STUDY ON THE EFFECT OF SHOT PEENING ON THE RESIDUAL STRESS IN Al-SiC COMPOSITE

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ABSTRACT

Silicon carbide whiskers and particulates reinforced aluminium alloys show promise as metal matrix composites stiff and high-strength light-weight applications.

The magnitude of the residual stress have a very important effect on the yield stress and fatigue strength of the metal matrix composite.

Many techniques are available for residual stress measurement on mechanical parts. X-ray diffraction, bending deflection and hole drilling are three techniques which are commonly used.

This paper shows a study on the measurement of residual stress on the MMC components by the incremental hole drilling method and the X-ray diffraction method. The modified hole drilling method is used for measuring the macroscopic residual stress gradient in depth and the X-ray method is applied to study the surface residual stresses in the matrix.

Different aluminium matrices (2124, 6061) and different SiC fiber proportions have been tested. The effects of shot-peened treatment on the residual stress distribution of these materials will be analysed and compared.

Comparison between measurement with the X-ray diffraction method and the incremental hole drilling method will be also be shown.

KEYWORDS

Residual stresses , metal matrix composite , X-ray method , hole drilling method , 2124 , 6061, shot peening , machining, volume fraction, triaxial state stress.

INTRODUCTION

Advanced composites show considerable promise for weight and volume critical applications, for example, aircraft and space vehicles. Aluminium alloys reinforced with SiC whiskers and particulates are new, potentially useful, structural materials with high strength and high modulus.

When a metal matrix composite (MMC) is cooled down to room temperature from the fabrication or annealing temperature, residual stresses can be induced in the composite due to the mismatch of the thermal expansion coefficients between the metal matrix and the reinforcement. The magnitude of the residual stress has a very important effect on the yield stress and fatigue strength of the metal matrix composite.

Many techniques are available for residual stress measurement on mechanical parts. X-ray diffraction, bending deflection and hole drilling are three techniques which are commonly used [1]–[3]. In this study, the X-ray method and the hole drilling method are used.

METHODS OF MEASUREMENT OF RESIDUAL STRESS

X-ray stress measurements

(a) General principle

When using atomic planes as strain gauges, it is possible to achieve non destructive X-ray stress measurements in crystalline materials.

The strain $\varepsilon_{\phi,\psi}$ in the ϕ,ψ direction (fig.1) is given by the general relation:

$$\varepsilon_{\phi,\psi} = \frac{1+\nu}{E} \{[\cos^2\phi\,(\sigma_{11}-\sigma_{33})+\sin^2\phi\,(\sigma_{22}-\sigma_{33}) + \sin 2\phi\ \sigma_{12}]\sin^2\psi + [\cos\phi\,\sigma_{13}+\sin\phi\,\sigma_{23}]\sin 2\psi\} + \frac{1}{E}[\sigma_{33} - \nu(\sigma_{11}+\sigma_{22})] \quad (1)$$

where E and υ are the bulk mechanical constants of the material.

Using X-ray elastic constants values S_1 and $1/2.S_2$ corresponding to the (hkl) set of atomic planes chosen for the measurement in the material, $\varepsilon_{\phi,\psi}$ can be written as follows:

$$\varepsilon_{\phi,\psi} = \frac{d_{\phi,\psi} - d_0}{d_0}$$

where $d\phi,\psi$ is the atomic interplanar spacing of the (hkl) set of planes in the ϕ,ψ direction and d_0 is the atomic interplanar spacing of the same set of planes for an unstressed specimen.

The last expression in equation 1 corresponds to the normal strain ε_N which can be written :

$$\varepsilon_N = \frac{d_N - d_0}{d_0}$$

where d_N is the spacing of (hkl) atomic planes which are parallel to the specimen surface.
Equation 1 can then be written :

$$\varepsilon_{\phi,\psi} = \frac{d_{\phi,\psi} - d_N}{d_0}$$

and as the unknown spacing d_0 can be replaced in the denominator by d_N with negligible error then:

$$\varepsilon_{\phi,\psi} - \varepsilon_N = \frac{d_{\phi,\psi} - d_N}{d_N} = \frac{1}{2} S_2 [\, A \sin^2\psi + B \sin 2\psi \,] \qquad (2)$$

where $A = \cos^2\phi\,(\sigma_{11} - \sigma_{33}) + \sin^2\phi\,(\sigma_{11} - \sigma_{33}) + \sin 2\phi\,\sigma_{12}$

and $B = \cos\phi\,\sigma_{13} + \sin\phi\,\sigma_{23}$

Differentiating the Bragg law $2d\sin\theta = \lambda$, equation 2 can then be written:

$$2\theta_{\phi,\psi} = 2\theta_N - 2\,\mathrm{tg}\theta_N\,\frac{1}{2} S_2 [\, A\sin^2\psi + B\sin 2\psi \,] \quad (3)$$

