doi: 10.32620/oikit.2023.98.04

UDC 621.982:669.295

Borysevych Volodymyr, Xiang Zhang

Current state of development of advanced forgings processes

National Aerospace University "Kharkiv Aviation Institute", s. Kharkiv, Ukraine

With the vigorous development of high-tech industries such as aviation and aerospace, new challenges have been brought to the traditional forging process. Forgings with a single structural feature and conventional forging processes in the past can no longer fully meet the development of contemporary industry. Therefore, it is urgent to develop new forging processes to meet the higher requirements for forgings. First of all, this article classifies the traditional forging processes, which helps to better understand the different types of forging processes. Then, the analysis of different types of forgings and their forming processes will help to better understand the forming characteristics of different methods of improvement. Comparative analysis found that the selection of forging process and route should fully consider the shape and size of the forgings. In actual production, often one type of forging may have multiple types of shape features. The complexity of the structure makes it impossible to obtain such forgings through only one type forging process or one-step forging. Greatly increased the difficulty of forging, limiting its development and application. Therefore, It is necessary to develop multi-types and multi-steps forging processes. And it is urgent to do further research on the metal forming mechanism and defect generation mechanism of complex forgings in the forging process.
Key words**:** forging processes, forgings, multi-types forging, multi-steps forging.

Introduction

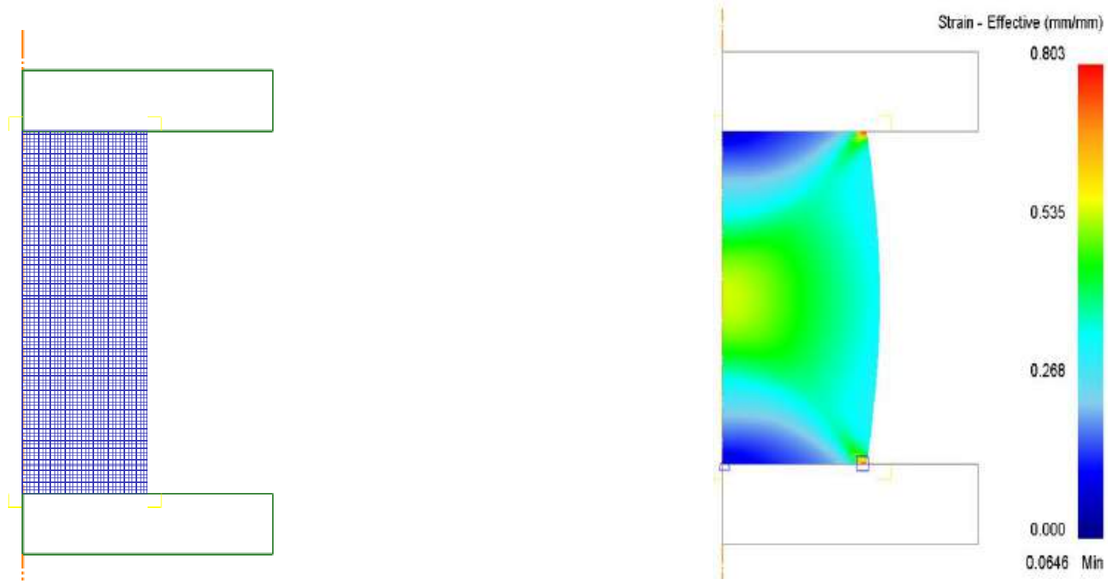
The booming development of contemporary aviation, aerospace, automobile and high-tech industries, especially the research and development of new generation aircraft and new energy vehicles have continuously increased requirements for large capacity, low energy consumption and long life, which urgently requires its key bearing and transmission components to have Features of high performance, light weight and high power efficiency. Forging can improve material utilization, improve material structure and mechanical properties, and realize batch forming and manufacturing. Therefore, forging technology is widely used in aviation industry production. Aviation forgings generally use materials with high specific strength and specific stiffness, including titanium alloys, ultra-high-strength steels, and aluminum alloys [1,2].

At present, forging technology is quite mature, and forging equipment is becoming more and more advanced. Different types of forgings need to use different forging processes. The choice of forging process directly affects whether the quality of forgings is qualified. We must have a sufficient understanding of the forging process and the type of forgings to ensure the smooth progress of the forging process. Therefore, this paper will classify typical forging processes and forgings. It is intended to provide some guidance for researchers and technicians in this field.

1. Classification of forging process

1.1. According to the forming mechanism

The forging process can be divided into open forging, closed die forging, ring rolling and special forging according to the forming mechanism. Open forging mainly produces forgings with small batches. Forging equipment such as forging hammers and hydraulic presses are used to form blanks to obtain qualified forgings. The basic process of open die forging includes upsetting, drawing, punching, cutting, bending, twisting, shifting and welding. It adopts hot forging method [3]. During open forging, the metal flows easier to the free surface, such as the barreling shape produced during upsetting. Therefore, the final shape of the forgings cannot be accurately controlled and is often used as a preforming process [4].



2D Finite element model Strain distribution diagram

Fig. 1. Upsetting sumilation by Deform-2D [4]

Closed die forging refers to the forging obtained by pressing and deforming metal blanks in a forging die chamber with a certain shape. It is generally used to produce parts with small weight and large batches. According to different die structures, it can be divided into closed forging with flash and closed die forging without flash. Closed die forging and closed upsetting are two advanced technologies of die forging. Since there is no flash, the utilization rate of materials is high. It is possible to complete the finishing of complex forgings with one process or several processes. Divided into hot forging, warm forging and cold forging according to temperature [5].

