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Laser surface melting of Ti–6Al–4V alloy

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Surface hardening of Ti–6Al–4V alloy with laser surface melting (LSM) in a nitrogen atmosphere has been studied. In LSM, hardness increased almost three-fold in comparison to that of the substrate, the latter having a Vickers hardness of 350, by the formation of TiN in the range of 100 μm of melt depth. Hardness, then, decreased slowly and reached a minimum of 580 VHN at a maximum melt depth of 750 μm. α′-Ti was formed in the heat-affected zone (HAZ) with a VHN of 450. Ageing treatments were performed for all specimens at 450 °C and different ageing times (1–20 h). Short ageing treatments increased the hardness in the melted zone as well as in the HAZ (1–3 h). Long ageing treatments (7–20 h) resulted in uniform hardness distribution in the melted zone.

1. Introduction

Titanium and its alloys are known for their high specific strength as well as corrosion and fatigue resistance [1]. However, they suffer from low wear and gall resistance; this, in turn, limits their use in tribological applications [2].

There are processes available that increase the surface hardness of titanium alloys through modification of composition or microstructure. Conventional nitriding techniques such as ion-nitriding, nitrogen gaseous nitriding, salt-bath nitriding and others, utilize the formation of TiN in the surface layer [3–5]. The thickness of the layer is a function of process temperature and time. However, they all have the disadvantage of requiring high treatment temperatures and extensive hours of processing.

Ion implantation has recently emerged as a new technique to improve surface hardness of titanium alloys [6–8]. When ion species such as nitrogen, carbon and boron are implanted into surface layers of titanium alloys, they form hard titanium-based metallic compounds such as TiN, TiC and TiB. The thickness of the hardened surface layer, though, is only a few micrometres. Additional disadvantages of ion implantation are the requirements of long processing times and the limitation of specimen sizes.

Laser processing techniques, such as laser surface melting (LSM) and laser surface alloying (LSA), are widely used for surface modification. Improved hardness, corrosion and wear resistance have been observed for ferrous and non-ferrous alloys [9–14]. In addition, laser processing offers more practical working conditions, such as short processing time, unlimited specimen size and easy control of the treated surface thickness. In the study presented, the laser surface melting of Ti–6Al–4V alloy was carried out, in a nitrogen atmosphere, possibly to form TiN in the surface layer and thus increase the surface hardness. The resulting microstructures were analysed with X-ray diffraction and hardness measurements. Ageing treatments were carried out to introduce further microstructural changes and determine their effect on the hardness achieved in the melted regions.

2. Experimental procedure

The material investigated in this study was the commercial grade Ti–6Al–4V alloy. As-received material was cut and polished to obtain flat surfaces for laser processing. Laser surface melting experiments were carried out in nitrogen gas atmosphere. A GTE Sylvania Model 975 CO_2 gas transport laser, which provides a nominal output power of 5 kW continuous infrared radiation at a wavelength of 10.6 μm, was used. The beam diameter at the laser exit aperture was 45.7 mm and could be focused down to 0.5 mm through a focusing lens. A schematic drawing of the laser processing apparatus is shown in Fig. 1. The specimen is mounted on a rotating table, swept through the beam that is focused on the specimen surface. The laser power was 5 kW and the scan speed of the laser beam was 7 mm s^{-1}. Approximately 2 cm^2 laser-melted or alloyed surfaces were obtained with an overlap of 50%. Following laser processing, specimens were cut parallel to the laser beam raster direction. With suitable polishing and etching, melt depth and width as well as gross microstructural characterization were made through scanning electron microscopy. A Vickers microhardness test was used to determine the hardness increments in the laser surface-melted samples. X-ray diffraction analysis was used to identify the phases present after laser surface melting.

