Thermal Fatigue Behavior Evaluation of Shot-Peened JIS SKD61 Hot-Work Mold Steel

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Thermal fatigue cracking is one of the most important failure mechanisms in hot work die steels. Shot-peening can be used in a much wider field to obtain higher static strength, as well as better fatigue resistance. This study investigates the shot-peening effect on the microstructure and mechanical properties of hardened JIS SKD61 hot-work steel. The thermal fatigue test is based on cyclic induction heating and water cooling. A non-peened specimen with a hardness of 510HV0.05 was used as the reference material. The scanning electron microscopic observations showed craters on the surface and a severely worked hardened area in the shot-peened specimen subsurface. The microhardness values of the shot-peened surface are about 720 and 750HV0.05 for the Almen intensity of 15 A (typical shot-peened specimen) and 18 A (severe shot-peened specimen), respectively. The work hardening depths of typical shot-peened and severe shot-peened specimens are about 20 and 30 µm, respectively. The thermal fatigue properties of shot-peened specimens, including the mean crack length and crack distribution density, are better than those of non-peened specimens. Only a slight improvement in thermal fatigue properties occurred for the severe shot-peened specimen compared with typical shot-peened specimen. [doi:10.2320/matertrans.M2013019]

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1. Introduction

JIS SKD61 steel has good hardening ability, high toughness and excellent red hardness with less structural distortion, maintaining good dimensional stability through the hardening process.¹,² During the die casting process mold steel is heated using molten metals such as aluminum or magnesium, followed by cooling with water which causes mechanical stress on the hot work die. Such cyclic thermal stress will lead to plastic deformation, causing further heat crack initiation.³⁵ Thermal fatigue cracking is the most common failure behavior in all hot work die damage mechanisms.⁵ Hence, a higher level of thermal fatigue resistance, thermal shock resistance and excellent high temperature strength are required in hot work die steel.

Shot-peening is a cold working process used to produce a compressive residual stress layer that modifies the mechanical properties of metals. It entails impacting a surface with shots (round, metallic, glass, or ceramic particles) with force sufficient to create plastic deformation.⁶⁷ Most shot peening applications in the past were concerned only with increased fatigue durability. Shot-peening can be used in a much wider field to obtain higher static strength, as well as better fatigue resistance.⁸ In a previous study the thermal fatigue characteristics of H13 die steel with various surface treatments were investigated by Ivanov et al.⁹ They reported that the thermal fatigue resistance of hot work steel had an improvement ratio of 20% using shot-peening. Medvedeva¹⁰ concluded that different tool steels shot-peened to induce compressive surface residual stresses, exhibited different surface stress relaxation resistance when subjected to elevated temperatures up to 873 K. Shot-peening treatment for fatigue properties improvement in tool steels is known,¹¹¹² but only a few reports investigated thermal fatigue behavior applications on hot-work mold steels. Hence, this study evaluates the shot-peened effects on the mechanical and thermal fatigue behavior of JIS SKD61 hot work steel.

2. Experimental Procedures

2.1 Materials and characterization

The chemical composition of JIS SKD61 hot-work steel is listed in Table 1. The specimens were sectioned from a round steel bar and machined to φ25 mm × t 50 mm dimensions. All of the specimens were heated to 1298 K austenitizing temperature for 20 min, followed by 2 kg/mm² N₂ gas quenching and tempering at 898 K. The vacuum hardened specimens were used as reference materials, with some of the vacuum hardened specimens subjected to shot-peening treatment.

Al-type Almen strips were used to measure the Almen intensity and the shot-peening according to the following conditions: 0.2 MPa ejection pressure, 90° shot direction angle, 110 ± 10 mm nozzle distance from surface, and 15, 18 A (Almen A) peening intensity with 200%, 400% coverage, respectively. The shot-peening media used was steel balls with a diameter of 1.1 ± 0.2 mm and a hardness of 62 ± 2 HRC. The specimen and treatment notations are listed in Table 2.

2.2 Thermal fatigue testing

The thermal fatigue testing equipment was based on cyclic induction heating using 0.4 MHz high frequency and 30 kW power to induce fast heating on the specimen surface. A schematic of the experimental set-up used in the thermal fatigue test is shown in Fig. 1. In order to rapidly simulate the die casting temperature condition a circular coil made of copper tube was designed to furnish the heating and cooling stage simultaneously in one rotation cycle. Several holes were drilled in the coil within 30° range of the inserted specimen for water jets and the remaining 330° range for heating. The specimen was gradually heated in the heating region to the maximum surface temperature of about 973 K.
Water injection from the holes in the coil brought the specimen to a minimum temperature of about 473 K in the cooling region. The thermal fatigue testing procedure was defined as one cycle for a point on the specimen that was heated to the maximum temperature and subsequently cooled by water jets. The each cycle time was 0.3 s while rotating at 200 rpm. The temperature was measured using an infrared meter using a stopper to decrease the water spray influence.

