Research Article

Improved localized fatigue wear resistance of large forging tools using a combination of multiple coupled bionic models

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Abstract

It is important to solve the partial fatigue wear of large forging dies, where the service life can be short. The purpose of this paper is to use laser remelting biomimetic technology to prepare a coupling biomimetic model combination on the mold surface, strengthen the local fatigue wear resistance of the mold, and extend the service life of the mold. Three types of laser energies were used to prepare the coupling biomimetic elements and analyze the microstructure and phase composition of the specific gravity melting zone. The biomimetic units were combined into a variety of coupling biomimetic models (fringe, mesh, and dense array models with different laser energies), and the number of fatigue cracks and the weight of wear loss of the coupling biomimetic model were compared at different temperatures. The mechanism of the coupling bionic model was analyzed, and the coupling bionic surface with a dense row structure was determined to have strong anti-fatigue wear performance. According to the Range Method, the relationship between wear and fatigue temperature and laser energy of the coupled bionic model was determined. Using DEFORM software to simulate the stress, temperature, and wear conditions of the front axle die surface, different coupling biomimetic model combinations were prepared on the abrasive surface. The die wear and cut edge width of the forgings were reduced after practical production, which proved that the laser bionic local strengthening method can effectively prolong the service life of a die.

Keywords Localized fatigue wear resistance · Coupling bionic model combination · Large forging tool · Laser remelt technology

1 Introduction

Due to the harsh working environment of forging dies, the plastic flow and fatigue cycle of the blank in the forging process lead to fatigue cracks and wear on the surface of the die [1], resulting in decreased service life. Research has found that the volume of the front axle mold of the truck (size: $2010\times655\times324$ mm^3) is dozens of times that of the connecting rod mold, but the service life is about one third of the connecting rod mold and experiences uneven wear, leading to significant waste of mold production and processing resources. Therefore, to explore the failure mechanism of large forging molds, DEFORM simulation software was used to carry out machining simulations of large forging molds (as shown in Fig. 1), and the mechanism leading to mold failure was determined and analyzed. It can be found from the figure that the surface working temperature of large forging dies is between 280 and 701 °C, and the contact and heat transfer time are different. It has been determined that the problem of uneven contact and heat transfer between forgings and molds will occur in the production process. As a result, the working

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face experiencing high temperature appears to suffer from serious fatigue and wear, which leads to scrap failure of the mold and shortens the service life of the mold. Therefore, it is necessary to strengthen the surface of the mold to extend its service life.

At present, die surface strengthening technology such as chemical heat treatment strengthening, surface plating strengthening, high-density surface strengthening, and pre-hardening technology of die steel [2] usually takes the whole die as the strengthening object.

However, the above strengthening technologies have limitations when dealing with large forging dies. For example, to enhance the wear resistance, fatigue resistance, and plastic deformation resistance of the mold, a factory will carry out nitriding treatment on the surface of the mold, which is a process that is complex, time-consuming, and costly [3]. Although a hard nitriding layer will be formed on the surface of the mold after nitriding treatment, mechanical cracks will also be formed under the action of cyclic stress, leading to scrapping of the mold. A way to overcome this is to increase the thickness of the nitriding layer, but this leads to high manufacturing costs due to a much longer nitriding treatment and can be quite complex. Therefore, it is important to improve localized anti-fatigue and wear performance of the die without using complex secondary processes.

Bionics is a multidisciplinary and comprehensive discipline. It is the result of the mutual penetration and integration of life sciences and engineering technology. The research content has evolved from the bionic development of biological structure and structure to the bionics of material preparation. Engineering bionics is the intersection of bionics and engineering science. Starting from engineering needs, learning and simulating biology, research goals focus on technological invention and engineering creation. For example, energy savings and material reduction in the automotive industry is an important goal pursued by the industry, and it is also an urgent need in the field of automotive engineering. So, through the study of bionics, it has been found that the body surface of many organisms has evolved over millions of years to form non-smooth surfaces to adapt to different living environments [4]. Yet there is more than one factor at work in adapting organisms to their environment. It is the result of the coupling and coordination of different forms, structures, and materials of organisms. For example, dragonfly wings [5] have complex microstructures and are primarily composed of membranes, which are supported by longitudinal and transverse venous networks. As a result, it can survive harsh conditions.

In this study, large automotive forging molds were the primary research objects. It can be useful to utilize biomimetic concepts and laser biomimetic remelting technology to prepare a coupling biomimetic model in the areas of significant fatigue wear on the surface of the mold and improve the service life of the mold. Laser remelt technology as an advanced technology adopts high-power-density and high-intensity laser beams to heat the material surfaces in a non-contact way, which enables rapid cooling and obtains different tissues from the substrate. The laser remelt coupling technology is used to prepare the coupled bionic model combinations with different morphologies on the surface of the material. Coupling bionic surfaces are formed between the combinations, which has broad research prospects in improving the service life of the mold.

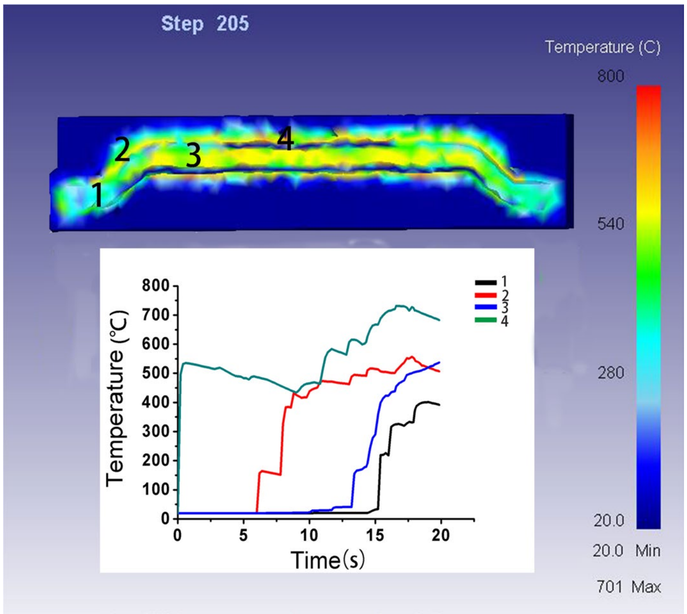

Fig. 1 Surface temperature field distribution of large forging die

Laser coupling biomimetic surfaces [6, 7] is an effective way to prepare biomimetic morphology and structure on the material surface to improve the material performance without changing the material matrix. Many research papers have focused on this solution relative to die fatigue wear. Zhang et al. [8] found that the average peak power density and effective peak power density have significant impacts on the size and morphology of the unit. When the effective peak power density was 595–1448 W/mm^2, a coupling bionic unit with higher hardness was obtained. In addition, Wang et al. [9] studied the mechanical properties of coupling biomimetic units prepared under different laser energy densities and determined that the units prepared with a laser energy density of 160 J/cm^2 showed good tensile properties. The tensile properties of the unit tend to decrease with an increase in energy density. In addition, the mechanical properties of coupling bionic units with different spacings were also discussed, which verifies that the strength of the coupling bionic unit increases with the density of the unit [10]. The laser biomimetic remelting unit was prepared on AISI H13 die steel surfaces by using laser biomimetic remelting technology. The effects of different unit appearance [11], unit size [12], and sample surface alloying [13] on the fatigue properties of laser biomimetic remelting samples were studied. It was concluded that a U-shaped laser biomimetic remelting unit shows a mechanism of micro strengthening and crack tip passivation and provides properties of oxidative corrosion resistance, so as to improve the fatigue resistance of the sample. In a practical application, Shi et al. [14] used laser melting technology to prepare a bionic coupling brake disc, and the results showed that the bionic unit plays a role in strengthening the braking and effectively resisting crack initiation and propagation. However, there are few studies and applications of laser remelt coupling biomimetic technology to fabricate coupling biomimetic surfaces for large forging dies.

