Three-Point Bending Fracture Properties of Multilayer Metal Hot Forging Die Specimen

Huajun Wang¹, Qingyang Liu², Nian Han, Liang Yao and Chundong Zhu

School of Materials Science and Engineering, Wuhan University of Technology, Wuhan 430070 China
Email: ¹ wanghuajunhb@163.com; ² 376368471@qq.com

Abstract. Multilayer metal hot forging dies deposited by the plasma transferred arc welding presents high wear resistance, oxidation resistance and high temperature stability. In the process of hot forging, bending load made the cavity of multilayer metal hot forging die easily failure. We investigated the bending performance of multilayer metal hot forging die by three-point bending test. The model of bending specimen used H13 as the substrate, transition layer was W6Mo5Cr4V2 and outer layer was Ni60A. Mechanical properties of H13 homogeneous specimens and multilayer metal specimens were tested and compared. ABAQUS finite element method was used to simulate the process of three-point bending under temperature gradient. The results show that crack appears firstly in the H13 substrate and Ni60A layer, expands and meets in the transition layer gradually, results in specimen fractures. At service temperature, bending performance of the multilayer metal specimens is better than homogeneous specimens.

1. Introduction

Hot forging dies have very poor service conditions. The process of fast heating and cooling leads to thermal stress and organizational change, then the chamber surface will occur wear, thermal fatigue, and soften deformation failure [1, 2]. It restricts the service life of hot forging die. Several techniques, such as the PTAW, carburizing, boronizing, nitrocarburized, thermal diffusion technology, electroless plating, CVD and PVD, are use for hardfacing [3-5]. One or more layers of high performance material coatings are formed on the surface of hot forging die, then a special multilayer structure obtained. Due to its high bonding strength, wear resistance, corrosion resistance and impact fatigue resistance at high temperature. This method is widely used in hot die repair and life prolonged.

Wang and co-workers [6] proposed that a continuously running homogeneous hot forging die. Its temperature field is divided into three regions: temperature fluctuation zone, temperature equilibrium zone and temperature drop zone. According to the temperature distribution characteristics of hot forging die, required high temperature alloy coatings can be prepared in different thickness region. Its hardness is characterized by the gradient distribution. Kashani [7] prepared Inconel625, Stellite6 and Stellite21 coatings on the surface of the H11 material by TIG welding. Through pin-on-disk testing at different temperature, he found that alloy coating improved the high temperature wear resistance. Xie[8] proposed a composite surfacing repair method by adding transition layer between substrate and outer layer. It improved the bonding property of substrate and coating. Liu [9] compared the organization and performance of the coating structure, between wear resistant layer surfacing and transition layer + wear resistant layer gradient overlay welding. He indicated that transition layer was beneficial to rational transition of alloying elements and microstructure, improved the bonding
strength. Imran [10] successfully prepared multilayer metal die casting dies on the surface of copper substrate. The transition layer is 41C stainless steel, coating is H13 steel.

In the process of hot forging, the cavity of the multilayer metal hot forging model is non-uniform stressed. The surface is subjected to bending load inevitably and the coating materials are usually hard and brittle. Therefore, Deng[11] prepared specimens with different thickness by PTAW, researched the effect of thickness on bending strength by three-point bending test at room and high temperature. Through tensile and impact toughness test, Imran [12] held that multilayer metal hot forging die specimen impact toughness is fine. However, the fracture mode of the multilayer metal die at service temperature has not been investigated intensively.

This paper prepared the specimens of multilayer metal hot forging die by PTAW. Three-point bending test and mechanical property test of the multilayer metal hot forging die were carried out by the universal tensile testing machine. The deformation mechanism of multilayer metal hot die fracture at room temperature is explained by FEM, and predicted the mechanical properties of the specimens under the service temperature.

2. Experimental Procedure

2.1. Materials and Specimens Preparation

The temperature field of hot forging die in work can be divided into three regions: temperature fluctuation zone (600-700 °C), temperature equilibrium zone (400-600 °C) and temperature falling zone (200-400 °C). According to the thermal physical parameters of material, the Ni60A alloy is suitable for the temperature fluctuation zone, the W6Mo5Cr4V2 high speed steel as temperature equilibrium zone and H13 hot forging die steel as temperature drop zone. Thermal physical properties of the above three materials in respective service temperature range as shown in Table 1.

Multilayer metal blanks were prepared by PTAW. Firstly, W6Mo5Cr4V2 high speed steel transition layer was prepared by spray welding on the surface of H13 substrate. Heating at 500 °C for 30 minute in furnace and polished the weld layer to 1mm. Secondly, prepared the Ni60A coatings by welding, annealing at 500 °C for 2 hours to avoid weld cracks. Finally, prepared the specimens according to the experimental design by wire cutting, as shown in Figure 1b. Parameters were shown in Table 2.

