The influence of fiber arrangement on the mechanical properties of short fiber reinforced thermoplastic matrix composite

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ABSTRACT. *Short fibers are becoming increasingly popular reinforcing elements in products made by extrusion or injection molding. Short fiber reinforcement allows the polymer to be processed employing the same methods as those used for unreinforced polymers. In short fiber composites, loads are not directly applied on the fibers but are applied to the matrix and transferred to the fibers through the fiber ends. Thermoplastics reinforced with short fibers are increasingly used in many industrial applications due to their attractive mechanical properties, rapid processing and relatively low manufacturing cost. However, the concentration and the orientation of the fibers vary from one point to the other. In this work, multifiber composite model was analyzed under tensile load. The purpose of this work is to analyze the influence of fiber arrangement on the Von Mises stress of glass fiber reinforced thermoplastic nylon-66 matrix composite using finite element analysis (FEA).*

RÉSUMÉ. *Les fibres courtes sont devenues, de plus en plus, des éléments de renfort dans des produits fabriqués par extrusion ou par moulage par injection. Le renforcement par des fibres courtes permet au polymère d'être traité en utilisant les mêmes méthodes que celles utilisées pour les polymères non renforcés. En composites à fibres courtes, les charges ne sont pas directement appliquées sur les fibres, mais sont appliquées à la matrice et transférées sur les fibres à travers les extrémités. Les thermoplastiques renforcés par des fibres courtes sont de plus en plus utilisés dans de nombreuses applications industrielles en raison de leurs propriétés mécaniques intéressantes, un traitement rapide et relativement faible coût de fabrication. Cependant, la concentration et l'orientation des fibres varient d'un point à l'autre. Dans ce travail, le modèle de composite multifibre a été analysé sous une charge de traction. Le but de ce travail est d'analyser l'influence de l'arrangement des fibres sur les contraintes de Von Mises dans un composite à matrice thermoplastique nylon-66 renforcé par des fibres de verre en utilisant l'analyse par éléments finis (FEA).*

KEYWORDS: *finite element, short fiber, thermoplastic composite.*

MOTS-CLÉS : *éléments finis, fibres courtes, composites thermoplastiques.*

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1. Introduction

Short fiber reinforced polymers can also be classified into two groups depending on the type of polymer: thermoplastic and thermoset. Thermoplastic materials offer clear advantages over thermosets. In fact, thermoplastics can be repeatedly softened by increasing temperatures and hardened by cooling, contrary to a thermoset, which, once cured, cannot be reshaped or remold at elevated temperatures (Kammoun Slim, 2011).

Thermoplastics have many advantages over metal parts including weight, ease of fabrication and economy. Although the advantages have allowed them to proliferate in various industries, the lack of structural load carrying capacity has hindered their use in automotive and aerospace industries. To mitigate the disadvantage, short fibers such as glass or carbon fiber, etc. are added to these polymers to improve the elastic modulus, strength to weight ratio, creep resistance, and dimensional stability. This increase in the load carrying capacity is what allows these composites to be widely explored in the automobile and aerospace component industry. However, the application of fiber-filled thermoplastic materials has been limited in many cases due to the inability to accurately predict performance and durability as the behavior of the polymer composites depends primarily on the fiber length and the fiber orientation distribution (Kulkarni *et al*., 2012).

The matrix serves two very important functions: it bonds the fibrous phase and, under an applied force, it deforms and distributes the stress to the high-modulus fibrous constituent. The ultimate properties of composites depend on the distinct properties of the constituents, shape and size of the individual reinforcing fibers or particles, their structural arrangement and distribution, the relative amount of each constituent, and the interface between reinforcement and matrix (Houshyar *et al*., 2009). Accurate experimental data is not available, since it is not possible to produce physical samples with perfectly aligned fibers. The main drawback of this model is that it estimates elastic properties only when fiber aligns to the loading direction of the composite. But in practice, in short fibers reinforced composites, the fibers are not aligned in the direction of the applied load (Vannan and Vizhian, 2014). Controlling the fiber orientation distribution in short fiber reinforced composites made with a thermoplastic polymer matrix affects the mechanical performance of the material in the fiber direction (Creasy *et al*., 2004).

