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The influence of cracks on the mechanical behaviour of particulate MMCs: an experimental study

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THE DETERIORATION OF THE MECHANICAL PROPERTIES of particulate Metal Matrix Composites (MMCs) caused by macroscopic cracks is studied, experimentally, in comparison to the behaviour of the respective matrix alloys. Two Al-based MMCs, reinforced with fine SiC particles, extensively used in aerospace engineering, are employed. The study is focused on the influence of cracks on the fracture strength of MMCs and on the variation of the critical Crack Opening Displacement (COD) versus the inclination of the crack with respect to the loading direction. The role of the plastic anisotropy induced during manufacturing is also investigated.

1. Introduction

THE STRENGTH AND THE STIFFNESS of ceramic particle reinforced MMCs is considerably increased compared to the respective quantities of the unreinforced matrix alloys. This is attributed to the presence of the stiffer particles and the thermal expansion mismatch between the matrix and the reinforcement, which causes a high density of dislocations during the cooling process [1]. Taking also into account that particulate MMCs can be mechanically processed using classical manufacturing technologies developed for monolithic alloys [2], as well as their improved and attracting thermal and mechanical properties, such as low sensitivity to thermal shocks and temperature changes, high surface durability, high thermal and electrical conductivity and high absorption of plastic deformation under impact (in case of ductile metal matrices), one would expect that MMCs could substitute conventional alloys in practical applications. However, and beyond their advantages, the use of MMCs is yet rather restricted, since both their ductility and fracture toughness are considerably lower than the respective quantities of the unreinforced alloy [3]. Similar conclusions are drawn concerning the plastic anisotropy induced during manufacturing, which appears to reduce considerably the strength of cracked composite material while its influence on the respective cracked matrix alloy is almost negligible [4].

In general, it is known that in particulate matrix composites the primary load-bearing element is the matrix material. Especially, in the case of a ductile matrix, the role of the reinforcing particles is to block the motion and slip of dislocations limiting in this way the plastic deformation of the composite material. According to Kelly's theory [5], the maximum strengthening achieved is controlled by the shear modulus of the matrix and the fineness of the particle dispersion. However it is clear, that a much more detailed investigation of the mechanisms responsible for the deterioration of the mechanical properties of MMCs in presence of macroscopic cracks is essential, if one aims at the development of new materials with improved damage tolerance. It was only very recently, that POZA and LLORCA [6] investigated experimentally and numerically the strength and ductility of Al-Li/SiC composites and concluded that the progressive fracture of the reinforcing particles reduced the strain-hardening rate of the composite, precipitating the onset of plastic instability and failure. Unfortunately, the relative literature, especially for modern MMCs, is limited and extensive experimental study of the above phenomena is necessary, in order to quantify them.

Towards this direction, a series of experimental results are presented in the next section, concerning the fracture stress and the critical COD of MMCs' specimens, cracked at various inclinations with respect to the loading direction. Two pairs of materials were tested, namely the 8090 and 2124 matrix alloys and MMCs. Both materials are produced by BP with the aid of a novel powder metallurgy process. An aluminum-based matrix (Al-Li and Al-Cu, respectively) is used, reinforced with 20% per volume of fine silicon carbide (SiC) particulates of diameter $\sim 3\text{x}10^{-6}$ m. According to the process adopted by the manufacturer, the raw materials, i.e. the atomized aluminum alloy powder and the silicon carbide microgrit, are bought-in to an internal specification covering chemistry and size. The powders are then processed and blended to a homogeneous mixture. The mixed powders are then canned, degassed and hot isostatically pressed to full density using conventional aluminum powder metallurgy practices. The hot-pressed billets are decanned and converted to wrought product using standard metal working equipment and techniques. The materials were available in the form of rolled sheets of thickness equal to 1 mm and a special heat treatment was applied to the specimens prior to testing, according to the manufacturer's instructions, in order to obtain their optimum mechanical properties. The treatment included gradual heating of the specimens up to 505°C, keeping the temperature constant for 90 minutes, and immediately cold water quenching, as it is described in the respective Processing Handbook [7]. No visible distortion or surface cracking of the specimens was observed due to the quenching.

The mechanical properties of the materials were determined with the aid of preliminary standardized tension tests and are recapitulated in Table 1. It is clear from this table that the composite materials show increased stiffness compared to their matrix alloys by almost 25% for both "pairs" of materials (where the term "pair" denotes the combination of the MMC material with its respective matrix alloy). On the other hand, the tensile strength of the 8090 MMC composite is 34% higher than that of the matrix alloy while for the case of 2124 pair, the improvement is about 43% . On the contrary, and as it was expected, the ductility of the MMCs, is reduced by 11% in the case of the 8090 pair and by 27% in the case of the 2124 pair. The higher the gain in stiffness and strength, the higher the loss in ductility! However, in case of macroscopically cracked specimens, the above conclusions are not any more valid, and the use of MMCs does not appear to be advantageous, as it will become evident in the next section.