3. Results and discussion

Laser melting in a nitrogen gas atmosphere resulted in the formation of white dendrites covering the whole melted zone; the latter having a thickness of 750 μm

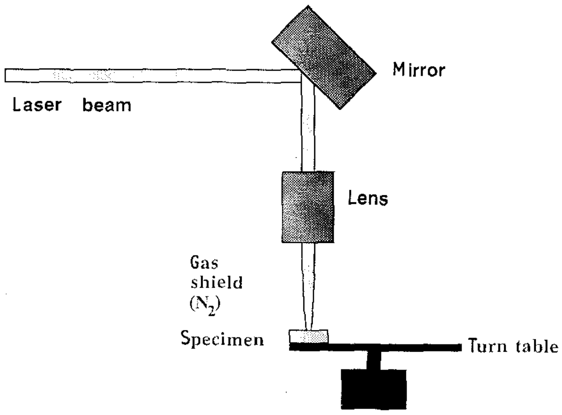

Figure 1 The laser-processing apparatus.

(Fig. 2). X-ray diffraction taken of the surface indicates the formation of TiN in the layer, exhibited by high-intensity TiN peaks, together with some low-intensity α-Ti peaks (Fig. 3a). This TiN formation on the surface, though not fully consistent with the high hardness of TiN, is still indicated to be present by the microhardness data shown in Fig. 4. VHN values of over 1000 were obtained in an area to a 100 μm depth from the surface. Hardnesses decreased to about 580 VHN at the bottom of the melted zone. Similar results are also reported in the literature [13]. To understand the microstructural alteration of the low-hardness regions, about 80% of the melted zone was polished away. X-ray diffraction taken from this surface revealed a decrease in TiN content and an increase in α-Ti content in the microstructure (Fig. 3b). Hardening in this region is believed to be due to a nitrogen solid-solution effect. The presence of α-Ti in this region can be explained in terms of the high nitrogen content, because nitrogen is known to be an α stabilizer.

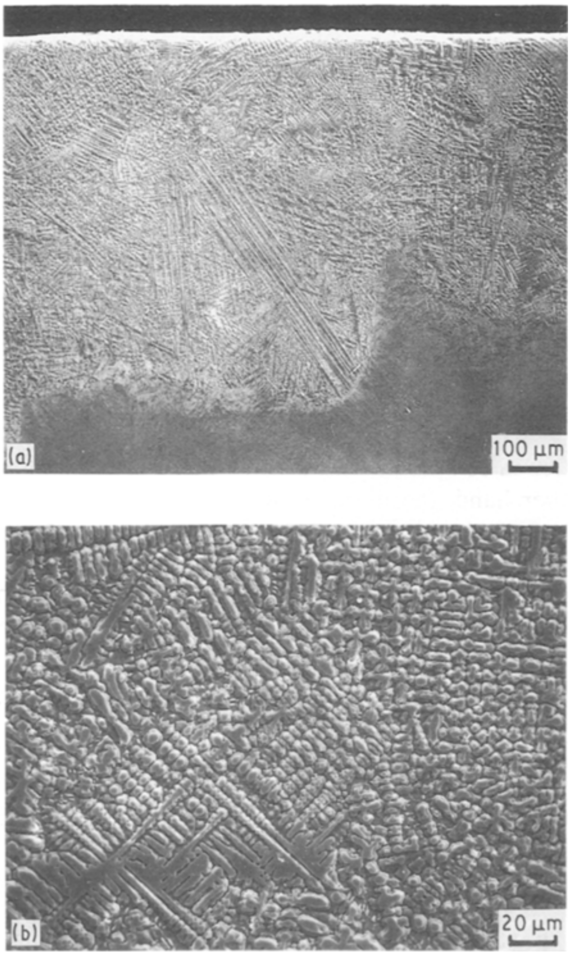

Figure 2 The laser surface-melted structure of Ti–6Al–4V alloy: (a) the melted zone; (b) close-up view of (a) showing the dendritic structure.

