Journal of New Technology and Materials (JNTM)
J. New Technol. Mater.
Vol. 09, N°02 (2019)35-44

OEB Univ. Publish. Co.

Analysis of crack behavior in an Epoxy-fiber composite under thermal and thermo-mechanical loading

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Received date: Aug. 29, 2019 ; revised date: Sep. 03, 2019 ; accepted date: Nov. 05, 2019

Abstract

The mechanical behavior of composites depends on commissioning stresses and environmental conditions of use. They are usually subjected to complex mechanical loadings. Their endurance and their lifespan require knowledge of their behavior under such solicitations. The fiber-matrix junction is usually made at high temperatures. When cooling this junction to ambient temperature, internal stresses arise from the difference in the thermal expansion coefficients between the matrix and the fibers. The combination of these stresses with those of commissioning determines the reliability and the performance of the composite. In this study, a numerical model has been developed to analyze the effect of this combination on the lifetime in terms of stress intensity factors variation in modes I and II at the heads of an initially interfacial crack. An epoxy matrix reinforced with fibers. This variation is analyzed according to the orientation of the crack, the intensity of commissioning stresses, the elaboration temperature of the composite, of the combination of stresses of commissioning-internal stresses, the nature of the fibers and their volume fraction.

Key words: Epoxy matrix composite; oriented crack; stress intensity factor; Residual stresses; finite element analysis.

1. Introduction

The service life of composite materials requires mastery of the damage mechanisms. These results from mechanical stresses, thermal or their combination (thermomechanical) and environmental conditions more or less severe especially for polymer matrix composites. Under the effect of such solicitations and in the long term, the physical and mechanical characteristics fall considerably. From this fact, the prediction of the durability of composites requires the setting up of experimental devices and the development of three-dimensional numerical models enabling the analysis and understanding of the mechanisms responsible for the degradation of these materials.

Polymer matrix composites are particularly vulnerable not only to commissioning stresses but also to environmental media. These composites are widely used in aircraft structures, civil engineering, hydrocarbon electronics. Nevertheless, these composites are, over time, sensitive to macroscopic failure, A phenomenon resulting from microscopic damage (crack formation) by the degradation of thermomechanical properties [1].

Due to the nature of their polymer matrices, the modeling of their mechanical behavior is very delicate to implement. These composites reinforced with long fibers are strongly anisotropic and lead in the case of an elastic approach to a large number of coefficients to be determined in the case of a laminate [1].

The lifetime of composites in general is closely related to their elaboration techniques and commissioning conditions. Thus, these conditions are largely responsible for their degradation. In the case of metal matrix composites, performance improvement is strongly influenced by the nature of the matrix microstructure. Indeed, a study has shown that their modification leads to an increase in resistance to damage [2-4]. In other works, the volume fraction of the reinforcement, its distribution and its size significantly affect the resistance to degradation [5-9]. Some work has used the Puck damage criterion to analyze the initiation and propagation of cracks in the fiber and/or matrix. The behavior of these cracks determines the predominant fracture mode of the composite. They also show that the presence of defects in the direction of crack propagation accelerates its instability [10]. Other authors used the finite element method FEM and XFEM for analysis of crack initiation and propagation in composites. The finite element method was used for the study of crack behavior and damage in composites [11-13]. Another study used the energy release rate at the tips of an interfacial crack as a parameter characterizing fiber-matrix separation using a cylindrical axisymmetric model [14]. Other authors numerically analyzed the stress intensity factor in Mode I (K_I) and Mode II (K_{II}) in the heads of an interfacial crack based on its location and loading intensity. They took into account the combinations of different coating materials and the substrate [15]. One study, developing a three-dimensional finite element model, analyzed the energy release rate using the integral J method as a criterion for interfacial damage. They showed that the results obtained from the integral model Contour / cohesive zone are comparable with those obtained using the reference model (J-integral method and VCCT) [16]. The techniques of implementing composites determine among other things the resistance of their damage. Thus, during their elaboration at relatively high temperatures (fiber-matrix junction temperature), residual stresses arise during the cooling process of these temperatures at ambient temperature. These stresses are mainly due to the difference in thermal expansion coefficients between the fiber and the matrix. Too large a gap weakens the adhesion between these two constituents, and consequently promotes the initiation and the propagation of fatigue microcracks. The effect of these stresses on the mechanical behavior of composites has been the subject of several studies. Some of them are the most recent. A study has shown the role of residual axial thermal stresses, cyclic loads and the presence of notches on the tensile performance of a fiber-reinforced magnesium-barium-alumina-silicate-SiC composite (BMAS) ceramic [17]. In another study, an analysis of the factors responsible for the birth of residual stresses in composites and their effects on fiber and matrix properties was developed. This study presents analytical, numerical and experimental methods for the prediction of thermal residual stresses [18]. Other work has shown the effects of residual stresses and their interactions on the mechanical behavior of MMC metal matrix composites [19]. This author explains that these stresses are responsible for the degradation of their mechanical characteristics and their initial performance. The analysis of residual stresses on the high temperature behavior of composites is also highlighted in this study. Other work, using the finite element method, concluded that the thermal residual stresses in the epoxy matrix reinforced with boron fibers are closely related to the volume fraction of the fibers, their size and interaction. The presence of an interfase between the fiber and the matrix promotes partial relaxation of these stresses [20].

Using the Extended Finite Element (XFEM) method, a study showed that variations in thickness and interphase force relative to fibers and/or matrix can have a predominant effect on crack behavior (propagation and deviation). They conclude that the initial deviation of the crack occurs most often when conditions favor secondary cracking in the interphase compared to a neighboring matrix crack [21].