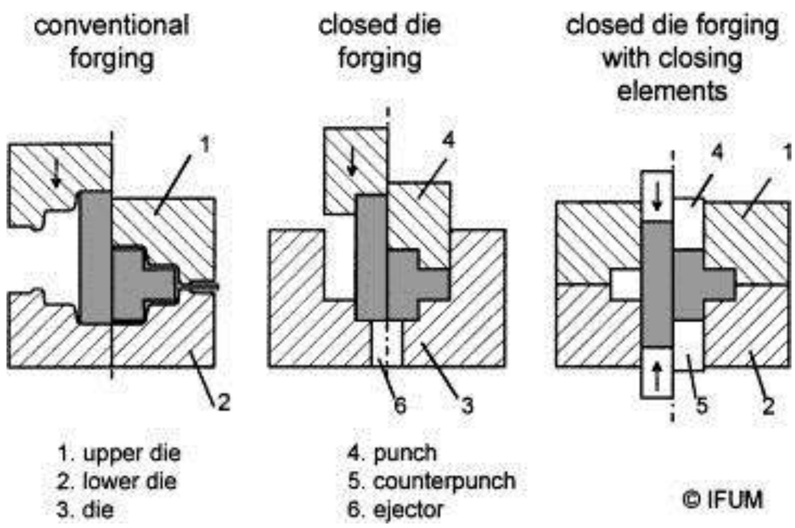


Fig. 2 Closed die forging [6]

Ring rolling refers to the production of ring parts with different diameters through special equipment ring rolling machines, which are widely used in machinery, automobiles, trains, ships, aviation, aerospace, petrochemical, nuclear energy industries and other fields.

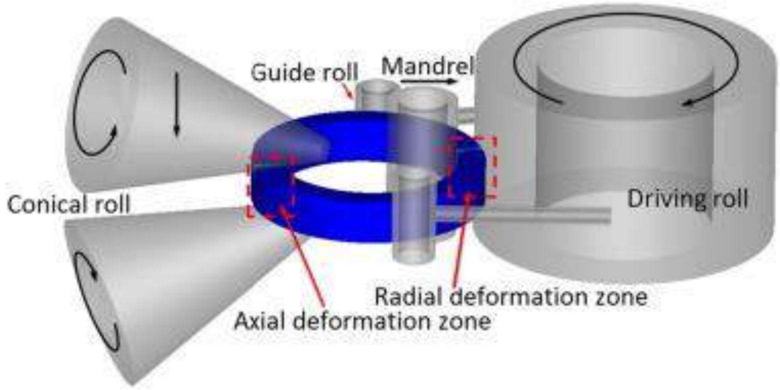


Fig. 3. Ring rolling process [7]

Special forging includes roll forging, cross wedge rolling, radial forging, liquid die forging and other forging methods, which are more suitable for the production of parts with special shapes. For example, roll forging can be used as an effective pre-forming process, which can greatly reduce the subsequent forming pressure. Cross wedge rolling can produce steel balls, transmission shafts and other parts. Radial forging can produce large forgings such as barrels and stepped shafts.

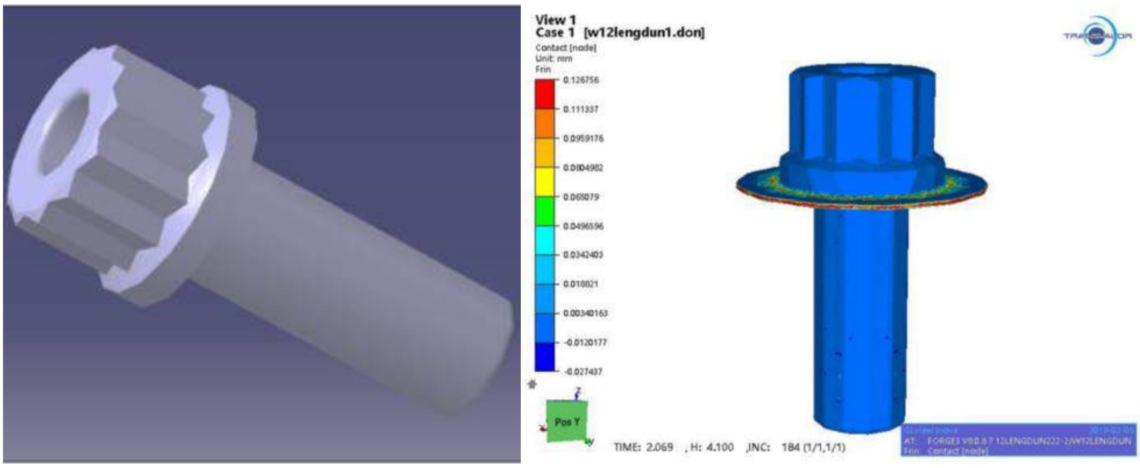
1.2. According to the movement mode of the forging die

According to the movement mode of the forging die, forging can be divided into pendulum rolling, pendulum swivel forging, roll forging, cross wedge rolling, ring rolling and cross rolling. Rotary forging, rotary forging and ring rolling can also be processed by precision forging. Roll forging and cross rolling are often used as front-end working of thin materials. Rotary forging, like free forging, is also partially formed, and its advantage is that compared with the size of the forging, it can be formed even when the forging force is small. However, the material expands from the vicinity of the mold surface to the free surface during processing, and the accuracy cannot be guaranteed.

