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ORIGINAL ARTICLE

The microstructure and properties change of dies manufactured by bimetal-gradient-layer surfacing technology

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Abstract The finite element model of a die manufactured by the bimetal-gradient-layer surfacing method was established based on ZG29MnMoNi casting steel. Then, simulation was conducted to analyze the temperature field of the die and its cycle features under working conditions. By comparing the microstructure and properties of cast-steel matrix of the die before and after producing 5761 parts on a 63MN hot die forging press, sensitive indexes that affect the service life of the surfacing die were determined. The results have shown that the microstructure of cast-steel matrix before and after service is both pearlites and ferrites. When it is closer to the welding line, the carbides precipitate out more obviously, the dendrites segregate less, and the microstructure tends to be more compact. The mechanical properties are decreased as a whole after service: the tensile strength, yield strength, reduction of area, and elongation are declined by 7, 17, 24, and 18 %, respectively. Meanwhile, microhardness and impact toughness have shown a decrease of 10 and 28.6 %, respectively. The working temperature has a strong relationship with microstructure and property changes. The performance of cast-steel matrix after service can still satisfy the operating requirements of the 63MN hot die forging press, which can be recycled in remanufacturing process.

Keywords Cast-steel matrix · Surface welding · Temperature field · Microstructure · Properties

Die plays a key role in fast-developing industries such as aerospace, automotive, machinery, and etc., and the demand is still increasing. The traditional method of manufacturing hot forging die is to machine the forged modules. However, this method has many defects such as low material utilization, large amount of finish, long production period, high cost, and so on [1], which impedes the upgrading of products and lowers their competition ability.

In this paper, a new method, bimetal-gradient-layer surfacing method, was adopted, which was to apply surface welding on casting steel. This kind of die can not only keep the plasticity and toughness of matrix material but also ensure the red hardness of the working layer [2]. The new method can lower the cost of mold-making considerably and shorten the manufacturing cycle and improve the dies' service life, which is expected to substitute die steel with "casting-steel+bimetal surfacing layers." Therefore, this method has wide application prospect and great economic benefit [3].

The performance of dies manufactured by bimetallic-gradient-surface welding method mainly depends on the properties of casting-steel matrix and surfacing layers. For die manufactured by bimetal-gradient-layer surfacing method, its surface layer is consisted of welding materials with high strength and hardness and will not do surfacing treatment like peening, nitriding, or etc. on it. By contrast, the cast-steel matrix is the determining factor, which has a relatively poorer performance and can practically determine the service life of a hot forging die. Thus, it is important to find out the evolution rules of microstructure and properties of cast-steel matrix before and after service for optimizing and improving the matrix materials, which can accelerate its popularization and application, as well.

Because of the complex working conditions, the failure forms of hot forging die are complicated, which include cold-hot fatigue, surface damage, excessive deformation,

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fracture, and etc. [4]. The failure of hot forging die is mainly attributed to the thermal load and mechanical load, and the thermal load is the main one [5]. Therefore, the temperature distribution and transfer characteristics of casting-steel matrix should be focused on while conducting simulations [6, 7].

By comparing the microstructure and properties of casting-steel matrix of dies manufactured by bimetallic-gradient-surface welding method (which was used on a 63MN hot die forging press before and after service) and by simulating the thermal load in the production process, the evolution laws of microstructure and properties of casting-steel matrix were revealed. Then, the possibility of reutilization and the optimization of matrix material selection were analyzed.

1 Experimental materials and welding process

1.1 Experimental materials

The sampling position and the lower die modal of a particular kind of crankshaft are shown in Figs. 1 and 2.

In this paper, we chose ZG29MnMoNi casting steel as the matrix material and chose JX03 and JX02 (designed by Chongqing Jiepin High Tech. Development Co. Ltd) as the welding wires. Table 1 shows the ingredient of ZG29MnMoNi, JX03, and JX02.

1.2 Surfacing process

ZG29MnMoNi should be preheated before surfacing process, and the temperature for preheating was 450 °C. After 10 h heat preservation [8], we used ZX5-250 DC welding machine to do surfacing. The protective gases were argon and carbon dioxide (volume ratio was 4:1). Welding current 130A, welding voltage 26 V, and welding velocity 3 mm·s^{-1} were adopted. The thickness of welding pass was about 5 mm, and the weld interpass temperature was more than 300 °C. The last step was to temper it at 550 °C and to cool it in furnace.