2 Materials and experimental methods

The die used in this research was a forging die for the front axle of a truck. The grade of die steel was 4Cr2MoVNi, and the composition was (wt%): C 0.41, Cr 2.06, Mo 0.46, Ni 1.49, Mn 0.68, and Si 0.25, with an annealed micro-hardness of 345HV$_{0.3}$. Using DK7732 edm equipment produced by the Huadong group, the material was cut into rectangular samples of 40 mm × 20 mm × 6 mm. A round hole with a diameter of 3 mm was cut at one end of the sample to be suspended on the suspension frame of the fatigue testing machine. 80–600 mesh sandpaper was used to polish both sides of each sample to eliminate the influence of machining marks on the experiment.

Under the work of other personnel in this group, the anti-wear properties of the oblique stripe-coupled biomimetic specimens with inclination angles of 0°, 30°, 45°, 60°, and 90° were tested. According to the experimental results, the wear properties at 45° were best. Therefore a stripe-like coupling bionic unit model when at a tilt angle of 45° was chosen, according to previous experience [15–17]. Therefore, a 400 W ND-Yag (YASKAWA) laser was used, and the laser parameters are shown in Table 1. Strip and mesh coupling monomer models with a spacing of 2 mm were prepared under the polished sample surface, as shown in Fig. 2a. The microstructure and phase composition of coupling bionic units were analyzed by scanning electron microscopy (SEM) (Zeiss, Evo 18, Germany) and X-ray diffraction (XRD) (D/Max, 2500 PC, Japan) prior to the fatigue test. An HXD-1000 Vickers micro-hardness tester was used to measure the micro-hardness of the coupling unit and substrate under 0.30 kg loading, 10 s holding time, and a test point distance of 0.1 mm.

After fastening all samples with fine wire, they were suspended in batches in the self-made high-temperature induction fatigue test furnace. The working principle of the fatigue furnace is shown in Fig. 3. The fatigue furnace is primarily composed of a control system, a high-temperature induction heating furnace, and a cooling water tank. The control system can set the furnace temperature, sample holding time, and control motor rotation direction and time. The water tank was cooled by flowing water to maintain the temperature at room temperature. The working process of the fatigue furnace is that the blank samples and the samples with the coupling bionic unit were fastened with fine iron wires, respectively, and suspended in the self-made high-temperature induction fatigue test furnace at 500 °C, 600 °C, and 700 °C in batches. When the thermocouple display reached the

Table 1 Laser parameters used

No.	Electric current (A)	Pulse duration (ms)	Defocusing amount (mm)	Frequency (Hz)	Speed (mm/s)	Laser energy (J/cm^2)
1	160	7	154	4	1	153.5
2	170	6	154	4	1	161.3
3	180	6	154	4	1	174.5

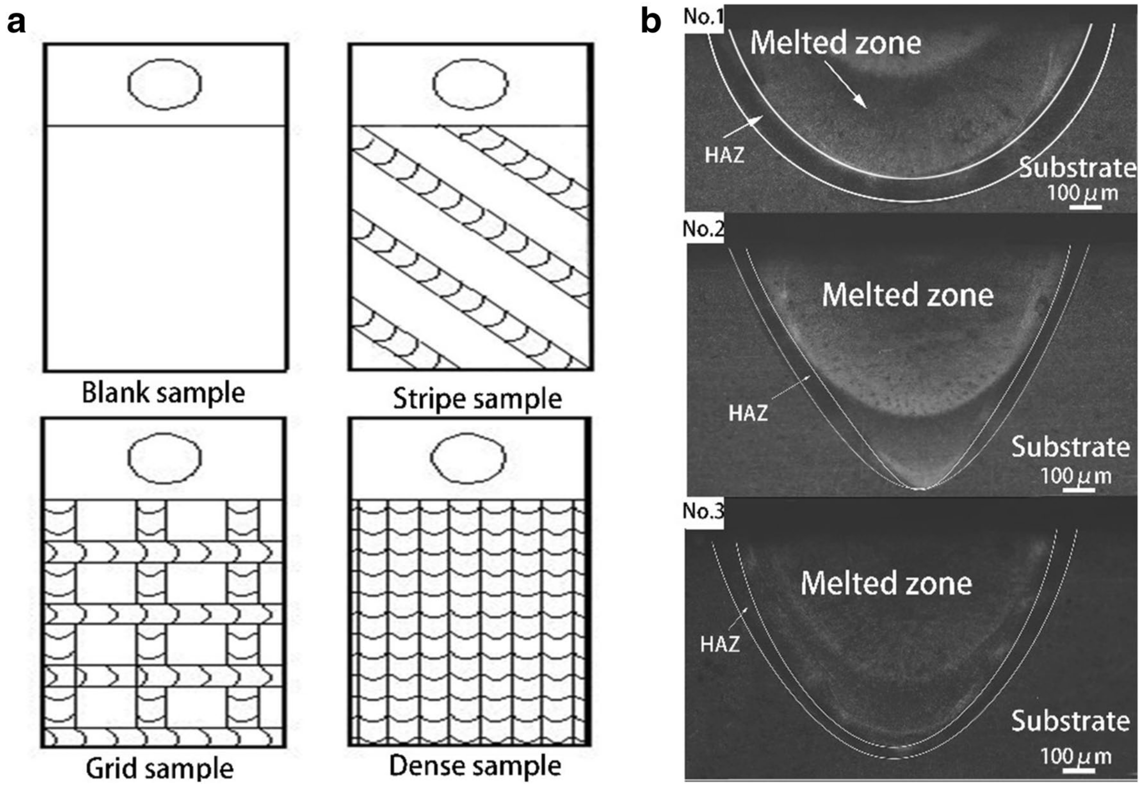

Fig. 2 **a** Laser biomimetic coupling model sample and **b** unit shape

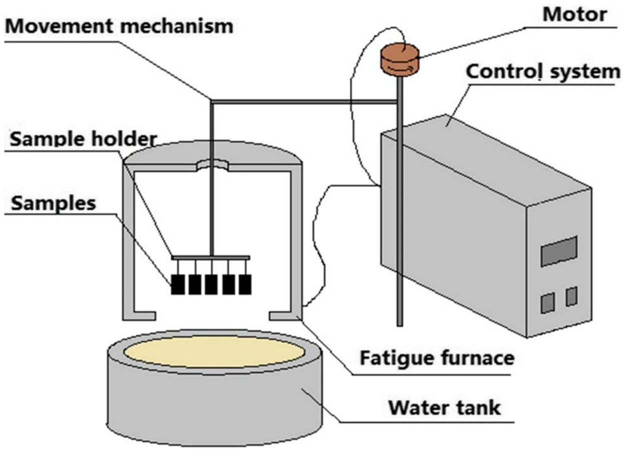

Fig. 3 Working principle diagram of fatigue machine

target requirement, the holding time was 180 s, and then the samples were transferred to the water tank and cooled to room temperature. This fatigue test was repeated 3600 times. After every 400 times, the samples were soaked in 3% HCl to remove the oxide skin on the surface. The sample was then washed in anhydrous ethanol with ultrasonic cleaning equipment and ventilated to dry.

