Gianni Albertini[1]
Dipartimento di Fisica e Ingegneria dei materiali e del Territorio - Università Politecnica
delle Marche and Istituto Nazionale per la Fisica della Materia - U.d.R. Ancona, Via Brecce Bianche, 60100 Ancona, Italy

Fabrizio Fiori[2], **Alessandra Giuliani**[3], **Franco Rustichelli**[4]
Istituto di Scienze Fisiche - Università Politecnica delle Marche and Istituto Nazionale per la Fisica della Materia - U.d.R. Ancona,
Via Ranieri 65, 60131 Ancona, Italy

EVALUATION OF RESIDUAL STRESSES INDUCED BY FATIGUE CYCLING IN AA359+20%SiC$_p$ BRAKE DRUMS USING NEUTRON DIFFRACTION

Neutron diffraction experiments for the evaluation of residual stresses induced by fatigue cycling in metal-matrix composite (MMC) automotive components are presented. The studied components are three brake drums, manufactured by Teksid a/Centro Ricerche FIAT. One of them was used to study the residual stress state in the as-cast condition. The other two brake drums were submitted to fatigue cycling („bench tests"), respectively not-leading and leading to failure. The macro- and micro-stress components are evaluated and compared for the three studied components.

Key words: **neutron diffraction, residual stresses, metal matrix composites**

OSZACOWANIE ZA POMOCĄ DYFRAKCJI NEUTRONOWEJ NAPRĘŻEŃ WEWNĘTRZNYCH WYWOŁANYCH CYKLICZNYM OBCIĄŻENIEM ZMĘCZENIOWYM W BĘBNACH HAMULCOWYCH Z AA359+20%SiC$_p$

Przedstawiono próby wykorzystania dyfrakcji neutronowej do oszacowania naprężeń wewnętrznych wywołanych cyklicznym obciążeniem zmęczeniowym w elementach dla przemysłu motoryzacyjnego wykonanych z kompozytu o osnowie metalowej (MMC). Badanymi elementami są trzy bębny hamulcowe, wyprodukowane przez Teksid/Centro Ricerche FIAT. Jeden z nich był wykorzystany do zbadania stanu naprężeń wewnętrznych w stanie lanym. Pozostałe dwa bębny hamulcowe zostały poddane laboratoryjnej próbie zmęczeniowej pod cyklicznym obciążeniem, w jednym przypadku prowadzącym, a w drugim nieprowadzącym do zniszczenia. Oszacowano i porównano składowe makro- i mikronaprężeń dla tych trzech badanych elementów.

Słowa kluczowe: **dyfrakcja neutronowa, naprężenia wewnętrzne, kompozyty o osnowie metalowej**

INTRODUCTION

The brake drum is one of the most suitable component for the introduction of MMCs into automotive applications (replacing cast iron), because of the properties combination of matrix and reinforcement: wear resistance, stiffness, thermal behavior, fatigue resistance and, above all, weight and noise reduction.

A very important parameter to be controlled in components for technological and industrial applications is the residual stress field, as it can strongly influence their fatigue life under operation. On the other hand typical operating conditions, such as thermal or fatigue cycling, can influence the residual stress level. In particular, in MMCs residual stress are always present already after casting, due to the difference in elastic constant and thermal expansion coefficient between the matrix and the reinforcement, and one should take them into account in numerical models for simulating component performances and lifetime predictions.

Experimental investigations of residual stresses can be carried out using both destructive and non-destructive techniques. Among the latter, X-ray and neutron diffraction are extensively used. The main difference between these two techniques is the possibility to measure bulk stress with neutrons (thanks to their high penetration power in the matter), while X-ray are limited to surface regions.

The results of neutron diffraction experiments for residual stress measurements in MMC fatigued brake drums are presented below, in the framework of a general research aiming to establish mathematical and numerical (finite element) modeling for the simulation of performances of automotive and aeronautical MMC materials and components.

[1,4] Professor, [2,3] Doctor

STUDIED BRAKE DRUMS

Teksid/CR FIAT (Italy) manufactured three AA359+20%SiC$_p$ brake drums (Fig. 1), having the same geometric characteristics: external diameter 240 mm, internal diameter 180 mm, total height 55 mm. The original composite material was supplied by DURALCAN and was processed through DISAMATIC low pressure sand mould casting. All the drums were treated by a T6 temper.