(b) Biaxial state

In a biaxial state, σ_{i3} expressions are equal to zero ($\sigma_{13} = \sigma_{23} = \sigma_{33} = 0$) and equation 3 can be written:

$$2\theta_{\phi,\psi} = 2\theta_N + K\,A \sin^2\psi$$

$$\text{where} \quad K = -2\mathrm{tg}\theta_N \frac{1}{2} S_2$$

$$\text{then} \quad 2\theta_{\phi,\psi} = 2\theta_N + K\,[\cos^2\phi\,\sigma_{11} + \sin^2\phi\,\sigma_{22} + \sin 2\phi\sigma_{12}]\,\sin^2\psi \qquad (4)$$

From measurements carried out in 3 suitable ϕ directions (i.e. $\phi = 0°, 45°, 90°$), we can obtain by multiple linear regression the values σ_{11}, σ_{22} and σ_{12} of the biaxial stress tensor.

The measurement in only one ϕ direction gives a linear plot of $2\theta_{\phi,\psi}$ vs.$\sin^2\psi$:

$$2\theta_{\phi,\psi} = 2\theta_N + K\,\sigma_\phi \sin^2\psi \quad (5)$$

which slope is proportional to the stress σ_ϕ in the ϕ direction.

(d) Experimental procedure

Experiments have been carried out on 2124 aluminium alloys reinforced with SiC particulates or whiskers whose volume fraction range varied from 15% to 40%. X-ray measurements were made using the portable equipment designed and built at CETIM. A position sensitive detector collects either X-ray chromium Kα photons diffracted by the (222) set of aluminium atomic planes for measurements in the matrix, or X-ray manganese Kα photons diffracted by the (208) set of silicon carbide atomic planes for measurements in the particulates. In both cases the stress measurement is obtained from the strain present at a depth of about 10 μm.

For all the measurements the focal spot size was 2mm in diameter and we proceeded to 7ψ exposures in each ϕ direction. These measurements were carried out in either 3ϕ directions (ϕ=0°, 45°, 90°) for the biaxial state and in each case the whole stress tensor was obained by multiple linear regression using X-ray elastic constants reported in table 1.

HOLE DRILLING MEASUREMENT

(a) Principle of the hole drilling method

The hole-drilling method involves monitoring the change in strain when a hole is drilled into a residually stressed component. Measurement is made by means of a special three-element strain gauge rosette. These strain measurements can then be related to the original residual stress in the analysed sample at the hole location .

To obtain the gradient of the residual stress with depth , the hole is drilled by steps . For each hole, the depth "z", and the surface strains $\varepsilon_i(z)$ are measured. Once the hole drilling is complete, the residual principal stresses, $\sigma_1(z)$ and $\sigma_2(z)$ can be calculated from equations involving measured values of $\varepsilon_i(z)$ and the calculated correlation coefficients. G.S.Schajer has carried out ([5]) an extensive review of the mathematical formulation for the stress calculation procedure. The integral method can be considered as the most "fundamental" of the four methods. CETIM uses this method for different kinds of materials and components [3]. The theoretical approach can be summarized as follows :
For determining the principal residual stresses (σ_{1hi} and σ_{2hi} , with $\sigma_{1hi} > \sigma_{2hi}$) and their directions with respect to any reference axis for each depth "hi", three independent strain measurements must be made . The equation for the radial strain corresponding to the principal residual stresses is :

$$\varepsilon_{in}(\theta_i) = A_{in} (\sigma_{1hi} + \sigma_{2hi}) + B_{in} (\sigma_{1hi} - \sigma_{2hi}) \cos 2\theta_i \qquad (8)$$

The coefficients A_{in} and B_{in} depend on the following parameters: the hole diameter, the position of the strain gauges, the position of the layer i, the depth of the hole, the elastic constants of the material. θ_i is the angle between the first strain gauge and the maximum principal residual stress. CETIM has developed a special finite element software (CATROR) for calculating A_{in} and B_{in}. Details are given in Ref.[3]. In the case of Al-SiC composite, for the case of composite billets without extrusion, we consider that the composite is an isotropic material . In the case of whiskers reinforced extruded material, if the Young's modulus is not the same in the longitudinal direction and in the transversal direction, the calculation of an equivalent strain in each strain gauge direction is necessary.

