FINITE ELEMENT SIMULATION AND EXPERIMENTAL DETERMINATION OF RESIDUAL STRESSES AFTER EXTRUSION PROCESS IN METAL MATRIX COMPOSITES

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ABSTRACT

The introduction of reinforcement in a Metal Matrix causes micro-stresses which may prove to be very detrimental for the life of the component. Submitting the components to annealing thermal treatments introduce thermal mismatch stresses. They are generated during cooling due to the difference in the thermal expansion coefficient of the two phases.

Finite Element Calculation have been performed to study this effect and the results have been experimentally validated by X-ray diffraction, SEM investigation and EDAX on an AA2009 + 25% SiCp extruded shaft for helicopters, simplified as a thin extruded tube.

1. INTRODUCTION

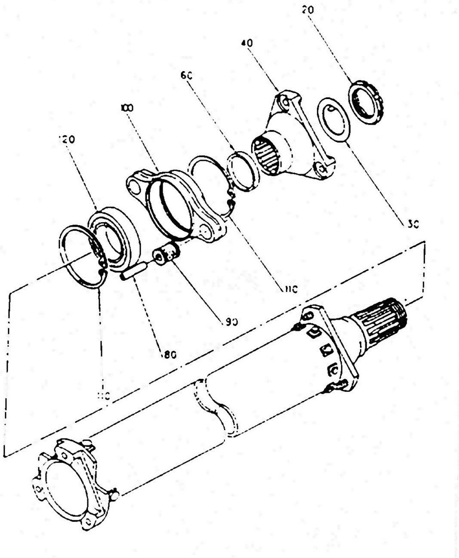
Since the 1980s, the automotive and aeronautical industries of Europe, Japan and United States, have shown the feasibility of using particulate reinforced MMC structural components such as brake disks, connecting rods or engine blocks in cars, blade sleeves, tail rotor spider plates, shafts in helicopters and floor struts and stringers in aircraft. The methodology developed provided optimised forming parameters to produce MMC components free of defects such as porosity, microstructural heterogeneity, with minimised internal residual stresses, with mechanical properties tailored to the in-service loading conditions. In all application areas where they can be used as structural components, Metal Matrix Composites are of great interest. In fact, an added ceramic reinforcement, having stiffness higher than the metal matrix but similar density, increases the specific stiffness of the material. Weight saving and increased mechanical properties are thus obtained in components made of aluminium or steel if composite materials are used in their place. Such potential applications made MMC strongly widespread in the aerospace and automotive industries. In fact a weight reduction enhances the fuel efficiency.

On the other hand, introducing reinforcement usually causes micro-stresses, which proved to be very detrimental for the component life. Also submitting the components to annealing thermal treatments will introduce thermal mismatch stresses. They are generated at cooling, due to the difference between the thermal expansion coefficients of the two phases.

In order to study these latter effects, a Finite Element Calculation has been performed on an AA2009 + 25% SiCp extruded shaft for helicopters. A simplified form was considered: a thin (1.65 mm thickness) extruded tube. The results have been validated experimentally by X-ray diffraction, SEM investigation and EDAX technique.

2. MATERIALS AND METHODS

A thin AA2009 + 25 vol. % SiCp tube for aeronautical porpoises was studied: it is a component of a helicopter intermediate drive shaft as shown in the figure 1.



“**Fig. 1.** Helicopter intermediate drive shaft.”

The composition of the AA2009 aluminium alloy is given in Table 1.

“**Table 1.** Chemical composition of the AA2009 aluminium alloy.”

Chemical composition (%)	Element	Cu	Mg	Si	O	Fe	Zn	Others		Al
								Each	Total	
	min	3,2	1	-	-	-	-	-	-	the remaining
	max	4,4	1,6	0,25	0,60	0,20	0,10	0,05	0,15	

The components manufacture has been carried out by a specialist of profile extrusion. A Ø 83 mm thin tube was realized. The extrusion was made in two steps:

