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The processing of a magnesium–alumino-silicate matrix, SiC fibre glass-ceramic matrix composite using a pulsed Nd–YAG laser

Part II *The effect of process variables*

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The first part of this work outlined the findings of trials investigating the Nd-YAG pulsed laser processing of a magnesium alumino-silicate matrix, SiC fibre glass-ceramic matrix composite. The tests studied the influence of the laser pulse parameters, principally upon the material removal rate. In Part II, associated trials are reported, in which the laser process variable's influence upon the *quality* of the processed surface is the most significant criterion for assessment. The effect of different types and pressures of assist gas and point of focus have been examined by electron microscopy, and the maximum speed of cut for various thicknesses of the composite material has been identified. As with the work on the pulse parameters, the findings have been compared with those obtained in previous work on a borosilicate glass matrix, SiC fibre composite.

1. Introduction

In Part I of this work [1] the results of varying the laser parameters used to process a magnesium alumino-silicate (MAS) matrix, SiC fibre glass-ceramic matrix composite (GCMC) were reported. The analysis concentrated on the material removal rates and the microscopical examination was concerned primarily with the geometry of the holes and kerfs produced by the different conditions. The study continues with an investigation into the effects of various process parameters, with a greater significance being placed on the quality of the cut surface in terms of induced damage (microcracking, phase modification due to excessive heat input) and levels of redeposited material. The intention is that by systematic and comprehensive testing of the process variables and comparison with the results of similar work on related CMCs, an insight may be gained into the effective laser processing of these and other composite materials.

2. Experimental procedure

2.1. Material under examination

These tests continue the work on the material as specified fully in Part I [1] of this work. The GCMC consists of proprietary Nicalon™ 201 SiC fibres, filament-wound into unidirectional sheets. Twelve such sheets, when laid-up in alternate 0°–90° layers and hot pressed form a plaque 3.5–5.0 mm thick, and thicker or thinner plates may be fabricated by adjusting the number of plies accordingly. The matrix is carefully compositionally tailored within the $MgO–Si_2O–Al_2O_3$ system, the details of which are given in the relevant section of Part I, with the relevant ternary phase diagram. As with the borosilicate glass matrix composite with which this is being compared [2, 3], the fibre content of the plaques has been measured at 30–35 vol %, but with local variations estimated to lie within the range 20–65 vol %. This high degree of inhomogeneity may be assumed to be responsible for some of the scatter in the processing test data, but should be accepted as a characteristic of these materials.

2.2. Facilities and general laser configuration

Full details of the facilities used for these tests were given in Part I [1] of this paper. As a summary, the laser used was a Lumonics JK701 Nd-YAG instrument, used with the LD2 (Low Divergence) Resonator. A custom-built nozzle assembly allowed rapid adjustment when necessary, and the supply of assist gas to the process zone up to a maximum pressure of approximately 8 bar. A Unidex 400 CNC controller connected to a three-axis workstation permitted 600 mm × 600 mm × 300 mm of accurate and programmable travel of the workpiece for duplicating test geometries on different specimens.

2.3. Test methodology

One of the principal aims of this work was to produce comparative data on the processing of related composite materials. In this way it is hoped that in addition to determining the effect of adjusting the various lasing parameters when processing a specific composite, information may be gathered on the influence of the material chemistry and microstructure on the process. Having investigated the influence of certain pulse parameters in Part I [1], this next stage addresses how various processing conditions influence the quality of the laser machined surface.

For trials of assist-gas type and pressure, a through-cut or kerf was machined to provide a surface for microscopical examination. The effect upon hole geometry of the height of the point of focus with respect to the surface of the material was examined by drilling a number of through-holes, which were subsequently sectioned and measured for entry and exit diameters.