The three batches of samples after the fatigue tests were placed into a customized linear reciprocating friction and wear machine for the surface friction and wear test. The wear testing machine motor drives the eccentric wheel to induce linear reciprocating friction and wear movement. The experimental load was 50 N, the wear time was 10 h, and the motor speed was 690 RPM. Before and after the tests, the samples were cleaned ultrasonically with anhydrous ethanol, and then dried with a hair dryer before weighing. To ensure weight measurement accuracy, a JA5003 analytical balance (Shanghai anting electronic instrument factory) with an accuracy of 0.001 g was used to measure each sample five times. The wear performances of the laser bionic samples were studied using weight changes before and after the wear tests, wear morphology of the sample surface, and the coupling bionic unit in the resistance to wear.

In actual production conditions, a forging press with a load of 12,500 KN (Germany) was used for experimental production. The blank is Q235 and heated to 1200 °C for forging. According to the wear conditions of the forging surface and the developing trend of cut edge width, the mold performance was evaluated, and the reliability of the laboratory results in production and processing was verified.

3 Results and discussion

3.1 Coupling biomimetic unit microstructure analysis

As shown in Fig. 4a, the structure of the coupling bionic element was divided into the melting zone and heat-affected zone. Figure 4b, c show that the grain size in the melting zone is refined and distributed in a more uniform and regular grid shape. However, the grain boundary of the substrate is fuzzy, and the size is different from that of the melting unit. The results show that the laser remelting technology can rapidly solidify the substrate and refine the grain. Figure 4d shows the XRD pattern of the substrate and unit. It was concluded that the phase composition of the laser melting unit and substrate is martensite. In the XRD patterns, the half-peak full widths (FWHM) of the same diffraction peaks were compared. The FWHM of the unit was 0.393, which was slightly higher than the FWHM of the substrate at 0.334. According to Scherrer's classical formula and Berks' empirical formula, it was concluded that laser remelting bionics technology can promote martensification, refine grains, increase dislocation, and strengthen properties. The average micro-hardness of the unit was $612HV_{0.3}$, which was higher than that of the substrate.

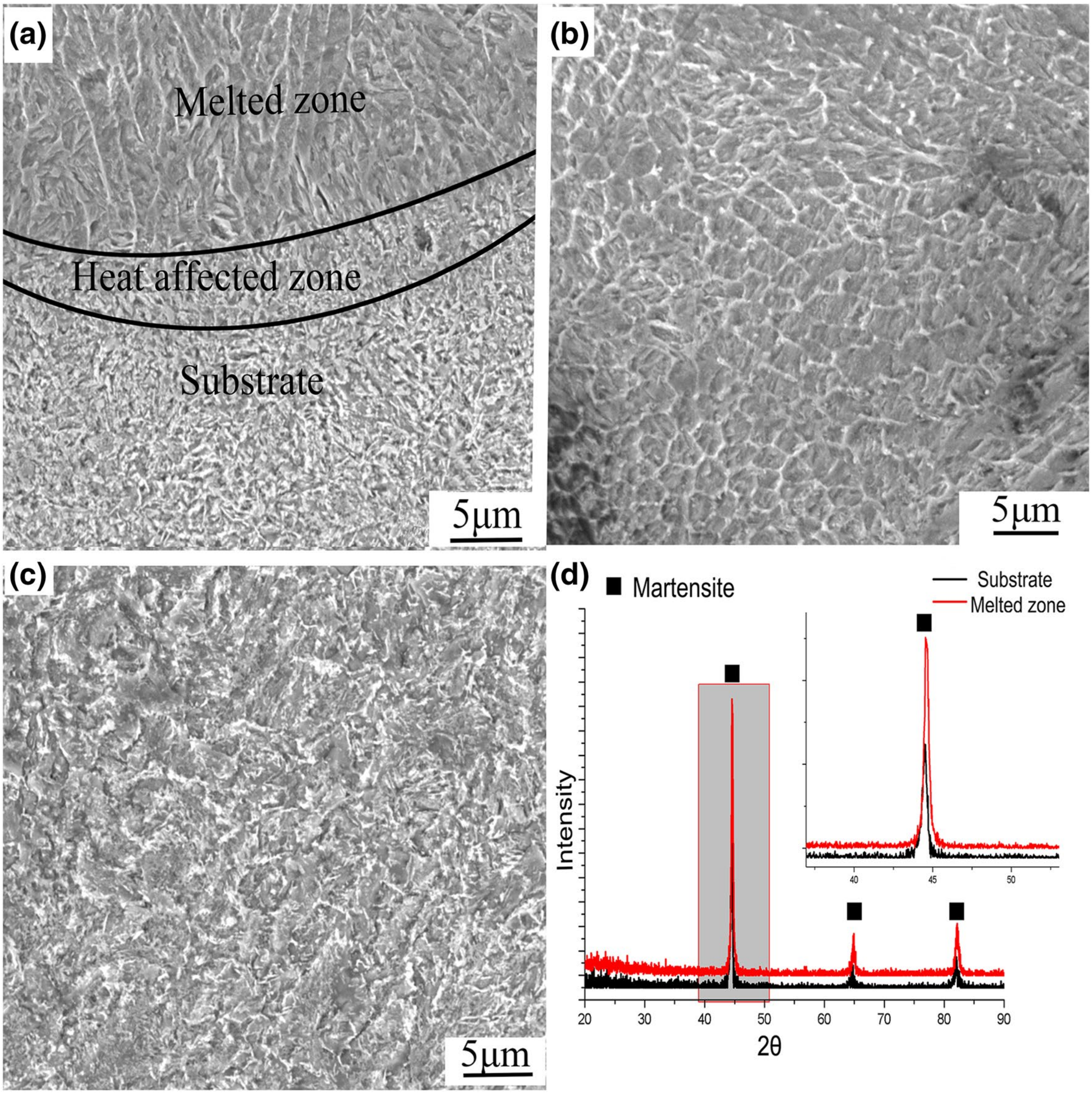

Fig. 4 **a** Heat-affected zone and substrate in the fusion zone **b** 5 k units scanning images **c**. 5 k substrate scanning images **d** XRD diagrams

3.2 Fatigue test

In engineering applications, a crack length greater than 0.25 mm is defined as the effective length [18]. Figure 5 shows the histogram of the number and length of surface cracks after 3600 fatigue tests. It was observed from the figure that the number and maximum length of fatigue cracks significantly increased with an increase of fatigue temperature. In addition, with the increase of laser energy, the number and length of the fatigue cracks on the surfaces of the samples remain unchanged. The crack length and number of cracks of the untreated samples at different temperatures were significantly higher than that of the laser-coupled biomimetic samples. The number of cracks on the bionic surface of densely arranged structures were reduced by about 30%.

