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RESEARCH ON MATERIAL FLOW-STRESS BEHAVIOR AND THE DIE-FORGING PROCESS FOR FORGED-STEEL BRAKE DISCS FOR HIGH-SPEED TRAINS

RAZISKAVA PLASTIČNE DEFORMACIJE IN PROCESA UTOPNEGA KOVANJA JEKLA ZA ZAVORNE DISKE ZELO HITRIH VLAKOV

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Due to the large size and complicated features, the brake discs of high-speed trains are difficult to forge, so a reasonable design of the process and the die parameter are prerequisites for successful forming. The flow stress of 23CrNiMoV, a forged-steel brake disc material for high-speed trains, was investigated by a uniaxial compression experiment on a Gleeble 1500 test machine. Based on the obtained flow-stress data, a series of numerical simulation analyses of the die forging of high-speed-train brake discs were carried out by using finite-element software. The effects of forging temperature, flash groove parameters and forming speed on the flow filling, forming load and temperature change of metal during die forging were studied. The simulation results were optimized and better process parameters were obtained. Based on the obtained process parameters, the simulation of the forming process was completed and a better forming quality was obtained.

Key words: flow stress; brake disc; die forging; flash groove; numerical simulation

Izdelovanjeoziroma utopno kovanje zavornih diskov za zelo hitre vlake je težavno zaradi njihove velikosti in komplicirane oblike. Za njihovo uspešno izdelavo, je zato potrebno predhodno načrtovati primeren proces kovanja in parametre kovaškega orodja. Avtorji so na eksperimentalnem termomehanskem eno-osnem tlačnem stroju Gleeble 1500 določili krivulje tečenja jekla 23CrNiMoV, ki se uporablja za zavorne diske zelohitrih vlakov. S pomočjo dobljenih eksperimentalnih podatkov so izvedli serijo analiz in numeričnih simulacij utopnega kovanja zavornih diskov na osnovi računalniške metode končnih elementov. Študirali so vplive temperature kovanja, parametrov srha, hitrosti oblikovanja na potek polnjenja utopnega orodja in njegovih obremenitev ter temperaturnih sprememb med samim kovanjem. Rezultate simulacij so optimizirali in na ta način dobili popolnejšo računalniško programsko opremo za simulacijo kovanja diskov in tako optimalnejše procesne parametre, kar je omogočalo tudi kvalitetnejšo izdelavo diskov.

Ključne besede: napetost tečenja, zavorni diski, utopno kovanje, kovaški odrezki (srh ali brada), numerična simulacija

1 INTRODUCTION

Most of the high-speed trains use disc brakes because of their small friction fluctuations and good braking effect.[1,2] As the speed of trains increases, more stringent requirements are placed on the performance of the basic brakes.[3,4] Since the kinetic energy of the object is proportional to the square of the speed, as the train speed increases, the energy required to switch by the brake disc also increases dramatically. Therefore, there are higher requirements for the material of the brake disc, such as high wear resistance, sufficient strength, high temperature stability, etc.[5]

For train brake discs, the most common brake disc materials are forged steel, cast iron and some composite materials. Forged steel has good mechanical properties at room temperature and high temperature, good toughness, high resistance to thermal cracking, and good wear resistance and thermal fatigue resistance.[6]

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23CrNiMoV forged steel is a high-speed-train brake-disc material. It has good plasticity and toughness and excellent low-temperature mechanical properties, which can meet the requirements of low-temperature and high-load use.[7] The resistance of low-alloy steel is not high during hot forging, so it is easy to form under normal circumstances. However, for the forging of large-sized products such as brake discs with complex heat dissipation ribs, high pressure and low wear die life limit the promotion and application of forging production.

