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# Friction stir welding of thick plates of aluminum alloy matrix composite with a high volume fraction of ceramic reinforcement

F. Cioffi [a], R. Fernández [a], D. Gesto [b], P. Rey [c], D. Verdera [b], G. González-Doncel [a,*]

[a] Centro Nacional de Investigaciones Metalúrgicas (CENIM) CSIC, Av. de Gregorio del Amo, 8, E-28040 Madrid, Spain
[b] Centro Tecnológico AIMEN, Planta de Tecnologías de Unión, C/Relva n° 27, E-36410 O Porriño, Spain
[c] Centro Tecnológico AIMEN, Área de Materiales y Procesos de Fabricación, C/Relva n° 27, E-36410 O Porriño, Spain

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The microstructure and mechanical properties of joints conducted by friction stir welding, FSW, at different rotational speeds in thick plates of a composite material with a high volume fraction of reinforcement, namely 2124Al/25vol%$SiC_p$, are studied. Original particle-free regions vanish during the stirring process, leading to a homogeneous particle distribution. Occasional breakage of some large particles occurs. Tunnel defects appear at low rpm, and disappear at high rotational speeds. The size of the thermo mechanically affected zone, TMAZ, increases with increasing rpm. Ductility of the welds in the range of 10–15% is achieved in compression tests whereas a rather brittle behavior is obtained in tension. A strength difference, SD, effect between compression and tensile test is obtained. This accounts for the little detrimental effect of the FSW process on the matrix–reinforcement interface. The SD effect is attributed to the presence of a microscopic residual stress.



## 1. Introduction

Discontinuously reinforced aluminum alloy metal matrix composites (MMCs), with ceramic particles in the range of 10–25 vol%, are known to exhibit higher Young modulus and strength [1,2], better wear resistance [3,4] and better high temperature properties than the corresponding monolithic alloys [5,6]. These improvements are accompanied by a very small increase in density, which makes these composites very attractive structural materials for many applications in the automotive and aerospace industries [3,7–9]. Furthermore, a noteworthy factor that makes them very attractive from the technological point of view relies in that their preparation takes advantage of conventional fabrication procedures used for monolithic alloys (casting, powder metallurgy, rolling, extrusion...). This implies limited modifications of already existing metal manufacturing plants and, hence, potential reduced cost in materials preparation in comparison, for example, to continuously reinforced composites [10,11].

The technological advantages of these materials, however, have not been yet fully exploited and their use is still restricted to very specific applications. Several reasons are usually suggested to explain this delay: it is believed that secondary operations such as welding [12,13], machining [14] and/or forging (extrusion, rolling,...) [15,16] involved in the manufacture of components imply difficulties which impede a massive use of these materials [12,14]. In particular, conventional fusion joining techniques present important drawbacks such as: reinforcement–matrix reactions; segregation of the reinforcement; high viscosity of the melt compared with that of the un-reinforced alloy; porosity derived from the occluded gas, and additional problems associated with the different coefficients of thermal expansion and conductivities between metal and ceramic particles [12,13, 17].

On the contrary, friction stir welding (FSW) is revealed as a promising alternative to the conventional methods to join MMCs [18–23]. The specific characteristics of this relatively new joining method are extensively described elsewhere [18,24–26]. Their advantages rely on a very unique characteristic: melting of the parent metal does not occur. As a consequence, the process is not detrimental for the original distribution of the ceramic particles. In fact, it can, instead, help to improve its homogeneity [27,28] As a drawback, however, it has been shown that the FSW parameters in these composites become more critical than for the corresponding un-reinforced alloys, and tunnel defects in the thermo mechanically affected zone, TMAZ, may easily appear [29]. Further efforts are, therefore, needed to understand the influence of the FSW process variables on the final microstructure in the joints of these composites.

In this work, the potentiality of this technique to joint plates of aluminum matrix composites with an elevated amount of reinforcement and high thickness is investigated: specifically, a 15 mm thick plate of 2124Al/25vol%$SiC_p$ composite has been

* Corresponding author. Tel.: +34 915538900x337.
*E-mail address:* ggd@cenim.csic.es (G. González-Doncel).

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studied. Taking advantage of the versatility of this technique the weld was conducted in two passes, one on each side of the plate, using a pin which length was about half of the plate thickness. To the best of these authors knowledge, no published work reports welds in plates of aluminum matrix composites of thickness above 8 mm [28,30,31]. Furthermore, joints of composites with a reinforcement content above 20% in volume have been rarely conducted using this technique [21,28,29,32,33]. In particular, the present study is focused on the microstructure and the mechanical properties of the composite joints obtained with different rotational speeds.

## 2. Materials and experimental details

The composite material studied was 2124Al/25vol%$SiC_p$ in the form of a 15 mm thick plate and denoted as AMC225xe by the supplier: Aerospace Metal Composites, AMC, UK. This composite is a high quality aerospace material produced by a proprietary powder metallurgy route and forged to the final thickness. The average SiC particle size is of about 2 μm.

The initial plate was sectioned in several pieces, with no extra care on the preparation of the surface edges to be joined: just a usual finishing from the mill was conducted to eliminate defects from the cuts. The pieces were heat treated to T6 condition. This consisted of a solution treatment at 530 °C for 2 h followed by quenching in oil bath at 20 °C and subsequent annealing at 160 °C for 18 h.

