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# Surface characterization of SiC whisker/2124 aluminium and $Al_2O_3$ composites machined by abrasive water jet

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The machinability of two classes of high-temperature composites (SiC whisker/2124 aluminium and SiC whisker/$Al_2O_3$) with an abrasive waterjet (AWJ) was investigated. The as-machined surfaces of the composites were characterized by scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS), and profilometry to determine the surface finish. Microhardness measurements were also performed on the as-machined metal matrix composites. AWJ appears to be a quite promising machining method due to its fast speed and economical operation. It gives relatively smooth surfaces coupled with minimum subsurface microstructural damage.

## 1. Introduction

It is known that a large percentage of the cost of a finished component for high-performance applications stems from the machining. High-temperature composites, metal matrix composites and ceramic matrix composites are considered to be strong candidates as structural materials for high-performance applications. High-temperature composites are also among "hard to machine materials", hence the improved machining of these composites is now being considered to be one of the urgent manufacturing science areas that need to be addressed. Because high-temperature composites are relatively new material systems, their machinability has not been studied except for the recent work by Utsunomiya *et al.* [1], though the machining of ceramics has recently attracted large attention from the materials science community [2–4]. Among various machining methods, several non-traditional methods seem to have emerged as promising machining methods for hard to machine materials. They are electrodischarge machining (EDM) [5], abrasive waterjet (AWJ) machining [6] and laser-beam machining [1, 4].

This paper focuses on the machinability of metal and ceramic matrix composites by an abrasive waterjet method. The results of the machining of these high-temperature composites will be discussed in terms of the surface finish and microstructural integrity as a function of the machining speed. Based on the results of conducted experiments, some concluding remarks are given as to the feasibility of these machining methods.

## 2. Experiments

The metal matrix composite used in this study was 25 vol % SiC whisker/2124 aluminium matrix (SiCw/Al) composite, and was procured from ARCO Chemical Company in plate form with a thickness of 6.3 mm. The ceramic matrix composite used was 7.5% SiC whisker matrix (SiCw/$Al_2O_3$) composite and was also supplied by ARCO Chemical Company.

Plates of the SiCw/Al composite, 6.3 mm thick, were cut by abrasive waterjet (AWJ) developed by Flow Systems, Kent, Washington, at three different cutting speeds, $V$ = 127, 381, and 635 mm $min^{-1}$, with the following cutting parameters: 40 × $10^3$ p.s.i. (~ 275.6 N $mm^{-2}$) water pressure, 0.33 mm orifice size, 1.19 mm nozzle diameter, 2.54 mm stand-off distance, and 80-mesh garnet flowing at 0.675 kg $min^{-1}$ as abrasive particles. These parameters are by no means optimized. The optimization task requires further investigation and will be conducted in the future.

Plates of the 7.5% SiCw/$Al_2O_3$ composite, 6.3 mm thick, were cut by AWJ at three different cutting speeds, $V$ = 12.7, 25.4 and 50.8 mm $min^{-1}$ with the same cutting parameters as for SiCw/Al composites, except for the abrasive used which was 70-mesh SiC abrasive at a flow rate of 4.95 kg $min^{-1}$.

The machined surfaces of composites were evaluated by using scanning electron microscopy (SEM), optical microscope and profilometry. The computer interfaced profilometry was used to evaluate the surface finish of the machined composites. Microhardness measurements were also performed on the surfaces and subsurfaces of the machined composites, to examine the effect of the machining on the microstructures.

