INFLUENCE OF NOTCH TIP RADIUS AND FIBRE ORIENTATION ON THE FATIGUE STRENGTH OF A SHORT GLASS FIBRE REINFORCED POLYAMIDE 6

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Abstract

An experimental investigation on the combined effect of notch tip radius and fiber orientation on the static and fatigue strength of a short fiber reinforced polyamide is presented. Fatigue tests were conducted on injection molded plates having two symmetric V-shaped notches, with a fillet radius varying from 0.5 to 2 mm. Moreover, the injection moulding conditions were varied by injecting the plates longitudinally and laterally through a film gate on the top face and a side gate on the lateral face, respectively. Fatigue strength is influenced by the size and position of the injection gate. The influence of the notch root radius is negligible, with the exception of the smallest radius of 0.5 mm. Experimental analysis of fibre orientation proved that by injecting the specimens laterally, the fiber orientation in the gauge section is modified. Moreover, it was observed that the smallest radius of 0.5 mm alters the fibre orientation at the notch root.

1. Introduction

The fatigue behavior of short glass fiber reinforced polymers is becoming more and more a main concern in the design of mechanical parts, particularly when they are employed in components which undergo significant mechanical loading, e.g. in the automotive industry. In the present study, the results of an experimental investigation on the combined effect of notches and fiber orientation on the fatigue strength of a polyamide 6 reinforced with short glass fiber are presented and analyzed.

The present research follows the path traced by a previous work [1] where the effect of circular notches having a relatively large radius of 7.5 mm has been studied for small injection-molded plates in conjunction with the effect of different fiber orientation patterns obtained varying type and position of the injection gate. Previously, the notch effect on the fatigue strength of short glass fiber reinforced polyamides had been studied by means of experimental tests conducted on notched specimens [2-4] having central notches with notch tip radii smaller than the one used in [1] and closer to the ones commonly used in real components. In [2], it was shown that the fatigue strength decreases with increasing hole diameter, but not with relative hole diameter (i.e. diameter divided by the net gauge section), although a reduction with respect to the unnotched specimen was still observed. Moreover, holes were drilled and were not obtained by moulding. In [3], specimens with mild and sharp notches were manufactured by injection moulding and tested in the dry as moulded state. Under these conditions, a strong sensitivity to notches was found. Nevertheless, the combined effect of notches and fiber orientation was not investigated.

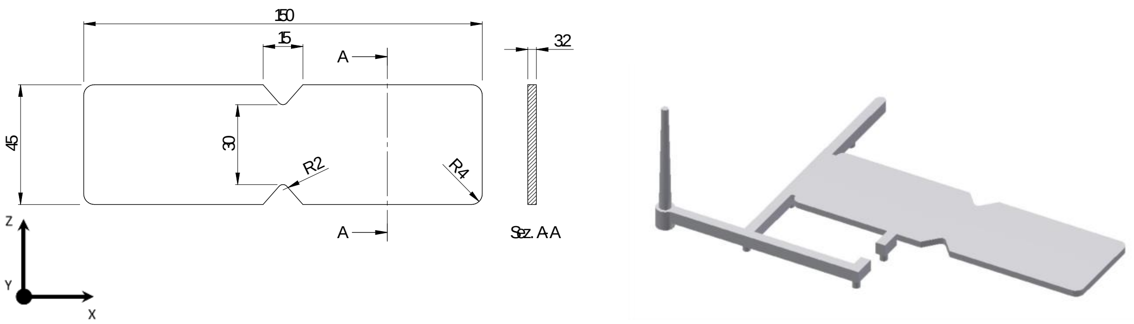
In this work, the combined effect of fiber orientation and notches with dimensions close to the ones of real applications were investigated. The mold employed in [1] was modified in order to obtain small plates with lateral V-shaped notches with tip radii of 0.5, 1 and 2 mm. All the three types of specimens were injection molded through a film gate on the top face of specimens and a side gate on a lateral face of the specimens. In this way, the combined effect of notches and fiber orientation distributions was studied for different values of the notch tip radius.

