ductility, %
Ruthenium	$5 \cdot 10^{-7}$	2250	HCP	0.075	4.3	12.5	490	472	–
Rhodium	$1 \cdot 10^{-7}$	1960	BCC	0.043	6.2	12.4	420	275	9…15
Palladium	$1 \cdot 10^{-6}$	1552	–	0.108	1.0	12.0	190	121	25…40
Osmium	$5 \cdot 10^{-6}$	3050	HCP	0.095	7.5	22.5	–	580	–
Iridium	$1 \cdot 10^{-7}$	2410	HCP	0.054	5.3	22.4	230	528	2
Platinum	$5 \cdot 10^{-7}$	1759	BCC	0.0921	4.3	21.4	140	170	30…50

Palladium is light, low-melting metal. Can be machined easily with forging, forming, drawing, rolling, polishing, welding. Typical supplying shapes are rods, powders, foils, wires.

Pure Pd is used for filters for hydrogen, protective coatings. In combinations with Pt, Co, Ag, Au, Ni, palladium serves as catalyst in chemical industry, electro-radio engineering (resistors, contacts), in manufacturing of solders, capacitors and spinnerets for fibers drawing, medicine (needles, syringes, tips, prosthetic).

Osmium is hard and brittle metal of blue-grey color. Can be found in sulfide copper-nickel ores. Os has low ductility (plastic deformation can be conducted at temperature more than 1500°C). Pure Os is produced as powder and pressed rods. Typically Os is used in alloyed state (with Pt, Co, W) for manufacturing of compass needles, axes, rotating parts of watches, measuring devices, contacts, painting dyes, catalysts in organic synthesis.

Iridium is hard metal with silver-white color, possesses high corrosion resistance and is supplied as powder, rods, wires. Ir is used as alloying elements for many alloys. In pure state Ir is used as a foil for cathodes, manufacturing of crucibles, protective coatings. Ir+Pt alloys are used for crucibles, anodes, contacts, potentiometers, wearing articles, heart pacemakers, surgical tools and jewelry. All length standards are made of 10 % Ir+Pt alloy. Alloys of W+Ir are used for thermocouples (up to temperature 2000…2300°C).

Platinum is metal with silver-white color, was invented by Spanish engineers in 18th century. Pt ore can be found in Earth crust as alloys with Fe, Pd, Ir, Rh, Cu, Ni. Mainly commercially pure Pt is produced as foil (thickness up to 0.0025 mm) and wire (diameter up to 0.001 mm), ingots, powders. Pt can be polished and welded easily, possesses high corrosion resistance.

Pt alloys are used for corrosion-resistant capacities – boilers, crucibles, retorts, measuring devices and as catalysts, thermocouples, thermometers, electrical contacts, magnets, electrical heaters, potentiometers, high-melting solders, surgical tools, jewelry, protective coatings etc.

3.5. Conductors for different industrial application

This group of conductors includes refractory (or high-melting) metals and alloys, metals and alloys with average melting point, metals and alloys with low-melting point and solders (brazes).

3.5.1. Application of refractory metals in radio-technical engineering

Group of refractory metals (with melting point more than 1800°C) includes such metal elements as tungsten W, rhenium Re, tantalum Ta, molybdenum Mo, niobium Nb, hafnium Hf, vanadium V, zirconium Zr. Zirconium and hafnium possess polymorphic transformation. Rhenium, hafnium and zirconium have HCP crystalline lattice, the rest of metals – BCC one. Majority of mentioned metals were discovered more than 200 years ago (rhenium and hafnium – one hundred years ago). Development of supersonic aviation and rocket engineering stipulated wide application of refractory materials in aerospace structures.

Refractory metals used in electronic engineering are known as **electro-vacuum materials** because of application in main conductive elements of electro-vacuum and gas-discharge devices. In such devices refractory materials show such properties as:

– high mechanical strength that permits article to be low-deformable at high temperatures;

– high value of electrical resistance that permits to use them in filamentary cathodes (or cathodes of direct incandescence);

– low thermal expansion coefficients of refractory metals permit to join them directly with electro-vacuum glass and ceramics;

– high corrosion resistance of refractory metals at low temperatures (high oxidation rate appears over 600°C, this is why at high temperatures refractory metals can be used in inert atmosphere and vacuum);

– high erosion resistance permits to use refractories at conditions of gas discharge;

– low proper emission activity of materials permits to use then for inner electrodes (screens, reflectors, grids, supporting device etc).

Tungsten, molybdenum and their alloys are used for manufacturing of electronic lamps, high-voltage rectifiers, X-ray tubes, heating elements of furnaces (with operational temperature up to 3000°C), welding electrodes, thermocouples, relay contacts.

Tantalum, niobium are used for gas absorbers, film resistors for motherboards, electrolytic capacitors.

Rhenium and its alloys are used for thermo-couples (W-Re) for measuring temperatures up to 2800°C, protective coatings for articles made of copper, silver, tungsten, molybdenum, high-precision resistors for chips.

Vanadium and its alloys are used for non-oxidizing electrical contacts, superconductors, solders for refractory metals soldering, articles of X-ray tubes etc.

Hafnium in pure state is used for reinforcement of lamps, wires for potentiometers, plates of welding electrodes, optical glasses, cermets etc.

Zirconium is used for manufacturing of reinforcements of lamps and laser structure.

3.5.2. Metals with average melting point used in electrical radio engineering

This group includes metals with melting temperature up to 1800°C, i.e. iron, nickel, cobalt and their alloys. Generally these alloys are very ductile and can be processed by work hardening. Application of mentioned alloys in electro-vacuum engineering is restricted by their average refractory properties, lower strength and ability to be low-deformable at high temperature. Therefore they can be used at moderate thermal loads. All mentioned metals are ferromagnetic and their α_ρ is 1.5 times more than thermal resistance coefficient of majority of metal conductors.

For mentioned metals Matisson’s rule is the following

$$\rho = \rho_{\text{therm}} + \rho_{\text{res}} + \rho_{\text{M}}, \qquad (3.12)$$

where ρ_{M}– portion of electrical resistance stipulated by distortion of spinal order.

Iron is the cheapest and available metal with ρ=0.097 µOhm·m. Iron alloys are mostly wide-spread structural materials of up-to-date engineering.

Iron is main and cheapest component of magnetic materials, high-temperature resistant alloys and alloys with high electrical resistance.

Low-carbon-steels are used in manufacturing of shells (bases) of metal electronic lamps, cases of resistances and capacitors.

Stainless steels are used for articles of cathode-ray (electron-beam) tubes, i.e. modulators, anodes, deflection electrodes and cylinders. Also other steel grades are used for wires, current stabilizers, mercury rectifiers, articles of inner conductive elements – anodes, screens, grids etc.

Nickel creates alloys with all metals of periodic table and serves as main component of many magnetic (alnico, alni, alnisi, permalloy etc), resistive (constantan, Germal silver, nikeline etc), thermal-resistant (Nichrome) and special (platinite, invar, covar etc) alloys.

Nickel is used in cadmium- and iron-nickel electrical cells, heaters, thermometers of resistance, magnetostrictive vibrators of ultrasonic devices, as material for protective coatings, nickel oxides are used for manufacturing of glasses of variable colors (from purple to yellow).

Cobalt (Co) is metal of grey color with light blue tint, was found in 1835. Content of cobalt in Earth crust is $3{\cdot}10^{-3}$ %. Density of Co is 8650 kg/m^3, melting point is 1500°C. Up to 450°C it exists in α-modification (HCP), above – in β-modification (BCC), specific electrical resistance ρ=0.064 μOhm·m, elasticity modulus is 209 GPa, ultimate strength is 260 MPa, relative elongation – up 5 %.

Cobalt is produced as sheets, plates, castings and powders (quantity of impurities is from 0.02 up to 3 %).

Co possesses high dyeing ability and is used for colorizing of glasses with selective permeability, in photography and alarm systems. Also Co serves as alloying element for speed-cutting steels, hard alloys. Introduction of Co to magnetic alloys increases their coercive force Hc (resistance to demagnetizing) and vibro-resistance (ability to keep level of magnetic properties at vibration).

Cobalt can be used as protective coating, in special alloys with nickel and iron (Invar, Covar) cobalt is used in electronic lamps, micro-chips, semi-conductive devices.

3.5.3. Conductors with moderate and low melting temperature

This subgroup of conductors includes metals with melting point less than 700°C: lead, tin, zinc, cadmium, indium, gallium, mercury, stibium, bismuth, thallium and solders.

Lead is known from ancient ages, has grey color, very soft, ductile, low-strength metal. Density of lead is 11340 kg/m^3, melting point – 327 °C, elasticity modulus – 15.7 GPa, ultimate strength σ_B= 12 MPa, specific resistance – ρ= 0.207 μOhm·m. Quantity of lead in Earth crust is $1.6 \cdot 10^{-3}$ %. Lead sheets, tubes and wires of high purity (>99.9%) are produced.

Main consumers of a lead are cable-manufacturing (i.e. cable shells) and accumulator (cell plates) branches. Acid-lead accumulators take up 90 % of total amount, Ni-Cd, Ni-Fe, Ag-Zn ones – up to 10 %.

Lead (Pb) is also used for typographic and low-friction alloys, electrical fuses, different solders and brazers, elements of X-ray protective armors, fire arms, semiconductors, thermal generators (telluride and selenide of lead), superconductors (Cu+Pb alloy), dyes, glasses, enamels (PbO) etc.

Tin (Sn) is also ancient metal (Sanskrit word “stannum” means stable). Density of tin is 729 kg/m^3; melting point – 232 °C, elasticity modulus – 54 GPa, ultimate tension strength – 10.0…40.0 MPa, maximum relative elongation δ =40 %; specific resistance – 0.113 μOhm·m. Tin is soft and ductile metal, can be rolled in sheets and foils which are used in paper and mica capacitors.

Tin compounds are used for manufacturing of glazing coatings and enamels (SnO_2), glasses (mat, ruby, with conductive surface), dyers (SnCl), ferroelectrics ($BaSnO_3$), tin-organic compounds SnR_4-type (where R is carbon-hydrogen radical) for agriculture (insecticide) and chemical industry (catalysts).

So-called “grey” tin (α-Sn) is used for semi-conductors, shape-memory alloys (Sn-Cu), mirrors of telescopes (alloy of 25 % Sn and 75 % Cu) etc.

Zinc (Zn) is light, malleable metal (can be rolled easily to sheets), has density 7140 kg/m^3, melting point – 419℃, elasticity modulus – 99.2 GPa, specific resistance – 0.0592 μOhm·m, crystalline lattice is HPC, $\sigma_в$=150 MPa, high corrosion resistance, i.e. 40 % of metal protective coatings consist of zinc compounds. Zn coating is more cheap and reliable than chrome plating and nickeling. Only Fe and Pb are cheaper than Zn. Zn is more chemically active as iron and used for metal articles protection from damages and deterioration.

Zinc and its alloys are used in manufacturing of typographic, antifriction, copper alloys, dyes, rubber, oscillographs, plastics, semi-conductors, reflactive coatings, galvanic elements, cells, capacitors, photo-elements etc.

Cadmium (Cd) was discovered in 1817. This metal has HCP lattice, density is 8650 kg/m^3, melting point – 321℃, elasticity modulus – 63 GPa, ultimate tension strength is 95 МПа, δ=44 %, specific resistance – ρ=0.074 μOhm·m.

Cadmium is used for coatings of steels and other alloys, manufacturing of typographic (cliche), anti-friction (sliding bearings), low-melting, noble and copper alloys. Low-melting alloys (Cd+Bi, Sn, Pb) are used as solders (Wood's alloy). Alloys of Cd with Au and Ag are noble and used in jewelry and for electrical contacts.

Also cadmium and its alloys are used for manufacturing of electrical fuses (alloy of Cd+Sn+Pb), thermal-vision detectors for infra-red radiation (alloy of Cd+Hg+Ti), elements of solar batteries (CdS), semi-conducting devices (CdS, CdSe), nickel-cadmium cells, nuclear reactors (for regulators of neutron reation rate), dyes (CdS).

Indium (In) (from the word "indigo" (i.e. navy blue) due to vivid blue spectrum line) is heavy, attractive metal of white grey color. It has density 7300 kg/m^3, melting point – 150℃, elasticity modulus – 10.5 GPa, ultimate tension strength – 2.25 MPa, specific resistance ρ=0.09 μOhm·m, tetragonal FCC lattice.

Indium and its alloys are used in bearing alloys (increase their mechanical properties, wettability, corrosion resistance), low-melting (alloy of In, Bi, Pb, Sn, Cd are used for fuse element of fire alarm systems), as solders in semi-conductors manufacturing (InSb), thermal-vision detectors and coercive force measurers (InAs), solar cells, transistors (InS).

Moreover In is applied as protective coating in nuclear (regulating rods), jewelry and dentistry engineering, glasses manufacturing (optical glass, surface-conductive glass, high-reflective mirrors).

Gallium (Ga) is silver-white soft metal visually similar to tin. It has orthorhombic structure that leads to changing of density (from 5900 to 6090 kg/m^3) and specific resistance (from 0.449 to 0,257 μOhm·m) at melting. Melting point is 30℃, ultimate tension strength is 19.6 …37.2 MPa. Gallium possesses electrical and thermal anisotropy, contracts at crystallization, stays liquid at quite wide temperature range (from 30 to 2230℃).

Ga and its alloys and chemical compounds are used for manufacturing of thermometers with operational temperature up to 1200 ℃, low-melting alloys (for example an alloy of In and Ga has melting point 16℃), germanium and silicon semi-conductors (as acceptor impurity), semi-conductive devices (diods, transistors, photo-elements, dosimeters, lasers, solar cells) based on $A^{III}B^{V}$ group (GaW, GaP, GaAs, GaSb), glasses with high refraction coefficient or with high permeability of infra-red radiation, mirrors with high reflection ability.

Mercury (Hg) is known from ancient times, quantity of Hg in Earth crust is $8.3 \cdot 10^{-6}$ %. Crystallization temperature of Hg is -39℃, density – 13500 kg/m^3, specific resistance – ρ=0.958 μOhm·m.