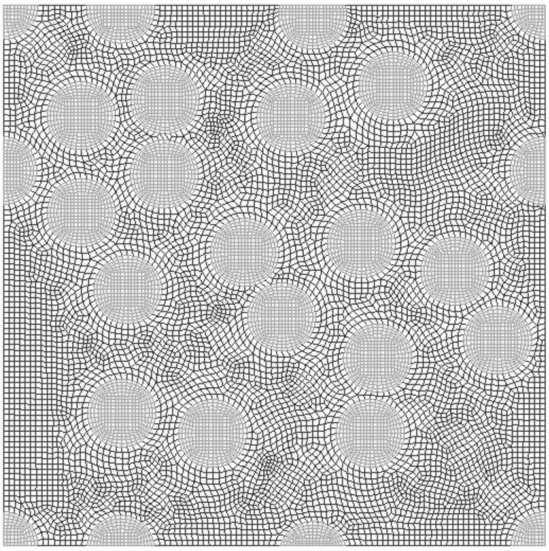
1. Extrusion of billet (Ø 355mm) to a Ø 170mm bar;
2. Tube direct extrusion (Ø 83 mm, thickness 1.65mm).

A tube of 6m long was extruded and then treated in T4 conditions (4h at 498° C, followed by water quenching and natural aging).

In order to analyse the residual micro-stresses due to the introduction of reinforcement in the AA2009 matrix and to evaluate thermal mismatch stresses generated during cooling of the T4 heat treatment, Finite Element Calculation (FEC) have been performed. The results have been experimentally validated by X-ray diffraction, SEM investigation and EDAX.

A RU300 Rigaku Denki x-ray source equipped with a conventional vertical diffractometer and a Ni filtered Cu-kα line (wavelength λ= 0.154 nm) was used for the purposes of phase recognition (at Università Politecnica delle Marche). Residual stress analysis was performed at the X1 diffractometer of the Technician University of Berlin (D). The slits defined a “gauge surface” of 1x3.14 mm^2 . Not filtered CuKα radiation was used and thus both the $CuK\alpha_1$ (λ_1 = 0,154061 nm) and $CuK\alpha_2$ (λ_2 = 0,154178 nm) wavelengths were used.

A Scanning Electron Microscope Philips XL20 equipped with an EDAX microanalysis device was also used (at Università Politecnica delle Marche).

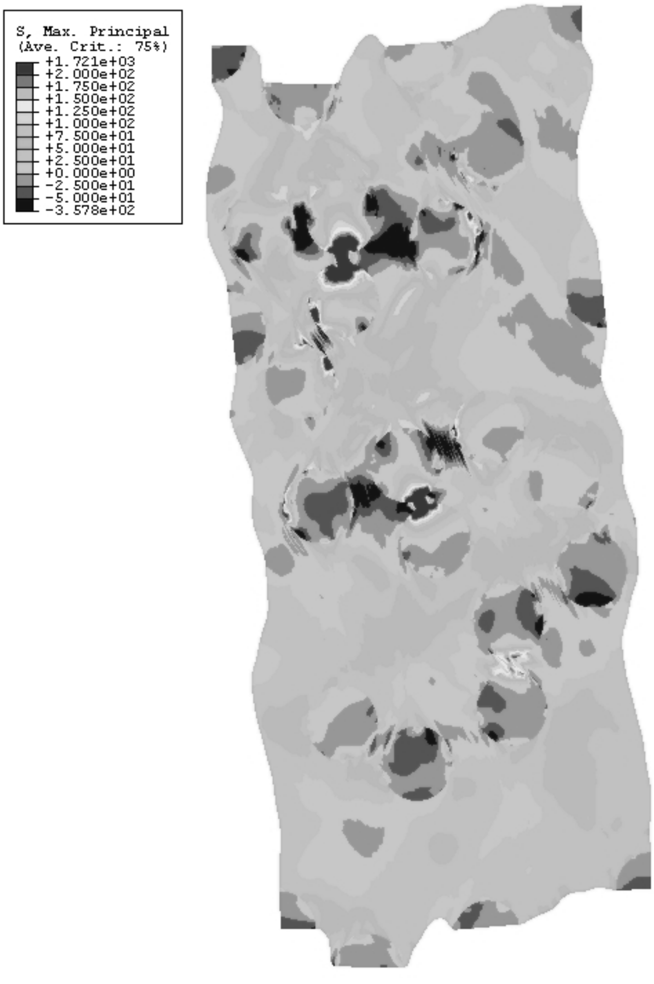


"**Fig.2.** Periodic unit cell"

3. FINITE ELEMENTS ANALYSIS

A periodic unit cell micromechanical approach was taken with explicit representation of both particle and matrix phases in a finite element model. The unit cell geometry and the finite element mesh are shown in Fig.2.Appropriate elastic properties for the SiC and elastic–plastic properties for the AA2009 matrix were used. ABAQUS® was used for the finite element simulations. A plot of the maximum tensile principal residual stress in the material, after a large strain (50%) and unloading, is shown in Fig.3.

