eXPRESS Polymer Letters Vol.1, No.12 (2007) 810–816
Available online at www.expresspolymlett.com
DOI: 10.3144/expresspolymlett.2007.112

Machining of glass fiber reinforced polyamide

F. Quadrini, E. A. Squeo*, V. Tagliaferri

Department of Mechanical Engineering, University of Rome Tor Vergata, Via del Politecnico n°1, 00133 Rome, Italy

Received 27July 2007; accepted in revised form 24 October 2007

Abstract. The machinability of a 30 wt% glass fiber reinforced polyamide (PA) was investigated by means of drilling tests. A disk was cut from an extruded rod and drilled on the flat surface: thrust was acquired during drilling at different drilling speed, feed rate and drill diameter. Differential scanning calorimetry (DSC) and indentation were used to characterize PA so as to evaluate the intrinsic lack of homogeneity of the extruded material. In conclusion, it was observed that the chip formation mechanism affects the thrust dependence on the machining parameters. A traditional modeling approach is able to predict thrust only in presence of a continuous chip. In some conditions, thrust increases as drilling speed increases and feed rate decreases; this evidence suggests not to consider the general scientific approach which deals the machining of plastics in analogy with metals. Moreover, the thrust can be significantly affected by the workpiece fabrication effect, as well as by the machining parameters; therefore, the fabrication effect is not negligible in the definition of an optimum for the machining process.

Keywords: *polymer composites, machining, drilling, cutting forces*

1. Introduction

Machining of polymers is employed when the quantity of items does not justify the cost for molds, or when a product needs a costly dimensional accuracy. As high performance polymers have been increasingly used for a large number of industrial applications, the machining quality is becoming a central factor for the development of new processes and materials. Nevertheless, the knowledge about the polymer behavior under machining is very limited, as well as the definition of suitable models for the prediction of cutting forces. In the scientific literature, machining of plastics is poorly treated. In the oldest references, an experimental approach is preferred, assuming that plastics behave as metals. In 1967, a significant effort was given by Kobayashi, who collected several experimental observations in his book 'Machining of plastics' [1]. This text has been considered a reference for a long time in this field. Also the latest scientific reviews mention it to show the dependence of the cutting forces on process parameters. For example, in 1977, Roy and Basu defined generalized equations for evaluating the main cutting force and the surface roughness in terms of cutting speed, feed, depth of cut and tool-nose-radius in turning Nylon 6 and Teflon [2]. In conclusion, they assessed that, in general, turning of thermoplastics does not differ greatly from turning of metals. Nowadays, this statement seems to be absolutely erroneous as polymers behave in a completely different way as compared to metals. However, a significant contribution in the study of polymer behavior was given by Ferry in his book 'Viscoelastic properties of polymers'. Even if it does not deal directly with machining, a lot of experimental and theoretical observations are reported in this book. Those are not in agreement with the assumption of a similar behavior of polymers and metals under machining; for polymers, it is mandatory to consider the time-dependent properties, the time-temperature superposition and the never neg-

*Corresponding author, e-mail: squeo@ing.uniroma2.it

ligible viscous behavior [3]. Probably, this effort could not be completely received by Kobayashi, who was studying polymer machining in the same period, as well as by Roy and Basu that continued the same experimental approach. Nevertheless, it is very singular that also subsequently the analogy between plastics and metals continued to exist.

In 1993 Hocheng *et al*. studied the machinability of some reinforced thermosets and thermoplastics in drilling [4]. They discussed the chip characteristics and the specific cutting energy to reveal the mechanism of material removal. They observed that the level for fiber loading and the deformation behavior of matrix polymer determine the extent of plasticity in chip formation and the chip length. In a further study, they also observed that, drilling fiber reinforced-thermoplastics, the edge quality is generally fine except in the case of concentrated heat accumulation at tool lips, which is generated by high cutting speed and low feed rate [5].

