# Effect of minor Sc and Zr addition on the mechanical properties of Friction Stir Processed 2024 Aluminium alloy

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The effect of Friction Stir Processing (FSP) on the mechanical properties of a Sc, Zr modified 2024 aluminium alloy was investigated in the present paper. The room temperature tensile properties of the material were obtained in longitudinal direction respect to the processing one and compared with those of the unstirred material and unmodified alloy. Tensile tests were also performed at higher temperatures and different strain rates in the nugget zone. The superplastic properties of the recrystallized material were evaluated and the differences with the parent material as a function of the strong grain refinement due to the Friction Stir Process were put in evidence. The high temperature behavior of the material was studied, in longitudinal direction, by means of tensile tests in the temperature and strain rate ranges of 450–525°C and $10^{-1}$–$10^{-3}$ $s^{-1}$ respectively. 

## Introduction

The presence of minor Sc and Zr produces, in Al Alloys, a strong increase in strength, ductility and Fatigue life [1]. This is due to the formation of very fine disperse $Al(Sc, Zr)_3$ particles acting as grain boundary pinners and than as grain structure stabilizers up to very high temperatures [2]. This aspect permits to increase the possible use temperatures of commercial Al-alloys. The strengthening mechanism is due to the coherent thermodynamically stable particles with ordered $L_{12}$ structure [3]. It has been demonstrated that a minor Sc and Zr addition in Al alloys is sufficient to raise the recrystallization temperature by 150°C [4].

It is clear that it is possible to achieve superplasticity at high strain rates, in conventional materials, by making a strong reduction in grain size; this can be obtained by using a process such as equa-channel-angular pressing or Friction Stir Processing in which the samples are subjected to a severe plastic deformation leading to a strong grain refinement.

The FSP process is a solid state process and therefore solidification structure is absent and the problem related to the presence of brittle inter-dendritic and eutectic phases is eliminated [5–7].

The Frictioned zone consists of a weld nugget, thermo-mechanically affected zone and a heat affected zone. The process results in the obtaining of a very fine and equiaxed grain structure in the weld nugget obtained through a continuous dynamical recrystallization process causing a higher mechanical strength and ductility.

The strong grain refinement produced by the process lead the microstructure to the fine dimensions proper of the possibility to exhibit superplastic properties [8–10].

In FSP the work piece does not reach the melting point and the mechanical properties of the material are much higher compared to the traditional techniques [11–13].

The aim of the present work is the study of the effect of minor Sc and Zr addition on the mechanical properties of 2024 aluminium alloy subjected to Friction Stir Processing.

## Experimental procedure

The material used in the present study was a commercial 2024 aluminium alloy with the addition of 0.26 Sc and 0.13 Zr (wt%), this Sc and Zr quantity was chosen because of the strong grain refinement effect observed in previous studies [14]. The used sheets with 5 mm

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thickness, were Friction Stir Processed by employing a steel flat tool with rotating speed of 1000 RPM and a traveling speed of 5.2 mm/s, the tool was rotated in the clockwise direction while the specimens, fixed at the backing plate, were moved. The nib was 4.5 mm in diameter and 4.8 mm long, and a 20 mm diameter shoulder was machined perpendicular to the axis of the tool; the tilt angle of the tool was 3°.

