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Laser surface melting of W2 tool steel: effects of prior heat treatment

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The feasibility of repair welding of W2 tool steel die material using a laser melting technique has been investigated. It is shown that aside from microstructural modifications, surface cracking occurs due to laser melting followed by rapid solidification. The nature and density of these cracks are found to be dependent on the initial microstructure and/or heat treatment before laser processing. The best result was obtained for a sample annealed at 790° C for 2 h.

1. Introduction

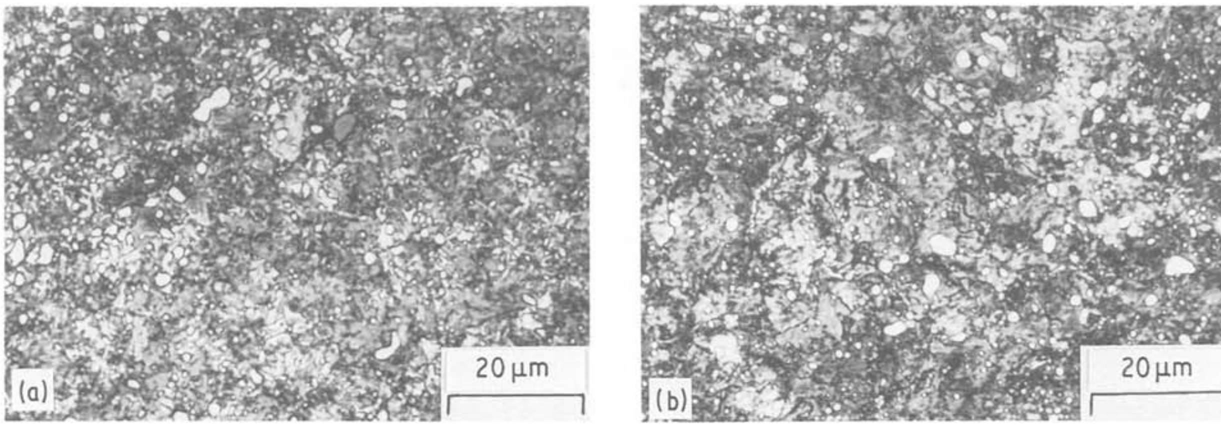
The most widely used steel for dies conforms to the ASTM specification for W2 tool steel. The processing of W2 tool steel for dies includes surface melting, heat treating, welding etc. The recent applications of directed energy sources, such as lasers, help in processing a variety of materials including W2 tool steel. The beneficial effects of laser surface treatment are minimum distortion, development of compressive residual stresses, refinement of grains, increased solid solubilities of alloying elements and modification of segregation patterns. However, laser surface melting, like conventional welding processes, introduces porosities, irregular boundaries and cracks in both fusion and surrounding regions which impair the surface properties of laser-treated parts. The highly localized heating of a metal substrate while it is being laser treated and the extremely non-uniform temperature distribution associated with this (from the vaporization temperature of the metal down to the temperature of the surrounding atmosphere) are conducive to the development of plastic deformation in the fusion zone and the surrounding region of the same substrate. It has been proved [1] that high-temperature plastic deformation taking place during laser treatment of a metal has a substantial effect on its fine structure. The conclusion has been drawn that the development of plastic deformation in the region around the fusion zone is of dominant importance in crack formation. The local heating during laser treatment and the non-uniform temperature field which is created cause thermal stresses in the solidified region as well as in the surrounding region. These stresses can be subdivided into temporary stresses, existing during heating and cooling, and residual stresses [2]. Most attention is normally paid to the latter. On the other hand, the temporary thermal stresses may have a substantial effect on the strength of the laser-treated material. This can primarily be seen in the effect of plastic deformation of the heat affected zone, which is directly associated with the magnitude of the temporary thermal stresses and the manner in which they are distributed [3]. All these thermal stresses developing close to a source of heat must be taken into account when the deformation of structures and the nature of brittle fracture are analysed. In the present study, laser surface melting of W2 tool steel was performed using a 2 kW, continuous-wave CO_2 gas laser. The nature of the cracks in the heat-affected zone was then investigated as a function of different prior heat treatments.

