

# Mechanical properties of some PM aluminide and silicide reinforced 2124 aluminium matrix composites

B. Torres, M. Lieblich\*, J. Ibáñez and A. García-Escorial

*Physical Metallurgy Dept., Centro Nacional de Investigaciones Metalúrgicas, CENIM-CSIC, Avda. Gregorio del Amo 8, 28040 Madrid, Spain*

*Keywords:* Powder processing; Aluminium alloys; Composites; Intermetallic compounds; Mechanical properties.

\* Corresponding author.

Fax: 00 34 91 5347425

E-mail address: marcela@cenim.csic.es (M. Lieblich)

## Abstract

Tensile properties of PM 2124 aluminium composites reinforced with  $\text{Ni}_3\text{Al}$ ,  $\text{NiAl}$ ,  $\text{Cr}_3\text{Si}$  and  $\text{MoSi}_2$  intermetallic powder particles have been investigated in tempering conditions T1 and T4. Intermetallics were produced by SHS and composite powders consolidated by extrusion. 2124/ $\text{MoSi}_2$  showed the highest thermal stability, and the best mechanical properties even after comparison with those of 2124/ $\text{SiC}$  composite after processing through the same route.

## Introduction

Aluminium matrix reinforced with intermetallic powder particles (AMCIPs) has been recently developed [1-3] as a possible answer to the transport industry's need to replace heavy and/or costly Fe- and Ti-base parts with lighter and cheaper materials. Ceramic reinforced Al alloys have been considered suitable candidates for these purposes over the past few decades. However, their potential for large-scale use has been restrained because they present a few general drawbacks, such as high abrasiveness and brittleness, and recycling difficulties, together with more specific problems such as a high mismatch between the coefficient of thermal expansions (CTE) of matrix and reinforcement, which results in poor thermal fatigue resistance when service conditions involve thermal cycles. Some advantages that intermetallics have over ceramics are that they are less brittle and abrasive, and that their CTE are closer to that of the Al matrix. AMCIPs are also much easier to recycle because it is not necessary to separate both components of the composite before melting. Apart from these technological aspects, AMCIPs are very interesting from a scientific point of view because they have been submitted to few research studies, and consequently, the current knowledge regarding their behaviour and its controlling factors is still quite limited.

In the present work, 2124 aluminium alloys reinforced with 15 vol.% of two aluminides, Ni<sub>3</sub>Al and NiAl, and two silicides, Cr<sub>3</sub>Si and MoSi<sub>2</sub>, have been produced through a low-cost powder metallurgy (PM) route, and their tensile properties and microstructure have been investigated. Ni<sub>3</sub>Al and NiAl were selected because of their relatively high CTE [4,5]. In addition, Ni<sub>3</sub>Al reinforcement has already proved to promote a good tribological behaviour [6,7]. Cr<sub>3</sub>Si and MoSi<sub>2</sub> were chosen because of their high elastic modulus [8,9], quite close to that of SiC. Behaviour of these four, 2124/Ni<sub>3</sub>Al, 2124/NiAl, 2124/Cr<sub>3</sub>Si and 2124/MoSi<sub>2</sub>, composites is compared with a SiC reinforced 2124 alloy processed by the same PM route.

## Experimental procedure

The 2124 aluminium alloy powder particles of <60 µm diameter (chemical composition in weight %: Cu = 4.24, Mg = 1.4, Mn = 0.85, Si = 0.03, Fe = 0.06, Zr, Cr and Ti < 0.01 and Al = bal.), were obtained by argon atomisation by Alpoco, Sutton Coldfield, UK. The intermetallic reinforcing particles, Ni<sub>3</sub>Al, NiAl, Cr<sub>3</sub>Si and MoSi<sub>2</sub>, were obtained from pure elements by Inasmet, San Sebastián, Spain, by self-propagated high-temperature synthesis (SHS), followed by jet milling of the porous product and sieving. The median diameter of the Ni<sub>3</sub>Al and NiAl intermetallics was about 20 µm, and that of Cr<sub>3</sub>Si, MoSi<sub>2</sub> and the commercial SiC powders was about 5 µm. The shape of the reinforcing particles was irregular. The 2124 powder was mechanically blended with 15 vol.% of each intermetallic powder, uniaxially cold pressed, hot extruded at 450°C into bars of 8 mm diameter and water quenched by Creuzet, Marmande, France. The composite bars were studied as-produced, T1 condition, and in T4, which consisted of a solid solution treatment at 495°C for 30 minutes, water quenching and 48 hours of natural ageing.