2. Classification of problem forgings

There are many types of forgings, which can be roughly divided into: axisymmetric solid, axisymmetric hollow, special-shaped thin-walled, shaft, multi-ribbed ribs, brackets, forks, rings, etc. according to their appearance.

Axisymmetric solid forgings such as aviation-grade high-strength bolts. High-strength bolt materials for aviation are generally selected from high-temperature alloys with excellent properties, which have large deformation resistance, narrow forging temperature range, poor thermal conductivity, and poor plasticity. During warm forging, mold damage, unfilling, forging cracks, and uneven structure often occur question. Zhang et al [8] proposed a process route for cold forming of GH4168 (IN718) alloy high-strength bolts, and used finite element analysis to optimize process parameters such as mold structure, pressing speed, and lubrication conditions. Through verification, the life of the die has been greatly improved, and the tensile strength of the workpiece after extrusion has increased by 116%



3D model Finite-element simulation by Forge

Fig. 4. GH4168 (IN 718) Alloy high-strength bolts [8]

Axisymmetric hollow forgings such as hollow flanges generally have thin walls, complex structures, and high deformation resistance. Therefore, problems such as bending, cracking and mold breakage are prone to occur. Winiarski et al [9] proposed a two-step forming process of 42CrMo4 hollow flange, and verified the feasibility of the process through Deform2D/3D simulation software. First, the wall thickness of the workpiece is increased by extrusion, so that the metal flow distance during the flange filling process is reduced by 1.37 times, effectively reducing the risk of bending and folding.

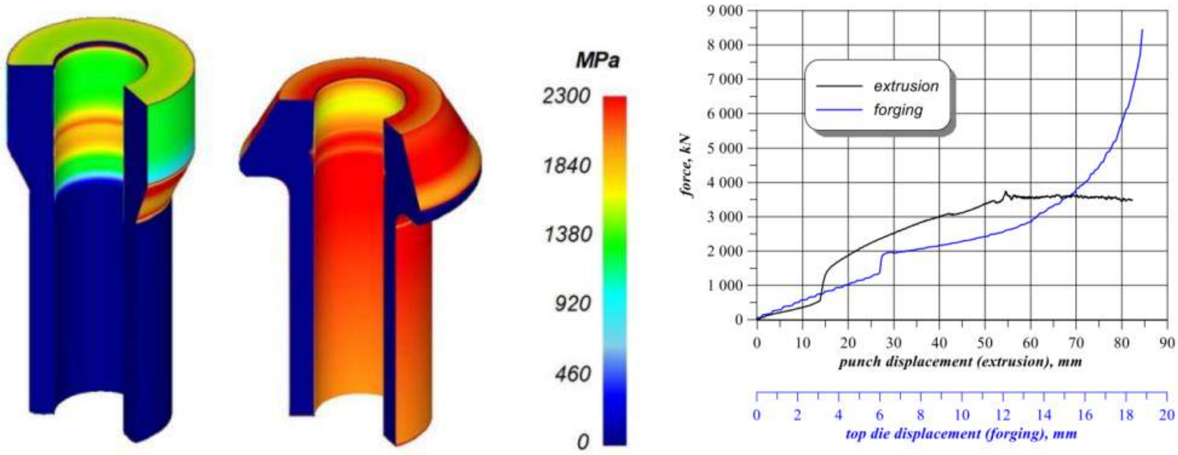


Fig. 5. Stress distribution and stroke-load diagram of forgings [9]

Special-shaped thin-walled forgings such as turbine blades, as the most critical aviation components, turbine blades are widely used in aero-engines. The temperature and microstructure evolution of forgings are greatly affected by temperature, which further affects the fatigue life and corrosion resistance of final forgings [10]. Shiyuan Luo et al [11] studied the influence of speed on the temperature and microstructure of Ti-6Al-4V turbine blade forging, pre-forged the billet through hammer forging, and then final forged the preformed workpiece through Die forging. Using Deform-3D software to compare the temperature and structure changes at different forming speeds from 100mm/s to 600mm/s, it was found that as the speed increased, the temperature loss due to friction and deformation heat decreased, and the temperature distribution of the forging was improved Uniformity. However, the phase transition time is short and the cooling rate is low, so the volume fraction of equiaxed α phase and lamellar α+β phase does not change significantly. A significant increase in temperature leads to a significant increase in the volume fraction of the β phase.

