Mechanical properties of aluminium-based metal matrix composites reinforced with α-alumina platelets

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ABSTRACT
The tensile properties of an aluminium-based metal matrix composite reinforced with α-alumina platelets were investigated from an experimental and a theoretical point of view. An increase in Young modulus, 0,2% proof stress, flow stress and ultimate tensile strength was observed over the unreinforced metal. These improvements were obtained at the expense of the tensile ductility. The experimental results were analyzed using both a dislocation model and a continuum model based on an iterative Eshelby method.

1. INTRODUCTION

Particulate metal matrix composites have been shown to exhibit significant improvements in certain physical and mechanical properties over their monolithic metallic counterparts. However, as the mechanical properties of the composite material are strongly dependant on the microstructural parameters of the system matrix-reinforcement, a judicious selection of a certain number of variables has to be achieved to optimize the properties of the composite. In particular, the shape, size, volume fraction and the orientation of the reinforcing particles, as well as the matrix composition or its thermal heat treatment have to be carefully chosen. In this paper, we will examine the strengthening of a squeeze-cast aluminium matrix composite reinforced with α-alumina platelets, several microstructural parameters of which were investigated.

2. MATERIALS AND EXPERIMENTAL PROCEDURE

2.1 Materials

The composite studied is an aluminium-based metal matrix composite reinforced with preforms elaborated by Elf-Atochem. These preforms consist of randomly oriented hexagonal and monocrystalline α-alumina platelets. The size of the platelets, which is defined by two parameters : a diameter (d) and a thickness (t), may vary depending on the synthesis conditions, as can be seen in table 1. However, whatever their size, the platelets have a mean aspect ratio which ranges from 1/20 to 1/10. The volume fraction of the platelets in a preform may vary between 15 and 35%.

Two aluminium matrixes (either an A9 pure aluminium matrix (99,9% Al) or a 6061 aluminium alloy (1% Magnesium, 0,6% Silicon)) were used to elaborate by the squeeze-casting technique the composite materials (Figure 1). The combination of different types of preforms with the two aluminium matrixes allowed us to study the influence of the variable parameters of the material on the tensile properties.

Table 1 : Definition of the different types of platelets

Type of platelets	Diameter d(μm)	Thickness t (μm)	Mean aspect ratio (t/d)
T1	5-10	0,5	1/15
T2	10-15	1,0	1/12,5
T3	15-25	1,2	1/16,5

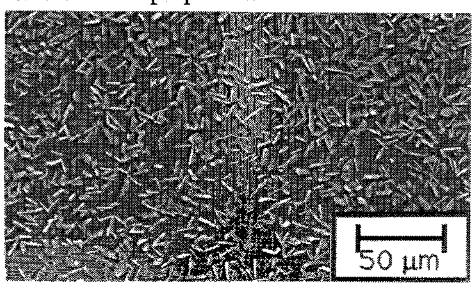


Figure 1 : Composite Al / α–Al_2O_3 platelets

2.2 Experimental procedure

The tensile tests were performed on flat bar tensile specimens, using an extensometer bonded to each side of the specimens. The true stress-true strain curves obtained allowed us to determine the tensile properties of the different types of composites : Young modulus, 0,2% proof stress ($\sigma_{E0,2}$), ultimate tensile strength and strain to failure. The pure aluminium matrix composites were tested in the as-cast conditions, whereas the 6061 matrix composites were tested after a 2 hour solution heat treatment at 535°C followed by a water-quench and by a 4 hour aging treatment at 175°C (T6 state) or by no aging treatment (T0 state).

3. RESULTS : TENSILE PROPERTIES OF THE COMPOSITE MATERIALS

The tensile tests results obtained for the different types of composites are plotted in figures 2, 3 and 4. In figures 2 and 3, the effect respectively of the size of the platelets and of their volume fraction on the stress-strain curve of the A9 aluminium matrix composite is clearly evidenced. In figure 4, the effect of the matrix composition and of its thermal heat treatment is shown.

