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Thermal barrier coatings produced by laser cladding

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A 2 kW CO_2 laser has been used to clad a mild steel substrate with two different ceramic coatings, namely yttria partially stabilized zirconia (8 wt% YPSZ) or a mixture of YPSZ and pure alumina powder. A range of laser processing parameters has been investigated. Results have been obtained showing the possibility of using the laser beam for producing a clad layer of thermal barrier coating with different topography depending on the processing conditions.

1. Introduction

In the last few years yttria partially stabilized zirconias (YPSZs) have been widely used as thermal barrier coatings in gas turbine engines [1, 2]. Such coatings are usually applied by a cladding process which involves bonding the oxide mixtures to the superalloy substrate by plasma spraying techniques [3]. Problems can, however, arise during service due to penetration and diffusion of corrosive contaminants in the fuel through pores and cracks in the ceramic, which affects the life of the coating. In the light of this problem, new coating techniques are being investigated by the authors using a high power continuous wave CO_2 laser [4–6].

Investigations on improving thermal barrier coatings by employing laser processing follow two distinct approaches. The first approach is to use a laser to modify a plasma sprayed layer (known as laser sealing) and the second is to deposit the complete coating by means of laser processing (laser cladding). Concerning the former approach, a CO_2 laser has been used to melt a thin ceramic layer of as-sprayed 8 wt % yttria YPSZ and thereby to seal the porosity which was formed by plasma spraying [7]. Fine microstructures, resulting from the rapid cooling, together with smooth and shiny layers were obtained for a wide range of laser parameters. Microhardness measurements have shown laser processing to lead to significant increases in hardness from ≈800 Hv for plasma sprayed material to 1400 Hv for laser sealed layers [4]. In a feasibility study by the authors [6] on laser cladding of an 8 wt % YPSZ it has been shown that layers of up to 2 mm thick can be deposited. In particular, clad layers in the range of about 0.1 to 1.5 mm could be produced with good bonding to the substrate with a relatively wide range of laser parameters, namely, power (P) 1.4 to 2.2 kW, beam diameter (D) 3 to 6 mm, traverse speed (V) 4 to 15 mm sec^{-1}, powder feed rate (F) 5 to 7 g min^{-1} [6].

2. Experimental procedure

This present investigation reports observations of some typical features of the clad layers of 8 wt % YPSZ and of the same YPSZ with the addition of 5 wt % Al_2O_3. YPSZ powder particles of an average size 55 μm and Al_2O_3 particles of an average size 60 μm, were continuously fed into a molten pool generated by a 2 kW continuous wave CO_2 laser. The feed rate used was 5.18 g min^{-1} and the laser power was in the range of 1 to 2 kW. Single tracks were produced on a mild steel substrate scanned relative to the 5 mm diameter laser beam. The energy/unit volume, i.e. power/($\pi \times$ beam radius^2 $\times$ traverse speed), i.e., $P/\pi r^2 V$, was varied by changing the traverse speed of the substrate over the range 1.5 to 17.5 mm sec^{-1}. Argon gas was blown from the nozzle to cool the lens and to protect the clad layer from the atmosphere. For comparison, a few tracks were produced without argon gas.

The upper surfaces of the clads were examined by microscopy (light and scanning) for the presence of porosity, cracks and rippling effects. Transverse sections were used to make measurements of track dimensions, microstructure and compositional analysis. The phases present in the starting powder and the clad layers were identified using X-ray diffraction with Cu$K\alpha$ radiation. A step scanning mode was employed for more detailed investigation of the phases with a 0.01 2θ step over the 2θ ranges of 27.5 to 32° for the monoclinic (m) $(1\,1\,\bar{1})$ and (1 1 1) peaks, and the cubic (c), tetragonal (t), non-transformable tetragonal (t′) (1 1 1) peaks. For the c,t,t′ (4 0 0) peaks and the t,t′ (0 0 4) peaks a 2θ range between 72 to 75.5° was used. The X-ray examination was carried out on the upper surface without grinding and polishing in order to prevent mechanically induced phase transformation.