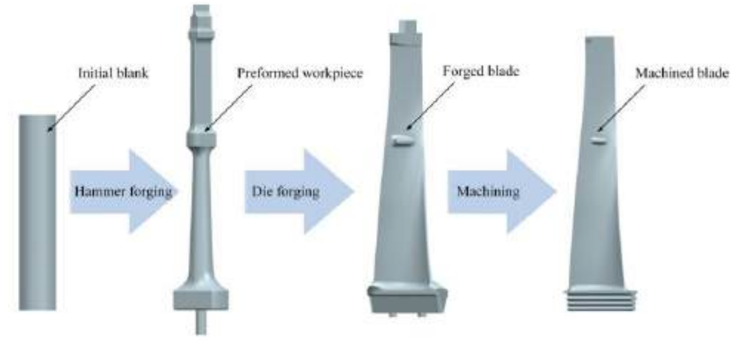
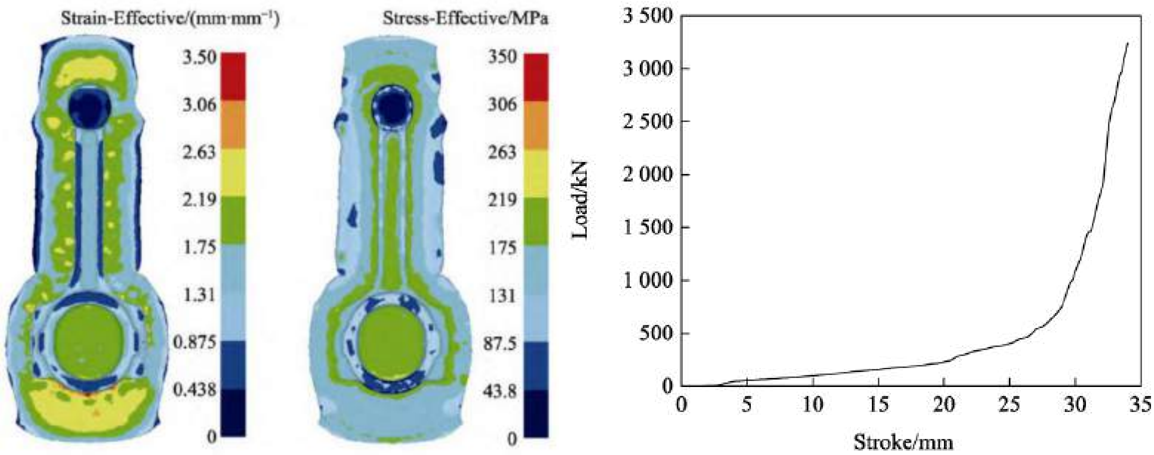


Fig. 6. the procedure diagram of blade manufacturing [11]

Shaft forgings such as engine connecting rods, as important parts in the engine transmission mechanism, have high performance requirements and must have high enough dimensional accuracy, fatigue strength, and structural rigidity [12]. At present, the production of connecting rods mainly relies on the closed die forging process, and the blank is forged and formed by using a special die, so as to obtain the required forgings. Jia et al [13] built a simulation model of connecting rod pre-forging to analyze the influence of different blank temperature, mold temperature, forging speed and friction factor on the forming load. Regression analysis of the forming load was carried out through the four-factor and three-level response surface test, and the parameters in descending order of significant influence on the forming load were: billet temperature, friction factor, die forging speed, and die temperature. On this basis, combined with the multi-island genetic algorithm for optimization, it was found that the forming load was reduced from 6549.5 kN to 3226.6 kN, a reduction of 50.74%.

Multi-reinforced ribs forgings such as aircraft bulkheads and aircraft load-bearing beams. In order to reduce the weight of equipment without weakening the performance of strength and stiffness, such forgings usually adopt a structural form of large-scale integration, thin-walled lightweight and complex shape [14].



a b c

a) Equivalent strain distribution b) Equivalent stress distribution
c) Stroke-Load diagram

Fig. 7. Finite-element simulation by Defom-3D [13]

The ultra-large-size forgings with multi-rib is very complex. The irregular and overlarge forgings requires the heavy-duty press with high stiffness and high energy [15]. Wei et al [16] explained the material transfer problem of large-scale multi-rib members in the forming process of local loading by the numerical simulation and physical simulation. The results show, the material transfer effect is inevitable during the local loading process. Therefore, exploration of the material transfer effect in the local loading forming process is meaningful and provides guidelines for improving or eliminating the forming problems in the development of the isothermal local loading forming technology for ultra-large-size components with multi-rib.

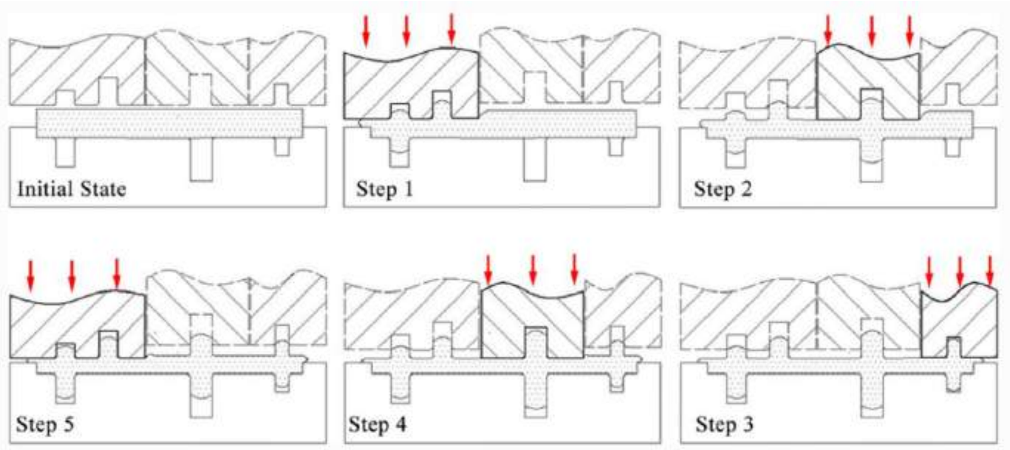
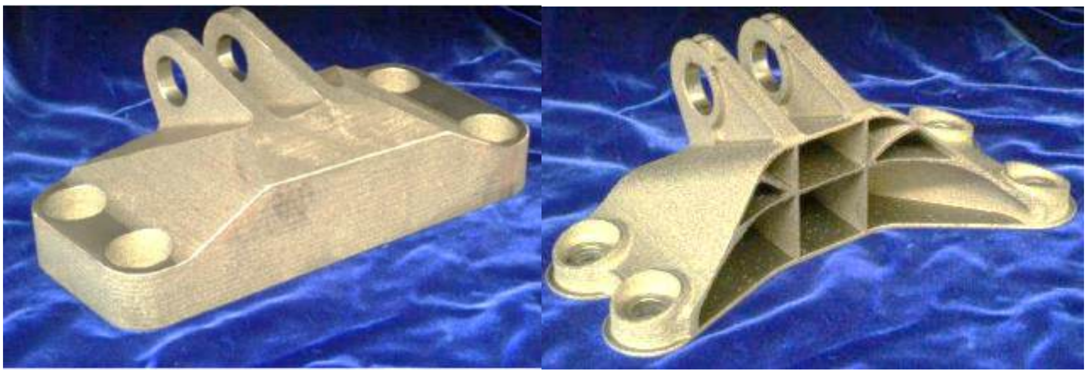