2. Experimental

2.1. Mechanical testing

Static and fatigue tests were performed on specimens made of injection-molded polyamide 6 reinforced with 30 % by weight of short E-glass fiber (PA6 GF30). For this material, the nominal fiber diameter was 10 µm and the average fiber length was 300 µm after the injection-molding process. The specimen shape and dimensions are shown in Figure 1. The specimens consisted of small plates, 150 mm long, 45 mm wide and 3.2 mm thick, characterized by the presence of two lateral V-shaped notches symmetric with respect to the longitudinal mid-section of the specimen. They were obtained by means of an injection molding process in which the design of the mold allowed to use two different feed system layouts, like in [1].

In one layout, the specimen was injected through a film gate located on the top face of the specimen in order to induce a longitudinal melt flow during cavity filling. The use of this feed system, as reported in [1] and successively confirmed in [5], resulted in a symmetric fiber orientation distribution that was predominantly longitudinal. In the other one, a side gate located on a lateral face of the specimen induced an asymmetric filling of the specimen cavity causing a less homogeneous fiber orientation distribution. For the manufacturing of the specimens studied in this work, the mold was equipped with interchangeable inserts so that three different notch tip radii could be obtained, namely 0.5, 1 and 2 mm, with the same net cross-section width equal to 30 mm.



(a) (b)

Figure 1. Shape and dimensions of the specimen (a) and layouts of the feed system (b).

A total of six test specimen batches were manufactured and used for tensile and fatigue tests, comprising all combinations of the three different notch tip radii and top or side injection. The material was conditioned prior to testing in order to let the matrix reach hygro-termal equilibrium with an ambient at 23°C and 50 % of humidity. Uniaxial static and fatigue tests were performed at Politecnico di Milano using an Instron 8501 servo-hydraulic dynamic test system, with a load capacity of 100 kN. All the tests were conducted at a controlled room temperature of 23◦C (±2◦C) in an air conditioned laboratory environment with uncontrolled humidity. The quasi-static tensile tests were carried out at a crosshead speed of 5 mm/min. The fatigue tests were performed in the range of cycles to failure from 10^3 to 10^6. These tests were load controlled tension-tension fatigue tests in which sinusoidal load cycles were applied at a frequency of 4 Hz with a load ratio R=0.1 (i.e. the ratio of minimum to maximum applied load). The failure criterion for fatigue tests was specimen separation. In these tests, if the failure criterion was not met prior to 10^6 load cycles the tests were interrupted (run-out).

2.2. Fibre orientation analysis

In order to find a possible correlation between the fatigue behaviors and the fibre orientation distributions at notches induced by the different injection gate types and positions, experimental analysis of specimen microstructure was carried out. Measurements of fiber orientation distributions were performed on tested specimens by means of the optical section method. By this method, 2D polished sections are taken from the area of interest and then evaluated using an in-house image analysis facility developed at the University of Leeds [6]. Each fibre that meets the 2D section is seen as an elliptical footprint, and measuring the ellipticity and the orientation of the major axis of these images allows the two polar angles θ and ϕ that specify the orientation of each fibre (with respect to the reference frame shown in Figure 1) to be determined.

Results are presented as maps of the values of the average of the square of the cosine of the polar angles (for instance $\langle\cos^2\theta_X\rangle$ as shown in Figure 2). Here white means a high level of orientation with respect to the X axis (flow direction). Average values through the thickness can also be plotted as a function of the distance across the sample width (between the notches along the Z axis), in order to visualize and compare results.