To determine the highest speed where complete penetration of each plaque was achieved whilst minimizing the wastage of test material, a technique of accelerating the cut speed was used to identify approximate limits. This is possible using the CNC controlled table; an initial speed may be entered in the controlling programme, from which the speed of traverse is accelerated. It is then simply a matter of measuring the extent of the cut, and from that calculating the actual speed at the point at which full penetration fails. It should be noted, however, that this method may introduce an error associated with the effects of heat flow in the material. There is evidence that a build up of heat in the process zone effectively assists the cutting process in steady-state conditions; this test technique does not permit such a steady state to be established, and it is therefore possible that an erroneous maximum speed may be indicated. For this reason, many of the results (particularly on the thinnest material) were verified by performing a constant speed cut.

For each of these tests, laser pulse parameters were selected to relate to the previous tests, so that legitimate comparison could be made between material removal rates and resulting surface quality and damage induced.

3. Laser processing results

3.1. Type and pressure of assist gas

In the case of the trials on the borosilicate glass matrix material [2], the choice of assist gas was found to have a great influence on the quality of the laser-cut surface. The pressure at which it was supplied was less important, as long as it was still capable of ejecting the vaporized material and preventing the debris from spattering the lens cover-glass. This introduces an effective lower limit of approximately 2 bar supply. The tests were repeated for the MAS matrix material, the choice of gases being nitrogen, argon, oxygen and air.

As the material removal rate was not the main point of interest with this series of trials, but rather the quality of the processed surface, kerfs were cut rather than holes drilled. This provided a suitable surface for microscopical examination, and minimized the extent of redeposited material resulting from the inability of the assist gas to flush a blind cavity adequately.

The results of these tests are discussed in the next section, as part of the microscopical survey.

3.2. Variation of focal point

The laser beam is generally focused on the surface of the material. There is, however, some interest in investigating the effect of focusing the pulse above and below the surface, not least the influence this has upon the hole geometry. The results of the corresponding tests on the GMC material were interesting in that while the holes produced were parallel or slightly divergent (exit hole diameter greater than entry) for the range of focus point $+1$ mm to -1 mm with respect to the surface, outside this range the holes became increasingly convergent. This would have to be attributable to internal reflections of the beam through the depth of the hole, but does have implications for hole shaping.

Fig. 1 shows the results obtained from these trials on a 2 mm thick plaque of the MAS matrix material. The pulse parameters were 7.0 J pulse energy, 2.0 ms pulse width and 38.1 Hz pulse repetition rate. This gives a peak power of 3.5 kW. A 5 bar nitrogen gas assist was used.

While the graph shows a trend of convergent–divergent–convergent profile as the focal point is raised from -5 mm to $+5$ mm, there is a much greater correlation between the entry and exit diameters than had been obtained with the GMC material. This suggests that with this thickness of material, a more consistent hole may be drilled in this material. There is also evidence that the effective limits within which the hole produced is parallel or divergent, extends from -1 mm to $+3$ mm, whereas this was ± 1 mm for the glass matrix composite.

3.3. Maximum cut speed

Trials to investigate the maximum speed at which this composite could be laser cut at different levels of peak power and for various material thicknesses have been performed. The results are presented in Fig. 2.

The corresponding trials on the GMC material benefitted from the procurement of a number of plaques, the thicknesses of which varied slightly even for the same number of constituent fibre plies. This permitted the analysis to comment on the influence of fibre volume content, as for some of the plaques, despite a range of through-cut thickness, the volume of SiC fibre cut was nominally the same. This has not been possible with the MAS matrix composite, as the investigation has been performed on a single plaque of each number of plies.