Cylindrical tensile specimens of 3 mm diameter and 10 mm gauge length were machined from the extruded bars while maintaining the tensile axis parallel to the extrusion direction. Yield stress (YS), ultimate tensile strength (UTS) and elongation to fracture ( $\epsilon_f$ ) were determined at room temperature at a strain rate of  $10^{-4} \text{ s}^{-1}$  employing at least two specimens for each material and

condition. Microstructural characterisation was performed by scanning electron microscopy (SEM) equipped with energy dispersive X-ray spectroscopy (EDS). Specimens were prepared by standard metallographic techniques without any chemical etching.

## Results and Discussion

Table 1 shows results of tensile tests performed for each material and condition. From the analysis of the data of Table 1 the following main features can be pointed out:

- i) 2124/Ni<sub>3</sub>Al and 2124/NiAl aluminide reinforced composites in T4 break before achieving the YS.
- ii) 2124/Cr<sub>3</sub>Si composite presents higher YS in T4 than in T1, whereas UTS and  $\epsilon_f$  are lower.
- iii) YS, UTS and  $\epsilon_f$  of 2124/MoSi<sub>2</sub> and 2124/SiC composites increase after the T4 treatment.
- iv) The best tensile results are presented by the 2124/MoSi<sub>2</sub> extruded material in T4.
- v) Finally, values of tensile properties of 2124/SiC obtained in this work are in the same range as others reported in the literature (YS between 360MPa and 485MPa, and UTS between 440 MPa and 610 MPa [10,11]).

Table 1

Tensile properties in T1 and T4 of 2124 reinforced with 15 vol.% of Ni<sub>3</sub>Al, NiAl, Cr<sub>3</sub>Si, MoSi<sub>2</sub> and SiC.

	2124/Ni <sub>3</sub> Al		2124/NiAl		2124/Cr <sub>3</sub> Si		2124/MoSi <sub>2</sub>		2124/SiC	
	T1	T4	T1	T4	T1	T4	T1	T4	T1	T4
YS (MPa)	280	-	320	-	330	360	330	390	340	370
UTS(MPa)	370	-	430	-	470	420	460	520	450	500
$\epsilon_f$ (%)	3.5	-	4	-	5	0.5	5	8	3.5	6.5

The larger size of the aluminide particles would explain the lower tensile properties of 2124/Ni<sub>3</sub>Al and 2124/NiAl composites, but it obviously cannot be the main cause of the extreme brittleness of these composites in T4. Therefore, as the 2124 alloy was the same in all materials, the difference in mechanical properties among composites must be related to specific diffusion reactions occurring between the matrix and the reinforcements during high temperature exposure.

Microstructure of the composites was investigated and illustrated in Fig. 1. Fig. 1a-d shows the microstructure of Ni<sub>3</sub>Al and NiAl reinforced composites in T1 and T4. As can be seen, whereas only very small diffusion reaction phases appear at the interface between matrix and reinforcements in T1, large interphases form during the T4 treatment. These new phases have been identified as Al<sub>3</sub>Ni containing Cu, the layer closer to the Al matrix, and Al<sub>3</sub>Ni<sub>2</sub>, the layer closer to the Ni<sub>3</sub>Al or NiAl reinforcement [2, 12, 13]. The formation of these diffusion reaction phases occurs with a volume increase compared to that occupied by the original Ni<sub>3</sub>Al or NiAl particles [2,14]. Cavities and cracks appearing in these composites may be related to high tension promoted by this volume expansion. It should be pointed out that, in complex systems such as those studied in this work, which are very far from the equilibrium, it is not easy to predict the type of reaction phases that will appear or at which temperature or time they will nucleate, because not only the equilibrium phase diagrams should be known, which is not always possible, but also kinetics considerations should be taken into account.