MATERIALS

The composite materials investigated were aluminum alloys 2124 and 6061 reinforced with silicon carbide whiskers or particulates in volume fraction ranging from 15% to 40%. These materials are made by ACMC (Advanced Composite Materials Corporation, Greer, SC, USA) and were manufactured by powder metallurgy according to a classical process [6]. The heat treatment used is T6. Some samples studied are blasted after extrusion by ACMC and some samples are shot-peened with the following peening conditions using the SOVITEC alumino-silicate glass beads (table 2).

RESULTS

Fig.2 and Fig.3 show the results measured by the hole drilling method on the shot peened billet reinforced by 15 % SiC_p with two different matrix (2124 and 6061). For the both cases, the residual stresses are compressive and isotropic . But the level of the maximum residual stresses in the case of 2124 (fig.2) is more important than the case of 6061 (fig.3) matrix . In fact , the

The presence of shear stress σ_{13} and σ_{23} involves a misorientation of the stress tensor with respect to the main axis of the specimen.

For the measurement in only one ϕ direction with positive and negative ψ exposures, the plot of $2\theta_{\phi,\psi}$ vs. $\sin^2\psi$ gives an ellipse:

$$2\theta_{\phi,\psi} = 2\theta_N + K\,[\sigma_\phi \sin^2\psi + (\cos\phi\,\sigma_{13} + \sin\phi\,\sigma_{23})\sin 2\psi] \qquad (7)$$

which main axis slope is proportional to σ_ϕ and which split is proportional to $(\cos\phi\sigma_{13} + \sin\phi\sigma_{23})$.

This non linear variation of $2\theta_{\phi,\psi}$ vs. $\sin^2\psi$ due to the presence of shear stress σ_{13} and σ_{23}, is generally observed in two phase materials after some hard mechanical treatment such as turning, milling, grinding [4]. In each phase these shear stresses have been found equal in intensity and opposite in sign [5] and the mean value is supposed to be equal to zero at the limit between each constituent.

For example, experiments have been carried out by [6] on carbon steels under the same conditions of severe grinding. Increasing the carbon content produces an increase of shear stress σ_{13} in the αFe phase as a result of an increase of the second phase Fe_3C.

(d) Experimental procedure

Experiments have been carried out on 2124 aluminium alloys reinforced with SiC particulates or whiskers whose volume fraction range varied from 15% to 40%. X-ray measurements were made using the portable equipment designed and built at CETIM. A position sensitive detector collects either X-ray chromium Kα photons diffracted by the (222) set of aluminium atomic planes for measurements in the matrix, or X-ray manganese Kα photons diffracted by the (208) set of silicon carbide atomic planes for measurements in the particulates. In both cases the stress measurement is obtained from the strain present at a depth of about 10 µm.

For all the measurements the focal spot size was 2mm in diameter and we proceeded to 7ψ exposures in each ϕ direction. These measurements were carried out in either 3ϕ directions (ϕ=0°, 45°, 90°) for the biaxial state or 6ϕ directions (ϕ=0°, 45°, 90°, 180°, 225°, 270°) in the triaxial state when necessary and in each case the whole stress tensor was obained by multiple linear regression using X-ray elastic constants reported in table 1.

HOLE DRILLING MEASUREMENT

(a) Principle of the hole drilling method

The hole-drilling method involves monitoring the change in strains when a hole is drilled into a residually stressed component. Measurement is made by means of a special three-element strain gauge rosette. These strain measurements can then be related to the original residual stress in the analysed sample at the hole location .