2. Experimental procedure

W2 tool steel (C = 0.6 to 1.4 wt %, V = 0.25 wt %) samples in the shape of a cylindrical disc with 2.54 cm diameter and 1.27 cm thickness were used for this study. The samples were subjected to different heat treatments prior to laser treatment. One sample was austenitized at 890° C for 1 h and then quenched in water at room temperature, while a second sample was austenitized at 890° C for 1 h first, then quenched in water at room temperature and finally tempered at 270° C for 70 min. The third sample was annealed at 790° C for 2 h. After heat treatment all samples were mechanically polished and etched in picral to reveal the microstructures. These specimens were then mounted on a electrically controlled *x–y* table and irradiated with a continuous-wave CO_2 laser beam of 10.6 μm wavelength at a power level of 1650 W. The beam was focused at the surface of the specimen to obtain a spot size of 0.2 mm. Single-scan laser melting was employed with a scan rate of 8 cm min^{-1}. After laser treatment specimens were polished, etched and then examined by scanning electron microscopy (SEM).

3. Results and discussion

Table I serves to illustrate the variation in hardness value of samples for different heat treatments before they were laser treated. Optical micrographs of microstructures of the three samples in Table I are seen in Figs 1a, b and c, respectively. These are typical microstructures representative of different heat treatments in W2 tool steel. The microstructure in Fig. 1a shows spheroidal carbide (white dots) in a matrix of untempered martensite. The microstructure in Fig. 1b consists of undissolved particles of carbide (white) in



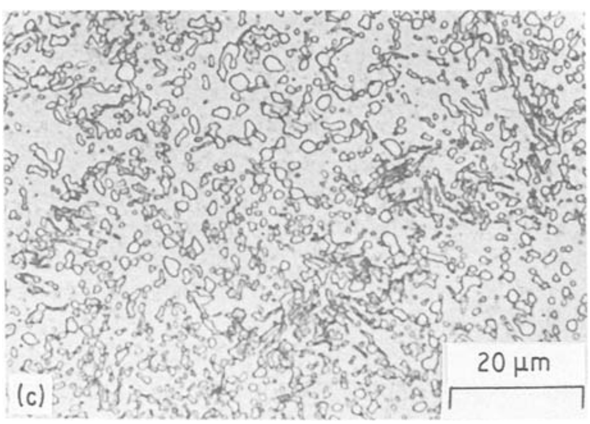


Figure 1 Optical micrographs of W2 tool steel with different heat treatments. (a) Austentized at 890° C for 1 h, then quenched in water at room temperature. (b) Austentized at 890° C for 1 h, then quenched in water at room temperature and finally tempered at 270° C for 70 min. (c) Annealed at 790° C for 2 h.

a matrix of tempered martensite (dark background), and the structure in Fig. 1c has ferrite, lamellar pearlite and also some spheroidal carbide (white dots) particles in a matrix of ferrite.

The SEM micrograph in Fig. 2 shows evidence for the "rippled" topograph in a laser track which has been the object of considerable attention by other investigators [4, 5]. Porosity and liquid drops ejected during laser interaction are also visible in this micrograph. The presence of cracks in this solidified region is a predominant feature of the micrograph. Similarly Figs 3a, b and c are micrographs of the area surrounding the fusion zone in the laser-treated samples with prior heat treatments listed in Table I. In these micrographs also, we notice the presence of cracks. According to the nature of these cracks, the region surrounding the laser fusion zone can be subdivided into two principle regions: a high-temperature zone (HTZ) located immediately next to the fusion line, and a comparatively low-temperature zone (LTZ). The metal in the HTZ is the most highly heated metal. A feature of this zone is the comparatively sparse network of cracks. Away from the fusion line, in the LTZ, the number of relatively broad bands decreases. The narrow HTZ is the most vulnerable part of the area surrounding the fusion zone. A micro-redistribution of alloy elements takes place in this region [3]. It has also been concluded earlier [6] that there is a very high vacancy concentration and vacancy clusters in this region. High ledge atoms and vacancies could provide activated sites for the initiation of cracks in the HTZ. The development of high temperatures in the region around the fusion zone is conducive to intensive recrystallization. The plastic deformation in this region is the effect of slip formation. It has been noticed [3] that slip in this high-temperature region is accompanied by a noticeable amount of grain-boundary migration. If migration is retarded (in the alloy), slip takes place along grain boundaries with very small displacement and is accompanied by an accumulation of dislocations. This may cause intergranular breakdown to develop. This accounts to the mechanism by which cracks initiate in the HTZ and propagate in the LTZ.