Table 1. The mechanical properties of the materials used in the present study.

		8090			2124	
	Alloy	MMC	Change [%]	Alloy	MMC	Change [%]
Modulus of elasticity [GPa]	92.5	114.0	23	80.0	109.9	37
Tensile strength[MPa]	428	575	34	435	622	43
Ductility [%]	4.5	4.0	-11	6.7	4.9	-27

2. Mechanical behaviour of MMCs in presence of cracks

The dramatic changes in the stress and strain fields in a specimen or in a structure due to macroscopic cracks and the complications imposed are of such a nature that an almost independent branch of Mechanics, the Fracture Mechanics, was developed, devoted exclusively to their study. The fracture toughness, K_{IC} and the critical COD are the two simplest and most widely used concepts for the description of the critical conditions leading an initially stationary crack to growth and finally to catastrophic propagation. Although it is not likely that a single parameter can serve as a complete failure criterion [8], K_{IC} and critical COD are widely applied in Fracture Mechanics, mainly due to their simplicity. Besides the fact that the independence of these quantities of the geometry of the specimens used for their measure is still under discussion [9] and a lot of disagreements and ambiguities concerning the correct method of their measure are stated, the critical COD (and a number of other single-parameter fracture criteria like the $J-$integral and the K_{IC} ones) is considered, even today, to be a unique tool for the in-situ inspection and fracture safety assessment of cracked structural members already in function. For this reason, experimental results concerning these parameters are presented here, in an effort to enlighten the change of the behaviour of MMCs caused by macroscopic cracks.

2.1. Fracture strength of cracked MMCs and their matrix alloys

Four series of uniaxial tension tests were carried out using specimens made from each one of the materials under study. The specimens were rectangular Single Edge Notched (SEN) plates of length l =100 mm, width b=50 mm and thickness d=1mm (Fig. 1). The cracks, of length a_0=10 mm, were artificially machined at one side of the specimens, at a distance $h = l/2$ from their lower edge, using an extra thin cutting disc (thickness δ_0=0.2 mm). The tips of the cracks were smoothened using a diamond wire of diameter 0.2 mm in order to eliminate the double singularity existing in case of artificial cracks (see further Fig. 3a). The inclination of the cracks varied between $\beta = 90°$ to $\beta = 10°$ with respect to the load direction, which was parallel to the long dimension of the specimens (Fig. 1). For each crack inclination angle, three to ten tests were executed depending on the repeatability and scattering of the results. The results of these experiments are shown in Fig. 2, in which the variation of the fracture strength is plotted versus the crack inclination angle, β, for both pairs of materials. The fracture strength of each material is reduced over the fracture strength of the respective intact material.

It can be seen from Fig. 2 that in the case of the 8090 pair, the composite material is of higher strength only for cracks tending to become parallel to the loading direction ($\beta \leq 30°$). For crack inclinations between 30° and 90° the two materials have almost the same reduced strength, which varies between 25% and 30% of the strength of the intact specimens. The absolute values of the fracture strength are recapitulated in Tables 2 and 3. It is evident from Table 2, that for cracks perpendicular to the load direction (β=90°), the matrix alloy is of slightly superior absolute strength (about 2%) compared to the respective reinforced MMC, while for cracks with β=10° the absolute strength of the reinforced material is by about 17% higher than that of the matrix alloy.

Table 2. The fracture strength of cracked 8090 Alloy and MMC specimens in MPa.

Material ↓/ Crack Inclination →	90°	70°	30°	10°
8090 Alloy	132.5	119.6	144.1	210.2
8090 MMC	129.8	120.7	146.2	245.5

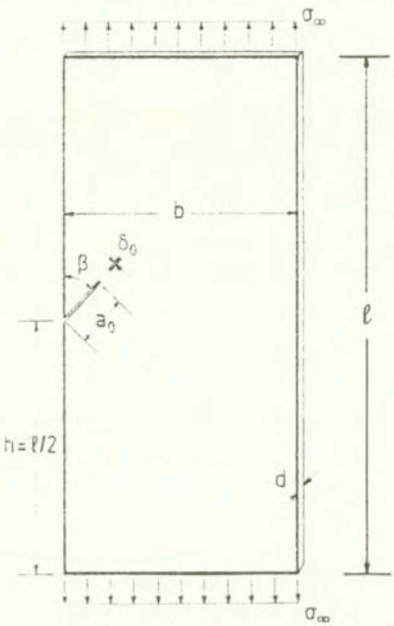


FIG. 1. The geometry of the specimens and the loading configuration.