Mercury is used in chemical industry as catalyst for production of chemicals and organic substances, in metallurgy for production of metal powders, alloys and pure metals, in power engineering (mercury-steam turbines and heat-carriers of nuclear rectors), in lamps (luminescent, daylight, quartz, gas-filled), for manufacturing of barometers, pressure-gages, thermometers, gates, interrupters, in pumps of vacuum devices, mercury rectifiers and relays, in manufacturing of dyes (HgO) and luminophors (HgS).

Antimony (or stibium) (Sb) is known from 3 millenniums B.C. Contents of antimony in Earth crust is $5 \cdot 10^{-5}$ %, in meteorites – $1 \cdot 10^{-5}$ %.

Sb is silver-gray brittle metal with high reflective ability. Its density is 6690 kg/m^3, melting point – 630℃, specific resistance – 0.4 μOhm·m, ultimate tension strength – 9.8 MPa, elasticity modulus – 5.8 GPa. There are more than 200 grades of Sb alloys. Antimony is used for production of solders, typographic, antifriction alloys, cable coatings, cell grids, material for bullets etc.

Also Sb compounds are used in manufacturing of optical glasses and ceramics, organic synthesis and plastics manufacturing, pharmaceutical, textile, varnish-paint, match and rubber (vulcanization) branches of industry, in gages and detectors of computing machines, chips, solar batteries (AlSb, GaSb, InSb).

Bismuth (Bi) is known from the 15-th century. Bi is silver-white glazing metal with pink tint. It has density 9800 kg/m^3; melting point – 271,3℃; specific resistance ρ=1.16 μOhm·m, elasticity modulus – 34 GPa; ultimate tension strength – 18.6 GPa.

Main consumers of Bi are metallurgical, pharmaceutical, chemical and glass industry, nuclear, rocket, electronic engineering. Bi is the component of low-melting alloys: Wood's alloy (25 % Pb, 12.5 % Sn, 12.5 % Cd, 50% Bi) has melting point 60℃; Newton's alloy (31 % Pb, 19 % Sn, 50 % Bi) – 95℃. Such alloys are used as solders and fuses of alarm systems.

Alloy of Mn+Bi is used for manufacturing of powerful permanent magnets, Bi+Sb – amplifiers and switches. Bi serves as donor impurity for germanium, Bi-glass film has high magnetic and super-conductive properties. Also Bi is used in magnetic-ohm gages (resistance of which depends on field intensity). Bi compounds are used in production of enamels, glass, solar cells, thermo-electrical fridges (BiSe, BiTl, BiSb), semi-conductors ($AgBiS_2$, BiAgCs), super-conductors ($CaBi_3$, $SrBi_3$, PdBi).

Thallium (Tl) is silver-white metal with blue tint. Three main modifications of Tl are known: α-Tl with HCP lattice, β-Tl and γ-Tl with FCC lattice. Thallium density is 11850 kg/m^3, melting point – 303°C, specific resistance 0.18 μOhm·m, elasticity modulus – 8 GPa, ultimate tension strength – 8.8 MPa. By physical-mechanical properties Tl is close to the lead, by chemical – to alkali metals.

Ti is used in semi-conductive devices (as alloying element), scintillometers, gas-discharge (Tl vapor), luminescent and fluorescent lamps, thermal-vision detectors, lenses and prisms of optical devices (monocrystals, TlBr, Tl-iodine), special glasses.

Alloy of Hg and 8.3 % Tl is used for low-temperature thermometers; alloy of 3.5 % Tl + 96.4 % Pb +Ca+Fe – for insoluble anodes; alloy of 8 % Tl + 72 % Pb +15 % Sb and 5 % Sn – for bearings.

Solders are materials creating binding layer between joining articles in process of soldering. As solders metal, alloys and oxides are used. Solders are produced as rods, wires, sheets, strips, spirals etc.

All solders are divided into soft (so-called **brazers**) with melting point up to 400°C and hard – with melting point from 500 to 1500°C. Alloys of tin (10…90 %) and lead, tin and zinc are used as soft solders. To give special properties to a solder it can be alloyed with following elements: antimony increases solder strength, cadmium – electrical conductivity

Alloys of Ag+Cu+Zn and Cu-Zn are used as hard solders.

3.6. Conductors of high electrical resistance

Conductive materials of high electrical resistance are necessary to adsorb electrical energy and conversion it to heat. Typical application is resistors, heating elements and thermocouples.

Main requirements to materials of this group are high specific resistance (ρ not less than 0.3 μOhm·m) and stability of properties with time, low thermo-electromotive force in pair with copper and thermal coefficient α_ρ, moderate ductility and mechanical strength, ability to operate at temperature up to 1000°C.

By application such materials can be divided on resistive, thermal-resistant, materials for thermocouples.

Resistive materials are produced as wire, shapes, rods, strips, foil and used for manufacturing of rheostat, wired and filmed resistors.

Alloys having deformed crystalline lattice (solid solutions) and materials based on metal compounds (oxides, carbides, silicides) with low thermal coefficients α_ρ are used as high-resistive conductors.

Mostly wide spread high-ohmic alloys are such alloys of copper and nickel as **manganin** and **constantan**.

Manganin (86 % Cu, 12 % Mn, 2 % Ni) has ρ=0.42…0.48 μOhm·m and thermal EMF with respect to copper 1.0…2.0 μV·^{o}C^{-1}. It is produced as soft and hard wire and strips, micro-wire in glass insulation and used as template resistive set of resistors, bridges, shunt circuits of electrically-measuring devices.

Manganin containing up to 60…70 % of Mn is known as radio-manganin. It possesses quite high resistance and α_ρ close to zero and is used for production of compensative and stabilizing elements of electrical circuits.

At elevated temperatures manganine articles oxidize through the time that leads to changing of contact resistance. To escape of loosing precision of such device of auto-pilots and special navigation equipment silver (up to 10%) is added to manganine composition.

Constantan (60 % Cu, 40 % Ni) has ρ=0.42…0.52 μOhm·m, thermal EMF with respect to copper 40 $\mu V \cdot {}^\circ C^{-1}$. The name of the alloy originates to the word «constant» that means stability of its resistance in temperature range ± 100°C. Constantan is produced as wire in oxide insulation.

Constantan has high coefficient of strain-sensitivity

$$d = \frac{\Delta R / R}{\Delta l / l}, \qquad (3.12)$$

where R and l are original resistance and length of a conductor; ΔR and Δl – their absolute changing. Therefore constantan is major material for manufacturing of strain-gages, rheostats, potentiometers, airplane heating devices (deicers), cells, crew suits, thermocouples copper-constantan and iron-constantan for measuring temperatures up to 1000 °C.

More cheap copper-nickel resistive alloys are nickeline (68.5 % Cu, 30 % Ni, 1.5 % Mn) and German silver (Nickel silver) (65 % Cu, 15 % Ni, 20 % Zn) which are used in launching rheostats and wired resistors.

High precision low-dimension resistors and potentiometers are manufactured of noble metals alloys (Pt+8 % Ni), (Pt+5 %W), (Pd+40 %Ag).

Film resistive materials are used for production of fixed and alternative resistors in filmed form. Film is deposited on a substrate by vacuum evaporation or by spreading of resistive material or by bombing by ions of inert gas.

For such film elements following materials are used: chromium, tantalum, tantalum nitride, rhenium, nichrome, silicides of metals, cermets, composites and carbon-containing materials. Specific resistance of metal silicides belongs to the range 5…35 μOhm·m.

Thermal-resistant materials are used for heating devices powered passing electrical current.

Main requirement to such materials are high resistance and low rate of interaction (low-oxidized or low-vaporized in vacuum) with ambient atmosphere.

For operation in air atmosphere up to 500°C such materials as constantan, nichrome, fechral (Fe+Cr+Al alloy), chromals, refractory, noble metals and alloys, non-metal materials based on $MoSi_2$, SiC, Al_2O_3 are used.

Nichromes (65…80 % Ni, 10…30 % Cr, up to 1.5 % Si, up to 3.5 % Al) has high oxidation resistance at open air at high temperatures that can be explained by appearing of protective layer of stable oxide film Cr_2O_3 и NiO. Nichromes have ρ = 0.83…1.45 μOhm·m and produced as strips and wires of difrent diameter (up to microns).

Nichromes are used for manufacturing of rsisators and rheostats, heating elements for utility usage, industrial and laboratory furnaces operating in air, vacuum and other mediums up to 1200℃.

Cheaper alloys are ferro-nichromes (contain iron up to 8…23 %), they have elevated ductility and are used as conventional nichromes.

Chromium-aluminum alloys (fechrals and chromals) are cheaper than nichromes but less manufacturable, more hard and brittle. Therefore such alloys are produced as strips and wires of relatively large cross-section and used for heaters and rheostats of high power.

Fechrals (12…15 % Cr, 3.5…5 % Al, 1.0 % Si, up to 0.7 % Mn and Fe) have specific resistance ρ=1.18…1.34 μOhm·m and operation temperature up to 900℃.

Chromals (21.5…28 % Cr, 4.5…5.8 % Al, 0.6 % Ni, 0.3…0.5 % Mn, 0.6…0.7 % Si, rest is Fe) have ρ=1.4…1.5 μOhm·m and operation temperature up to 1200℃.

At temperatures above 1200℃ above-mentioned materials can't be used due to intensive oxidation and melting and can be replaced by refractory, noble metals and non-metals. Heating devices of noble metals (Pt, alloys of Pt-Ir, Pt-Rh) can operate up to 1500...1600℃. such materials are used for high-precision furnaces, at operation in aggressive mediums, vacuum systems, cathodes of electro-vacuum devices etc.

Materials for thermo-couples are produced of pure metals and alloys. Typically following systems of materials are used:

1. Copper-constantan has thermo-EMF E_T=40 $\mu V\cdot{}^{\circ}C^{-1}$ and thermal operation range $\Delta t°$= (-271…275℃).

2. Irono-constantan has E_T=56 $\mu V\cdot{}^{\circ}C^{-1}$ and thermal operation range $\Delta t°$=(-271…1000 ℃).

3. Platinum-Platinum-Rhodium alloy has E_T=6.4 $\mu V\cdot{}^{\circ}C^{-1}$ and thermal operation range $\Delta t°$=(-25…1600 ℃).

4. Tungsten-Rhenium has E_T=14 $\mu V\cdot{}^{\circ}C^{-1}$ and operational temperature up to 2000℃ and more.

Thermocouples are mainly produced of following alloys: copel (56 % Cu, 44 % Ni), alumel (95 % Ni, rest is Al, Si and Mg), chromel (90 % Ni and 10 % Cr).

Copel by chemical composition is very close to constantan by less thermally-resistant as alumel and chromel. Copel has high ductility and is manufactured as wire.

Alumel has thermal resistance up to 1200℃, high ductility (can be processes by forging and drawing), has magnetic properties.

Chromel has good mechanical properties and thermal-resistance but has no magnetic properties.

Following thermocouples and compensating wires can be produced of mentioned alloys:

1. Chromel-alumel with E_T= 40 $\mu V \cdot °C^{-1}$, $\Delta t°$=(-60…1200°C).
2. Chromel-copel with E_T= 70 $\mu V \cdot °C^{-1}$, $\Delta t°$ (-60… 800°C).

3.7. Non-metal and composite conductors

Different composites, ceramics (oxides) and some modifications of carbon can be used as conductors too for manufacturing of contact and current-conductive elements.

3.7.1. Materials based on conductive modifications of carbon

For manufacturing of electro-carbon articles such substances as carbon, carbon-black, pyrolitic carbon, different types of coal (coke, anthracite, wooden) are used. As binding agents resol and silicon-organic resins are used.

Following groups of elements are produced of mentioned materials:

- sliding contacts (brushes) of electrical machines (graphite, carbon-graphite and copper-graphite);
- live coals of lightning devices (projectors, cinema-projectors, light-coping and spectrum devices) and electrical furnaces;
- coal regulating resistors having variable resistance of contact coal surfaces (resistance depend on degree of pressing) which are used for electrical current regulation;
- coal contacts of copper-graphite and silver-graphite mixture impregnated with lead-tin alloys;
- microphone powders (anthracite) and membrane (pressed mixture of 75% of coke and 25 % of tar pitch with consequent sintering) for microphones and throat microphones;
- carbon-containing and boron-containing fixed and variable resistors for shunts, relay-regulators and ignition circuits;
- coal electrodes of galvanic elements;
- contacts of movable current-conductive devices of подвижных токосъемных устройств electric locomotive and trolleybuses.

3.7.2. Conductive materials based on oxides

Majority of metal oxides at normal conditions are dielectrics. But if oxidation in not completed fully (stoichiometric composition s disturbed) or embedding of impurities their conductivity becomes higher and they can be used as contact or resistive layers. Mostly oxides of tin (SnO_3) and iridium (In_2O_3) are used as thin films produced by thermal evaporation in vacuum with consequent condensation; by oxidation of films deposited on tin substrate or by cathode or ion-plasma spraying. Such films have high adhesive strength and transparency in visual and infrared spectrum bands.

Oxide conductors are used as conductive layers of inner walls of glass balloons of electric-vacuum devices, electrodes of electric-luminescent capacitors and liquid-crystal indicators, transmitting television tubes, imaging transmitters and amplifiers etc.

3.7.3. Conductive composites

First group of conductive composite is the mixture of conductive filler with dielectric binder. As conductive phase metals, graphite, carbon black and carbides are used. Function of binder is fulfilled by organic and non-organic (bakelite, glyptale, epoxy, silicon-organic resins) dielectrics.

Conductive composites are used for manufacturing of resistors with fixed and variable resistance (filmed and volumetric).

Second group of conductive composites is **contactols**, i.e. electrically conductive adhesives, paints, coatings, enamels. Powders of silver, gold, palladium and nickel are used as filler in such materials.

Contactols are used for increasing electrical conductivity of metal surfaces, metallization of surfaces, creating of electrical and thermal contacts with semi-conductive materials.

Electrically conductive paints, coatings, enamels are used for removing superficial currents of leakage in measuring devices, shielding of rooms and devices from interference, creating of electrically conductive communications on dielectrics, electrical schemes, heating elements of anti-ice airplane system.

Third group of conductive composites include **cermets**, i.e. metal-dielectric composition with non-organic binder (ceramics). Main advantage of cermets is possibility to control their specific resistance by means of changinh quantity of electrically conductive phase.

