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Hot-roll bonding of aluminium matrix composites with different volume fractions of alumina

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Metal matrix composites (MMC) with volume fractions of 0.08, 0.11 and 0.14 alumina (Al_2O_3) were fabricated by roll bonding. This low-cost approach to MMC manufacture has the flexibility of controlling the volume fraction of the MMCs by varying the oxide thickness on the anodized aluminium foil, and the number of layers of these foils to be sandwiched between plain aluminium sheet as the matrix metal. The fragmentation of the laminate alumina is achieved by a series of hot- and cold-rolling operations. The resulting reinforcing alumina particles have platelet shape measuring approximately 20 μm × 11 μm × 5 μm instead of a stringer shape as expected. It is found that the improvement in modulus and strength did follow very closely with the rule of mixtures. A small scatter of measured data, especially the resistivity of the MMCs, was observed. This can be explained by the inefficient bonding between the reinforcing alumina and the matrix metal as demonstrated later in this study.

1. Introduction

Aluminium is a lightweight and relatively weak metal. Its applications are limited when high modulus and strength are required. Although high-strength aluminium alloys have been developed, the additions of alloying elements and microstructural control have very little effect in enhancing the stiffness [1]. The demands for lightweight, high-modulus and high-strength materials have led to the development of MMCs [2–6].

Common reinforcing fibres in MMCs are either in continuous or discontinuous form. MMCs with continuous fibres usually have better physical and mechanical properties (such as higher strength and stiffness) but they lack the isotropic properties in the transverse direction of the reinforcement. Thus, substantial attention has been paid to the development of discontinuous reinforced MMCs because of their relatively lower cost of manufacture, more consistent properties and the characteristic isotropic properties. Because of this isotropy of their microstructure, their properties are also isotropic and hence the high uniaxial stiffness and strength of aligned microstructure are not achieved. Furthermore, these MMCs are expected to have fairly good forming properties as monolithic materials. They are expected to be processed by conventional secondary-forming operations such as rolling, forging and perhaps even deep drawing.

The production of MMCs in the present studies involves the formation of thin Al_2O_3 laminate on commercially pure (CP) aluminium foil by anodizing. The bonding between the matrix and the alumina is achieved by hot rolling followed by cold rolling. The aim was to produce MMCs with a low volume fraction (below 0.15) of Al_2O_3 finely dispersed in the aluminium matrix. The physical and mechanical properties of this material may not be comparable with MMCs produced by conventional MMC production techniques in terms of modulus and strength. However, the inexpensive production route coupled with a moderate increase in modulus, strength and retained good electrical conductivity, render such an MMC a valuable alternative material for use in electricity transmission applications. The production technique used in making this MMC is very similar to the pack-rolling process in aluminium foil fabrication. With minimal need for equipment alteration, an aluminium sheet rolling plant can be converted to produce this form of MMC in semi- or fully continuous production runs. This process will greatly reduce the cost of MMCs and at the same time maintain consistent properties. The nature of the sheet-rolling operation could produce continuous coils of MMC that could be used as an electrical conductor in a long and continuous form for power lines or lightning conductors. The MMC produced by this method can compensate for the deficiency in modulus and strength of the electrical grade aluminium conductors currently employed.

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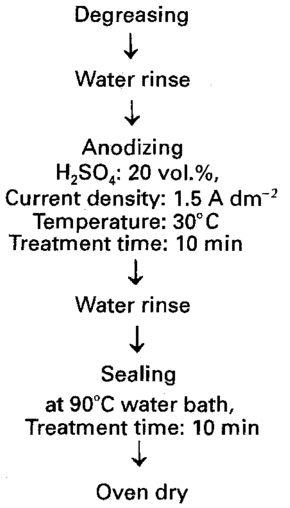

Figure 1 Anodizing flow sequence used in the preparation of alumina.

2. Experimental procedures

Unlike alumina used in making conventional MMCs as reported elsewhere [7–9], the reinforcing alumina here is formed by anodizing. CP aluminium foil of thickness 0.018 mm was used as the base metal for the production of alumina by anodizing. The operating procedures are presented in Fig. 1 [10, 11]. The temperature of the electrolyte was maintained at around 30 °C, aiming to achieve a porous oxide morphology which supposedly aids good bonding between the matrix metal and the alumina layers [12]. With a current density of 1.5 A dm^{-2} and a duration of 10 min, the foil was anodized in the above electrolyte resulting in an oxide of 5 μm thickness on each side of the foil surface.

