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WEAR INDUCED HARDENING OF LASER PROCESSED CHROMIUM-CARBON STEEL

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Introduction

Laser surface hardening is a technique for producing enhanced wear resistant layers. It has several technical advantages like local treatment, alloying and easy computer numerical control. High quench rates (10^4 - 10^8 °C/sec) can result in new metastable structures with improved wear properties. This rapid cooling after melting the surface is due to the thermal conductivity into the substrate. In steels laser treatments may result in grain refinement, increased homogeneity and a highly alloyed matrix. Consequently, a higher tensile stress and a good ductility might be expected. On the other hand large thermal gradients during quenching give rise to tensile stresses in the surface layer. Local plastic yielding occurs and is sometimes followed by surface cracking. Residual stresses up to 450 MPa have been reported [1].

Laser hardening can be achieved either by melting a steel surface, alloying it or heating it without melting. This paper reports the microstructure and the wear performance of a laser melted chromium carbon steel. The transformation of austenite into martensite during abrasive wear has been studied in detail. A comparison has been made between conventionally hardened material and laser melted steel. For that purpose samples have been conventionally hardened, i.e. heating above austenitizing temperature followed by a quench, whereas another part has been laser melted.

Hardening

The material under investigation is commercial chromium steel. Its hardness in soft annealed state is 240 HV. The chemical composition is listed in table 1:

Table 1

The chemical composition of X210CrW12

Elements:	Fe	C	Cr	W
wt%:	bal	2.05	11.05	0.62

Some of the samples are conventionally hardened as follows: The steel is heated to 980°C for 20 minutes. After a quench into water the material is annealed at 180°C for 1 hour. This results in a martensitic structure with a hardness of 900 HV in conventionally hardened material. For the laser treatments a Spectra Physics 820 1.5 kW CW-CO_2 laser has been used. The beam is directed to the surface by one fixed molybdenum mirror and a ZnSe lens in order to minimize power losses. The focus distance to the surface of the specimen is adjustable. The sample is mounted on an X-Y table.

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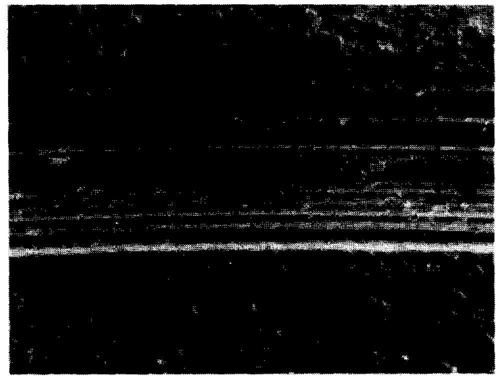

Fig. 1 (Left) Interference microscope image of worn laser melted chromium steel after 10 000 turns. Used light source: Sodium light ($\lambda/2$ = 294,6 nm).

Fig. 2 (Right) Wear track on conventionally hardened steel after 10 000 turns.

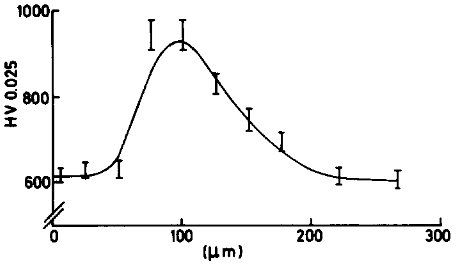

Fig. 3a Hardness profile of a wear track on laser melted chromium steel after 10 000 turns.