Mostly composition of 70 % Cr and 30 % SiO is known. This cermet is used for production of thin-film resistors, glasses with Pd and Ag for thick-film resistors of chips.

3.8. Superconductors

Many materials show physical phenomenon as sharp reduction od specific resistance at temperature close to absolute zero. Such phenomenon is known as **superconductivity** and temperature T_{sc} at which the phenomenon happens in known as **critical transition temperature**. Superconductivity was found in 1911 in mercury at 4.2 K.

It is established that superconductivity appears in case when electrons attract to each other that possible in medium with positively charged ions which in their turn weaken forces of coulomb repulsing between electrons. Electrons with opposite spins only can be attracted and create pairs known as **Cooper**

pair or **superconductive pair**. Such paired electrons don't disperse on crystalline defects and impurities, thermal oscillation of crystalline lattice nodes is negligible that leads to very low resistance of superconductors.

Phenomenon of superconductivity is reversible and can be braked if conductor is disposed inside magnetic field with intensity H_{cr}. Depending on behavior in magnetic field superconductors of first type (or **soft**) and second type (**hard**) can be distinguished. Terms soft and hard don't related to their hardness but to different value of H_{cr} (it is low in "soft" conductors and high in "hard" ones).

Superconductors of the first type have sharp transition to superconductive state at constant value of H_{cr}. Superconductors of the second type transit to original state to superconductive one consequently and can be characterized by lower H_{cr1} and upper H_{cr2} critical intensity of magnetic field.

There are 26 metals having superconductivity phenomenon. Only niobium, vanadium and technetium are conductors of the second type. Other 13 elements have superconductive properties at elevated temperatures (elementary semi-conductors are in this list). Au, Ag, Cu have no superconductivity.

Besides of pure metals several intermetal compounds and alloys possess superconductivity phenomenon. Nowadays more than 2000 superconductive materials are known.

But they have very low transition temperature T_{sc} that requires cooling by liquid helium (because the temperature of helium liquidizing is 4.2K). This process is complicated and expansive. Therefore superconductors with liquidizing temperature more than hydrogen liquidizing (20.4 K) or more than nitrogen liquidizing (77.4 K) are quite prospective.

Nowadays such alloys and compounds of niobium (Nb_3Sn, Nb_3Ga, Nb_3Ge) with transition temperature from 18.3 to 24.3 K have the highest critical parameters.

One of the main directions of superconductors application is creation of very powerful magnetic fields. Superconductive coils permit to obtain fields with intensity above 107 A/m in synchrophasotrons and other accelerators, reactors of thermo-nuclear synthesis, magneto-dynamic convertors of heat energy to electrical one.

Electrical machines with superconductive coil are nowadays under intensive developing. They permit to reduce mass and overall dimensions of such machines in 5…7 times. Developing of superconductive transformers, transmission facilities, coils, resonators of high quality are economically well grounded.

The phenomenon of superconductivity disturbance by magnetic field is used in cryotronic cell of computing machines, memory and switching schemes.

Application of superconductors in measuring engineering for creation of very-sensitive bolometers, magnitonometers, indicators of ultra-low currents and voltages is quite prospective.

4. MAGNETIC MATERIALS

4.1. Fundamentals of materials magnetizing

Magnetic materials are ones that can interact with outer magnetic field and having definite magnetic properties which depend on following physical phenomena: movement of electrons over nuclear (orbital moment appears), rotation of electrons over its own axes (spin magnetic moment appears), arrangement of electronic shells of atom, electro-static interaction of electron's shells of neighboring atoms and non-compensated spins, energy relationships in a substance related to creation of closed macroscopic regions (domains).

Electronic shell of an atom and its nuclear have proper **magnetic moments**. Magnetic moment of entire electron shell is vector sum of spin and orbital moments of shell electrons. It is approximately 1000 times more than the moment of nuclear and defines magnetic properties of an atom and entire substance.

Visual view of a substance and its properties are defined by partial or full compensation of spin and orbital magnetic moments of electrons. Depending on compensation type following groups of materials can be distinguished: diamagnetics, paramagnetics, ferromagnetics, anti-ferromagnetics, ferrimagnetics (non-compensated anti-ferromagnetics) (Fig. 4.1).

Diamagnetics are materials with full compensation of magnetic moments. In **paramagnetics** magnetic moments of particles are disordered at absence of external magnetic field. **Antiferromagnetics** are substances in which anti-parallel orientation of magnetic moments occurs spontaneously. **Ferromagnetics** generally are characterized by magnetic order stipulated by presence of macroscopic regions (domains) with parallel orientation of magnetic moments. **Ferrimagnetics** have anti-parallel magnetic moments but with different absolute value that leads to domain magnetization.

Domain is the region of spontaneous magnetization with parallel orientation of magnetic moments of electrons. Linear dimensions of domains are from 10^{-3} mm to 0.5 mm and total magnetic moment in 10^{15} times more that atom magnetic moment. Domains are divided from each other by boundary layer known as "Bloch wall" having dimensions of several hundreds of interatomic distances (for example, for in iron their thickness is 100 nanometers). Inside of each layer (boundary) continuous changing of magnetic moments orientation happens from one domain to another.

Magnetic properties of materials are defined by such characteristics as magnetic anisotropy, magnetostriction, magnetizability, magnetic permeability, losses etc.

Monocrystalls of ferromagnetics possess magnetic anisotropy and have axes of easy and hard magnetizing quantity of which is defined by crystalline lattice symmetry. For example, iron with cubic lattice has six directions of easy magnetization (defections of the cube ribs), nickel with cubic lattice – eight directions, cobalt with hexagonal lattice - only two directions of easy magnetization directed antiparallel to along prism axes.

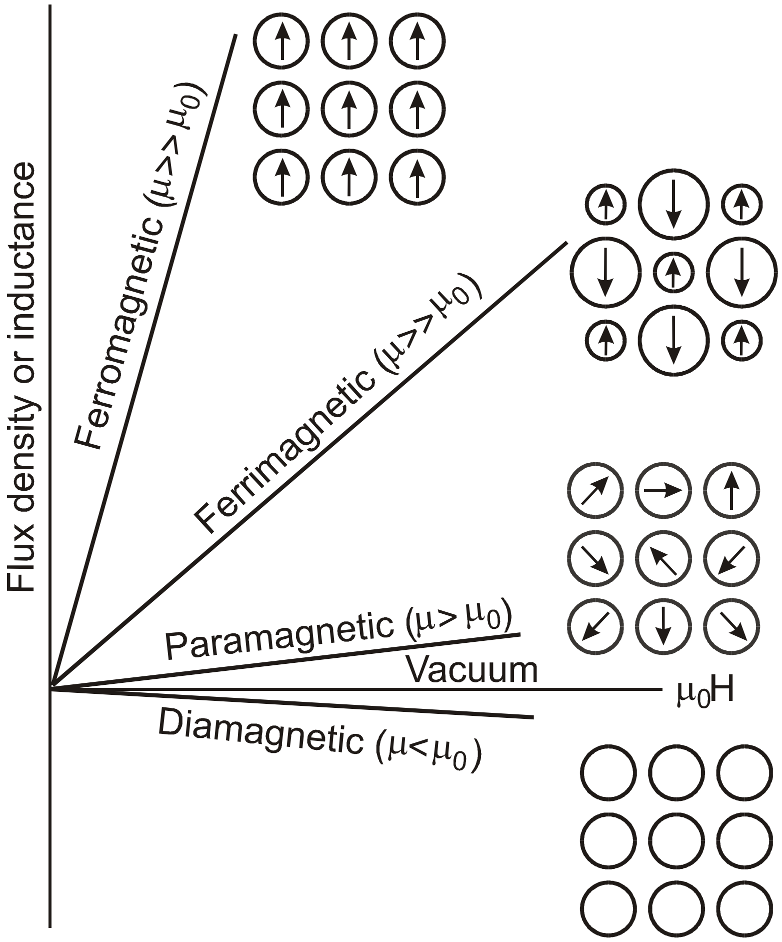


Fig. 4.1. Classification of magnetic materials by behavior in magnetic field

It was established experimentally that changing of magnetic state of a specimen leads to changing of its linear dimensions. This phenomenon is known as **magnetostriction**. Magnetostriction can be **linear** and **volumetric**. **Linear** is estimated by coefficient of relative deformation (magnetostriction coefficient) in direction of magnetic field $\lambda_l = \Delta l / l$. **Volumetric** is characterized by relative changing of a specimen volume at magnetizing $\lambda_V = \pm \Delta V / V$. Magnetiostriction can be both positive and negative. For example λ_l in iron is positive in weak fields and negative in strong fields.

Magnetization M (A/m) is the value of magnetic moment of unit material volume related to intensity of magnetic field H by relation

$$M = \chi H \, , \qquad (4.1)$$

where χ – magnetic susceptibility.

Magnetic susceptibility (dimensionless value) is characteristic of a material to change its magnetic moment under effect of outer magnetic field and numerically equal to magnetization at unit intensity of magnetic field.

Magnetic induction B can be determined as (if magnetization M is known)

$$B = \mu_0(H + M) = \mu_0 H(1 + \chi) = \mu_0 \mu H, \qquad (4.2)$$

where $\mu_0 = 1.257 \cdot 10^{-6}$, H/m– magnetic constant; $\mu_0 \mu$– absolute magnetic permeability μ_a, H/m; μ– relative magnetic permeability.

From the (4.2) following relationship is obtained: $\mu = 1 + \chi$.

Graphical visualizing of dependence between magnetic induction B, magnetization M and main structural parameters of conventional induction coil and core are shown on the Fig. 4.2.

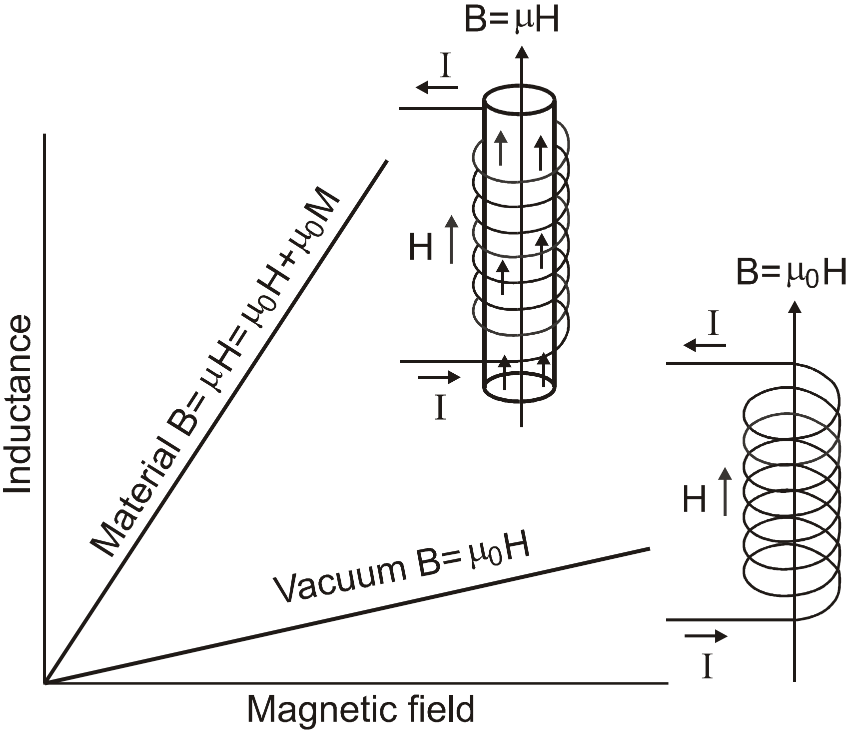


Fig. 4.2 Dependence between main magnetic parameters

4.1.1. Magnetization curves of magnetic materials

Dependence of magnetic induction B on intensity of outer magnetic field H is known as **magnetization curve** (Figs. 4.3, 4.4).

Growing of induction B under effect of outer field is stipulated by two main processes: **by displacement of boundaries** and by **rotation of magnetic moments of domains**. Original section of a curve (region 1) characterizes reversible displacement of domain boundaries. This process is accompanied by increasing volume of those domains magnetic moments which apply lowest angle with direction of outer field and vice versa – by decreasing of volume at unfavourable orientation of a vector of spontaneous magnetization. After removing effect of outer field domain boundaries return to original state and residual magnetization is absent (dash line a0).

At the region of more strong fields (region II) displacement of domain boundaries is irreversible slip-stick character (Barkhausen effect) and is accompanied by residual magnetizing after external magnetic field removal (section 0n).

Further increasing of magnetic field intensity leads to more significant influence of secondary mechanism of magnetization – i. e. mechanism of rotation at which magnetic moments of domains steadily rotate in direction of outer field (region III). This process is also irreversible so it is accompanied by residual magnetizing at external field removal (section 0к) and by **hysteresis phenomenon**.

When all magnetic moments of domains are ordered (fully rotated from the direction of weak magnetization to the direction parallel to outer field direction) **saturated state** occurs (region IV). Negligible growth of induction B at this section is stipulated by increasing of magnetization of exact monodomain due to force lines of magnetizing field (so-called para-process). This process is reversible (dash line df) because vector of magnetization returns to the direction of weak magnetization after external filed removal.

