Ceramic–metal composites produced by laser surface treatment

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The injection of SiC particles (150 μm size) into laser surface melted commercial purity titanium, Ti–6Al–4V (wt-%) alloy, and Ti–2·5Cu (wt-%) alloy has been investigated using 1·75 kW laser power, 5 mm beam diameter, 0·15 g s^{-1} powder flowrate and traverse speeds ranging from 7 to 20 mm s^{-1}. Partial dissolution of SiC occurred and fine dendrites of TiC nucleated at the particle/matrix interfaces and also within the matrix. Silicon enrichment of the matrix and a eutectic constituent were observed. The microhardness of the melted zone was increased to 600–650 HV (500 g). MST/964

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Introduction

The use of laser radiation to improve the surface properties of titanium has been the subject of a number of investigations.[1–10] Ayers and co-workers[1–5] injected hard particles of TiC and WC into laser surface melted zones on various substrates and demonstrated that wear resistance was improved. For example, Ti–6Al–4V (wt-%) alloy injected with 30–50 vol.-%TiC had a hardness of 450 HV; the coefficient of friction decreased when the TiC content was increased, reaching a minimum at 50 vol.-%TiC (Ref. 5).

The high reactivity of titanium with gases such as nitrogen and oxygen led to the development of a new method of improving the wear resistance[6–10] involving laser surface melting in a nitrogen atmosphere. A pulsed Nd–YAG laser and a CW CO_2 laser* having powers of 200 W and 2–5 kW, respectively, were used. In one report, for example, the hardness was increased from 200 to 700 HV in a single pass using a CW CO_2 laser and this increase was explained as being due to the formation of TiN in the form of dendrites: the thickness of the layer containing TiN was in the range 5–12 μm (Ref. 6). When a pulsed Nd–YAG laser was used, hardness levels up to ~1200 HV were obtained.[6]

Alloying with carbon has also been carried out by coating the substrate with carbon powder before laser melting; the hardness was increased to 650 HV as a result of the formation of TiC (Ref. 9).

In the present paper, preliminary results on the injection of SiC particles into titanium substrates using laser surface melting are reported and the effect of this process on structure and hardness is also discussed.

Experimental procedure

Commercial purity (CP) titanium and Ti–6Al–4V (wt-%) alloys were received in the form of plates 10 mm thick and Ti–2·5Cu (wt-%) alloy was received as sheet 3 mm thick. A CW CO_2 laser was used to give a power density of the order of 10^5 W mm^{-2}. The laser parameters used were 1·75 kW laser power, 5 mm beam diameter, and 0·15 g s^{-1} powder flowrate; and traverse speeds in the range from 7 to 20 mm s^{-1}, were used.

Particles of SiC having an average size of 150 μm were injected into the melt pool by blowing with argon gas from a feeding system connected to the laser head. The experimental arrangement has been described in a previous paper.[10] A shrouding system using argon gas protected the melt zone from contamination.