It was observed from the figure that with the increase in fatigue temperature, the number of surface fatigue cracks of the same kind of coupled biomimetic samples after the same kind of laser energy processing was obviously improved. Under the same laser energy, the number of fatigue cracks on the surface of the sample decreases with the change of the coupled bionic model. The specific regular is dense sample < grid sample < stripe sample; under the same fatigue temperature, the number of fatigue cracks on the surface of the sample did not significantly increase with the increase of laser energy. The preliminary conclusion is that the laser energy shows no obvious influence on the initiation and propagation of fatigue crack. Figure 5b1–b3 show the histograms of the maximum crack length on the surface of the coupled bionic sample processed by three laser parameters after 3600 fatigue tests. Compared with the blank samples, the maximum crack lengths of all coupled bionic surfaces were smaller than that of the blank samples. With the increase in fatigue temperature, the maximum crack length of the bionic model prepared with the same laser energy increases. With an increase in laser energy, the maximum crack length of the same coupling bionic model at the same fatigue temperature is slightly shortened, but there is no obvious rule in the overall change. Finally, at the same laser energy and fatigue temperature, the maximum number of cracks was compared, and it was found that the dense sample < grid sample < stripe sample. Therefore, it was concluded that the length and number of cracks in untreated samples at different temperatures were significantly higher than those in laser-coupled bionic samples. Therefore, among the samples with coupled bionic surface, the fatigue resistance of samples with grid sample is stronger than the stripe samples. In addition, the samples with dense structure had the least number of cracks and the smallest crack length. Therefore, with the increase in density of the coupled bionic model, the fatigue resistance of the sample was enhanced.

According to the fatigue test results at various temperatures, it was found that the temperature and thermal

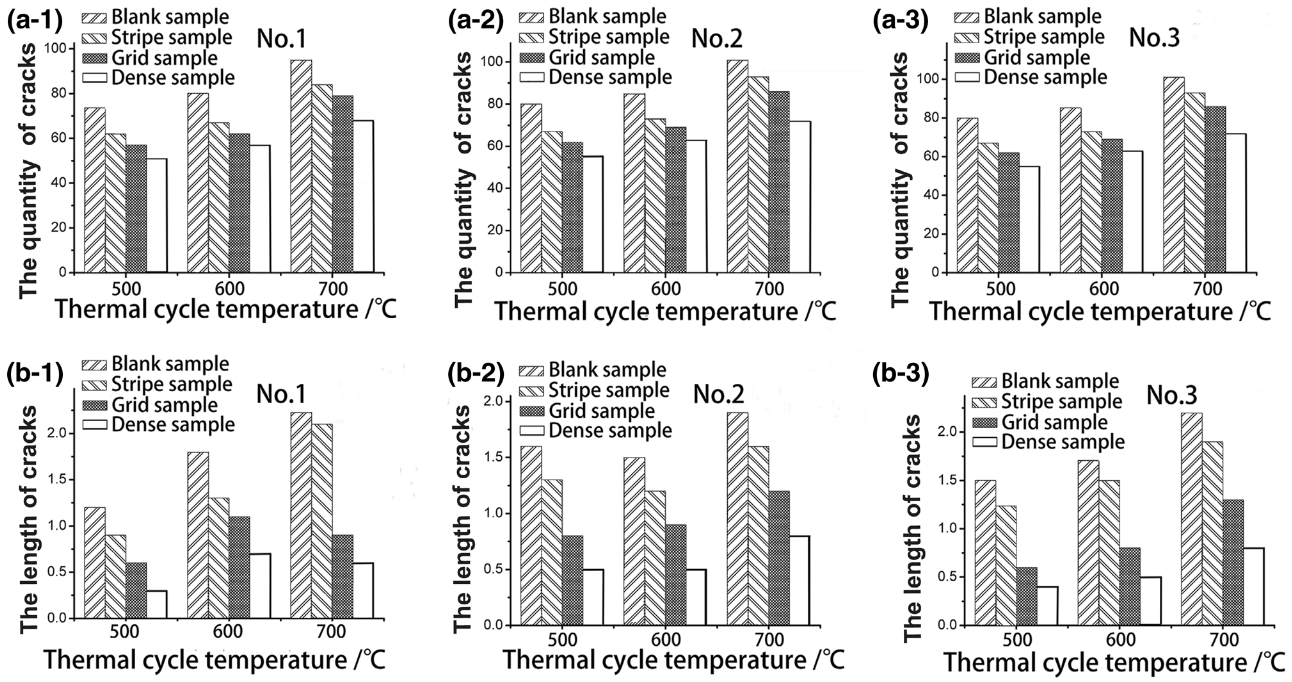

Fig. 5 The quantity (**a**) and length (**b**) of cracks after thermal fatigue testing at various thermal cycle temperatures (No. 1: 153.5 J/cm^2, No. 2: 161.3 J/cm^2, No. 3: 174.5 J/cm^2)

stress during thermal fatigue cycling significantly affect the length and number of cracks. Previous experiments showed that with the increase of fatigue temperature, the thermal stress on the surface of the sample was strengthened, providing energy for the crack initiation and propagation. However, the hardness of the laser-coupled biomimetic unit is far greater than that of the substrate, as shown in Fig. 6a. When the crack extends to the unit, the propagation resistance increases, which causes the crack to stagger or deflect, thus hindering the crack extension. In addition, the structure refinement of the laser-coupled biomimetic unit leads to residual compressive stress on the surface of the unit [19, 20], neutralizing the tensile thermal stress and inhibiting the initiation of fatigue cracks. Figure 5b shows that the precipitates of the unit are few after multiple thermal fatigue tests. The dispersion of precipitates strengthens the surface of the substrate and maintains its mechanical properties. In addition, the unit remains plastic and ductile, which inhibits the initiation of fatigue cracks.

3.3 Wear testing

Figure 7 is the histogram of the grinding weight loss of samples after 3600 cycles of fatigue testing under different laser energies. It can be seen from the figure that the maximum weight loss of samples with a coupled bionic surface is 0.175 g, which is significantly less than the untreated

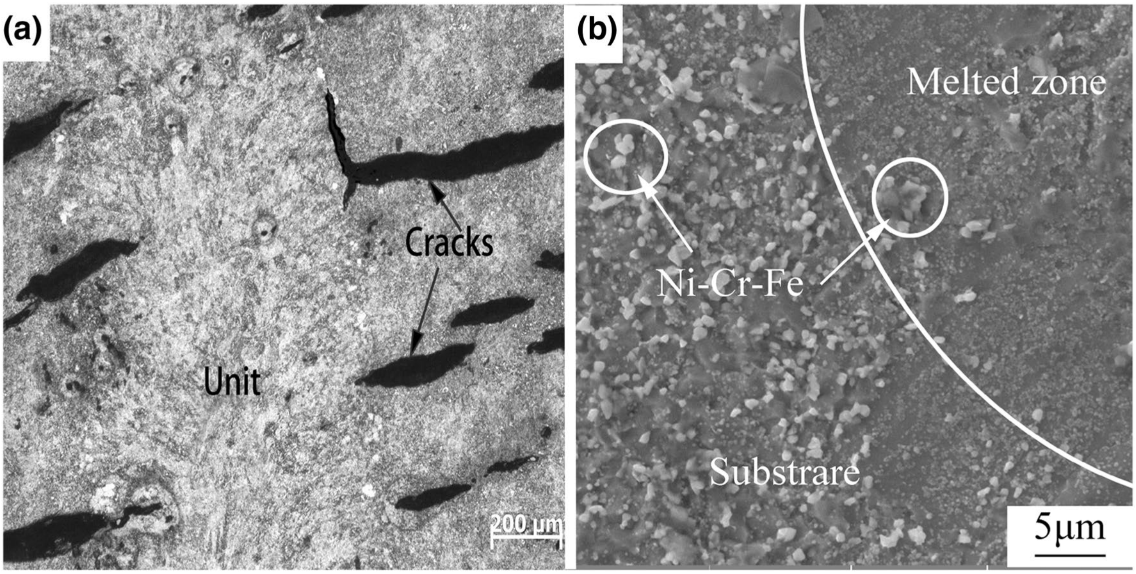

Fig. 6 **a** Morphology of crack growth and **b** images of post-fatigue microstructure