Fig. 8. Schematic diagram of the local loading process [16]

Brackets forgings usually have the characteristics of long longitudinal axis and large difference in cross-sectional area. It is widely used in aerospace, aviation, automobile and other fields, and is of great significance to the lightweight structure. GE Corporation of the United States once publicly held a competition to invite talents from all over the world to participate in the design and improvement of its titanium alloy aircraft engine bracket, and finally achieved a weight reduction of 80%. But because its complex structure can only be processed by additive manufacturing technology, the cost is very expensive [17]. Therefore, it is very meaningful to apply die forging technology to the production of brackets.



GE Original Parts Award-winning parts

Fig. 9. Aircraft bracket [17]

Borysevych et al [18] equated the complex cross-section problem of the bracket to a plane problem, and used numerical simulation technology to conduct a full-factor test, and studied the influence of the height of the flash groove bridge, the inclination angle of the bridge, and the volume ratio of the flash to the workpiece on the workpiece forming. Since the upper and lower parts of the parting line are not symmetrical, an asymmetrical bridge solution is proposed. It was found that the increase of the height and the inclination angle is more beneficial to the forming. When the inclination angles of the upper and lower parts of the bridge are 15° and 4° respectively, the deformation of the metal flowing through the bridge is the most uniform, and the cavity is well filled. At the same time, it was found that if the size of the rib is changed, the filling of the cavity will not be satisfied. Therefore, the ratio of flash to workpiece volume is one of the factors affecting workpiece forming.

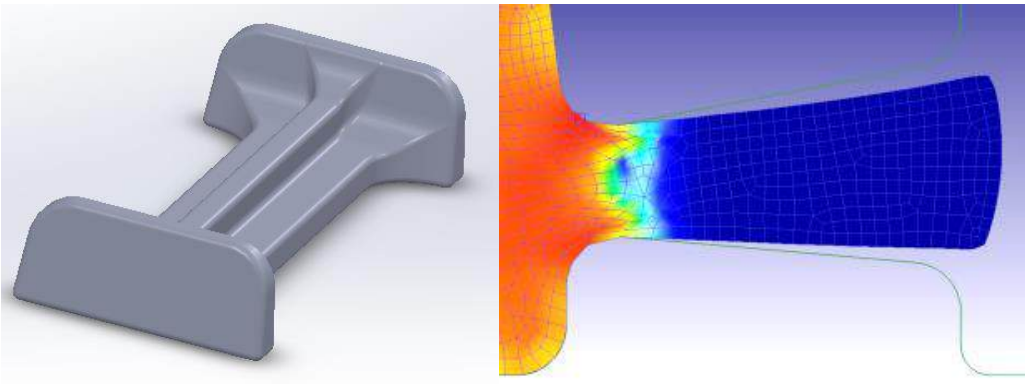
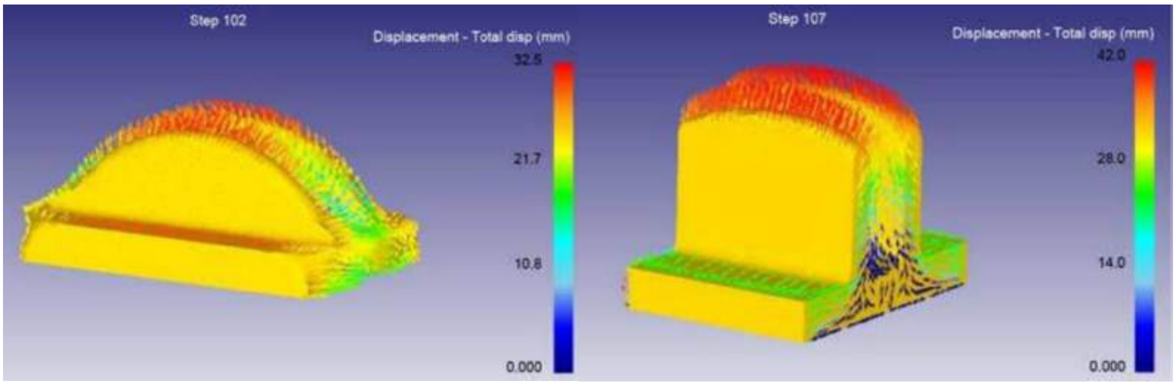