With reference to Fig. 2, it is once again found that the maximum cut speed is inversely related to the material thickness, and (although only three data points are plotted) approximately hyperbolic in trend. It may be reasonable to speculate that this is evidence for a thermal conductivity influence in the cutting process. It has already been shown that in these materials, the removal of the matrix phase is largely by the conduction of heat from the fibres to the matrix. In the

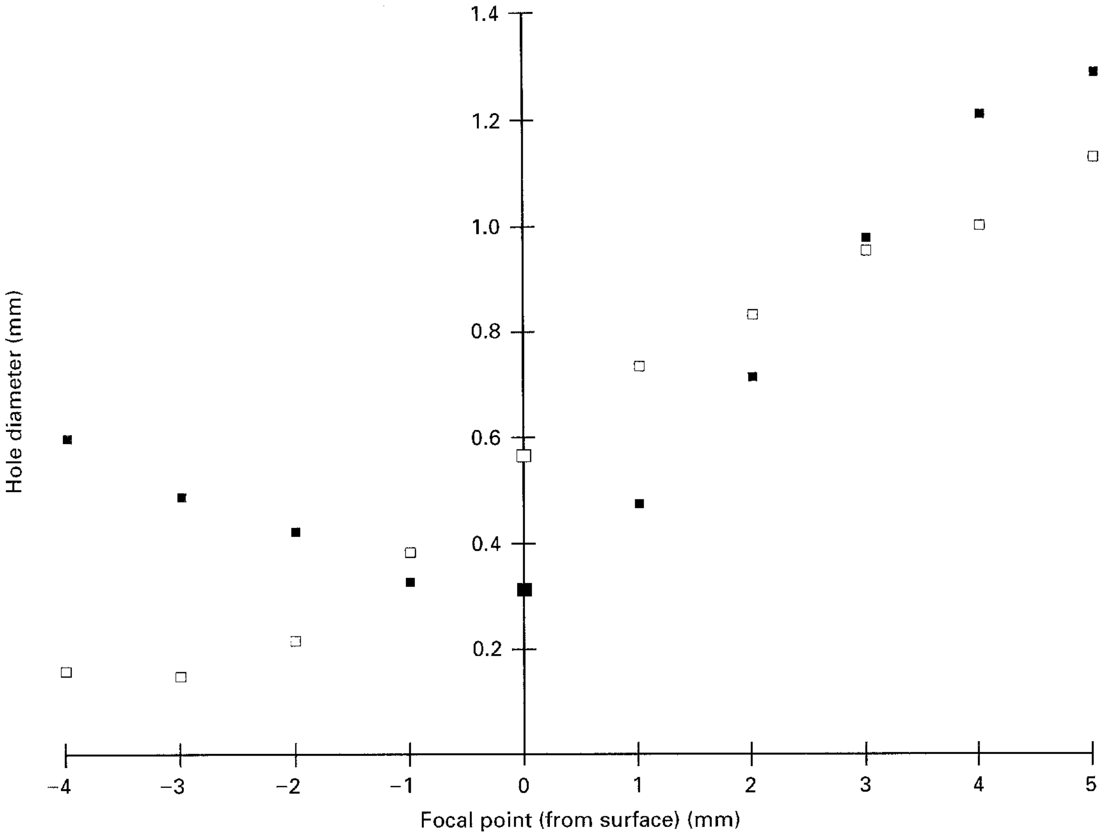

Figure 1 Focal point trials, 2 mm thick plaque, 5 bar gas assist. (■) Entry hole diameter, (□) exit hole diameter.