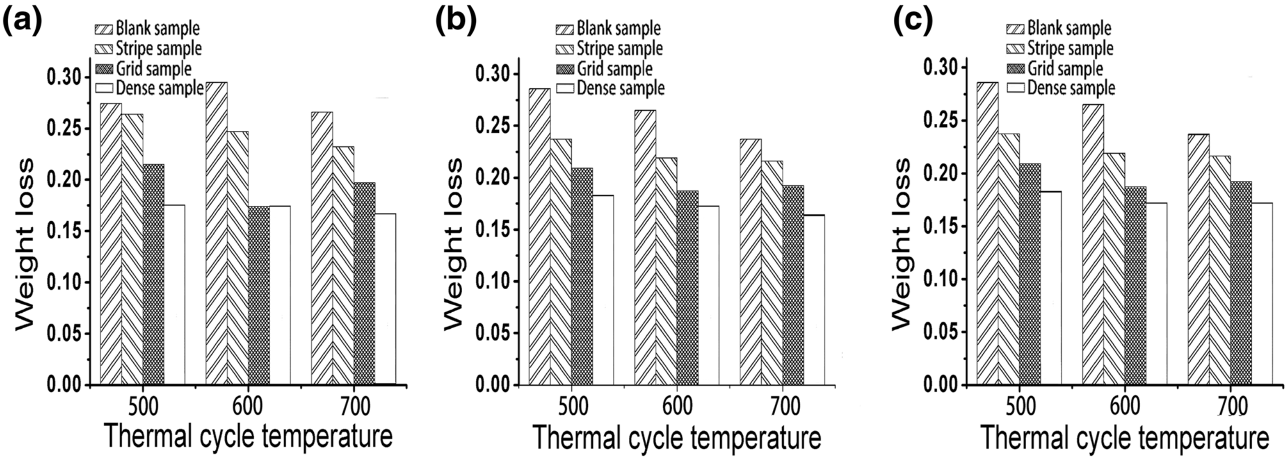

Fig. 7 Weight loss of samples treated at different laser energies by grinding at different temperatures **a** No. 1 **b** No. 2 **c** No. 3

samples. One reason is that the hardness of the unit is higher than that of the matrix. In the wear process, the abrasive will stagnate or roll over on one side of the unit to reduce the wear behavior. At the initial stage of wear, the unit and the substrate are in the same plane. During the wear process, the unit will experience the pressure released by the load higher than the substrate, thereby reducing the contact area between the sample and the friction pair, which induces weight loss. This means that the weight loss of biomimetic models prepared with the same laser energy decreases slightly with an increase in fatigue temperature. Analysis shows that the cooling process will create the surface of the sample hardening phenomenon, improve the surface hardness of the sample, and enhance the wear resistance of the sample surface. In contrast, with an increase in laser energy at the same fatigue temperature, the hardness of the coupling biomimetic unit will increase, leading to improved wear resistance of the sample.

Second, it was found that the maximum wear loss rate decreases with an increase of the body density of the coupling bionic unit. It was concluded that with higher density of the coupling bionic unit on the surface of the sample, the micro-hardness of the surface of the sample will increase, thereby enhancing the wear resistance of the sample.

The Range Method is used to analyze the orthogonal test results and determine the general relationship between the influence of various factors on the grinding weight loss. The experimental results and analysis are shown in Table 2.

In the table, $\bar{y}_{ik}$ is the average of the test indices corresponding to factor i at level k. As $\bar{y}_{ik}$ increases, the effect of factor i at the k level is more significant. The best combination of factors is the optimal parameter combination of the experiment. In the table, R_i represents the range of factor i, which reflects the range of change of the test index when the level of factor I changes. That is, the greater R_i is, the greater the influence of this factor on the test. Therefore, the primary and secondary factors affecting the grinding loss weight are model category > fatigue temperature > laser energy. The best combination to improve wear resistance is shown in C3A1B2. Therefore, the specific principles of matching the coupling bionic model in different areas of the mold surface are as follows: According to the serious fatigue wear on the surface of the mold, it is divided into three regions. The A region with serious fatigue wear is matched and combined as C3A1B2, the bionic model of dense row structure processed by No. 2 laser energy was adopted, the B zone with moderate fatigue wear is matched and combined as C2A3B3, that is, the bionic model of grid structure processed by No. 3 laser energy, and the matching combination of the C area with relatively shallow fatigue wear is C1A2B1, that is, the bionic model of striated structure processed by No. 1 laser energy.

Table 2 Results and analysis of grinding weight loss

No.	Fatigue temperature (℃)	Laser energy (J)	Model category	Experimental results (g)
1	500	153.5	Dense sample	0.175
2	500	161.3	Grid sample	0.246
3	500	174.5	Stripe sample	0.237
4	600	153.5	Grid sample	0.174
5	600	161.3	Stripe sample	0.235
6	600	174.5	Dense sample	0.172
7	700	153.5	Stripe sample	0.232
8	700	161.3	Dense sample	0.173
9	700	174.5	Grid sample	0.192
$\bar{y}_{i1}$	0.219 (A1)	0.194	0.173	$\sum y_i = 1.836$
$\bar{y}_{i2}$	0.194	0.218 (B2)	0.204	
$\bar{y}_{i3}$	0.199	0.200	0.235 (C3)	
R_i	0.025	0.024	0.062	

3.4 Mold surface processing simulation

In this section, the equivalent stress distribution and wear condition of the surface during mold production and processing were analyzed and studied using the simulation software DEFORM. In this model, the working surface of the forging die is the main surface, and the contact surface of the forging material is the driving surface. In the actual forging process, the forging pressure is 12,500 KN. The simulated load on the mold surface was 1900 MPa, and the mold surface was divided into grids for simulation.

Figure 8a is the surface stress distribution diagram of the forging die. According to the figure, it was found that different parts of the mold bear different pressures, and the maximum stress is 1760 MPa. Most stress distributions range from 560 to 1170 MPa. Since the deformation range of the middle part of the mold is small, the stress is also small. The stresses in parts 2 and 3 are higher than in the other parts, according to the diagram analysis. The reason for this is that the blank must undergo plastic deformation to meet the requirements of the workpiece. Figure 8b shows the analysis diagram of simulated wear on the mold surface. It was found from the figure that the wear primarily focuses on the rounded corners of the edges (part 2 and part 3), and the wear depth ranges from 1.280 to 1.868 mm. According to the optimal combination of model and energy obtained in the laboratory, a close coupling bionic model was prepared at the rounded corners of the edge of the mold surface, a grid-like model was prepared