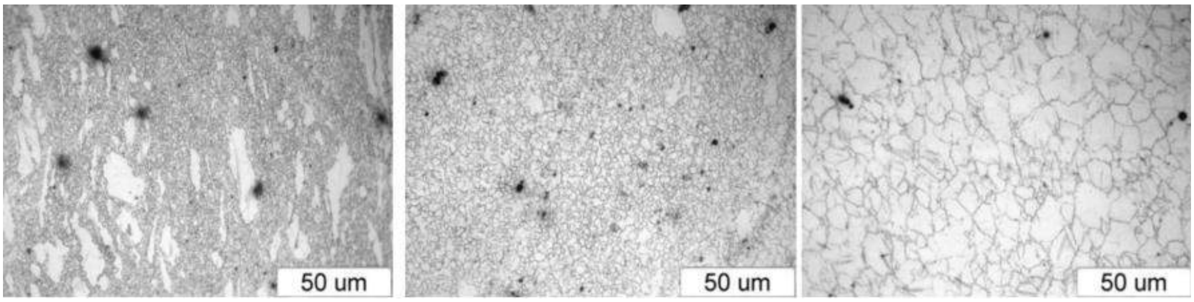
Fig. 10. The 3D model and 2D simplified model of bracket [18]
(metal flow simulation by Deform-2D)

Dziubińska [19, 20] proved that it is possible to process the two-rib bracket through the Three-slide forging process, and analyzed the forming process of the semi-open die and the closed die by using the finite element analysis method. It was found that the forgings formed in the semi-open die had shape defects, resulting in increased material consumption. However, compared with the closed die, it can reduce the cost of the tools, and is more suitable for the production of bracket products with semicircular ribs or triangular ribs. While the shape of the forging formed in the closed die is more regular, which is more suitable for the production of bracket products with rectangular bases.



a) In open die b) In closed die
Fig. 11. The distribution of the displacement field of the bracket [20]

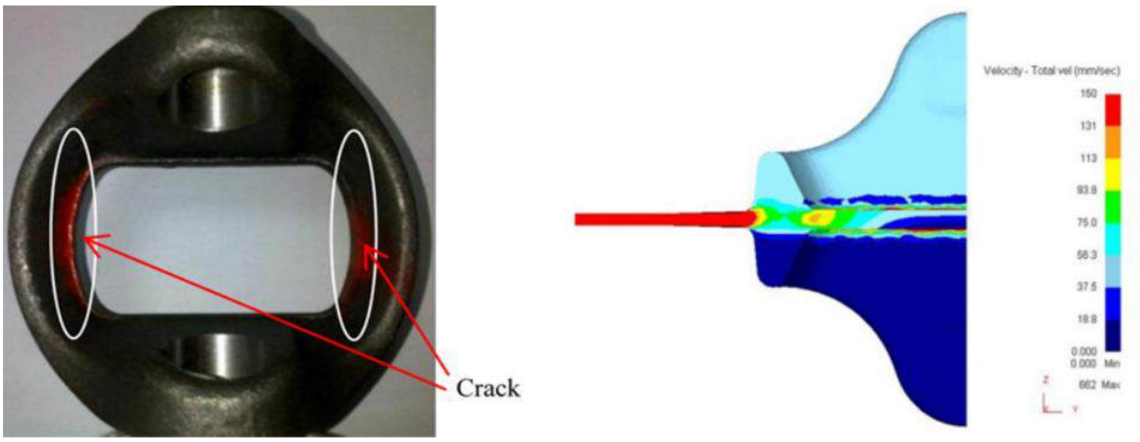
Then, a qualitative analysis was performed on the bracket formed in the semi-open die, and it was found that the forging had poor microstructure homogeneity due to the complexity of the metal flow. Cracking easily occurred in the rib forming zone where the strain was greatest. If we want to obtain forgings with good homogeneous by this method, we need to heat treat the workpiece.



Rib zone Web zone Transition zone

Fig. 12. Microstructure of brackets forging with one rib from AZ31 alloy read in the different zone [19]

Fork-shaped forgings, such as The duplex fork, are important components of universal joints in automobile transmission structures. Due to its complex structure, the part has a high degree of deformation during the forging process, and the metal flow is complicated, and it is very easy to occur defects such as dissatisfaction and cracking. Traditional defect analysis is generally based on experiments, and conclusions are often drawn from experience. Hu et al [21] developed a two-step forging process, using the upsetting to remove scale and unequal thick flash groove dies to complete the final forging. The different parameters of the optimized forging process (including the pre-upsetting stroke, friction factor, mass of workpiece, and preform positioning offset) were analyzed using the finite element method. It was found that the huge speed difference between the slug and the rib was the main factor of cracking during forging. Burr grooves of unequal thickness can reduce this speed difference more effectively than damping grooves, and the reliability of this process has been verified in trial production.



physical diagram Distribution diagram of the metal flow velocity

Fig. 13. The duplex fork [21]

Thin-walled metal rings are typical ring forgings, which are widely used in launch vehicles, nuclear submarines, rocket fuel storage tanks, and large pressure vessel flanges. Such forgings are generally processed by ring rolling, but due to the complexity of the process, its application and development are greatly restricted.

Therefore, Chen et al [22] established a three-dimensional rigid-plastic thermomechanical coupling finite element model, and studied the plastic transfer process and plastic distribution characteristics of the metal ring during the forming process. The effects of the initial inner diameter and height of the workpiece, the feed speed of the upper die and the rotational speed of the lower die on the plastic forming are analyzed. The results show that the plastic deformation of the workpiece is uniform along the tangential direction from the upper surface, but not uniform along the axial and radial directions. Especially, the plastic deformation of the ring at the upper surface position on radial is the most nonuniform, and the plastic deformation uniformity at the axial middle position on is the worst. As the feed rate and initial temperature increase, the plastic deformation uniformity of the ring becomes better and the degree of defomation decreases accordingly. With the increase of the friction coefficient and the rotational speed of the lower die, the uniformity of the plastic deformation of the ring becomes worse, and the degree of deformation increases accordingly.