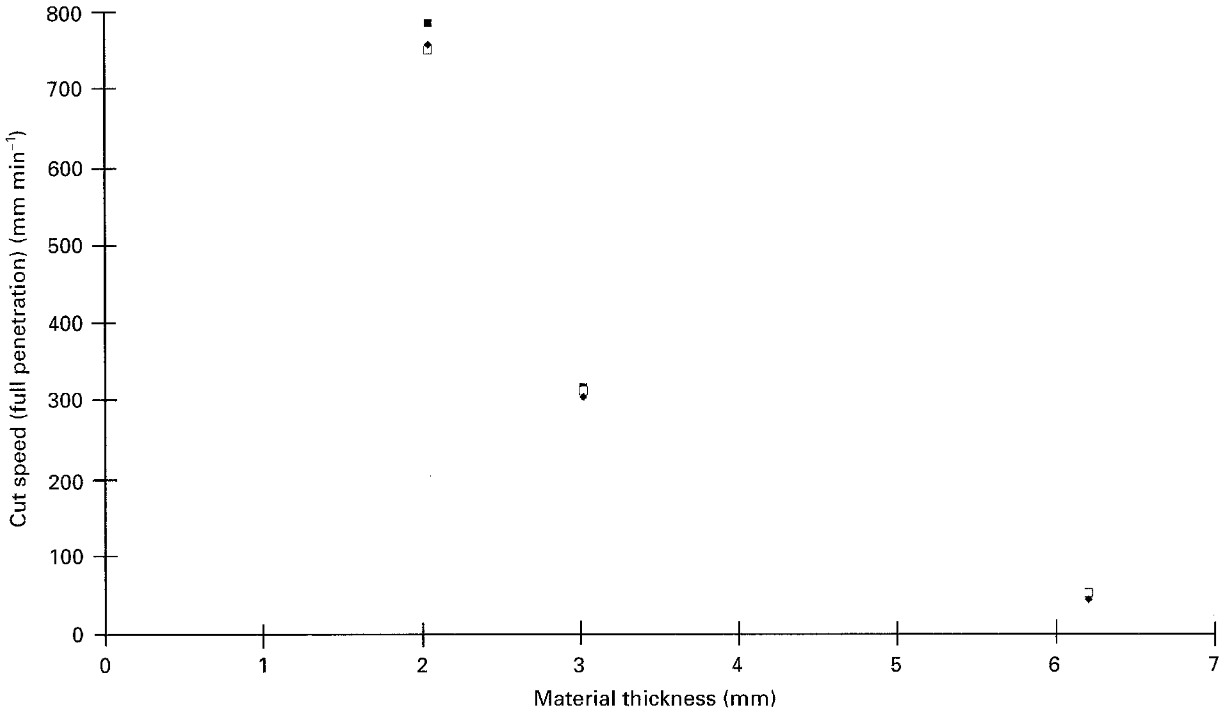

Figure 2 Cut speed versus thickness at various peak powers, 5 bar N_2 gas assist. Maximum cut speeds at (■) 5.0 kW, (□) 3.5 kW, (◆) 2.5 kW.

case of the GMC material this is especially so, as the borosilicate glass is almost completely transparent to the 1.06 μm wavelength of the YAG laser. Whilst there is other evidence from these tests to suggest that the MAS matrix couples to some extent with this laser wavelength, the conductive effect is certain still to be a significant factor. In a continuous process such as kerfing, the heat flow from the immediate process zone is therefore of great interest, but very difficult to model due to the inhomogeneity and anisotropy of the material. It would not be unreasonable to assume, however, that in processing relatively thin sheets of the composite, this effect is more marked than in thicker sections where there is greater potential for conduction away from the cutting zone. As such an effect is almost certain to aid the cutting penetration (although not necessarily the cut quality), this would explain the increasingly rapid cutting speeds with the thinner material.

There is a 5%–10% increase in the cut speed achievable over the results obtained for the GMC material. As found with the previous tests, the thinnest plaque could be cut, even at the lowest peak power, at speeds which produced a perforated line, i.e. repetition-rate limited.

4. SEM examination and discussion

4.1. Type and pressure of assist gas

Four gases (nitrogen, argon, oxygen and air), each supplied at 5 bar were investigated. In addition, three different cut speeds (60, 80 and 100 mm min^{-1}) were performed with each combination, but as found with the GMC material, the choice of assist gas had very little effect on the maximum speed of cut achievable. There is a marginal improvement (5%–10%) in the maximum cut speed with the high pressure of assist gas, with no perceptible difference in the cut surface quality As suspected, the major influence of the choice of assist gas was found to be on the surface quality of the kerf.