In 1995, Alauddin *et al*. summarized a lot of experimental observations in their review, without any correlation between the result of a machining operation and the machined material properties [6]. In 1999, Eriksen studied the influence of cutting parameters on the surface roughness of a machined short fiber reinforced thermoplastic [7] that was in turn correlated with the mechanical strength [8].

Recently, in 2002, Xiao and Zhang investigated the role of viscous deformation in machining of polymers, but all the theoretical treatment was derived from metals [9]. Moreover, the viscous effect was taken into account only by means of the glass transition temperature. It is evident that this parameter is not sufficient to completely justify the complex mechanisms at the basis of polymer behavior under machining. Because of the emerging interest about high performance polymers, in 2005, Kim *et al*. studied the effect of the consolidation process on the drilling performance and machinability of PIXA-M and PEEK thermoplastic composites [10]. They observed that the fabrication process can significantly affect the material machinability, as the induction-processed composite material produced equivalent or better holes than the autoclave-processed composites. Moreover they also discussed unique chip characteristics during drilling both autoclaved and induction heat-pressed thermoplastic composites. In 2006 Mata *et al.* studied the physical cutting of polyamide composites by means of the theoretical model of Merchant [11]. This study was extended in 2007 by Davim *et al*. [12]. Turning tests were carried out on large diameter rods (50 mm) of unfilled PA6 and 30 wt% glass fiber filled PA66. However, they did not consider the effect of fiber orientation distribution on cutting forces. In 2003 Sanomura had already discussed this aspect [13]. Studying the fiber orientation of short-fiber reinforced thermoplastics, he observed a change in radial distribution in the extruded materials. In such cases, few fibers perpendicular to the extrusion direction are present in the central region and many fibers parallel to the extrusion direction are present in the surface region.

As previously mentioned, almost only the reported works are available on the machining of thermoplastics. Also in these cases, plastics to machine are never analyzed by means of the techniques typical for polymers (as the differential scanning calorimetry) because of the analogy with metals, that are generally studied by means of different techniques. In the traditional approach [2], the thrust force F could be modeled as a function of the cutting speed (v) and feed rate (f) by Equation (1):

$$F = Kv^{\alpha}f^{\beta} \tag{1}$$

where K, α, and β are constant.

Many more studies deal with machining of continuous fiber composites with thermosetting matrix. For example, a significant contribution was already given in 1990–91 in the study of drilling glass fiber [14] and aramid [15, 16] composites.

In this work, the authors studied the machinability of a glass fiber reinforced polyamide by means of drilling tests. As a complex fiber orientation distribution is expected in the material, drills were performed on the same disk and in two different configurations: along the disk radius at constant cutting speed and feed rate, and along the external periphery at different values of cutting speed and feed rate. Calorimetry and indentation were used to quantify the lack of homogeneity of the material. A significant trend in mechanical properties was measured along the workpiece because of the fabrication process; cutting forces seem to be strongly dependent on this property distribution. In conclusion it was also observed that the chip formation mechanism significantly affects the machining result in terms of machined part quality and cutting forces. A traditional approach, Equation (1), was used for modeling thrust and its validity was discussed.

2. Materials and methods

A commercial glass fiber reinforced polyamide was used for experimentation (commercially, Tecamid 66 GF30®). A 30 wt% glass fiber content was expected from datasheet as well as a density of 1.35 g/cm^3, a tensile modulus of 9.7 GPa, a tensile strength of 200 MPa, a thermal conductivity of 0.27 W·m^{-1}·°C^{-1} and a specific heat capacity of 1.5 J·g^{-1}·°C^{-1}.

A disk 30 mm thick was cut from a round bar (70 mm of diameter) and used for drilling and characterization tests. In order to make a comparison, a disk of unfilled PA66 with the same dimensions was also used in the experimentation.