3. Results and discussion

Fig. 1 shows the height of the clad layer as a function of energy per unit volume; clad heights up to 1.3 mm were produced illustrating that laser processing is capable of coating to values similar or higher to that of thermal barrier layers (≈0.4 mm) produced by plasma spraying. All of these tracks were produced with good

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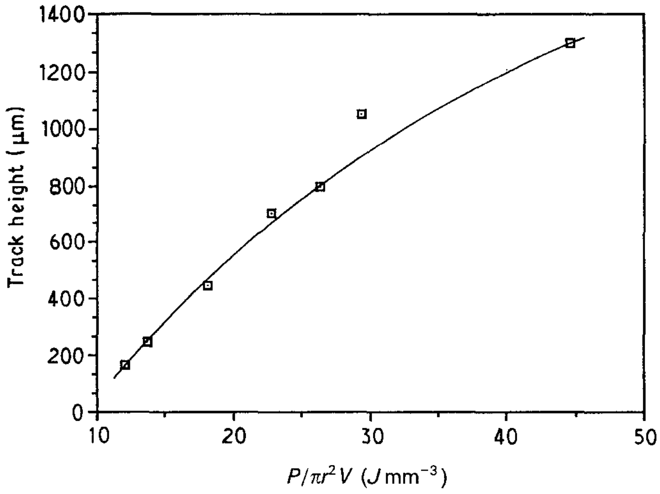


Figure 1 Clad thickness as a function of energy per unit volume for 8 wt % YPSZ clad on mild steel substrate; power, 1.4 kW; feed rate, 5.18 g min^{-1} and beam diameter, 5 mm.

bonding to the substrate, without an intermediate layer which is typically used with plasma sprayed layers to improve the bonding between the substrate and ceramic.

Figs 2 and 3 show the upper surface of clad layers of 8 wt % YPSZ produced using the same processing conditions except that no argon shrouding gas was used for the sample shown in Fig. 3. Features of note in these samples are relatively coarsely spaced surface ripples, and a striated structure oriented approximately perpendicular to the coarse ripples. In the argon shrouded sample illustrated in Fig. 2 the ripples are spaced at 50 to 150 μm intervals and lie nearly perpendicular to the traverse direction. Laser surface melted metallic alloys, typically show ripples with a herringbone pattern on which detailed studies have been reported [8, 9]. The rippling phenomena derive essentially from the temperature dependence of surface tension in the liquid, and temperature gradients, giving rise to surface tension driven flow (Marangoni effect).

Compared with typical metallic materials, YPSZ has a lower thermal conductivity, whose value is effectively invariant with temperature; thus the temperature gradients and surface tension effects will differ from those in typical metallic melt pools leading to differences in ripple formation. The pattern shown in Fig. 2 indicates progressive solidification along the laser track with periodic ripple formation. A similar effect, although with considerable fluctuations in the contours is seen in the laser sealed material [10].

In the clad material produced without argon shrouding (Fig. 3) in general the ripples showed a greater curvature and are concentrically spaced at intervals of 100 to 300 μm. The surface becomes black as compared with the bright surface of the argon shrouded surface; this is interpreted as due to composition changes, reaction with oxygen in the melt pool producing an oxygen-rich non-stoichiometric layer which is black in colour. The solidification pattern appears to have involved growth from a number of nucleation centres to form approximately equiaxed grains. In the material produced with argon shrouding (Fig. 2), the widely spaced features normal to the ripples may correspond to boundaries between grains, growing approximately parallel to the traverse direction. Shallow cracks were detected in the argon shrouded material, while more cracking was observed in the absence of argon.

