Micromechanical characterization of Al 8090/SiC composites by nanoindentation

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The reinforcement of metallic alloys (mainly aluminum and magnesium) with hard ceramic particles (SiC or Al_2O_3) has been extensively studied. The addition of ceramic reinforcements improves the stiffness as well as the wear and creep resistance, and to a minor extent the strength [1, 2]. Further improvements in the elastic properties could be attained by using Al/Li alloys as matrices in these composites. The Young's modulus of aluminum alloys is increased by approximately 6% for every 1 wt.% of lithium and the density is reduced by 3%, which improves significantly the specific modulus of these materials [3]. For instance Al/Li-SiC composites exhibit elastic modulus over 100 GPa with relative densities around 2.6 leading to specific stiffness 50% above that of standard aluminum and titanium alloys [4].

The mechanical properties of metal matrix composites have been analyzed through micromechanical models which can be broadly divided into three groups: models based on the modified shear-lag approach, mean field models and models based on the finite element analysis of a unit cell, representative of the composite. All these methods are based on the properties of the matrix and the reinforcements and the damage micromechanisms experimentally observed [5, 6]. The mechanical response of the matrix is usually assumed as the behavior of the unreinforced alloy and the particle properties as the bulk ceramic. However, the microstructure of the matrices is modified due to the reinforcement. The observed dislocation density is higher, the grain size is reduced and the nucleation of incoherent precipitates is favored by the higher defect's density. For these reasons the matrices are expected to be harder than the unreinforced alloys. In addition, the mechanical properties of the ceramic reinforcements could be modified from those of the bulk ceramics as their processing and treatment could be rather different [7].

The evaluation of *in situ* mechanical properties of the composites' constituents is necessary to improve the accuracy of the predictions obtained by the models. However, this analysis has experimental limitations due to the small scale of the components, which makes difficult the use of conventional microindentation techniques to estimate the hardness of the individual constituents. To overcome these limitations it is proposed the use of nanoindentation, a technique developed over the last decades for probing the mechanical properties of materials at very small scale.

Nanoindentation has been used recently to evaluate *in situ* mechanical properties of metal matrix composites in a few papers. Matrix hardness has been estimated and related to the accelerated ageing behavior of these materials, the effect of particle clustering on residual stresses and the properties of the matrix-reinforcement interface [8, 9]. However, as far as the author's knowledge, there is not a systematic use of nanoindentation to evaluate the mechanical properties of the constituents in discontinuously reinforced metal matrix composites and this is the aim of this investigation. Nanoindentation should provide the hardness and Young's modulus of the metal matrix and the ceramic reinforcements.

The investigation was carried on a commercial Al/Li alloy 8090 reinforced with 15 vol.% of SiC particles. The material was supplied by Cospray (Banbury, United Kingdom) in the form of an extruded rectangular bar of 25.4×62.5 mm^2 cross section. This bar was produced by spray codeposition of the matrix and the particles onto a substrate. It was artificially aged to reach the peak-aged condition (T651). The size of the reinforcements was 7.5 ± 2.4 μm and the aspect ratio 2.4 ± 1.2. The particles were oriented with the longer axis in the extrusion direction. The average grain size of the matrix was 12 μm in the longitudinal direction, parallel to the extrusion direction, and 6 μm in the long and short transversal directions, perpendiculars to the extrusion direction. Further details about the microstructure of this material have been described elsewhere [4].

In a nanoindentation test, the surface of the material is indented by a hard tip with known properties (usually made of diamond). Several properties, such as the modulus of elasticity and the hardness, can be derived from the continuous measurement of load and depth of penetration [10]. The shape of the load-depth of penetration curve is an indication of the mechanical behavior of the material tested. Stiffness and strength at very local scales can be evaluated by means of nanoindentation, allowing the analysis of different phases. In the case of the Al 8090/SiC composite, two constituents should be characterized: the aluminum matrix and the ceramic reinforcement.

Fig. 1 shows the load–depth of penetration curves provided by indentations carried out with a Berkowich

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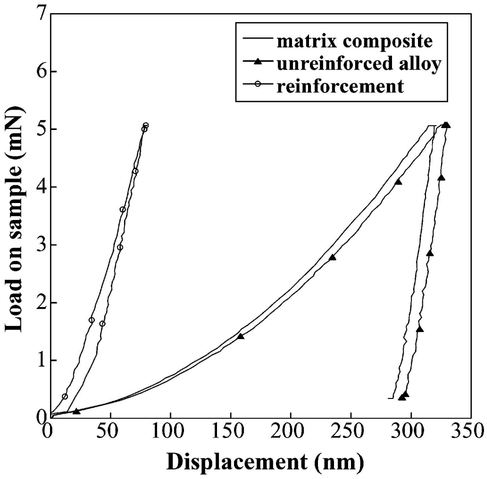

Figure 1 Experimental load–depth of penetration curves after nanoindentation tests.