Alternating layers of anodized aluminium foil and 0.1 mm thick plain aluminium sheets used as matrix material were sandwiched together to form hot-roll preforms. The initial estimation of the MMC volume fraction was calculated by recording the number of layers of anodized aluminium foil stacked between the plain aluminium sheets. Special attention was given so that the anodized sheets were uniformly spaced within the preform, aiming to obtain more uniform mechanical properties. Hot-roll preforms with initial calculated volume fractions of 0.08, 0.11 and 0.14 were assembled.

The final bonding of the preforms was achieved by pre-heating them in an electric muffle furnace to 550 °C followed by rolling in a laboratory-scale two-high rolling mill. The preforms were maintained at 550 °C for about 1 h before rolling to achieve a uniform temperature. Thermocouples were attached to the preforms during pre-heating to ensure the samples were not overheated. Bonding of the multi-layer preforms did not occur until a noticeable 40%–50% reduction in thickness was reached. The initial shape of the alumina before hot rolling was in the form of continuous layers. To break up these alumina layers into smaller fragments, cold rolling was employed. Owing to the better flowability of the hot matrix metal, the hot break down rolling operation itself did not effectively fracture the anodized alumina layer. Subsequent cold-rolling operations were used to break up further the alumina laminate. The finished cold-rolled MMC sheet thickness was about 1.3 mm.

A flat dumb-bell shaped miniature tensile specimen was adopted for the physical and mechanical tests because this shape is suitable for both tensile tests and resistivity measurements. For each MMC volume fraction, specimens in two directions, along (0°) and transverse (90°) to the rolling direction, were taken for testing. Because the amount of residual stress is one of the major factors affecting resistivity, specimens of the same type were further divided into two batches. One batch was annealed to 500 °C for 1 h and the second batch was tested in the as-cold-rolled condition in order to compare the differences in mechanical properties and resistivity of the stress-relieved specimens. The moduli and strength were measured with a MTS-Sintech Universal testing machine. The resistivity was measured with a four-point probe device.

3. Results and discussion

The rolling operations broke up the laminate alumina and dispersed it in the aluminium matrix. From the optical micrographs shown in Fig. 2a–f, the fragmented alumina particles were found to be fairly uniformly distributed throughout the matrix. The uniform spacing between the reinforcing alumina particles is helpful in strengthening the MMCs [13]. With the aid of a computer-based optical image analyser, the geometric shape of the alumina is reported in Table I. The alumina particles have an average aspect ratio of about 2 in the cross-section that is aligned longitudinally with the rolling direction (0 °), and an average aspect ratio of about 4 in the cross-section transverse to the rolling direction (90 °). From this information it can be concluded that the particles do not take the shape of stringers at it was expected. Instead, they are in the shape of rectangular platelets measuring about 20 μm × 11 μm × 5 μm in size. This outcome can be explained in that more pronounced straining occurred along the direction of rolling and, therefore, the degree of deformation and fragmentation are also higher in that direction. At 90° to the rolling direction, very little straining occurred and, therefore, very little alumina fragmentation occurred. As a result, rectangular platelet alumina particles were formed with their longer axis aligned at 90° to the rolling direction. Studies [14] have shown that the yield strength of the MMC decreases with increase in platelet dimensions.

Although the MMCs in this study do not have the "ideal" morphology, the data in Table II still show encouraging results in the physical and mechanical properties. To compare the experimental results with theoretical estimations, a modified rule of mixtures [15] is used, which is

$$\sigma_{\mathrm{MMC}} = \sigma_{\mathrm{f}} V_{\mathrm{f}}\left[1 - \left(\frac{\sigma_{\mathrm{f}} d}{4l\tau}\right)\right] + \sigma_{\mathrm{m}}(1 - V_{\mathrm{f}}) \qquad (1)$$

where σ_m is the strength of the matrix, σ_f, the strength of the fibre, and V_m, V_f are the volume fractions of the