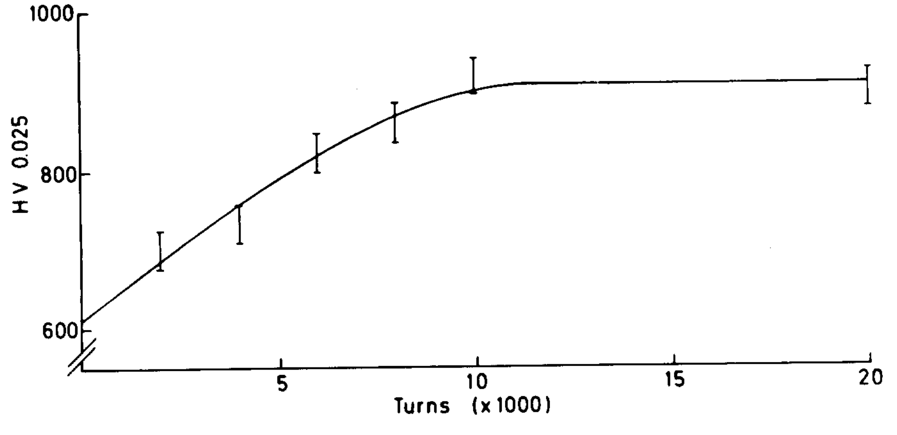

Fig. 3b Wear induced hardening.

Melted tracks are made near each other with some overlap, resulting in a completely melted surface. The surface is coated by a black writing marker. The absorption of gritblasting has been found to be too low. The application of a DAG graphite coating results in the highest absorption, however surface cracking occurs because of the alloying of extra carbon. The laser parameters are summarized in table 2:

Table 2

Laser processing parameters

Coating	black ink		DAG graphite	
Power	1500	W	1500	W
Focal length	127	mm	127	mm
Position focus above surface	15	mm	15	mm
Speed	4	cm/sec	25	cm/sec
Distance between melt passes	1	mm	1	mm
Shieldgas	argon		argon	
Hardness	550-600	HV	1200-1500	HV

The hardness is found to be 550-600 HV. This is in line with Bergmann's measurements [2]. The surface roughness Rz is 13 μm. The melt depth varies between 60 - 100 μm. Higher hardnesses up to 1500 HV have been obtained if a DAG graphite coating has been applied. Apparently the material is less ductile and extensive cracking occurs. Consequently, wear experiments on the DAG coated samples have not been carried out.

Wear behaviour

The macroscopic wear performances of laser melted chromium steel and conventionally hardened steel are tested on a pin-on-disk wear tester [3]. Before wearing, the hardened surfaces are slightly polished with SiC paper and diamond paste. This does not introduce extra hardening. A ruby crystal ball with a diameter of 5 mm is pressed upon a rotating sample. The ball does not show any significant damage during the experiments. Before each test the ball is rotated or replaced to have a well defined starting condition. For all experiments a constant speed of 5.0 cm/sec and a constant load of 2.3 N have been chosen. As can be calculated using Hertzian stress analysis, the contact area between the laser melted steel and the ruby ball is only elastically deformed for the given hardness, load and ball diameter [4]. The effect of humidity is reduced by supplying absolute ethanol.

The amount of wear is determined with an interference microscope. A typical example of a wear track after 10.000 turns on laser melted steel is shown in fig. 1. The wear resistance of laser melted steel is not significantly better than in the case of conventionally hardened material. Although the wear volumes are the same, the wear mechanisms involved are different. Fig.2 shows a wear track on conventionally hardened chromium steel after 10000 turns. From fig.1 and fig.2 we conclude that the laser processed material exhibits more ductile behaviour. Another difference is the absence of individual large carbides in the laser melted material which take part in the wearing process of the conventionally hardened steel. In the latter case carbides (1-3 μm in size) are pulled out of the matrix as a whole.

Hardness measurements on wear tracks of laser melted chromium steel reveal a wear induced hardening. The hardness is measured across the weartracks with a Vickers hardness tester. A load of 25 grf. is used. In fig. 3a the hardness profile is given after 10000 turns. Fig. 3b shows the wear induced hardnesses of laser treated material as function of turns. An increase in hardness is found from 600 HV up to 900 HV.

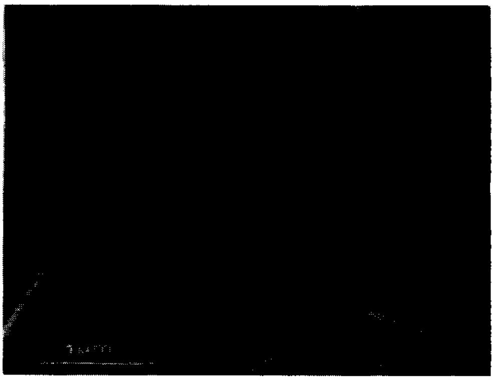

Fig. 4 SEM Image of austenite cells with segregated carbides in laser melted steel.