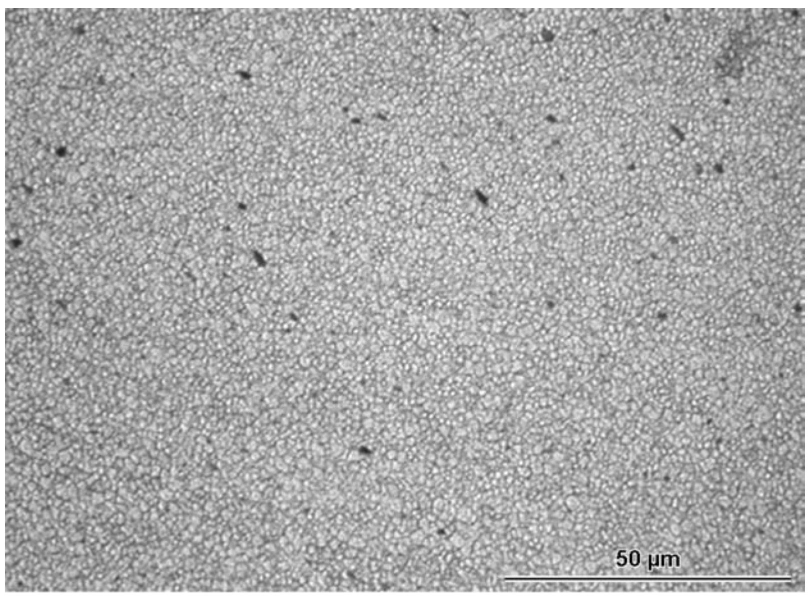
Tensile tests were performed in order to evaluate the mechanical properties of the material at room temperature and at higher temperatures (450–525°C) and different strain rates ($10^{-1}$–$10^{-3}$ $s^{-1}$) by employing specimens obtained by EDM from the nugget zone cut parallel to the processing direction; before tests, the surfaces of the specimens were mechanically polished in order to eliminate all the possible surface defects effects. The tensile tests were carried out using a LLOYD Instruments LR5K testing machine equipped with a resistance furnace.

The strain rate sensitivity coefficient ($m$) of the material was calculated employing the following equation:

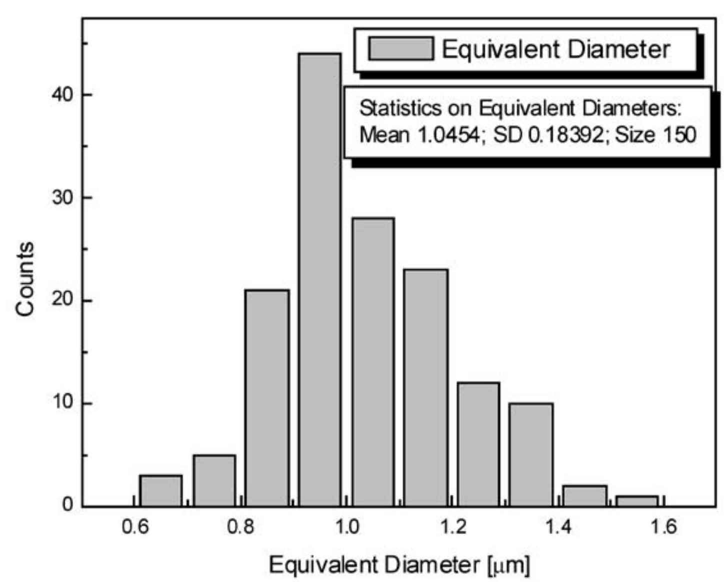
$$m = \left.\frac{\partial \log \sigma}{\partial \log}\right|_{\varepsilon,T} \tag{1}$$

The $m$ value was calculated by interpolating the data obtained by tensile tests at an equivalent strain of one. The cubic interpolation was applied between $\sigma$ and $\dot{\varepsilon}$ logarithmic values.

Surfaces were prepared by standard metallographic techniques and etched with Keller's reagent and grain




(a)




(b)

*Figure 1* Very fine and uniform microstructure observed in the nugget zone (a), revealing a mean grain size of 1 micron (b).

structure of the severely deformed zone was characterized by optical microscopy.

## Results and discussion

The AA2024 modified by the addition of minor Sc and Zr 5 mm sheets were successfully processed by FSP and no superficial porosity or defects were observed in both top and rear surface.

Light microscopy observations were widely performed on the transverse cross-sections of the specimens, the FSP process of the Sc and Zr modified 2024 aluminium alloy revealed the classical formation of the elliptical "onion" structure in the center of the specimen; this is a structure characterized by fine and equiaxed recrystallized grains (Fig. 1a), the higher temperature and severe plastic deformation results in grains smaller than the base metal, such process is strongly favored by the precipitation of the very fine $Al_3$(Zr, Sc) particles; the statistical analysis performed on 150 grains revealed a mean equivalent diameter dimension very close to one micron (Fig. 1b).