As noted above, the fiber-matrix junction is obtained at higher temperatures. After their cohesion, their deformation resulting from thermal expansion will be the same. This behavior is manifested by the development of internal compressive stress in the matrix and stress in the fibers when the temperature increases and vice versa when it decreases [22]. Thus, the internal stresses induced respectively in the matrix σ_m and in the fibers σ_f are balanced according to the equation:

$$f(\sigma_m + \sigma_f) = 1 \qquad (1)$$

The difference in deformation caused by the thermal expansion coefficient of the matrix and the fibers taken separately and that (expansion) of the composite can be accommodated according to the relationship:

$$\boldsymbol{\alpha_m \Delta T - \varepsilon_c = \sigma_m / E_m} \qquad (2)$$

$$\varepsilon_c - \alpha_f \Delta T = \sigma_f / E_f \qquad (3)$$

Where α is the thermal expansion coefficient, the indices m, f represents the matrix and the fibers respectively, and ΔT is the temperature variation from the reference temperature T_0 given by: (T_0-T).

By combining the expression (1) with the relations (2) and (3), the internal constraints generated respectively in the matrix « σ_m » and in the fibers « σ_f » are written:

$$\boldsymbol{\sigma_m = f E_m E_f \Delta\alpha \Delta T / E_c} \qquad (4)$$

$$\sigma_f = (1-f) E_m E_f \Delta\alpha \Delta T / E_c \qquad (5)$$

Where, Ec the Young composite module, Δα the difference in thermal expansion coefficients between the matrix and the fibers. Based on these relationships (4) and (5) and as a first approximation, the residual stresses are directly proportional to this difference and the fiber volume fraction.

This work falls within this context and aims at numerical analysis by the finite element method of the mechanical behavior of polymer matrix composite materials during the commissioning process. In other words, under the effect of the combination of the residual stresses to the commissioning stresses. This behavior is analyzed in terms of the variation of stress intensity factors in matrix crack heads in Modes I and II. The effect of the location of the fracture fronts, its orientation, the intensity of the commissioning stresses (mechanical loading), the level of residual stresses (thermal loading), the combination of these two stresses (thermomechanical loading), the nature of the fiber, its volume fraction and the difference in the thermal expansion coefficients between the matrix and the fibers were particularly studied.

2. Modeling of the finite element

The numerical model, developed to achieve the previously fixed objective, is shown in Figure 1. This model, which makes up an elementary cell, consists of a cylindrical matrix of length L and radius R_m reinforced by a straight axial fiber of radius R_f. In this model the crack is initiated at the fiber-matrix interface. This crack is oriented in the matrix around its head noted « 1' », as shown in Figure 2. The latter also illustrates the boundary conditions imposed on the cracked cell.

The two-dimensional crack propagation simulation was developed using the finite element code ABAQUS version 6.13 [23]. The cell was meshed with four-sided elements with a total number of 520541 elements. This mesh has been particularly refined in a neighborhood very close to the fracture fronts (Fig. 3).

Uy=URx = URz= 0.
Ux= Uy =Uz = URx =URy=URz=0 (Recessed), present the boundary conditions imposed on this structure.

The composite analyzed consists of an epoxy matrix reinforced with silicon carbide fibers (SiC), Glass E, Kevlar 49 and Carbon HR whose properties are grouped in Table I. The elastic approach and flat stress conditions were used for the estimation of fracture energy in crack tips in opening the mode « K_I » and « K_{II} » shear.

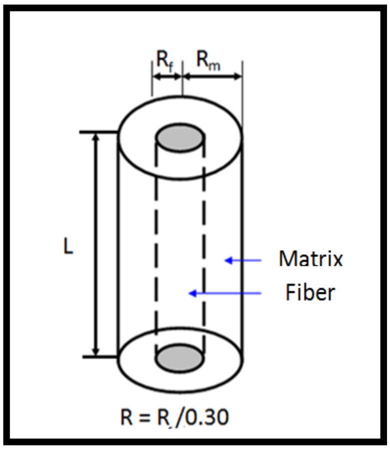

Figure 1. Schematic representation of the analyst model

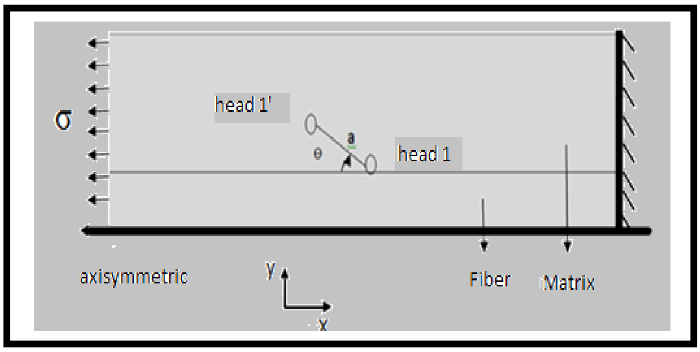

Figure 2 . Schematic representation of the studied model

Table 1. Mechanical characteristics of the materials used [24-25-26]

Materials	Modulus of elasticity Longitudinal E (MPa)	Poisson's ratio (υ)	Coefficient of thermal expansion α[°C^{-1}]
Epoxy R 368-1	3050 ± 30	0.35 ± 0.02	4 e-005
SiC	450000	0.16	0.5 e-005
Glass E	74000	0.25	0.5 e-005
Carbon HR	230000	0.3	0.02 e-005
Kevlar 49	130000	0.4	0.2 e-005

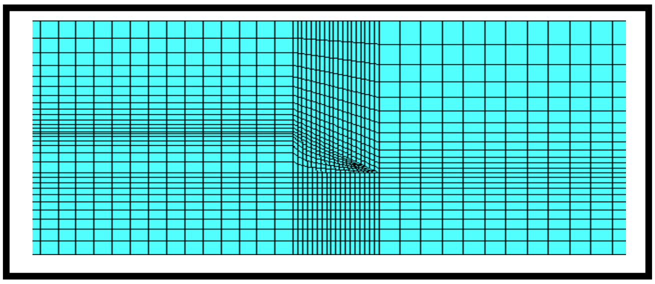

Figure 3. Mesh of the elementary cell

2.1. Analysis of the stress intensity factors

2.1.1. Case of an interfacial crack

Crack propagation in mixed mode can be analyzed by finite elements or boundary elements; the advantage of such a numerical method is that the stress intensity factor is more accurate in terms of nodal displacements in the vicinity of the crack tip which are called displacement correlation method. In this analysis, the displacement correlation method is used. To do this, definitions are given in Figure 4. After obtaining solutions by finite elements or boundary elements for the cracked structure obtained, the displacement value of nodes a-e (Fig. 4b) is determined. The stress intensity factors in open mode (K_I) and shear mode (K_{II}) have been defined [27].