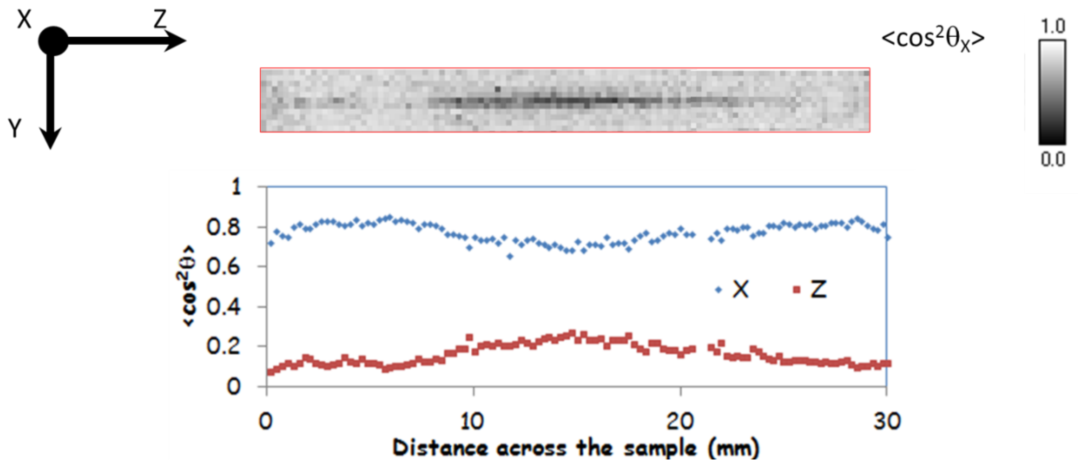


Figure 2. Visualization of fibre orientation analysis results

3. Results and discussion

3.1. Results of static tests

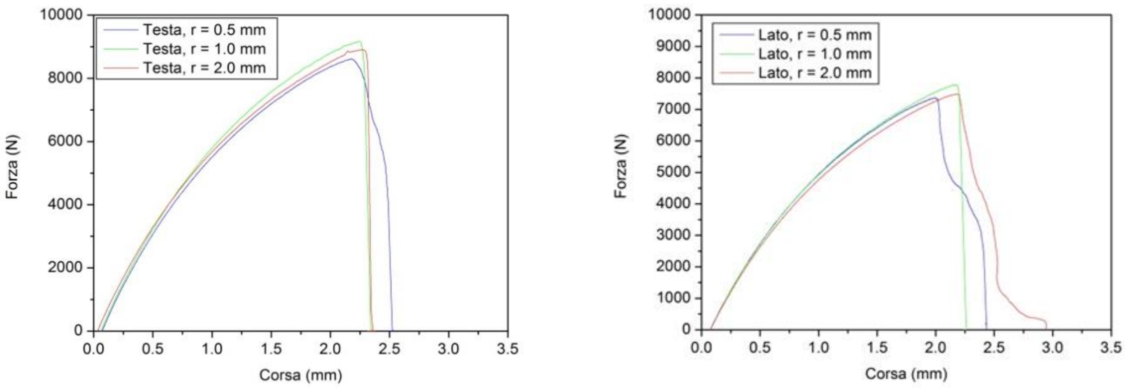
Three tensile tests were conducted for each type of specimen, i.e. for each combination of the three notch tip radii and the two different feed system layouts. The results of some of these tests, one for each specimen type, are shown in Figure 3(a) and 3(b). In these diagrams the nominal stress, i.e. the ratio of applied load to initial net cross-section area of the specimen, is plotted against the displacement of the crosshead of the testing machine. The values of the ultimate tensile strength (UTS), i.e. the maximum nominal stress, averaged over the three quasi-static tensile tests conducted for each specimen type are listed in Table 1, together with the values obtained in [1] for the case of a 7.5 mm notch radius.

Notch radius	Top gate	Lateral gate
R (mm)	σ_r *(MPa)*	σ_r *(MPa)*
0.5	*89.1*	*75.6*
1.0	*94.7*	*80.5*
2.0	*94.3*	*79.3*
7.5*	*94*	*78*

*Results obtained for circular notches reported from [1].

Table 1. Ultimate tensile strength values

It can be noticed that, for the same layout of the feed system, the difference in the static strength for the specimens having a notch tip radius equal to 1, 2 and 7.5 mm was negligible, while in the case of a notch tip radius equal to 0.5 mm a reduction of 5% was obtained respect to the previous cases. Considering specimens with the same notch tip radius, the variation of the injection location from the top to the side resulted in a reduction of about 15% in terms of the maximum load reached during the tests for all the three values of the notch tip radius.