The thermal fatigue testing in this study was conducted with 3000 cycles. After testing, the surface thermal crack morphology and crack propagation behavior beneath the surface were investigated using an optical microscope (OM, Nikon OPTIPHOT-100) and a scanning electron microscope (SEM, JEOL JSM-5600) with Energy Dispersive Spectrometer (EDS). The thermal fatigue properties including the mean crack length and crack density (number of cracks per unit length) were revealed from a polished longitudinal cross-section investigated using an optical microscope. The micro-hardness profiles after thermal cycling for all treated and tested specimens were measured using Vickers indentation on the polished cross-section with an applied load of 0.49 N.

3. Results and Discussion

3.1 Characteristic of shot-peened layer

A SEM micrograph of the surface morphology of the SSP specimen is shown in Fig. 2(a). The surface roughness with a higher Ra value obtained in the case of SSP specimens is consistent with the SEM observations, which detected craters on the surface of the shot-peened specimen. The TSP specimen shows a similar surface morphology compared with the SSP specimen. Higher than 100% coverage on shot-peened specimens depicts the surface roughness value (Ra) in the range between 15–20 µm. As illustrated in Fig. 2(b), from the overall cross-sectional SEM observation view for SSP specimens, a severely deformed work hardened area is observed just below the surface. The difference in microstructure between the work hardened area (elongated grain) and the substrate (equiaxed grain) can be clearly observed in Fig. 2(b). The residual stresses produced by shot-peening from plastic deformation are well known and the maximum compressive residual stress at the surface is depending on the peening intensity used. The higher peening intensity in the SSP specimen shows higher compressive residual stress near the surface compared with the TSP specimen.

Cross-sectional micro-hardness profiles of shot-peened specimens with different Almen intensity.

Table 1 Chemical compositions of JIS SKD61 (mass%).

<table>
<thead>
<tr>
<th>Element</th>
<th>Mass %</th>
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<tbody>
<tr>
<td>C</td>
<td>0.398</td>
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<tr>
<td>Si</td>
<td>0.968</td>
</tr>
<tr>
<td>Mn</td>
<td>0.406</td>
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<tr>
<td>P</td>
<td>0.018</td>
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<tr>
<td>S</td>
<td>0.008</td>
</tr>
<tr>
<td>Cr</td>
<td>5.145</td>
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<tr>
<td>Mo</td>
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</tr>
<tr>
<td>V</td>
<td>0.920</td>
</tr>
<tr>
<td>Fe</td>
<td>Bal</td>
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Table 2 Nomenclatures of specimens and treatments.

<table>
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<th>Notation</th>
<th>Treatment</th>
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<tbody>
<tr>
<td>NP</td>
<td>Quenched and tempered at 898 K</td>
</tr>
<tr>
<td>TSP</td>
<td>Shot-peened with the Almen intensity of 15 A</td>
</tr>
<tr>
<td>SSP</td>
<td>Shot-peened with the Almen intensity of 18 A</td>
</tr>
</tbody>
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3.2 Surface cracking

The surface morphologies of shot-peened and non-peened specimens with a hardness of 510 HV0.05 after thermal fatigue...
testing are shown in Fig. 4. After thermal fatigue test of 3000 cycles, cracks, black region in Fig. 4(a), were obviously observed at the NP specimen surface of the heated area between the surface oxides identified by the SEM-EDS as shown in Fig. 4(d). Because the oxides are formed at the specimen surface and the crack surface of crack opening, the oxides formed below the specimen surface are not removed by polishing. Hence, the gray region presented in Figs. 4(b) and 4(c) indicates the crack opening and the oxides at the crack surface.

In Birol’s study,\(^\text{16}\) the specimens were heated by an oxyacetylene flame to the maximum die cavity surface temperature of about 1023 K within about 30 s. Cooling was performed by forced air, adjusted so as to bring the surface temperature to around 723 K, during the next 30 s. The each thermal fatigue cycle was taken 60 s, and the first crack was detected on the surface after 5000 thermal cycles. For comparison, the area of surface crack of tested specimen at a value of 15–20% was chosen in this study and Birol’s result. The total testing time after 3000 thermal cycles was only taken 15 min in this study. It means that the testing condition used in this study can simulate the die casting temperature condition more rapidly and effectively.

The maximum width of the main crack is about 0.3 mm and with many fine cracks for NP specimen. However, the TSP specimen presented fine cracks with inter-granular morphology after thermal fatigue testing. A thinner crack with less crack area can be observed in the shot-peened specimens after thermal fatigue testing, as shown in Fig. 4. This shows that the crack initiation and propagation in hot-work steel can be effectively decreased by shot-peening treatment. The thermal stress occurring in the early stage during the testing will be depressed by the compressive stress near the surface of the shot-peened specimen. The crack initiation can be delayed by the plastic deformation between the craters and then propagated along the inter-granular structure with increasing thermal cycles.