$$K_I = \sqrt{\frac{2\pi}{L}}(D_1[v^e - v^d + 3v^a] - D_2[v^c - v^b + 3v^a]) \quad (6)$$

$$K_{II} = \sqrt{\frac{2\pi}{L}}(D_1[u^e - u^d + 3u^a] - D_2[u^c - u^b + 3u^a]) \quad (7)$$

Where: L is the distance between nodes a-c or a-b , v^i is the following displacement (y) at nodes a-e and u^i is the following displacement (x) at node a-e.
D_1 and D_2 may be expressed as:

$$D_1 = \frac{(1+\gamma)\lambda_0}{cosh(\pi\varepsilon)} \cdot \frac{G_1}{k_1 e^{\pi\varepsilon} + \gamma e^{-\pi\varepsilon}} \quad (8)$$

$$D_2 = \frac{(1+\gamma)\lambda_0}{cosh(\pi\varepsilon)} \cdot \frac{G_2}{k_2 \lambda e^{-\pi\varepsilon} + e^{-\pi\varepsilon}} \quad (9)$$

Where:

$$\varepsilon = \frac{1}{2\pi} \ln \gamma \quad (10)$$

$$\gamma = \frac{G_1 + K_1 G_2}{G_2 + K_2 G_1} \quad (11)$$

$$\lambda_0 = \left(\frac{1}{4} + \varepsilon^2\right)^{1/2} \quad (12)$$

$$\lambda = 1/2 + i\varepsilon \quad (13)$$

Where: (k_i) is defined for axisymmetric problems 3-4v_i.
ε is the constant of the bimaterial, and (G_1, G_2, v_1) and (v_2) are the respective shear modulus and Poisson coefficients of the two materials (matrix and fiber). The shear modulus can be expressed as follows:

$$Gi = E_i/(2(1+v_i)) \quad (14)$$

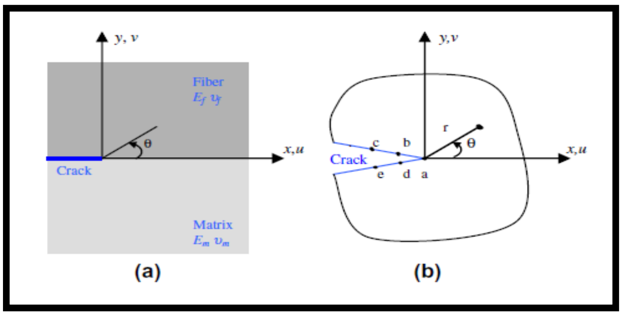

Figure 4. (a) The interface crack between fiber and matrix and (b) nodes at the crack surfaces

2.1.2. Angle of crack propagation

In Mode I and II, stress intensity factors are known. In this case, the prediction of the crack propagation angle, under the application of a load, can be estimated. The most suitable method here is the theory of maximum stresses. According to this theory, the crack propagates in a direction perpendicular to the tangential maximum stress. In this study the crack growth angle is obtained from the theory of maximum tangential stress. This angle is therefore written:

$$\theta = 2\tan^{-1}\left[\frac{1}{4}\left(\frac{K_I}{K_{II}} \pm \sqrt{\left(\frac{K_I}{K_{II}}\right)^2 + 8}\right)\right] \quad (15)$$

3. Results

The behavior of the interfacial crack is analyzed here in terms of variation of the stress intensity factors in modes I and II into crack tips, noted «1» and «1'», and oriented from an angle ϴ to the fiber-matrix interface (Fig.2). The effect of the location of the fracture fronts, its orientation, the intensity of the commissioning stresses (mechanical loading), the level of residual stresses (thermal loading) the combination of these two stresses (thermomechanical loading), the nature of the fiber, its volume fraction and the difference in the coefficients of thermal expansion between the matrix and the fibers were particularly studied.

3.1. Effect of crack orientation

A crack of size « a », initiated at the Epoxy-SiC (epoxy-silicon carbide) interface, developed at temperature «T», is oriented from an angle (ϴ) in the epoxy matrix around its head denoted «1» The unidirectional fractured composite is subjected to uniaxial tension forces along the fibers. The results, obtained and illustrated in figures 5 to 10, illustrate respectively the variation in the stress intensity factor of the k_I opening mode and the K_{II} shear mode (Mode II) depending on the orientation of the crack, tension forces, temperature of elaboration and combination: applied-residual stresses, simulated here by thermomechanical stresses. For a crack position at ϴ=0°, corresponding to an interfacial crack initiated parallel to the tension force direction, the stress intensity factor in Modes I « K_I» and II « K_{II}» at head «1'» are zero. This shows explicitly that such a crack tip is stable from a propagation point of view. The applied stresses act as cracks closing stresses (Fig.5). A progressive ϴ orientation of the matrix crack at the head «1'» leads to an intensification of the fracture energy in Mode I. Its maximum value is reached when the crack is oriented perpendicular to the interface with the fiber (Fig.5). In Mode II, this crack position results in a zero fracture criterion (Fig.6). Thus, under the effect of the commissioning stresses, this cracking front propagates in pure opening mode. This criterion assumes maximum values when the crack is inclined 45° from the interface. At this orientation, the shear stress « τ » becomes maximum and the K_{II} stress intensity factor tends towards its maximum value. In other words, a matrix crack oriented at 45 ° propagates in mixed modes (I and II).