2 FEM analysis of temperature field during service

Seventy percent failure of hot forging dies can be attributed to the heat stress in temperature fluctuation area. Therefore, to research the die temperature gradient and the temperature fluctuation is essential [9]. Based on the production process, the initial parameters were set as follows: the work piece material: AISI-4140; the mold material: AISI H-13 (to establish a matched model of the thickness of casting-steel matrix and surfacing layers, the AISI-H13 steel was used as the mold material in our simulation firstly to achieve the temperature field and stress distribution of a die under working condition. Then, by combining the simulation results and the properties of materials, the 3D models of casting-steel matrix and surfacing layers are further optimized. After that, on the condition of sufficient loading capacity, a reasonable range of thickness of both casting-steel matrix and surfacing layers is achieved for die cavities under different combined stresses. Lastly, a matched model of the thickness of casting-steel matrix and surfacing layers is established; the initial forging temperature of work piece: imported from the results of pre-forging process; the initial temperature of die 250 °C; the work piece was treated as a plastic body; the mold was treated as a rigid body; blank and dies were all meshed; the friction coefficient 0.3; the heat convection coefficient 0.02 N/s mm C; the radiation coefficient 0.3; and the forming speed 280 mm/s. Tables 2 and 3 show the time and heat transfer coefficient of each stage.

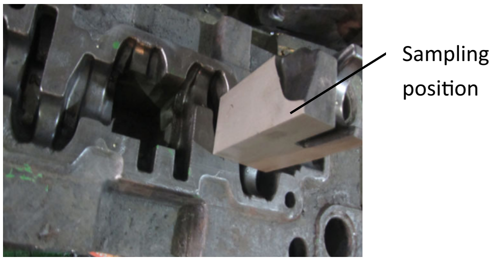


Fig. 1 The test piece

After the first cooling process, the work piece will be removed from the dies. Then, the pre-forging will be loaded, which is followed by forging, pressure maintaining, and cooling process. After N (N is big enough) times forging cycle processes, the temperature change within the die tends to be a stable value, which means the temperature field of forging die under continuous working condition has reached its equilibrium [10, 11].

Figure 3 shows the temperature field of the forging lower die under continuous working condition. Seven feature points were selected along the normal direction of the cavity isotherm every 7 mm from P1 (28 mm off the cavity surface) to P7 (about 70 mm off the cavity surface). From the picture, we can see that, when the die temperature reached its equilibrium, the temperature beyond 30 mm from the surface is below 360 °C and the temperature is below 300 °C when the distance from the surface is beyond 50 mm. Finally, the temperature of regions beyond 70 mm is approximately equal to the initial preheating temperature of 250 °C.

Figure 4 shows the variation curve of temperature with time under continuous working cycle in both forging and

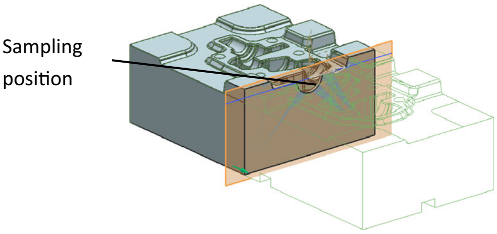


Fig. 2 Section of lower die in simulation

Table 1 The chemical component of the ZG29MnMoNi, JX03, and JX02

	C	Si	Mn	P	S	Ni	Mo	Cr	Cu	Al	W	V	Fe
ZG29MnMoNi	0.25	0.23	1.35	0.25	0.02	0.40	0.25	0.50	0.20	~	~	~	Rest
JX03	0.25	0.72	1.61	0.013	0.004	1.5	1.69	5.51	~	0.21	1.04	0.24	Rest
JX02	0.23	0.79	2.44	0.014	0.012	1.9	1.46	4.54	~	~	~	0.18	Rest

cooling processes. Compared to the initial preheating temperature (250 °C), each region's temperature had a moderate rise after continuous working cycles.

However, the temperature of P7 is close to the initial preheating temperature 250 °C, and the temperature of P1 is only 360 °C, as well. With the increase of the working cycle, the steady heat transfer process reached its equilibrium and the temperature of each part stabilizes at a constant level.

3 Microstructure and properties analysis of the cast-steel matrix

In this paper, the experimental sample was cut down from the lower die manufactured by bimetal-gradient-layer surfacing method, which was used on 63MN hot die forging press for production. The referential sample was cast in the same furnace, and it was treated in the same way with the experimental sample by bimetal-gradient-layer surfacing method and heat treatment.