## 3. Results and discussion

The results of the surface finish evaluations by

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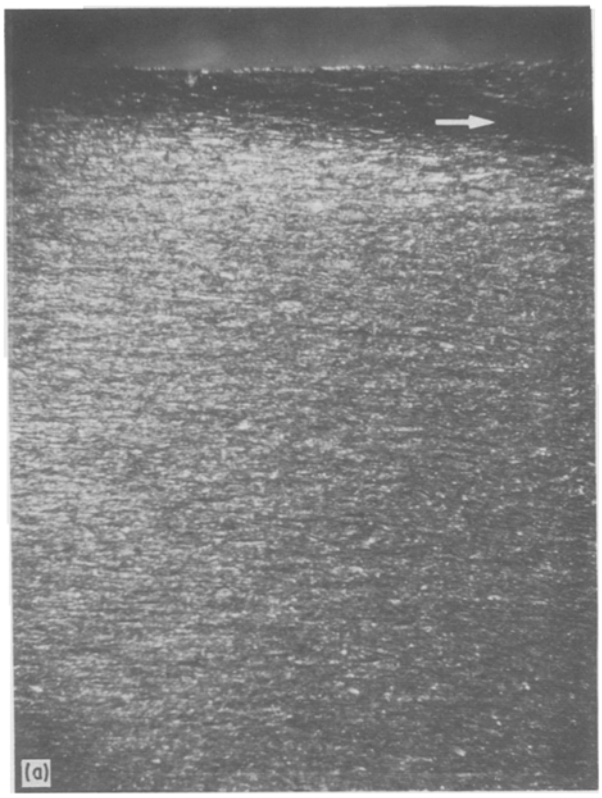
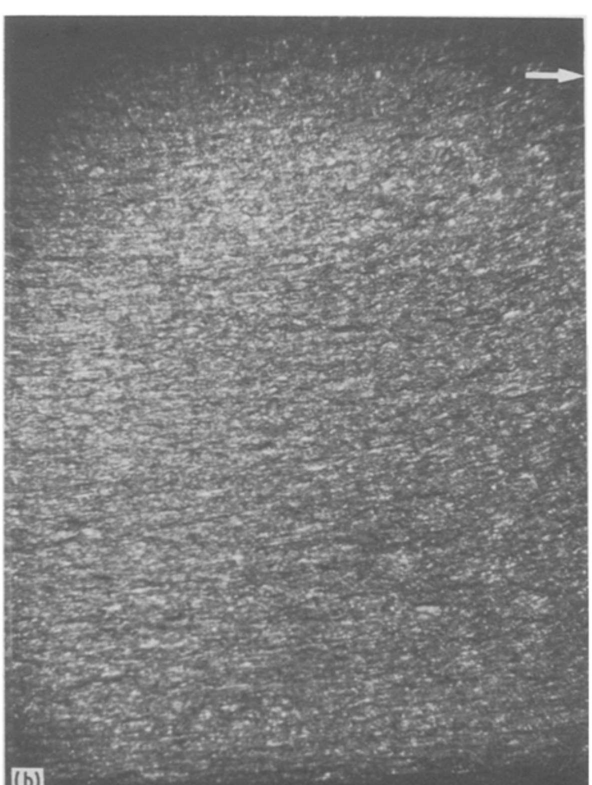
profilometry at three different cutting speeds are summarized in Table I. The surface finish parameters include roughness, waviness, and lay. When subsequent finishing operations are required, the waviness rather than roughness is more important. This is particularly true if no subsequent surface finishing is expected to follow. In the present study, surface finish is expressed in terms of average waviness height measurement, the detail of which has been described elsewhere [7].

Typical as-machined surfaces of 25% SiCw/Al composite at different cutting speeds are shown in Fig. 1 where (a), (b) and (c) denote the surfaces at cutting speeds of 127, 381 and 635 mm min$^{-1}$, respectively. It is clear from Fig. 1 that as the speed increases, surface roughness increases and striations become more visible. These machined surfaces were examined by SEM and the results at slower to higher cutting speeds are shown in Figs 2a, b and c, respectively. In Figs 1 and 2, white arrows denote the cutting direction. The SEM micrographs of Fig. 2 reveal the extent of the surface damage due to the abrasive waterjet cutting action. It follows from Fig. 2 that the severity of surface feature increases with the cutting speed and the surface feature appears to be full of grooves induced by abrasive jetting. To see the grooves more clearly, a higher magnification scanning electron photograph was taken of the specimen in Fig. 2b and it is shown in Fig. 3. It becomes clearer, from Fig. 3, that abrasive particles become embedded in the metal matrix. EDS analysis has confirmed that the particles seen in Fig. 3 are indeed garnet particles (see Fig. 4 where $F_e/M_n$ peaks denote garnet composition).