The welds have been carried out in two runs, one on each side of the plates, taking advantage of the PDS-4 Intelligent Stir FSW machine from MTS located in AIMEN. Both the advancing and the retreating sides coincide in the two runs. A 2-piece fix tool with a threaded pin (length of 7.62 mm) which included three ground flats was used. The shoulder diameter was slightly above 20 mm while the pin diameter varied from 7.95 to 6.35 mm. The internal face of the shoulder was not flat, but inclined 7° to create a conical surface. The shoulder and the pin were made on H13 steel (48 HRc) and MP159 alloy, respectively. Both the advancing and the retreating sides coincide in the two runs. Welds were conducted in the composite at increasing rotational speeds, namely: 300, 550, and 800 rpm, holding the advancing speed at 75 mm/min and a tilt angle of 1.5°. For security reasons, the machine operated under position control, trying to achieve the same force from the shoulder (about 8.5 kN). For this purpose, a slight change in the vertical tool position was required since different rotational speeds imply different heat inputs, different plastic behaviors of the material, and, hence, slightly different forces. In this manner, the variable of rotational speed is isolated, maintaining the remaining parameters nearly constant in the three experiments. Tool wear occurs during FSW of this composite [29,32]. This could be appreciated from the appearance of the pin at beginning and the end of each run (of approximately 250 mm total length). Therefore, the pin used in the welds performed at 300 and 550 rpm was replaced for a new one in the weld conducted at 800 rpm, the most severe wearing conditions.

The metallographic sections of the welds were prepared by conventional procedures. These involved grinding in successively finer sandpaper and polishing down to 1 μm diamond paste. In some cases, also etching with a solution of 0.5% HF in water was employed. Microstructural characterization was carried out using optical microscopy, OM, and scanning electron microscopy, SEM. Observations were carried out both before and after etching.

Ultra-micro hardness was measured using an automatic Berkovich indenter and a load of 300 mN on a transverse section of the weld conducted at 800 rpm, the one where no tunnel defects appeared. These measurements were done with the aim of distinguishing the different regions of the weld.

Finally, tensile and compression test have been conducted to evaluate the influence of the rotational speed on the mechanical properties of the joints. For this purpose, tensile specimens were machined with the tensile direction perpendicular to the welding direction such that the tunnel defects in the nugget were avoided. The samples were small, with a gauge length of 15 mm and a diameter of 2.5 mm, and threaded heads. The gauge length of these samples covered different microstructural regions developed in the welds. Tests were conducted at $1 \times 10^{-3}\,s^{-1}$ of initial strain rate. Due to the heat input provided by the stirring process, the precipitation state after welding will differ from that imposed by the initial T6 condition. For this reason, evaluation of the mechanical properties in the as processed and after a subsequent T6 conditions is required. As it will be shown, the ulterior T6 treatment accentuated the dispersion of the tensile behavior of the welds, leading frequently to a brittle behavior. Therefore, the compressive behavior of the welds was also evaluated in the as processed conditions. Compression samples were machined in the shape of small cylinders, of 3 mm in gauge diameter and 5 mm in length, with the same orientation as the tensile samples. For comparison, tensile and compression specimens machined from the base material (T6 condition) were also tested. The fracture surfaces of the tensile samples were observed using SEM and longitudinal cross sections were also observed by OM to identify the position of the fracture with respect to the weld center or the different microstructural zones.

## 3. Results and discussion

The microstructure of the composite shows a homogeneous distribution of the SiC ceramic particles if observed at low magnification. At high magnification, however, particle-free areas in the form of elongated regions and some particle agglomerates along parallel bands are visible, Fig. 1. The size of the particle-free areas ranges from 20 to 250 μm of length and 3–15 μm of width, and are uniformly distributed throughout the base material. The horizontal alignment of the particle-free regions, Fig. 1, is a consequence of the cold forging process used to reduce material thickness. Despite the severe deformation induced by this process, it seems that

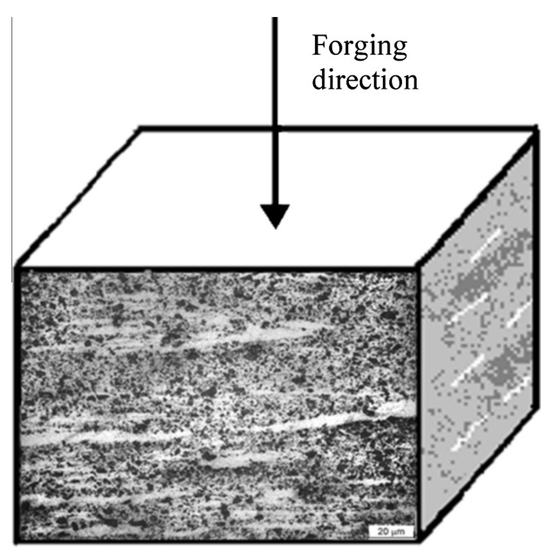


**Fig. 1.** Microstructure of 2124Al/25vol%$SiC_p$ composite material showing the reinforcement free zones and their orientation with respect to the forging direction. (Lateral view is a schematic representation constructed to complete the image).