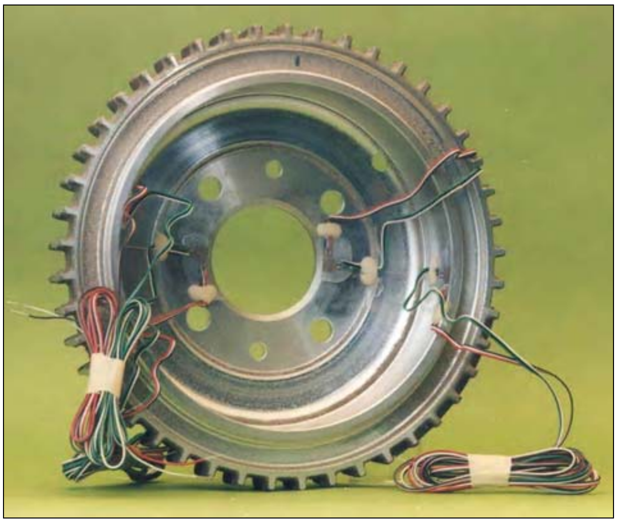

Fig. 1. One of the studied brake drums (by Teksid/CR FIAT - Italy)

Fig. 2. Brake drum n. 3 after failure

The components were submitted to the following fatigue cycles:

- No fatigue cycling, „as-cast” (sample n. 1).
- Fatigue cycling not leading to failure (sample n. 2): i) 15 000 N for 2 065 000 cycles; ii) 25 000 N for 2 600 000 cycles; iii) 30 000 N for 2 500 000 cycles; iv) 35 000 N for 2 500 000 cycles.
- Fatigue cycling leading to failure after 782 000 cycles at a load of 25 000 N (sample n. 3).

In the component n. 2, no fracture and no initial crack were detected in any phase of the fatigue test, while a big inclusion was found by fractographic examination of the breaking area of the n. 3 drum. Figure 2 shows component n. 3 after failure.

NEUTRON DIFFRACTION EXPERIMENTS

As-cast brake drum

The measurements were performed at the G5.2 diffractometer of LLB - Saclay (F), in the gauge points shown in Figure 3, corresponding to the most critical zone under operating conditions. A wavelength $\lambda = 0.345$ nm and a gauge volume of 2x2x2 mm^3 were used. The investigated diffracting planes were the (200) for Al ($2\theta \approx 102.5°$) and the (311) for SiC ($2\theta \approx 77.5°$). The reference unstrained interplanar distance for the matrix was experimentally evaluated from a powder obtained by grinding the sample, while the original powder obtained from the supplier was used as a reference for the reinforcement. The diffractometric elastic constants for the considered lattice planes for Al and SiC were taken as the mean value of the ones obtained from Voigt and Reuss models [1] (Al: $E = 67$ GPa, $\nu = 0.35$; SiC: $E = 386$ GPa, $\nu = 0.19$).

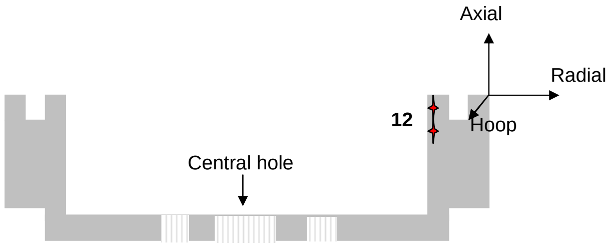

Fig. 3. Component geometry and measurement points

Not failured fatigue cycled brake drum

Also this component was investigated at the G5.2 diffractometer of the LLB - Saclay (F), in the gauge points shown in Figure 4. In this case the neutron wavelength was λ = 0.316 nm: The same diffraction planes and gauge volume as in sect. *As-cast brake drum* were used, and the reference unstrained interplanar distances for the matrix and for the reinforcement were evaluated using the same powders used for the as-cast drum.

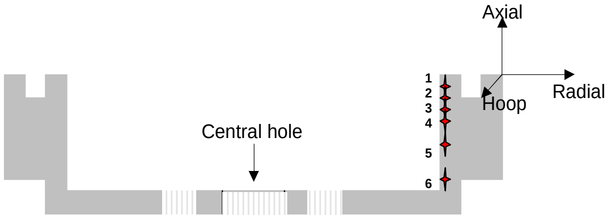

Fig. 4. Measured points after bench tests

Brake drum after fatigue cycling leading to failure

This component was investigated at the E3 diffractometer of HMI - Berlin (D), with a wavelength λ = = 0.137 nm and a gauge volume of 2x2x2 mm^3. The gauge points were the same as in Figure 4. The investigated diffracting plans were the (311) for Al ($2\theta \approx 68.2°$) and the (200) for SiC ($2\theta \approx 62°$). The reference unstrained interplanar distances for the matrix and for the reinforcement were evaluated using the same powders used in the previous cases. The diffractometric elastic constants for the considered lattice planes for Al and SiC were taken as the mean value of the ones obtained from Voigt and Reuss models [1] (Al: E = 69 GPa, ν = 0.35; SiC: E = = 339 GPa, ν = 0.23).