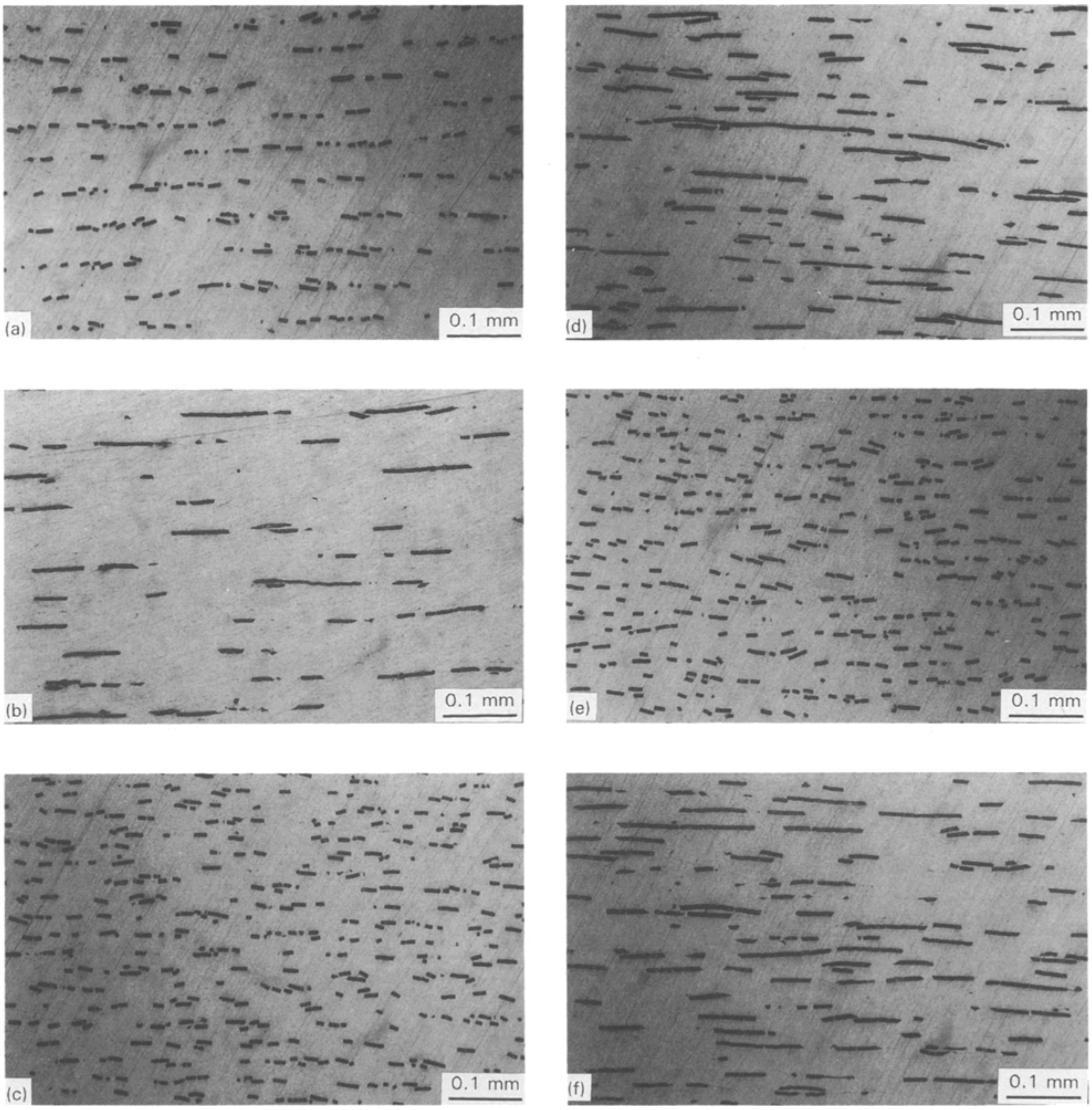

Figure 2 Optical micrographs of cross-sectional views of MMC with (a, b) 0.8, (c, d) 0.11, (e, f) 0.14 volume fractions taken at the (a, c, e) longitudinal, and (b, d, f) transverse orientations with reference to the rolling direction.

TABLE I Volume fraction of MMCs and geometric shape of the reinforcing alumina

Volume fraction	Alumina geometry[a]			
	0°		90°	
	Average length (μm)	Aspect ratio	Average length (μm)	Aspect ratio
0.08	10.5	1.98	20.5	4.3
0.11	11.8	2.21	20.4	4.1
0.14	11.4	2.09	20.2	3.64

[a] 0° = Longitudinal to rolling direction, 90° = transverse to rolling direction.

matrix and fibre in the MMC. However, the aspect ratio, d/l, in Equation 1 is more applicable to MMCs containing discontinuous fibres in the form of stringers. Further modification of Equation 1 is necessary to reflect better the geometric shape of platelets in this MMCs. Equation 1 is then re-written as Equation 2 to reflect the actual geometry of the platelet-shape alumina

$$\sigma_{\mathrm{MMC}} = \sigma_f V_f \left\{ 1 - \left[\frac{\sigma_f w t}{4(lt + lw)(2)\tau} \right] \right\} + \sigma_m (1 - V_f) \tag{2}$$

where w, l and t are the average width, length and thickness of the platelets, and τ is the matrix shear strength given by $\tau = \sigma_m/2$.