The difficulty of forging the brake disc is mainly reflected in two aspects. First, there are many high and narrow heat-dissipation ribs on the disk body, which is particularly difficult to form during die forging. Second, due to the large size of the disk, the required tonnage of the equipment is high. At the same time, in order to ensure the filling of the heat-dissipation ribs, the demand for forging force will be further improved. This will increase the wear of the die. How to use reasonable forming means, suitable forming process, economical forming equipment and mold to ensure its forming is the main problem facing the current brake disc forging production, which seriously hinders the development and application of high-speed-train steel brake discs. At this stage, there is no more mature forging process research and experience of steel brake discs of high-speed train, only a small number of references provide a description of the characteristics, materials and construction of steel forged brake discs.[1,2,5] For the forging process of forged steel brake discs, most of the production experience of large-scale disc-shaped forgings is used for rough-type production, which causes a large amount of waste in production, the product stability is extremely poor, and the cost of the product is also high.[8]

The numerical simulation of the forging process is an effective method to solve the above problems, which can demonstrate the manufacturing process through computer.[9–11] However, accurate numerical simulation results depend on environmental parameters consistent with the actual conditions, especially the rheological properties of the forging materials.

In this paper, the flow stress of forged steel brake disc material 23CrNiMoV for high-speed trains was studied by uniaxial compression test on a Gleeble 1500 testing machine. The finite-element numerical simulation method is used to simulate the forging of the brake disc. The influence of the process parameters and the dimensions of the flash groove on the forging process are studied, which is helpful in the design of the forging process and structure for certain brake-disc forgings.

2 DIE FORGING PROCESS FOR A HIGH-SPEED-TRAIN BRAKE DISC

This paper studies the open-die forging process of a forged-steel brake disc. The forgings are shown in **Figure 1**. The material of the brake disc is 23CrNiMoV, which belongs to low-alloy structural steel. It has the advantages of high strength, high yield ratio, no temper brittleness and good toughness. It is suitable for forging brake discs.

The brake disc is a hollow circular disc body. One end surface of the circular disc body is the braking surface, and the other surface is provided with a relatively complicated heat dissipating rib, which requires a relatively high flow of metal during forming. In addition, considering that the closed die forging requires the volume of the billet to be accurate, it is necessary to ensure that the volume of the billet and the volume of the die cavity are equal. However, in the actual production process, because the dimensional accuracy of the billet is affected by factors such as blanking and heating, it is difficult to meet the above requirements, causing volume fluctuations, which will not only affect the forging formation, but also cause the forging die to be damaged due to the oversized billet.

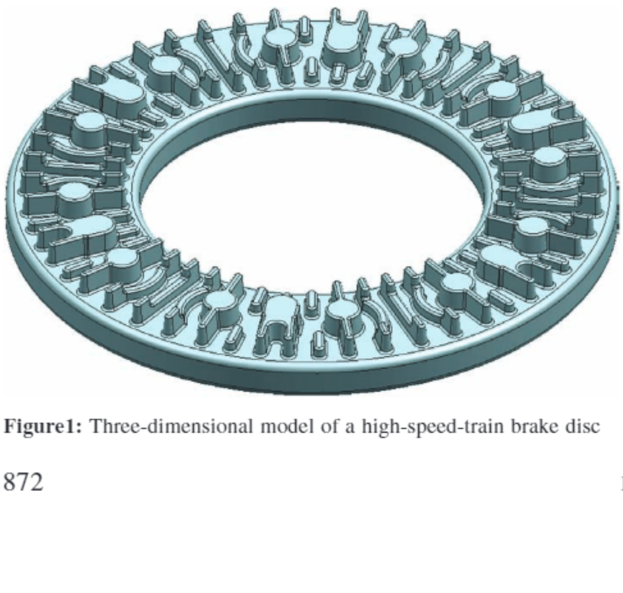

Figure1: Three-dimensional model of a high-speed-train brake disc

Therefore, the brake disc is suitable for open die forging. On the one hand, the flow of metal during forming is not limited by the cavity, and the volume of the billet does not need to be too strict. On the other hand, on the open forging die, there will be a corresponding flash groove, so that when the metal flows to the flash groove, the flash groove will generate sufficient resistance to force the metal to flow towards the edge of the die cavity, thus ensuring that the forging has a more accurate size.