Fig. 3 shows the surface of the cut produced at 80 mm min^{-1} with 5 bar nitrogen gas assist. As may be seen, there is evidence of oxidation, with silicate material unevenly deposited over the entire cut surface. These deposits are not heavy, however, and there is no significant difference in the degree of deposition between the top and bottom of the kerf. The morphology of the redeposited material is primarily ~ 10 μm "droplets" of silicate glass, but close examination reveals that there is also a more uniform coating of submicrometre material over this.

The results are very similar when the assist gas is changed to argon, as depicted in Fig. 4. Once again there is a broken surface of the 10–15 μm globules, with a condensation of finer particles over the entire

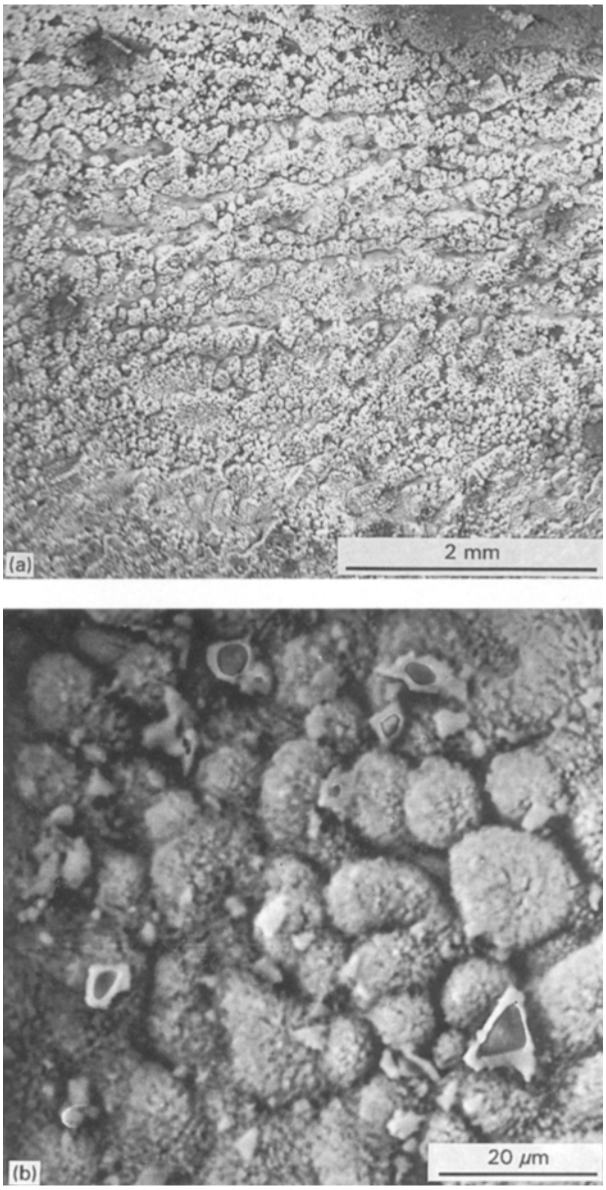

Figure 3 (a, b) The cut surface produced at 80 mm min^{-1}, 5 bar N_2 gas assist.