Table III shows the comparison of the experimental and theoretical strength of MMCs of various volume fractions estimated with this equation. From these results, higher volume fractions give rise to higher strengthening effects as expected. However, it is noticeable that there are some discrepancies between the experimental and the theoretical values. The theoretical

TABLE II Experimental results of physical and mechanical properties of MMCs

Volume fraction	Sample conditions		Tensile strength (MPa)	Modulus (GPa)	Hardness, Hv	Resistivity (10^{-9} Ωm)
(0.08)	Cold-	0°[a]	97	72.3	40.7	33.0
	rolled	90°	108	78		35.9
	Annealed	0°	85.2	73	31.8	36.8
		90°	94	87		35.6
(0.11)	Cold-	0°	99.7	99.4	49.2	39.6
	rolled	90°	116	108.5		39.9
	Annealed	0°	97.3	83.1	32.6	35.9
		90°	101.3	98.2		36
(0.14)	Cold-	0°	90.7	78	51.1	40.1
	rolled	90°	121	120		39.9
	Annealed	0°	88.8	82.8	35.8	36.8
		90°	98	103		39.7

[a] 0° = Longitudinal to rolling direction, 90° = transverse to rolling direction.

TABLE III Comparison of experimental and theoretical values of the tensile strength of MMCs

Volume fraction	Average experimental results (MPa)		Average calculated results (MPa)	
	Annealed	As-rolled	Annealed	As-rolled
0.08	94	108	83	122
0.11	101	118	87	134
0.14	103	121	92.8	146

data in the as-rolled condition are greater than the experimental data, whilst the reverse is true for MMCs in the annealed state. This can be explained by the fact that some scattering of data is due to (1) poor and inconsistent interfacial bonding between the alumina particles and the aluminium matrix which is illustrated in the scanning electron micrographs in Fig. 3; (2) residual stresses at the matrix and the alumina boundary were present, which were created during cold straining [16]; (3) the strength of anodized alumina particles, with its porous nature, is less than that produced by commercial alumina suppliers.

The higher experimental values for the annealed samples are probably due to incomplete recrystallization. The specimens were annealed at 500 °C for 1 h and this may have been too short a time or too low a temperature for the recrystallization process to complete, especially when there are reinforcing particles which act as barriers to the transformation.

Similarly, the modulus of the MMCs may also be estimated using the rule of mixtures. However, the true geometrical shape of the platelet alumina particles has to be considered again. To compare these experimental values with theoretical estimations, the modified Halpin–Tsai equation [17], is used for the calculation of the moduli. The modified equation is expressed as

$$E_{\mathrm{MMC}} = E_{\mathrm{m}} \frac{(1 + \xi \eta V_{\mathrm{f}})}{(1 - \eta V_{\mathrm{f}})} \qquad (3)$$