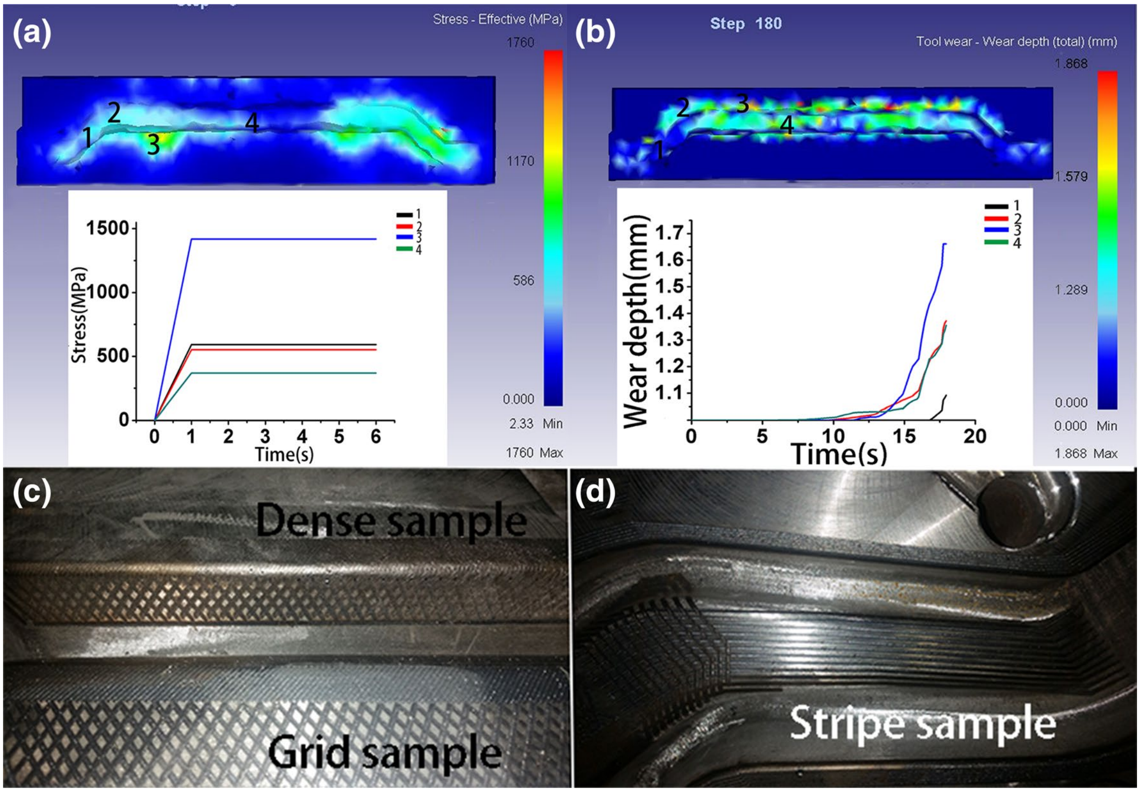

Fig. 8 Stress and tool wear distribution of the forging tool **a** stress **b** wear distribution **c** and **d** mold surface after remelting

at the convex part, and a striated model was prepared at the other parts. The mold surface with coupling bionic model combination is shown in Fig. 8c, d.

3.5 Analysis of engineering experiment results

According to the mold wear conditions of the measurement scheme, Fig. 9a shows the mechanism of edging of forgings during die processing. As shown in the figure, the edge of the mold was worn, resulting in excessive accumulation of materials on the forging surface. In the cutting and dressing process, the forging surface will leave cutting marks. Therefore, the width of the forging edge can reflect the wear of the die.

Figure 10 shows the surface topography of the hot forging tools before and after the factory test. When the molds were processed into 3600 pieces, the edges of the untreated molds were severely worn. As shown in Fig. 10a, c, a wear slope with a depth of about 2 mm was formed on the surface of the die. Compared to untreated mold edges

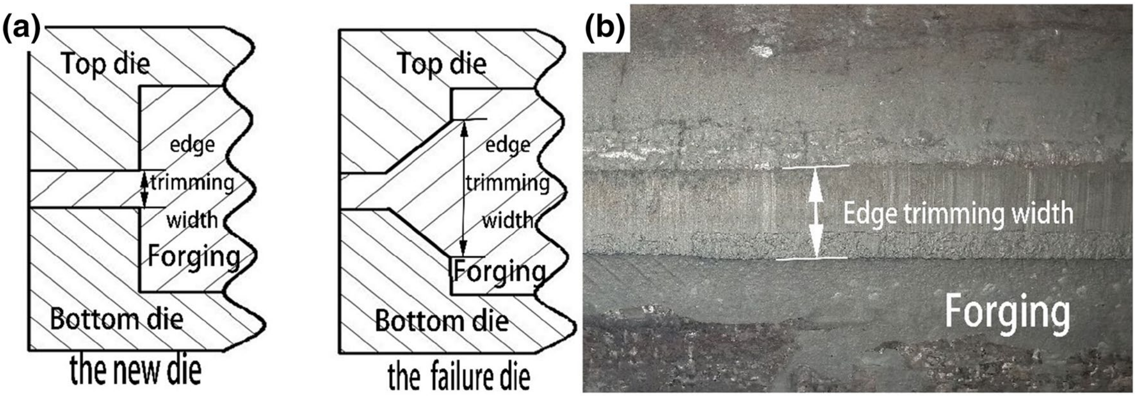

Fig. 9 **a** The mechanism of edging of forgings during die processing and **b** shape of cutting edge of forging