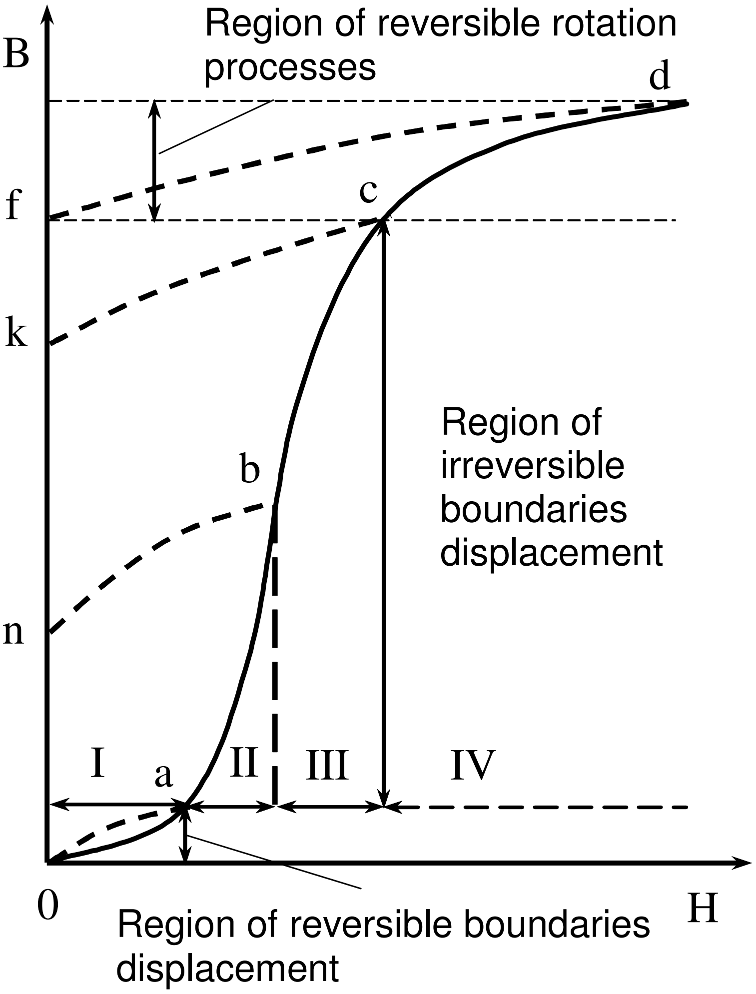


Fig. 4.3. Dependence of magnetic induction B on intensity of outer magnetic field H

Magnetic state of a substance can be described by dependence $M=f_1(H)$ and $B=f_2(H)$ therefore dual designation can be used for determination of residual induction ($B_{r_{\text{в}}}$ or $\mu_0 M_r$) and coercive force ($H_{C\text{в}}$ and H_{CM}) for the first and the second dependencies.

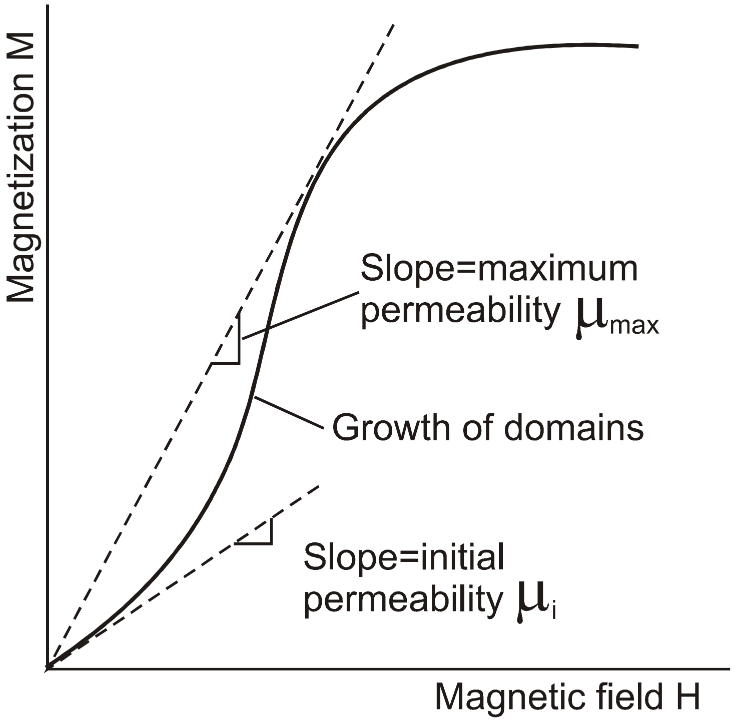


Fig. 4.4 Dependence of magnetization M on magnetic field H

Main stages of magnetization process are shown on the Fig. 4.5.

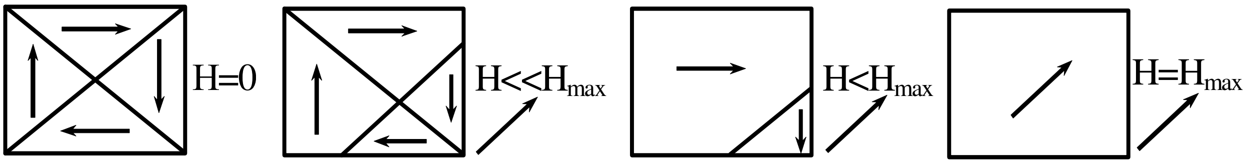


Fig. 4.5. Scheme of orientation of magnetic moments at magnetization

4.1.2. Magnetic hysteresis

Irreversible processes of material magnetizing (see Fig. 4.3, regions II, III) explain significant delaying of changing induction B on intensity of magnetic field H at cyclic **magnetization reversal** (**remagnetizing**) of materials. Such delaying phenomenon is known as **hysteresis**.

At magnetization of a material up to the induction of saturation B_S and consequent external field removal magnetic induction doesn't return to its original value because induction decreases not by magnetization curve but more slowly and at intensity H=0 becomes equal to so-call **residual induction**. Residual reduction can be removed by the field of opposite sign – by **coercive (delaying) force** Hc. By means of variation of amplitude of magnetic field the family of hysteresis loops can be obtained (Fig. 4.6). The hysteresis loop corresponding to induction of saturation Bs is known as **limit loop**.

Set of loops pikes creates **reference magnetization curve** joining origin of coordinates with the point corresponding to the Bs. Limit hysteresis loop defines magnetic parameters of a material: induction of saturation B_S, residual induction B_r and coercive force H_C. Furthermore the value of H_C is the main conditional criterion for division of **ferromagnetics** and **ferrimagnetics** on magnetic-soft and magnetic-hard ones (see paragraphs 4.3 and 4.4). Magnetic-soft have $H_C<1000$ A/m, magnetic-hard – $H_C \geq 1000$ A/m. Fig. 4.7 shows types of hysteresis loops for different engineering application.

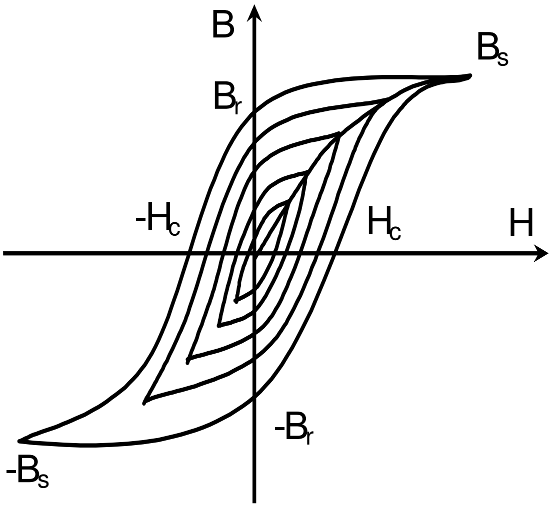


Fig. 4.6. Loops of cyclic remagnetizing of ferromagnetics

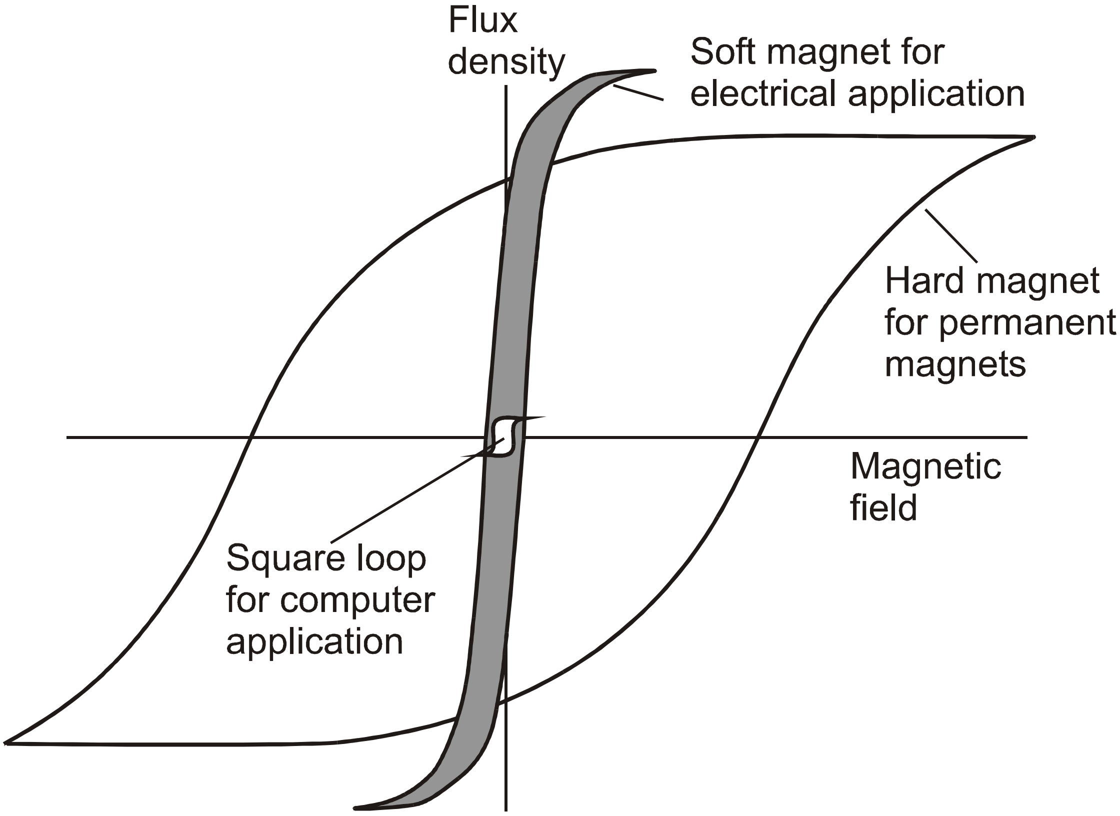
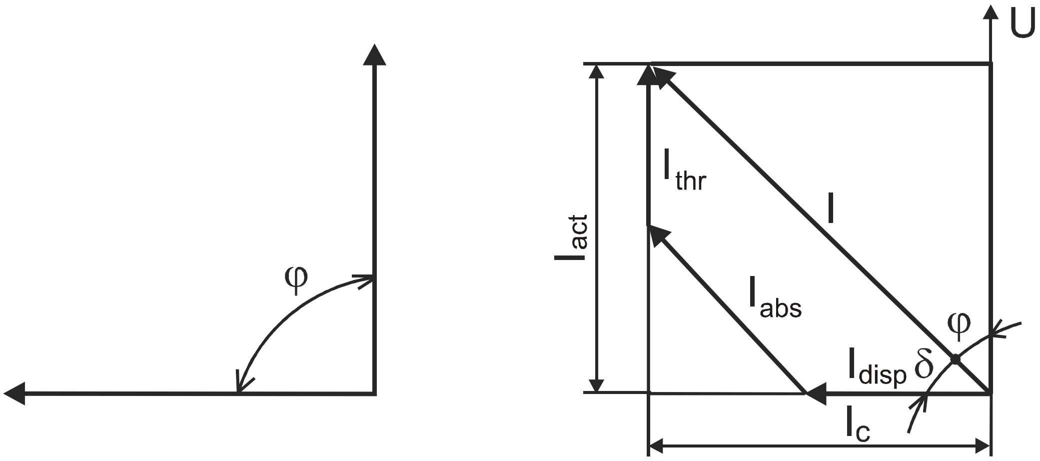


Fig. 4.7. Types of hysteresis loop for different engineering application

4.1.3. Magnetic losses

Process of magnetization reversal of magnetic materials by alternative magnetic field is accompanied by partial conversion of energy of magnetic field to heat that leads to magnetic material heating. This energy per unit time is known as **magnetic loss** and characterized by specific energy consumption of unit material volume or by **tangent of angle of magnetic loss tgδ_M**.

The angle of dielectric loss δ is the phase angle between current and voltage in capacity circuit (Fig. 4.8). In case of ideal dielectric the vector of current in capacity circuit with pass ahead the vector of voltage on 90°, i.e. δ=0 (Fig. 4.8, a). More power dispersed in dielectric less phase angle φ and more angle of loss δ (Fig. 4.8, b).



a b

Fig. 4.8. Vector diagram of ideal dielectric (a) and dielectric with loss (b)

There are the main types of loss (by mechanism of appearing): on **magnetization reversal** (or hysteresis), **eddy currents**, and **magnetic viscosity** (magnetic aftereffect).

Losses on magnetizing reversal are related to magnetic hysteresis and irreversible displacement of domain boundaries. Area of magnetic hysteresis loop is proportional to loss of unit volume of magnetic material per one cycle of magnetizing reversal. Energy of loss (J) on hysteresis can be estimated by empirical formula

$$P_{hys} = \eta B_s^n f V\,, \qquad (4.3)$$

where η– coefficient depending on material properties; n– power coefficient equal to the value from 1.6 to 2.0 depending on B_s value; f– frequency, Hz; V – specimen volume, m^3.

Loss on eddy currents can be observed at magnetizing reversal by alternative magnetic field. These currents are induced in magnetic material by alternative field (so-called **electromotive force of self-induction**). Empirical formula for determination loss on eddy currents (J) is the following

$$P_{e.c.} = \xi B_s^2 f^2 V\,, \qquad (4.4)$$

where ξ – coefficient depending on specific conductivity and geometry of magnetic material specimen.

To reduce $P_{e.c.}$ it is recommended to use materials with elevated specific resistance or gather cores of magnetic conductors from thin sheets insulated from each other by the layer of varnish or paper.

Loss on aftereffect is the result of delaying of measuring B as function on intensity H. It was established that after external magnetic field removal reduction of magnetization happens non-momentary but during definite time (from milliseconds up to several minutes). This phenomenon occurs due to self-magnetization of a material during demagnetization that requires definite energy for magnetization removal.

The value of such kind of loss (J) can be found as a difference between total magnetic loss and loss on hysteresis and eddy currents:

$$P_{aft} = P - (P_{hys} + P_{e.c.}). \tag{4.5}$$

Physical essence of this mechanism of loss is not well studied yet and some cases its influence on material heating can be neglected. But such loss has to be taken into account at operation in relatively weak fields, fields with high frequency and at impulse operation regime.