Figs 2 and 3 show fine striations oriented approximately normal to the ripples, whose nature has not been elucidated. The solidification mechanism is expected to be of the cellular–dendritic type to form the cubic phase and solidification shrinkage could lead to the surface features observed. The observed striations are indicative of such a solidification pattern. During cooling, in the solid state, however, athermal transformation from the cubic to non-transformable

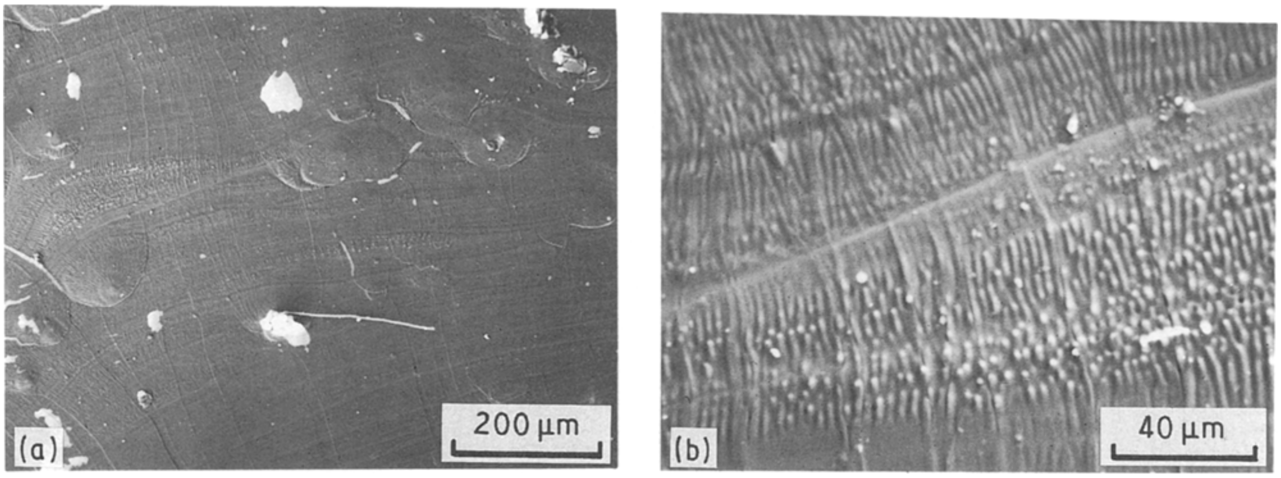


Figure 2 Topography of upper surface of YPSZ clad under argon shrouding gas showing rippling and fine striations (a) low magnification and (b) higher magnification, power, 1.7 kW; traverse speed 1.5 mm sec^{-1} and beam diameter, 5 mm.

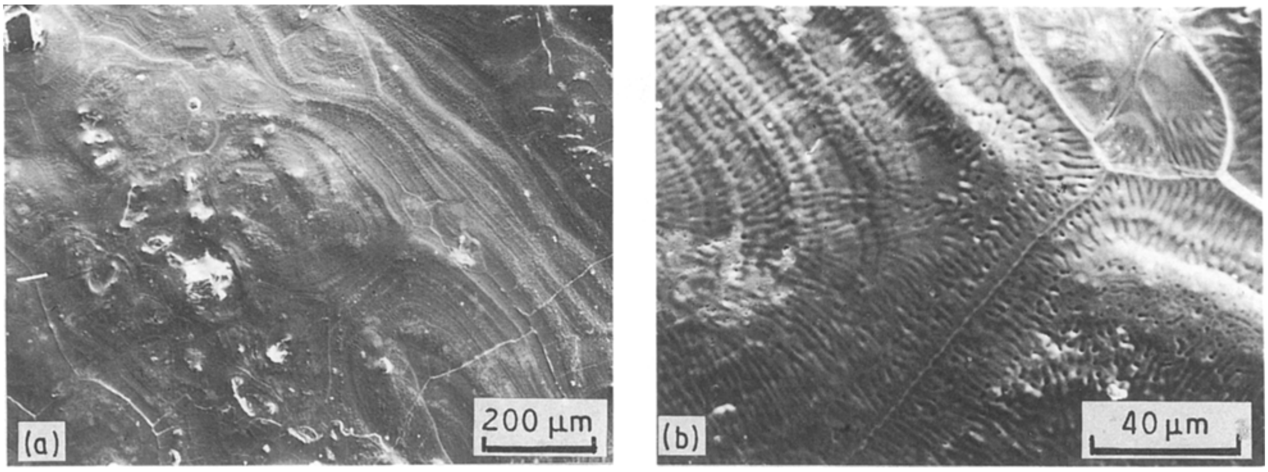


Figure 3 Topography of upper surface of YPSZ clad without argon shrouding showing rippling and fine striations (a) low magnification and (b) higher magnification, conditions same as Fig. 2.

tetragonal (t′) phase could also give rise to surface relief effects.