From 45 ° to 90 °, the stress intensity factor in mode I increases while that in mode II decreases (Fig 5, 6). This behavior is all the more marked as the composite is subjected to more intense forces of tension, whatever the location of the crack with respect to the interface (Fig.5 and 6).

Figure 7 and 8 shows the effect of the epoxy-SiC composite elaboration temperature on the matrix crack behavior. In Mode I, the intensity factor increases not only with the increase in the angle of orientation of the crack, but also with the increase of the elaboration temperature. The residual thermal stresses, induced in the epoxy matrix during the elaboration of the composite, are responsible for such behavior. These stresses act as interface crack closing stresses (Θ =0°), defined by a zero-stress intensity factor, and as opening stresses of matrix cracks located perpendicular to the interface (Θ =90°), characterized by maximum positive fracture energy (K_I). A crack oriented at (Θ =90°) propagates, under the effect of internal stresses of thermal origin, in purr Mode I.

Our results show that the operating temperature is a physical parameter that determines the mechanical behavior of composite materials. It is at the origin of the residual stresses in the matrix and in the fiber in the vicinity very close to the interface. These stresses cause the propagation of the matrix crack, in Mode I and Mode II. the instability of this crack is all the more likely that the composites are made at high temperatures. Cracks initiated in the epoxy perpendicular to the interface present a high risk of damage in Mode I of the composite when the epoxy matrix is jointly bonded to SiC fibers at relatively high temperatures.

Combination: commissioning stresses- residual stresses, simulated by thermomechanical stresses, determine the lifetime of composites in terms of the evolution of stress intensity factors in Modes I and II as shown in figures 9 and 10. The latter illustrates the variation of the stress intensity factor in Modes I and II as a function of the thermomechanical stress amplitude. The analysis of these figures indicates almost the same behavior as that resulting from the effect of the temperature elaboration with the values of the stress intensity factors in modes I and II slightly higher. This is mainly due to the size of the crack analyst. Our results show that, in addition to the applied tension stresses, the residual stresses of thermal origin can lead to the brutal propagation in the opening mode of the «1» front of the matrix crack. The high stress intensity factor values obtained are characteristic of such a risk.

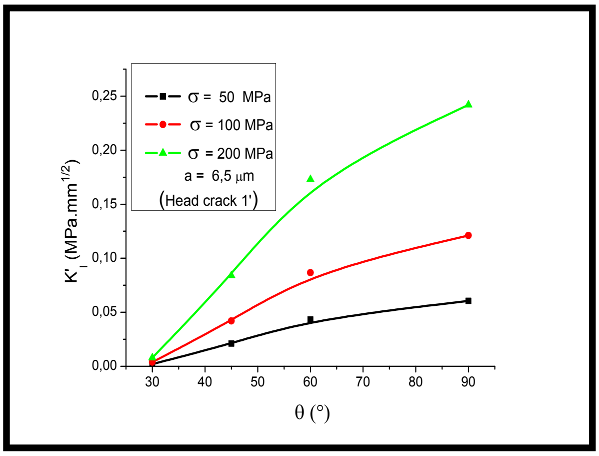

Figure 5. Variation of the stress intensity factor in mode I as a function of angle (θ) under mechanical loading

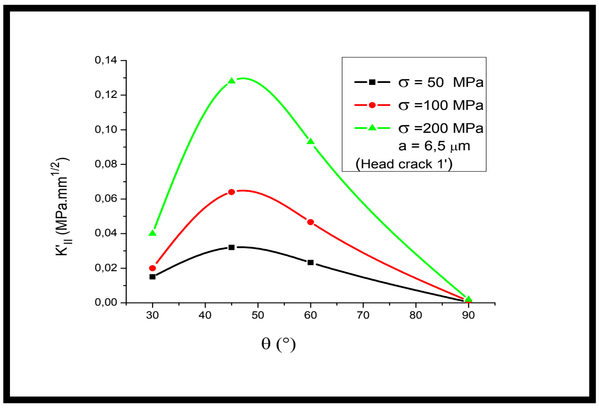

Figure 6. Variation of the stress intensity factor in mode II as a function of angle (θ) under mechanical loading

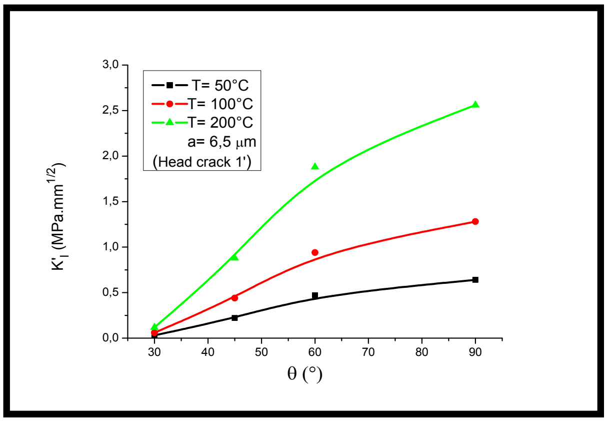

Figure 7. Variation of the stress intensity factor in mode I as a function of angle (θ) under thermal loading

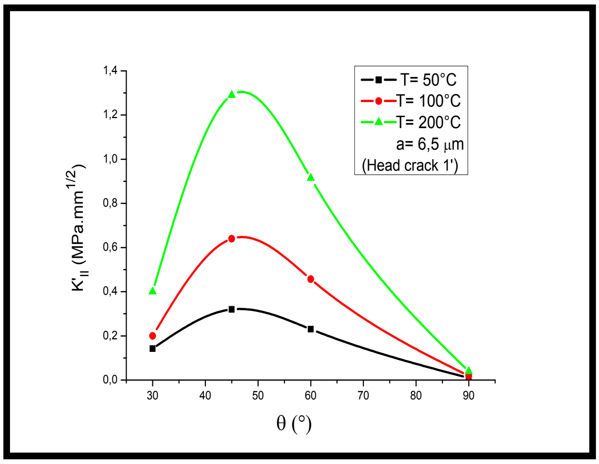

Figure 8. Variation of the stress intensity factor in mode II as a function of angle (θ) under thermal loading