DATA ANALYSIS

From the precise determination of the angular position (2θ) of the diffraction peak, the interplanar distance is calculated through the Bragg's law

$$\lambda = 2d \sin\theta \tag{1}$$

The strain of the considered lattice planes is defined as

$$\varepsilon = \frac{d - d_0}{d_0} \tag{2}$$

where d_0 is the unstrained interplanar distance. By measuring ε in the principal directions (assumed to coincide with the sample principal axes) and knowing the diffractometric elastic constants of the investigated lattice planes, the stress σ can be obtained by the Hooke's law.

In the case of composite materials, the measured stress (σ_{tot}) in each phase is the sum of macro- and microstress, averaged over the considered gauge volume. Thus, as microstresses average to zero over distances corresponding to a few grains, the macrostress can be evaluated as

$$\sigma_{macro} = f\sigma_{tot}^{reinf} + (1-f)\sigma_{tot}^{matrix} \tag{3}$$

where f is the volume fraction of the reinforcement. It is to be reminded that the macrostress averages to zero over the whole sample volume. Its value is the same in each phase, and it is the important stress component from the engineering point of view, as it directly influences the macroscopic features of the material.

Microstresses can be divided into elastic and thermal components, being the former due to the difference in elastic constants of the matrix and the reinforcement, and the latter to thermal expansion coefficient mismatch. The elastic microstress component can be calculated using, for instance, the method described in [2]. Anyway in the case of Al/SiC$_p$ composites, they turn out to be negligible as compared to thermal microstresses. As a consequence, microstresses in Al/SiC$_p$ composites can be considered to be almost entirely thermal.

RESULTS

In the as-cast drum (Fig. 5) the macrostress is tensile and of the order of 100 MPa in all the principal directions and for both the wall points. The thermal mismatch microstress is quite high in absolute value, especially in the silicon carbide reinforcement, where large compressive stresses (–800 MPa close to the top of the wall, –300 MPa in the point n. 2) are observed.

The macrostresses are higher after fatigue cycling without failure (Fig. 6). They are very high at the top of the wall (about 300 MPa in axial and hoop directions and 400 MPa in radial direction) and decrease going down along the wall until 80 MPa (at the point n. 5 in

Fig. 4), increasing again at the last point (n. 6 in Fig. 4) in the radial and hoop direction (200 and 300 MPa respectively). This last increase is probably induced by a stress rearrangement after the cycling, due to the component geometry. The thermal mismatch microstresses are lower than before cycling for both matrix and reinforcement, as already seen in other regions of the drum [3]. The thermal mismatch microstresses decrease from the top of the wall (70 MPa for Al and −300 MPa for SiC at the points n. 1 and 2 in Fig. 4) to the bottom (20 for Al and −40 MPa for SiC at the point n. 5 in Fig. 4), but they slightly increase in the last point.

In the case of the failured brake drum (Fig. 7), the macrostresses are released, also going in compression in certain regions. The thermal mismatch microstresses have values close to those found after the bench test without breaking (inside the experimental error) [4].