The tensile behavior of the studied material in the as received and FS processed conditions is plotted in Fig. 2 and compared with the unmodified 2024 aluminium alloy. The presence of minor Sc and Zr produces a strong increase in mechanical properties respect to the unmodified condition while the FSP produces an increase in the elongation to failure accompanied with a small decrease in strength; such FSP beneficial effect on room temperature tensile strength was demonstrated recently for different commercial Al-alloys [15, 16]. The effectiveness in grain refinement and mechanical properties stability was widely demonstrated also by other scientists by characterizing some Al-alloys with Sc and Zr addition similar to the same used in the present study [17, 18].

The Fig. 3 summarizes the flow stress behavior of the material as a function of strain rate at all the testing temperatures of the present study in a form of double logarithmic plot, the value used in the plot is relative to a true strain of one.

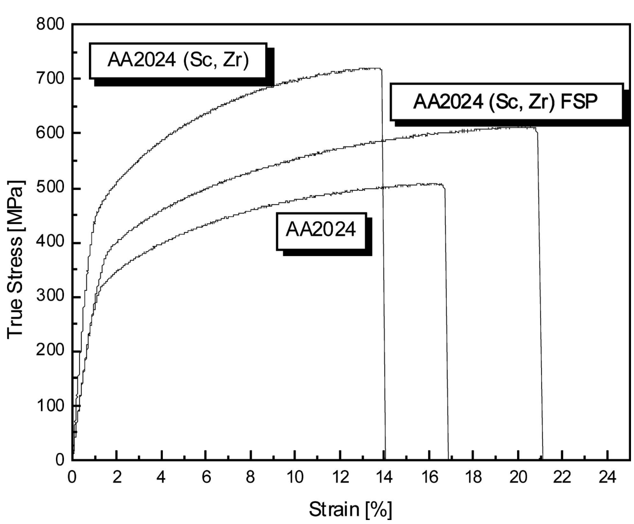



*Figure 2* Room temperature tensile response of FSP Sc and Zr modified alloy compared with the tensile behavior of unstirred (AA2024) and unmodified alloys (AA2024 (Sc, Zr)).

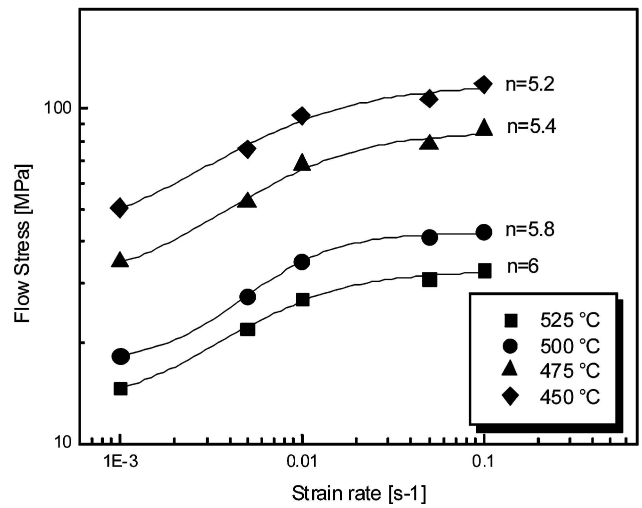



*Figure 3* Flow stress behavior of the material as a function of strain rate at all the testing temperatures.

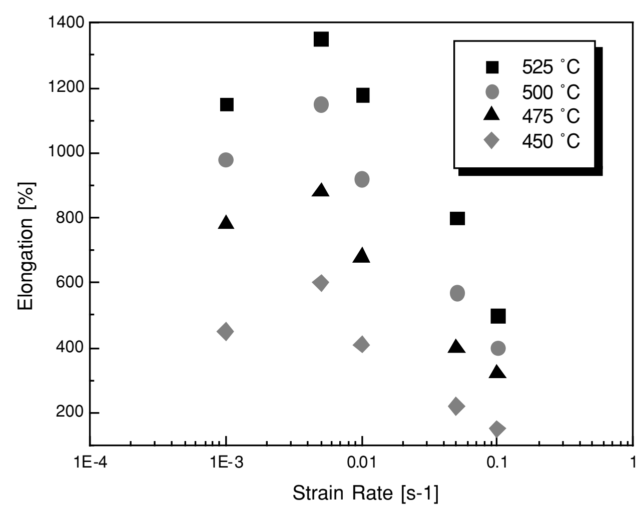



*Figure 4* Variation of the total elongation to failure as a function of the different initial strain rate.