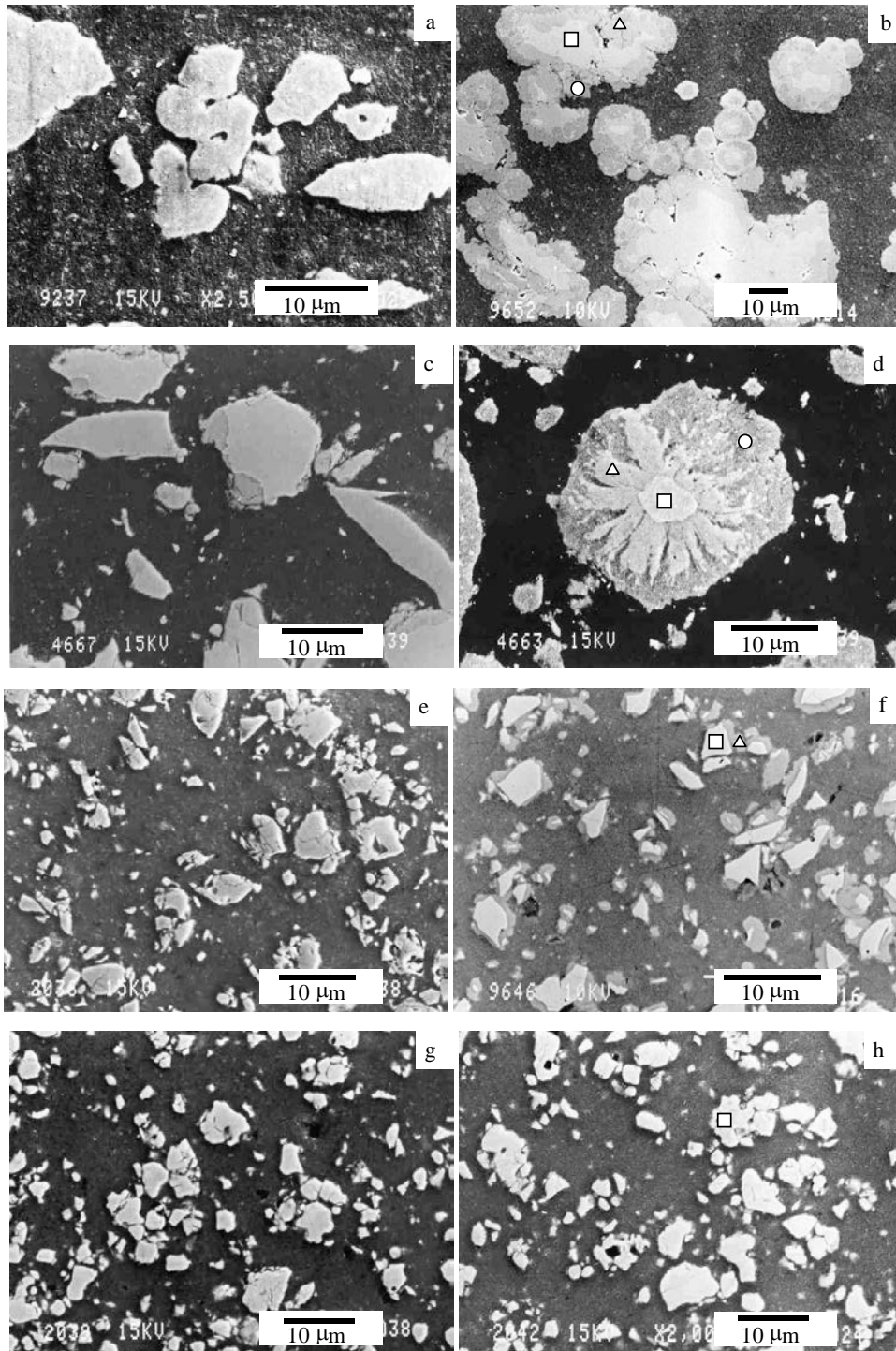


Fig. 1. Microstructure of a) 2124/Ni<sub>3</sub>Al in T1 and b) in T4 (□Ni<sub>3</sub>Al, ΔAl<sub>3</sub>Ni<sub>2</sub>, ○Al<sub>3</sub>Ni with Cu), c) 2124/NiAl in T1 and d) in T4 (□NiAl, ΔAl<sub>3</sub>Ni<sub>2</sub>, ○Al<sub>3</sub>Ni with Cu), e) 2124/Cr<sub>3</sub>Si in T1 and f) in T4 (□Cr<sub>3</sub>Si, ΔReaction phase), g) 2124/MoSi<sub>2</sub> in T1 and h) in T4 (□MoSi<sub>2</sub>).