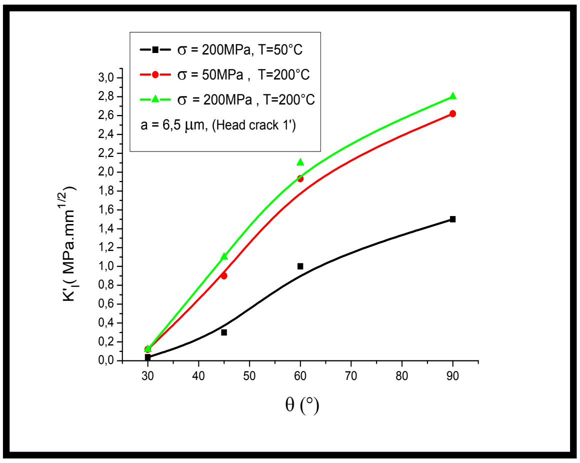

Figure 9. Variation of the stress intensity factor in mode I as a function of angle (θ) under thermomecanical loading

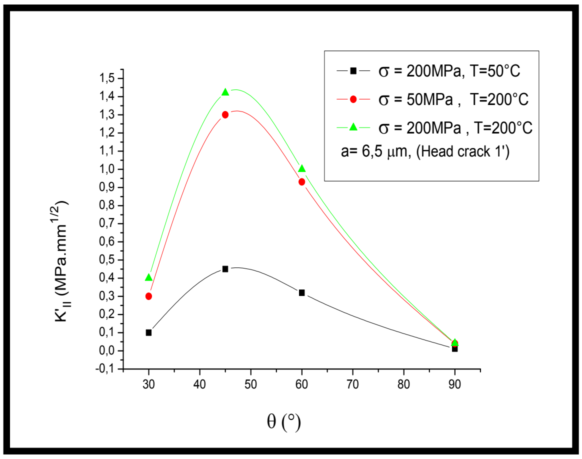

Figure 10. Variation of the stress intensity factor in mode II as a function of angle (θ) under thermomecanical loading

3.2. Effect of nature and fiber volume fraction

The composites, analyzed in this section, consisting of an epoxy matrix reinforced with fibers of different natures, defined by their coefficients of thermal expansion and their Young modulus, are produced at a temperature of 200°C. The latter, which provides the fiber-matrix junction, is responsible for the mechanical connection between these two components. If this temperature conditions the mechanical resistance of the fiber-matrix interface by better adhesion between these two components, it gives rise to residual stresses in the matrix and fiber in the vicinity of the interface. These stresses result from cooling these temperatures to room temperature due to the difference between the thermal expansion coefficient of the fiber and that of the matrix. In addition to the operating stresses of the composite, these stresses may be responsible for the damage to this material. Therefore, the analysis of their level and distribution is a necessity for the prediction of the lifetime of these composites. This is therefore the objective of this part of the work. This prediction is analyzed in terms of variation of the stress intensity factor in Mode I « K_I » and Mode II « K_{II} » as a function of the crack position, the difference of the matrix and fiber thermal expansion coefficients and the volume fraction of the fiber. The composite studied, consisting of an epoxy matrix reinforced with glass fibers « E », Kevlar « 49 » and carbon « HR ». The interfacial crack size « a= 6.5 µm », defined by these two heads noted 1 and 1', was oriented around its head, noted 1, in the matrix at an angle Θ (Fig. 2) in order to evaluate the predominant mode of propagation. The results obtained are shown in Figures 11 and 12. The latter illustrates the effect of this orientation on the stress intensity factor in Modes I and II respectively. Our results clearly show that there is an orientation (Θ =45°) beyond which the crack front noted as «1» propagates in the open mode (Fig.11). Indeed, in the opening mode and for a matrix crack positioned at 45° from the interface, the crack front «1» is stable (the negative stress intensity factor), For this purpose, the residual compressive stresses located in the fiber act as closing stresses. Beyond this position of the crack, this mode of fracture grows rapidly and reaches its maximum value when the crack is oriented perpendicular to the interface with the fiber (Fig. 11). This shows explicitly that the effect of the residual compressive and tensile stresses induced in the fiber and in the matrix respectively determines the mode of propagation of the «1» front of the oriented matrix crack (in Mode I, close to a crack positioned at Θ < 45° and open at Θ > 45°). Thus and under the effect of normal and tangential residual stresses, the front «1» of a crack oriented at Θ < 45° propagates in pure mode II and located at Θ > 45° develops in mixed mode I and II. The stress intensity factor values shown in Figures 11 and 12 show that the predominant mode of propagation is the mode of opening. The kinetics of growth of the head denoted «1» of the crack is even more marked than the coefficient of expansion of the fiber is weak (Fig.11). In shear mode II, the fracture energy in the head «1» increases with the increase in the angle of orientation of the crack (Fig.12) and reaches its maximum value when the crack is oriented at 45° by the fiber-matrix interface. The values of this energy are extremely smaller than those resulting from Mode I. This clearly shows that the tip «1» propagates, under the action of residual stresses, preferentially in Mode I. In this mode of fracture, the «1» front of the matrix crack located at the interface is stable. In this case, these internal tension stresses, which are thermally induced in the epoxy matrix, act as closing stresses of this fracture front (Fig.13). This closure is defined by null values of the stress intensity factor in Mode I (Fig.13). An orientation of this front in the epoxy promotes its growth in the opening mode. The latter becomes predominant when the crack is located perpendicular to the interface. In shear mode (Mode II), the fracture energy reaches its maximum value when the crack is tilted 45° from the interface (Fig.14). Recall that this position corresponds to the highest shear stresses, and the crack tip, noted as «1'», develops in mixed mode I and II. The values of the stress intensity factors in Modes I and II are all the more important because the fiber has a small thermal expansion coefficient.