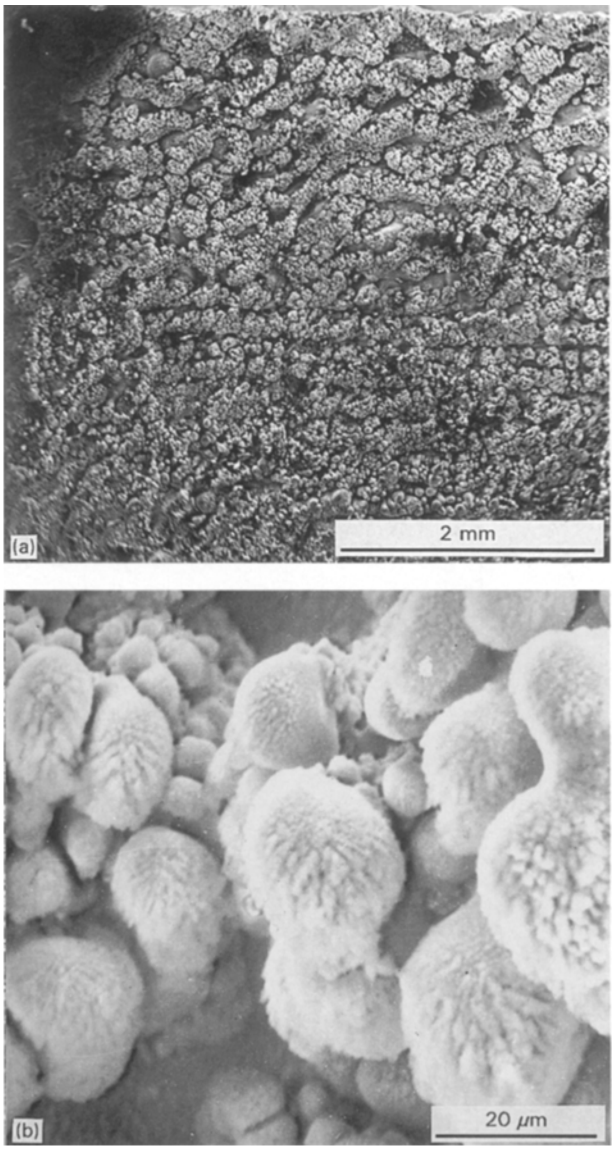

Figure 4 (a, b) The cut surface produced at 80 mm min^{-1}, 5 bar Ar gas assist.

surface. In all the specimens prepared for examination, the deposited material was found to be well adhered to the bulk material.

The cut produced using air does exhibit a variation in the scale and morphology of the deposited material between the top and bottom of the plaque, Fig. 5. The top surface, to a depth of approximately 3 mm, has a thicker layer of the glass material, which in places shows evidence of craze cracking. In some places, but increasingly towards the lower edge of this region, the deposited material is more globular, but in these instances the droplets are larger, up to about 150 μm diameter. Over this there is, once again, a deposition of the smaller droplets. However, the bottom section of the kerf reverts to the appearance noted in the cases using nitrogen and argon.

Finally, the results obtained from using oxygen are shown in Fig. 6. In this case there is a heavy deposition of glass material over the entire process surface. There are small regions that exhibit the globular morphology, but overall, oxidative damage is severe. It was noted when preparing the specimen for examination that although a through-cut had been achieved even at 100 mm min^{-1}, the redeposited material had partially re-sealed the cut. Whilst the cut edge was quite easily broken open, this did tear out some de-bonded fibres from the lower edge of the plaque.

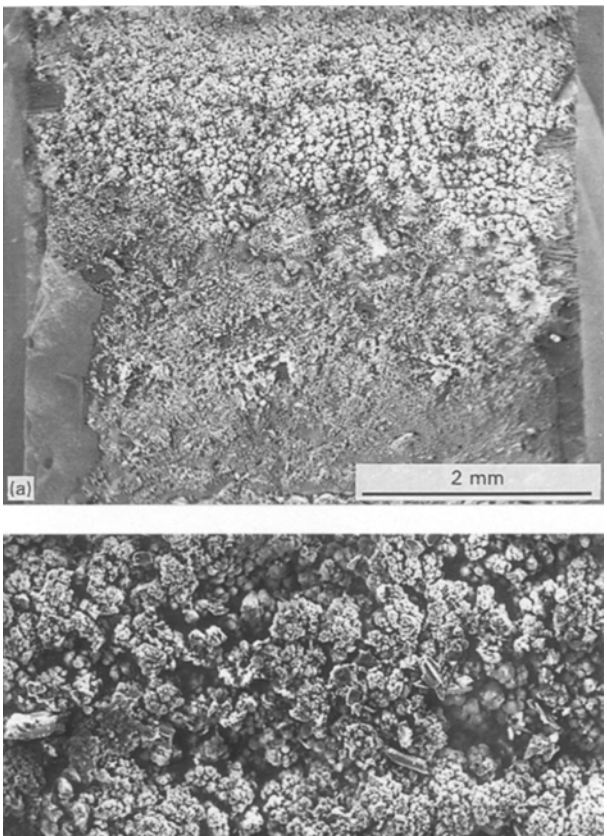

Figure 5 (a, b) The cut surface produced at 80 mm min^{-1}, 5 bar air gas assist.