In multiple cases at operation in high-frequency currents of low intensity dispersion of energy in magnetic material can be estimated by tangent of loss angle. Angle of loss complements up to the right angle (90°) the angle of phases displacement between current and voltage in induction coil with core made of magnetic material. In this case active energy of losses can be determined by formula

$$P_A = I^2 \omega L tg\delta_M, \tag{4.6}$$

where I – current in a coil, A; ω=2πf, Hz; L– coil induction, H.

4.2. Classification of magnetic materials

All magnetic materials can be divided by three main groups (in accordance with GOST): magnetic-soft, magnetic-hard and materials of special application.

Terms “magnetic-soft” and “magnetic-hard” correspond to magnetic properties of materials but not to mechanical ones. For example mechanically sost materials can be magnetic-soft and magnetic hard.

Magnetic-soft materials possess ability to be remagnetized even in weak fields because they have high magnetic permeability, narrow hysteresis loop with low coercive force H_C and low loss on magnetization reversal. Such materials are used in alternative fields as magnetic-conductors in dynamic mode.

Magnetic-hard materials have high coercive force and high specific energy in operational gap, wide hysteresis loop and significant losses. Magnetization of such materials is very difficult but can keep given energy for a quite long time. Therefore such materials are used mainly for manufacturing of permanent magnets in static mode.

The process of magnetization of materials of both groups is very similar but processes of displacement of domains boundaries and rotation of their magnetic moments differ quantitatively and qualitatively. In magnetic-soft materials magnetizing happens mainly due displacement of domain boundaries, in magnetic-hard – due to rotation of their magnetic moments. The shape of hysteresis loop, induction of saturation B_S and residual induction B_r are approximately the same in materials of both groups but the value of coercive force Hc can differ significantly (up to $2 \cdot 10^6$ times).

The group of special magnetic materials includes ones having properties of above-mentioned groups but have auxiliary non-typical properties.

By chemical nature all magnetic materials can be **metal** and **non-metal**. Metal materials are powder and monolithic (produced by casting), non-metal (ferrites) are simple and complicated depending on quantity of metal oxides.

Magnetic materials can be classified by their crystalline structure: ferrites with **cubic**, **hexagonal** structure and **garnet-like** structure.

4.3. Magnetic-soft materials

Main field of magnetic-soft materials application is manufacturing of magnetic conductors of transformers, throttles, relay, coil cores etc. Main requirements to magnetic-soft materials are high value of magnetic permeability μ_H and μ_{max} (to reduce open-circuit current), high induction of saturation B_S (to ensure passing of maximum magnetic flows by low-dimension magnetic conductors), low level of magnetic loss (to increase operational temperatures of articles).

Majority of magnetic-soft materials are produced as sheets and strips there are strong requirements to their high-ductility, quality of surface (absence of rust, scale, irregularities etc) which permit to increasing filling coefficient of magnetic article and a s result to reduce their dimensions.

By the value of specific resistance magnetic-soft materials are divided on materials for low (sound) frequencies (low-carbon steels, electrotechnical steel, non-coercive alloys) and high frequencies (ferrites and magnetic dielectrics). Moreover classification based on typical properties or distinctions of application is used too: for example materials with high value of B_S (low-carbon and electrotechnical steels), alloys with high original permeability μ_H etc. Separate group of magnetic-soft materials include such prospective materials as amorphous magnetic semi-conductors etc.

4.3.1. Low-carbon steels

The group of low-carbon steels includes grades of iron and steels with percentage of carbon up to 0.1%: commercially pure iron («armco iron»), carbonyle and electrolytic iron (high-purity) etc.

Commercially pure iron (99.9% Fe, 0.04 % C) is cheap and manufacturable material with high magnetic properties in permanent fields (μ_{max}=3500…4500, H_C=50…100 A/m). It is produced by refining of cast iron in convertors, marten and electrical furnaces.

Articles made of commercially pure iron are used for magnetic conductors operating in permanent fields and manufacturing of magnetic alloys.

Electrolytic iron after remelting in vacuum and annealing contains 0.01% C and has H_C=7.2 A/m, μ_{max}=15000. It is very expensive.

Carbonyle iron after annealing in hydrogen contains 0.01 % C, has H_c=6.4 A/m, μ_H=2000. It is used for coil cores and magnetic dielectrics manufacturing (for magnetic component).

4.3.2. Electrotechnical steels

Low electrical resistance of low-carbon steels makes difficulties for their application in alternative fields because of low magnetic permeability and high loss on eddy currents. Therefore iron-silicon alloys (so-called electrotechnical steels) have become to use engineering more than 130 years ago.

Silicon dissolves in iron and distorts crystalline lattice, as a result electrical resistance becomes 7 times more. Optimal content of Si in electrotechnical steel is not than 4.8 %.

Electrotechnical steels are produced by hot and cold rolling as strips and sheets. Cold rolled steels are more anisotropic.

General electromagnetic properties of electromagnetic steels: μ_H=3000…8000; H_C=10…65 A/m; ρ=0.25…0.6 μOhm·m.

Nowadays electrotechnical steels are main cheap magnetic-soft material used for magnetic conductors operating in alternative fields of low frequency (up to 1 kHz). Isotropic steel is used in electrical machine-building (rotors of electrical machines), anisotropic (texturized) steel – for powerful transformers.

4.3.3. Low-coercive alloys

This group includes alloys with high original magnetic permeability in weak fields and negligible coercive force Hc: permalloy, alsifer, alfenol, hyperco etc.

Permalloys are alloys of iron and nickel alloyed with Si, Mn, Cr, Mo. It was established experimentally that magnetic induction growths with the growth of field intensity if low amount of energy can be spent for magnetizing (orientation of magnetic moments and overcome magnetic-striction and anisotropy influence). Typically magnetic-striction coefficient of Fe and Ni has different sign that permits to create alloys with low coercive force.

Magnetic properties of permalloys depend on chemical composition, casting method, thermal treatment and article shape, physical properties – on presence of impurities.

Depending on magnetic properties permalloys of the first class (with normal magnetic properties), second class (with elevated magnetic properties) and third class (supermalloys) (with very high magnetic properties) are considered. Such alloys are produced by casting methods (open, in vacuum furnaces, plasm remelting).

Semi-finished articles of permalloy are produced as cold-rolled and hot-rolled strips, sheets, wires, rods with consequent thermal treatment in vacuum or in hydrogen medium.

Permalloys can be magnetized easily in weak fields, are characterized by high sensitivity to mechanical loads, reduced values of Bs (two times less than in electrotechnical steels). Magnetic properties of permalloys depend on mechanical stress that requires application of special non-magnetic protective cases filled with elastic substance of permalloy cores to protect them from undesirable mechanical loading and failure.

Permalloys are divided on low-nickel (40 …50 % Ni) and high-nickel (72…80 % Ni). Alloying elements add required properties to permalloys. Molybdenum and chromium increase specific resistance ρ and original magnetic permeability μ_H but reduce simultaneously sensitivity to mechanical loads and induction of saturation B_S. Copper increases constancy of magnetic permeability, increases manufacturability and thermal stability of ρ.

Magnetic permeability of high-nickel permalloys is several times more than low-nickel and many times more than electrotechnical steels have. But their specific resistance is three times less and induction Bs is 1.5 times less than in low-nickel alloys.

According to the GOST designation system permalloy grade includes two-digit number which means percentage of Ni and possible following capital Cyrillic letters and consequent numbers which mean alloying element and its quantity in percent. For example, an alloy 76НХД contains 76% Ni and alloys by chromium and copper (quantity of each alloying element is up to 1 %).

Permalloys are characterized by following magnetic properties: low-nickel – μ_{max}=16000…35000, H_C=8…32 A/m, ρ=0.49…0.9 μOhm·m; high-nickel – μ_{max}=50000…1500000, H_C=0.3…1.0 A/m, ρ=0.55…0.6 μOhm·m.

Permalloys are used for manufacturing of strip, twisted and formed magnetic conductors of low-dimension power and impulse transformers, throttles, relays, articles of magnetic chains, elements of computing systems operating in alternative fields with frequency of several dozens of kilohertz.

Alsifers (was discovered in Japan in 1930^{th}) are alloys alternative to permalloys. Typical composition of alsifers is ternary alloy of Al 9.5 %, Si 5.4 % and iron. Alsifer in casting alloy with high magnetic permeability (μ=50000…70000), low coercive force (H_C=0.4…3.2 A/m), high hardness and brittleness. Articles of alsifer are produced by casting only with consequent polishing, electric spark and anode-mechanical machining.

Main advantage of alsifer is simple manufacturing technology at large amount of allowable raw materials. It is produced in vacuum furnaces. Alsifer is used for casted screens, cases of devices, machines and apparatus, articles of magnetic conductors and as magnetic phase of magnetic dielectrics.

Besides of ternary alloys also binary alloys of Al and Fe (alfenols), ternary systems Al-Mo-Fe (thermenols) and Fe-Co-Cr (hyperco) are used.

Alfenol is deformable alloy with cubic lattice containing up to 17% Al, 2.5% Cr and in several alloys up to 2.5 % Re. Alfenol is produced in induction furnaces, it has high manufacturability – cab machined by forging, rolling, forming. Magnetic proprerties of alfenol are μ_{max}=117000, H_C=1.6…2.8 A/m, ρ=1.5 μOhm·m.

Alfenols alloyed with Re have high wear resistance therefore this alloy is used for core of heads of magnetic recording devices.

Hyperco is ternary alloy of Fe, Co (26.5…28 %) and Cr (0.5%). It has high induction B_S, can be processes by machining, forging and rolling at high temperatures. Hyperco is used for manufacturing of stators and rotors of electrical machines and elements of magnetic conductors.

4.3.4. Ferrites

Ferrites are non-metal magnetic materials (ferromagnetics). By composition ferrites belongs to oxide substances with electronic conduction produced by ceramics technology from iron oxide and oxides of transition metals. There are many types of ferrites differ of each other by chemical composition, crystalline structure, manufacturing technology, properties, structural arrangement and field of application.

Mostly such composition of ferrites as $MeO \cdot Fe_2O_3$ (for example, $MgO \cdot Al_2O_3$), or $3Me_2O_3 \cdot 5Fe_2O_3$ (garnet $[Mg_3Al_2(SiO_4)]_3$), where Me – is ion of one-, two- or three- valent metal are used in electrical engineering. Their typical crystalline structure is solid solution of **magnetic** and **non-magnetic ferrites**. Magnetic ferrites are nickel, manganese and lithium; non-magnetic – zinc and cobalt. Non-magnetic ferrites are used for elevation of magnetic permeability and coercive force reduction. Magnetic properties of a ferrite can be regulated by components quantity.

According to the GOST designation system following ferrites designation can be met. At the beginning of designation the numerical value of original magnetic permeability is shown, following Cyrillic capital letters Н and В means low and high frequency bands. Following letters М, Н and Л characterize composition of a ferrite – manganese-zinc, nickel-zinc and lithium-zinc. Next letter means recommended operational regime: И – impulse; С – strong field; РП – for radio-damping devices; ВТ – for computing devices. In some cases digits 1, 2 or 3 can be presented which mean definite properties. For example designation 3000 НМС means low-frequency manganese-zinc ferrite with μ_H=3000 developed for operation in strong fields.

Properties of ready ferrites depend significantly on manufacturing method used. For example, the **method of oxides** includes following technology: ferrite powder is obtained by preliminary sintering of ready oxides, milling and consequent adding of plasticizer (spirit, paraffin), forming and burning at 1100…1400℃. As a result ferrites having composition of solid solution can be obtained.

More stable and uniform properties of ferrites can be obtained by the **method of thermal decomposition of salts**. The best results by repeatability of properties **the method of simultaneous deposition** guarantees. The most advanced up-to-date method is growing of ferrite monocrystals with consequent cutting them with diamond saws, ultrasound and laser.

By structural arrangement ferrite articles can be divided on ring, pot, round and rectangular cores, E-cores and channel cores.

By properties and application following groups of ferrites can be distinguished: magnetic-soft (low- and high-frequency), microwaves frequency ferrites, with rectangular hysteresis loop, magnetic-hard, magnetic-striction, thermal-magnetic.

Ferrites are hard and brittle materials which can be machined by polishing, finishing, diamond and ultrasonic cutting; by properties they are close to ceramics.

Ferrites properties are: density 3000…5000 kg/m^3; coercive force H_c=10…10^5 A/m; ρ=10^{-2}…10^8 Ohm·m; tgδ_M=0.005 …0.1; λ_l= -(2…250)10^{-6}; μ_{Max}= 50…6000.

Drawbacks of ferrites: low thermal stability and induction of saturation B_S=0.01…0.4 T, low susceptibility of magnetic properties, high shrinkage at sintering (10…20 %).

Magnetic-soft ferrites and microwave frequency ones are used for manufacturing of coil cores, magnetic antennas, magnetic conductors of transformers, rotors and stators of micro-motors, articles of beam deflectors, attenuators and phase changers of microwave frequency devices, magnetic amplifiers, screens and heads of sound recording devices operating at frequencies f=0.2…300 MHz and temperatures 0…450 ℃.

4.3.5. Magnetic dielectrics

Magnetic dielectrics are composite materials consisting of dielectric binder (phenolic, epoxy resin, polyethylene, polychlorine-vinyl, glass, glass-enamel, rubber) and powder ferromagnetic filler (electrolytic and carbonyle iron, alsifer, permalloy, ferrites). Volume fraction of a binder is 4…59 % by volume.

Magnetic dielectrics have low magnetic permeability μ_H= 10…250 because magnetic fields of ferromagnetic particles are oriented opposite to external magnetic field at magnetizing. Moreover the mechanism of magnetizing by displacement of particles is absent due small absolute dimensions of particles which generally has single-domain structure.

Magnetic dielectrics are high-frequency magnetic materials (operational temperature is f=0.01…60 MHz), have higher stability of magnetic properties, low loss on hysteresis and eddy currents (main loss is due to magnetic aftereffect), positive thermal coefficient of magnetic permeability α_μ.

Cheap technology of magnetic dielectrics manufacturing similar to plastics one permits to reduce consumptions and obtain articles high higher precision comparing with pure ferrites. But by magnetic properties magnetic dielectrics are worse than ferrites.