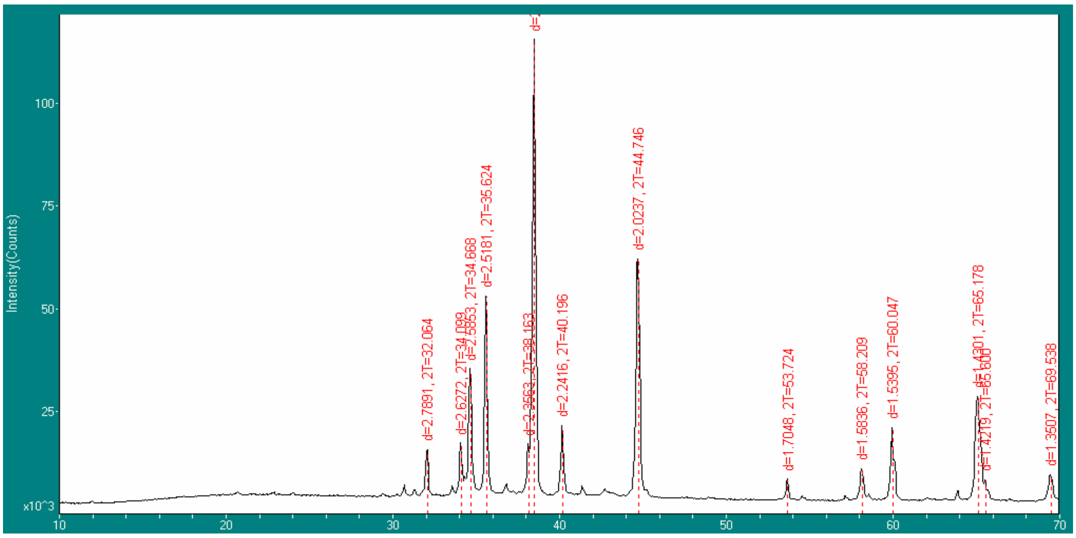
Evident in the plot is the high local level of maximum principal stress in some of the particles and in the separating matrix material for high strains, strains reflexive of those experienced during extrusion. The average minimum stress in the particles varies between –160 MPa and –120 MPa; the average maximum stress in the matrix is between 76 and 160 MPa. These values correlate well with the experimentally measured values shown in the following Table 4.



"**Fig. 3.** Contour plot of maximum principal stress in MPa"

3. MICROSTRUCTURAL INVESTIGATION

A check of the microstructure of the extruded sample was performed. In fact, the optimal production process minimizes the residual stress from mechanical or thermal processing and improves the material strength. Fine dispersions or precipitate phases can increase the yield strength of the material by forming a barrier to the dislocation motion. The x- ray diffraction was used first to detect the precipitate. Fig.4 reports the obtained diffraction profile. The main precipitate obtained is Mg_2Si, which was assumed to nucleate during the thermal treatment. Their presence is generally beneficial because Mg_2Si precipitate acts as a barrier to the dislocations motion. In any case if the load transfer is excessive, it can lead to the particles failure.

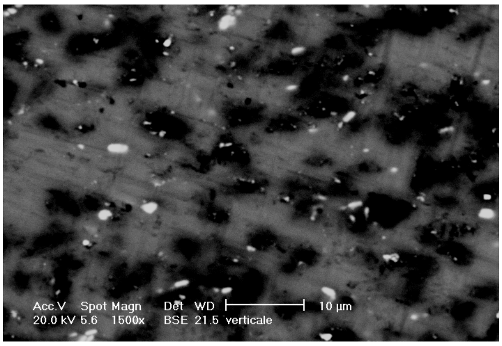


2θ (°)	d(Å)	Peaks
32.064	2.7891	Mg_2Si
34.099	2.6272	SiC
34.668	2.5853	SiC
35.624	2.5181	SiC
38.163	2.3563	SiC
38.51	2.3358	Al
40.196	2.2416	Mg_2Si
44.746	2.0237	Al
53.724	1.7048	Fe_3Si
58.209	1.5836	Mg_2Si
60.047	1.5395	SiC
65.178	1.4301	Al
65.6	1.4219	Fe_3Si
69.538	1.3507	Cu_2Mg