The values of these fracture criteria obtained in «1» crack tips are much larger than those derived from the «1'» crack front. This illustrates explicitly that the residual stresses, which are responsible for the propagation of these crack heads, are highly localized in the vicinity of the fiber-matrix interface. Their level drops as you move away from that interface. The stress intensity factors at heads of matrix cracks oriented with respect to the interface are all the more marked as the difference in the coefficients of thermal expansion between the matrix and the fibers is more pronounced and whatever the mode of propagation of the matrix crack .

Our results clearly show that, compared to the «1'» front and in the opening mode, the risk of instability of the «1» crack front is more likely when the matrix crack is oriented perpendicular to the interface. The values of the stress intensity factors resulting from these two crack heads are characteristic of such behavior (Fig.11 and 13). For this purpose, only the crack front propagation noted as «1» is taken into account in the analysis of the effect of the fiber volume fraction.

The composite chosen for this effect consists of an epoxy matrix reinforced with glass fibers. Figures 15 and 16 show the influence of this fraction on the stress intensity factors in Modes I and II at the crack head «1» respectively. The analysis of these figures clearly shows that these factors are all the more important as the volume fraction of the reinforcing material increases, regardless of the orientation of the crack around its «1» tip. This behavior explicitly shows that the fiber-fiber interaction determines the level of residual stresses in the epoxy matrix. This level is all the higher the stronger the interaction, in other words, when the fibers are located in the very close proximity of each other [20]. It is therefore these stresses which are responsible for the increase of these two criteria of rupture.

Recall that the crack front noted « 1 », located at the fiber-matrix interface (epoxy-glass), is essentially subjected to residual shear stresses (near the interface : the matrix is in tension and the fiber in compression). For orientations less than 45°, the normal residual compressive stresses, negative in relation to those of tension, induced during the elaboration of the composite in the fiber, act as a constraint to the closure of this front. The negative values of the stress intensity factor (Fig.15) are characteristic of this closure. For such orientation, this crack head propagates in pure II mode. An orientation greater than 45°, the normal residual tension stresses, generated thermally in the matrix, lead to the opening (Mode I) of this crack tip, defined by the values of the positive stress intensity factor. This factor increases with increasing the angle of orientation of the matrix crack. Its maximum value is obtained when the crack is located perpendicular to the interface (Fig.15). In other words, for orientations above 45°, the cracking front, noted 1, propagates, under the effect of the interfacial shear residual stresses and the residual matrix tension stresses, in mixed mode II and I respectively.

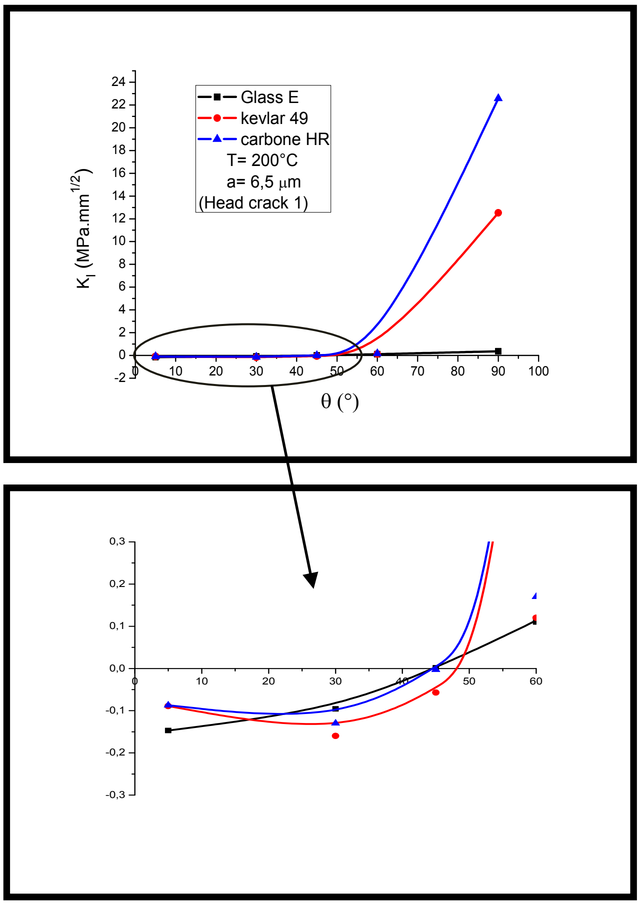

Figure 11. Variation of the stress intensity factor, in mode I, according to the nature of the fiber and the orientation of the crack with respect to the interface

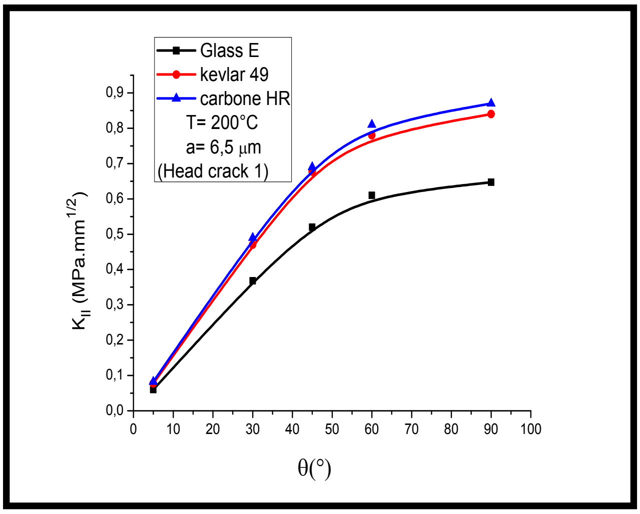

Figure 12. Variation of the stress intensity factor, in mode II, according to the nature of the fiber and the orientation of the crack with respect to the interface