Magnetic dielectrics can be divided on mechanically **hard** (ferroplastics) and **elastic** (ferroeleastics). In ferroplastics as dielectrics such materials as glass, glass-enamels, mechanical mixture of liquid glass, talc and chromium anhydride, organic dielectrics; as a filler – electrolytic and carbonyle iron, alsifer, molybdenum permalloy are used. Ferroplastics are used for manufacturing of induction coil cores of high frequency generators, filters, circuits and coils with variable induction (adjusting coils).

Ferroelastic are produced of rubber, polyethylene and polyvinylchloride (dielectric phase) and carbonyle iron or milled nickel-zinc ferrites (magnetic phase). Their specific resistance is $\rho=10^2…10^4$ μOhm·m. Ferroelastics are used for manufacturing of magnetically operated sealed switches, relays, combined magnetic screens, ferromagnetic coatings of cables etc.

4.3.6. Amorphous magnetic-soft materials (AMM)

These materials are disordered magnetics in which period of atoms displacement is violated and crystal-like state exists at interatomic distances only (so-called close order is valid). Amorphous state in such materials occurs at high cooling rates therefore particles can't exceed right ordered crystalline structure. All methods of AMM production are based on quick ($10^4…10^6$ degrees/s) cooling rates from liquid, gas and ionized state.

Amorphous magnetic materials contain 75..85 % of one or several transition metals (Ni, Co, Fe) melted with 15…25 % of glassy matrix (boron, carbon, silicon, phosphorus (metalloids)). Embedding of metalloids reduces saturation, decreases Curie point, increase specific resistance, hardness, strength and corrosion resistance. Auxiliary alloying elements are Cr (increases corrosion resistance), Ta, V, Mn (increases specific electrical resistance), Mo (increases frequency properties) etc. Amorphous magnetic-soft materials are anisotropic because of internal stress happened in manufacturing process but more chemically uniform. Typical properties of amorphous magnetic materials: $\rho=1.25…1.8$ μOhm·m, coefficient of rectangularity of hysteresis loop – $k_{rec}=0.93…0.985$; magnetic striction $\lambda_l=(15…30)10^{-6}$ (comparable with magnetic striction of crystalline ones).

The most prospective AMM are – iron-copper-nickel (40% Fe; 40% Ni;

14 % P; 6 % B), high-cobalt (70 % Co; 5 % Fe; 15 % Si; 10 % B) and high-iron (80 % Fe; 16 % P; 3 % C; 1 % B) amorphous alloys. They are used for manufacturing of memory cells, magnetic conductors, cores of impulse transformers, magnetic heads and screens operating in alternative fields with frequency up to 100 kHz.

4.4. Magnetically-hard materials (MH)

4.4.1. Distinctive features and classification of magnetic-hard materials

As it was mentioned above MH materials are ones that can be remagnetize with some difficulties, having wide hysteresis loop and high specific energy W_{max} in operational air gap.

If magnetization reversal of MH material is absent the demagnetizing curve (hysteresis loop) has only one part in second quadrant (Fig. 4.9).

Quality of permanent magnets are mainly characterizes by values of B_r and H_C. More these values better material for permanent magnet, less its dimensions and weight. Permanent magnet having the shape of closed ring (torus section) has no inner magnetic field because magnetic lines are closed and magnet doesn’t leave magnetic energy to outer space.

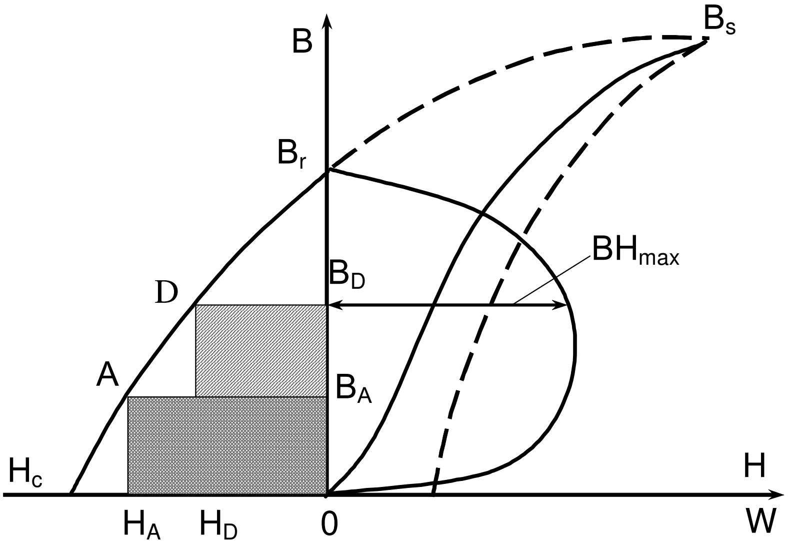


Fig. 4.9. Demagnetizing curve and dependence B=F(W) of magnetic-hard material

To leave energy in magnetic circuit the air gap or gap filled with nonmagnetic material (diamagnetic, dielectric) has to be presented. In this gap the device using magnetic energy is placed. At the edges of magnet poles appear. Poles create demagnetizing filed, for example H_A, which reduces induction B_r up to the B_A (residual induction of disconnected magnet). The value of residual induction depends on the shape, length of magnet and also on the gap spacing (the position of point A on demagnetizing curve is defined by the gap spacing). Less magnet length and more gap more demagnetizing influence of magnet poles and less induction B_A.

By known demagnetizing curve and set of B_A it is possible to determine values of H_A and draw the curve of magnetic energy inside of gap. It can be found from the Fig. 4.9 that point D corresponds to the maximum value of specific (per unit volume) magnetic energy $W_{max}=B_DH_D/2$ which is the main parameter of MH material. In some cases the value proportional to W_{max} energy – $(BH)_{max}$ is used (Fig. 4.10). This parameter is known as **energy product**. The value of W_{max} for MH materials has the value from 1 up to 128 kJ/m^3.

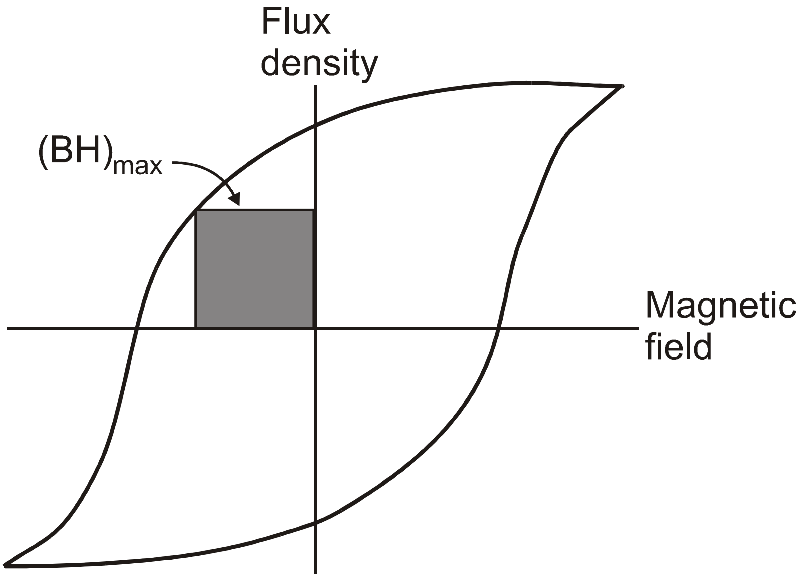


Fig. 4.10. Physical meaning of energy product parameter on hysteresis loop

Magnetic-hard materials can be classified by magnetic properties, manufacturing technology, field of application.

Depending on **field of application** MH materials can be classified as: materials for permanent magnets, for hysteresis motors, for magnetic recording. By magnetic properties materials can be divided on materials with low (H_C up to 25 kA/m), average (H_C up to 75 kA/m) and high (H_C>75 kA/m) value of coercive force.

By technological criterion MH materials can be divided on alloys, intermetal compounds, ferrites and their compositions. MH alloys can be subdivided on casting and powder MH materials.

Problem 4.1

Determine the maximum power or BH product for the magnetic material with properties shown on the figure 4.11.

To determine BH-product it is necessary to find areas of several rectangles have been drawn is second quadrant of BH curve. Maximum area of a rectangle defines magnetic material power:

BH_1=12,000x280=3.4·10^6 gauss·oersted;
BH_2=11,000x360=4.0·10^6 gauss·oersted;
BH_3=10,000x420=4.2·10^6 gauss·oersted;
BH_4=9,000x460=4.1·10^6 gauss·oersted;
BH_5=8,000x500=4.0·10^6 gauss·oersted;

Finally the power of magnetic material is 4.2·10^6 gauss oersted.

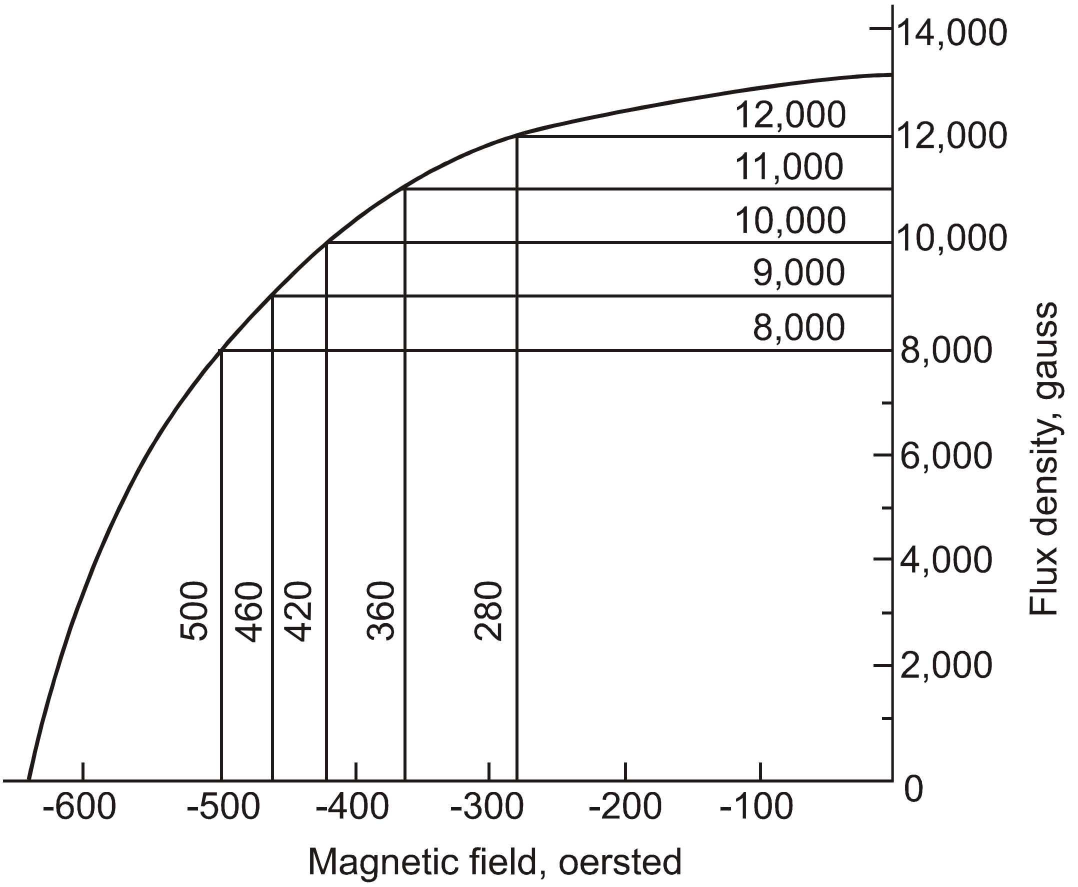


Fig. 4.11. Second quadrant of B-H curve for permanent magnetic material

4.4.2. Magnetic-hard alloys

The group of MH alloys includes high-carbon steels, low-deformable and plastically deformable alloys (which can be casting and metal-ceramic, i.e. produced by ceramic technology).

4.4.2.1. High-carbon steels

High-carbon steels are the most ancient materials for permanent magnets Generally high-carbon steels with quantity of carbon up to 1.1 % alloyed with Cr (up to 3 %), tungsten (up to 8 %), cobalt (up to 15 %) and quenched on martensite state are used for this purpose. Such steels are susceptible to ageing and have low energy product $(BH)_{max}$= 1…2.5 kJ/m^3.

Chromium increases corrosion resistance of a steel and tungsten - residual induction and impact toughness. The best properties cobalt-alloyed steels possess. Introduction of cobalt increases coercive force of carbon steel in four times. Magnets of carbon steels are produced by rolling and forging with consequent machining in annealed state. Then steels are subjected to quenching and low-tempering. Nowadays magnets of high-carbon steels are used rarely.

4.4.2.2. Low-deformable magnetic-hard alloys

This group of alloys represents mostly wide-spread magnetic-hard materials. Typically such alloys are ones of iron, aluminum, nickel, silicon and cobalt and possess high coercive force, good casting properties, high hardness, can't be machined (excluding polishing).

There are many kinds of such alloys as alni (20…34 % Ni, 11…18 % Al, rest is iron), alnisi (Fe plus 13…18 % Al, 32…35 % Ni, 1.0…1.5 % Si, 0.4…0.5 % Ti), alnico (Fe plus 12…16 % Ni, 6…13 % Al, 2…8 % Cu, 14…15 % Co), magnico etc.

Alni alloys (designation by GOST is ЮН) are anisotropic, contain solid solution particles based on iron therefore such alloys belong to dispersion-strengthening ones. To make their properties to be more stable Cu up to 8%, Zr, Ti, Nb can be added. Permanent magnets of different shapes (disks, rods, rings) for relays, electrical machines and devices are used. Their coercive force not less than 36 A/m, W_{Max}=3.6…18 kJ/m^3, B_S=0.43…1.3 T.

Alnico and **magnico** alloys possess elevated magnetic properties and low density due special thermal treatment – cooling of casted magnets in strong magnetic field. Magnets of complicated shape are produced of such alloys.

Alnisi alloys have H_C=58 kA/m, B_r=0.43 T, W_{max}=8 kJ/m^3 and are used for manufacturing of massive casted magnets with cross-section up to $3{\cdot}10^{-3}$ m^2.