To obtain the gradient of the residual stress with depth , the hole is drilled by steps . For each hole, the depth "z", and the surface strains $\varepsilon_i(z)$ are measured. Once the hole drilling is complete, the residual principal stresses, $\sigma_1(z)$ and $\sigma_2(z)$ can be calculated from equations involving measured values of $\varepsilon_i(z)$ and the calculated correlation coefficients. G.S.Schajer has

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yield stress of the 6061 matrix composite is smaller than the 2124 matrix composite [4] .The results of the X-ray diffraction method is shown in table 3. It can be seen that the values obtained by the two methods of measurement are very close .

The second example shows the results obtained with two extruded 2124 samples with 25% SiC reinforcement. Here the nature of the reinforcement (SiCw or SiCp) are studied. Figure 4 and figure 5 show the residual stresses measured on the two samples. Compressive residual stresses were found for a depth of 100 µm . In fact, the surface of the extruded materials is blasted. So there is the same gradient as in a shot-peened surface but with a smaller prestressed layer because the blast peening is a surface finishing process and not a surface treatment process. The blasts used are often smaller. In this case, we have not the technological parameters, because the treatment has been realised by ACMC as a surface finishing treatment for their products . For this finishing condition, the nature of the reinforcement does not play a very important role concerning the level of the residual stresses. Table 4 shows the results obtained on the surface by the X-ray diffraction method. We can see for this case, that the residual stresses gradient is very important in the surface layer.

The last example shows the effect of the volume fraction of whisker on the extruded and blasted composite with a 2124 matrix. Figure 6 shows the comparison of residual stresses obtained on the composites with 25% SiCw and 40% SiCw reinforcement. It can be seen that the volume fraction has not an important effect on the maximum residual stress but the prestressed layer is smaller in the case of the composite with 40% SiC_W. In fact, except the yield stress the effectiveness of shot peening depends also on the hardeness increase, for the same shot peening intensity, the residual stresses and prestressed layer may be decreased .

Table 5 shows the results obtained by X-ray diffraction method for 3 volume fractions (0, 25%, 40% SiC_W). It can be seen that the level of the surface residual stresses decrease when the volume fractions increase for the same blasted and shot peening conditions. The maximum residual stresses is found in the case of unreinforced aluminium alloy. So the shot peening intensity must increase so as to increase the compressive residual stresses in MMC .

CONCLUSION

This study shows that the hole drilling method and the X-ray diffraction method are two suitable methods to evalute the residual stresses in Al-SiC metal matrix composite . The former measure the mean stress in two phases (Al and SiC), the latter can separate the residual stresses in the matrix and in the reinforcement. In this study, the residual stresses induced by the manufacturing process (finishing and surface treatment) were analysed. The results obtained by two methods are very similar in considering the scatter of the two methods, the stress gradient in the samples .

Blast peening and shot-peening can induce the compressive residual stresses which are beneficial for the fatigue life.

The residual stresses induced by shot-peening is deeper than the blast peening. The maximum level of residual stresses are very low in comparison with the yield stress of different composites. In fact, the intensity of shot peening used in this study is not very high. So, it is possible to find an optimum shot-peening condition to increase the fatigue life of the metal matrix composite. Further, the fatigue tests will be carried out to show the eventual effect of the shot-peening treatment on the fatigue behaviour and their relationship with the residual stresses induced by the treatment.

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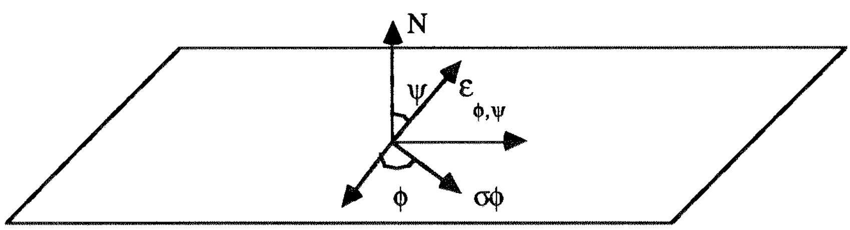