Quantitative prediction of the strength of the short fiber reinforced thermoplastics is a complex problem. A reason for this is the non-uniformity of stress distribution along the short fiber length and radial interface in these composites; this implies that the average stress carried by fibers at the point of failure will be less than their ultimate tensile strength. Fiber reinforced composite is subject to longitudinal tensile loading; the main part of the load is born by the fibers. The short fibers are considered to be uniaxially aligned with the stress applied in the axial direction of the fibers as described in figure 1. It is considered composite containing fibers, which all have the same length and diameter, and are all parallel (Hong Gun Kim and Lee Ku Kwac, 2009). The technique provides a method for achieving a uniform, homogeneous dispersion of reinforcing fibers and thermoplastic resin.

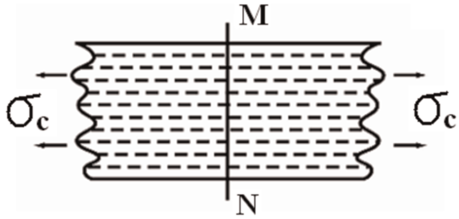


Figure 1. Schematic diagram of short fiber reinforced composite with far field composite stress σ_c

It has been a well-known mechanism that when a fiber composite is under a uniaxial tension, the axial displacements in the fiber and in the matrix will be different because of the differences in tensile properties of these two components. As a result, shear strains will be created on all planes parallel to the axes of the fibers. The shear strain and the resulting shear stress are the primary means by which load is transferred to fibers (for a short fiber composite), or distributed between and supported by the two components of composites. The effective properties of the fiber-reinforced composites strongly depend upon the geometrical arrangement of the fibers within the matrix. This arrangement is characterized by the volume fraction, the fiber aspect ratio and the fiber spacing parameters (figure 2).

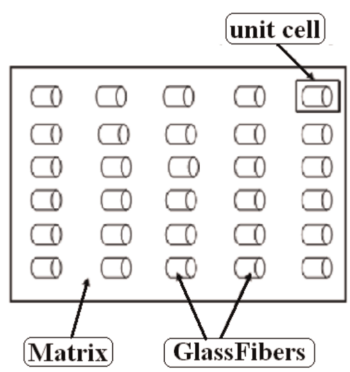


Figure 2. Composite domain showing short fibers reinforced in matrix

The factor aspect ratio affects the stress transfer from the matrix to the fiber (Prince *et al*., 2012).

Take the mean fiber center-to-center spacing normal to their length to be $2R$. In addition, for the short fiber case where fiber ends do not meet, the maximum fiber volume fraction also varies with the distance between fiber ends. Let us assume this distance between the ends of two fibers in a composite to be $2\delta_f$ as shown in figure 3.

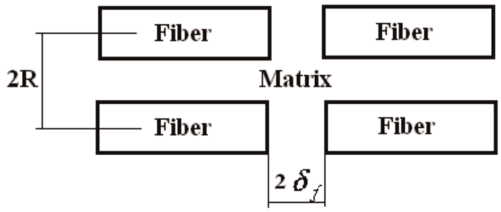


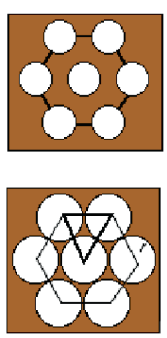
Figure 3. Distance between fiber ends

2. Fiber packing

In the theoretical analysis of aligned, short fiber composite, the fibers are modeled to be uniformly packed in regular arrangements with each fiber having a circular cross-section and the same diameter (figure 2) (Ka Yan Liu, 1997). There are two simple packing models: a square array and a hexagonal array with circular section reinforcement. From the two figures, it is readily apparent that volume fractions higher then 90% are impossible and that even 78% fiber loading would be very difficult to achieve. In practice, the maximum volume fraction is around 60% in unidirectional aligned fiber composites.