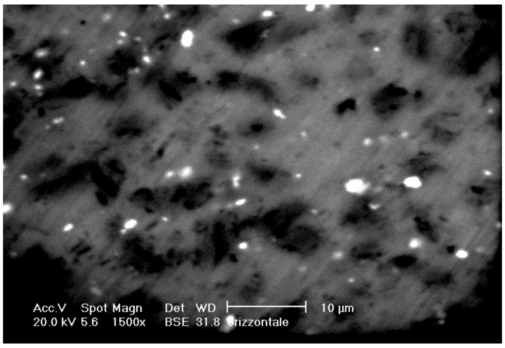
“**Fig. 4.** Extruded tube: X-ray diffraction scan and principal peaks identification.”

In order to validate the results obtained by the x-ray diffraction, the scanning electron microscopy was used. The samples were cut so that two surfaces with different orientation with respect to the sample could be examined: one perpendicular and one parallel to the extrusion direction. The latter was along a radial direction of the tube. The analysis were performed in backscattering mode.

The different atomic numbers allowed discriminating AA2009 matrix from SiC reinforcement. The different areas colour in figure 5 corresponds to SiC particles (Black) and matrix (Grey).



"**Fig. 5.** a. SEM magnificated image of an area through the thickness of the tube."



"**Fig. 5.** b. SEM magnificated image of an area along the extrusion direction."

As expected, the size of the SiC particles is about 6 µm. They are homogeneously distributed in the samples both in the extrusion direction and through the tube thickness. No clustering effect of relevant important is observed. EDAX microanalysis was also performed in different zones of the sample and the following results were obtained:

1. Wt % values for the alloy elements found in the matrix are those foreseen in literature for the AA2009 (inside the experimental error), except the Si percentages that are higher than what foreseen (probably due to contribution from SiC particles, not well discriminated from the matrix).
2. Al residues are found in the reinforcement: also this fact can be attributed to a non perfect discrimination between matrix and SiC particles.
3. The most interesting result is obtained at the interface between matrix and reinforcement, where percentages of Mg, Cu or Si are detected not higher than those normally obtained in the AA2009 matrix. This observation can lead to the conclusion that Mg_2Si precipitates (previously detected by x-ray diffraction) are homogeneously distributed in the matrix and not located at the interface as it happens in the case of other composites precipitates [2, 3].

4. RESIDUAL STRESS ANALYSIS

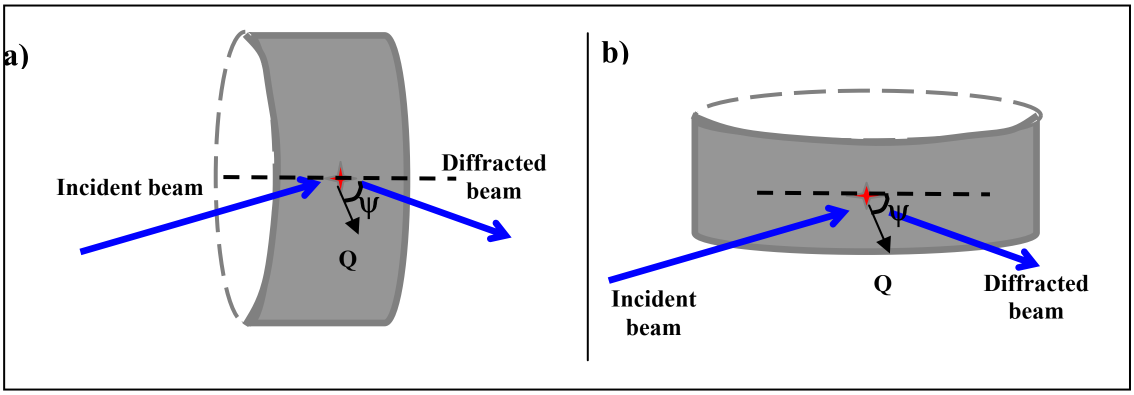
Residual stress analysis has been performed using x-ray diffraction in order to validate the simulation results. The difference in the thermal and elastic properties of the matrix and the reinforcement, as shown in table 2, are expected to induce residual stresses both of thermal and of mechanical nature.

"**Table 2.** Thermal expansion coefficient, Young Modulus and Poisson ratio of the Aluminium matrix and of SiC reinforcement."

