Crack Repair of Hot Work Tool Steel by Laser Melt Processing

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Tool steel used in hot work such as die-casting is required to have the resistance to heat checking which results in fine shallow cracking on the part surface. Laser melt processing, which can produce a localized shallow melted zone, has been adapted to repair such kind of cracks. However, the melted zone has a detrimental effect on impact toughness because the laser heating may generate hard structures during the processing. In this paper, the effect of laser melt processing on repairing cracks was evaluated by means of the Charpy impact test and fractography. The test results suggested that when this laser melt processing can eliminate an extensive damaged volume through heat treatment after laser melt processing, the impact toughness is able to recover again to the initial state after heat treatment.

KEY WORDS: hot work tool steel; laser melting; impact toughness; crack repair.

1. Introduction

Cast dies are subjected to various complex impact loads during thermomechanical processes. The high stress leads to a considerable plastic deformation and abrasion with the increase in operation time. Thus, it is required that tool steels used for hot work should have some properties such as the resistance to thermal deformation, thermal shock and heat checking that takes place on the tool steel surface. The dies used for mass production will be usually repaired or reshaped every 104 shots. Grinding, milling or arc melting processes are usually used for removing the damaged region and then the removed portion is filled. There have been many reports on laser surface treatment for steels. It is known for steels that the laser process can locally heat the material to the austenitic region and the material will be transformed to hard structures due to self-quenching. Laser processing is considered as one of the practical approaches to improve the damaged region. This is because laser processing can simultaneously remove the cracks or defects and carry out heat treatment. Henze et al.3) did some study on the influence of the metal filler on the strength of Cr–Mo–V dies. It should be noted the filling material was welded in the convex area of the worn zone. Ernst et al.2) described the feasibility of crack repairing for the damaged area in the die with a deep crack using the Nd:YAG laser system. In addition, Kato3) reported that the fatigue strength of a shaft containing a small crack could be improved by CO2 laser hardening. Brown et al.4) suggested that the laser weld repair for cracks of ship building steels is more effective rather than the arc weld repair because of shorter work and lower cost.

2. Experimental Method

The chemical composition used in this work is shown in Table 1. The block was homogenized and solution treated at 1 303 K for 1 800 s (0.5 hr) and then cooled in the air and tempered at 873 K and 828 K for 1 800 s (0.5 hr) respectively with hardness of HRC48. Figure 1 shows the machined CT (compact tension) specimen with dimension of 63×55×25 mm. The specimens were fatigue precracked so that the fatigued crack takes place by the sinusoidal wave of 20 Hz and the load ratio of 0.1. Then Charpy impact specimens of 5×6×55 mm were machined from the above-men-

Table 1. Chemical composition of the tested steel (mass%).

| Element | C    | Si   | Mn   | P    | S    | Ni   | Cr   | Mo   | V   |
|---------|------|------|------|------|------|------|------|------|-----|
| mass %  | 0.37 | 0.94 | 0.42 | 0.013| 0.001| 0.14 | 4.95 | 1.15 | 0.5 |

Fig. 1. Schematic view of the impact specimen.
tioned CT specimens by an electrical discharge machine (EDM).

Laser processing for crack repairing was carried out as follows. The laser source was Nd:Y AG with Ar protect (shielding) gas. The frequency of the laser was 75 Hz and the laser beam was focused on the V notch root of specimen. The power of laser was fixed at 1 kW and the scan rate was 10 mm/s. After the laser processing, some of impact specimens were heated at 873 K for 3 600 s (1 hr) and some were quenched and tempered under the initial heat treatment condition.

The impact tests were carried out at 300 K and 873 K. A scanning electron microscope (SEM) was used to make fractographic observations.

3. Results and Discussion

The tensile strength and the impact toughness of the tested tool steels at 300 K and 873 K are shown as Table 2. When the test temperature is higher, the 0.2% proof strength and the tensile strength are lower. The fracture elongation hardly changed with the varying temperatures. The impact toughness was higher at higher temperature and the reduction of area was so.

The geometry shape and the structure of the V notch root of the impact specimen before and after laser melting processing are shown in Figs. 2(a) and 2(b). Figure 2(a) shows a fatigue crack at the V notch before the laser processing. Fig. 2(b) shows the macroscopic structure after the laser melt processing. The structure after the laser melt processing is roughly divided into three zones. In Zone I, a melted zone, there exists the cellular dendrite-like structure, which consists of lath martensite and retained austenite in the melt zone of a nail shape. It is found that zone II, HAZ (heat affected zone), was also transformed into the martensite partially. Zone III exhibits as the base metal with little influence of melting heat. There is an approximately 1 mm long pre-crack ahead of the V notch root in Fig. 2(a). As shown in Fig. 2(b), the crack can be removed by laser processing without damage. The repair effect of laser processing for the tool steel with cracks will be evaluated by Charpy impact testing.

Figure 3 shows the micro-Vikers hardness distribution in the laser processing zone. The hardness in the melted zone and the HAZ adjacent to the melted zones has higher hardness than that in the base metal, because hard martensite was formed. The HAZ hardness nearby the base metal decreases greatly. The hardness of the heat-treated specimen after laser processing, which was quenched and tempered under the initial condition, distributes uniformly through the cross section. In another case of the specimen that was heated at 873 K for 3 600 s (1 hr) after laser processing in order to soften the melted zone, the hardness in the melted zone decreases, but still higher than that in the base metal.