2.1. Hexagonally packed fibers

The fiber arrangement of this type is schematically shown in figure 4 suppose there are totally *n* fibers within the composite. Considering the hexagonal element in figure 4a, and according to the definition of fiber volume fraction of a composite, we



Area of Triangular Cell

$$r.2rSin\frac{\pi}{6} = r^2\sqrt{3}$$

Area of Fiber Section in cell

$$3\frac{\pi r^2}{6} = \frac{\pi r^2}{2}$$

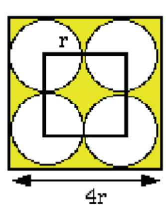
Maximum Area Fraction

$$\frac{\pi}{2\sqrt{3}} = 0.9$$

(a)

For a Square array

$$\frac{\pi r^2}{4r^2} = 0.78$$



(b)

Figure 4. Fiber packing

have the maximum fiber volume fraction in this case:

$$V_{\mathrm{fms}} = \frac{V_{\mathrm{fiber}}}{V_{\mathrm{total}}} = \frac{3\pi r^2 l_f}{3^{\sqrt{3}}/_2} (2R_{min})(l_f + 2\delta_f) \tag{1}$$

$$V_{\mathrm{fmh}} = \frac{\pi}{2\sqrt{3}} \left(\frac{r}{R_{min}}\right)^2 \left(\frac{1}{1 + {}^{2}\delta_f/_{l_f}}\right) \tag{2}$$

For the case when the fiber length is so long as $1 >> \delta_f$ that the fiber end effect can be neglected, the expression becomes:

$$V_{\mathrm{fms}} = \frac{\pi}{2\sqrt{3}} \left(\frac{r}{R_{min}}\right)^2 \tag{3}$$

2.2. Square-packed fibers

The fiber arrangement in this case is shown in figure 4b, and we have accordingly:

$$V_{\mathrm{fms}} = \frac{V_{\mathrm{fiber}}}{V_{\mathrm{total}}} = \frac{\pi r^2 l_f}{(2R_{min})^2 (l_f + 2\delta_f)} \tag{4}$$

$$V_{\mathrm{fms}} = \frac{\pi}{4} = \left(\frac{r}{(R_{min})}\right)^2 \left(\frac{1}{1 + {}^{2}\delta_f/_{l_f}}\right) \tag{5}$$

For long fiber case, it becomes:

$$V_{\mathrm{fms}} = \frac{\pi}{4} = \left(\frac{r}{(R_{min})}\right)^2 \tag{6}$$

It can be seen by comparing equations (3) and (6) that in either of the two packing forms the relationship of or the difference between the maximum fiber volumes fractions of these two packing forms is given by:

$$\frac{V_{\mathrm{fms}}}{V_{\mathrm{fmh}}} = \frac{\sqrt{3}}{2} \tag{7}$$

That is, the maximum possible fiber volume fraction for square-packed fibers is less than that of hexagonally packed case. Note that when the effect of fiber orientation is considered, the fiber arrangement may not be as regular as the two examples shown here (Ning Pan, 1993).

3. Fiber length

A critical minimum fiber length is needed to build up sufficient stress to fracture the fiber. This critical length, l_c, is given by:

$$l_c = {}^{\sigma_f d}/_{2\tau} \quad (8)$$

Where σ_f is the ultimate tensile strength of the fiber, d is the fiber diameter and τ is the interfacial shear strength between the fiber and the matrix or the shear strength of the matrix, whichever is less. The critical fiber length is defined as the minimum fiber length required for the maximum fiber stress to equal the ultimate fiber strength at its mid-length (O'Gara *et al.*, 2010) (figure 5).