Table 3. The fracture strength of cracked 2124 Alloy and MMC specimens in MPa.

Material ↓ /Crack Inclination→	90°	70°	50°	25°	10°
2124 Alloy	182.7	206.6	217.5	261.5	287.1
2124 MMC	187.1	186.6	180.4	248.8	357.7

The next characteristic of Fig. 2, which deserves attention, is that the fracture stress for specimens with crack inclinations about $\beta \cong 60°$ is clearly lower compared to that of specimens with $\beta = 90°$, both for the alloy and the reinforced material. In other words and contrary to common sense, a cracked specimen with $\beta \cong 60°$, is at a worst position and the crack is most prone to propagate compared to a specimen containing a crack with $\beta = 90°$, i.e. perpendicular to the load. This phenomenon was already observed experimentally by SIH and KIPP [10] from early seventies. Later it was predicted theoretically by THEOCARIS and ANDRIANOPOULOS [11] for relatively brittle materials, using a modified strain energy-density criterion. A similar experimental result is mentioned by THEOCARIS *et al.* [12], who observed that for dynamic crack propagation, and in case the branching phenomenon was suppressed, the crack tended to place itself in an optimum direction, corresponding to an inclination of about $\beta = 70°$. However, a unified explanation of these phenomena and a soundness interpretation of them in physical terms is still pending.

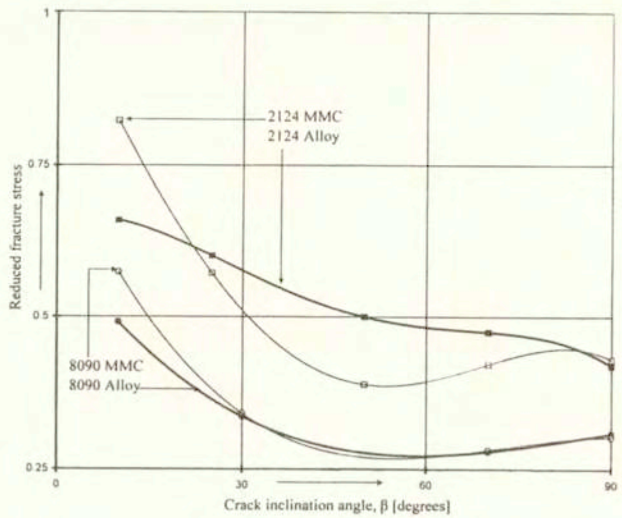


FIG. 2. The fracture stress of the 8090 and 2124 matrix alloys and MMCs reduced over the respective fracture stress of the intact material, versus the inclination of the crack, β.

The conclusions drawn from Fig. 2 for the 2124 pair are of the same nature. However, in this case the matrix alloy appears to be of superior reduced strength for the whole band of crack inclinations between $\beta = 20°$ and $\beta = 90°$. Only for cracks with $\beta \leq 20°$ the composite material excels with respect to the matrix alloy. Moreover, and as it is concluded from Table 3, the matrix alloy has significantly higher absolute fracture stress (about 17% for $\beta = 50°$) compared to the reinforced material. As far as it concerns the variation of the fracture strength versus the crack inclination angle, the anomaly observed for $\beta = 60°$ in the behaviour of the 8090 pair of materials, is not detected at all for the matrix material, while for the composite one it is weak. Such a behaviour is justified, according to what is mentioned in [11], since the 2124 matrix alloy is relatively ductile compared to all three other materials.

2.2. Crack Opening Displacement and its critical value

The COD method of test is standardized according to the ASTM as well as according to the British Standards, either in the form of compact specimens or in the form of three-point-bend specimens. However, it is doubtless that the reliable measure is a very difficult task. The techniques that have been developed, varying from the infiltration technique to the empirical extrapolation of clip gauge measurements, may be considered satisfactory for the case of conventional metallic materials, but are difficult to be applied in the case of MMCs, because their brittleness results in very small absolute values of the COD and the experimental "noise" covers the main phenomenon. The δ_5 procedure proposed recently by HELLMANN and SCHWALBE [13] is the one widely used today for MMCs. The main restriction of the conventional standardized methods is that they have been developed for cracks either perpendicular (compact specimens)or parallel to the loading direction (three-point-bending specimens).