X-ray diffraction examination of the laser clad materials showed the structure to be virtually all t′ phase (Fig. 4). The presence of t′ is attributed to the rapid cooling in the solid state associated with laser processing (Table I and Fig. 4). Using the method of Miller *et al.* [11] the data indicate that $\approx 2\%$ of cubic phase may be present. The r phase has previously been reported to be formed under specific conditions [12, 13] at low yttria content (less than 4.5 mol %); it was also observed in small amounts in the present study. Thus, when the cooling rate is very high as in laser cladding, the r phase can be formed at higher yttria contents than previously reported [12]. The X-ray data for the powder (Table I and Fig. 4) indicate that the structure consists of t, m and a small amount of c phase.

Features of a surface view of a clad layer of 8 wt % YPSZ containing 5 wt % Al_2O_3 are shown in Fig. 5. The equiaxed type grains are interpreted as having formed by solidification from central "cores" considered to be of zirconia based solid solution in accordance with the high concentration of ZrO_2 shown by EPMA (Table II). The two phase lamellar structure growing from these cores is thought to be a eutectic of $ZrO_2 + Al_2O_3$. This interpretation is supported by the back scattered electron image and EPMA (Table II), which indicate a high concentration of alumina in these regions.

Examination of transverse sections of 8 wt % YPSZ showed only a very small penetration of the clad layer into the substrate (Fig. 6). Electron probe microanalysis showed a small amount of dilution of the clad layer by iron from the substrate; the iron content of the clad was less than 5 wt % for a distance of up to $\approx 20\,\mu m$ from the interface. Observations of surfaces produced by fracturing clad layers showed the solidification growth pattern to be essentially columnar (Fig. 7). Three zones were, however, observed. The zone adjacent to the substrate showed relatively narrow columnar crystals extending for a distance of

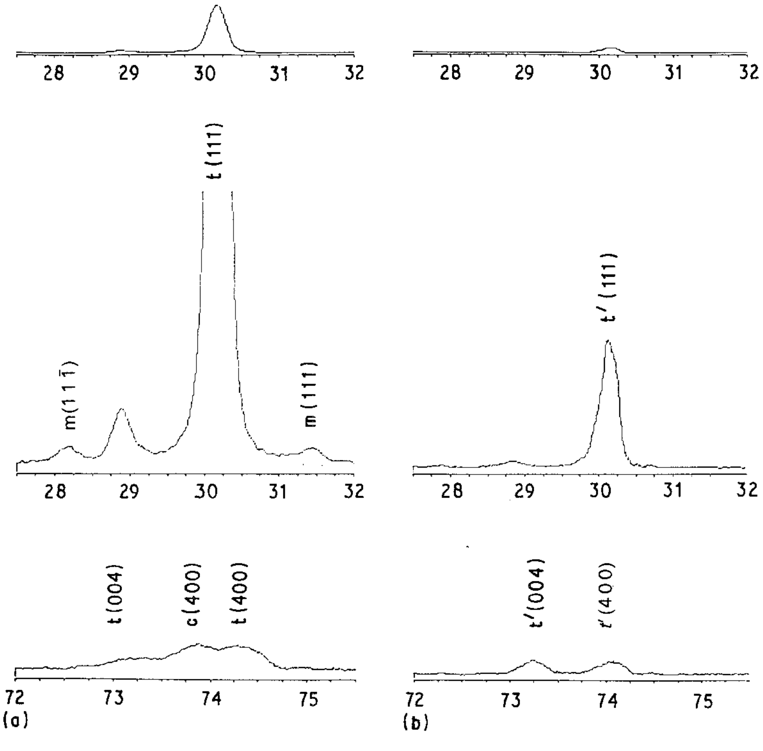


Figure 4 X-ray step scanning showing the presence of t′ and the absence of m phase after laser cladding (a) starting powder and (b) typical laser clad material.