Figure 4 shows the stress–strain curves for the base metal specimen and the laser butt-welded specimen at 300 K and 873 K. The tensile strength and the fracture elongation of the laser welded specimen (T) decrease in comparison with that of the base metal (N) at both test temperatures. The area under the stress–strain curve of the weld specimens significantly differs between at 300 K and 873 K. This means that the micro-structure and thus ductility has been improved to a certain extent due to heating (or softening) at the test temperature. It was observed from SEM that the tensile fracture appearance was of a quasi-cleavage type at 300 K, while that at 873 K was of an equi-axis dimple type.

Figure 5 illustrates load–displacement curves in the instrumented Charpy impact testing. From these measured

| Temp. K | Tensile properties | Impact toughness (Absorbed energy) |
|---------|-------------------|-----------------------------------|
|         | σ0.2 MPa | σb MPa | % | % | J/cm² |
| 300     | 1290      | 1520   | 16.7 | 49.0 | 34 |
| 873     | 571       | 801    | 17.6 | 76.1 | 128 |

![Fig. 2. Comparison of V-notch profile (a) before and (b) after laser processing.](image1)

![Fig. 3. Microhardness distribution of the laser processed specimens.](image2)
curves, the following points can be understood. On the V-notch specimen (a) and (b), the maximum impact load is higher at 300 K than at 873 K. This results are similar to those for the tensile testing. The absorbed energy at 300 K is lower than that at 873 K. As for the fatigue pre-cracked V-notch specimens, the absorbed energy considerably reduces at both temperatures. This is because the strain concentration at the tip of the fatigue crack is greater than that of V-notch. Therefore, there become less energy required for crack initiation. Figures 5(c) and 5(d) give the curves for the repair specimen by laser processing. The effect of laser processing cannot be recognized since the absorbed energy at 300 K is very low. But at 873 K the effect of processing appears. Figures 5(e) and 5(f) are for the specimens of heat-treated, quenched and tempered after laser processing. The shapes of the curves at both test temperatures resemble those of the initial condition ((a), (b)).

The impact test results at both test temperatures are compiled into Fig. 6. The impact values of the specimens at 873 K are higher than those at 300 K. It can be inferred from the stress–strain curves in Fig. 4. In the case of the fatigue precracked V-notch specimen these values markedly reduce for the reason of a difference in strain concentration between V-notch and fatigue crack. Though the crack was removed by laser processing, the impact value at 300 K was not recovered because of the brittle microstructure and the low tensile strength. But toughness was recovered at 873 K. After the laser processing, the specimens were heated to 873 K for 3600 s (1 hr) or quenched and tempered under the initial heat treatment conditions in order to recover toughness to an initial level. Both heat treatments after laser processing could recover the impact values from the less values to the initial ones due to the processing. Impact fracture processes generally consist of the crack initiation process and the crack propagation one. In Fig. 5, $U_0$ represents the total absorbed energy under the load–displacement curve. $U_1$ represents the energy required...
until the load reaches the maximum level after the onset of fracture initiation, while \( U_2 \) that is the energy after the maximum level is considered as that for crack propagation. \( U_2 \) that is the energy after the maximum level is considered as that for crack propagation. Figure 7 gives the ratio of \( (U_1/U_0) \) and \( (U_2/U_0) \) respectively. For V-notched specimens, although the crack initiating energy ratio \( (U_i/U_0) \) is high, the ratio of the crack propagation energy is higher at 873 K. But, in the fatigue pre-cracked specimen, the absorbed energy at both 300 K and 873 K is low. The most of absorbed energy will be consumed for the crack propagation rather than the crack initiation. As for the repair specimen by laser processing, the absorbed energies at 300 K are exhausted for the crack initiation, but these at 873 K are improved. The ratio of the absorbed energy for the heat-treated specimens after laser processing are recovered to nearly the same value of V notched specimens. From these results, the specimen repaired by laser processing seems to behave as the impact fracture process similar to the sound V-notched specimen.

Figure 8 shows macroscopic SEM fractographs at both test temperatures. The fracture surface at 300 K of V notch specimen as shown in Fig. 8(a) consists of the stretched zone formed by ductile slip deformation in the crack initiation period and the radial, flat quasi-cleavage one in the crack propagation period. On the other hand, at 873 K, the width of the stretched zone became wider and a characteristic wrinkle pattern came after. In the case of the specimen with fatigue precrack shown in Figs. 8(c) and 8(d), the stretched zone became narrower, since less energies were required for the crack initiation.

The fracture surface at 300 K of the repaired specimen which has hard structures in Fig. 8(e) exhibits the brittle fracture pattern as a trace of hardened in the melted zone and the HAZ. Meanwhile, a brittle pattern is not observed in the fracture surface at 873 K in Fig. 8(f) even in the melted zone because the hardened structure was softened during heating to the test temperature. The fracture patterns, Figs. 8(g) and 8(h), of the repaired specimens which were heat-treated under the initial heat treatment condition after the laser processing show fracture patterns similar to those in Figs. 8(a) and 8(b).

The following can be summarized from the above-mentioned experimental results: The impact toughness after laser processing is lower, though cracks existing at the V notch root can be removed by the laser processing. Therefore some heat treatment is required in order to recover the reduced toughness. Further investigations will be needed for practical applications from a viewpoint of wear, fatigue and other performances.

4. Conclusion

YAG laser processing was applied to repair cracks on the surface layer of tool steels. The results of this study are summarized as follows:

(1) The laser processing is applicable to remove crack on surface layer.
(2) As the impact toughness becomes lower by the processing, some heat treatment is needed.
(3) The impact fracture process of the specimen is improved due to laser processing followed by heat treatment.

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