Fig.1

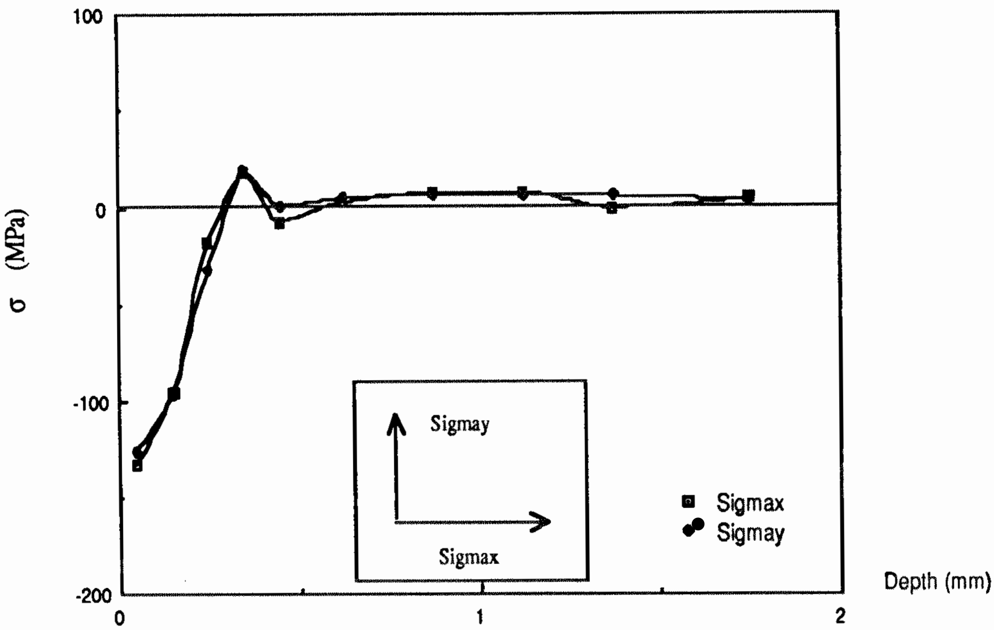

Fig.2 Residual stresses measured on the shot peened sample (2124+15% SiC_p)(±11MPa)

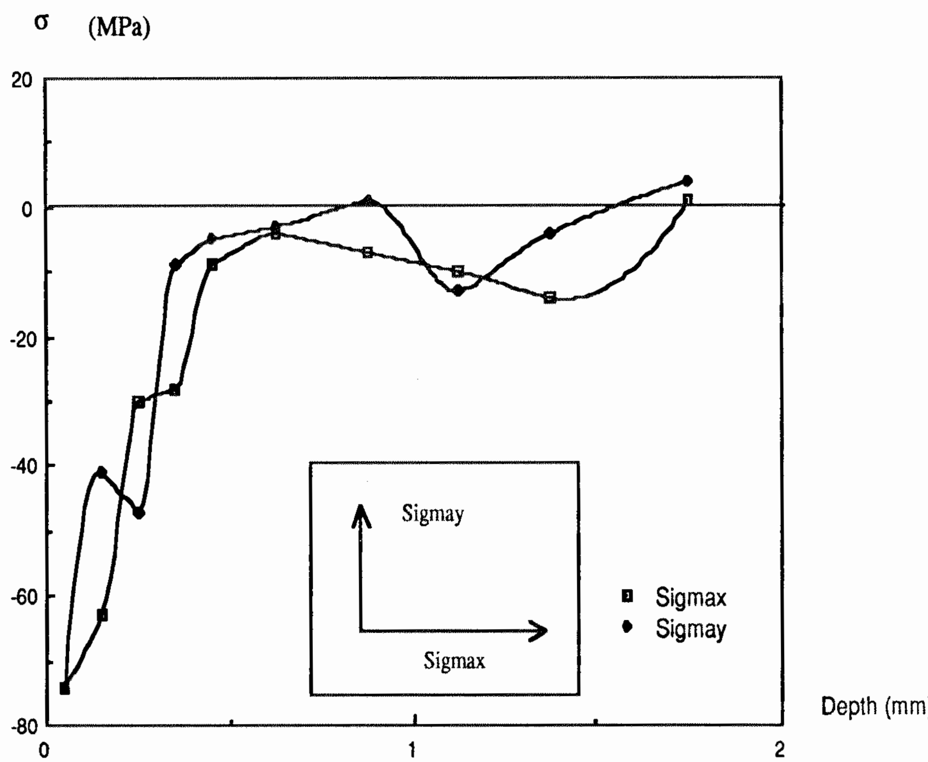

Fig.3 Residual stresses measured on the shot peened sample (6061+15% SiC_p)(±11MPa)