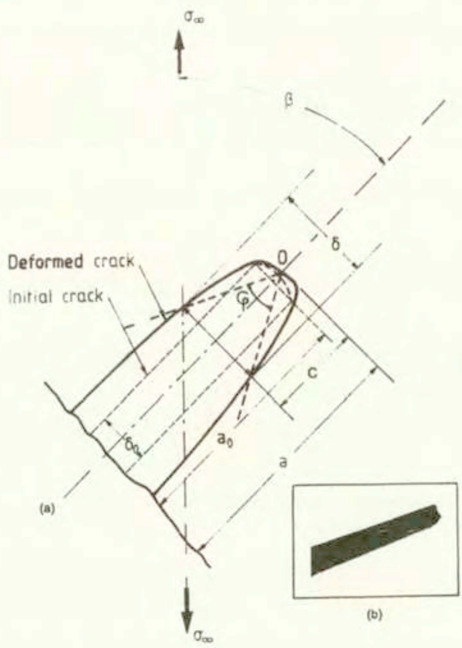


FIG. 3. (a) Schematic representation of the distorted crack tip area and the method adopted for measuring the COD. (b) The distorted crack tip area in case of a crack with $\beta = 70°$ in a specimen made from 8090 alloy, just before failure.

In Fig. 3a the method adopted in the present study for the measurement of the COD ($\equiv \delta$) is explained. The angle φ was not a-priori defined since it depends on the technique followed and it varies between 30° and 45°[14]. However, it was indicated by KNAUF and RIEDEL [14] that the exact point of measurement seems to be unimportant for the final results, as long as the measurement is executed within the distance from the crack tip for which the HRR-field dominates the deformation field. Thus, for the purposes of the present study and taking into account the dimensions of the initial crack, it can be proved that it is sufficient to execute the measurement of COD at a distance c from the current crack tip position, defined from the relation $c/a \approx c/a_0=0.2$ (Fig. 3a), as it is analytically described in [8] (the crack-tip blunting is ignored).

The additional problems confronted in case of cracks inclined with respect to the loading direction, rendering the conventional standardized methods inapplicable, are the following two ones:

i. The loss of symmetry of the crack configuration and the lack of symmetry axis, since prior to its initiation the crack is not developed in a self-similar manner. This is schematically shown in Fig. 3a and, also, in Fig. 3b in which the tip of a crack with $\beta=70^o$ in a specimen made from 8090 alloy is shown, just before catastrophic crack propagation. The same phenomenon is shown, also, in Figs. 4(a,b), in which the asymmetrically blunted tip of an inclined crack is shown, together with its initial symmetric configuration prior to the loading process, as it was obtained with the aid of a scanning electron microscopy.

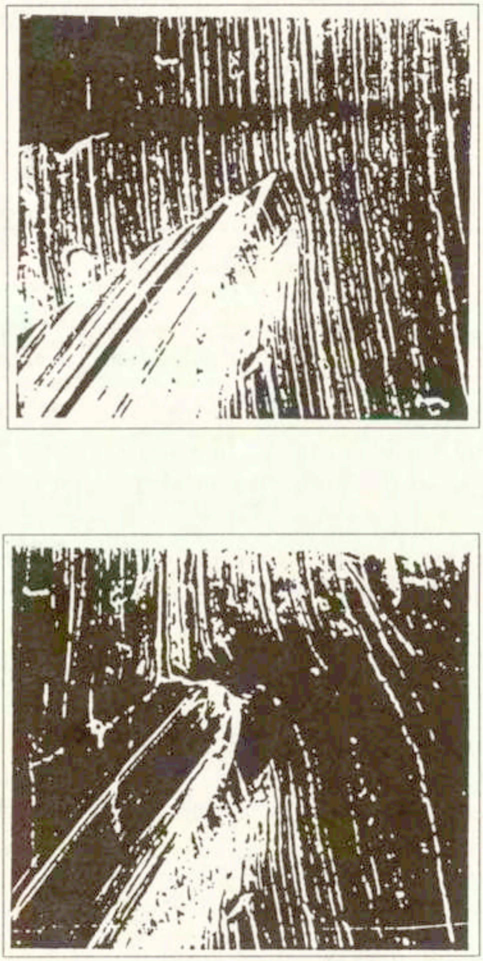
ii. The rigid-body rotation, inevitably accompanying the blunting of the crack-tip [15, 16].

Concerning the geometry and specimen-size dependence of the critical COD, it has been shown by Cowling and Hancock [17] that the onset of crack growth does not occur always at a unique critical value of COD even for a given thickness of the specimens. This phenomenon is attributed to the difference in triaxiality. However, for practical applications the critical COD concept is widely used as a useful lower limit of the fracture behaviour [9].