Fig. 5 (Left) Slip-bands with a pile-up of dislocations bound at a cell boundary.
Fig. 6 (Right) Pile-up of dislocations near a cell boundary.

Fig. 7 (Left) Martensite twins beneath a worn surface.
Fig. 8 (Right) Cracked martensite (see arrow) near a worn surface.

TEM observations

The microstructure of laser melted chromium steel has been investigated by transmission electron microscopy (JEM 200 CX at 200 kV) both on worn and unworn samples. Disk type samples specimens parallel to the surface are made and thinned electrochemically using perchloric acid. It is hardly possible to make TEM samples of the small worn tracks produced on the pin-on-disk tester. Therefore 3 mm TEM disks are thoroughly ground on SiC-paper, producing abrasive wear. After this the surface is smoothed with diamond paste. Thinning these samples from the bulk side results in an electron transparent area just below the worn surface. To get information from deeper regions the worn surface is further thinned in an argon ion milling machine.

The laser melted layer shows austenite cells surrounded by segregated carbides. The cell diameter varies from 0.5 to 8 μm, depending on laser process parameters and local quench rates in the melt. The higest scan speeds (25 cm/sec) of the laser beam results in the smallest sizes (0.5 to 2 μm). EDS measurements indicate that chromium is more concentrated in the cell wall than in the interior of the cell. Fig. 4 shows a SEM image of austenite cells. The contrast is obtained by using 200 KV electrons and the sample is thin enough to be transparent for electrons. The carbides are of the M_3C type. In the austenite cell the defect structure due to quenching is mainly characterized by a high dislocation density and pile-ups of dislocations. Fig. 5 shows a slip band with a pile-up of dislocations bound at both sides by a cell wall. A pile-up of edge dislocations near the cell wall is depicted in fig. 6. Although austenite has a low stacking fault energy only a few stacking faults are observed. In contrast, Pearce found a much higher density of stacking faults in chromium cast-iron [5] (in the as-cast condition). This discrepancy with our observations can be ascribed to a higher quench rate during laser treatment. During laser surface melting less segregation of alloying elements occurs resulting in a higher chromium concentration in the matrix compared with cast-iron. As a consequence, the stacking fault energy in our material is likely to be enhanced by the higher chromium concentration in the matrix, in accordance with our observation of just a few stacking faults.

Martensite is not found in unworn samples. The high carbon content suppresses the M_s temperature. Wear experiments show a hardening up to 900 HV and TEM-study on worn disks reveals α-martensite formation, as has been reported before by Rigney and co-workers [6][7]. Fig. 7 shows martensite twins. The electron diffraction patterns from the austenite and the deformation induced martensite can be indexed according to the Nishiyama-Wassermann orientation relationship, i.e. $(001)_\alpha//(0\bar{1}1)_\gamma$. A more heavily deformed martensitic structure is found nearer the surface. Some cracks are present in the martensitic phase (fig. 8). These cracks might be favoured by the residual tensile stresses, which are still present after laser melting. The nucleation mechanism for martensite can be described according to Brooks et al. by a pile up of dislocations [8,9]. If the stresses are high enough to produce a shear of 1/6 <112>, a pseudo bcc stacking is obtained. Hcp-Martensite is not to be expected, since stacking faults are absent.

Conclusions

Laser melting of X210CrW12 chromium steel results in austenite with segregated M_3C carbides. During wear the material transforms into α-martensite. The hardness of the laser processed material increases from 550 HV to 900 HV in the worn material. Cracks are present in the brittle martensite. Supersaturation of alloying elements increases the stacking fault energy of the laser melted austenite. The absence of stacking faults prevents the formation of hcp-martensite. The laser melted material is more ductile than conventionally hardened material. The abrasive wear resistance did not differ significantly.

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