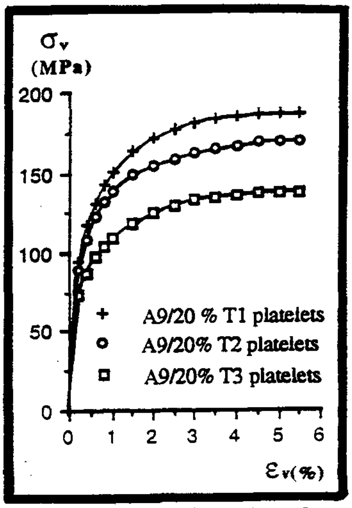


Figure 2 : Effect of the size of the platelets

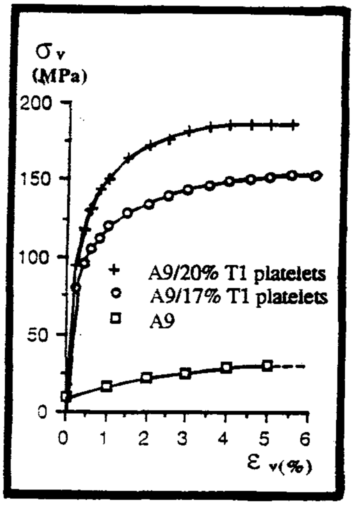


Figure 3 : Effect of the volume fraction of the platelets

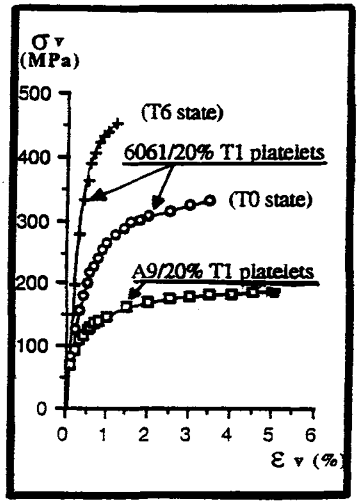


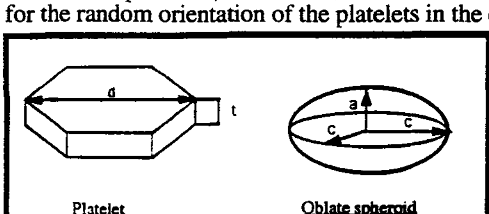
Figure 4 : Effect of the matrix composition and of its thermal heat treatment

4. DISCUSSION

In this section, we will attempt to justify the experimental observations in the light of theoretical considerations. A particular emphasis will be laid on the effect of the microstructural parameters investigated on the tensile properties.

4.1 Young modulus

To account for the values of Young moduli, an iterative Eshelby method developped by Hamann et al [1] was used. This method allows to calculate the elastic moduli and the internal stress fields of a composite material containing several families of ellipsoïdal inclusions. In the calculations, as shown in figure 5, the platelets were represented by oblate spheroïds. Nine families of oblate spheroïds allowed us to ensure a correct simulation of the material. The representative inclusions of each family were characterized by the same elastic constants, the same aspect ratio $a/c=t/d$ (<1) and the same volume fraction $f_I = F/9$ (where F is the total volume fraction of the oblate spheroïds). However, various orientations were attributed to the inclusions in order to account for the random orientation of the platelets in the composite.



$c=d/2$
$a=t/2$

Figure 5 : Simulation of the morphology of the platelets by oblate spheroïds

The typical values which were chosen to perform the calculations are summarized in table 2. It should be noticed that in the simulations, the platelets were assumed elastically isotropic although they are monocrystalline. It was done keeping in mind that the plalelets are randomly oriented, thus leading to a macroscopically isotropic material. In table 3, we reported the experimental and calculated Young moduli. A very good agreement between the theoretical and experimental results is observed.

Table 2 : typical values of the parameters

	Matrix	Reinforcement
Young modulus	-A9 : 62 GPa -6061 : 69 GPa (T6 state)	Al_2O_3: 380 GPa
Poisson's ratio	0,33	0,25
Aspect ratio of the platelets	—	1/15
Volume fraction	80%	20%

Table 3 : comparison between the experiment and the theory

	Experimental values	Theoretical values
Al / Al_2O_3	95	95
6061 / Al_2O_3	104	102,8

A further investigation on the influence of the volume fraction and of the aspect ratio of the reinforcement showed us that there was a very good correlation between the experimental and theoretical evolutions [2].

4.2 Strength of the composite : 0,2% proof stress, flow stress

In this paragraph, we will successively review the mechanisms generally recognized as contributing to the increase in the 0,2% proof stress and more generally to the increase in the flow stress of MMCs (over the unreinforced metals). After a brief general survey, we will assess the contribution of each strengthening mechanism on the 0,2% proof stress of a pure aluminium matrix composite reinforced with alumina platelets.

4.2.1. Strengthening mechanisms : general study

---> *Strengthening of the matrix metal of the MMC over the unreinforced metal*

As evidenced by several authors [3]-[4], the microstructural state and subsequently the mechanical properties of the matrix material are very different from those of the unreinforced metal. It is mainly due to the generation of dislocations during the cooling of the MMC and to a decrease in grain and subgrain size.