3 PARAMETER SETTING FOR NUMERICAL SIMULATION AND THE FLOW STRESS OF 23CrNiMoV

Due to the cyclic symmetry of the high-speed-train brake-disc products, in order to reduce the finite-element simulation calculation, the 1/12 model is used. The established model is imported into the DEFORM-3D software pre-processing interface. The 1/12 billet is divided into 50,000 tetrahedral meshes. The die material is AISI-H-13, which is preheated to 300 °C; the heat transfer coefficient between the billet and the die is 11 N/(s·mm·°C); the friction boundary condition between the billet and the die adopts the shear friction model:

$$\tau_f = mk = m\frac{\overline{\sigma}}{\sqrt{3}} \tag{1}$$

where τ_f is the frictional force on the contact boundary; m for the friction factor, the thermo-thermal forming is generally between 0.2 and 0.5, thus 0.3 is taken in this paper; k is the shear yield strength of the material; $\overline{\sigma}$ is the equivalent yield stress.

The flow stress of the material can be obtained by thermal simulation experiment.[12] The flow stress of 23CrNiMoV in the temperature of (900; 1000; 1100; 1200) °C and the strain rate of (0.5; 1; 10) s^{-1} is obtained through a uniaxial compression experiment on a Gleeble 1500 test machine. The specimen is a cylinder with a diameter of 8 mm and a height of 12 mm. Before each testing, all the specimens were heated to the deformation temperature at a heating rate of 10 °C/s and held for 3 min to obtain a uniform temperature. According to the

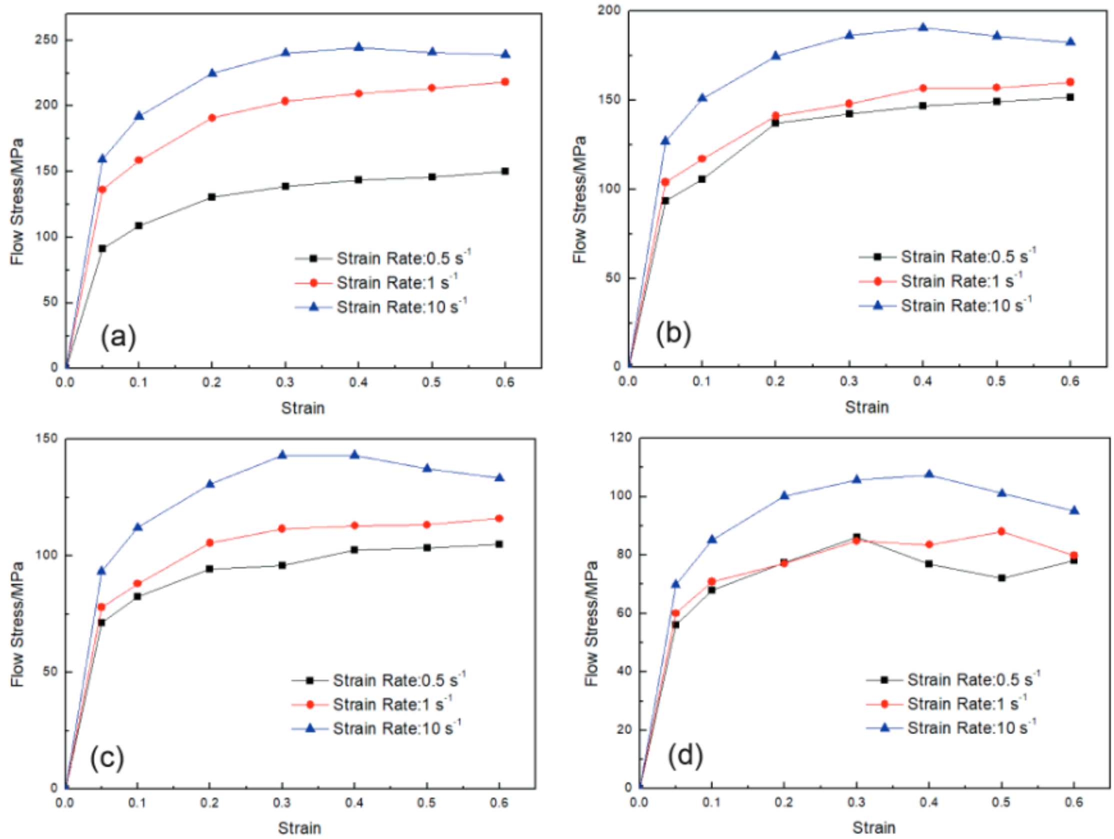

Figure 2: The stress-strain curves of 23CrNiMoV at different temperatures: a) 900 °C, b) 1000 °C, c) 100 °C, d) 1200 °C

Table 1: Numerical simulation parameters of gear forging

Forming temperature (°C)	Punch velocity (mm/s)	Bridge width of flash (mm)	Material of billet	Material of die	Preheating temperature of die (°C)	Friction factor
1000–1200	100–200	15–25	23CrNiMoV	AISI-H-13	300	0.3

data obtained from the test, the stress-strain curve of the material is drawn as shown in **Figure 2**.