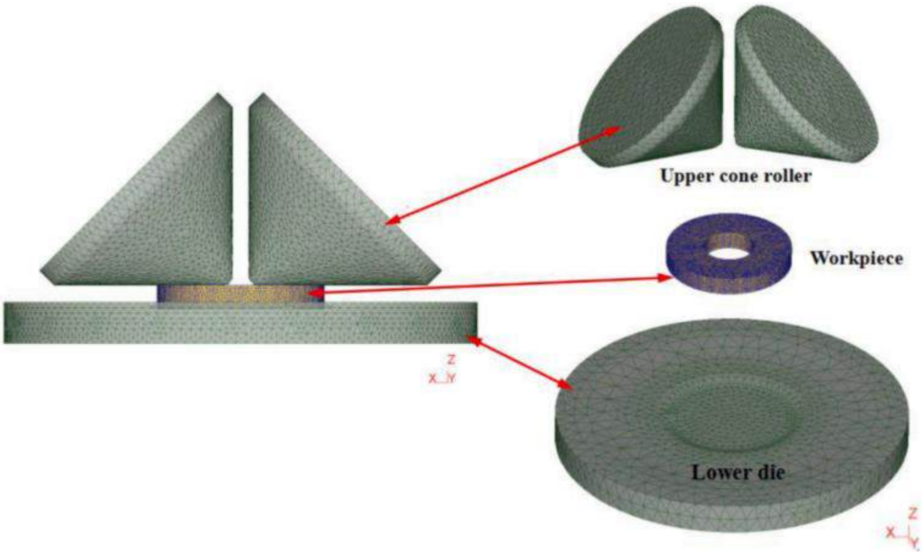


Fig. 14. Schematic diagram of the finite element model [22]

3. Conclusion

This article first classifies the common forging processes, and expounds the forming methods, advantages and disadvantages of these processes. Then, the forgings are classified according to the shape characteristics, and the forming process of these forgings is analyzed, and the following conclusions are drawn:

1. Compared with traditional processing technology, forging technology can save materials and improve the mechanical and organizational properties of workpieces. The current forging process is very mature, but there is still a lack of sufficient understanding of the metal flow laws and the causes of defects during the forging process, which greatly limits its application and development in high-tech fields. Therefore, further research on the metal deformation mechanism and defect generation mechanism in the forging process is urgently needed.

2. The selection of forging process and route should fully consider the shape and size of the forging. With the help of finite element analysis, a reasonable process route can be efficiently selected, and qualitative analysis can be performed on various influencing factors in the forming process. Finally, the purpose of saving time and labor, reducing die wear and improving the quality of forgings is realized. Therefore, it is

necessary to classify existing forgings.

3. Most of the forgings listed in this article only have a certain shape feature. In actual production, one type of forging may have multiple types of shape features. For example, the bracket forging not only has a long longitudinal axis and a large cross-sectional shape, but also may have a curved and ribbed structure at the same time. This complex structure is often caused by lightweight requirements. However, due to its complex structure, it cannot be obtained through only one type forging process or a one-step forming process route. The complexity of the process greatly limits the application and development of such forgings. Therefore, in order to cope with the rapid development of high-tech industries, it is urgent to do further research on the multi-types and multi-steps forging process of complex forgings.

Reference

1. Yang He. Research progress on non-uniform deformation controlled by local loading and precise plastic forming / Yang He, Sun Zhichao, Zhan Mei, Guo Lianggang, Liu Yuli, Li Hongwei, Wu Yuejiang // Journal of Plastic Engineering. – 2008. – № 15 (2). – P. 6–14.

2. Liu Songliang. Application status of large-scale aviation forging materials and forming technology / Liu Songliang // Large Casting and Forging. – 2021. – № 6, – P. 16–18.

3. Li Qi. Fault Diagnosis and Maintenance Technology of Hydraulic System of Free Forging Hydraulic Press / Li Qi // Science and Technology Innovation and Application. – 2022. – № 32. – P. 161–165.

4. Zhang, X. Selection of the rational geometry of specimen for compression test / Zhang X., Borysevych V., Chen J. // Авиационно-космическая техника и технология: сб. науч тр. / Нац. аерокосм. ун-т ім. Н. Є. Жуковського «ХАІ». – Харків, 2022. – № 2. – С. 14 – 20.

5. Xiong Juhua. Analysis on Die Forging / Xiong Juhua // Science and Technology Innovation Herald. – 2009. – № 17, – P. 37–37.

6. Doege E. Closed die technologies for hot forging / Doege E., Bohnsack R. // Journal of Materials Processing Technology. – 2000. – № 98(2). – P. 165–170.

7. Zhu, X. Blank design method for C-section profile ring rolling based on FEM and RSM / Zhu X., Ma B., Su G., Hu Y., Liu D. // Alexandria Engineering Journal. – 2023. – № 65. – P. 649–660.

8. Zhang Xiang. Research on forming process of GH4169 high-strength precision bolts: Master's thesis, Nanchang Hangkong University, 2019. – 149 p.

9. Winiarski G. Numerical analysis of a two-stage forming process for a hollow part with external flange / Winiarski G. // Journal of Physics: Conference Series. – 2021. – Vol. 1736. No. 1. – P. 1–8.

10. Luo S. Numerical analysis of die wear characteristics in hot forging of titanium alloy turbine blade / Luo S., Zhu D., Hua L., Qian D., Yan S. // International Journal of Mechanical Sciences. – 2017. – № 123. – P. 260–270.