(a) (b)

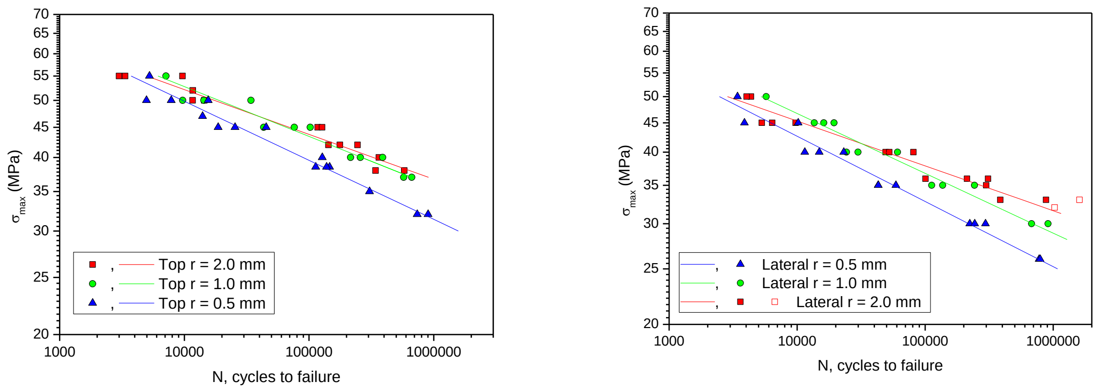
Figure 3. Comparison of three nominal stress-displacement curves obtained by quasi-static tensile tests on specimens with different values of the notch tip radius, r, (a) top injection; (b) side injection.

3.2. Results of fatigue tests

The results of the fatigue tests performed on specimens injected in the longitudinal direction are shown in Figure 4(a), while the ones obtained from specimens injected laterally are shown in Figure 4(b). The fatigue test results are reported in diagrams on log-log scales in which the maximum applied nominal fatigue stress σ_{max}, i.e. the ratio of maximum applied load to the initial net area of the specimen cross-section, is plotted against the cycles to failure N_f . The stress-life (Wöhler) curves which interpolate the experimental data are plotted for each batch of specimens as well. These curves are straight lines since the relationship between the maximum stress and cycles to failure was assumed to be described by the Basquin relation, that is:

$$\sigma_{max} = \sigma'_f N_f^{-b} \tag{1}$$

The values of the material parameters of this equation, the fatigue strength exponent b and the fatigue strength coefficient σ'_f , were determined by means of linear regression on experimental data and are listed in Table 2.



(a) (b)

Figure 4. Results of fatigue tests performed on specimens with different values of the notch tip radius, r, (a) injected through a film gate located on the top face; (b) injected through a side gate located on a side face.

Notch radius	Top gate		Lateral gate	
r (mm)	*σ'_f (MPa)*	*b (-)*	*σ'_f (MPa)*	*b (-)*
0.5	*125.5*	*0.100*	*121.8*	*0.114*
1.0	*115.1*	*0.085*	*122.4*	*0.105*
2.0	*105.2*	*0.076*	*93.2*	*0.078*
7.5*	*96.6*	*0.064*	*88.1*	*0.073*

*Results obtained for circular notches reported from [1].

Table 2. Fatigue strength coefficient, σ'_f, and exponent b of the Basquin equation.

3.3. Analysis of fibre orientation

3.3.1 Influence of gate size and position

The fibre orientation distribution was analysed in the gauge section of one specimen for each batch, using the method described in Section 2.2. Results are presented in terms of average

values of $< \cos^2 \theta_X >$ and $< \cos^2 \theta_Z >$, average of the square of the cosine of the angle between the fibres and the X axis and the Z axis of the reference frame shown in Figure 1. Averaging is performed through the thickness of the gauge section of each specimen.
The values of $< \cos^2 \theta_X >$ and $< \cos^2 \theta_Z >$ for the samples having notch root radius of 2 mm injected longitudinally and laterally are shown in Figure 5a) and Figure 5b) respectively. It appears that by using the side gate we obtained a different fibre orientation. In the case of injection through the side gate, fibres have a lower degree of alignment along the stresses acting in the gauge section, thus explaining the observed different mechanical behaviour between specimens having the same notch root radius, but different injection gates. The average values of $<\cos^2\theta_x>$ across the sample between the notches was 0.76 for the top injection and 0.70 for the side injection.