Numerical analysis of the final forging process with different process parameters and die structure was carried out using the thermo-mechanical coupling analysis mode. The parameters used in the simulation are shown in **Table 1**.

4 RESULTS AND DISCUSSION

4.1 Effect of forging temperature on the forming result

The die-forging temperature has a great influence on the flow filling of the metal and the tonnage demand of the equipment. For the die forging of large parts, in order to reduce the required forming force, hot forming is generally employed. In this paper, the brake-disc parts of high-speed trains have a diameter of 750 mm and must be heated to a higher temperature to ensure that the tonnage of the equipment meets the forming requirements. However, too high a temperature causes a sharp increase in various defects, such as oxidation, decarburization, overheating, and over-burning. Therefore, considering the forging force demand and heating quality, three temperatures of (1000; 1100; 1200) °C were selected for the simulation analysis.

Figure 3 shows the load-stroke curves of the upper die during the simulated forging temperature at (1000; 1100; 1200) °C and the upper die velocity is 100 mm/s. As can be seen from the figure, the slope of the load curve becomes larger as the upper die moves to half of the entire stroke. This is because the metal starts to flow to the flash groove at this time, and the deformation resistance increases. When the upper die moves to contact with the lower die, the upper and lower dies abut and the simulation stops, and the upper die load reaches the maximum.

The load-stroke curves at the three die forging temperatures are in an increasing trend, but the load on the upper die is very different when the upper and lower dies are hit, as shown in **Figure 4**. The higher the initial temperature of the billet, the smaller the load on the upper die, and the maximum load and temperature change substantially linearly. This is because as the initial temperature of the billet increases, the deformation resistance of the metal material during forging is reduced, which is favorable for the flow of the metal, so that when the billet

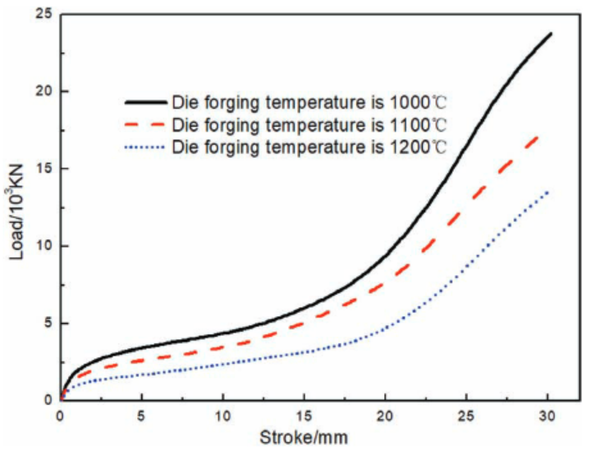

Figure3: Load-stroke curve of the upper die for different die-forging temperatures (the upper die velocity is 100 mm/s)

temperature is increased, the corresponding die load is also reduced. Therefore, in the selection of the die-forging temperature of the brake disc, the die-forging temperature should be increased as much as possible under the premise of ensuring the heating quality of the forging, so as to reduce the tonnage demand of the equipment, the force of the die can be reduced, thereby improving the life of the die.

4.2 Effect of forming velocity on the forming result

It can be seen from **Figure 2** that the rheological properties of the 23CrNiMoV material are greatly affected by the strain rate, and the higher the strain rate, the higher the deformation resistance of the material. In die forging, the strain rate of the material is controlled mainly by the speed of movement of the die. Since the lower die remains in the forging of the high-speed-train brake disc, the forging is completed by the downward movement of the upper die, so the moving velocity of the upper die is changed to (100; 150; 200) mm/s respectively. The die-forging temperature is 1100 °C, and the other process parameters remain unchanged. Based on the above parameters, three simulations were executed. The load-stroke curve obtained by numerical analysis is shown in **Figure 5**.