TABLE I Surface finish of SiCw/Al and SiCw/$Al_2O_3$ composites cut by AWJ

| Materials | Cutting speed (mm min$^{-1}$) | Surface finish ($\mu$m) |
|---|---|---|
| 7.5% | 12.7 | 3.18 |
| SiCw/$Al_2O_3$ | 25.4 | 3.56 |
| | 50.6 | 3.81 |
| 25% | 127 | 2.54 |
| SiCw/Al | 381 | 2.79 |
| | 635 | 3.81 |





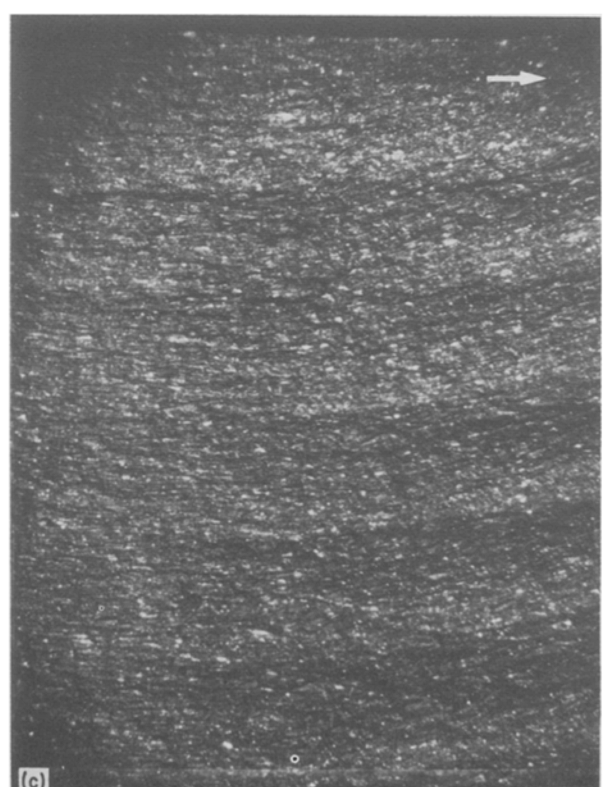
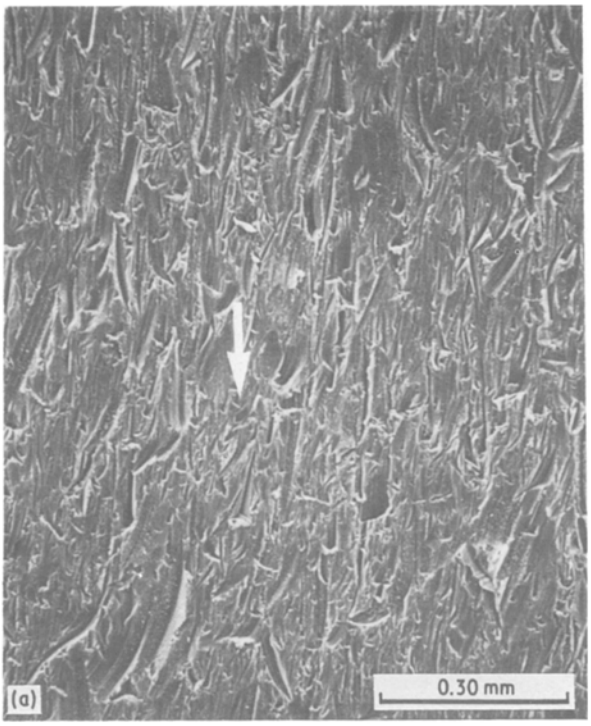
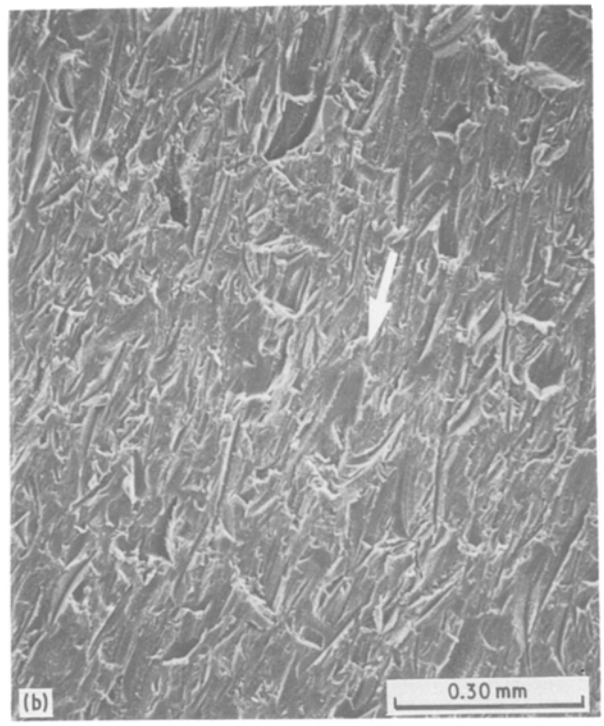