Fig. 1e and f show the 2124/Cr<sub>3</sub>Si composite in T1 and T4, respectively. In the T1 condition, no reaction products could be observed by SEM at matrix-reinforcement interface. On the contrary, in T4 some dissolution of intermetallic particles has been detected, along with the appearance of a Cu-containing Al-Cr phase at the interface, Fig. 2. This phase is too narrow to be identified by SEM, but according to the ternary Al-Cr-Cu phase diagram [15], quite complex ternary phases are expected. A smaller amount of diffusion reaction products and defects such as cavities or cracks are produced in this case than in the Ni-aluminide composites.

Finally, Fig. 1g and h shows the microstructure of the 2124/MoSi<sub>2</sub> composite. One should note in this figure that no diffusion reaction products have been detected between matrix and reinforcement in either the T1 or T4 conditions. This indicates that the kinetics of transformation to the equilibrium state in this system is lower than in the former ones.

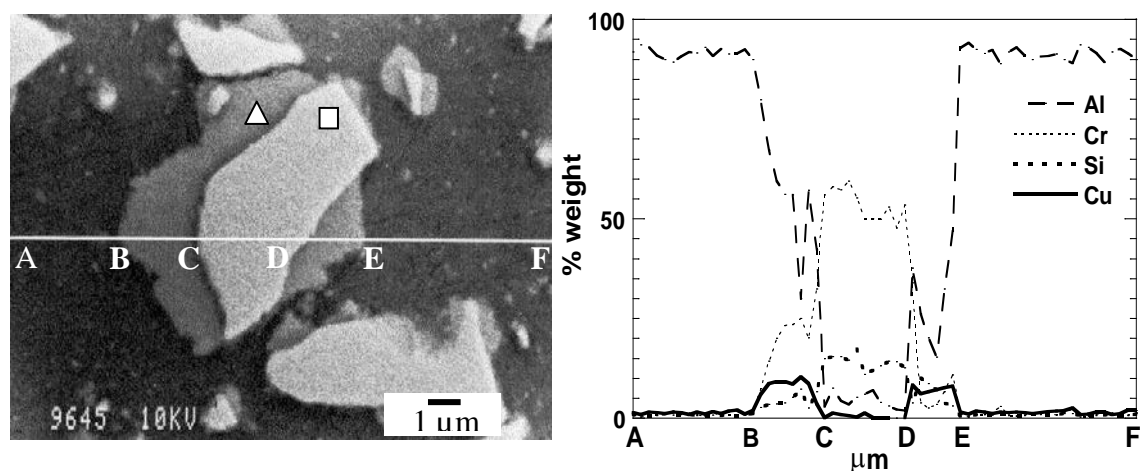


Fig. 2. 2124/Cr<sub>3</sub>Si composite in T4 and concentration lines of Al, Cr, Si and Cu (□Cr<sub>3</sub>Si, ΔReaction phase).

The parallelism between these microstructural features and the mechanical properties of the intermetallic reinforced composites presented in this work is evident in the sense that the composites that underwent fewer diffusion reactions were those that had better properties:

- Composites reinforced with Ni<sub>3</sub>Al, NiAl and Cr<sub>3</sub>Si developed new interphases during T4. Some of these interphases consume age hardening elements, such as Cu, from the matrix, diminishing its age hardening ability, and thus, the efficiency of the T4 treatment. On the other hand, brittleness of these composites can be related to these new interphases, which may be brittle themselves and/or their bonding to the matrix or to the reinforcing particles may be weak. In addition, the appearance of very large cavities and cracks in T4 in the aluminide reinforced composites would also explain the extreme fragility of these materials.

- The only intermetallic that did not present evident dissolution during the solid solution treatment was MoSi<sub>2</sub>, which is the only reinforcement that gave rise to a clear increase in the mechanical properties of the 2124 composite when passing from the T1 to the T4 condition.

These results indicate that in the aluminide and silicide reinforced composite investigated, the presence of interphases, at least in sizes detectable by SEM, invariably resulted in inferior mechanical properties. This negative effect of the formation of diffusion reaction products is not necessarily a general rule in composites, since some interfacial reactions have often been sought [16-19] to improve bonding between reinforcement and matrix.