A superplastic typical sigmoidal behavior of the flow stress with the initial strain rate for all the investigated temperature identifying three different regions of superplastic deformation was recognized, an increase in flow stress as increasing strain rate and decreasing temperature was observed for all the studied conditions. The apparent stress exponent, $n$, was determined from the plots as an inverse of the slope showing a variation from 5.2 at 450°C to 6 at 525°C.

The variation of the total elongation to failure as a function of the different initial strain rate is shown in Fig. 4, the tensile ductility decrease as increasing the strain rate for all the temperatures investigated reaching good levels of deformation in the high strain rate regime for the higher temperatures investigated, the presence of $Al_3$(Zr, Sc) particles favors the retaining of the ultrafine grain size

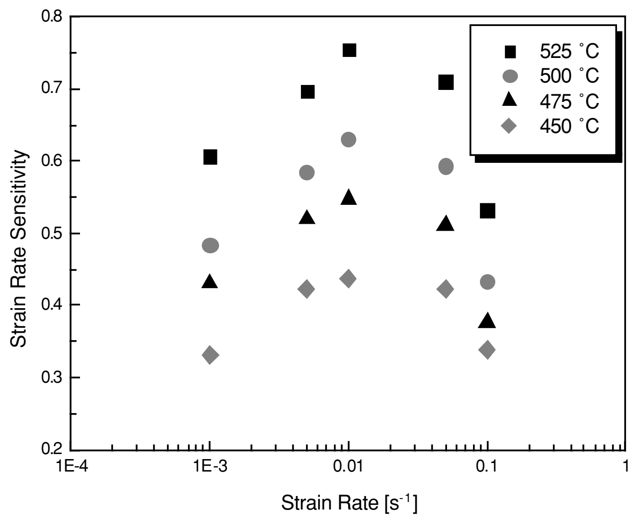



*Figure 5* Strain rate sensitivity variation as a function of strain rate for all the temperatures.

at the higher temperatures [19], leading to the exhibition of exceptional ductility and reduced flow stress respect to the unmodified alloys in Friction Stir Processed conditions [20, 21]. In [20] the possibility to achieve superplasticity in commercial 2024 Al-alloy via FSP has been widely demonstrated, in the present study it is shown the enhanced improving of such properties thanks to the addition of minor Sc and Zr.

As it can be seen in the Fig. 5, the maximum of the strain rate sensitivity, calculated at a true strain of one, is high at temperature ranging from 500–525°C.

The low temperature regime, the maximum of the strain rate sensitivity is relatively lower than that in the high temperature regime. It was observed a characteristic feature of the superplastic behavior of the material with an high strain rate sensitivity of the flow stress. In addition, very large elongations were observed in the temperature and strain rate ranges, where high m values were found; the maximum ductility and the highest *m* values were recorded in the intermediate superplastic region, the same superplastic behavior was also observed by other alloys reinforced with Sc and Zr (with quite similar Sc and Zr addition) produced by Equa Channel Angular Pressing [22], revealing the stability of grain size produced by severe plastic deformation in the same way of FSP.

## Conclusions

The effect of minor Sc and Zr addition on the superplastic behavior of a 2024 aluminium alloy was investigated in the present study. The material was Friction Stir Processed showing good strength and ductility values at room temperature because of the very fine structure, revealing an increase in room temperature ductility respect to the unstirred material. The tensile tests performed in the temperature range 450–525°C at different strain rates showed the occurrence of high ductility and high strain rate sensitivity levels at testing strain rates above $10^{-2}\ s^{-1}$.

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