*Figure 1* The AWJ machined surfaces of 25% SiCw/Al composites at different cutting speeds, $V$ = (a) 127, (b) 381 and (c) 635 mm min$^{-1}$. The cutting direction is shown by white arrows.



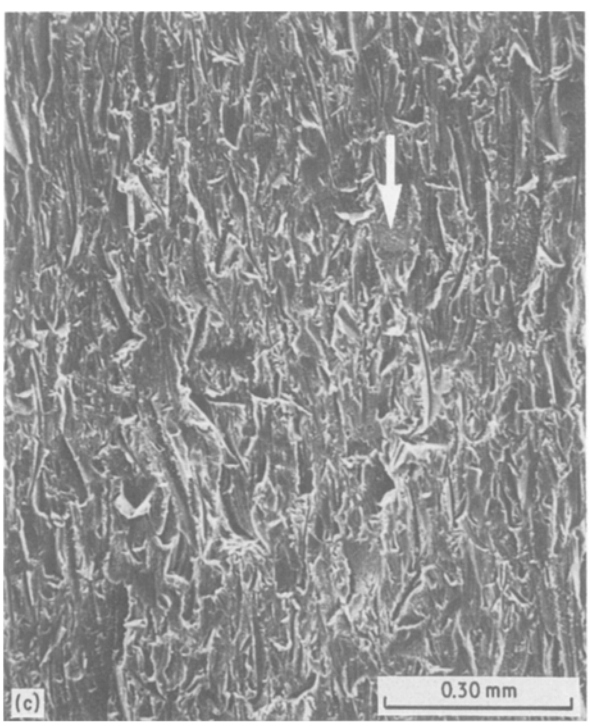




*Figure 2* Scanning electron photographs of Fig. 1, $V$ = (a) 127, (b) 381 and (c) 635 mm min$^{-1}$.

Another notable action of the abrasive waterjet is that it causes micromelting in some areas of the matrix as shown in Fig. 5. This is not surprising if one considers the velocity, approximately 400 m sec$^{-1}$, at which 80 mesh abrasive particles travel just before they hit the target material. Abrasive waterjet erodes the aluminium matrix, but it either pulls, breaks or avoids SiC reinforcement as shown in Fig. 6 where the upper portion of the photo is the AWJ machined surface and the lower portion for the diamond saw-cut surface.

In order to determine the effect of the AWJ cutting on the microstructure of SiCw/Al composites, microhardness measurements were conducted on various points in the composites cut at the intermediate cutting speed from the very surface to the mid-depth across the thickness. The results of the microhardness tests are summarized in Table II. It follows from this that the abrasive waterjet does not work-harden the surface. However, this point deserves further investigation.

The results of the surface finish evaluations by profilometry for 7.5% SiCw/$Al_2O_3$ composites machined at various cutting speeds are summarized in Table I. Typical surfaces of 7.5% SiCw/$Al_2O_3$ composites machined at three different speeds are shown


*Figure 3* Higher magnification of Fig. 2b indicating abrasive particle embedded in the composite.