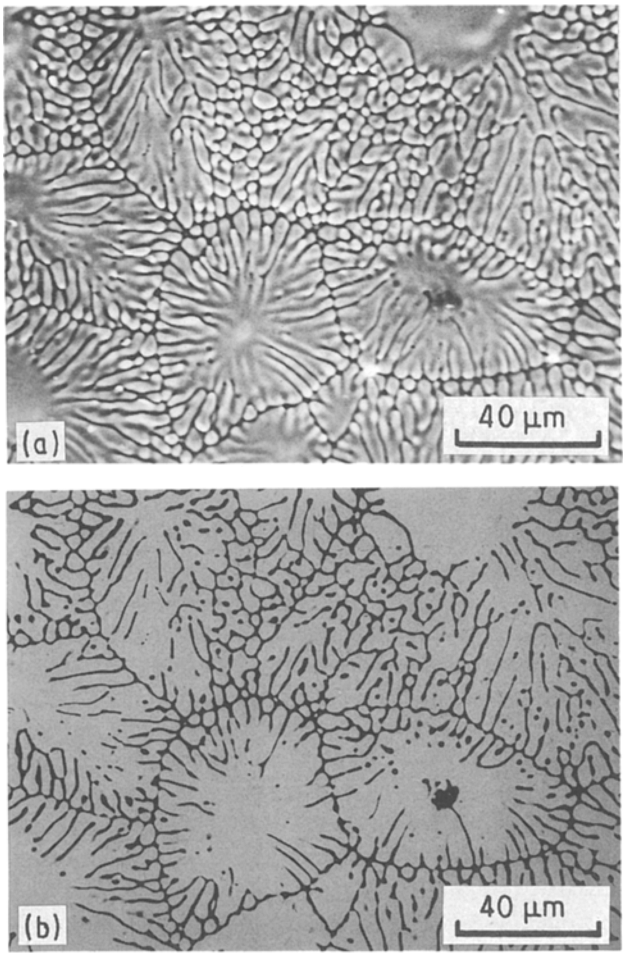


Figure 5 Scanning electron micrographs showing the effect of 5 wt % alumina on the morphology of YPSZ clad layer, (a) SE image and (b) BSE image.

TABLE I Interplanar spacings obtained by X-ray diffraction from the YPSZ starting powder and laser clad material

d (nm)*	Phase	Plane	*d* (nm)†	Phase	Plane
0.317 28	m	$\bar{1}11$	–	–	–
–	–	–	0.2969	t′	111
0.2959	t	111	–	–	–
0.284	m	111	–	–	–
0.256	t, c	110, 200	0.2557	c	200
–	–	–	0.1895	r	116
0.189 74	Yttria	110	–	–	–
0.180 57	m, c	$\bar{1}22$, 220	0.1814	r, c	–, 220
–	–	–	0.1611	t′	–
–	–	–	0.1554	t′	113
0.153 94	m, c	$\bar{3}02$, 311	0.154	t′	131
0.147 95	c	222	0.148	c	222
0.129 60	t	004	–	–	–
–	–	–	0.129	t′, r	004, $00\underline{12}$
0.1287	c	400	0.128 55	c	400
–	–	–	0.128 10	t′	400
0.127 66	t	400	–	–	–
–	–	–	0.1179	t′, c	–, 331
–	–	–	0.1175	t′	–

*Starting powder.
†Clad layer.