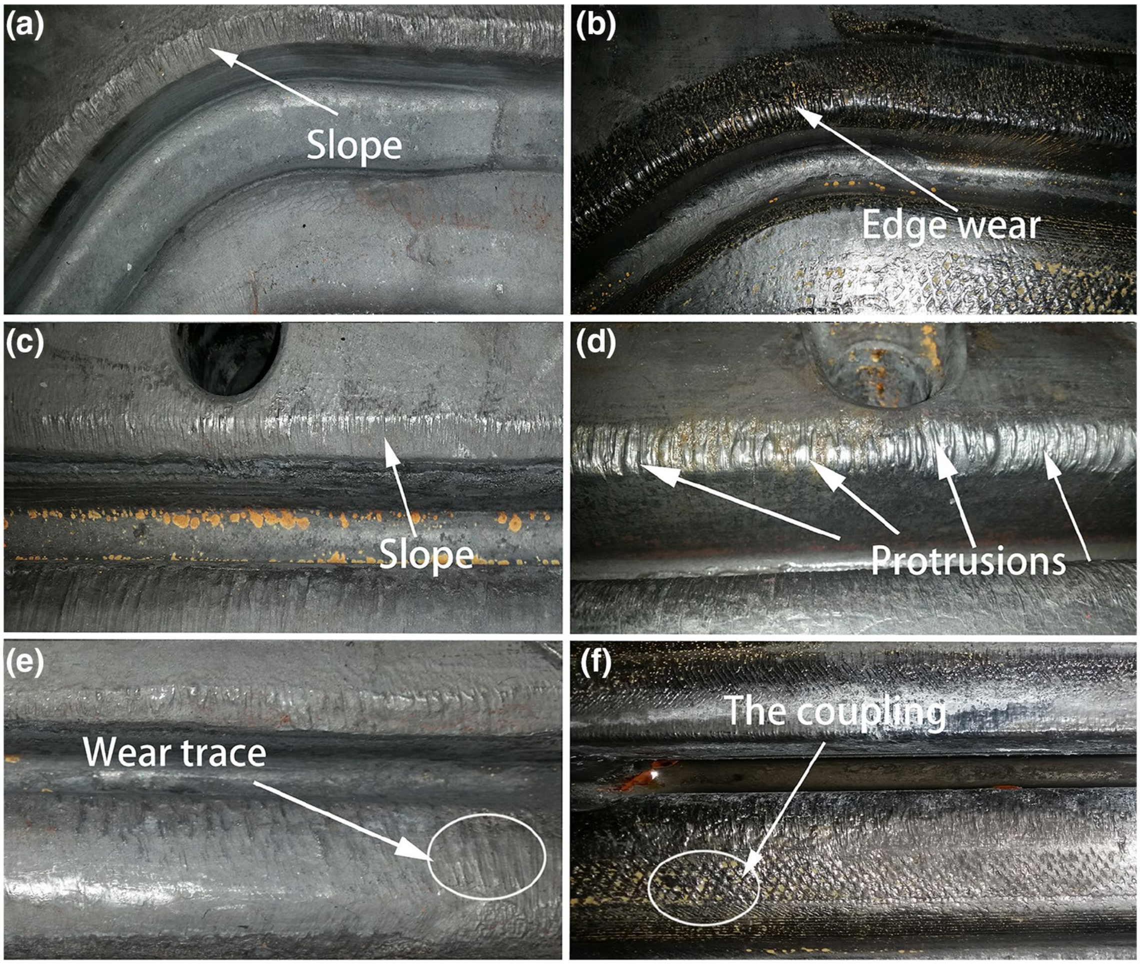

Fig. 10 Surface fatigue wear after failure of the mold and remelting. **a**, **b** the bending part of the forging; **c**, **d** the straight part of the forging; **e**, **f** the boss of the forging

(Fig. 10b, d), the bionic surface does not show a slanted surface but is distributed with protrusions about 1 mm deep on the worn surface. These bumps can impede the flow of metal and reduce wear during forging. Figure 10e, f show the wear conditions of the boss. The comparison of the wear degree of the boss shows that the shape of the coupling bionic structure remains on the surface of the boss. In the following production process, the coupling bionic surface will still hinder the crack propagation direction and resist the wear between forging and die. On the contrary, the surface of the untreated die boss has significant wear marks and severe deformation.

Figure 11a, b show the straight part of the forging machined by the untreated mold. It was found that the edge cut gradually widens. In the picture, it was observed that the surface of the first piece is smooth, and no crack defects occur. When forging 3600 pieces of the surface, the die rough crack density is very large, and the edge widths are 12 mm and 23 mm, which reflect the degree of mold wear. Figure 11c, d are the straight part of the forging piece processed by the die after laser melting. Compared with Fig. 11a, b, it was found that the edge appearance of the first piece was the same, and the forging surface quality was very good without cracks and fleshy conditions. When 3600 pieces were processed, the edge width was also widened, but the edge width of the forged pieces produced by the melting mold is 5 mm smaller than that of the untreated ones. At the same time, there are many cracks in the forging pieces processed by untreated molds. Therefore, it can be concluded that the mold after melting treatment can hinder the development of cracks.

Figure 12a, b show the bending part of the front axle of the first piece and the 3600 pieces processed by the untreated mold. It can be observed from the figure that the edge width of the newly machined front axle is smaller than that of the forging piece machined by the "soon-to-fail" die. In Fig. 12a, the width of the edge cut off at the bending of the forging is about 12 mm. When forging

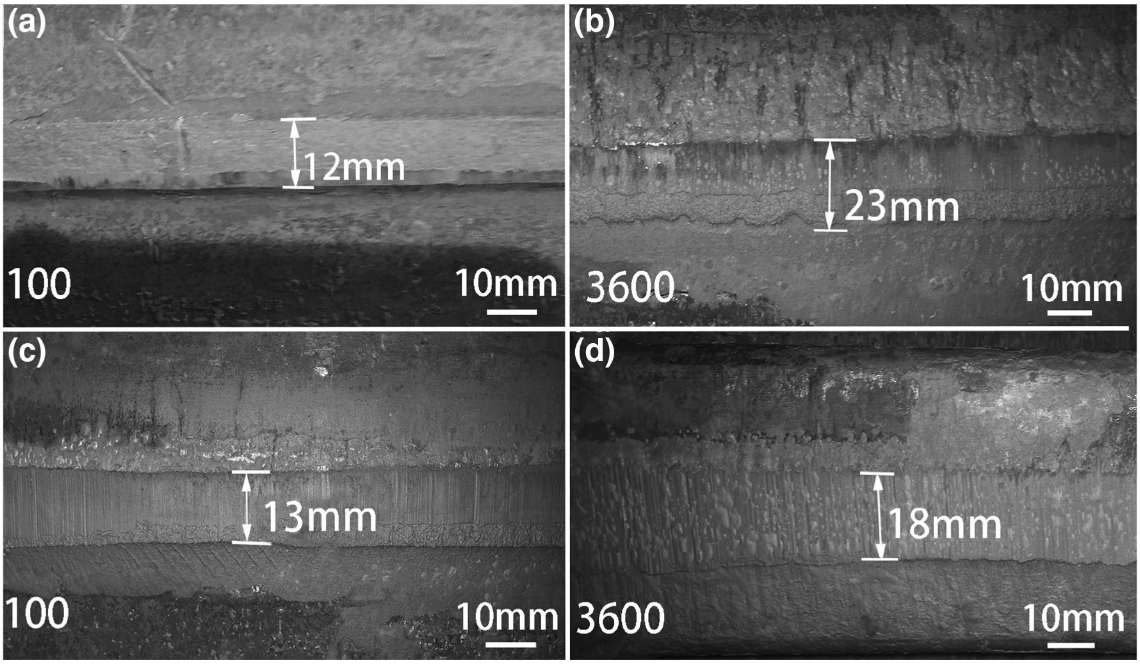

Fig. 11 Development trend of cut edge width on straight forging pieces. **a**, **b** Untreated mold; **c**, **d** laser melting mold

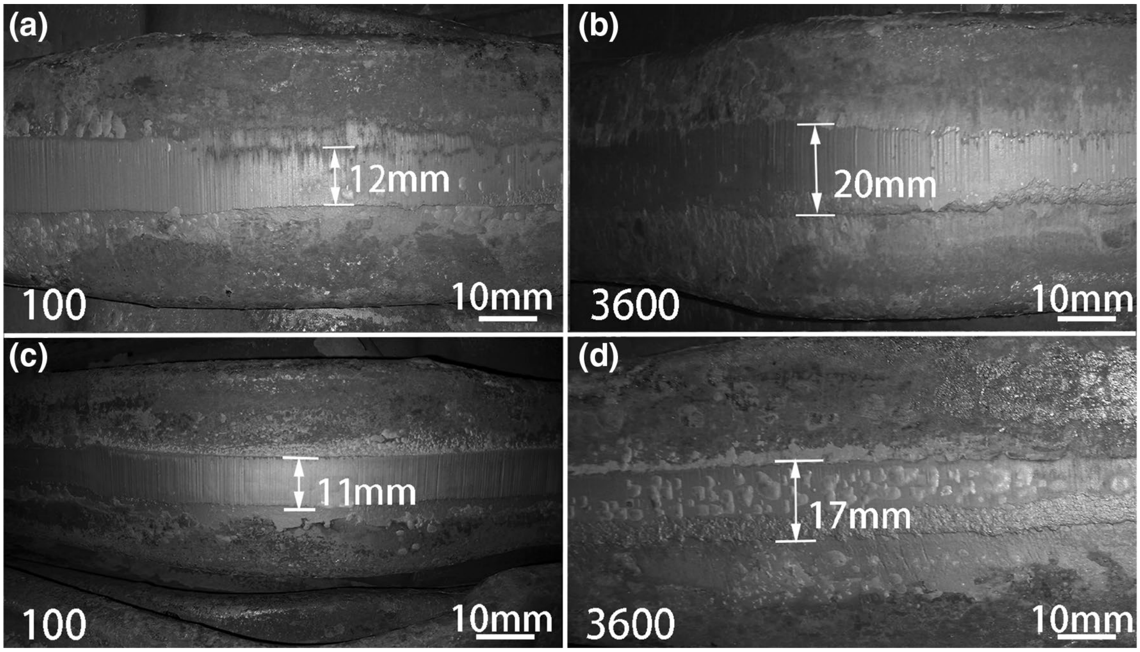

Fig. 12 Development trend of the cut edge width on curved forging pieces. **a**, **b** Untreated mold and **c**, **d** laser melting mold