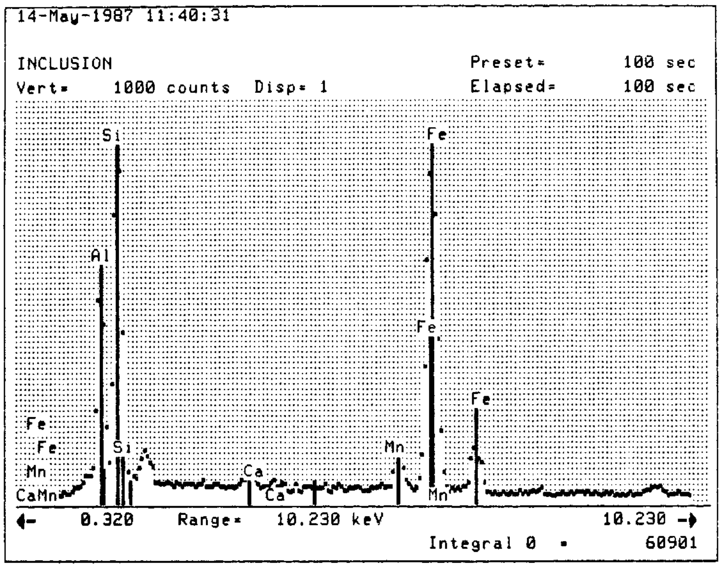



*Figure 4* The abrasive particle embedded as seen in Fig. 3 was identified by EDS as garnet (Fe/Mn).

in Fig. 7 where (a), (b) and (c) denote the AWJ-cut surfaces at slow, medium and high speed, respectively. The surface becomes rougher and striations become more visible as cutting speed increases. Scanning electron micrographs of these surfaces are shown in Fig. 8 where (a), (b) and (c) again denote the cases of slow, medium and high speed. It is noted in Fig. 8 that the extent of grooving increases with increasing cutting speed. Portions of Figs 8b ($V = 25.4\,\mathrm{mm\,min^{-1}}$) and c ($V = 50.6\,\mathrm{mm\,min^{-1}}$) are examined by SEM at higher magnification and the results are shown in Figs 9a and b, respectively. Fig. 9 reveals that at higher speed, AWJ caused a limited plastic deformation compared with lower speeds. This limited plastic deformation resulted in the appearance of a rough machined surface.

As mentioned earlier, the abrasive waterjet cutting parameters are by no means optimized. We are currently investigating how to improve the surface finish quality for subsequent finishing processes by controlling several parameters, i.e. pressure, nozzle size, abrasive morphology and flow rate.

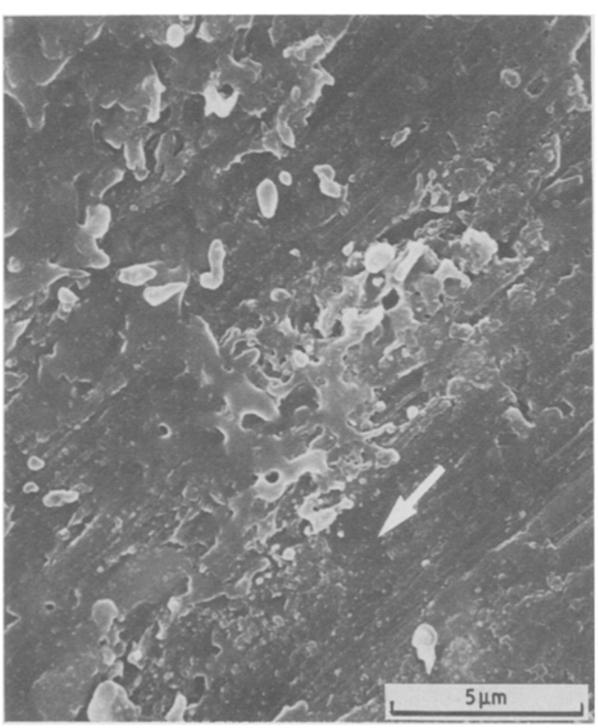



*Figure 5* Micromelting of the composite AWJ machined at $V = 127\,\mathrm{mm\,min^{-1}}$.

## 4. Conclusion

Based on the preliminary results of current investigation to determine the feasibility of machining a few selected high-temperature composites by AWJ, the following concluding remarks can be made.

1. Abrasive waterjet appears to be a quite suitable method to machine metal matrix composites. It is fast and yields relatively smooth surfaces with minimum subsurface damage. AWJ also appears to be a promising machining method for ceramic matrix composites, though it needs further improvements such as durability of nozzle.

2. Machined surfaces do not show any microstructural changes. The microhardness tests on SiCw/Al composite have revealed that AWJ does not work-harden the surface.