3.1 Microstructure change of the cast-steel matrix

To reflect the microstructure and properties changes of matrix better, we chose four positions with different distances off the welding line to do the experiments: 5, 25, 45, and 65 mm, respectively. The changes of metallographic microstructure, microhardness, tensile properties, impact toughness, and fracture morphology were analyzed according to the different thickness.

Table 2 Parameters of different stages

Process	Number of times	Heat transfer coefficient/W $(m\cdot°C)^{-1}$
Blank placing	5	1
Forging	Depending on the mechanical press	11
Pressure maintaining	2	2
Cooling and lubricating	2	8

The cast-steel matrix has gone through three stages before service: (1) quenching (900 °C heat preservation for 7 h and then water cooling) and tempering (680 °C heat preservation for 6.5 h and then air cooling) heat treatment of cast ingot, (2) bimetal-gradient-layer surfacing process, and (3) stress-removing tempering process after surfacing (550 °C heat preservation for 2 h and then sand cooling).

Figure 5 is the microstructure of the referential cast-steel matrix, which has gone through the three stages mentioned above and thus can be treated as the cast-steel matrix before service. From Fig. 5a, we can see that there is reticular segregation within the matrix even after two heat treatment processes. The segregation defect is inevitable in the casting process, and the limited element diffusion during heat treatment can not eliminate the segregation completely. From Fig. 5b, we can see that the microstructure before service is mainly made up with ferrite and pearlite. The ferrite is gray and white, and the pearlite is black.

Figure 6 shows the microstructure of different parts of the cast-steel matrix after service. From Fig. 6a, we can see that the reticular segregation has reduced significantly, and the microstructure tends to be more uniform and compact in area 5 mm off the welding line; Fig. 6c shows that in an area 25 mm off the welding line, the reticular segregation has decreased moderately and no connection between reticular segregation can be found; in an area 45 mm off the welding line, as can been seen in Fig. 6e, the reticular segregation has reduced slightly while connection between reticular segregation can still be found locally; Fig. 6g shows that the number of reticular segregation has witnessed no obvious change in an area 65 mm off the welding line; finally, all these four areas are mainly made up with pearlite, ferrite, and a small amount of carbide, which is very similar to the microstructure of the cast-steel matrix before service.

Table 3 Performance index of die material used in 63MN hot die forging press

Index	Yield strength, σ_s	Tensile strength, σ_b	Elongation, δ	Reduction of area, ψ	Impact energy, A Kv	Hardness HRC	Equivalent carbon content
Normalizing	≥400 MPa	≥600 MPa	≥14 %	≥30 %	≥20 J	≥20	0.5~0.6

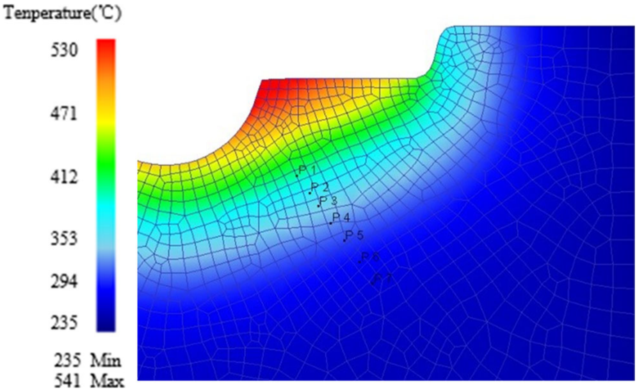


Fig. 3 The points on the cast-steel base at the initial hot forging

Having compared the microstructure of the matrix before and after service, we can find that the composition segregation within the cast-steel matrix has been weakened or eliminated. In addition, the closer it is to the welding line, the more obvious is the elimination. During service, the die has experienced the preheating process (250 °C) and continuous working cycle (300 °C), which decomposed and broke the dendrite. Impurities like sulfur, phosphorus, etc. segregated at grain boundary, and some residual austenite decomposed into carbides, which gathered and precipitated out from a certain crystal face. Meanwhile, nodularization occurred in the cast-steel matrix, and the microstructure became more uniform and compact after service.