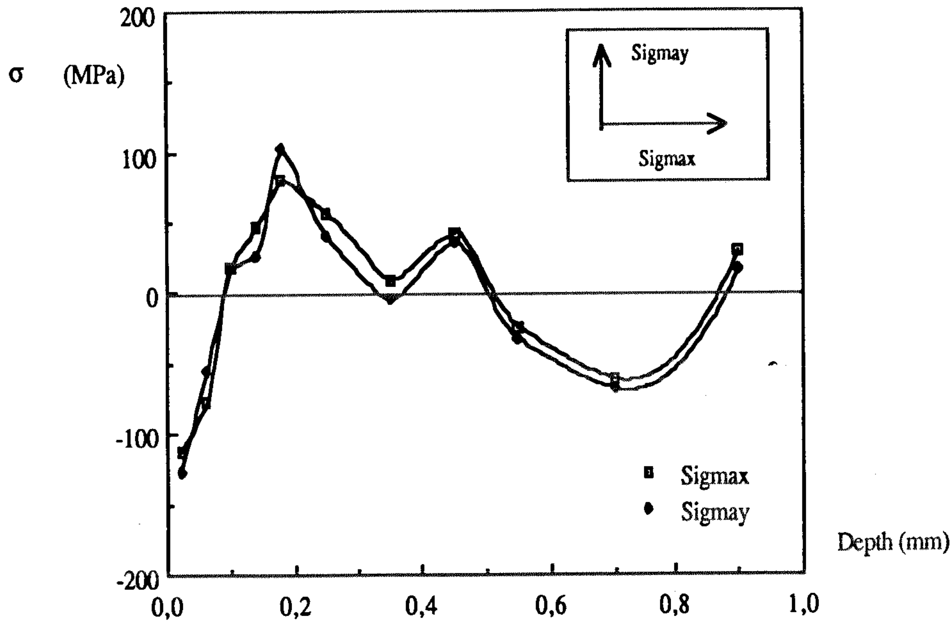

Figure 4 Residual stresses obtained by the hole drilling method on an extruded composite of 2124 reinforced by 25% SiCp.

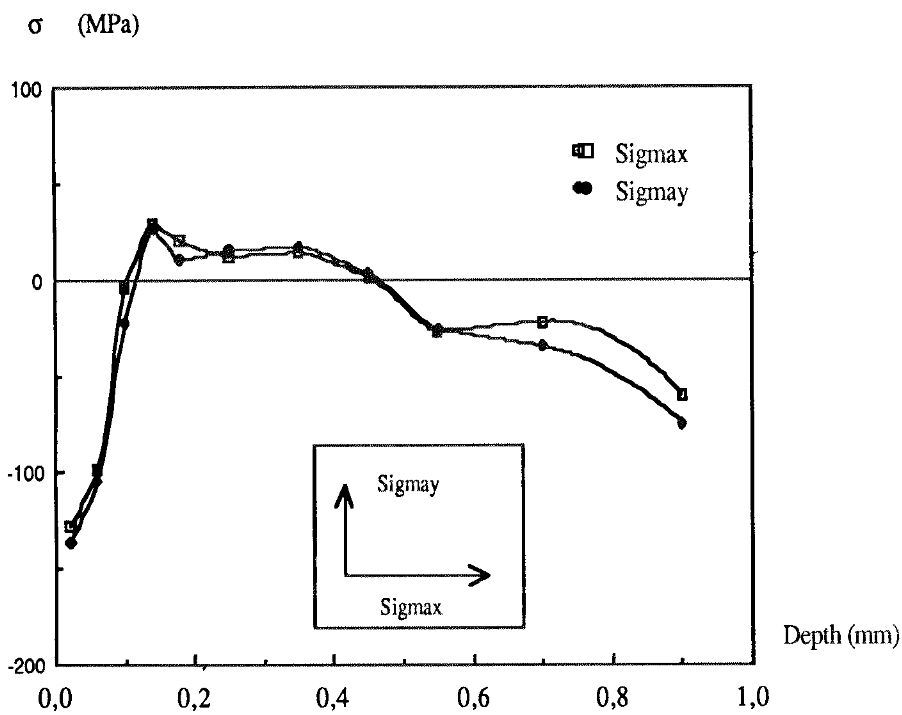

Figure 5 Residual stresses obtained on an extruded composite of 2124+ 25% SiCw (±18MPa)