3. In case of SiCw/Al composite. AWJ does not cut SiC whiskers, and it either pulls or breaks them, but

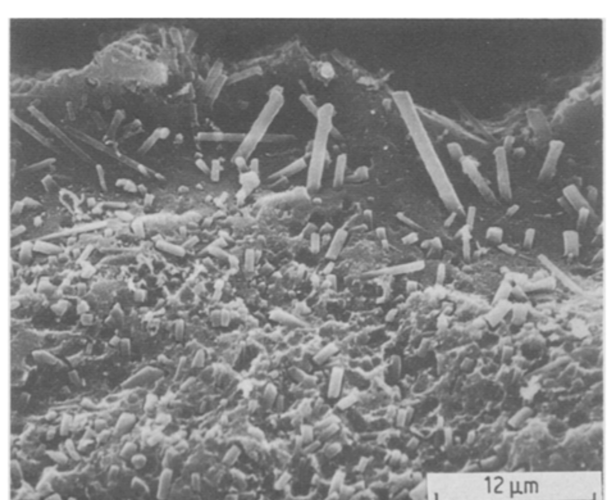
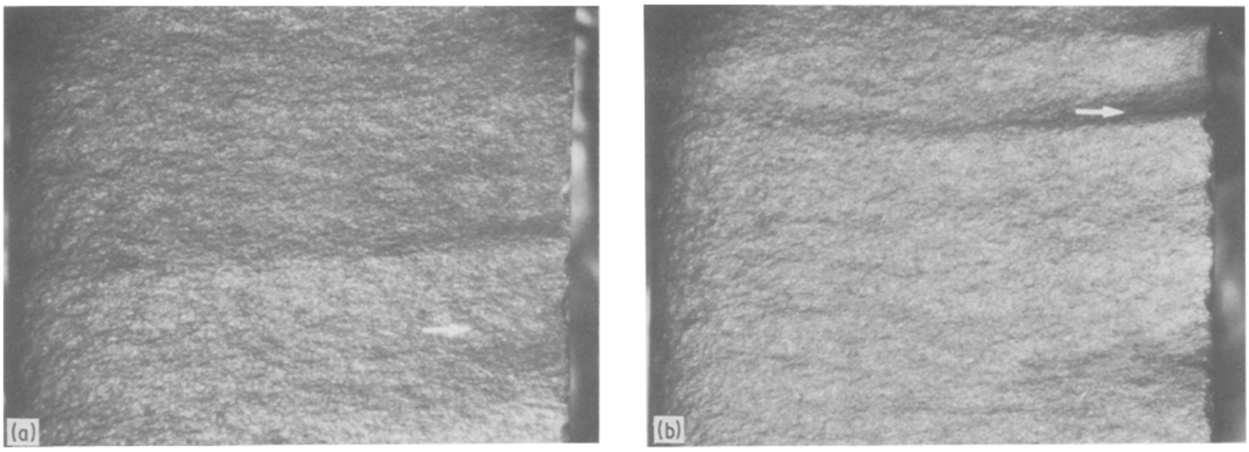



*Figure 6* Scanning electron photograph of the profile view in the AWJ machined 25% SiCw/Al composite as seen in the top half of the photo, while the lower half denotes the diamond saw-cut surface, which is perpendicular to the top surface.



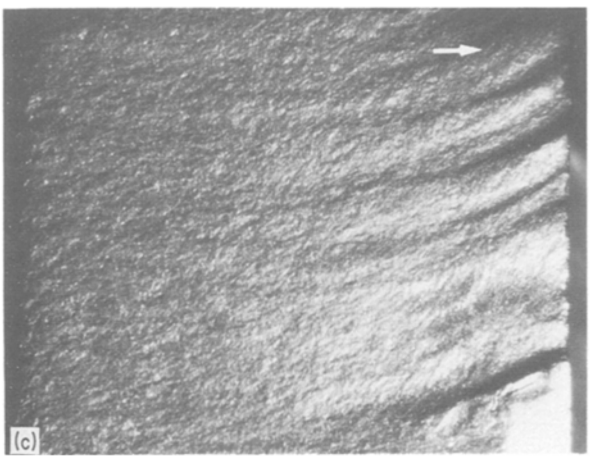


*Figure 7* AWJ machined surfaces of 7.5% SiCW/$Al_2O_3$ composites, at cutting speed $V$ = (a) 12.7, (b) 25.4 and (c) 50.6 mm min$^{-1}$. The cutting direction is marked by white arrows.