It can be clearly seen that when the moving velocity of the upper die is increased, the maximum load of the upper die is correspondingly reduced. This is because when the upper die moves fast, the contact time between the billet with the air and the die is short, and the temperature is lowered more slowly. As shown in **Figure 6**, although the same initial forging temperature of 1100 °C is used, the lowest temperatures of the forgings at different speeds are (889; 924; 960) °C, respectively. The higher temperature makes the deformation resistance of the metal at a lower value, and the metal flows more easily, so the load on the die is also reduced, which offsets the effect of the increase of strain rate on the increase of the deformation resistance. However, it can be seen from **Figure 7** that with the increase of the moving speed of the upper die, the temperature effect is difficult to offset the speed effect, and the reduction of the maximum load of the upper die has a tendency to slow down. Therefore, it is not possible to adopt a higher speed forming in production, which requires comprehensive consideration.

4.3 Effect of bridge width of flash on forming result

For open die forging, the flash groove is an important structure to ensure full die forging and die life. The flash groove is composed of a bridge portion and a chamber portion. The chamber portion mainly accommodates excess metal, and has no influence on the forming of the forging piece. The role of the bridge is to prevent the outflow of metal, and the width of the bridge has a good regulation of the resistance of the metal into the chamber. For the die forging of high-speed-train brake discs, the width of the flash groove bridge is changed, as shown in a and b in **Figure 8**, respectively, 15 mm, 20 mm and 25 mm. Keeping the other process parameters unchanged, the curve of the maximum load of the

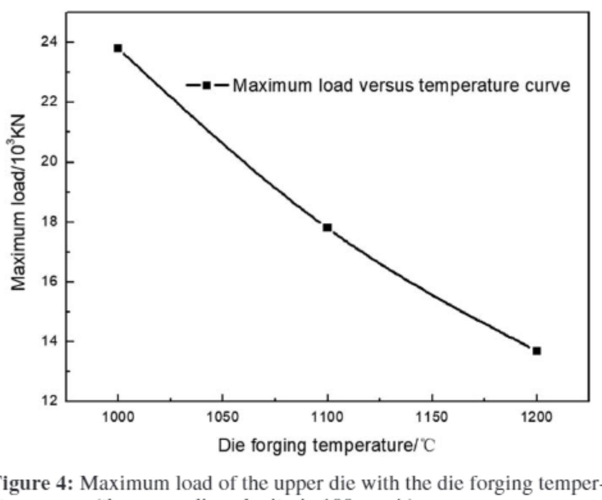

Figure 4: Maximum load of the upper die with the die forging temperature curve (the upper die velocity is 100 mm/s)

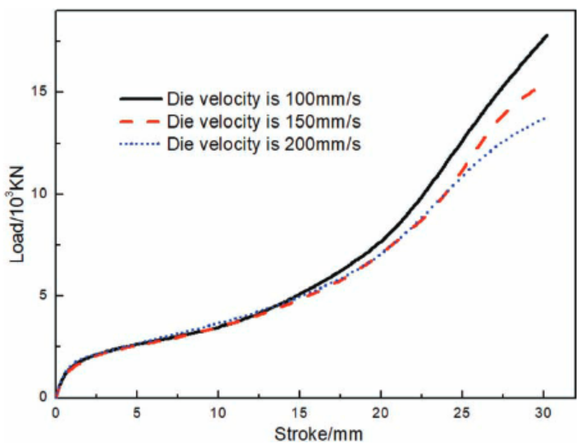

Figure 5: Load-stroke curve of the upper die for different upper die velocity (the die forging temperature is 1100 °C)