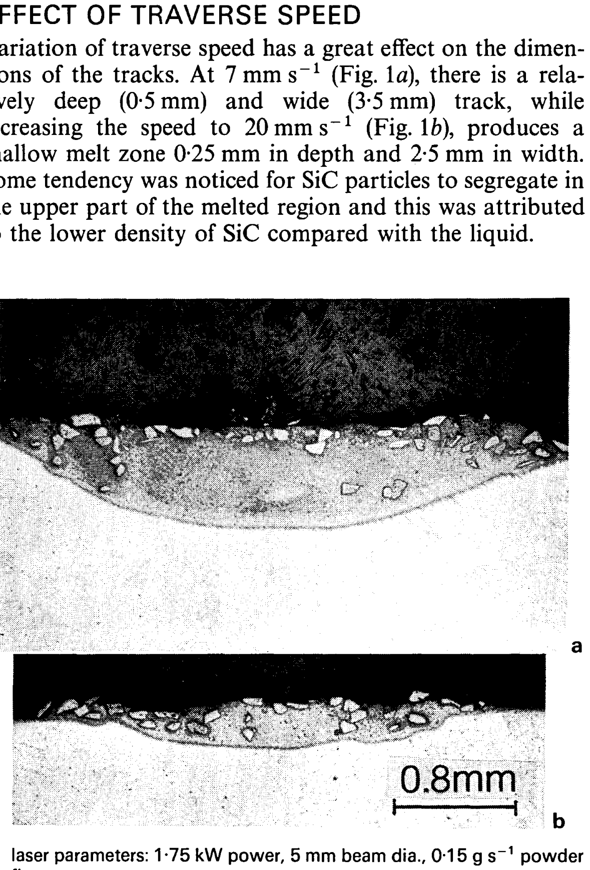
Sections of processed material were investigated using optical and scanning electron microscopy (SEM), electron probe microanalysis (EPMA), and hardness tests. X-ray diffraction examination using Cu Kα radiation was carried out on the top surfaces of processed tracks, following metallographic polishing.

* YAG yttrium–aluminium–garnet; CW continuous wave.

Results and discussion

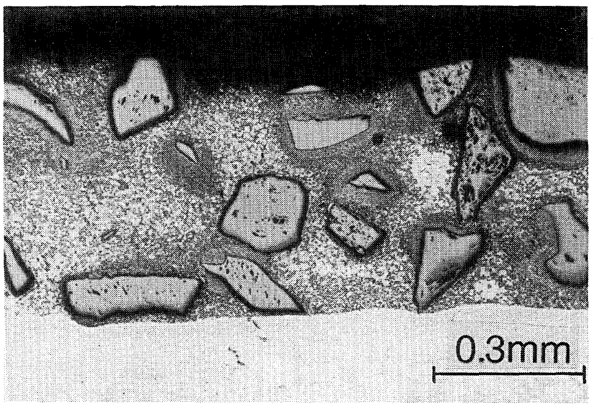
EFFECT OF TRAVERSE SPEED

Variation of traverse speed has a great effect on the dimensions of the tracks. At 7 mm s^{-1} (Fig. 1*a*), there is a relatively deep (0·5 mm) and wide (3·5 mm) track, while increasing the speed to 20 mm s^{-1} (Fig. 1*b*), produces a shallow melt zone 0·25 mm in depth and 2·5 mm in width. Some tendency was noticed for SiC particles to segregate in the upper part of the melted region and this was attributed to the lower density of SiC compared with the liquid.



laser parameters: 1·75 kW power, 5 mm beam dia., 0·15 g s^{-1} powder flowrate

1 Transverse section after injection of SiC particles into laser surface melted CP Ti at traverse speeds of *a* 7 mm s^{-1} and *b* 20 mm s^{-1} (optical micrographs)



2 Longitudinal section of Fig. 1*a* (optical micrograph)

MICROHARDNESS

The microhardness in all the samples processed at 7 mm s^{-1} traverse speed was measured in the melt zone (matrix), heat affected zone (HAZ), and the substrate (Table 1).

The hardness of the SiC particles was > 2000 HV; the average hardness of the matrix was 600–650 HV for all three alloys and is attributed to the formation of TiC. The melt zone hardness of the Ti–6Al–4V alloy is similar to that obtained[9] by laser surface alloying with carbon, which was 650 HV, and greater than that obtained[5] by laser surface injection of TiC, namely, 450 HV.