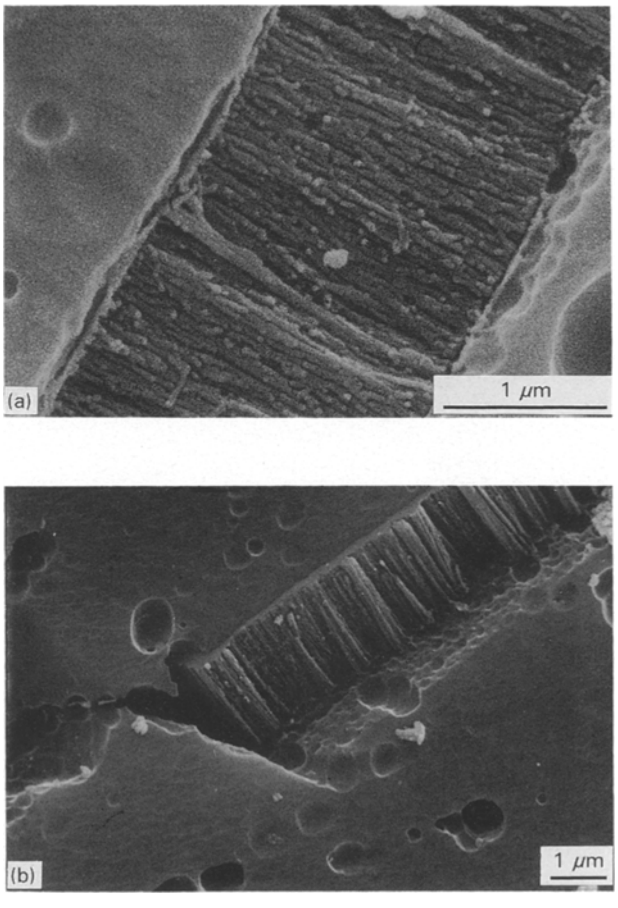

Figure 3 Scanning electron micrographs of alumina and aluminium matrix showing (a) the gap between them, and (b) the void at the end of the alumina due to poor interfacial bonding and incomplete fill of the matrix metal.

where $\eta = [(E_{\mathrm{f}}/E_{\mathrm{m}}) - 1]/[(E_{\mathrm{f}}/E_{\mathrm{m}} + \xi]$; $\xi = 2[l/(w)(t)]$. The estimated results are shown in Table IV. It can be seen that more obvious modulus enhancements are found in MMCs with 0.11 and 0.14 volume fractions. In this case, a certain minimum level of reinforcement must be present before effective strengthening can be noticed [18]. Also, the data in Table IV appear to be erratic. A larger amount of scatter in the data is apparent than that for the tensile strength data in Table III. This is probably to be

TABLE IV Comparison of experimental and theoretical values of the Moduli of MMCs

Volume fraction	Average experimental results (GPa)		Average calculated results (GPa)	
	Annealed	As-rolled	Annealed	As-rolled
0.08	87	78	87	106.3
0.11	98	108	93.4	112.5
0.14	103	120	99.9	118.7

expected because the value of modulus is more sensitive to poor interfacial bonding [19].The explanations used above for the strength data can also be applied to explain the inconsistency in the modulus data.

Bearing in mind the orientation and morphology of the alumina particles in the aluminium matrix, the electrical resistivity measured in the longitudinal and transverse directions should not be the same. It is expected that resistivity along the axis in which the alumina particles are elongated will be smaller when compared with the resistivity taken transverse to this direction. In general, the resistivity is expected to be a complex function of geometry in that the motion of electrons must follow a path along the electric field in the matrix but take account of the distortions in the electric field in the matrix due to the presence of the alumina particles [20]. For the same reasons, resistivity will be higher for MMCs with higher volume fractions of alumina. Referring to the resistivity data shown in Table II, slightly higher values can be observed for measurements taken along the rolling direction which is the direction normal to the long axis of the platelet alumina.

The original idea for the development of this hot-roll bonded MMC is for electrical conductor applications. The increase in resistivity in these MMCs is slightly discouraging. It is believed that the high resistivity is mainly caused by electron scattering by atomic-scale disturbances to the potential field of the lattice [21–23]. In addition to the above mentioned problems resulting in the high resistivity of the high volume fraction MMCs, measuring errors could also be another factor contributing to the unfavourably high resistivity.

4. Conclusions

As can be seen in this study, the mechanical properties such as the modulus and strength have been improved by the additions of reinforcing alumina as predicted by the well-known rule of mixtures. There are some discrepancies between the experimental results and the theoretical predictions for various reasons. However, the increase in physical and mechanical properties of the MMC generally behaved as expected. For annealed MMCs reinforced with 0.08, 0.11 and 0.14 alumina volume fractions, the strength increased by up to 34%, 45% and 40%, respectively. A similar enhancement of the moduli of the above MMCs by increments of 26%, 42% and 49% were also found.

The effect on the change of resistivity of the MMCs produced in this study is not as promising. Compared with electrical grade aluminium conductors, it was shown that the resistivity was increased by 36% for the MMC with 0.14 volume fraction of alumina. If this large increase in resistivity cannot be reduced, it may call into question the whole idea of replacing electrical grade aluminium in power-line applications with this MMC material. However, viewing the scanning electron micrographs in Fig. 3, the unsatisfactory resistivity results could well arise from the complexity of the interface between the reinforcing particles and matrix metal due to insufficient bonding. This will result in residual stresses and electron scattering at the interfaces [24]. The main obstacle limiting the use of this MMC in low power-loss applications lies in improving the conductivity of these MMCs. Modifying the bonding characteristics is the obvious direction to overcome this problem.