TABLE II Results of microhardness measurements on SiCw/Al composites

| Distance from surface ($\mu$m) | Microhardness Knoop |
|---|---|
| 80 | 220 |
| 180 | 220 |
| 3000 | 220 |

erodes the aluminium matrix. Impact of abrasive particles also caused localized micromelting in the matrix. Abrasive particle embedment was also observed.

4. In the case of SiCw/$Al_2O_3$ composite, no cracks were evident on the machined surfaces. Grooving by micromachining was evident. Some plastic deformation was also observed.

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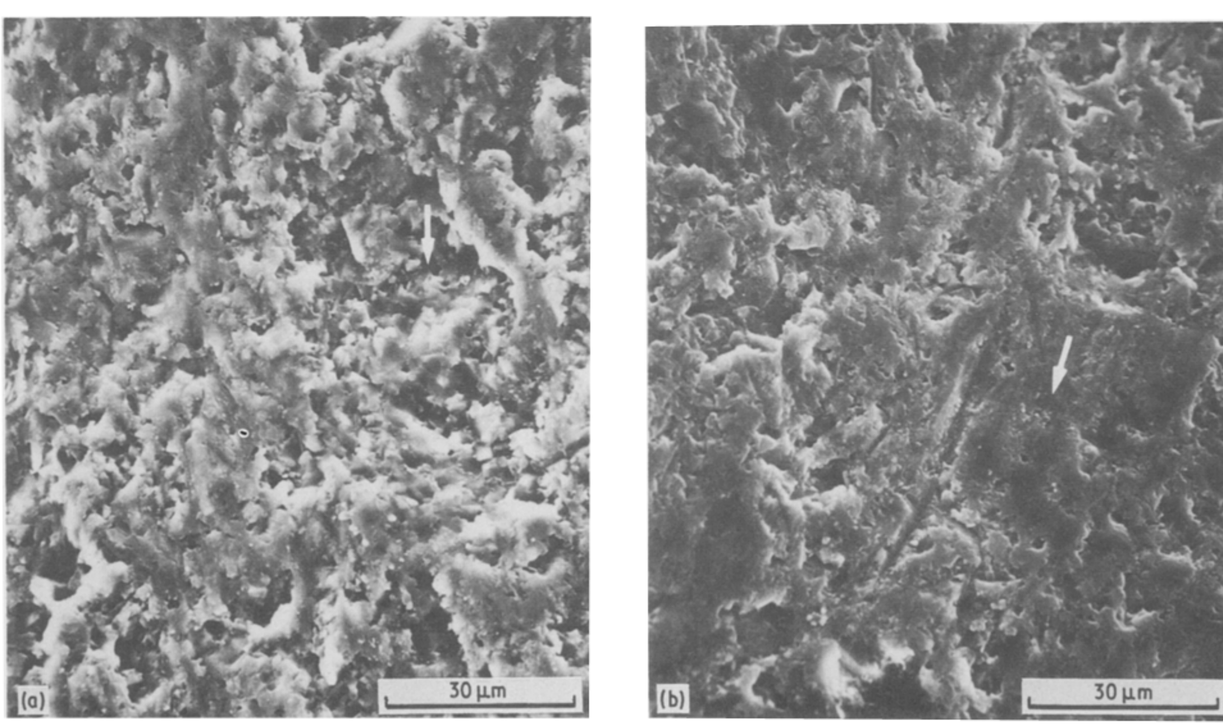


*Figure 8* Scanning electron photographs of Fig. 7, $V$ = (a) 12.7, (b) 25.4 and (c) 50.6 mm min$^{-1}$.