TABLE II EPMA of YSZAl clad layer (wt %)

Region	Zr	Y	Al
Average area analysis	63.5	5.7	2.5
Point analysis, grain centre	62	5.3	0.5
Point analysis, Al_2O_3 rich phase in lamellar structure	49	6.3	14.6

≈ 100 μm. The main part of the layer consisted of broader crystals whereas the upper zone was of fine crystals of ≈ 100 μm in extent. These features suggested that some solidification occurs from the upper surface downwards so producing the fine structure at the upper surface.

Microhardness measurements of polished transverse and longitudinal sections showed that the hardness was typically 1500 Hv (Fig. 8a) compared with less than 800 Hv for plasma sprayed material (Fig. 8b). The enhanced hardness of the laser clad materials may be accounted for by the absence of porosity, the relatively fine grain structure, the fine substructure of the t′ phase and the absence of the softer m phase. Of these the absence of porosity is considered to be the most important as the porous plasma sprayed layers are softer than commercially produced monolithic YPSZ.

4. Conclusions

The conclusions are as follows.

(1) The phases present in a laser clad layer of 8 wt % yttria partially stabilized zirconia (YPSZ) were mainly non-transformable t′ with small amounts of c and r phases.

(2) Surface features of note in the pale-coloured YPSZ layers produced under an argon shroud were

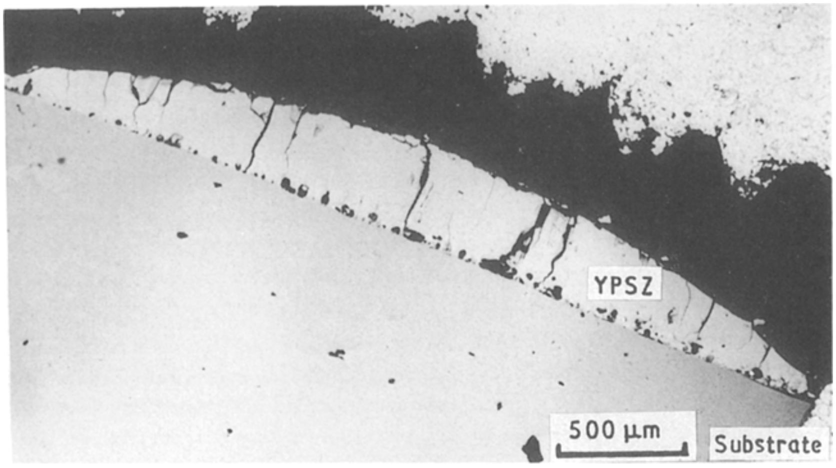
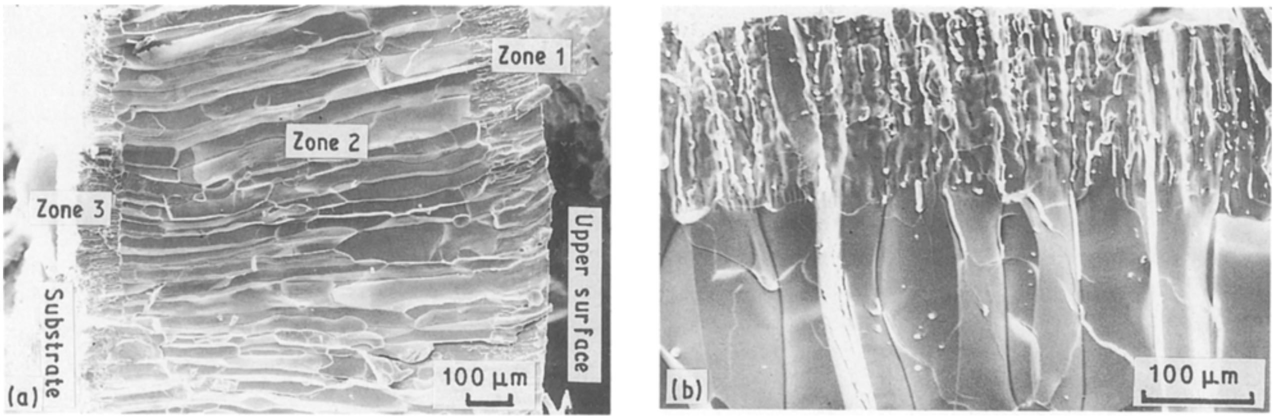


Figure 6 Transverse section of YPSZ showing the bonding with substrate.