to 3600 pieces, the cut edge width is 20 mm. Figure 12b shows an image of the bending of the first piece processed by the melting mold and the forging pieces of 3600 pieces with cut edge widths of 11 mm and 17 mm, respectively. From the appearance of the cut edge width, the forging edge is smooth, which reflects the smooth surface of the die. It can be found from Fig. 12a, c that the width of the cut edge is roughly the same. It was observed in Fig. 12b, d that the cut edge width of the untreated mold is wider than that of the melting mold. It can be concluded that the wear resistance of the mold treated by laser melting is stronger than that of the untreated mold.

Figure 13a, b show the trend curve of the cut edge width of forging. Observation and analysis show that the width of the untreated die forgings is larger than that of the coupling bionic surface (any part). In addition, the difference of the cut edge width between the flat and curved parts of the mold with laser coupling bionic surface is only 1 mm, and the difference between the cut edge width of the untreated mold is 3 mm. It was shown that the fatigue wear degree of different parts of the die were not only similar but can also be much less than that of the untreated die. Taking the number of forgings processed under the failure state of the untreated die as the standard, with the theoretical production life fitting curve of coupling bionic structure die, the die life can be increased by 1.57–1.80 times.

4 Conclusions

It was found that the coupling bionic unit has good fatigue wear performance under different temperature cycling conditions. It was determined with an increase in laser energy, the hardness and anti-fatigue wear properties of the unit are improved. It was also found that as the temperature increases, the surface hardening of the sample will also enhance the fatigue wear resistance of the unit. According to the analysis of the orthogonal test results, the main and secondary factors affecting the fatigue wear resistance of the coupling bionic element are the shape temperature and energy of the coupling bionic model. Therefore, a dense coupling bionic model was prepared in the part with high temperature and large wear degree, a grid-like coupling bionic model was prepared in the part with low temperature and moderate wear degree, and a striated coupling bionic model was prepared in the rest of the mold.

The results obtained in the process of practical application in the factory are consistent with the results of fatigue wear testing in the laboratory. Laser coupling bionic unit surfaces can improve the fatigue and wear resistance of die surfaces. After producing the same number of forgings, the cut edge width of the surface forgings with coupled bionic unit is reduced by 2–3 mm compared with that of untreated die forgings. Moreover, different coupling biomimetic unit model combinations were prepared according to the parts with different degrees of wear, so as to

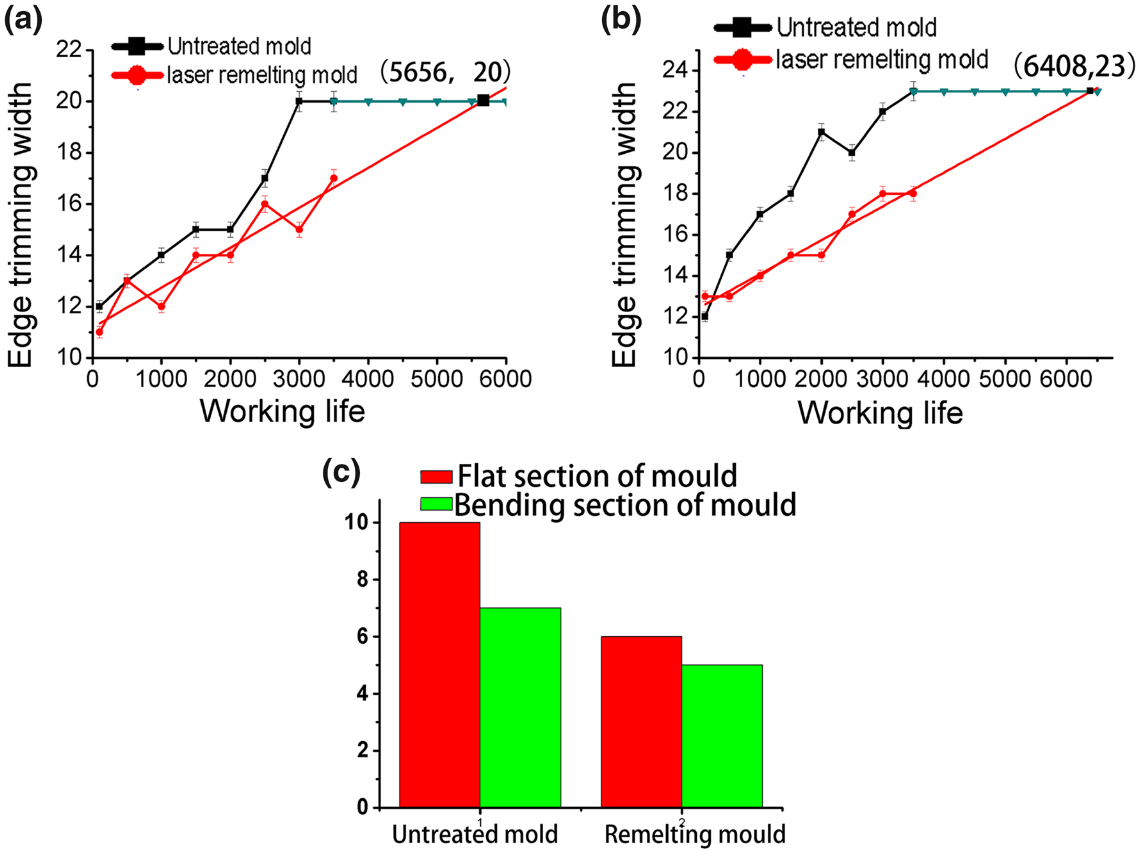

Fig. 13 Fitting curve of cut edge width difference and estimated life of laser remelting mold after fatigue wear at different parts **a** cut edge width of the bending part of the forging **b** cut edge width of the straight part of the forging **c** cut edge width difference after fatigue wear

locally enhance the anti-fatigue wear performance of the mold and create a consistent surface wear degree of the mold. In addition, according to the trend curve of the cut edge width of the forgings, the service life of the die with a coupling unit model is increased by 1.57–1.80 times. Therefore, according to the characteristics of non-uniform fatigue wear on the surface of large molds, the preparation of different coupling bionic model combinations to locally enhance the performance of molds can improve the service life of molds. Laser remelt technology eliminates the need for additional raw materials and consumes only electrical energy to process the mold surface, reducing processing time and improving efficiency, while effectively extending the replacement of the mold and saving the production cost of the enterprise.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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