- The first mechanism results from the relaxation of the internal thermal stress field induced by the difference in coefficient of thermal expansion (CTE) between the matrix and the reinforcement $\Delta\alpha$. The relaxation of the misfit strain ($\varepsilon_{ij}^{*th} = \Delta\alpha.\Delta T.\delta ij$) by the generation of dislocations leads to an increase in the yield stress of the matrix $\Delta\sigma_{CTE}$. It may be estimated by :

$$\Delta\sigma_{CTE} = \gamma.\mu.b.\sqrt{\rho} \quad (1)$$

where γ is a constant close to 1, μ and b are the shear modulus and Burgers vector of the matrix metal and $\bar{\rho}$ is the average dislocation density in the matrix. The preceding analysis assumes that the dislocations are uniformly smeared-out in the matrix. In the case of a pure aluminium matrix, this assumption seems to be reasonable, since the friction stress (which is opposed to the dislocation motion) is very weak. As a result, the dislocation motion and the relaxation of the internal stress field is considerably favoured.

- The second Hall and Petch type mechanism is supposed to be effective only for small grain sizes (<10 µm). For larger grain sizes, this mechanism can be considered as being negligible.

- From the above considerations, the yield stress of the matrix σ_y may be estimated as being the sum of the yield stress of the unreinforced metal (σ_0) and of $\Delta\sigma_{CTE}$:

$$\sigma_y = \sigma_0 + \Delta\sigma_{CTE} \quad (2)$$

In this analysis, we will consider that the matrix has an elastic-perfectly plastic behaviour, that is to say that there is no work-hardening of the matrix metal .

---> *Effect of the mean matrix stresses*

Particulate MMCs are characterized by internal stress fields, which are supposed to affect their flow strength. In particular, the long range (or mean) stresses in the matrix are likely to have a significant effect on the 0,2% proof stress and on the flow stress at larger strains of the composite. The effect of the mean matrix stresses can be assessed by using the approach of Arsenault and Taya [5]. They showed that when a composite is loaded in tension along the x3-axis, then the applied stress σ_A is related to the yield stress of the matrix σ_y and to the internal stress in the inclusions. In terms of mean matrix stress and in the particular case where the composite is isotropic in the 1-2 plane, the relation can be written as follows :

$$\sigma_A = \sigma_y - \langle <\sigma_{33}>_M - <\sigma_{11}>_M \rangle_{total} \quad (3)$$

It should be noted that by using a Tresca type criterion, Withers et al [6] obtained the same results.
The mean stress $<\sigma_{33}>_M - <\sigma_{11}>_M$ $_{total}$ in the matrix can be divided in three components :

- ---> a thermal mean stress due to the CTE misfit strain not relieved by the generation of dislocations, thus leading to thermal residual stresses.
- ---> a mean stress due to the applied stress σ_A
- ---> a mean stress due to the plastic strain ε_p defined by :
  $\varepsilon^p_{11}=\varepsilon^p_{22}=-\frac{1}{2}\varepsilon^p$, $\varepsilon^p_{33}=\varepsilon^p$ for a plastic loading along the x3-axis

The Eshelby's equivalent inclusion method allows to calculate the contributions to the mean stress in the matrix. It can be easily shown that the contributions due to σ_A and ε_p can be expressed in a simple way :

$$\text{--->} \quad <\sigma_{33}>^A_M - <\sigma_{11}>^A_M = B \times \sigma^A \quad (4.1)$$

$$\text{--->} \quad <\sigma_{33}>^P_M - <\sigma_{11}>^P_M = C \times \varepsilon^P \quad (4.2)$$

The contribution due to the thermal mean stress is in general more difficult to assess. Withers et al [6] showed that under certain (oversimplified) hypothesis, the following expression can be established:

$$\text{--->} \quad <\sigma_{33}>^{th}_M - <\sigma_{11}>^{th}_M = A \times \Delta\,\alpha.\Delta T' \quad (4.3)$$

where $\Delta T'$ ($< \Delta T$) is a parameter describing the residual stress state.

In such conditions, it can be easily demonstrated that relation (3) is equivalent to relation (5) :

$$\sigma_{yc} = \frac{\sigma_y - A \times \Delta\alpha.\Delta T' - C \times \varepsilon^P}{1+B} \quad (5)$$

where σ_{yc} is the flow stress of the composite and σ_y is defined by relation (2). The 0,2% proof stress can be evaluated from relation (5) setting ε^P equal to 0,2 %.