The specimen surface quality is fine and there are no weld cracks or shrinkage aging pore defects.

| Material       | Thermal expansion coefficient (×10⁻⁶K⁻¹) | Thermal conductivity (W·m⁻¹·K⁻¹) | Specific heat capacity (J·kg⁻¹·K⁻¹) | Elastic modulus (GPa) |
|----------------|------------------------------------------|----------------------------------|------------------------------------|----------------------|
| 4Cr5MoSiV1      | 10.3-12.2                                | 31.2-28.6                        | 506-587                           | 185-190              |
| W6Mo5Cr4V2      | 10.8-11.27                               | 27.1-26.5                        | 506-587                           | 180-195              |
| Ni60A           | 13.9-14.4                                | 26.34-25.56                      | —                                 | 180-195              |

| Parameter                  | Ni60A | W6Mo5Cr4V2 |
|----------------------------|-------|------------|
| Current[A]                 | 70    | 80         |
| Voltage[V]                 | 30    | 30         |
| Powder feeding rate[g/min] | 10    | 10         |
| Welding speed[mm/min]      | 50    | 50         |
| Arc oscillation width[mm]  | 12    | 12         |
| Standoff distance[mm]      | 8     | 9          |
| Preheating temperature[°C] | 500   | 500        |
| Overlap ratio[%]           | 40    | 40         |
2.2. Three-Point Bending Tests

The three-point bending test was carried out on the universal tensile test machine (Figure 2b). According to the experiment, the load-displacement curve between the bending load and the bending deformation of the specimen was plotted. The flexural strength ($\sigma_{bb}$) and flexural deflection ($f_{bb}$) of the specimens were calculated from data. The test span ($L_s$) was 80mm, compression speed was 1mm/min, and support roll diameter was 10 mm.

2.3. FEM Simulation

Three-point bending finite element model was established by ABAQUS. The bending process was simulated at room and service temperature. The characteristic model of homogeneous and multilayer metal specimens was established by model segmentation and optional material (Figure 3a). Contact conditions were: no friction between the three-point bending specimen, the support roller and the loading roller. Two support rollers were fixed point constraints. Restriction of X axis on the left and right symmetry axis of the specimen. Due to the possibility of ductile fracture and it needed large mesh distortion to simulate large strain deformation, we selected ductile damage as fracture criterion. The type of mesh unit was CPE4RT, which is used to simulate thick structures.

During the hot forging, the near-surface temperature of die exhibited gradient changes. The three-point bending experiment and the gradient temperature distribution were difficult to realized under high temperature. So the finite element model was used to simulate the three-point bending process of the hot forging die specimen under the temperature gradient. According to the temperature range of the hot forging die partition. The temperature of fluctuation zone, equilibrium zone and falling zone were set to 600°C, 500°C and 400°C respectively(Figure 3b).
3. Results and Discussions

3.1. Load-Displacement Curves

Load-displacement curves of homogeneous and multilayer metal specimens during three-point bending tests are plotted in Figure 4a. According to the formula (1) and (2), the bending strength of homogeneous and multilayer metal hot forging die specimen can be calculated (Table 3).

\[ \sigma_{bb} = \frac{3F_{bb}h_s}{2bh^3} \]  
\[ \sigma_{bb} = \frac{3EF_{3b}h}{bh^3-b(2h_s-h)^3} + \frac{3EF_{b}h}{bh^3-b(2h_s-h)^3} + \frac{3EF_{c}h}{bh^3-b(2h_s-h)^3} \]

In which, \( h_s \), \( h_t \), \( h_c \) is the thickness of the substrate, transition layer, cladding. \( E_s \), \( E_t \), \( E_c \) is the elastic modulus of the substrate, transition layer, cladding.

| Specimen   | Maximum bending load (N) | Maximum deflection (mm) | Bending strength (MPa) |
|------------|--------------------------|-------------------------|------------------------|
| Homogeneous| 29984.2                  | 8.9                     | 3598.1                 |
| Multilayer | 25250.5                  | 9.2                     | 3030.1                 |

Figure 4. Load- displacement curve under room temperature. (a) experiment; (b) simulation.

The bending strength of homogeneous hot forging die specimens is 18.7% higher than multilayer ones. That the strength of H13 is higher than Ni60A cladding at room temperature may be the answer. By comparing the simulated curves (Figure 4) with the experimental curves, the peak and slope are equal. This verifies the validity of the finite element calculation in this experiment.