According to Figs 3a, b and c it is also clear that the density of cracks in a region around the fusion zone is

TABLE I Hardness values of heat-treated samples

Heat Treatment	Rockwell hardness, R_c
1. Austenitized (890° C, 1 h) – quenched (water at room temperature)	64
2. Austenitized (890° C, 1 h) – quenched (water at room temperature) – tempered (270° C, 70 min)	42.5
3. Annealed (790° C, 2 h)	17

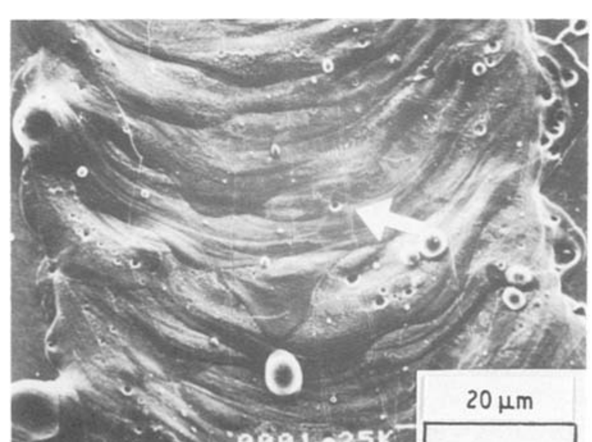
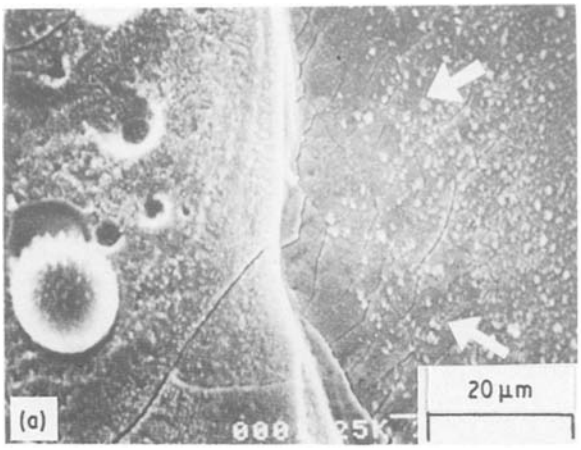
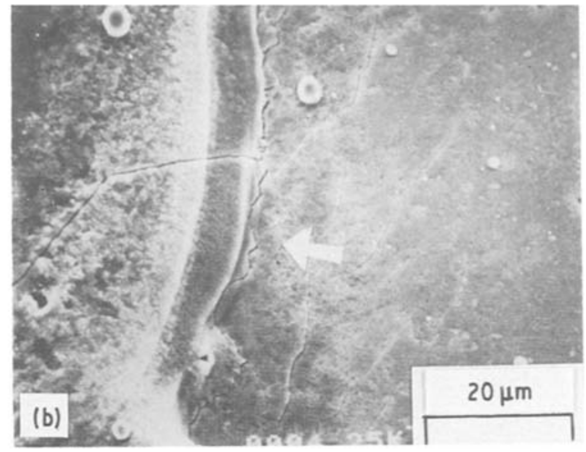


Figure 2 SEM surface-normal view of topographical features of laser-scanned W2 tool steel.





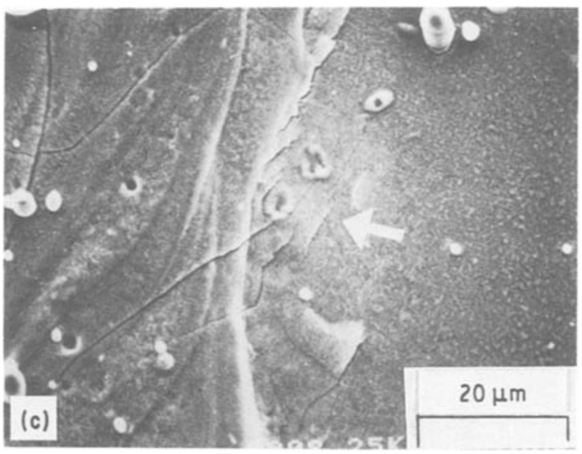


Figure 3 (a, b, c) Scanning electron micrographs of HAZ in laser-treated samples with heat treatment mentioned in Figs 1a, b and c, respectively. Arrows in figures show cracks.

affected by the heat treatment given to the sample before it is subjected to laser treatment. The density of cracks goes on decreasing from Fig. 3a to Fig. 3c. The sample in Fig. 3a has a fully untempered martensitic structure which undergoes a reversion to austenite within an area around the fusion zone. Within this reverted structure, profuse grain-boundary melting and void formation take place [6]. These are the nuclei for cracks. Also fully untempered martensite shows a very low level of toughness and offers the least resistance to crack formation and propagation. The sample in Fig. 3b undergoes stress relief during tempering which increases the toughness level. Hence, even though the nuclei for cracks are generated by reversion to austenite during laser treatment, it does offer some resistance to crack propagation. Finally, the structure of the sample in Fig. 3c is ferrite, lamellar pearlite and spheroidal carbide, which has the highest level of fracture toughness. These features help in the retardation of crack formation, thereby showing the lowest density of cracks [7].