The mean matrix stresses related to σ^A and ε^P contribute to an increase in the flow stress of the composite, since B (which verifies 0<1+B<1) and C are negative terms. They are referred to in the literature as back stresses since they reduce the mean matrix stress, thus hindering flow and increasing the flow stress.
The thermal residual stress may either increase or decrease the strength depending upon the reinforcement geometry and its relative orientation with respect to the loading direction.
Lastly we will notice that the model assumes a linear work-hardening of the composite material, the work-hardening rate being defined by the ratio h=-C / (1+B).

4.2.2. Evaluation of the contribution of the different strengthening mechanisms on the 0,2% proof stress of the composite investigated

As already mentioned, the platelets can be represented by oblate spheroïds of aspect ratio a/c=t/d in the calculations. To calculate the 0,2% proof stress of the composite from expression (5), $\Delta\sigma_{CTE}$ and the contribution of the mean matrix stresses have to be evaluated in the particular case where the reinforcing particles are randomly oriented platelets.

---> *Evaluation of $\Delta\sigma_{CTE}$*

The calculation of $\Delta\sigma_{CTE}$ necessitates the knowledge of the average dislocation density in the matrix $\bar{\rho}$. In the case of a MMC reinforced with oblate spheroïds, $\bar{\rho}$ was determined analytically by Lulay [7], who assumed that the CTE mismatch strain is relaxed by the punching of prismatic loops along the disk-plane (x1,x2 axis) (Figure 6) but not along the x3-axis.

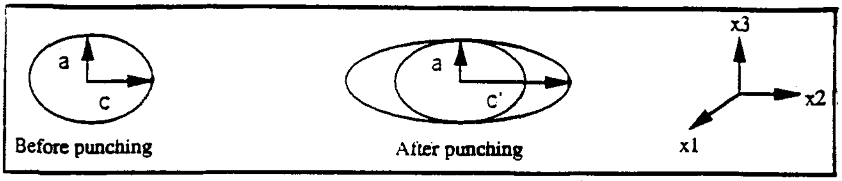


Figure 6

Once the punching distance c' has been calculated, the average dislocation density in the matrix can be easily evaluated from :

$$\bar{\rho}=\frac{3\,\pi \times \alpha' \times f}{4 \times a \times b \times (1-f)} \times \sqrt{2 \times (1+\beta^2)} \qquad (6)$$

where α' is a coefficient depending on the punching distance c', the aspect ratio β=a/c and the volume fraction f of the particles. It also depends on the CTE misfit strain ($\Delta\alpha.\Delta T$). A combination of relations (1) and (6) allowed us to assess the contribution of $\Delta\sigma_{CTE}$ on the strengthening of the composite investigated.

---> *Effect of the mean matrix stresses*

-The thermal residual stress field should not affect significantly the flow stress of our composite.Indeed, it can be shown [7] that in a composite reinforced with randomly oriented oblate spheroïds, the thermal residual stress field is hydrostatic (although the relaxation of the CTE misfit strain occurs only along the disk-plane). On the other hand, as already mentioned, in a pure aluminium matrix, the thermal stress field is supposed to be almost entirely relaxed.Thus, these two reasons imply that : $<\sigma_{33}>_M^{th} - <\sigma_{11}>_M^{th} = 0$.

-The contribution of the mean matrix stresses due to σ^A and ε^p necessitates an evaluation of the constants B and C defined previously. They were determined using the iterative Eshelby method already described, taking into account nine families of oblate spheroïds.

---> *Theoretical results. Comparison with the experimental observations*

A parametric study was conducted in order to examine the effect of the aspect ratio, size and volume fraction of the platelets on the 0,2% proof stress of our composite. In this study, a single parameter to be focused on was used as a variable, whereas the remaining parameters were set equal to their typical values shown in table 4. The other data necessary for the evaluation of $\Delta\sigma_{CTE}$ are summarized in table 5. It should be noted that we chose a value of ΔT equal to 200°C. It is supported by the observations of Vogelsang et al [4], who observed in an in-situ TEM experiment, that the generation of dislocations during the cooling from an elevated temperature of a 20% particulate MMC started only at 500K. Moreover, the work of Seyed et al [8] performed on a 6061 matrix composite reinforced with 20 % SiC particles showed that only below 573K, the effect of the thermally induced dislocations is significant. Above this temperature, recovery phenomena may lead to an annihilation of the emitted dislocations. As recovery is supposed to be enhanced in a pure aluminium matrix , we chose a temperature drop of 200°C.