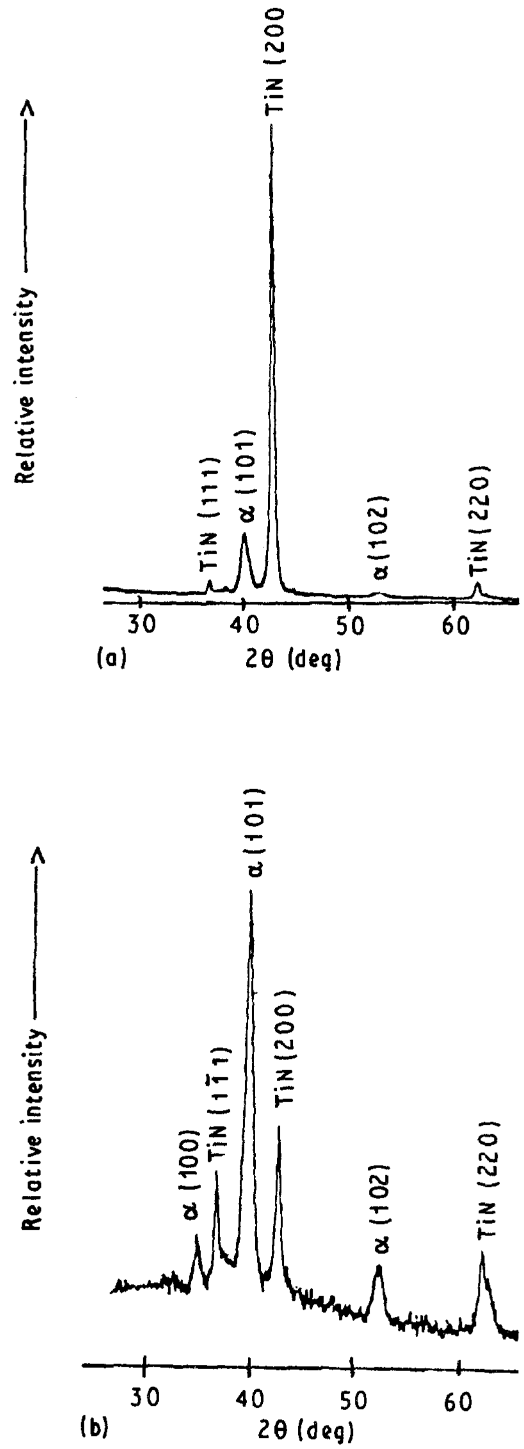

Figure 3 XRD patterns of the laser surface-melted Ti–6Al–4V alloy: (a) the polished surface; (b) after removal of 80% of the melted layer.

In the heat-affected zone (HAZ), hardness is fairly constant at about 450 VHN. During laser melting, temperature at the HAZ can easily reach β-phase field temperature. Rapid cooling from this field can cause martensitic transformation. Uniformity of hardness

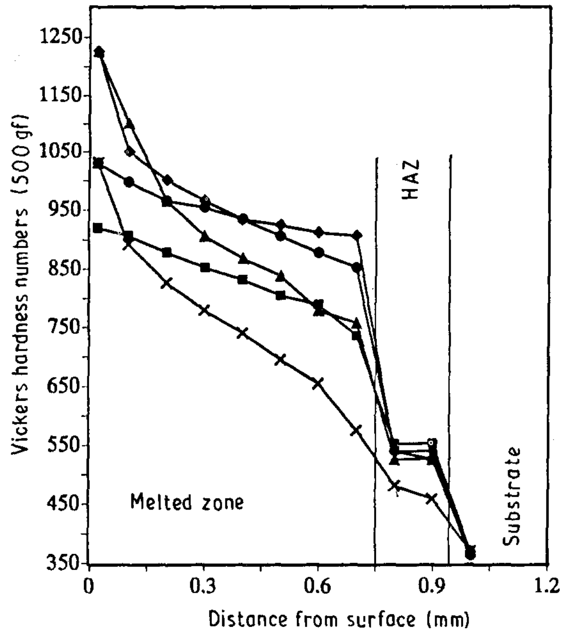

Figure 4 The hardness distribution of Ti–6Al–4V alloy that was laser surface melted under nitrogen gas and aged at 450 °C for: (▲) 1 h, (◆) 3 h, (●) 7 h, (■) 20 h. (×) As-LSM. Power 5 kW, scan speed 7 mm s^{-1}.