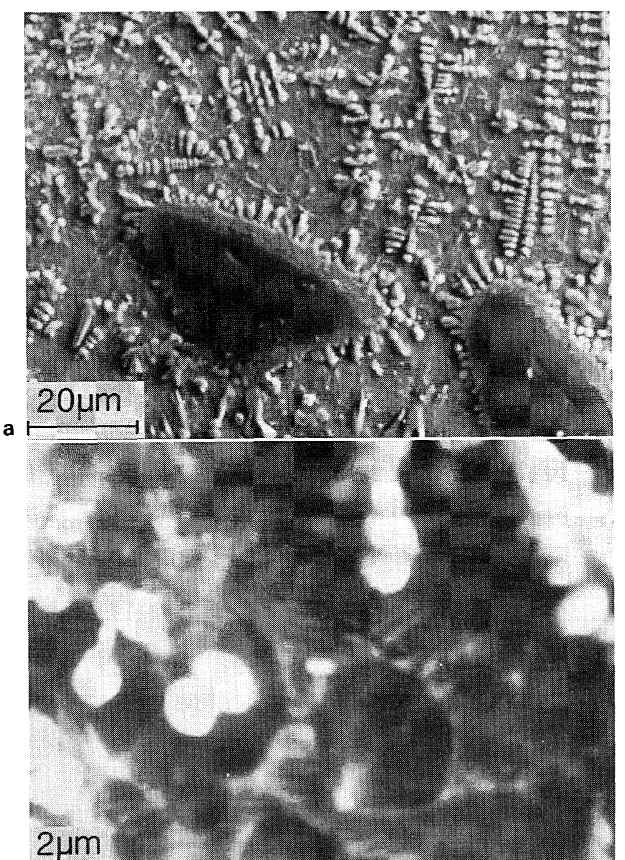
Table 1 Microhardness data for alloys injected with SiC

	Microhardness, HV (500 g)		
Alloy	Melt zone	HAZ	Substrate (as received)
CP Ti	650	250	210
Ti–6Al–4V (wt-%)	650	425	355
Ti–2·5Cu (wt-%)	600	350	245

CP commercial purity.

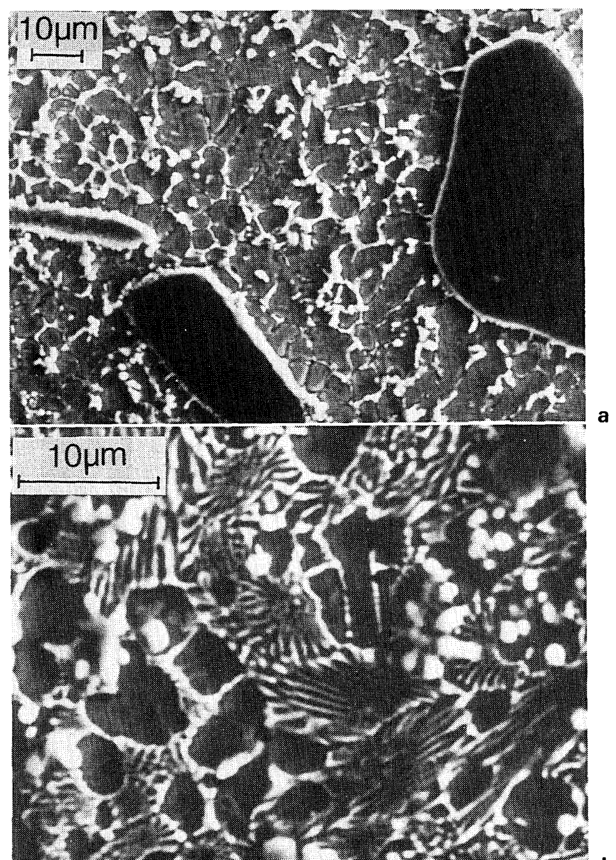
MICROSTRUCTURE

The microstructure of CP titanium injected with SiC particles at 7 mm s^{-1} is shown in Fig. 2. The melt zone is free from cracks and porosity. Using SEM, partial dissolution of SiC particles and nucleation of dendrites at the particle/matrix interfaces were revealed (Fig. 3*a*). These dendrites have a secondary arm spacing of about 2 μm, which is consistent with cooling rates in excess of ~ 10^3 K s^{-1}. The matrix contained fine grains less than 5 μm in diameter showing a martensitic structure and lamellar eutectic regions having spacing less than ~ 1 μm were also present (Fig. 3*b*). By EPMA of the matrix regions (including the TiC dendrites) in CP titanium processed at 7 mm s^{-1} (Fig. 3*b*), an average silicon content of 5 wt-% was obtained. A similar structure was revealed after injection of SiC particles into Ti–6Al–4V (Fig. 4) and Ti–2·5Cu alloys, but a larger proportion of the eutectic constituent was observed