Having in mind the above-mentioned restrictions, series of uniaxial tension tests were carried out, using SEN specimens with crack-length to specimen-width ratio equal to 0.2. The dimensions of the specimens were again of 100 mm length, 50 mm width and 1mm thickness (Fig.1). Specimens with cracks both perpendicular and inclined with respect to the loading direction were tested. An Instron loading frame was used (maximum loading capacity 250 kN) for the execution of the tests. During the loading procedure, the area around the crack tip was monitored using a high-speed video camera. The COD was measured afterwards using suitable computer image processing software and a series of successive photographs of the crack configuration. The critical COD value was detected from the load versus clip gauge displacement plot as it is described by Landes and McCabe [18]. Four series of tests were carried out, one for each material. For each configuration the value of the critical COD reported is the outcome of three to ten tests, depending on the repeatability of the results.

Characteristic results of the above series of experiments have been plotted in Figs. 5 - 7, for the 2124 pair of materials. In these figures, the reduced COD is plotted versus the reduced applied stress. The reduction for the COD was realized by dividing the difference δ-δ_0 (i.e. the current value of COD, δ, minus the initial

(a)



(b)

FIG. 4. Asymmetrically blunted crack in a copper specimen, prior and during loading, as it is obtained with the aid of Scanning Electron Microscopy (Magnification: x 1000) (a) Configuration prior to loading. (b) Configuration during loading, for a load equal to 75% of the failure load. (Courtesy: V.Kytopoulos, Microscopy Laboratory, LTM/NTUA)

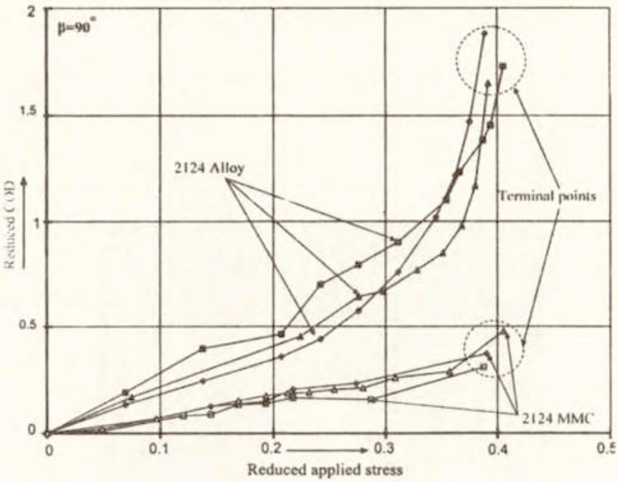


FIG. 5. Experimental results for the reduced COD versus reduced applied stress for the 2124 pair of materials and for crack inclination angle equal to $\beta = 90°$

thickness of the artificial crack, δ_0) by δ_0. The applied stress was reduced over the respective fracture stress of the intact material. In each figure the results of six characteristic tests are plotted, three of them corresponding to the matrix alloy (filled symbols) and three of them corresponding to the reinforced composite (empty symbols). In Fig. 5 the crack inclination is equal to β=90°, in Fig. 6 it is β=50°, while in Fig. 7 it is β=10°. For comparison, the same quantities are plotted in Figure 8 for the 8090 pair of materials and for the configuration corresponding to β=90°.

It can be seen from these figures that the variation of the COD versus the applied stress is initially almost linear and then it increases more or less abruptly (exponentially), up to the critical crack initiation point. Extensive numerical study of the results of the tests indicated that the best-fit curve is an exponential one of the form:

$$\frac{COD - \delta_0}{\delta_0} = m\left(\frac{\sigma}{\sigma_f}\right)^n \tag{2.1}$$

where σ_f is the fracture stress of the intact material and m, n are numerically determined constants, the values of which are recapitulated in Tables 4 and 5, for the 8090 and 2124 pairs respectively. The scattering of the results is not significant for all four materials and all different configurations employed in the experimental procedure.

In Figs. 9 and 10 the critical reduced COD, δ^*, is plotted versus the crack inclination angle, β. The value of the critical COD is obtained as the average of

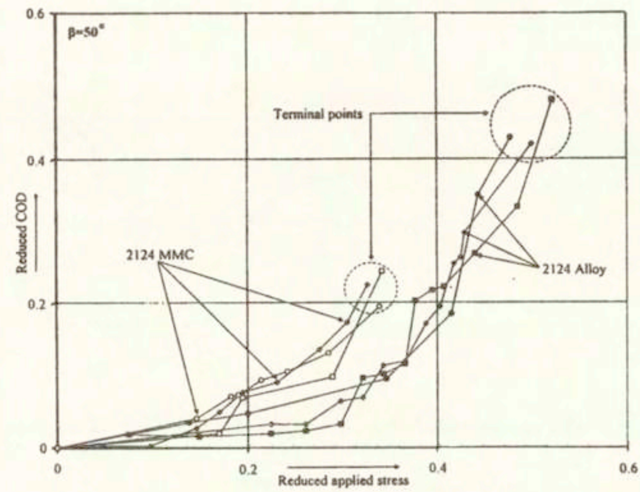


FIG. 6. Experimental results for the reduced COD versus reduced applied stress for the 2124 pair of materials and for crack inclination angle equal to $\beta = 50°$