### 3.3 Crack length and crack density

Typical pit-like thermal cracks can be observed clearly, as shown in Fig. 5. The cross-sectional OM micrographs suggest that crack propagation is perpendicular to the surface, instead of the branched or dendritic cracks morphology. Persson\(^\text{17}\) mentioned that the cross-sectional crack path is distinguished by different testing temperatures; relatively straight cracks dominated after heat cycling to 973 K, and the branched or dendritic cracks are observed when the thermal cycling temperature reaches 1123 K. In Fig. 5, the testing temperature was 973 K for this testing method. Clearly, the transverse crack without dendritic crack was observed. Iron oxide, confirmed by the SEM-EDS, is also observed on the specimen and crack surface, especially in NP specimens. Because the thermal cracks are developed at the surface before 3000 thermal cycles, the cracks are still exposed to the air at the 973 K temperature during the thermal fatigue test. The cracks in the NP specimen were created earlier compared with the TSP and SSP specimens due to the thick iron oxide around the crack in the NP specimens. The crack presented a narrow shape in the TSP and SSP specimens. The SSP specimen shows no evident oxide, which positively reflected the delay in crack initiation for shot-peening treatment, as shown in Fig. 5.

Based on the investigated transverse crack morphology, the polished cross-section micrograph also analyzed crack features such as the mean crack length and crack density, respectively. Two crack features in the specimen surface after 3000 thermal cycles for different treated specimens are shown in Fig. 6. The mean crack length of NP, TSP and SSP specimens are 270, 195 and 175 µm, respectively. Compared to the NP specimens, the mean crack length of the TSP specimen decreased 28% to 195 µm. However, this is only a slight improvement by about 10% for the specimen after repeated shot-peening treatment (SSP) compared with the TSP specimen; see Fig. 6(a). However, the crack density decreased by about 50% for TSP specimens compared with NP specimen. The SSP specimen shows better thermal properties than TSP specimen, see Fig. 6(b). This reveals that the compressive stresses could effectively retard the cracks.
deformed on the surface. The crack density is an important factor for the amount of crack growth, which is attributed to the surface structure and initial residual stress state. Some cracks propagated into the material due to the stress concentration. Shot-peening treatment was used successfully to overcome the dangers of surface damage, and used in thermal fatigue testing. It can be concluded that shot-peening treatment can provide excellent mechanical properties and produce good thermal fatigue resistance.

3.4 Hardness after thermal fatigue

The micro-hardness profile was measured using a Vickers micro-hardness tester with an applied load of 0.49 N to investigate the hardness response to thermal fatigue. Figure 7 shows the micro-hardness profiles of TSP and SSP specimens after 3000 thermal fatigue test cycles. One can see that thermal cycling to 973 K causes softening in the surface area for all shot-peened specimens. After 3000 cycles at 973 K the initial surface hardness for the TSP and SSP specimens was reduced approximately in the 400–450 HV range. The hardness increased with increasing depth from the surface down to the substrate. The SSP specimen presented a higher hardness value than the TSP specimen from the surface to center region, but the difference is not evident (see Fig. 7). The temperature difference between the maximum and minimum temperature in cyclic induction heating is larger than 473 K, so the thermal stress is estimated to be 500 MPa, and it could accelerate steel softening and further cause fracture. On the other hand, at the steel tempering temperature micro strain is completely released during the 0.5h holding time. However, the maximum temperature reached 973 K in this thermal testing, which is higher than the steel tempering temperature. Hence, the micro strain decreased rapidly after 3000 thermal test cycles.

4. Conclusions

From cross section SEM observations of SSP specimens, the severely deformed work hardened area is near the surface. The micro-hardness values near the surface were about 750 and 720 HV, for SSP and TSP specimens, respectively. The work hardened depths of TSP and SSP specimens were about 20 and 30 µm, respectively. After 3000 thermal test cycles, spread cracks with dendritic morphology could be observed in the NP specimen. However, the TSP specimen presented fine cracks with inter-granular morphology after thermal fatigue testing. Thin crack width and less crack area could be observed in the tested shot-peened specimens.

From the cross-sectional investigation of tested specimens, the cracks in the NP specimen were created earlier compared with the TSP and SSP specimens due to the thick iron oxide around the crack in NP specimens and the narrow shaped cracks for TSP and SSP specimens. The crack density decreased by about 50% for the SSP specimens compared with the NP specimens. It can be concluded that shot-peening treatment can provide excellent mechanical properties and the compressive stresses could effectively retard the cracks formed on the surface.

Acknowledgement

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REFERENCES