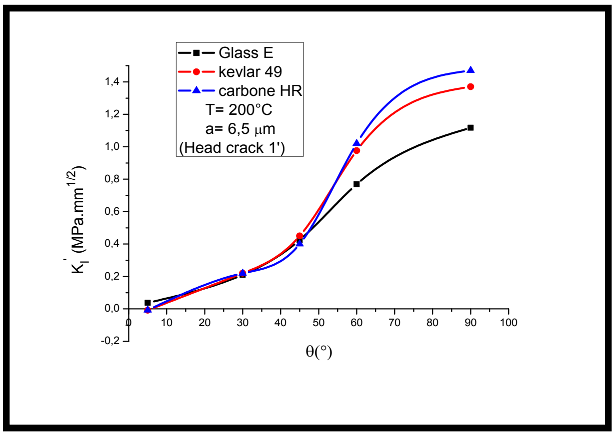

Figure 13. Variation of the stress intensity factor, in mode I, according to the nature of the fiber and the orientation of the crack with respect to the interface

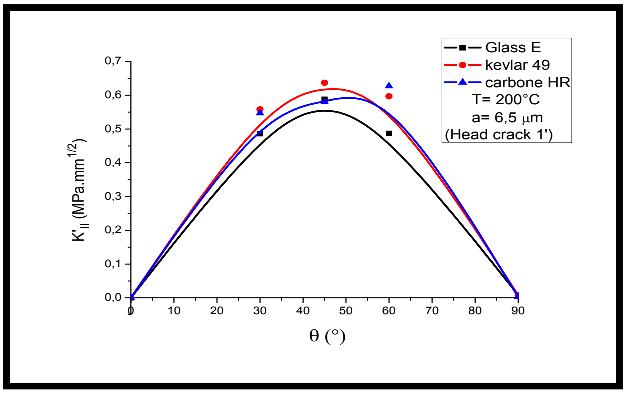

Figure 14. Variation of the stress intensity factor, in mode II, at the crack head «1'» according to the nature of the fiber and the orientation of the crack with respect to the interface

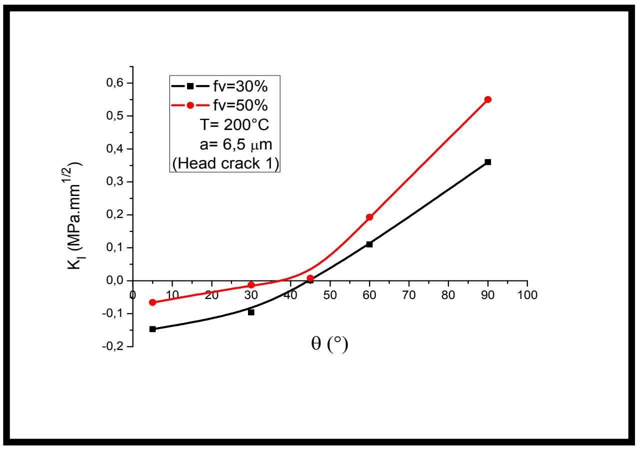

Figure 15. Effect of the volume fraction of the fiber on the stress intensity factor, in mode I

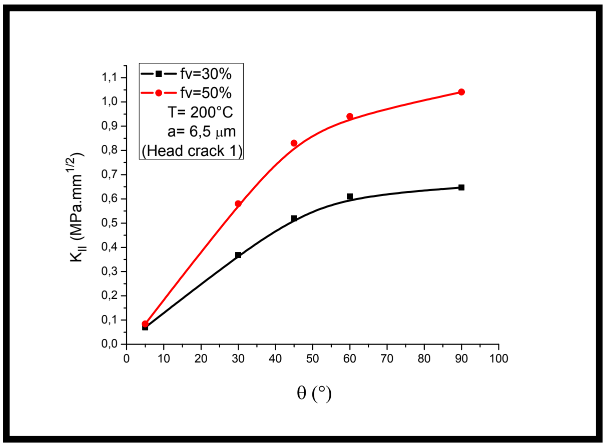

Figure 16. Effect of the fiber volume fraction on the stress intensity factor, in mode II

4. Conclusion

The results obtained in this study lead to the conclusion that:

In the opening mode and under the effect of the tension stresses applied parallel to the fiber-matrix interface, the fracture energy in the head noted «1'», initiated at the matrix-fiber interface and defined by the angle Θ =0°, is all the more important that this front tends to orient itself perpendicularly to this interface (Θ = 90 °). This energy increases with the increase in the amplitude of the commissioning stresses. In shear mode II, the stress intensity factor reaches its maximum value when this crack front is oriented Θ = 45° with respect to the interface. The values of this factor are directly related to the intensity of the applied stresses. For extreme positions Θ=0° (interfacial crack) and Θ = 90° (crack perpendicular to the interface), this fracture criterion is null;

- Composite elaboration temperatures determine the level of internal thermal stresses in the matrix and fiber. These stress condition the mode of propagation of crack fronts «1» and «1'» in Modes I and II. The fracture criterion for these two modes increases when the composite is elaborated at high temperatures;

In other words, the risk of damage to the composite by cracking is all the more likely that the matrix is jointly bonded to the fiber at high temperatures. Under the effect of these stresses and in the opening mode, the matrix crack front, noted 1', is much more unstable than the crack head noted 1;

- There is an orientation (Θ=45°) beyond which (Θ >45°) the crack front noted as «1», under the effect of residual stresses, propagates in the opening mode and below which (Θ< 45°) this crack head is stable. It tends to close under the effect of residual stresses normal of compression induced in the fiber. This front propagates in pure mode I for orientation at (Θ<45°) and in mixed mode I and II for a crack positioned at (Θ >45).