Viewed from the type of hot-roll bonding equipment involved in the making of MMCs as demonstrated in this work, hot-roll bonding is a comparatively simple method in the manufacture of composite materials. Further study on this topic with the aim to improve the interfacial bonding between the alumina and the matrix metal will be helpful in better appraising the value of MMCs produced by this hot-roll bonding technique.

References

1. T. W. CLYNE and P. J. WITHERS, "An Introduction to Metal Matrix Composites", 1st Edn (Cambridge University Press, 1993).
2. M. G. BADER, T. W. CLYNE and G. R. CAPPLEMAN, *Compos. Sci. Technol.* **23** (1985) 287.
3. Z. HASHIN, *J. Appl. Mech.* **50** (1983) 481.
4. M. TAYA, M. DUNN and H. LILHOLT, in "Proceedings of the 12th Risø International Symposium on Metal Matrix Composites – Processing, Microstructure and Properties", edited by N. Hansen, E. Juul Jensen, T. Lefers, H. Lilholt, T. Lorentzen, A. S. Pedersen, O. B. Pedersen and B. Ralph (Risø National Laboratories, Roskilde, Denmark, 1991) p. 149.
5. P. G. PARTRIDGE and C. M. WARD-CLOSE, *Int. Mater. Rev.* **38** (1993) 1.
6. W. WEI, *Met. Mater.* Aug. (1992) 430.
7. A. R. BUNSELL, in "Proceedings of the 9th Risø International Symposium on Mechanical and Physical Behaviour of Metallic and Ceramic Composites", edited by S. I. Andersen, H. Lilholt and O. B. Pedersen (Risø National Laboratories, Roskilde, Denmark, 1988) p. 1.
8. M. H. STACEY, *Mater. Sci. Technol.* (4) (1988) 227.
9. M. DELETTER, F. CAMBIER, C. LEBLUD and M. R. ANSEAU, *Acta Metall.* **31** (1983) 893.
10. V. F. HENLEY, "Anodic Oxidation of Aluminium and Its Alloys" (Pergamon Press, UK, 1982).
11. "Metals Handbook", Vol. 5, 9th Edn (American Society for Metals, Metals Park, OH, 1982).
12. H. C. YUEN, B. RALPH and W. B. LEE, *Scripta Metall. Mater.* **29** (1993) 695.
13. S. OCHIAI and K. OSAMURA, *J. Mater. Sci.* **24** (1989) 3536.
14. R. J. ARSENAULT, in "Proceedings of the 9th Risø International Symposium on Mechanical and Physical Behaviour of Metallic and Ceramic Composites", edited by S. I. Andersen, H. Lilholt and O. B. Pedersen (Risø National Laboratories, Roskilde, Denmark, 1988), p. 279.
15. B. R. HENRIKSEN and T. E. JOHNSEN, *Mater. Sci. Technol.* **6** (1990) 857.
16. B. CORNWALL and V. D. KRSTIC, *J. Mater. Sci.* **27** (1992) 271.

17. J. C. HALPIN and S. W. TSAI, Air Force Materials Laboratory, AFML-TR-67-423 (1967).
18. F. J. HUMPHREYS, A BASU, and M. R. DJAZEB, in "Proceedings of the 12th Risø International Symposium on Metal Matrix Composites", edited by N. Hansen, D. Juul Jensen, T. Leffers, H. Lilholt, T. Lorentzen, A. S. Pedersen, O. B. Pedersen and B. Ralph, (Risø National Laboratories, Roskilde, Denmark, 1991) p. 51.
19. H. C. YUEN, MPhil thesis, Brunel University, Uxbridge, Middlesex, UK (1993).
20. J. E. SCHOUTENS, in "Electrical Conductivity in Continuous-Fibre Composites in Metal Matrix Composites: Mechanisms and Properties", edited by R. K. Everett and R. J. Arsenault, (Academic Press, New York, 1991).
21. J. E. SCHOUTENS and F. S. ROIG, *J. Mater. Sci.* **22** (1987) 181.
22. *Idem, ibid.* **22** (1987) 181.
23. D. ABUKAY, K. V. RAO and S. ARAJS, *Fibre Sci. Technol.* **10** (1977) 313.
24. F. S. ROIG and J. E. SCHOUTENS, *J. Mater. Sci* **21** (1986) 2409.

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