Note

Effect of a Current Pulse on the Thermal Fatigue Behavior of Cast Hot Work Die Steel

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1. Introduction

In hot metal forming operations, the life of hot work die is restricted due to their extreme working conditions in terms of thermal and mechanical loadings.¹⁾ The die material is damaged through a process of non-isothermal low cycle fatigue under frequent hot and cold working conditions. Alternate heating and cooling of the die during the die-casting cycle causes TF.^{2–7)} TF is the most important failure mode in die casting. It is the gradual deterioration and eventual cracking of a material by alternate heating and cooling during which free thermal expansion is partially or completely constrained. It has been indicated by much research that fractures of components and structures are often produced by the propagation of the TF cracks. Die failure is significant losses for the die-casting industry, owing to the high cost of dies. Therefore, studies of the delay of the crack nucleation and the reduction of the crack propagation velocity are necessary to the increase of die material life.

TF of cast hot work die (CHWD) materials causes a dangerous type of fracture. Consequently, how to improve the TF resistance of hot work die is always one of the problems of concern to die industry. It is important, therefore, to develop new methods of increasing the resistance to TF. In the

present study, the effect of current pulse on the TF behavior of CHWD steel was investigated. The purpose was to enhance the resistance of the TF and to prolong the life of the CHWD. It was expected that the preliminary results could be significant for the development of CHWD.

2. Experimental Procedure

The composition of the CHWD steel used in this study is provided in **Table 1**. The TF samples are machined to a gage size of $45 \times 12 \times 3$ mm³, as shown in **Fig. 1**. An additional notch with the gage width of 0.18 mm and length of 2 mm is machined by electric spark machining for the investigation of TF crack nucleation and propagation. Before final machining, the following heat treatment process was performed: austenizing at 1353 K for 30 min, oil quenched, followed by tempering at 853 K for 3 h and air cooled. The TF test process has been described in detail in one of our previous studies.⁶⁾ The TF crack of the samples nucleates after about 250 cycles. The TF sample is used for CPT after the 200 cycles, since at this time the TF crack do not nucleate. Then every 200 cycles the current pulse is exerted on the sample. Current pulse passage is followed by heat release. Owing to the existing of notch, the current concentration is so remarkable that the notch root is quickly heated and cooled. The super high speed quenching is accomplished around notch root. The schematic of the experimental system is shown in **Fig. 2**. Through controlling the conduction angle of the silicon controlled rectifier (SCR) by the trigger circuit, the samples connected in series in this circuit are gained instantaneous pulse current. The current density is equal to 54 MA/m² in the sample, and the duration of the pulse is equal to 120 μ s.

3. Results and Discussion

The main crack length of the samples untreated and treated with electric pulse after TF cycles is shown in **Fig. 3**. Comparing with these curves, it can be seen that samples untreated and treated with current pulse have different TF resistance. It is also found that the TF crack nucleation is more early in the untreated sample than that in the sample treated with current pulse. Evidently, the TF crack propagation velocity is 1.9 times faster in the untreated sample than

Table 1. The chemical composition of the CHWD steel. (mass%)

C	Cr	Mo	Ni	Si	Mn	S	P
0.3~0.5	10.0~13.0	0.5~1.2	0.8~1.0	0.7~1.0	0.2~1.0	<0.03	<0.03

Fig. 1. The dimension of TF sample.

Fig. 2. The schematic of the experimental system.

in the sample treated with current pulse. It is obvious that the CPT during TF cycles of the samples can delay the crack nucleation and reduce the crack propagation velocity. Therefore, the TF resistance is improved by CPT.

The typical optical micrographs of TF crack morphologies of the samples treated without and with current pulse are shown in **Figs. 4(a)** and **4(b)**, respectively. The results indicate that after 600 cycles, many tiny cracks nucleate at notch root (Fig. 4(a)), and the longest of these cracks is 0.22 mm. However, the tiny cracks do not nucleate at notch root when the CPT is applied to the sample, as shown in Fig. 4(b). Furthermore, comparing with these samples, it can be seen that the circular heat affected zone is formed at the notch root of the sample treated with current pulse. The microstructures of the heat affected zone around notch root of the samples untreated and treated with current pulse are shown in **Figs. 5(a)** and **5(b)**, respectively. According to our previous study, the microstructures of the untreated sample are mainly composed of martensite and bainite (Fig. 5(a))⁷; however, the microstructures of the heat affected zone

Fig. 3. Main crack length of the samples untreated and treated with current pulse after TF cycles.

around notch root of the sample treated with current pulse are mainly composed of superfine martensite and fine grained carbon compound (Fig. 5(b)).⁸ It is obvious that the microstructures around the notch root are modified after the treatment of current pulse.

The TF crack nucleation needs an inoculation period. A quantity of microscopic defects will form in the samples after a certain amount of TF cycles. The sample is treated under current pulse before the TF cracks do not nucleate. Owing to the existing of notch, the current concentration is so remarkable that the notch root is quickly heated and cooled. The super high speed quenching is accomplished around notch root. Therefore, the heat affected zone is formed at the notch root. The microstructures of the heat affected zone around notch root are analyzed after CPT. The results indicate that the superfine martensite and fine grained carbon compound are found around notch root. The hardness, ductility and wear resistance around notch root have been promoted under the influence of superfine structure.⁸ It is obvious that the superfine microstructure which is advantageous to enhancing the obdurability of the materials is formed at the notch root by the CPT, thereby it can promote the energy required when the cracks nucleate in the notch root and can suppress the growth of the cracks. In addition, some study⁹ has proved that the tiny cracks can be healed under CPT without melting, and the healing of tiny cracks can be produced within very short time. It is thought that the transient thermal compressive stress caused by high rate heating is an important factor causing the healing of cracks.⁹

It is worth noting that the TF is well known to be very sensitive to defects which are generally accepted to have excess energy. A quantity of microscopic defects which will become sources of the cracks nucleation will form in the samples after a certain amount of TF cycles. Any defect area in metal has greater electric resistance. When the cur-

Fig. 4. The TF crack morphologies of the samples treated without and with current pulse after 600 cycles. (a) The untreated sample and (b) the sample treated with current pulse.

Fig. 5. The microstructures of the heat affected zone around the notch root of the samples untreated and treated with current pulse. (a) The untreated sample and (b) the sample treated with current pulse.

rent pulse is applied to the sample, the pulse passage is followed by heat release. The heat is released at first in all these areas. Additional heat energy facilitates the transition of the structure to a state of more equilibrium.¹⁰⁾ Therefore, an “unusual” property of CPT is the localization of heating in defect areas. The CPT acts as an “aiming healing” of defects.

4. Conclusion

The CPT during TF cycles of the samples can delay the crack nucleation and reduce the crack propagation velocity. In addition, it can be seen that the circular heat affected zone is formed at the notch root of the sample treated with current pulse. The microstructures of the heat affected zone are mainly composed of superfine martensite and fine grained carbon compound. It is obvious that the superfine microstructure which is advantageous to enhancing the obdurability of the materials is formed at the notch root by the CPT, thereby it can promote the energy required when the cracks nucleate in the notch root and can suppress the growth of the cracks. The TF resistance of sample increases

under the influence of current pulse.

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