- The combination of the residual stresses of thermal origin to the stresses of commissioning of tension increases the risk of propagation of the «1» front of a matrix crack in Modes I and II by increasing stress intensity factors. Residual stresses are largely responsible for this behavior. In addition to the stresses applied, the residual stresses can lead to the brutal propagation of this front;

- The nature of the fiber, defined by the difference of thermal expansion coefficients between the epoxy matrix and the fiber, conditions the behavior of the crack fronts oriented with respect to the interface, noted «1» and «1'». A more pronounced gap leads to high fracture energy in these heads in Modes I and II. The stress intensity factors relating to two propagation modes are all the more important that the coefficient of thermal expansion of the fiber is low;

- The residual stresses of thermal origin, generated in the epoxy matrix, are directly related to the volume fraction of the glass fibers. An increase in the latter leads to an intensification of the energy at the tip of the oriented matrix crack, denoted «1», in Mode I and Mode II. The interaction of fields of these stresses strongly localized in the matrix near the interface with the fiber is responsible for the strong instability of this fracture front.

The stress intensity factor (SIF) in Mode I and Mode II depends on the position of the initiated crack from the matrix to the fiber-matrix interface. The angle of orientation of crack propagation determines the predominant mode of failure. This instability of the crack is closely related, not only to the temperature of elaboration of the composite, but also to the volume fraction of the fibers and their nature.

References

[1] M. Naebe, M. M. Abolhasani, H. Khayyam, A. Amini , B. Fox , Crack Damage in Polymers and Composites, Polymer Reviews ISSN: 1558-3724 (Print) (2016) 1558-3716

[2] T. J. Downes, J.E. King, Compos. Part A – Appl. Sci. Manuf. 24 (3) (1993) 276–281

[3] D. M. Knowles, J. E. King, Acta Metall. Mater. 39 (5) (1991) 793–806

[4] J. J. Lewandowski, C. Liu, W.H. Hunt Jr, Mater. Sci. Eng. A107 (1989) 241–255

[5] M. S. Bruzzi, P. E. McHugh, Int. J. Fatigue 26 (8) (2004) 795–804

[6] D. Zhao, Eng. Fract. Mech. 47 (2) (1994) 303–308

[7] Y. Flom, R.J. Arsenault, Acta Metall. 37 (9) (1989) 2413–2423

[8] J. K. Shang, R. O. Ritchie, Acta Metall. 37 (8) (1989) 2267–2278

[9] Z.Z. Chen, K. Tokaji, A. Minagi, J. Mater. Sci. 36 (20) (2001) 4893–4902

[10] Chi-Seung Lee, Jeong-Hyeon Kim, Seul-kee Kim, Dong-Man Ryu, Jae-Myung Lee ,Initial and progressive failure analyses for composite laminates using Puck failure criterion and damage-coupled finite element method, j. Composite Structures, November (2014)

[11] L. Leon, Jr. Mishnaevsky, P. Brondsted , Three-dimensional numerical modelling of damage initiation in unidirectional fiber-reinforced composites with ductile matrix, J. Materials Science and Engineering: A V. 498, I. 1–2, 20 December (2008)81–86

[12] S. Sellam, B. Serier, F. Bouafia, B. Bachir Bouidjra, H. Sardar Sikandar , Analysis of the stresses intensity factor in alumina–Pyrex composites, J. Computational Materials Science 72 (2013)68–80

[13] T.Tang , Y. Hammi, M. F. Horstemeyer, P. Wang , Finite element micromechanical analysis of the deformation and stress state dependent damage evolution in fiber reinforced metal matrix composites, J. Computational Materials Science, March (2012)

[14] Y.F. Liu, Y. Kagawa, The energy release rate for an interfacial debond crack in a fiber pull-out model, Composites Science and Technology, 60, 2, (2000) 167-171

[15] K. Aslantas, S. Tasgetiren, Finite element analysis of longitudinal debonding between fiber and matrix interface, Indian Journal of Engineering & Material Sciences , 11 (2004) 43-48

[16] S. Ramdoum, H. Fekirini, F. Bouafia , S. Benbarek , B. Serier, Luciano Feo , Carbone/epoxy interface debond growth using the Contour Integral/Cohesive zone method j. Composites Part B: Engineering Volume 142, 1 June 2018, 102-107

[17] Konstantinos G. Dassios , Dimitris G. Aggelis, Evangelos Z. Kordatos Konstantinos G. Dassios , Dimitris G. Aggelis, Evangelos Z. Kordatos , Cyclic loading of a SiC-fiber reinforced ceramic matrix composite reveals damage mechanisms and thermal residual stress state, journal Composites August (2012)

[18] M. Safarabadi , Understanding residual stresses in polymer matrix composites, J. Residual Stresses in Composite Materials (2014)197–232

[19] M. M. Aghdam, S. R. Morsali ,Understanding residual stresses in metal matrix composites , J. B. Part II: Residual stresses in different types of composites. Pages 233-255. November 2013

[20] A. Metehri, B. Serier, B. Bachir bouiadjra, M. Belhouari, M.A. Mecirdi, Numerical analysis of the residual stresses in polymer matrix composites , Materials and Design 30 (2009) 2332–2338

[21] M. Braginsky, C. P. Przybyla, Simulation of crack propagation/deflection in ceramic matrix continuous fiber reinforced composites with weak interphase via the extended finite element method, j.compstruct. 2015.10.038

[22] Arsenault. R et Taya. M, Metal matrix composites: thermomecanical behavior, pregamon press, Oxford; 1989

[23] ABAQUS, User's Manual, 6.5, Hibbit, Karlsson & Sorensen Inc.F

[24] Glossaire des matériaux composites –CARMA- actualisation décembre 2004

[25] C. RADO, These de doctorat, institut nationale polytechnique de Grenoble,1992

[26] M. Locatellil, B. Dalgleich, K. Nakashima, A. Tomsia, and A.Glaeser, New Approaches to JJoining Ceramics for High-Temperature Applications, Ceramics International 23(4):313-322 • December 1997

[27] H. Kebir, J. M. Roelandt, J. Gaudin , Simulation de Ia propagation de fissures dans les solides élastiques en modes mixtes par Ia méthode des équations intégrales duales, Revue Européenne des Éléments Finis, HERMÈS / LAVOISIER, , 9 (8), (2000)893-916