For aligned short fibers where the length is shorter than l_c, the maximum fiber stress is not reached. If internal stress effects between adjacent fibers are ignored, fiber failure does not occur (O'Gara *et al.*, 2010). For aligned short fibers where the length is greater than l_c, the composite failure will be mainly accompanied by fiber breakage. The stress is assumed to increase linearly from the fiber end until it reaches the ultimate fiber strength at a distance ½ l_c from the fiber end. It is impossible to measure the strength of the glass fiber present in a particular lot of material. The strength is dependent on the elemental composition of the glass, as well as the processing conditions during its manufacture and its incorporation into the composite. Several experimental techniques have been developed to measure the interfacial strength between the matrix and the fiber, including, the fiber fragmentation test, the protruding fiber length test and the microindentation test, to name a few. However, a round-robin test revealed that it is not possible to reliably measure the interfacial strength or the critical fiber length. Thus, as an approximation, we assume that there is good adhesion between the matrix and the fiber, and thus, the limiting shear strength of the matrix can be used. The shear strength

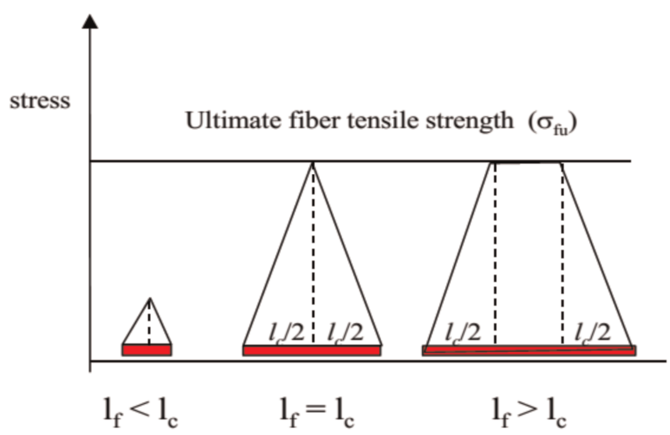


Figure 5. This figure shows how the stress varies along the length of a fiber (l_f) when the fiber is shorter than the critical length (l_c) and longer than the critical length

Table 1. Matrix strength, Von Mises shear strength and critical fiber length (O'Gara et al., 2010)

Material	σ_m (MPa)	τ_m (MPa)	l_c (μ)
PBT	53.0	30.6	494
PA	6.6	46.9	244
PC	61.5	35.5	415

of the matrix is itself difficult to measure and very little data exists in the literature. Assuming an isotropic matrix, the shear strength can be estimated by the Von Mises criterion from the tensile strength of the unfilled matrix (O'Gara *et al.*, 2010):

$$\tau_m = {}^{\sigma_m}/_{\sqrt{3}} \tag{9}$$

The calculated matrix shear strength, τ_m, and the resultant critical fiber length for each material (polybutylene terephthalate [PBT], nylon-66 [PA] and polycarbonate [PC]) are given in table 1 using fiber strength of 2.4 GPa and the average diameters in table 2 (O'Gara *et al.*, 2010).

4. Finite element modeling

The finite element software CASTEM is used in the FE simulation. In order to study the elastic behavior of multifiber composite under simple tensile loading, an axisymmetric multifiber consisting of two fibers and the surrounding matrix have been considered as shown in figure 6. The composite is subjected to a uniform tensile stress σ.

Table 2. Fiber diameter statistics for each material (O'Gara et al., 2010)

Material	Min (μm)	Max (μm)	Mean (μm)	Standard deviation
PBT	8.0	18.2	12.6	1.8
PA	6.1	14.0	9.5	1.2
PC	6.6	18.3	12.3	1.7