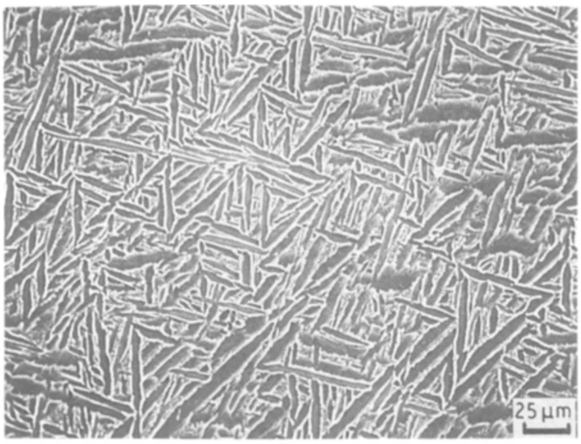

Figure 5 The microstructure of the HAZ of the laser surface-melted Ti–6Al–4V alloy.

values in the HAZ seems to indicate the formation of α′-Ti in this region (Fig. 5).

To understand the hardening mechanisms operative in the melted zone, laser-melted samples were aged at 450 °C for different periods. Ageing for 1 h increased hardness by 20% in the melted zone (Fig. 6). This might be due to the precipitation of Ti_2N, because excess nitrogen is expected to be present in this region as also observed in other research [15]. Hardness in the HAZ also increased by 15%, reaching a constant value of 530 VHN. The increase in hardness in the HAZ is an indication of soft α′-Ti decomposition to the relatively hard α + β phase mixture. Further ageing increased the hardness slowly; at the end of 20 h ageing, the hardness in the HAZ was about 570 VHN. This is consistent with the fact that, upon decomposition of α′, a stable α + β structure is produced.

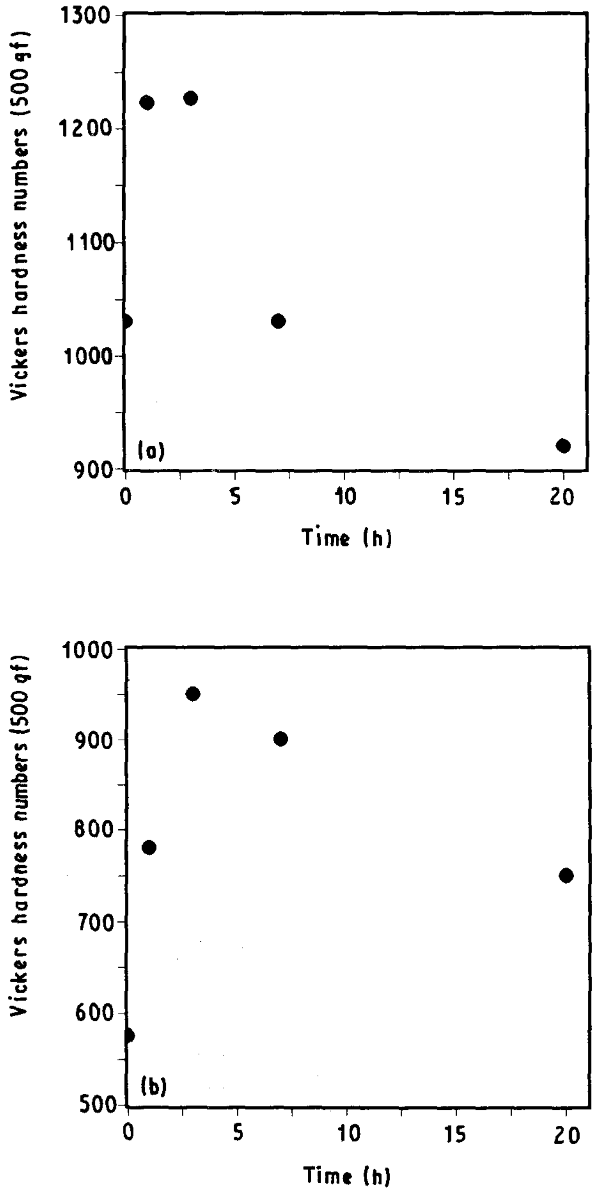

Figure 6 The hardness change of laser surface-melted Ti–6Al–4V alloy as a function of ageing time at 450 °C: (a) at the surface; (b) at maximum melt depth.