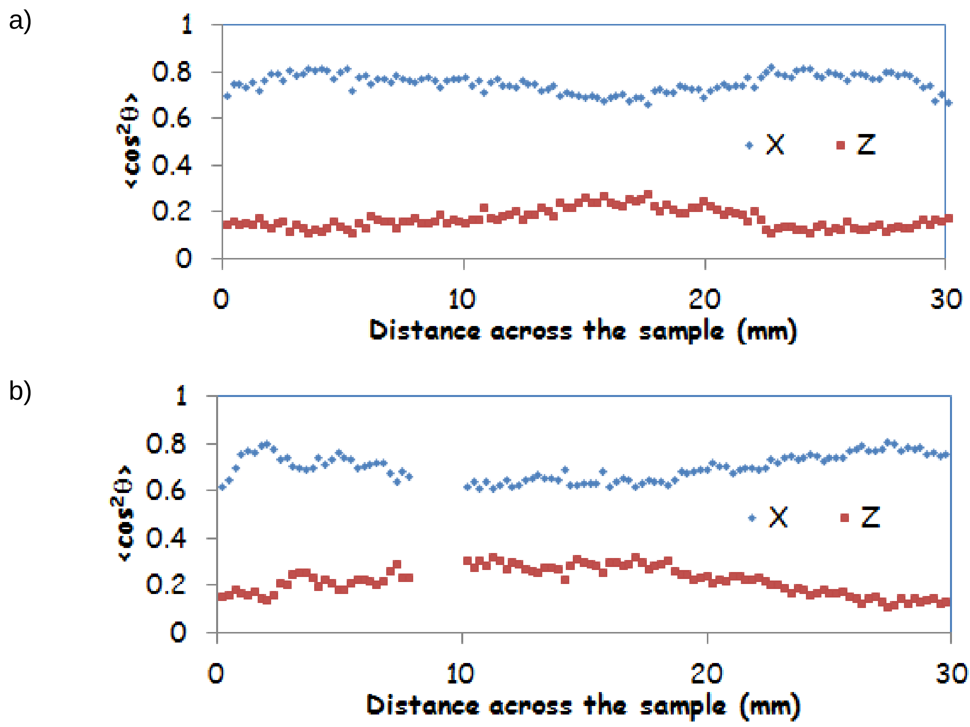


Figure 5. Results of fibre orientation analysis for the specimens with notch root radius of 2 mm: (a) top injection and (b) side injection

3.3.2 Influence of the notch tip radius

Results displayed in Figure 4 and Table 2 show that the variation of the notch tip radius from 2 to 1 mm, for both longitudinally and laterally injected specimens, does not influence significantly the fatigue strength, as previously observed also in the case of static strength. On the contrary, when the notch tip radius is further reduced to 0.5 mm a non-negligible reduction of the fatigue strength is observed particularly at high number of cycles, while at low number of cycles this reduction tends to vanish. The fatigue strengths at 1 million load cycles listed in Table 3 confirms and quantifies this observation.

In order to discuss this effect, it is interesting to compare these results with the ones presented in [1] and reported in the last rows of Table 2. These tests were carried out on specimen constituted by small plates with two symmetric lateral circular notches with a radius of 7.5 mm and having the same net cross-section area of the ones of the present study. Although these tests have been conducted with the same test conditions used in the present study, this comparison has some limitations since the tests have been conducted at a frequency of 2 Hz, not at 4 Hz as in the test presented here (moreover the material did not belong to the same batch). Nevertheless, the comparison of the maximum nominal stress at 1 million load cycles, calculated using the material coefficients of the Basquin equation listed in Table 2 and reported in Table 3, shows again that significant differences in the fatigue strength happens only in the case of specimens with a notch tip radius of 0.5 mm.

Notch radius	Top gate	Lateral gate
r (mm)	*σ_w (MPa)*	*σ_w (MPa)*
0.5	*31.4*	*25.2*
1.0	*35.7*	*28.9*
2.0	*36.7*	*31.6*
7.5*	*39.9*	*32.0*

*Results obtained for circular notches reported from [1].