11. Luo, S. Influence of forging velocity on temperature and phases of forged Ti-6Al-4V turbine blade / Luo S., Yao J., Li J., Du H., Liu H., Yu F. // Journal of Materials Research and Technology. – 2020. – № 9(6). – P. 12043–12051.

12. Wang Xiangjun. Research on Optimization of Die Forging Process Parameters of Connecting Rod Head / Wang Xiangjun, Wang Dayong, Wang Peitao, Zhang Zhen, Zhou Penglei // Journal of Plastic Engineering. – 2019. – № 6. – P. 143-151.

13. Jia D.W. Research on Factors Influencing Forming Load of Connecting Rod Die Forging Based on Response Surface Method / Jia D.W. // Precision Forming Engineering. – 2023. – № 15(05) . – P. 193–201.

14. Yuan S. J. Developments and perspectives on the precision forming processes for ultra-large size integrated components / Yuan S. J. // International Journal of Extreme Manufacturing. – 2019. – № 1 (2) . – P. 1–18.

15. Yang H. Recent developments in plastic forming technology of titanium alloys / Yang H. // Sci China Technol Sci. – 2011. – № 54(2) . – P. 490–501.

16. Wei K. Exploration of the material transfer effect in local loading forming of ultra-large-size integrated component with multi-rib / Wei K. // The International Journal of Advanced Manufacturing Technology. – 2020. – № 108. – P. 1413–1427.

17. Carter W. T. The GE aircraft engine bracket challenge: an experiment in crowdsourcing for mechanical design concepts / Carter W.T., Emo D.J., Abbott D.H., Bruck C.E., Wilson G.H., Wolfe J.B., Finkhousen D.M., Tepper A., Stevens R.G // International Solid Freeform Fabrication Symposium. University of Texas at Austin, 2014. – P. 1402–1411.

18. Borisevich V. V. Choice of Rational Parameters of the Flash Groove Bridge in Simulation of Open Forging / V. V. Borisevich, Мохсен Закизаде Байгара // Open Information and Computer Integrated Technologies / National Aerospace University “Kharkiv Aviation Institute”. – 2016. – № 71. – P. 136–144.

19. Dziubinska A. The microstructure and mechanical properties of AZ31 magnesium alloy aircraft brackets produced by a new forging technology / Dziubińska A. // Procedia Manufacturing. – 2015. – № 2. – P. 337–341.

20. Dziubinska A. A new method for producing magnesium alloy twin-rib aircraft brackets / Dziubinska A. // Aircraft Engineering and Aerospace Technology: An International Journal. – 2015. – № 87 (2) . – P. 180–188.

21. Hu C. Process optimization for design of duplex universal joint fork using unequal thickness flash / Hu C. // International Journal of Precision Engineering and Manufacturing. – 2015. – № 16. – P. 2517–2527.

22. Chen M.C. Research on plastic deformation transfer and distribution of large-diameter thin-walled metal ring parts in double-roll pendulum hot rotary forging process / Chen M.C., Chundong Z. // Journal of Manufacturing Processes. – 2022. – № 76(9) . – P. 379–396.

Надійшла до редакції 20.12.2023, розглянута на редколегії 20.12.2023

Сучасний стан розвитку розвитку прогресивних процесів ковки

Внаслідок стрімкого розвитку таких високотехнологічних галузей промисловості як авіа- та ракетобудування нові вимоги пред'являються до традиційних процесів штампування. Звичайні процеси штампування, що застосовуються у минулому, тепер не відповідають вимогам сучасної промисловості. Отже, потрібне термінове впровадження нових передових процесів штампування. Насамперед у статті оглядаються ті традиційні процеси штампування, які потребують модернізації. При цьому аналіз різних типів складної форми штамповок та процесів для їх одержання допомагає краще зрозуміти шляхи їх покращення. Порівняльний аналіз показує, що для правильного планування процесу необхідно повністю враховувати особливості форми та розмірів штампованих деталей. Особливості геометрії таких деталей унеможливлює їх отримання традиційними процесами штампування. Ускладнення форми штампованих деталей і неможливість їх отримання обмежує їх розвиток та застосування. Отже, необхідно розвивати нові складні процеси багаторівчакого, багатостадійного штампування. При цьому необхідно терміново проводити дослідження механізму формоутворення кондиційних деталей за відсутності дефектів у таких процесах штампування.

Ключові слова: процеси штампування, штампована деталь, багаторівчакове штампування, багатостадійне штампування.

Відомості про авторів:

Борисевич Володимир Володимирович – к.т.н., доцент каф. «Технології виробництва літальних апаратів», науковий керівник аспіранта Чжан Сяна, Національний аерокосмічний університет ім. М.Є. Жуковського "Харківський авіаційний інститут", +380508068817, Viber: 0680045369, v.borisevich@khai.edu, ORCID: 0009-0008-0623-324X

Чжан Сян – аспірант каф. «Технології виробництва літальних апаратів», Національний аерокосмічний університет ім. М.Є. Жуковського "Харківський авіаційний інститут", +8613133838248 Viber , ORCID: 0000-0001-6607-4270

About the Author:

Borysevych Volodymyr Volodymyrovych – candidate of technical science, associate professor of Technology of Aircraft Manufacturing Department, National Aerospace University “Kharkiv Aviation Institute”, Kharkiv, Ukraine, v.borisevich@khai.edu, +380508068817, ORCID: 0009-0008-0623-324X

Xiang Zhang – PhD student, Technology of Aircraft Manufacturing Department, National Aerospace University “Kharkiv Aviation Institute”, Kharkiv, Ukraine, +8613133838248 Viber, ORCID: 0000-0001-6607-4270