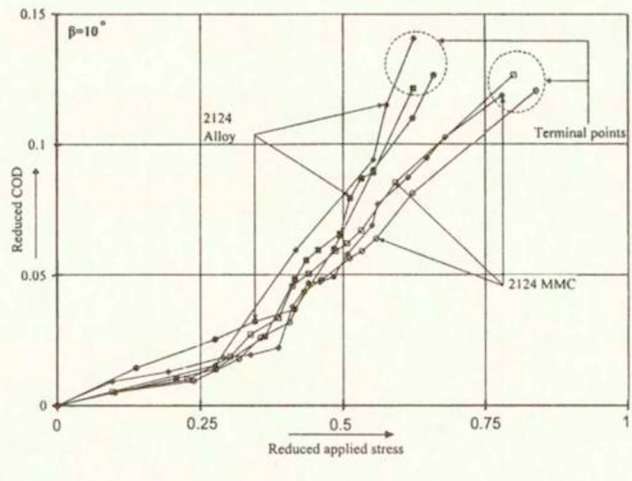


FIG. 7. Experimental results for the reduced COD versus reduced applied stress for the 2124 pair of materials and for crack inclination angle equal to $\beta = 10°$

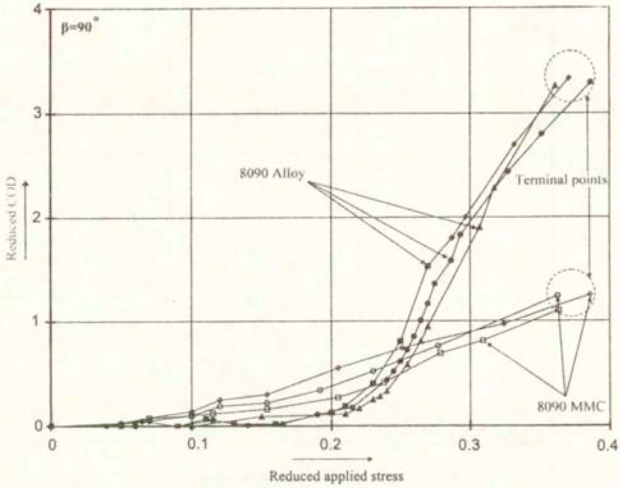


FIG. 8. Experimental results for the reduced COD versus reduced applied stress for the 8090 pair of materials and for crack inclination angle equal to $\beta = 90°$

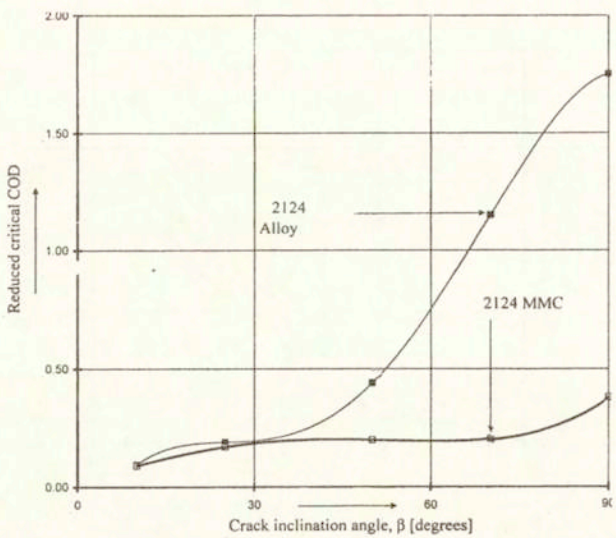


FIG. 9. The critical COD, reduced over the thickness of the initial crack, versus the inclination of the crack for the 2124 pair of materials.

Table 4. The constants m and n of Eq.(2.1) for the 8090 pair of materials.

	Alloy			MMC	
β [°]	m	n	β[°]	m	n
90	64480	8.341	90	15.31	1.903
70	3167	5.991	70	333.5	3.695
30	187.3	4.711	50	95.62	3.336
20	45.04	3.555	25	4.601	1.737
10	9.433	3.296	10	4.008	1.628
			8	1.661	2.487

Table 5. The constants m and n of Eq.(2.1) for the 2124 pair of materials.