Table 4 : Typical values of the parameters

Parameter	Typical value
Aspect ratio : a/c	1/10
Size : a (µm)	0,25
Volume fraction (%)	20

Table 5: Values of the data used to evaluate $\Delta\sigma_{CTE}$.

Data	Value
γ	1
Shear modulus of the matrix	23,3 GPa
Burgers Vector of the matrix	$2{,}86\times10^{-10}$ m
$\Delta\alpha$	16×10^{-6}/°C
ΔT	200°C

In figures 7, 8 and 9, we plotted the contribution of $\Delta\sigma_{CTE}$ and of the mean matrix stresses due to σ^A and ε^p (for ε^p =0,2%) on the 0,2% proof stress as a function of the aspect ratio, size and volume fraction of the platelets. Moreover, the 0,2% proof stress obtained from relation (5) was reported. The contribution due to ε^p (for ε^p =0,2%) is $\Delta\sigma_\varepsilon = -$ Cx0,002,whereas the contribution due to σ^A is $\Delta\sigma_{\sigma A} = \sigma_{E0,2} - (\sigma_y - \Delta\sigma_\varepsilon)$. It appears that the effect of σ^A and ε^p on the 0,2% proof stress is not negligible. However, it should be

noted that as expected, there is no dependance of the contribution due to ε^p with the size of the platelets. It is due to the fact that the size of the platelets is not taken into account in the Eshelby analysis.
To complete our study, we reported, in figures 8 and 9, the experimental values of 0,2% proof stress of the pure aluminium matrix composites, assuming that the platelets have a mean aspect ratio of 1/10. We observe experimentally as well as theoretically that the strengthening of our composite is all the more important as the platelets have a small size and a high volume fraction. The experimental values are sligthly below the predicted values. However, the model accounts rather well for our experimental observations.

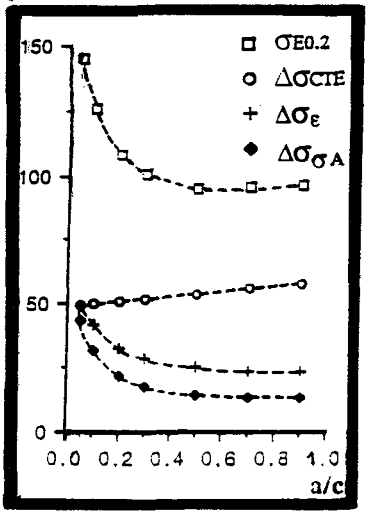


Figure 7 : Effect of the aspect ratio of the platelets

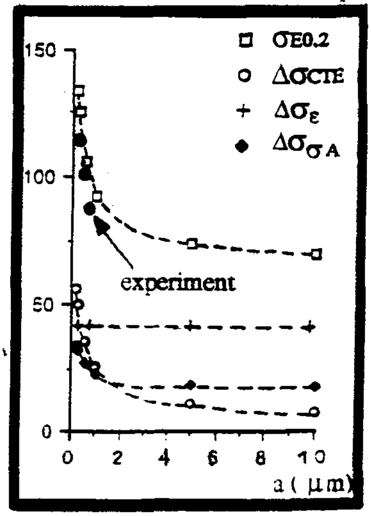


Figure 8 : Effect of the size of the platelets

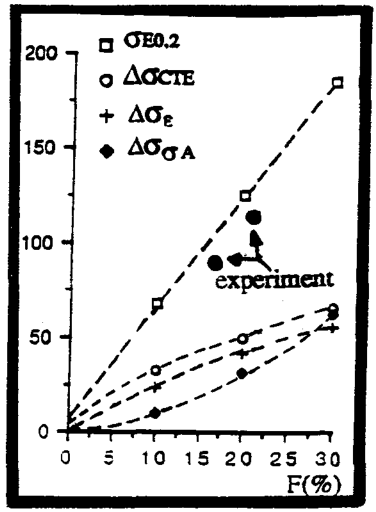


Figure 9 : Effect of the volume fraction of the platelets

5. CONCLUSIONS

The study showed the influence of several microstructural parameters on the tensile properties of a metal matrix composite reinforced with α-alumina platelets. The main conclusions of our study can be summarized as follows :

1-An iterative Eshelby method allowed us to account for the experimental values of Young moduli. A good agreement was observed between the experiment and the theory.

2-The strengthening mechanisms can be analyzed using a model based on punched-out dislocations and a continuum approach. The experimental observations were confirmed by the calculations.

3-The platelets used in this study are characterized by a small ratio thickness to diameter and by a small thickness. It places them in the range of values where the Young moduli are high and where the strengthening mechanisms are very efficient.

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