4.1. Composite property

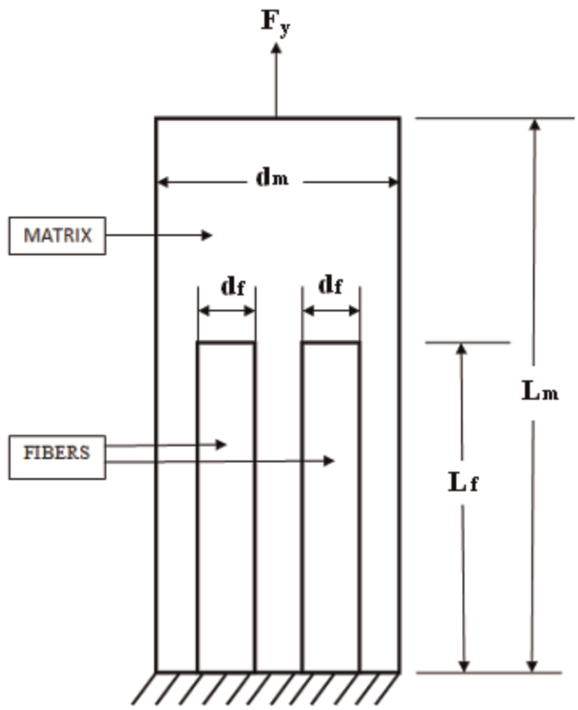


Figure 6. Finite element model for short fiber reinforced composite

Each element will have an isotropic property and be positioned corresponding to the centerline of the fibers. The model is small so a fine mesh of elements was used (Houshyar *et al.*, 2009). For simplicity, it is assumed that all fibers have the same length l_f and radius r_f (Lei *et al.*, 2012):

- l_f, r_f: length and radius of the fiber;
- l_m, r_m: length and radius of the cell.

$$l_m = {}^{l_f^3}\!\big/_{4} \times r_m^2 a_f^2 V_f \qquad a_f = {}^{l_f}\!\big/_{d_f} \qquad l_m = {}^{l_{\mathrm{f}} d_{\mathrm{f}}^2}\!\big/_{4} \times r_m^2 V_f \tag{10}$$

Using equation (10), we calculate the length l_m in the two packing in function of the volume fraction. Due to axisymmetry, the specimen can be considered as a 2-D elastic body. The following parameters are used in all calculations (O'Gara *et al.*, 2010):

– reinforced glass fibers with Young's modulus $E_f = 64$ GPa. Poisson ratio $v_f = 0.2$ and density of $\rho_f = 2.54$ g/cc;

– matrix is of nylon-66 with Young's modulus $E_m = 3$ GPa. Poisson ratio $v_m = 0.35$ and density of $\rho_m = 1.14$ g/cc.

4.2. Boundary conditions

The boundary conditions representing the application of tensile loads to a short fiber filled composite are constrained boundary conditions, *i.e.* at $Y = 0$, $U_y = 0$, matrix and fiber have zero movement in Y-direction (figure 6). Here the Y-axis is in the direction of the length interface of fiber and matrix and the model is axisymmetric to it we have applied the $F_y = 5.65 \times$ e-8N/μm^2 pressure at the end face of the matrix at $y = l_m$ (Prince *et al.*, 2012).

5. Results and discussion

Multifibers composite model is shown in figure 7. The Von Mises stress shows high stress concentration in the fibers ends. Glass nylon-66 composite exhibit a level of concentrated stress that was not uniform in both constituents and the difference between the stress in the fiber and the surrounding matrix was very high. This can result in

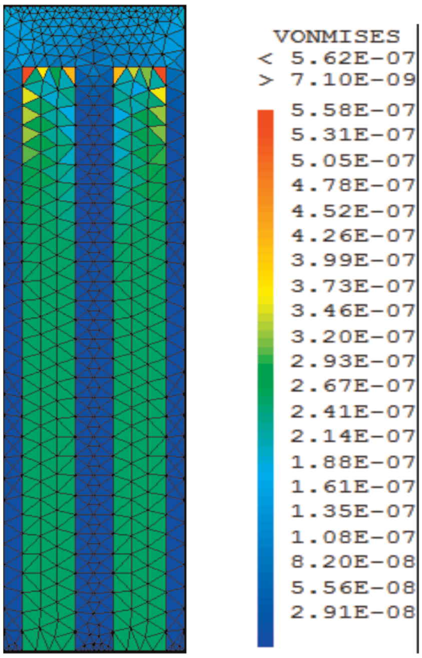


Figure 7. Von Misses stress at 30% volume fraction in multifiber model (hexagonal packing)