After 20 h ageing, surface hardness decreased by 10% in comparison with the as-LSM sample. On the other hand, the hardness distribution in the melted zone became almost uniform. As shown in Fig. 6 in the as-LSM sample, the hardness value at the bottom of the melted zone is around 45% less than that of surface hardness, but this difference is reduced to 16% after 20 h ageing treatment. The microstructure after 20 h ageing is shown in Fig. 7.

The observation of uniform hardness distribution in the melted zone, after 20 h ageing, can be attributed to the levelling of nitrogen concentration by diffusion and to the precipitation of a Ti–N compound in the previously low-hardness region. X-ray diffraction patterns taken from the surface, following the removal of 80% of the laser-melted layer, reveal the presence of a high TiN content there (Fig. 8b). Furthermore, comparison of Figs 3b and 8b clearly shows that the hardness increase is due to TiN precipitation after the long ageing period.

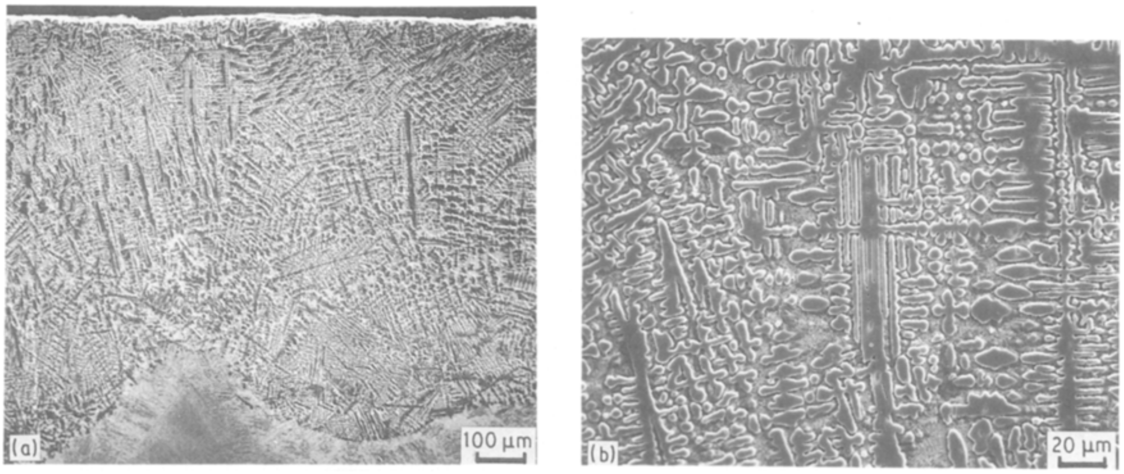

Figure 7 Laser surface-melted structure of Ti–6Al–4V alloy, after ageing for 20 h at 450 °C: (a) the melted zone; (b) disintegration and coarsening of the dendritic structure.