4.4.2.3. Deformable magnetic-hard alloys

Deformable alloys have high technological properties: formability, cuttability, machinability. They are produced as strips, sheets, wire, plates, rods. Main deformable magnetic alloys are cunife, cunico, vicalloy and alloys of noble and rare-Earth metals.

Cunife is alloy of copper (40…60 %), nickel (20… 40 %) and iron (20 %). Coercive force is H_C=21…47 kA/m, induction B_r=0.54…0.73 T, specific energy W_{max}=2.8…7.4 kJ/m^3. Alloys of cunife are anisotropic, ductile in cold state and brittle in hot state. High magnetic properties appear after compression up to 90% with consequent annealing (as a result single-domain ferromagnetic particles arranged along fiber of texture of solid solution appears).

These alloys are used for manufacturing of small magnets of measuring devices, compass pointers, tapes for magnetic recording.

Cunico alloy contains Ni (19 …23 %), Co (27…31 %), rest is copper. Typical properties are H_C=36…57 kA/m; B_r=0.34…0.53 T; W_{max}=3.2…4.0

kJ/m^3. This alloy is isotropic, manufacturing properties are close to the cunife alloys. Main application of this alloy is in devices for magnetic recording.

Vicalloy contains Co (51…54 %), V (10…13 %), rest is iron. It has H_C =24…38 kA/m; B_r=0.9…0.95 T; W_{max}=4…14 kJ/m^3. The alloy is quite ductile both in cold and hot state. Magnetic properties can be given to this alloy by compression (up to 95 %) and consequent annealing. Typical application is low-dimension magnets, high-strength tapes and wires for magnetic recording and elements of hysteresis motors.

Comol contains Co (11.2…12.5 %), Mo (11.5…12.5 %), rest is Fe. It can be also alloyed with tungsten. Such alloys are magnetically isotropic, have high Curie point (≥ 800°C), high hysteresis properties and thermal stability of magnetic properties. Density of such alloys are 8100…8900 kg/m^3, specific resistance ρ=0.4…0.55 μOhm·m. Ultimate strength of comol alloy after tempering is 588…1176 MPa, coercive force H_C=18…24.5 kA/m; B_r=1.0…1.2 T; W_{max} – up to 9 kJ/m^3.

Comol alloys are used for elements of hysteresis motor rotors and clutches, standard magnets of magnetometric devices, magnetic springs of devices etc.

Typical alloys for permanent magnets are also alloys of systems Cr-Co-Fe and Cr-W-Fe – **chromco** (25…30% Cr, 10…25% Co with iron) and **chrovo** (4.5…5.5 % Cr, 13.5…14.5 % W with iron). Such systems have high magnetic properties, very ductile in cold state. To get anisotropic properties the alloys are subjected to quenching with cooling in magnetic field and tempering at 540…620°C for 12…20 hrs. Properties of such alloys are: density – 7800 kg/m^3; $\sigma_в$=980…1000 MPa; ε=5 %, ρ= 0.6 μOhm·m, H_C=18…62 kA/m, B_r=0.8…1.25 T, W_{max}=6...16.3 kJ/m^3. These alloys are used for plate-like magnets and magnets of complicated shape, compass pointers, magnetic springs of devices.

Magnetic alloys based on noble metals include systems Ag-Mn-Al (almanal), silmanal, 77.8 % Pt – 22.2 % Fe, 75.7 % Pt – 23.3 % Co (platonax). The phenomenon of magnetizing of mentioned compositions can be explained as following: atoms of Ag and Al embedded to magnesium lattice change the spacing between neighboring atoms that leads to ferromagnetic properties appearing. Silmanal has low residual induction B_r =0.052 but high coercive force HC=480 kA/m. This alloy has linear demagnetizing curve with tangent of the slope to abscissa axis close to μ_0, i.e. this alloy can't be demagnetized. This phenomenon permits to use this alloy for manufacturing of "magnetic springs" having high stability of mechanical moment to effect of different demagnetizing fields and elements of precise measuring devices with movable magnets, ultra-tiny magnets (with mass of several milligrams).

Typical properties of platinum-based alloys are HC=520 kA/m, Bs=0.65…0.79 T; Wmax=40…45 kJ/m3; ρ=0.3 μOhm·m; σв=860 MPa, relatively high cost.

Supplying shapes of such alloys are rods, wires, sheets and strips.

4.4.3. Powder magnetic magnetic-hard materials

Permanent magnets of complicated shapes and high dimensional precision can't be produced generally of majority of magnetic-hard alloys because of high-hardness and brittleness and restricted set of manufacturing processes can be applied. Therefore the **methods of powder metallurgy** are wide spread for permanent magnets.

Powder materials are produced by compression of powders with consequent thermal treatment. Depending on distinctions of technology powder magnets can be divided on **metal-ceramic**, **metal-plastic** and **oxide**.

Metal-ceramic magnets are produced by ceramic technology (compression without binder and consequent sintering) of alloys of noble alloys, ЮНДК, cunico, cunife, comol, magnico, rare-Earth metals etc. Due to presence of porosity (up to 5%) of sintered material magnetic properties of metal-ceramic magnets are slightly lower than main material has. Ceramic technology is high-productive and cheap.

Metal-plastic magnets are produced by plastics technology: powders of alloys (ЮНД, ЮНДК) or ferrites are mixed with solid (rubber, phenolic-formaldehyde resin) or liquid dielectric and pressed with pressure up to 500 MPa with consequent curing at 120…180℃ for several hrs. ready articles have high precision and low superficial roughness.

Metal-plastic magnets have high specific resistance and can be considered as composite magnetic materials – **magnetic-dielectrics**.

Hard and ductile compositions are known as **magnetic plastics**, elastic ones – **magnetic-elastics**. For manufacturing of mentioned powder-like materials magnetic-hard ferrites and rare-earth metals are used. Ferrites are cheap and brittle (it is easy to mill them). Rare-earth metals give special properties to permanent magnets.

For manufacturing of magneto-elastic materials alloys **alni**, Fe-Co and ferrites are used. As a binder natural rubber and thermo-elastic resins are used. By mechanical properties magneto-elastic materials are flexible, elastic and manufacturable materials with density 2400…4000 kg/m^3. By magnetic properties they are close to isotropic ferrites but their specific resistance reaches 1…10 μOhm·m.

Metal-plastic materials can be produced practically without materials wasting and are used for manufacturing of **reinforced magnets**. Metal-plastic materials are used for magnetic lenses, stoppers, clips, magnets with mass up to 0.3 kg for measuring devices (in electricity counters, speedometers, eximeters etc). Magnetic-elastic materials are used as magnetic thin tapes for tightening, magnets of deflection systems of tubes and ion catchers, magnetic locks of devices, tape conveyors of pass lines etc.

For permanents magnets manufacturing such oxide magnetic-hard materials as ferrites of barium $BaO{\cdot}6Fe_2O_3$, strontium $SrO{\cdot}6Fe_2O_3$, and cobalt $CoO{\cdot}6Fe_2O_3$ are used. The method of manufacturing is ceramic one.

Magnetic-hard ferrites can be both isotropic and anisotropic. They have high stability of properties at effect of external magnetic fields and mechanical loads. Their density is 4400…4900 kg/m^3 (that is 1.5…1.8 times less than casted alloys); specific resistance in 10^6 times more; cost in 10 times less. Main drawback of this group of materials is low thermal stability of properties.

Magnetic hard ferrites are produced as washers and thin disks. Their designation includes letters and forehead digits that mean W_{max} expressed in kA·T/m. Following first letter (B, C or K) means barium, strontium or cobalt ferrite; second letter – A – anisotropic, И – isotropic; number after – coercive force on magnetizing in kJ/m. For example, designation 28БА180 means barium anisotropic ferrite with $(BH)_{max}$=28 kA·T/m and H_C=180 kA/m.

Magnetic-hard ferrites are used in manufacturing of electrical machines, electronic devices, running-wave tubes, magnetrons, magnetic lenses, polarized relays, magnetic separators, clutches and reducers.

4.4.4. Magnetic-hard materials for information recording

This group of materials is developed for video- and audio-recording, storage and input of information in computing machines. Their main goal is creation in reading device an alternative in time magnetic field that corresponds to recorded signal. To increase the level of reading signal residual induction has to be as maximum as it possible. Requirements to the H_C are very contradictive: from the one hand it has to be low to have ability to remove information easily; from the other hand H_C has to be high escape of self-demagnetizing. Optimal values of H_C belong to the range 20…50 kA/m.

Nowadays there are many kinds of magnetic carriers of information. Mostly metal or plastic tapes and wires made of magnetic-hard materials, metal disks and drums with magnetic powder ans galvanic coatings of Ni-Co alloy, ″magnetic rubber″ etc.

Porousless metal magnetic carriers are made of special stainless steel and cunico, cunife and vicalloys. To this group bimetal tapes of copper with deposited alloy of Fe-Ni-Al do relate. Main disadvantage of porousless carriers are high cost, difficulties in repair at tearing, quick wearing of playing and recording devices.

Plastic tapes with deposited powder magnetic layer are used in engineering for magnetic recording. Acetyl-cellulose, acetate-cellulose or lavsan tapes with thickness 20…50 μm are used as substrate (has high mechanical strength) and magnetic varnish consisting of 40 % of magnetic powder, binder and additives decreasing friction, wetting and separation of a powder particles – as magnetic layer.

As magnetic components powders of γ-Fe_2O_3, mixture of γ-Fe_2O_3 and Fe_3O_4, chromium dioxide CrO_2 are used.

Other magnetic carriers of information as disks, drums, cards, coins, pencils, documents with magnetic layer are used.

Main advantages of floppy-disks are low cost, simple arrangement and application, low dimensions. Advantages of disk carries comparing with tape one is high data transfer rate and short time of search.

4.4.5. Intermetal magnetic-hard materials

As intermetal materials for permanent magnets compounds of rare-earth metals with cobalt and based on manganese - Mn-Bi (bismanol), Mn-Al and Mn-Co are used.

Co containing compounds possess high coercive force (H_C=640 kJ/m). First permanent magnets made of powder of $SmCo_5$ bonded by polymeric resin had W_{max}=20 kJ/m^3 (technology of sintering and casting were not developed yet). Next years casted magnets of dispersion-solidified alloys of $Sm(Co,Cu)_5$ and $Ce(Co,Cu)_5$ were developed and magnets reached specific energy up to 80 kJ/m^3. Further generations of R_2Co_{17} magnets (R is rare-earth metal) possess W_{max} =124 kJ/m^3. In manufacturing of magnets of rare-earth metals also such elements as samarium, praseodymium, cerium, yttrium, lanthanum and neodymium are used.

Magnets of rare-earth metals re produced by casting, metal-ceramic and metal-plastic methods and by film deposition one. Metal-ceramic technology includes operations of R-Co alloy milling, dry and liquid-phase forming in magnetic field (to get magnetic properties), sintering in medium of argon or helium, thermal treatment (annealing with slow cooling) and magnetizing.

Metal-plastic method a powder of R-Co is mixed with organic (epoxy resin, polymers, rubber) or metal (alloys of lead and tin) binder and polymerize or heat.

High magnetic properties of rare-earth alloys based magnets are stipulated by their high magnetic anisotropy and magnetic striction, significant self-magnetizing and high Curie point, high hardness and brittleness. After magnetizing articles are subjected to polishing, electrical- and ultra-sound-milling.

Only near 5% of rare-earth metals are used in manufacturing of permanent magnets. Rare-earth alloys are also used for magnetic systems of running-waves lamps, magnets of measuring devices and micro-machines. Magneto-elastic materials based on rare-earth alloys are used as plates for magnetic memory, magnets of deflection and correction systems, magnetic locks etc.

The group of intermetal magnetic-hard materials also includes such compounds as Mn-Bi, Mn-Al и Mn-Co. These materials as single-domain particles together with pure iron particles and Fe-Co alloy (non-metal alloy exactly) create the group of micro-powder magnetic-hard materials.

Micro-powder materials are cheap and available. Their mechanical and magnetic properties are close to alnico alloys, specific energy is 26 kJ/m^3. Micro-powders are used for manufacturing of magnets for measuring devices, brake systems of counters, rotors of micro-motors etc.

4.4.6. Selection of magnetic-hard materials and prospectives of their development

Magnetic-hard materials with high magnetic properties are used in permanent magnets of electrical engineering. Following parameters have to be taken into account at selection material for a magnet: material energy-capacity, presence of expensive components, cost, thermal and temporal stability, operational conditions and production volume of articles.

More the value of W_{max} less a magnet volume and flow dispersion. Magnets of martensite steels with low energy W_{max} are characterized by large volumes and U-like shape; U-shape magnets of low-deformable alloys have less volume; magnets of rare-earth alloys have the shape of thick films covering the operational surface of pole tip.

Quality of magnet material in separate cases can be estimated by the cost of **magnet mass containing one joule of magnetic energy**. For example, this parameter for magnet of alloy ЮН14ДК24 is 73.5 times less then for magnet made of rare-earth metals. In aviation for comparison of magnetic-hard materials the **weight of a magnet per unit energy W_{max}** is used. If this parameter is assumed to be equal to **one** for magnets made of **martensite steels** then magnet of **alni alloy** is four times less, of **magnico alloy** – in 16 times, of ferrite – in 40 times, of **special magnetic-hard alloys** made of rare-earth metals – in hundreds times.

Energy-capacity of a magnet is not only quality characteristic of magnetic-hard material because its shape and dimensions also depend on magnet material resistance to effect of demagnetizing fields. The most stable are to demagnetizing are ferrites and alloys of rare-earth metals.

Nowadays such subgroups of magnetic materials based on RCo_5 and $R_2(Co,Fe)_{17}$ (R – is rare-earth metals) are widely used. They are more cheap and have better magnetic properties. Value of magnetic energy W_{max} of RCO_5 group has already reached their saturation but magnets of second generation – $R_2(Co,Fe)_{17}$ group – have only near 52…55 % of prospective maximum.

Also magnetic materials based on ferrites, low-deformable alloys also reached their maximum energy level and their further development is low-probable.

4.5. Magnetic materials of special application

This group of magnetic materials includes ones having such specific properties as rectangular hysteresis loop, alloys with high degree of μ dependence on temperature (thermo-magnetic materials), with negligible dependence of magnetic permeability on intensity of magnetic field (materials with μ=const), alloys with high magnetic striction (magnetic striction materials).