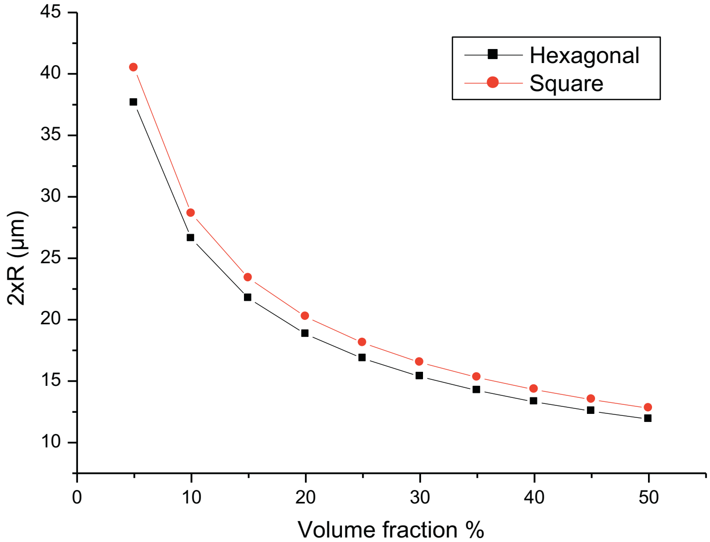


Figure 8. Evolution of R distance with volume fraction

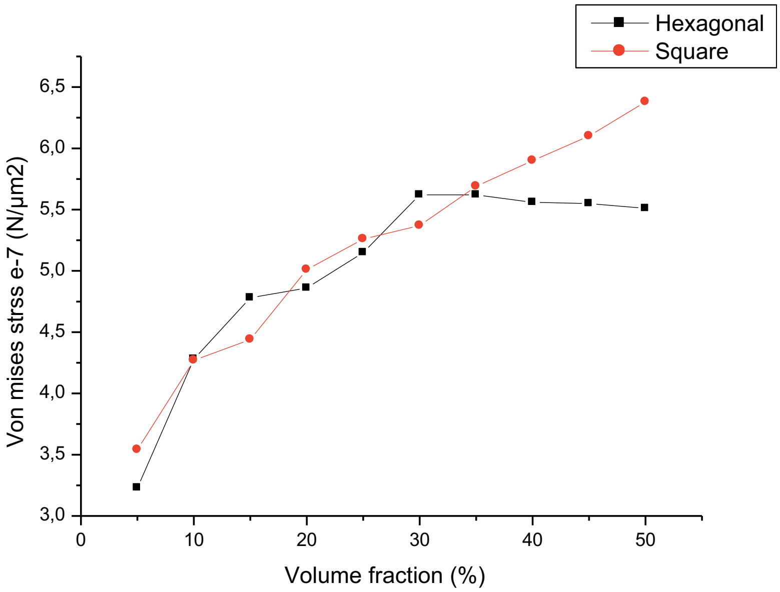


Figure 9. Evolution of Von Mises stress with volume fraction

interfacial failure at low stress. In figure 8, the distance *R* between fibers decrease when the volume fraction increase. At higher fiber volume fraction, the spacing becomes very small. As volume fraction increases, the stress increases too (figure 9). For fiber volume fractions higher than 0.3 (in the composite), the Von Mises stress increases linearly in square packing such as in hexagonal packing.

The Von Mises stress decreased linearly with the fiber spacing *R* (figures 10 and 11), these values were different due to fiber packing problems.