3.2 Properties change of the cast-steel matrix

Figure 7 shows the hardness of the samples' cross-sections along a straight line direction. The welding line of ZG29MnMoNi and transition layer (JX02) was chosen as a starting point, and hardness tests were done every 3 mm to the matrix direction. Because of the fusion effect of matrix and welding material, the closer to the welding line, the more welding material will migrate to the matrix, which results in a higher hardness of matrix near the fusion area both before and after service. From the hardness curve, we can see that the matrix thickness strengthened by surfacing is about 8 mm, and the hardness value tends to be constantly away from the welding line. The maximum decrease of matrix hardness is 80 HV, which occurred at area close to welding line. The global hardness reduced by 15 % approximately from 225 HV before service to 190 HV after service.

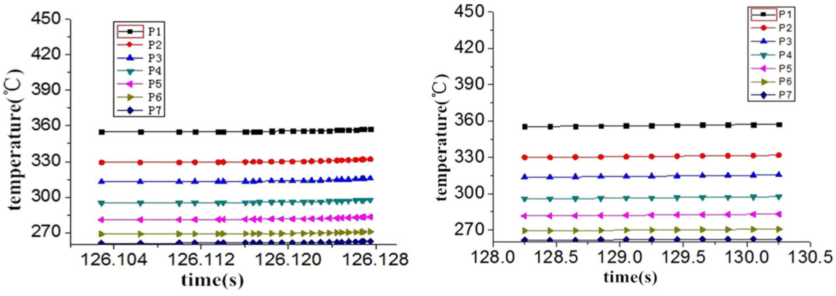
In general, strength is directly proportional to hardness. According to Fig. 7, the strength of different areas can be steady, which is irrelevant to the distance to the welding line. Therefore, the following mechanical properties testing of cast-steel matrix before service can be conducted on three parallel samples and took the average value.

Figure 8 shows the mechanical properties of the cast-steel matrix before and after service under room temperature. As can be seen from Fig. 8, the tensile strength, the yield strength, the reduction of area, and the elongation rate all reduced. Specifically, Fig. 8a shows that the yield strength σ_s decreased first and then increased within 65 mm off the welding line while the maximum difference is unapparent (14.6MP); the average yield strength of matrix after service is 461 MPa, which decreased by 17 %. As can be seen in Fig. 8b, the changing rule of tensile strength σ_b is consistent with yield strength after service. It decreased first and then increased within 65 mm off the welding line, and the average tensile strength after service is 635.5 MPa, which decreased by 7 %. From Fig. 8c, we can see that the changing rule of elongation had a tendency to increase within 65 mm off the welding line, and the average elongation of the matrix is 22.28 %, which decreased by 18 % after service. Similarly, the reduction of area got smaller when it was closer to the welding line. As Fig. 8d shows, the average reduction of area is 46 %, which decreased by 24 % after service.

In conclusion, the strength indicators like tensile strength and yield strength decreased by 7 and 17 % after service, respectively. Plastic indexes like reduction of area and elongation decreased by 24 and 18 % after service, respectively. Therefore, plasticity of the cast-steel matrix tends to be more sensitive compared to the strength, which decreased less after service.

When combining the microstructure and the mechanical properties, we can conclude that (1) the area 0–5 mm off the welding line was strengthened by welding material of transition layer and the microhardness, the yield strength, and the tensile strength there were relatively high; (2) the area 5–25 mm off the welding line was not strengthened by the

Fig. 4 Mold temperature distribution under continuous working cycle. **a** Forging process. **b** Cooling process



(a) forging process (b) cooling process

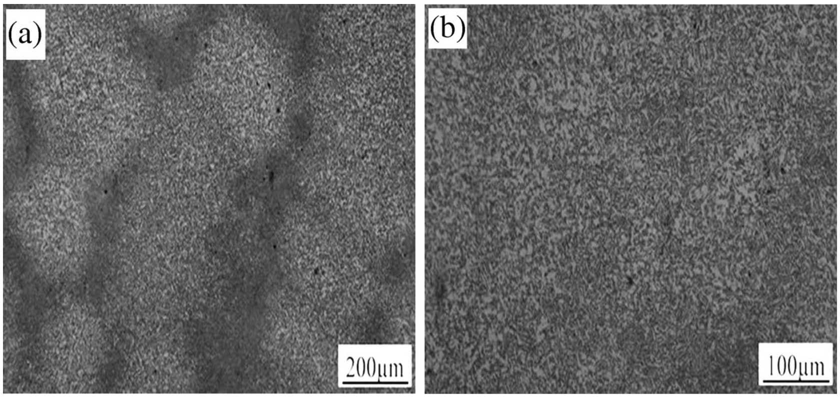


Fig. 5 Microstructure of cast-steel ZG29MnMoNi before service

welding material, though, the temperature cycle and stress there can be stronger, which resulted in dendrites cracking and segregation weakening. The carbides tended to be more uniform and the strength was lowest there; and (3) from the microstructure, we can see that the closer to the welding line, the easier are dendrite cracking and segregation weakening in the area 25–65 mm off the welding line, and the strength and plasticity indexes tended to be higher.