	Alloy			MMC	
β[°]	m	n	β[°]	m	n
90	13.11	2.360	90	7.122	2.407
70	5.884	2.458	70	2.660	2.308
50	7.664	4.032	50	33.29	3.770
25	0.943	4.128	25	0.859	1.848
10	0.351	2.304	10	0.351	2.579

all "terminal points" encircled with a dotted line in Figs. 5 - 8. It is observed from Figs. 9 and 10 that the function $\delta^*=\delta^*(\beta)$ is relatively smooth, dividing the (δ^*, β) space into two regions: one corresponding to safe combinations of the COD and crack inclination, and one to combinations leading to failure. Obviously, once the function $\delta^*=\delta^*(\beta)$ is available from a simple series of experiments, like the one described in the present section, it represents a powerful tool for the in-situ inspection of structural elements already in function: one can decide about the remaining life of the element without knowing the value of the applied load but only its relative direction with respect to the crack.

A slight deviation of the above referenced smooth variation is detected for the 8090 matrix alloy and for crack inclinations of about 20°. Indeed, for this geometry the critical COD appears to be higher compared to that corresponding to the configuration with β=30°. The same deviation is also observed for the respective composite material but in this case it is considerably weaker. An explanation of this peculiar experimental observation is not yet available and additional experimental data for other materials are required before definite conclusions are drawn.

An additional anomaly, worth to be mentioned, is the one observed in the behaviour of the $\delta^*=\delta^*(\beta)$ function for the 8090 MMC and for crack inclinations

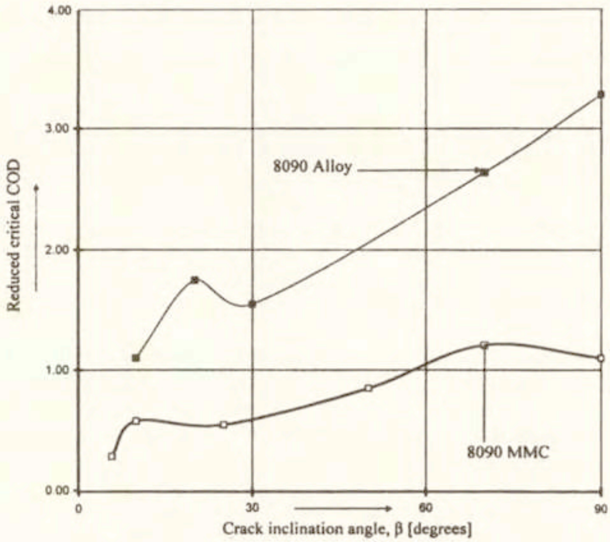


FIG. 10. The critical COD, reduced over the thickness of the initial crack, versus the inclination of the crack for the 8090 pair of materials.

roughly equal to 70°. Indeed, as it can be seen from Fig. 8, the reduced critical COD-value for β=70° exceeds slightly the respective value for the geometry with β=90°. This anomaly is, possibly, related to the respective one mentioned in the previous paragraph for the variation of the fracture stress of cracked materials with respect to the crack inclination. However, and besides the two anomalies just mentioned, the main conclusion from this paragraph is, again, that the influence of macroscopic cracks on the reinforced composite materials is of completely different nature and much more dramatic compared to the influence of macroscopic cracks on the unreinforced matrix alloys.

2.3. Influence of anisotropy on the strength of cracked MMCs

Among the advantages of the MMCs obtained through Powder Metallurgy processes (as it is the case of the BP 8090 and 2124 MMCs of the present study) is the fact that they are more or less homogeneous and isotropic materials, although their density is sometimes variable within the volume of the final product. However, after manufacturing, either by using hot or cold forming processes, the material obtains an oriented texture and exhibits significant anisotropy. It is exactly the purpose of the present paragraph to study the influence of this type of anisotropy on the strength of cracked MMCs, in comparison, again, to the behaviour of their matrix alloys.

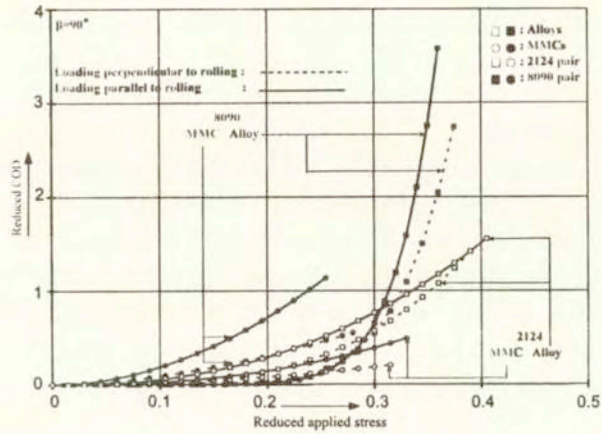


FIG. 11. Best fit curves for specimens loaded parallel and perpendicular to the loading direction for all four materials and crack inclination angle $\beta = 90°$

In order to achieve this target two types of SEN specimens, with cracks oriented perpendicular to the loading direction (i.e. β=90°), were subjected to tensile loading up to fracture. In the first type of specimens the load was applied parallel to the rolling direction (in other words, the initial cracks were machined perpendicular to the rolling direction), while in the second type of specimens the load was applied perpendicular to the rolling direction (and the cracks were machined parallel to the rolling direction).