Another noteworthy result of this work is that tensile properties of the 2124/MoSi<sub>2</sub> composite are higher those that of the 2124/SiC composite processed through the same route. Since, according to the literature [11], properties of the latter can be improved through optimized processing, it is expected that properties of 2124/MoSi<sub>2</sub> composite can also be improved in a similar manner if required. How to achieve this is the topic of current and future research, which involves optimization of, for example, reinforcement size range and mixing method. A study of matrix-MoSi<sub>2</sub> bonding to try to determine the mechanisms of stress transference between both components of the composite as well as its thermal stability is also in progress.

## Conclusions

Mechanical properties of 2124 aluminium alloy reinforced with 15 vol.% of Ni<sub>3</sub>Al, NiAl, Cr<sub>3</sub>Si and MoSi<sub>2</sub> powder particles are directly related with the thermal stability of the composites during processing and subsequent thermal treatment.

The best properties among the intermetallic reinforced composites are presented by 2124/MoSi<sub>2</sub>, which is also the most thermally stable.

The 2124/MoSi<sub>2</sub> composite presents higher YS, UTS and elongation to fracture than 2124/SiC processed by the same PM route.

## Acknowledgements

Financial support of the European Commission, project BRPR-CT-0547, and Spanish CICYT, project MAT98-1485-CE, is gratefully acknowledged. B. Torres acknowledges INASMET and CSIC for a grant in "Formación y Especialización en Líneas de Investigación de Interés Industrial".

## References

- [1] González Carrasco, J.L., García Cano, F., Caruana, G., & Lieblich, M. (1994). Mater Sci Eng A183, L5.
- [2] Lieblich, M., González-Carrasco, J.L., & Caruana, G. (1997). Intermetallics 5, 515.
- [3] Torres, B., Wang, Y., Lieblich, M., Ibáñez, J., Rainforth, W.M., & Jones, H. (2001). Z Metallkde 92, 604.
- [4] Williams, R.K., Graves, R.S., Weaver, F.J., & McElroy, D.L. (1985). High Temperature Ordered Intermetallic Alloys (p. 505). MRS Symp Proc 39.

- [5] Walston, W.S. & Darolia, R. (1993). High Temperature Ordered Intermetallic Alloys V (p. 237). MRS Symp Proc 288.
- [6] Díaz, C., González-Carrasco, J.L., Caruana, G., & Lieblich, M. (1996). Metall Mater Trans A 27A, 3259.
- [7] Wang, Y., Rainforth, W.M., Jones, H., & Lieblich, M. (2001). Wear 251, 1421.
- [8] Fleischer, R.L., Field, R.D., Denike, K.K., & Zabala, R.J. (1990). Metall Trans 21A, 3063.
- [9] Srinivasan, S.R., & Schwarz, R.B. (1992). J Mat Res 7, 1610.
- [10] McDanel, D. L. (1985). Met Trans A 16A, 1105.
- [11] Shin, K., Chung, D., & Lee, S. (1997). Metall Mater Trans A 28A, 2625.
- [12] Prince, A. (1988). Ternary Alloys 4 (p. 597). Petzow, G. & Effenberg, G. eds. VCH Verlagsgesellschaft GmbH, Weinheim, Germany.
- [13] Ferrer, C., Amigó, V., Salvador, M., Busquets, D., & Torralba, J. (1998). Rev Metal Madrid 34, 232.
- [14] Lieblich, M., González Carrasco, J.L., & García Cano, F. (1999). J Mater Sci Letters 18, 905.
- [15] Gosh, G. (1988). Ternary Alloys 4 (p. 311). Petzow, G. & Effenberg, G. eds. VCH Verlagsgesellschaft GmbH, Weinheim, Germany.
- [16] Ibrahim, I. A., Mohamed, F. A., & Lavernia, E. J. (1991). J Mater Sci 26, 1137.
- [17] Ueki, M., Naka, M., & Okamoto, I. (1996). J Mater Sci Letters 5, 1261.
- [18] Albiter, A., León, C. A., Drew, R. A. L., & Bedolla, E. (2000). Mater Sci Eng A289, 109.
- [19] Pandey, A. B., Mishra, R. S., & Mahajan, Y. R. (1996). Mater Sci Eng A206, 270.