4.5.1. Magnetic materials with rectangular hysteresis loop

Materials with rectangular hysteresis loop (RHL) are used for manufacturing of memory devices of computing machines, logical, switching, storage and recalculating schemes of automatics.

Main properties of materials with RHL are **coefficient of rectangularity of hysteresis loop** K_{rec} and **switching coefficient** K_q. Coefficient of rectangularity of hysteresis loop $K_{rec} = B_r / B_s$ characterizes interference immunity of memory cells: more the coefficient more ratio of desired signal to interference signal. Coefficient K_q means the quickness of a cell remagnetizing and numerically equal to the quantity of electricity per unit thickness of a core necessary for cell switching from the state $+B_s$ (recording of '1') to the state $-B_s$ (recording of '0'). Switching coefficient is measured in μK/m.

Materials with RHL are subdivided by several sub-groups: **ferrites**, **textured tapes** and **thin magnetic films**. Ferrites with RHL can be divided on two types: with **spontaneous** and **induced** rectangularity of hysteresis loop. In first ones the shape of a loop is defined by composition and conditions of sintering of material components, in second ones – by consequent thermal-magnetic processing. For majority of ferrites with RHL spontaneous character of hysteresis loop rectangularity is typical. It occurs in conditions of negligible irregularities and distortions of a microstructure, severe crystalline anisotropy and low magnetic striction. At the same time processes of irreversible displacement of domain boundaries are dominant in such materials.

Examples of above-mentioned magnetic materials are lithium ferrites of $Li_2O{\cdot}Fe_2O_3$ type and manganese-magnesium of $(Mn, Mg)\,O{\cdot}Fe_2O_3$ type (Table 4.1). Multi-component ferrites of Mg-Mn-Zn-Ca type are produced by introduction of zinc and calcium oxides to Mg-Mn ones to regulate magnetic parameters. Ferrites with RHL is more widely spread comparing with other materials with RHL due to their economic efficiency and simplicity of manufacturing. The main their disadvantage is low thermal stability of magnetic parameters, i.e. shrinkage area of hysteresis loop and reduction of K_{rec} that leads to increasing of interference signal at information recording.

Ferrites with RHL are produces as ring-like cores of low-dimensions of multi-hole motherboards, rulers and plates in which area near each hole fulfills the role of separate core.

At operation at elevated temperatures it is recommended to used cores of metal materials with RHL which differ from ferrites with RHL by higher thermal stability and elevated magnetic properties. Metal alloys with RHL are permalloy and alloys of Fe-Ni-Co system alloyed with Mo, Cu etc. They are produced as thin tapes (thickness is 3…500 μm). They have higher operational frequencies, less values on remagnetizing and more complicated technology of core manufacturing.

Nowadays thin magnetic films (0.1…1.0 μm) produced by deposition of magnetic material (permalloy, alloy Fe-Ni-Co, ferrites) to glass or metal (Cu, Al, Au) substrate are used in memory cells. Elements on glass substrate have higher quality, less dimensions but more expensive.

Table 4.1. Properties of magnetic materials

Material	Properties			
	H_C, A/m	K_{rec}	K_q, μK/m	T^0_θ, °C
Casted ferrites	10…1200	0.89…0.9	48…52	110…630
Mn-Mg ferrites	56…120	0.93…0.94	48…52	170…250
Multi-component ferrites Mg-Mn-Zn-Ca	9.6…24	0.91…0.93	48…52	110…170
Permalloys	20…24	0.95…0.96	79…81	300…630
Alloy Fe-Ni-Co	40…48	0.96	95	580

Thin magnetic films are characterized by single-domain structure through film thickness, single-axes magnetic anisotropy, absence of eddy currents. They don’t prone to ageing, can withstand impact loads. Memory cells are produced as element with dimensions 50×50 mm on which near up to 2300 cells with duration of switching near 10^{-7} s are disposed.

The quickest and maximum capacity memory cells can be produced of materials with **cylindrical magnetic domains** (CMD) appeared at definite conditions in thin monocrystalline plates and films of some ferrites having severe single-axes anisotropy. Originally CMD ferrites were obtained on rare-earth alloys (so-called ortho-ferrites) in which at definite intensity domains momentary obtain the cylindrical shape (with dimensions up to 0.08 μm) and keep the shape in definite range of external magnetic field. Dimensions in ortho-ferrites permit to organize density of information recording up to 0.1…1.0 bit/m^2.

Ferro-garnets of $R_3Fe_5O_{12}$ type and amorphous films of rare-earth metals have less dimensions than ferrites. CMD of ferro-garnets have dimensions of several micro-meters and ensure density of information recording up to 10…10^2 bit/m^2. Typically they are produced by growing (chemical deposition) of film on non-magnetic substrate like non-magnetic garnet $Cd_3Ga_5O_{12}$.

Amorphous magnetic films of alloys of transitions metals of rare-earth types like Cd-Co and Cd-Fe are most prospective, they have dimensions of CMD less than 1 μm guarantee the density of information recording up to 10^5 bit/m^2. They are produced by the method of spraying on glass substrate or by electrolytic deposition on copper substrate. They are characterized by low cost and simplicity of manufacturing.

4.5.2. Thermomagnetic materials

Thermomagnetic materials (TMM) are ones with strong dependence of magnetizing on temperature in the range -70…+180 °C in fields close to saturation. Typical representatives of such materials are thermo-magnetic alloys, multi-layer thermomagnetic materials and magnetic-soft ferrites with low Curie point t°_{θ}. Majority of TM are ones with linear dependence of magnetizing on temperature $\mu_0 M_s = F(t^{\circ})$. Rest of TMM have non-linear dependence of magnetizing of temperature with positive and negative curvature of $\mu_0 M_s = F(t^{\circ})$ dependence.

Since ferro-magnetic materials have high Curie point (in the range 350…1120 °C) to create TMM on their basis it is necessary to reduce its level. The first method is introduction of non-magnetic additives to ferromagnetic elements. An example is thermo-magnetic alloy of Ni and Cu (up to 30…40 %), so-called calmalloy. Second way of Curie point reduction is by structural transformation in alloys. For example an alloy of Fe+Ni (thermalloy) has reduced Curie point on 28…34 %; specially developed for thermal compensation alloys of Fe-Ni-Cr (compensators) containing near 35% Ni and 8…13 % Cr. Such alloys are characterized by high manufacturability, strong linear dependence of magnetic properties on temperature and repeatability of parameters.

Besides of thermo-magnetic alloys multi-layer (poly-metal) materials produced by simultaneous rolling of sheets and strips of thermo-magnetic alloys with different properties are used in engineering. Integral properties of such material are ensured by proper selection of original alloys and strips thickness. Advantages of these materials is stability of manufacturing technology, wide range of properties and possibility of preliminary estimation of TMM properties

Also thermo-magnetic properties can be found in powder metallurgy metals (Fe-Ni-Mo system) having magnetic properties analogous to casted TMM but with higher degree of repeatability.

Mn-Zn and Ni-Zn alloys are used for magnetic-soft ferrites. But they have low value of B_s and pure repeatability of properties.

TMM are produced as hot-rolled and forged rods, cold-rolled tapes and sheets. Typical application is magnetic shunt circuits for voltage regulators, magnetic auxiliary resistors, for thermal compensation of speedometers, measuring devices, counters of micro-wave frequency devices and for regulation magnetic parameters.

4.5.3. Magnetic-strictive materials

Physical phenomenon of magnetic-striction was discovered by English physician Joule in 1847. Majority of up-to-date magnetic-soft and magnetic-hard materials are characterized by definite magnetic-striction.

Magnetic-striction materials are ones having significant magnetic-striction and magnetic-elastic effects. At magnetic-striction phenomenon changing dimensions of a specimen disposed in magnetic field is observed. At magnetic-elastic phenomenon changing of magnetic properties happen at mechanical effect.

Main parameters of magnetic-striction materials besides of induction of saturation B_S, coercive force H_C, Curie point t^{0}_{θ} and coefficient of longitudinal magnetic-striction λ_l are:

- coefficient of magnetic-mechanical (electromechanical) coupling whch characterizes energy relationship at magnetic-strictive oscillations and numerically can be found as square root of ratio between transformed (magnetic or mechanical) energy to input energy (magnetic or mechanical correspondingly) in unit volume of magnetic-strictive material;
- magnetic-striction constant $a=d\sigma/dB$ which characterizes operational ability of materials for emitters;
- magnetic-striction constant of sensitivity $b=dB/d\sigma$ (σ – mechanical stress) which characterizes operation ability of receivers.

Magnetic-strictive materials can be classified by material type (pure metals, alloys, ferrites) or by application (for acoustic, radio-engineering devices, magnetic-elastic transformers).

Conventional magnetic-strictive material is nickel which now is in process of replacement with other metal alloys (Fe-Co (**permendur**), **alfer**, **hyperco**, **nicosi** and based on rare-earth metals) and piezo-ceramics. Permendur is magnetic-soft contains Co (48… 51 %), V (1.5…2 %), rest is iron. It has ultimate strength σ_B=1177 MPa , ε=1 %. Magnetic properties of permendur are shown in the Table 4.2. Permendur can be processed by forging and rolling at 900…1180°C with consequent quenching in water, after that ductility becomes quite enough for cold-rolling. Semi-finished article are forged rods, strips, cold-rolled tapes and sheets, wires and beaten strips.

Beside of magnetic-striction application permendur is used for magnetic conductors, electrical magnets, rotors and stators of electrical machines, pole contacts, magnetic lenses, transformers, telephone membranes etc.

Nikosi has high corrosion resistance and manufacturability, the highest coupling coefficient K_{CB} but its λ_l is less than Ni has. Nicosi contains Co (3.5… 4.5 %), Si (1.3…2 %), impurities near 6%, rest is Ni. Semi-finished products are thin tubes and sheets with thickness 0.1…0.2 mm. To increase magnetic-striction parameters nicosi articles are subjected to annealing (800… 1000°C).

Alfer is magnetic-soft alloy. It contains Al (7.5…13.8 %), rest is Fe, has combination of high magnetic striction, strength (σ_B=570…785 MPa) and specific resistance, relative elongation is ε=1…15 %. It can be machined by pressure, cutting, welding but is very brittle.

Besides above-mentioned alloys as magnetic-strictive materials systems of Fe-Cr, Fe-Ni, Fe-Pt, hyperco, ferrites (piezo-magnetic ceramics) are also used. Ceramics electrical resistance is in $10^8…10^{11}$ times more than other magnetic materials have therefore their loss on eddy currents is low and such articles can be produced as monolithic, with any dimensions and shape complexity, can operate at high frequencies.

As magnetic-strictive materials Ni, Ni-Zn, Ni-Co and multi-component ferrites are used, their generalized chemical formula is NiO-ZnO-CuO-CoO-FeO-Fe_2O_3. But low mechanical strength (σ_B in 7…10 times less than metals have) and low induction B_S restrict their field of application: transformers of electro-mechanical and magnetic-strictive filters, acoustic receivers and emmiters of low and moderate power are produced of ceramic magnetic-strictive materials only.

Table 4.2. Properties of magnetic-strictive materials

Material	Density, kg/m^3	λ_l, 10^{-6}	B_s, T	H_c, A/m	K_{CB}	t^o_θ, ^oC	$\rho\ 10^2$, μOhm·m
Nickel	8900	-(30…34)	0.61	56…64	0.3	360	8…9
Permendur	8150	60…100	2.4	128…160	0.37	980	26
Alfer	6700	35…50	1.34…1.5	48…56	0.23	–	90
Nicosi	8800	25…27	0.625	160…240	0.49	–	6…18
Hyperco	8100	55	2.42	80	0.14	–	14
Ferrites	5250	-(9…28)	0.33…0.55	28…320	0.14…0.38	260…590	>10^2

All groups of magnetic-strictive materials are implemented for manufacturing of sensitive elements of magnetic-elastic transformers used in automatics and measuring devices; cores of emmiters and receivers in electro-acoustics (echo-sound finders) and ultra-sound devices, cores of magnetic-strictive and electromechanical filters and delaying lines in radio-engineering and communication engineering; magnetic-strictive frequency stabilizers (besides of quartz) etc.

4.5.4. Magnetic materials with constant magnetic permeability

This sub-group includes materials (perminvar, isoperm and special ferrites) magnetic permeability od which doesn't depend in definite range on intensity of magnetic field H and have narrow hysteresis loop.

Perminvar was developed in 1921 in USA and contains Ni (40…68 %), Co (22…25 %), rest is iron. It can contain alloying elements of Mo (2...4 %) and Cr (up to 2 %). Constancy of magnetic permeability it saves in magnetic fields with intensity up to 320 A/m. Coercive force of such alloys is near $H_C \cong 300$ A/m. Perminvar semi-finished products are melted in induction ovens with consequent forging, hot and cold-rolling, complicated multi-step annealing. Perminvar is used in manufacturing of magnetic amplifiers core, transformers, coils with permanent induction, throttles, elements of computing machines and radio-technical devices.

Isoperm was developed in Germany in 1933. It contains up to 40 % Ni, rest is iron. Alloying elements of Cu (13…15 %) and Al (4…5 %) are also used. Magnetic properties of isoperm are reached by cold-rolling with strain degree up to 98.5%, consequent annealing (1000…1200℃ for one hr) and secondary cold-rolling with strain degree up to 50 %. The most stable and high magnetic properties can be observed in ternary isoperm of the system Ni-Cu-Fe having magnetic moments of domains oriented perpendicular to the rolling direction. Constancy of magnetic permeability can be seen up to field intensity of 600 A/m. Isoperms are used for manufacturing of induction coils core used in contours of high-frequency telephone apparatus.

Special ferrites containing additive of cobalt oxide CoO are also used at high-frequency fields.

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Навчальне видання

Тараненко Ігор Михайлович
Купріянова Тетяна Анатоліївна

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Видавець и виготовлювач
Національний аерокосмічнихй університет ім. М.Є. Жуковського
«Харківський авіаційний інститут»
61070, Харків–70, вул. Чкалова, 17
http://www.khai.edu
Видавничий центр «ХАІ»
61070, Харків–70, вул. Чкалова, 17

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