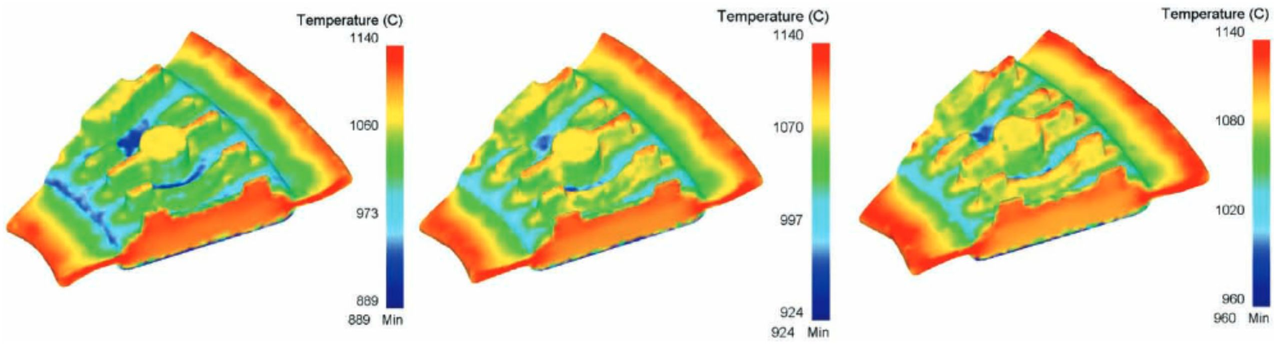

Figure 6: Forging-temperature distribution of different upper-die velocity (the initial forging temperature is 1100 °C): a) Die velocity is 100 mm/s, b) Die velocity is 150 mm/s, c) Die velocity is 200 mm/s

upper die and the bridge width of the flash groove is shown in **Figure 9**.

Through numerical simulation analysis, it is found that the width of the bridges of the three types of flashing grooves can make the form filling full. This shows that when the width of the flash groove is 15 mm, the resistance of the metal to the outside of the cavity is already large enough that the metal fills the cavity. This is reflected in the maximum load of the upper die, and the load change under the three parameters is also small. There is a small decrease when the width of the flash groove bridge is 20 mm, but the maximum load has a sharp upward trend with the increase of the width of the bridge. Therefore, from the perspective of improving the life of the mold, the width of the bridge portion of the flash groove should be as small as possible on the basis of forming. For the high-speed-train brake discs of this paper, a bridge width of 15 mm is suitable.

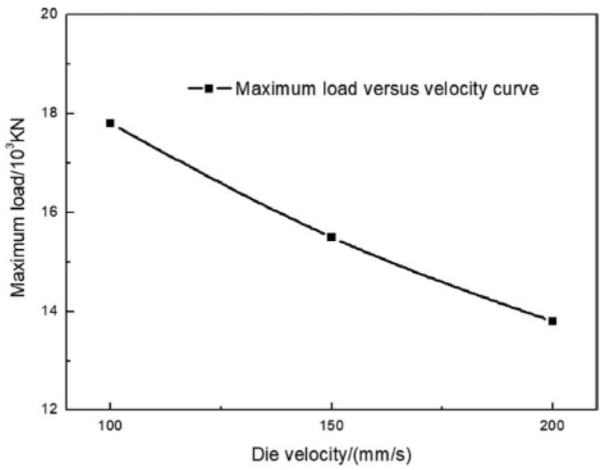

Figure 7: Maximum load of the upper die with forging die velocity (the die forging temperature is 1100 °C)

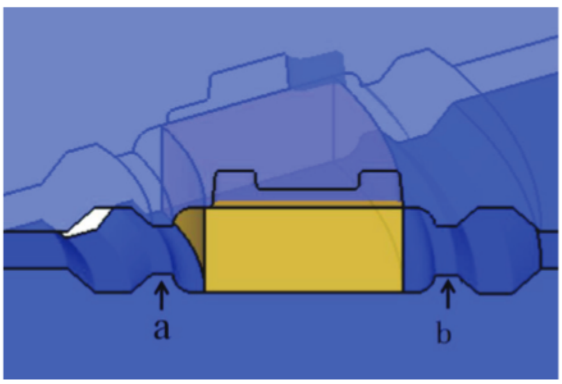

Figure 8: Schematic diagram of the structure of the flashing groove of the high-speed-train brake disc

4.4 Forming analysis with optimized process parameters

According to the above analysis results, the higher die-forging temperature and speed, the lower flash groove width can obtain high-quality forgings, and the die load is low. Therefore, the initial temperature of the billet is 1200 °C, the width of the bridging groove bridge is 15 mm, and the upper die velocity is 200 mm/s, and the numerical simulation of the forming process is performed.