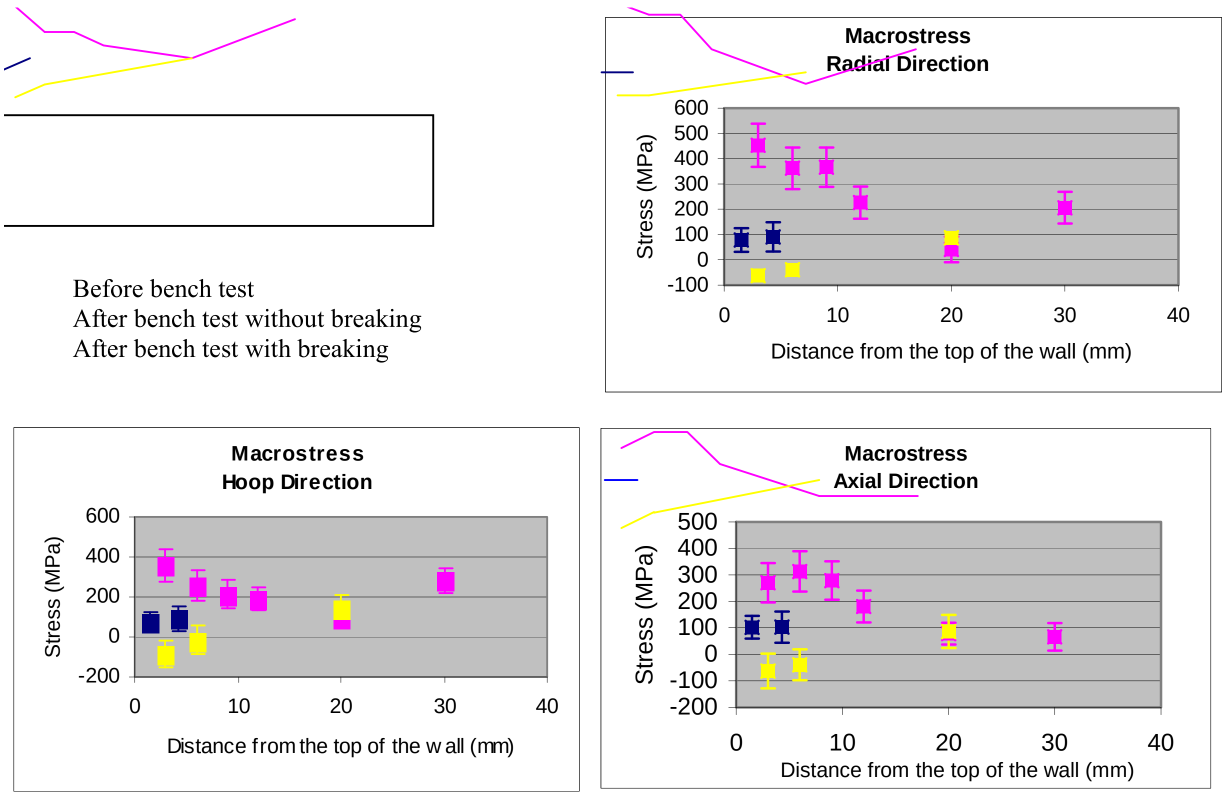

Fig. 5. Measured macrostresses

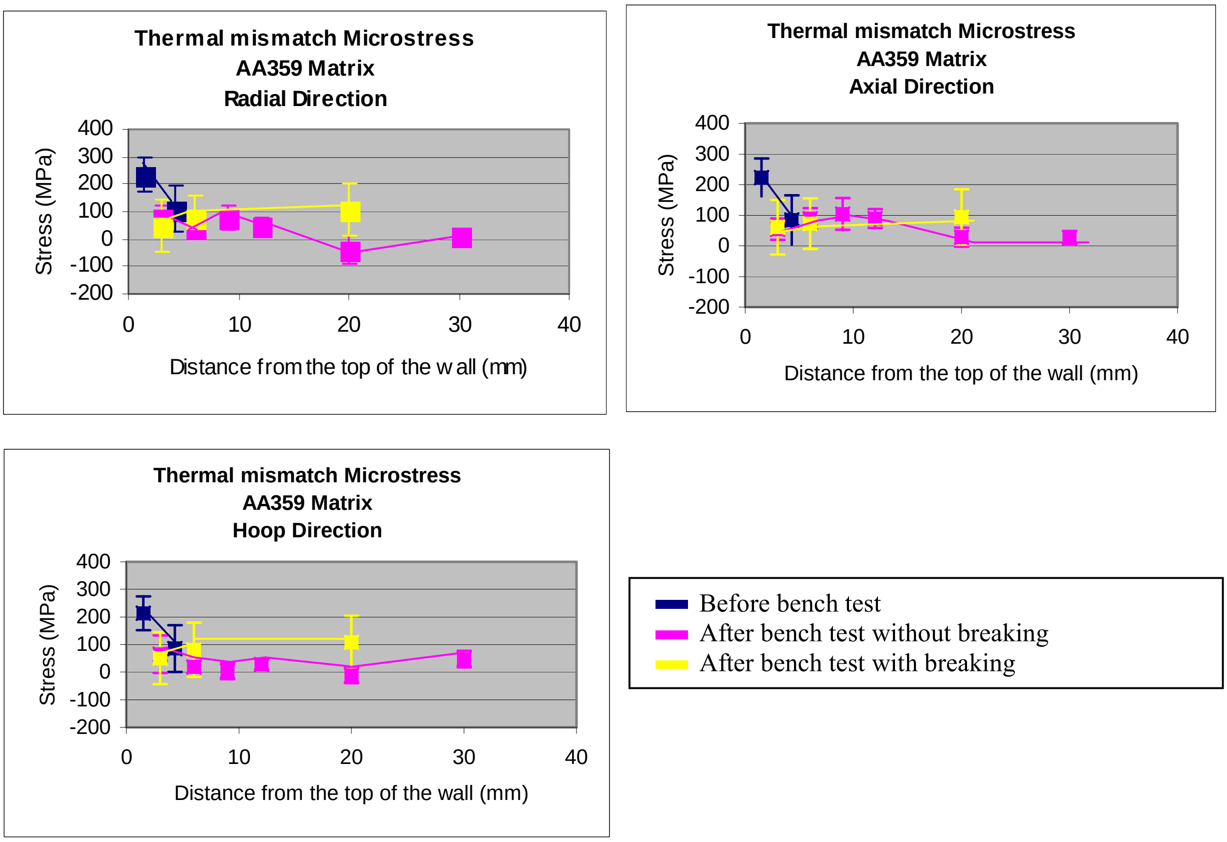

Fig. 6. Measured thermal mismatch microstress in the matrix

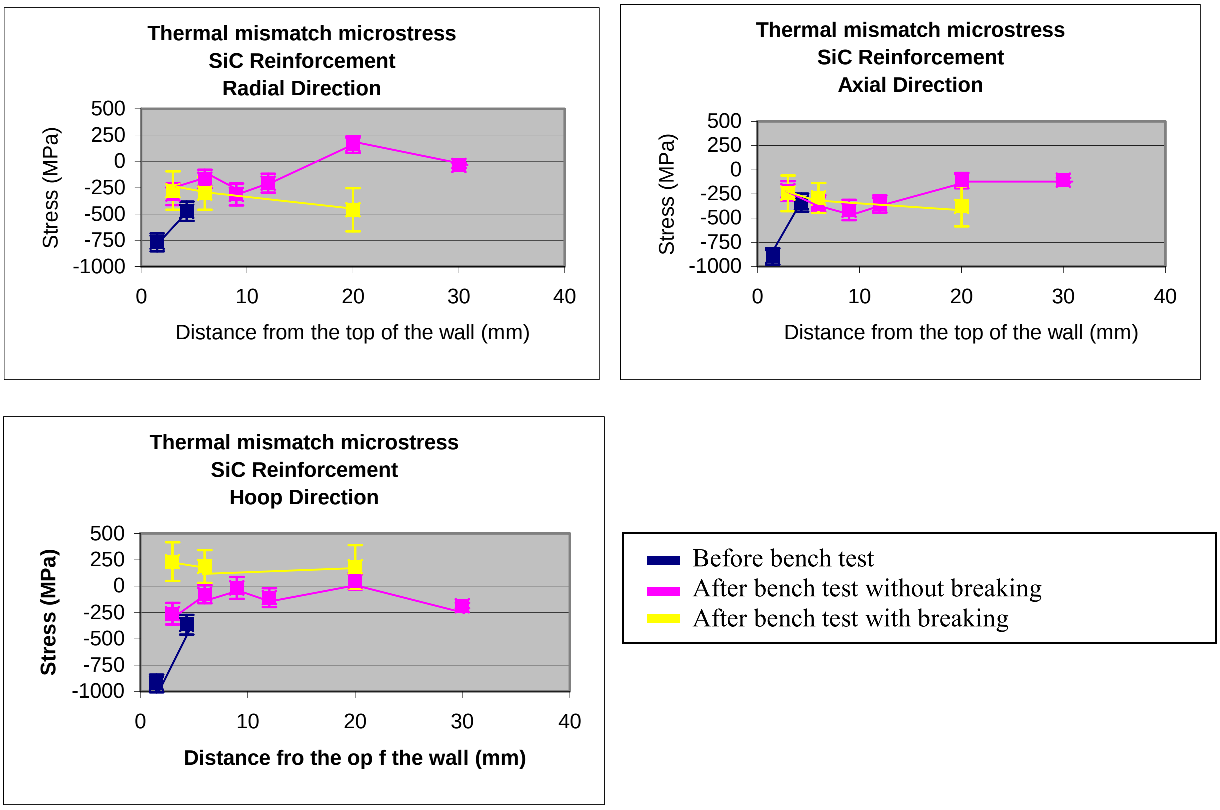

Fig. 7. Measured thermal mismatch microstress in the reinforcement

CONCLUSION

Neutron diffraction was successfully used for the determination of residual stresses induced by fatigue tests on MMC components for automotive technology (brake drums). The residual stress level was evaluated before fatigue cycling, where it is essentially due to the production processes, after a few series of fatigue loading and finally in a failured drum. Results show that macrostresses increase their value in the fatigue sample, reaching values approaching the yield stress of the material (about 400 MPa). As exptected, stresses are released after failure. On the contrary, fatigue cycling induces a reduction (in absolute value) of thermal microstresses.

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Recenzent
Andrzej P. Wilczyński