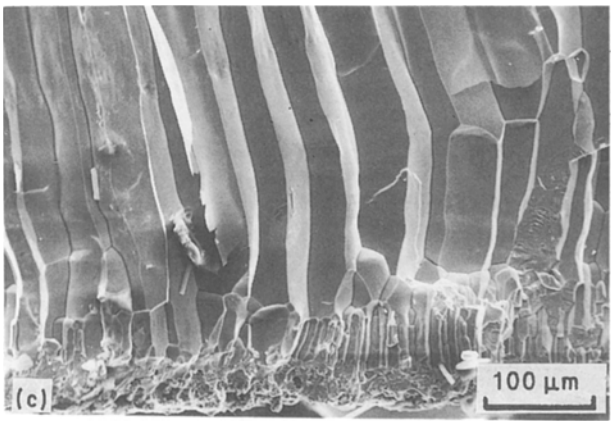


Figure 7 Fracture surface of YPSZ after bending test showing three different columnar zones, (a) general appearance, (b) zones 1 and 2 and (c) zones 2 and 3.

relatively coarsely spaced ripples and a finer striated structure oriented approximately perpendicular to the ripples. Without shrouding the clad layers were black; the coarse ripples showed a greater curvature and cracking was more extensive.

(3) The cladding process involved complete melting of the YPSZ powder in the laser generated melt pool followed by rapid solidification.

(4) Three zones of grains were observed in the cross-section of the layers but the grain structure was essentially columnar in each zone.

(5) The hardness of the YPSZ layer was approximately 1500 Hv compared with only 800 Hv for the plasma sprayed coating.

(6) The microstructure of the YPSZ + alumina layer consisted of primary grains of zirconia solid solution and a eutectic.

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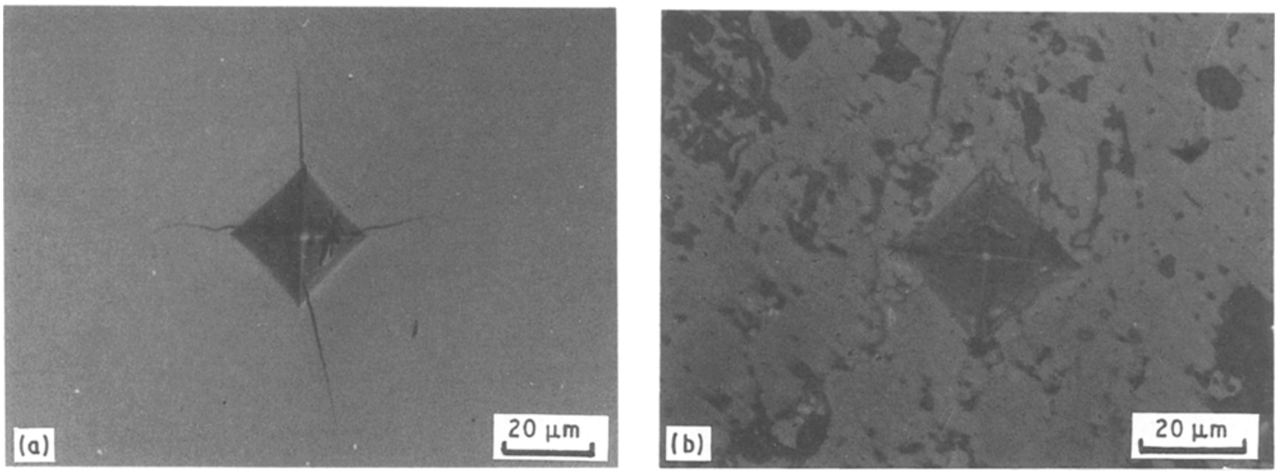

Figure 8 Optical micrographs showing hardness indentations in YPSZ; 500 g load, (a) laser clad and (b) plasma sprayed.

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