Figure 10 shows the filling of the metal after the die is abut. It can be seen that the heat-dissipation ribs on the surface of the brake disc are covered with contact points, i.e., when the upper and lower die are abut, the metal is completely filled.

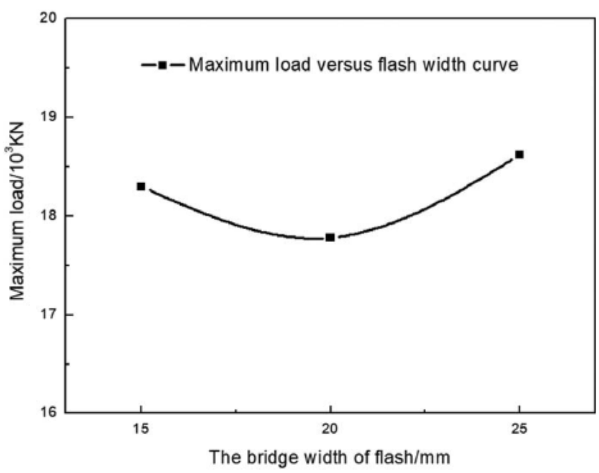

Figure 9: Maximum load of the bridge width of flash

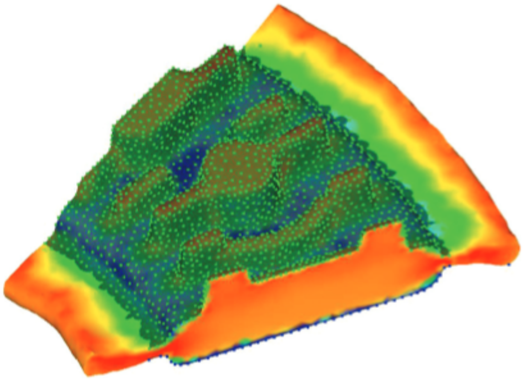

Figure10: Metal filling with optimized process parameters

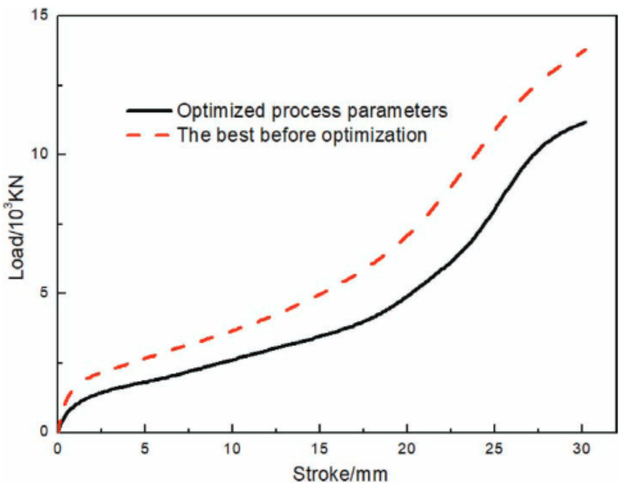

Figure 11: Load-stroke curve of the upper die with optimized process parameters

Figure 11 shows the variation of the load on the upper die with the stroke. It can be seen that when the upper and lower dies are abut, the upper die is subjected to a load of 1.12×10^3 kN, and the smallest of the above process combinations is 1.37×10^3 kN, which is 18.2 % lower. This shows that the setting of these parameters is better, and it is better than other parameter-setting schemes, which is more helpful for the formation of the brake disc, reducing the load of the press and prolonging the service life of the die.

5 CONCLUSION

Due to the large size and complicated heat-dissipation ribs, the brake discs of high-speed trains require large-tonnage equipment to be formed, so the die life is short. Optimization design of the process and die parameters through finite-element numerical simulation analysis method are the prerequisites for successful forming. Within the range of process parameters studied in this paper, high die-forging temperature, fast forming velocity and small bridge width of flash groove help to reduce the forming force requirement of the equipment, effectively improve the life of the die, and ensure the metal filling of the heat dissipation ribs.

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