In Figure 1 the configuration of the drilling tests is shown (Figure 1a) together with the experimental apparatus used (Figure 1c) and a typical acquired drilling curve (Figure 1b). A vertical-spindle knee-and-column type milling machine was used, equipped with a 24 kW high speed spindle. The spindle rotational speed was changed by means of an inverter and measured by an optical system. Therefore both drilling speed and feed rate could be changed during experimentation. Two drills were used having diameter of 5 and 2.5 mm; the drilling speeds were 2500, 5000, 10 000 and 20 000 rpm; the feed rates were 29, 57.5 and 100.5 mm/min. All the combinations of the mentioned parameters were considered making holes in proximity of the external disk circumference. Fixing the drilling speed at 2500 rpm and the feed rate at 100.5 mm/min, the holes were also made along two disk radii using both drills. Because of the difference in diameter, 4 holes were made by the 5 mm drill and 8 holes by the 2.5 mm drill. No coolant was used. A load cell (Kistler 9273) was placed on the table of the milling machine to measure the thrust during drilling. The workpiece was clamped to a vice, which was in turn fixed to the load cell. The load cell signal was amplified and sent to a data acquisition system. A single thrust value was extracted from each test, performing the average of the acquired cutting data, except for the initial and the final stages.

DSC tests were performed on 10 samples extracted along the disk radius, from the center to the external circumference. The DSC scans (by Netzsch DSC 200 PC) were carried out from room temperature to 280°C at 10°C/min, and peak temperature and area (i. e. the melting temperature and heat) were extracted. The instrument uncertainty can be estimated to be about 1°C for the temperature measurement and 5% of the measured value for the melting heat.

In order to locally characterize the workpiece mechanical properties, indentation tests [17, 18] were carried out along the disk diameter using a universal material testing machine (MTS Alliance RT/50), equipped with an indenter holder. A flat WC indenter with a diameter of 1 mm was set in the holder and 23 indentations were performed, 3 mm spaced each one from the other. During the tests, the applied load and the penetration depth were acquired. The instrument uncertainty for the force evaluation was 0.05% of the measured value. The indentations were performed at the test rate of 10 mm/min and the penetration depth was 1.2 mm. A pre-load of 50 N was applied; this value was optimized to reduce the initial non-linearity of the curves, due to the absence of a perfect parallelism

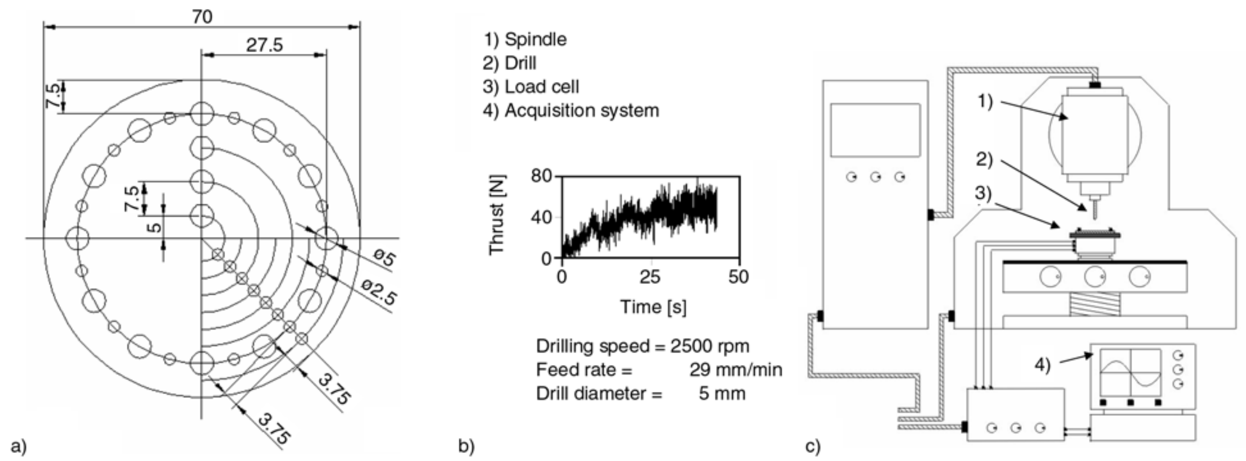

Figure 1. Drilling tests: a) configuration of tests; b) typical acquired curve during drilling; c) experimental apparatus for drilling