The micrographs in Fig. 2 and Figs 3a to c show that the major number of cracks are parallel to the direction of motion of the workpiece. According to Rosenthal's [8] analytical solution for a moving point heat source (like the one used in this study), the family of isotherms are developed around it as shown in Fig. 4. The rise of temperature in front of the heat source is steeper than the fall of temperature behind the source. The points on the workpiece passing through maximum temperature at the same instant are located on a line, Curve **n**, which is curved backward. This is due to the finite speed of heat flow in metals, which delays the occurrence of the maximum temperature in fibres parallel to the direction of workpiece motion. The more distant the fibres from the laser track the greater the delay. As a consequence, a steep thermal gradient is established and hence thermal stresses are developed in the material which are expected to give rise to cracks parallel to the direction of workpiece motion. These thermal stresses increase abruptly at the location of the source of heat, and away from it they decrease. The increase in the temporary thermal stresses in the vicinity of the source of heat, and the consequent increase in overall stresses in the workpiece, give rise to cracks in the laser track as well as in the surrounding region.

4. Summary

From the above observations we can summarize that cracks are produced in the fusion zone and in the

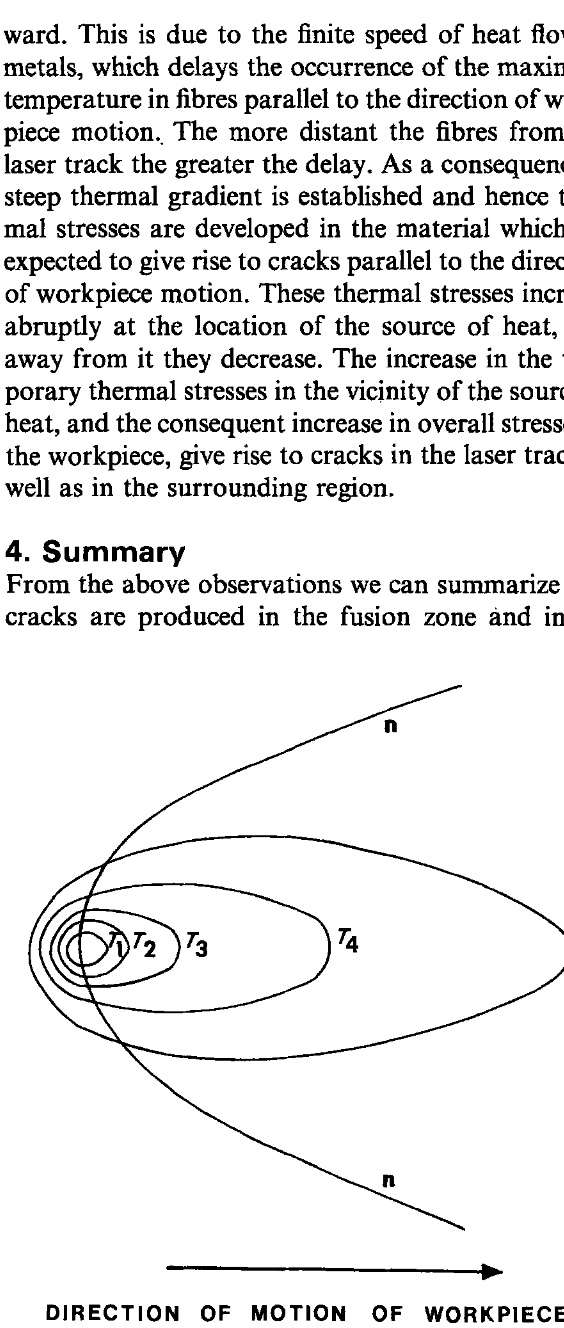


Figure 4 Temperature (T) distribution around heat source. $T_1 > T_2 > T_3 > T_4 > T_5$.

surrounding region of laser-treated material. The density of cracks observed in a region surrounding the fusion zone is affected by the heat treatment given to samples before they are subjected to laser treatment. Finally, most of the cracks in both regions are more or less parallel to the motion of the workpiece.

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