	Thermal Expansion Coefficient	**E (GPa)**	ν
Al 2009	24×10^{-6}	72	0,33
SiC	$4{,}5 \times 10^{-6}$	450	0,14

4.1. Experimental conditions

X-ray measurements were performed in the inner and outer part of the AA2009 + 25 vol. % SiCp tube. The lay-out of the measurements is shown in figure 6: the axial (fig.6.a) and hoop (fig.6.b) directions of the strain were investigated.



"**Fig. 6.** Lay-out of the X-ray diffraction measurements: a) ψ-scan along axial direction; b) ψ-scan along hoop direction."

The considered crystallographic planes were:

"**Table 3.** Interplanar distance Thermal expansion coefficient, Young Modulus and Poisson ratio of the Aluminium matrix and of SiC reinforcement."

Phase	**Plane (h,k,l)**	**Plane distance (nm)**	**Bragg angle 2θ**
Aluminium	(422)	0.82	≈ 139°
SiC	(420)	0.10	≈127°

The gauge region was at the surface of the "wall", localized as in the Fig.6. Measurements were performed in two corresponding points on the inner and outer surface of the cut tube. The high absorption of x-ray beams in the material makes sure that only the surface region is investigated. Thus the radial stress can be assumed as vanishing.

"**Table 4.** Total stresses in matrix and reinforcement phases."

	Aluminium phase (matrix)	Silicon carbide phase (reinforcement)
Axial direction (inner point)	13 MPa	-360 MPa
Hoop direction (inner point)	190 MPa	-120 MPa
Axial direction (outer point)	27 MPa	-360 MPa
Hoop direction (outer point)	176 MPa	-180 MPa

4.2. Results

The measured data were analysed through the method explained in Ref.[1] obtaining the experimental total stresses shown in Table 4.

For both phases, the errors are not higher than ± 50 MPa. The model developed in Ref. [1] was used in order to split macro and microstresses (Table 5).

“**Table 5.** Separation of macroscopic, elastic mismatch and thermal expansion misfit stresses.”

	Aluminium phase (matrix)	Silicon carbide phase (reinforcement)
Macrostresses	Axial (inner pt): -80 MPa Hoop (inner pt.): 112 MPa Axial (outer pt): -70 MPa Hoop (outer pt.): 87 MPa	
Elastic microstresses	Axial (inner pt): 8 MPa Axial (outer pt): 7 MPa Hoop (inner pt): -11 MPa Hoop (outer pt): - 9 MPa	Axial (inner pt): -39 MPa Axial(outer pt): -33 MPa Hoop (inner pt): 54 MPa Hoop (outer pt): 42 MPa
Thermal microstresses	Axial (inner pt): 85 MPa Hoop (inner pt): 88 Mpa Axial (outer pt): 89 MPa Hoop (outer pt): 97 MPa	Axial (inner pt): -240 MPa Hoop (inner pt): -287 Mpa Axial (outer pt): -256 MPa Hoop (outer pt): -309 MPa

Measurements on Al phase (axial direction) were also performed on outer surface of the not-cut tube in order to check if, cutting the tube (with the aim of measuring the inner surface too), new residual stresses were introduced. The behaviour of the graph was the same

5. CONCLUSIONS

The microstructure of the tube has been investigated. No defects such as cracks have been detected by non-destructive dye penetrating inspection.

We observed a good particles distribution by SEM. Mg_2Si precipitates (detected by x-ray diffraction) are homogeneously distributed in the matrix: their presence is generally beneficial because this precipitate acts as a barrier to the dislocations motion. In any case if the load transfer is excessive, it can lead to the particles failure.

The aluminium matrix has a larger coefficient of thermal expansion (CTE) than the reinforcement, while the reinforcement is stiffer than the matrix. This leads to two effects:

- upon cooling, tensile stresses are generated in the matrix and compressive stresses in the reinforcement. These are the thermal mismatch microstresses, expected to be isotropic,
- then under any applied or residual load, the stress is composed of a macrostress, which varies over a spatial range of many grains and is the same in each phase of the composite, and of an elastic mismatch microstress which represents the transfer of load to the stiffer phase.

We studied the inner and outer part of the tube. No difference has been noticed between them.

We observed quite low macrostresses, as expected due to the T4 thermal treatment. However, highest thermal microstresses has been detected, in particular in the SiC reinforcement.

The numerical evaluation predicts severe microstrains in the material. This result is in good agreement with the experimental measurements.

ACKNOWLEDGEMENTS

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