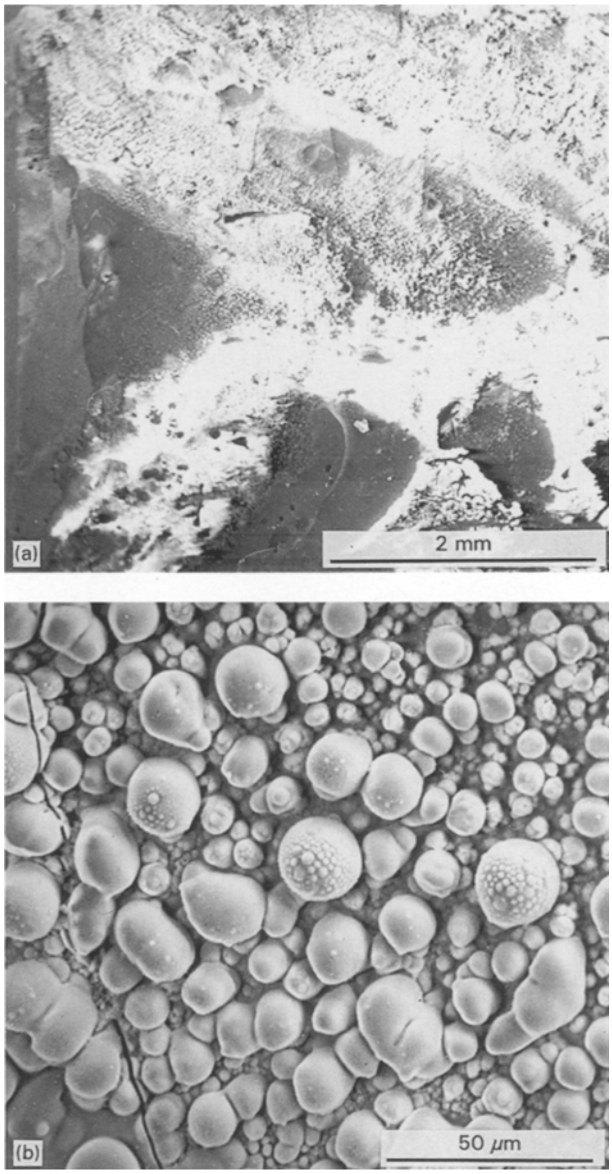

Figure 6 (a, b) The cut surface produced at 80 mm min^{-1}, 5 bar O_2 gas assist.

5. Conclusion

The geometry of holes drilled in the MAS material is very similar to that found in the GMC trials; however, the extent of redeposited material on the surface of the hole is significantly less. This is generally found to be the case when the process parameter cut trials are studied; the surface quality is better due to less oxidized material being redeposited on the kerf surface. When various assist gases are compared, it is found that oxygen should be avoided, as it reacts with the vaporized material and is deposited as a silicate glass on the surface. Nitrogen and argon give improved results, but air may be found to be an acceptable alternative considering its comparatively low cost.

Focusing the beam at different heights with respect to the material surface produces a hole-shaping effect, the profile of the penetration being divergent between the points -1 mm and $+3$ mm and convergent outside these limits.

The maximum cut speed has been ascertained for various thicknesses of material, although for the thinnest plaques tested (2 mm), the maximum speed is limited not by the laser power, but by the pulse repetition rate consistent with a continuous rather than perforated cut.

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