Table 3. Fatigue strength at 1 million load cycles

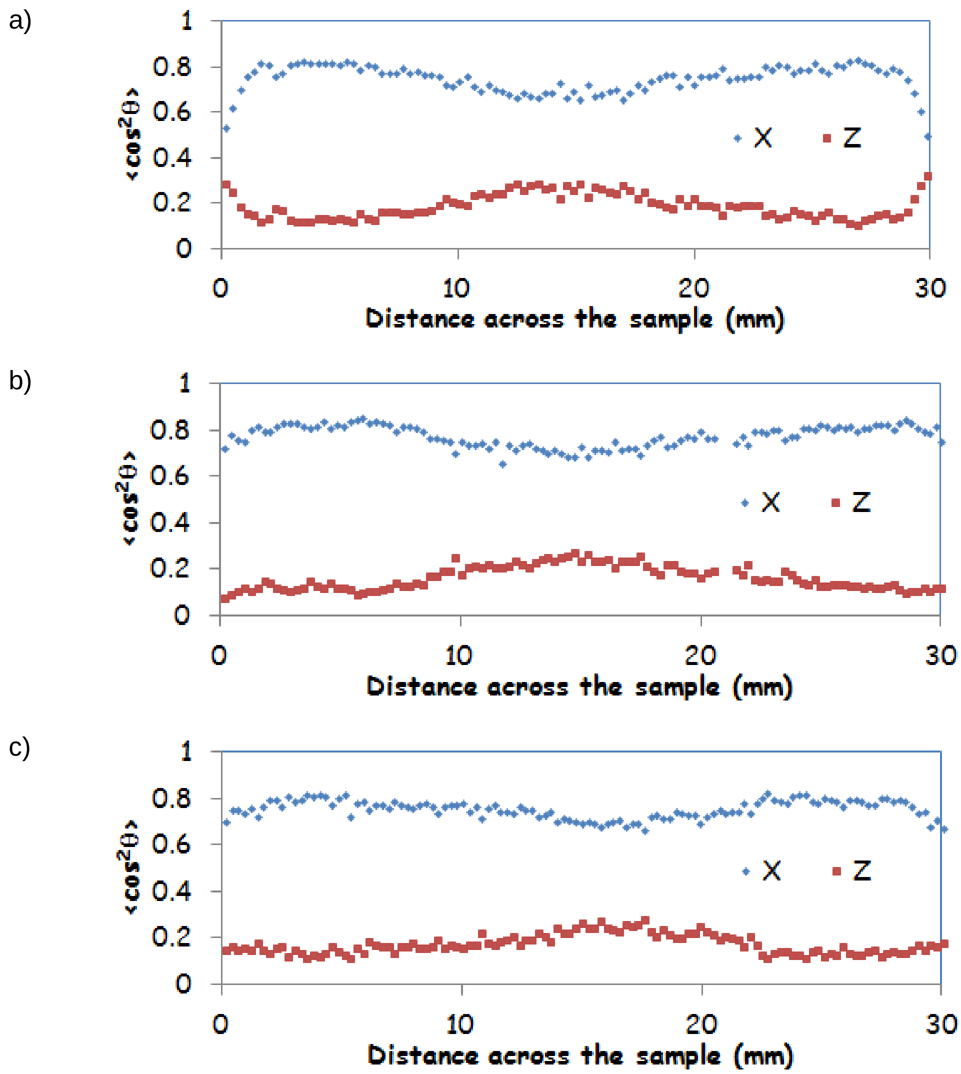


Figure 6. Results of the fibre orientation analysis for the specimens injected longitudinally (top gate), vith different notch root radius values: 0.5 mm (a), 1 mm (b) and 2 mm (c)

By comparing the fibre orientation results for the specimens injected longitudinally (having various notch root radiuses reported in Figure 6), it appears that, in the case of the smallest radius of 0.5 mm, fibres possess a very low degree of alignment with the X axis at the notch root, while a higher degree of alignment was observed in the case of 1 mm and 2 mm radii. Similar results were obtained for the case of lateral injection. These observations can explain the apparent reduction of strength in the case of the 0.5 mm radius. Previous experiments (7) have shown that the fracture toughness is strongly correlated with the average fibre orientation at the crack tip. The higher the degree of transverse fibres ($<\cos^2\theta_X>$ in this study) the higher the toughness.

4. Conclusions

The experimental investigations conducted on injection moulded, notched specimens made of short fibre reinforced polyamide, allowed for assessing the influence of the notch root radius and of fibre orientation upon fatigue strength. The following conclusions can be drawn:

- Fatigue strength is affected by the position of the injection gate, because fibre orientation is modified.
- Fatigue strength is not affected significantly by the size of notch root radius, provided that fibre orientation is not altered significantly by the notch, like in the case of the 0.5 mm radius.
- In order to be interpreted correctly, results of fatigue tests on notched specimens require support from fibre orientation analysis.

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