During service, the die has to endure thermal and stress cycles, which resulted in material softening. The dynamic recovery and dynamic recrystallization, which reduced the dislocation density, were attributed to the material softening. In addition, the dendrites broke and the residual austenites decomposed into carbides, which gathered and precipitated out from a certain crystal face. Various factors brought about the decrease of the cast-steel matrix's mechanical properties.

Figure 9 shows the impact property of the samples before and after service. The impact energy declined, and the further it was to the welding line, the smaller the value was. Meanwhile, the average impact energy of the matrix after service was 33.9 J, which decreased by 28.6 %. In general, when we tempered the cast steel at 300 °C for a long time, it would embrittle. This phenomenon can be attributed to the following two reasons: impurities like sulfur, phosphorus, etc. segregated at grain boundary; the residual austenites decomposed into carbides [12], which are consistent with the reasons of the decrease of strength and plasticity.

The appearance of fracture of different distances off the welding line is shown in Fig. 10. From Fig. 10a, we can see that the appearance of a fracture 5 mm off the welding line is a kind of dimpled fracture with many dimples, which are weak phases or impurities. As can be seen in Fig. 10b, c, d, another three positions' fractures are all quasicleavage fractures with obvious fracture features, which are characterized by river patterns. The research results of Zhang HJ, etc. demonstrates that the fracture brought about by segregation of impurities is mainly an intercrystalline fracture while the fracture generated by the gathering and precipitating out of carbides decomposed

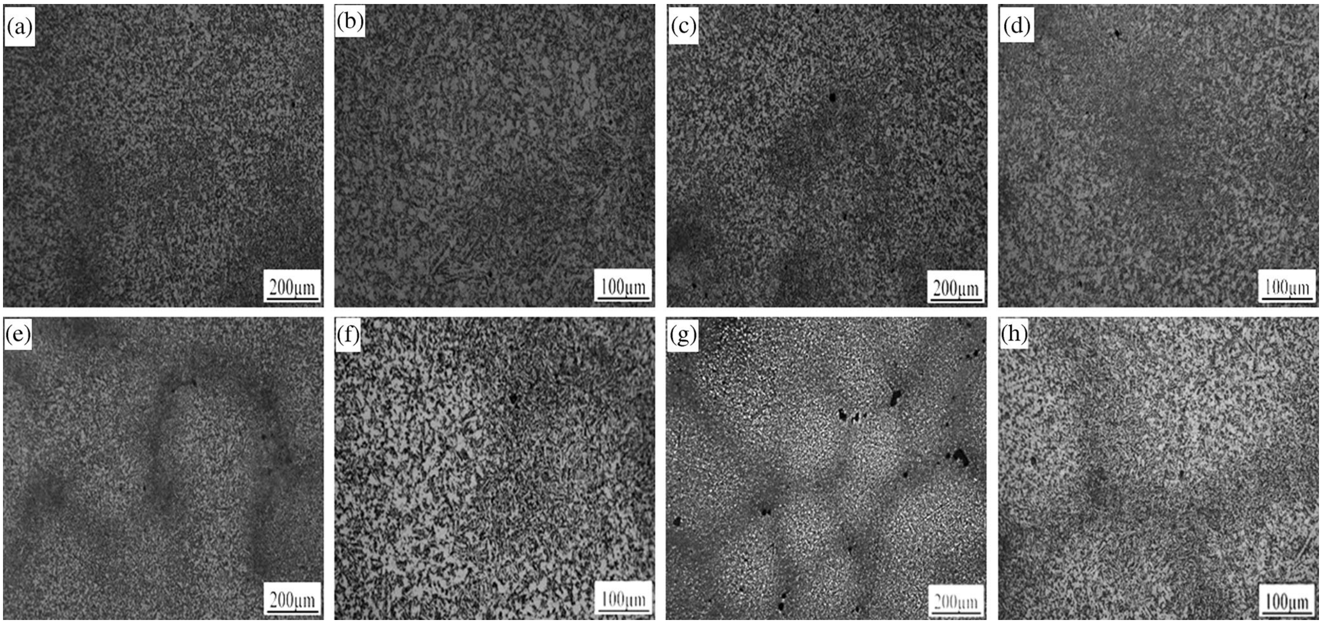


Fig. 6 Microstructure of different distances off the welding line after service. **a**, **b** 5 mm; **c**, **d** 25 mm; **e**, **f** 45 mm; **g**, **h** 65 mm