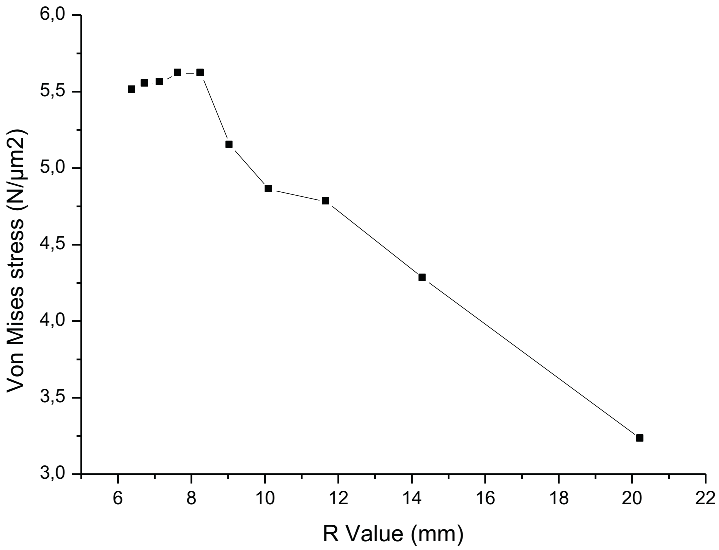


Figure 10. Evolution of Von Mises stress with R distance (hexagonal)

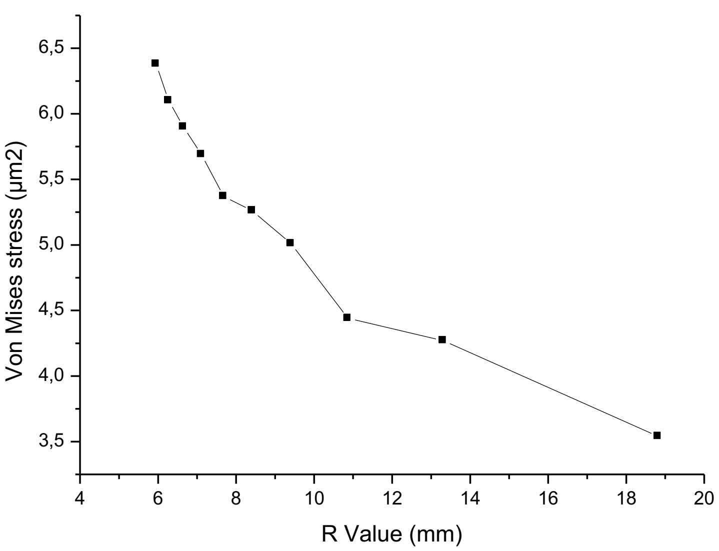


Figure 11. Evolution of Von Mises stress with R distance (square)

6. Conclusion

This study concerns the evolution of the Von Mises stress in thermoplastic matrix composite reinforced by short glass fiber. It is noted that, in the case of an embedded fiber with bonded fiber ends, the stress at the bonded ends has a finite value, and this stress is required as a boundary condition in order to derive the stress distribution in the fiber. Since the fiber and matrix often have quite different elastic moduli then the stress in each must be different – in fact the stress is higher in the material with the higher elastic modulus (usually the fiber). In fiber glass, the elastic modulus of the glass is much greater than that of the thermoplastic matrix so as the volume fraction of fibers is increased, the elastic modulus of the composite increases linearly.

However, this finite stress is not a predetermined value, which, in turn, results in difficulties in using the classical shear-lag model. Various assumptions of this finite stress have been made to solve the stress-transfer problem. The value of maximum fiber volume fraction monotonically increases as the fiber spacing decreases. Consequently, the value of the actual maximum fiber volume fraction may be lower than the present results; the small spacing between fibers will tend to limit flaw growth in the matrix to one direction. This small spacing between fibers may have important consequences. These ideal packing arrays are generally used to develop micromechanical models due to their simplicity. However, they are not observed in real composites except in a few localized regions. The different strains in different parts of the resin resulted in additional stress and generated a non-uniform stress distribution.

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