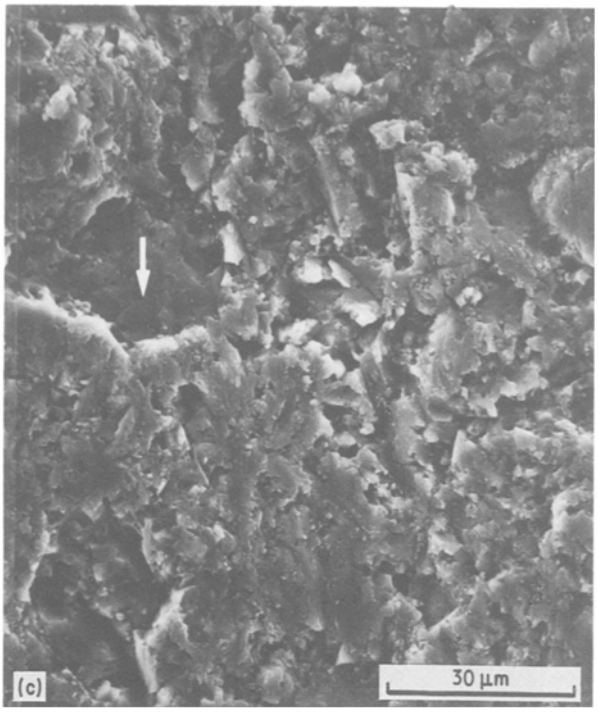


*Figure 8* Continued.

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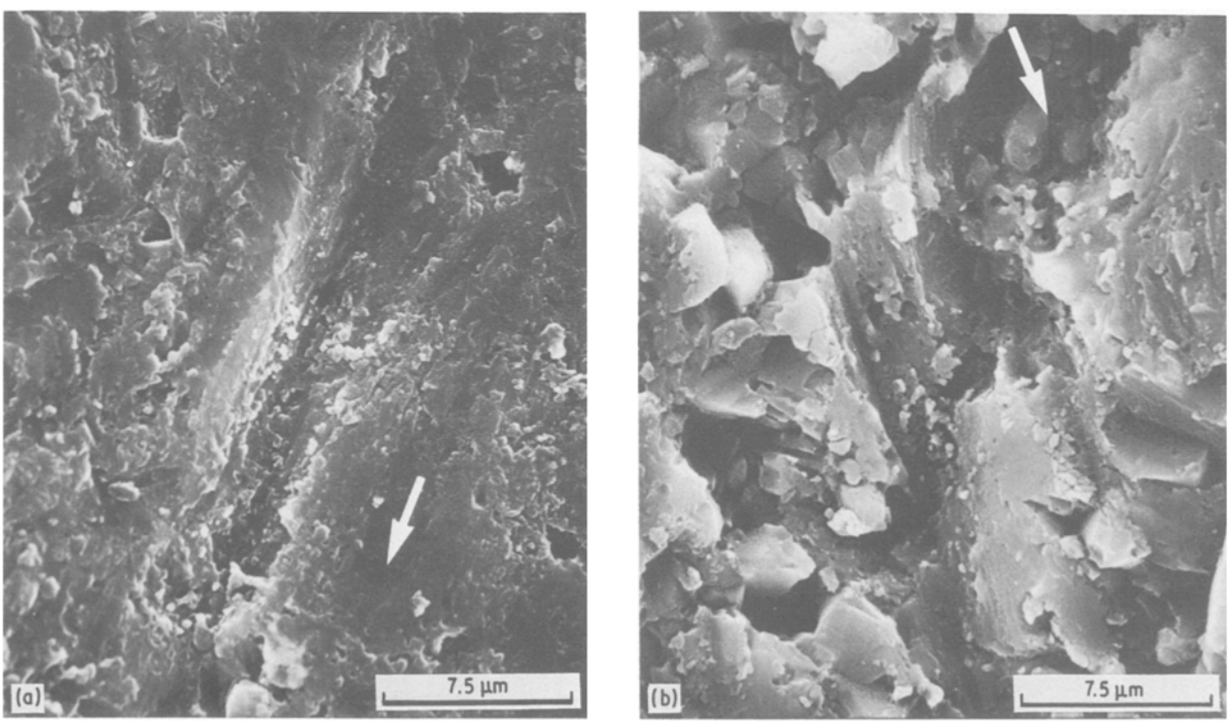


*Figure 9* Scanning electron photographs of Figs 8b and c at higher magnifications are shown by (a) and (b), respectively.