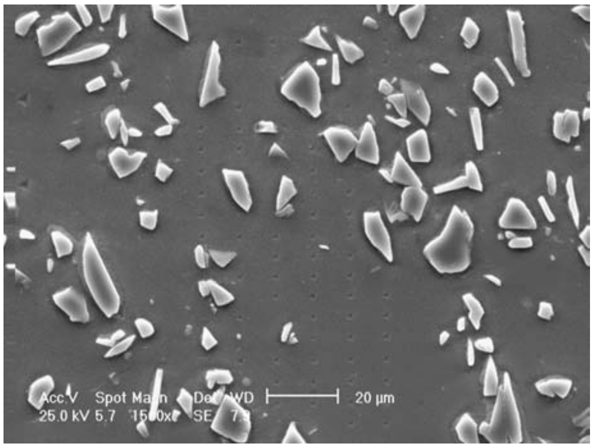

Figure 2 Microstructure and array of indentations of the Al8090-15% vol. SiC composite from scanning electron microscopy using secondary electron detector.

tip onto the composite and the unreinforced alloy. The comparison between the aluminum matrix inside the composite and the unreinforced alloy is remarkable. A typical ductile behavior is observed in both cases, but the small differences detected are enough to obtain significantly different values of hardness (Table I). The Young's modulus measurements are overlapped and it was expected no differences from the addition of ceramic reinforcement. However, the presence of subsurface particles could increase the Young' modulus measurement and also the scatter.

Nanoindentation tests were carried out with maximum loads ranging from 1 to 100 mN in the longitudinal and transversal directions of the original extruded bar. No appreciable differences of the modulus and hardness were observed for the matrix composite in both directions tested. The influence of load is also negligible at lower loads, although, properties obtained at 100 mN differed from those obtained at 1, 5 and 10 mN. Finally, indentations at maximum load of 5 mN were chosen to characterize the material.

Scanning electron microscopy was used in order to observe the small indentations and to study the influence of distance from particle reinforcement on the matrix properties. An array of nanoindentations in the composite is presented in Fig. 2. A summary of the experimental results is included in Fig. 3. Both hardness and Young's modulus are represented against the distance from the nearest particle together with the experimental band corresponding to the unreinforced alloy. Although several factors have undoubtedly influence on the results (maximum load, pile up effects, etc.) the behavior of the aluminum matrix is rather different of that observed in the unreinforced alloy. The hardness

TABLE I Young's modulus and hardness of unreinforced alloy and composite constituents measured by nanoindentation

	Bulk SiC [7]	Reinforcement SiC particles	Al8090 alloy	Matrix composite
Young's modulus (GPa)	414	300 ± 50	90 ± 2	98 ± 15
Hardness (GPa)	33	31 ± 6	1.86 ± 0.05	2.2 ± 0.2

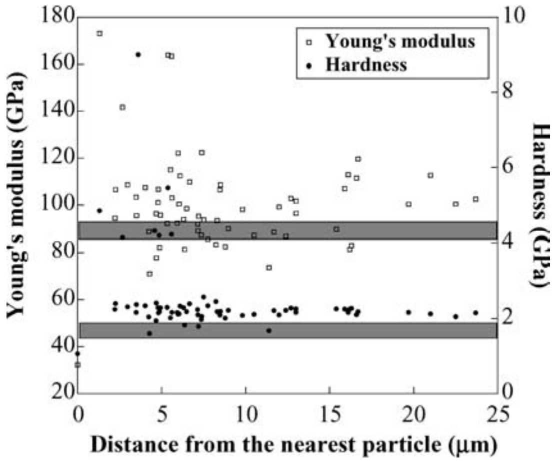

Figure 3 Young's modulus and hardness versus distance from the nearest reinforcement particle (values corresponding to the unreinforced alloy are represented as grey rectangles).

of the aluminum matrix shows a slow decrease with the distance to the nearest reinforcement particle, but even its lower value is around 15% higher than the hardness measured in the unreinforced alloy. This result is in agreement with the microstructure differences observed in reference [4]. On the other hand, the modulus variation is not clearly appreciated with the experimental scatter.

The ceramic reinforcement has also been analyzed. Silicon carbide is one of the ceramic reinforcement usually employed in metal matrix composites. Hardness and elastic modulus are well known for bulk silicon carbide, but these properties could be altered for the reinforcement particles as their manufacturing process is rather different. Table I compares Young's modulus and hardness measured in this work and the bulk values accepted in the literature [7].

In spite of the very well known difficulties associated with the relationship between indentation results and more general elastoplastic properties such as yield or ultimate strength, the need of taking into account these observations in the micromechanical models seems to be valuable. Unreinforced alloys and matrices show appreciably different properties.

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References
1. D. J. LLOYD, *Int. Mater. Rev.* **39** (1994) 1.
2. J. RODRÍGUEZ, A. MARTÍN and J. LLORCA, *Acta Mater* **48** (2000) 993.
3. K. K. SANKARAN and N. J. GRANT, *Mater. Sci. Eng.* **44** (1980) 213.
4. P. POZA and J. LLORCA, *Metal. Trans.* A **30** (1999) 845.
5. T. W. CLYNE and P. J. WITHERS, "An Introduction to Metal Matrix Composites," (Cambridge University Press, 1993).
6. P. POZA and J. LLORCA, *Metal. Trans.* A **30** (1999) 869.
7. D. W. RICHERSON "Modern Ceramic Engineering," (Marcel Dekker, Inc., 1992).
8. J. S. ZHANG, X. J. LIU, H. CUI, X. J. DUAN, Z. Q. SUN and G. L. CHEN, *Mater. Sci. Eng.* A **225** (1997) 96.
9. C. LIU, S. QIN, G. ZHANG and M. NAKA, *Mater. Sci. Eng.* A **332** (2002) 203.
10. W. C. OLIVER and G. M. PHARR, *J. Mater. Res.* **7**(4) (1992) 1564.

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