a injected SiC particles in Ti substrate; *b* eutectic regions, TiC (white areas), and transformed *β* (dark areas) in matrix

3 Microstructure of CP Ti obtained using traverse speed of 7 mm s^{-1}: laser parameters are given in Fig. 1 (SEM)



a injected SiC particles in alloy substrate; *b* eutectic regions, TiC (white areas), and transformed *β* (dark areas) in matrix

4 Microstructure of Ti–6Al–4V (wt-%) alloy injected with SiC particles at 7 mm s^{-1}: laser parameters are given in Fig. 1 (SEM)

Table 2 Electron probe microanalysis of CP Ti and Ti–6Al–4V injected with SiC at 7 mm s^{-1} traverse speed (C analysis by difference)

		Content, wt-%				
Alloy	Position	Ti	Si	C	Al	V
CP Ti	Dendrites	90·0	...	Bal.	...	...
	Within grains	Bal.	2·0	...	...	...
	Eutectic regions	Bal.	7·0	...	...	...
Ti–6Al–4V	Dendrites	88·0	...	Bal.	...	1·5
	Within grains	Bal.	2·0	...	6·1	4·3
	Eutectic regions	Bal.	10·0	...	4·4	3·4

in the Ti–6Al–4V alloy (Fig. 4*b*) compared with CP titanium or Ti–2·5Cu.

Examinations using EPMA, based on wavelength and energy dispersive spectrometry, were carried out on the dendritic crystals, the grain interiors, and the eutectic regions for CP titanium and Ti–6Al–4V alloy processed at 7 mm s^{-1} (Table 2). From these results, it can be seen that the dendrites are TiC, the silicon content of the eutectic region is higher than that in the grains, and the TiC in the Ti–6Al–4V alloy contains some vanadium.

The presence of TiC was also confirmed using X-ray diffraction examination of CP titanium processed at 7 mm s^{-1}: several strong peaks indexed as α-Ti, SiC, and TiC were observed (Fig. 5), which is consistent with the composition analysis.

By EPMA of the samples processed at 7 mm s^{-1}, a concentration gradient of silicon around the SiC particles was found which decreased with distance from the particles into the matrix (Table 3).

The extent of dissolution can be controlled by changing the traverse speed. For example, in Ti–6Al–4V injected at 20 mm s^{-1} less dissolution of SiC was produced and consequently there was less TiC formation (Fig. 6). The matrix was interpreted as a martensitic structure and possibly some retained β may be present. No lamellar structure was seen. The average silicon content in the matrix is less than 2 wt-% and the hardness of the melted region is reduced to 500 HV.

A possible solidification sequence of the melt zone of the CP titanium injected with SiC can be deduced by referring to the Ti–Si–C system. The ternary phase diagram has not been established experimentally, but the constituent binary systems provide a basis for a possible interpretation as is shown in Fig. 7.