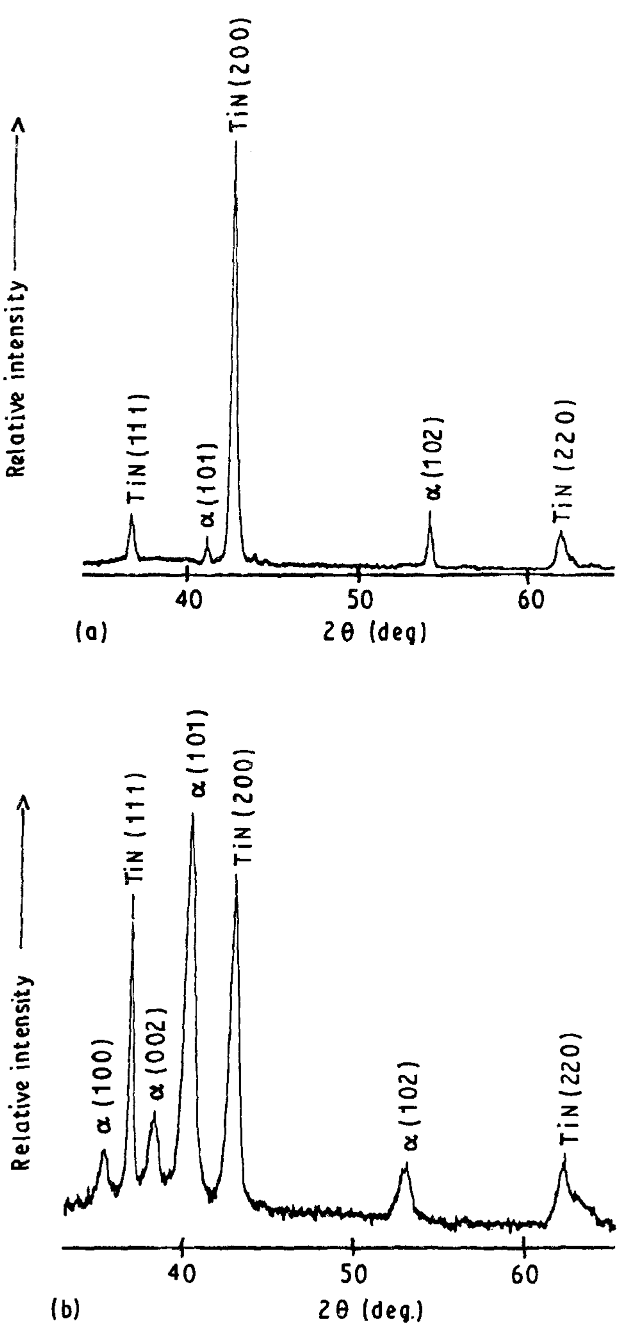

Figure 8 XRD patterns of laser surface-melted Ti–6Al–4V alloy after ageing for 20 h at 450 °C: (a) the polished surface; (b) after removal of 80% of the melted layer.

Diffusivity of nitrogen in α-Ti at 450 °C is calculated to be $3 \times 10^{-5}\,\mathrm{cm^2\,s^{-1}}$ [16]. This diffusion rate of nitrogen affects the hardness, after 7 h ageing, by lowering the nitrogen concentration and thus the hardness by 20% at the surface (Fig. 6a). The lowering of hardness due to nitrogen diffusion, from the surface to the interior, becomes much more effective after 20 h ageing, corresponding to a 0.3 µm calculated diffusion distance. A Ti–N compound precipitation is seen to start at the surface after short ageing times (i.e. 1–3 h) because of the high nitrogen concentration there (Fig. 6a). However, this precipitation in the rest of the melted zone starts only after 3 h ageing treatment as indicated by the increased hardness in these areas following such a treatment (Fig. 6b).

The hardness profiles obtained suggest that the ageing contribution to the hardness change in melted zone is the increased diffusion distance of nitrogen; this leads to a reduction in the solid-solution hardening effect of nitrogen at the surface while the precipitation of a stable Ti–N compound increases the hardness throughout.

4. Conclusions

An attempt was made to show that laser surface melting of Ti–6Al–4V in a nitrogen gas atmosphere produces a hardened surface layer of the alloy by TiN formation. The major conclusions may be summarized as follows:

1. Laser surface melting in a nitrogen atmosphere increased the surface hardness up to 1000 VHN by TiN formation.

2. Low-hardness values in the melted zone are due to a decrease in TiN content deeper in the melted zone.

3. Ageing treatments of 1 and 3 h increased the overall hardness in the melted zone. However, 20 h ageing treatment resulted in a more uniform hardness distribution in the melted zone.

4. The microstructure of the heat-affected zone is α′-Ti initially. Ageing treatments increased hardness by the decomposition of α′ and the precipitation of an α + β microstructure.

Acknowledgement

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