The results of these series of experiments are shown in Fig. 11, where the reduced values of the COD have been plotted versus the reduced stress for the two types of specimens and for both pairs of materials. The heavy lines correspond to the first type of specimens (load // rolling) while the dotted lines correspond to the second type (load $\perp$ rolling). The filled symbols correspond to the 8090 pair of materials while the empty ones correspond to the 2124 pair. The curves denoted by rectangular symbols (empty and filled) describe the behaviour of the two matrix alloys while the curves denoted by circular symbols (empty and filled) describe the behaviour of the respective reinforced composite materials. To avoid confusion, only the lines obtained as best fit curves from the numerical elaboration of the experimental results have been plotted in this figure, since the variation of the individual tests is identical to that observed in previous series of tests plotted in Figs. 3 - 6.

It is seen from Fig. 11 that the critical COD-value in the case of the MMC materials are considerably lower if the crack is oriented perpendicularly to the rolling direction. For example, for the 8090 MMC, the reduced critical COD-value changes from about 1.25, when the load is applied parallel to the rolling direction to about 0.4, when the load is applied perpendicular to the rolling direction, which correspond to a change of about 210% ! On the other hand, the reduced critical stress changes considerably from about 0.235 to about 0.275 respectively, which corresponds to a change of about 16% . On the contrary, in the case of the respective matrix alloy, the critical COD-value changes by only $\sim$ 25% (from $\sim$ 3.75 to $\sim$ 2.80) and the critical stress remains essentially constant (reduced by less than 5%). The conclusions for the second pair of materials are of similar qualitative nature, although not so impressive quantitatively.

Both observations imply, again, that SiC particles play a profound role in ultimate behaviour of 8090 MMC, which is completely different compared to the behaviour of their matrix alloys.

3. Discussion and conclusions

The primary conclusion of the present experimental study is that the presence of macroscopic cracks deteriorates the strength advantages of MMCs and their respective matrix alloys appear to be more attractive for mechanical applications. The example of the 2124 MMC for which the gain in strength versus its matrix alloy is less than 3% in the presence of cracks perpendicular to the loading direction is characteristic, especially if one considers the gain in strength on the case of intact specimens which is about 43% ! On the other hand, specific configurations (crack inclinations) were detected for which the unreinforced material appears to be stronger than the reinforced one. Only as the crack tends to become parallel to the external load (which means that the influence of the crack tends to disappear), the MMC appears to be again of superior strength.

This behaviour can be explained if it is taken into account that the fracture processes in the case of particulate reinforced MMCs are significantly influenced by the presence of particles, even if they are in the form of platelets, as it happens with both MMCs studied in the present work. Indeed it has been proved by IBRAHIM *et al.* [19] that for such materials the critical step for failure is void nucleation rather than void coalescence. Voids are generated when the local stresses exceed the stress necessary to decompose the particle. When the local plastic relaxation, that relieves stress concentration becomes difficult, as in case of pre-cracked materials, where the plastic relaxation is concentrated in the immediate vicinity of the tip of the macroscopic crack, then the final failure occurs at rather low strains.

As far as it concerns the COD and the class of failure criteria based on the critical COD concept, various drawbacks have been reported in scientific literature, ranging from uncertainties concerning the most representative point of measuring it to the relationship between COD and other critical mechanical quantities (like K_C or J_C) serving as crack initiations indices. However, in spite of these drawbacks, COD appears to be irreplaceable especially for in-situ applications, mainly due to its simplicity. Towards this direction the relationship between critical COD and crack inclination, extracted from the present series of experiments, constitutes an extremely useful tool for the determination of the remaining life of cracked structural members, since the knowledge of the exact value of the load level is not necessary. The only piece of information required, beyond COD, is a rough estimation of the inclination of the crack with respect to the loading direction.

Last but not least, it was concluded that the anisotropy induced during manufacturing affects considerably the mechanical behaviour of reinforced composite materials. The coexistence of plastically induced anisotropy and macroscopic cracks transforms completely the characteristics of MMCs and almost eliminates their advantages concerning both the critical COD and the fracture stress. The respective influence on the matrix materials is very small if it exists at all.

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