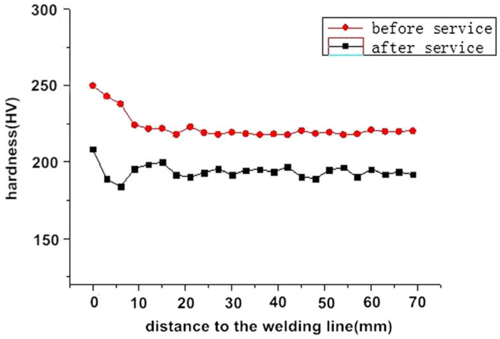


Fig. 7 Hardness of the cast-steel matrix

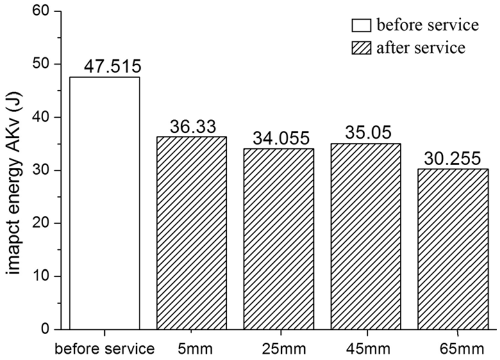


Fig. 9 The impact property of cast steel

from residual austenites is mainly cleavage and quasicleavage fractures [13, 14].

3.3 Impacts of temperature on the microstructure and properties

The maximum thermal stress on the die can be several times the maximum mechanical stress, and the temperature amplitude is the key factor influencing the thermal stress. Therefore, the temperature is of crucial importance to a die's service life [15–17].

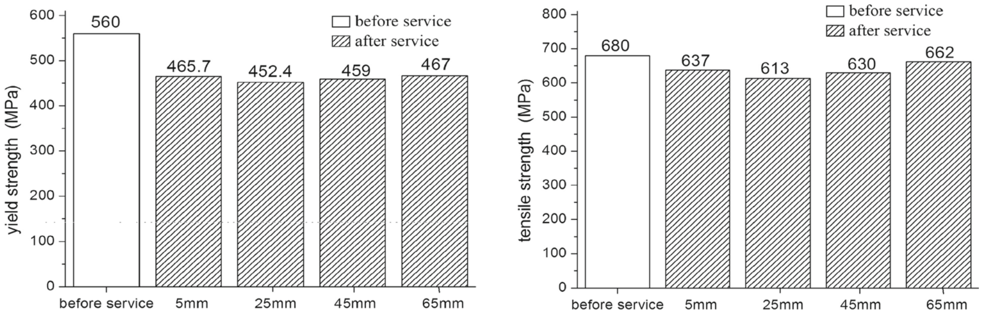
The relationship between the microstructure and mechanical properties changes after service, and the temperature can be as following:

(1) The area 5 mm off the welding line works under 320–340 °C in continuous working cycle, and the matrix material in this area refuses with the transition layer, which has much higher hardness than the cast-steel matrix. Therefore, the microhardness, the yield strength, and the tensile strength are relatively higher while the toughness tends to be lower.

(2) The area 5–25 mm off the welding line works under 280–320 °C in continuous working cycle, and the temperature cycle and stress there are relative high, which are similar to low-temperature tempering process. Dendrite cracking and segregation weakening occurred during service, and the carbides tended to be more uniform, which renders the lowest strength. Toughness, however, is a little higher than that of area 0–5 mm off the welding line.