The suggested solidification sequence involves the primary solidification of TiC dendrites. The silicon content of the matrix (5 wt-%), as anticipated, lies on a line in the

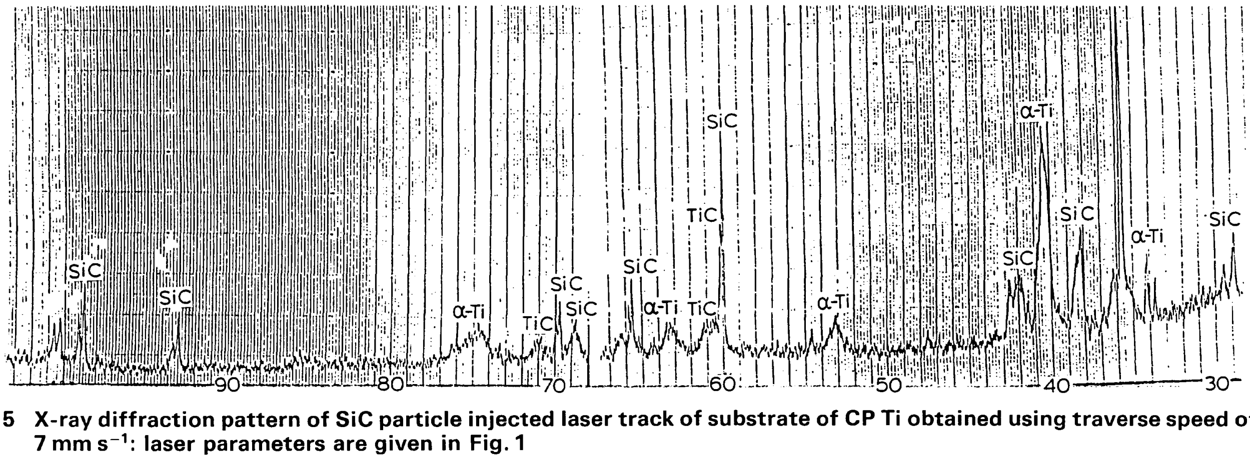
Table 3 Decrease of Si content with distance from SiC particles into matrix for CP Ti processed at 7 mm s^{-1}

Distance, μm	Si, wt-%
1	43·6
3	34·1
5	22·5
7	12·4
10	5·7

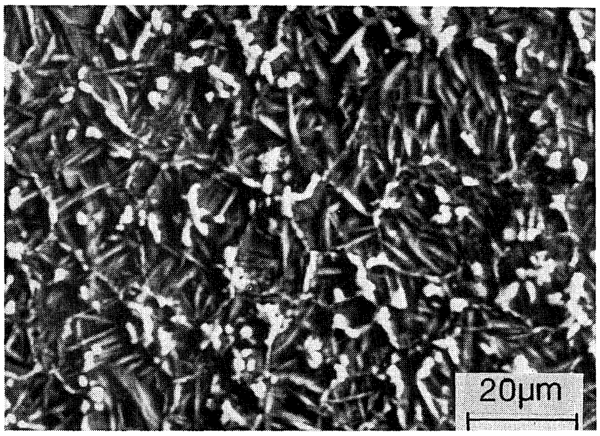
phase diagram joining titanium to SiC (Fig. 7). The proportion of TiC was ~ 20 vol.-%, which is consistent with the phase diagram. Primary solidification would be followed by a reaction involving L, β, and TiC. The regions that solidified as β (Fig. 7) may originate from a peritectic reaction $L+TiC \rightarrow \beta$ or a divorced eutectic $L \rightarrow \beta+TiC$. Subsequently, a eutectic would be formed, interpreted as $\beta+Ti_5Si_3+TiC$; the β and Ti_5Si_3 form in a lamellar morphology, while TiC appears as small dendrites. The β is transformed to α' on rapid cooling. Similar sequences would be expected from the Ti–6Al–4V and Ti–2·5Cu alloys, with differences in terms of volume fraction and composition of phases; for example, there is less TiC in Ti–6Al–4V than in the CP titanium and the volume fraction of the lamellar eutectic is greater in the Ti–6Al–4V alloy than in CP titanium.

Conclusions

1. It is observed that in all the processed samples there is partial dissolution of SiC and nucleation of TiC at the particle/matrix interface.