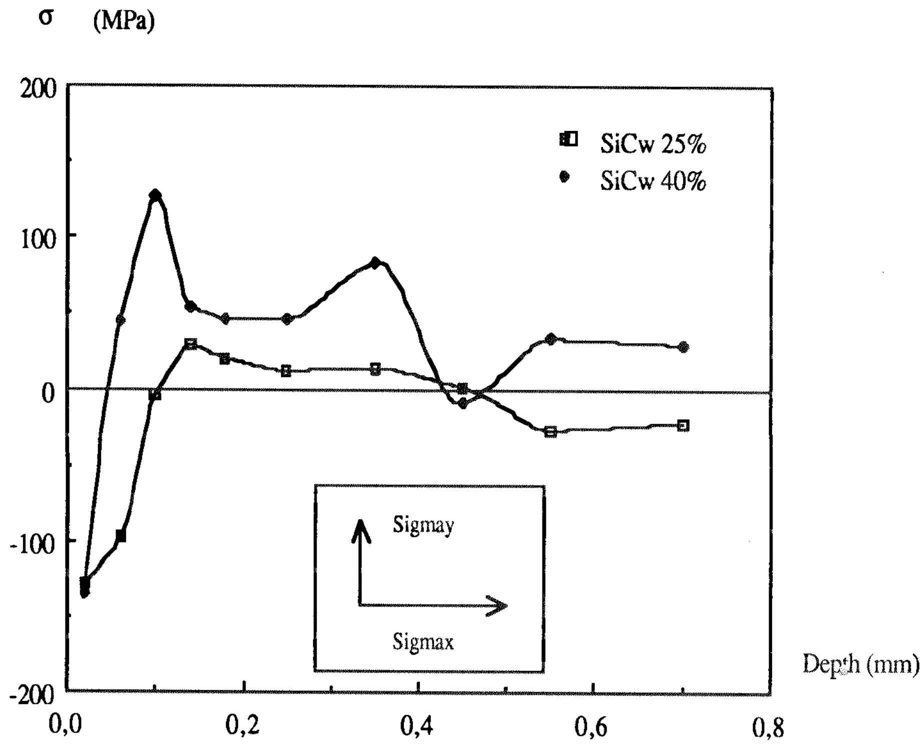

Figure 6 Comparison of the residual stresses obtained on two composites 2124 reinforced with two volume fractions of SiC whisker (25% (±18MPa) and 40% (±20 MPa)).

Material	Set of atomic planes	$\frac{1}{2} S_2 (MPa^{-1})$	$S_1 (MPa^{-1})$
Al	(222)	$17.9\ 10^{-6}$	$-4.65\ 10^{-6}$
SiCp	(208)	$6.63\ 10^{-6}$	$-1.82\ 10^{-6}$

Table 1 X-ray elastic constants used for the stress calculation.

Shot	Shot diameter	Almen intensity (A)
Glass	300 µm	0.15 - 0.2 mm

Table 2

Material \ Stress	σ_X (MPa)	σ_Y (MPa)
2124 + 15% SiCp	-112±9	-111±9
6061 + 15% SiCp	-51±6	-50±6

Table 3 Residual stresses measured by X-ray diffraction method on the shot peened composite reinforced by 15% SiC_p with different aluminium matrix (2124 and 6061)

Material \ Stress	σ_X (MPa)	σ_Y (MPa)
2124 + 25% SiCp	-29	-38
2124 + 25% SiCw	-57	-87

Table 4 Residual stresses measured by X- ray diffraction method on the compositen with a 2124 matrix reinforced by 25% SiC whisker or by 25% SiC particulate.

	Extruded and blasted		Shot peened	
Material \ Stress	σ_X (MPa)	σ_Y (MPa)	σ_X (MPa)	σ_Y (MPa)
2124	-115±8	-103±8	-156±10	-127±10
2124 + 25% SiCw	-57±12	-87±13	-66±11	-73±11
2124 + 40% SiCw	-32±15	-35±13	-48±13	-51±12

Table 5 The effect of the volume fraction of reinforced whiskers on the surface residual stresses in Al matrix obtained by X-ray diffraction method .