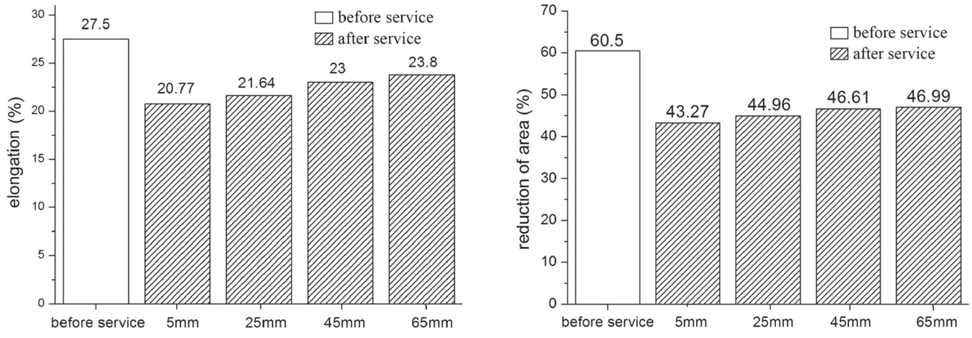
(3) The area 25–65 mm off the welding line works under about 250 °C during service, which is equal to the preheating temperature. Because the carbide framework can endure most loads in hardness and strength tests, and the closer it is to the

Fig. 8 The mechanical properties of cast-steel matrix. **a** Change of yield strength. **b** Change of tensile strength. **c** Change of elongation. **d** Change of reduction of area



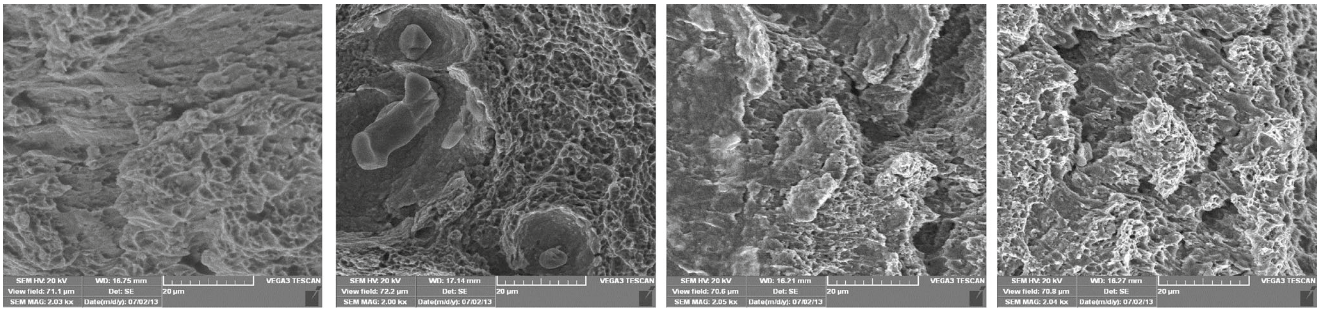
(a) change of yield strength

(b) change of tensile strength



(c) change of elongation

(d) change of reduction of area



(a) 5mm (b) 25mm (c) 45mm (d) 65mm

Fig. 10 Appearance of fracture of different distances off the weld area after forging. **a** 5 mm. **b** 25 mm. **c** 45 mm. **d** 65 mm

welding line, the easier is dendrite cracking and segregation weakening, the strength and plasticity indexes tend to be higher in this area.

3.4 Remanufacturing of the cast-steel matrix

The performance of the cast-steel matrix after service can still satisfy the operating requirements of 63MN hot die forging press. Therefore, dies manufactured by bimetallic-gradient-surface welding method can not only extend the service life and lower the cost but also be recycled several times, which is environmentally friendly.

4 Conclusion

By comparing the microstructure and properties of cast-steel matrix of dies manufactured by bimetallic-gradient-surface welding method before and after service and by simulating the thermal load in the production process, the changing laws of microstructure and properties of the cast-steel matrix are revealed. Conclusions drawn from this paper are the following:

(1) Under the effects of thermal and mechanical load, the microstructure and property changes of the cast-steel matrix tend to be different with various distances away from the welding line. When it is closer to the welding line, the carbides precipitate out more obviously, the dendrites segregate less, and the microstructure tends to be more compact.

(2) The temperature field changed with different distances away from the welding line, and the mechanical properties decreased with various working temperatures as a whole after service. Specifically on average, strength indexes like tensile strength and yield strength declined by 7 and 17 %, respectively; plasticity indexes like reduction of area and elongation declined by 24 and 18 %, respectively. Meanwhile, microhardness and impact toughness showed average decrease of 10 and 28.6 %, respectively.

(3) The performance of cast-steel matrix after service can still satisfy the operating requirements of the 63MN hot die forging press, which can be recycled in remanufacturing process.

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