5 **X-ray diffraction pattern of SiC particle injected laser track of substrate of CP Ti obtained using traverse speed of 7 mm s^{-1}: laser parameters are given in Fig. 1**



6 Microstructure of Ti–6Al–4V, obtained using traverse speed of 20 mm s^{-1}, in which TiC (white areas), but not SiC, can be seen in martensitic matrix: laser parameters are given in Fig. 1 (SEM)

2. The distribution and the dissolution of the SiC can be controlled by traverse speed.
3. The matrix of the processed commercial purity titanium consists of TiC and fine transformed β (i.e. α') grains surrounded by a lamellar eutectic structure.
4. The hardness of SiC particles was > 2000 HV, and average hardness of the melt zone reached ~ 600 HV (500 g load).

Acknowledgments

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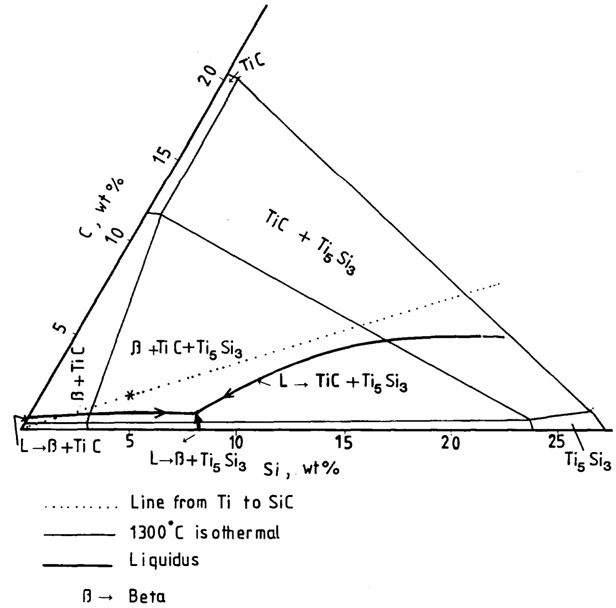

∗ approximate matrix composition in sample processed at 7 mm s^{-1}

7 Ti rich part of Ti–Si–C system: speculative form (semischematic) of liquidus and 1300°C isothermal section

References

1. J. D. AYERS and R. N. BOLISTER: *Wear*, 1980, **93**, 193.
2. J. D. AYERS, R. T. SCHAEFER, and W. P. ROBEY: 'Rapid solidification processing principles and technologies II', (ed. R. Mehrabian *et al.*), 212; 1980, Baton Rouge, LA, Claitors Publishing Division.
3. J. D. AYERS, R. T. SCHAEFER, and W. P. ROBEY: *J. Met.*, Aug. 1981, **33**, 19.
4. J. D. AYERS: 'Lasers in metallurgy', (ed. K. Mukherjee and J. Mazumber), 279; 1981, Warrendale, PA, The Metallurgical Society of AIME.
5. J. D. AYERS, T. R. TUCKER, and R. C. BOWERS: *Scr. Metall.*, 1980, **14**, 549.
6. S. KATAYAMA, A. MATSUNAWA, A. MORIMOTO, S. ISHIMOTO, and Y. ARATA: in Proc. 3rd. Int. Conf. on 'Welding and melting by electron and laser beam', Lyons, Sept. 1983, Commissariat à l'Energie Atomique.
7. S. KATAYAMA, A. MATSUNAWA, A. MARIMOTO, S. ISHIMOTO, and Y. ARATA: in 'ICALEO 83', Los Angeles, Nov. 1983.
8. H. W. BERGMANN, T. BELL, and S. LEE: *Z. Werkstofftech.*, 1985, **16**, 392.
9. A. WALKER, J. FOLKES, W. M. STEEN, and D. R. F. WEST: *Surf. Eng.*, 1985, **1**, (1), 23.
10. W. M. STEEN: 'Laser cladding, alloying, and melting', (ed. D. Belforte and M. Leritt); 1981, Tulsa, OK, Penwell Publishing Company.