3.2. Fracture Mode

Figure 5a shows the multilayer metal specimen stress distribution in the three-point bending under gradient temperature. The tensile stress on the substrate side is at the maximum value and crack is easily occurred. On the other hand, the stress in the cladding area is high; two high-stress channels appear on both sides of the loading roller and parallel to the loading direction. So the cladding side is also easy to crack. Due to the hardness and brittleness of the Ni60A coating, the crack propagation is promoted. The initial crack appeared on the Ni60A coating and the surface of the substrate, than crack expands and meets in the transition layer gradually, results in specimen fracture. According to the previous simulation, the fracture mode of the multilayer metal specimens at service temperature is nearly the same with the result in room temperature. The experimental results (Figure 5b) show the fracture mode of the multilayer metal specimen is consistent with the finite element.
3.3. Microscopic Fracture Morphology Analysis

Figure 6 is the fracture cross-section scanning electron microscope morphology of the multilayer metal bending specimen. It showed a fiber-like morphology (Fig.6a) and there are shallow dimples in the substrate. Therefore, from the fracture morphology the fracture mode of the substrate is ductile fracture. The brittle cleavage of hard particles observed in fracture of the transition layer in Figure 6b, the hard brittle property of the W6Mo5Cr4V2 steel leads transition layer to brittle fracture. Figure 6c is the fracture morphology of the Ni60A coating; hard particles have large brittle fracture on the fracture surface, so the fracture mode is brittle fracture too. During the three-point bending experiment, tensile stresses in the substrate, the stress is always at maximum value.

3.4. Analysis of Bending Properties under Temperature Gradient

The displacement load curves of homogeneous and multilayer metal bending specimens under temperature gradient are shown in Figure 7. When the bending deflection is 8mm, the bending load of H13 specimen is about 20000N, the bending load of multilayer metal hot forging die specimen is 22000N. This shows that the bending load of the multilayer metal specimen is 10% larger than the homogeneous specimen. Ni60A is a self-fluxing and high temperature red hardness alloy powder. Its thermostet physical properties are better than H13. Therefore, the thermal bending strength of multilayer hot forging dies is better than that of homogeneous ones.
4. Conclusions
(1) At room temperature, the bending strength of homogeneous hot forging die specimens is 18.7% higher than multilayer metal. The bending load of the multilayer metal specimen is 10% larger than the homogeneous specimen under temperature gradient.

(2) At room and service temperature, the fracture modes of multilayer metal specimen are similar: high-stress channel exists on both sides of loading roller; crack appears near the Ni60A cladding layer and extends to the transition layer. The tensile stress on the substrate side is always the maximum. Crack easily germinates and spreads to the transition layer. The cracks on both sides of the transition layer meet and finally fracture.

(3) The fracture cross-section micrographs of three-point bending test show that the fracture mode of substrate (H13) is ductile fracture, the transition layer (W6Mo5Cr4V2) and coating layer (Ni60A) are brittle fracture.

Acknowledgements
This work was financially supported by the Natural Science Foundation of China (51475346), Natural Science Foundation of China (51741506) and Wuhan University of Technology Graduate Outstanding Thesis Cultivation Project (2017-YS-006). The authors gratefully acknowledge Ms. Bing Xie for her assistance in experiment.

References
[1] J H Kang, I W Park, J S Jae and S S Kang 1998 A study on die wear model of warm and hot forgings Metals & Materials vol 4 pp 477-83
[2] K Venkatesan, C Subramanian, and E Summerville 1997 Three-body abrasion of surface engineered die steel at elevated temperatures Wears vol 203–204 pp 129–38
[3] B Navinšek, P Panjan, and F Gorenjak 2001 Improvement of hot forging manufacturing with pvd and duplex coatings. Surface & Coatings Technology vol 137 pp 255-64
[4] C. M. D Starling and J R T Branco 1997. Thermal fatigue of hot work tool steel with hard coatings. Thin Solid Films vol 308–309 pp 436-42
[5] W Roberts and B Johansson 1989 Tool steel EP US 4863515 vol 15 pp 557-9
[6] Wang H J, et al. 2011 Design method and verification for long life hot forging die. Material Research Innovations vol 15 pp 377-80.
[7] H Kashani, A Amadeh and H M Ghasemi 2007 Room and high temperature wear behaviors of nickel and cobalt base weld overlay coatings on hot forging dies Wear vol 262 pp 800-6
[8] Xie Bing, Luo Jian, Li Ainong and Hu Fang 2006 Study on microstructure and properties of gradient hardfacing layer for mould repairing China Mechanical Engineering vol 17 pp 338-43
[9] Y Liu, J Zhou, BI Huan, Y Ding and LU Shun 2011 Study on microstructure and mechanical properties of low alloy cast steel by surfacing with transition layer and anti-wear layer Hot Working Technology vol523 pp 881-92
[10] M K Imran, SH Masood, M Brandt, S Bhattacharya and J Mazumder 2011 Direct metal deposition (dmd) of h13 tool steel on copper alloy substrate: evaluation of mechanical properties Materials Science & Engineering A vol 528 pp 3342-9
[11] H Deng H Shi and S Tsuruoka 2012 Influence of coating thickness and temperature on mechanical properties of steel deposited with co-based alloy hardfacing coating. Surface & Coatings Technology vol 35 pp 63-70
[12] MK Imran, SH Masood, M Brandt, S Bhattacharya, S Gulizia, M Jahedid and J Mazumderc 2012 Thermal fatigue behavior of direct metal deposited h13 tool steel coating on copper alloy substrate Surface & Coatings Technology vol 206 pp 2572-80