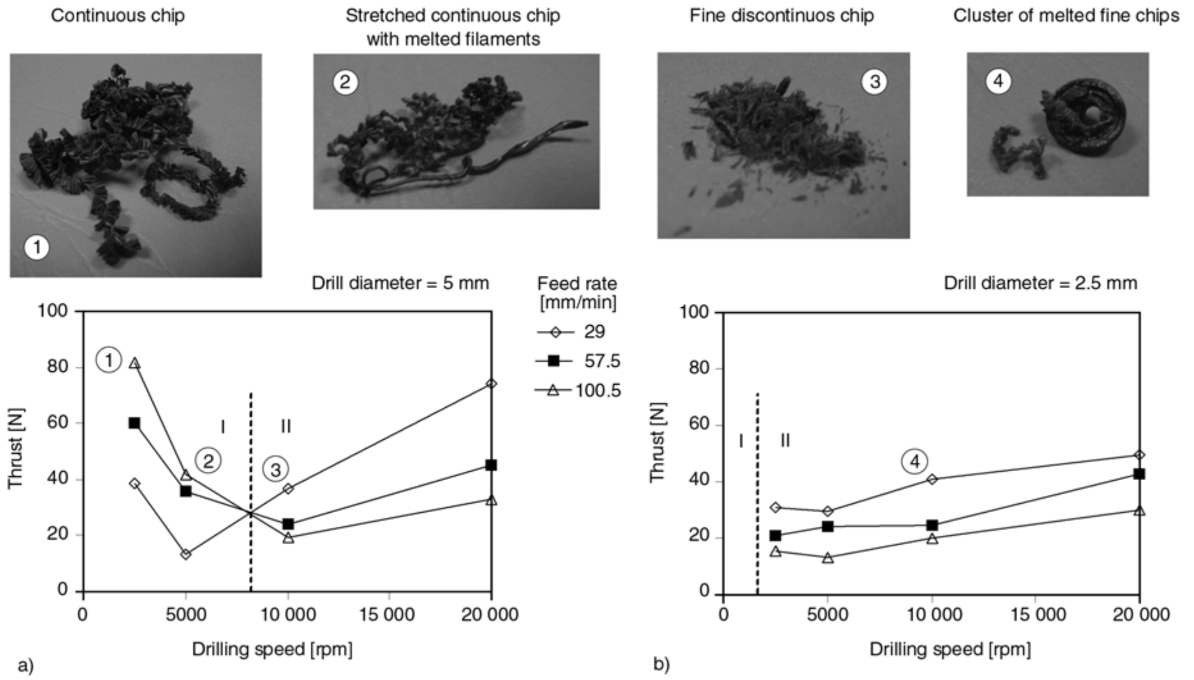

Figure 2. Drilling test results and aspect of the chip: thrust dependence on cutting speed and feed rate for the drill with diameter of a) 5 mm and b) 2.5 mm

between the disk and the indenter surfaces. From indentation curves, the initial curve slope (in the range 0–0.1 mm) and the load at the penetration depth of 1 mm were extracted.

3. Experimental results

Figure 2 shows the results of the drilling tests performed at the same distance from the center (27.5 mm), changing drill diameter, drilling speed and feed rate. In the same figure the typical aspect of the chip is also reported. Four different chip shapes were observed during tests. A continuous chip was obtained at low drilling speeds only for the 5 mm drill. Increasing the drilling speed, the chip tends to be highly stretched and, in some cases, starts to melt. Increasing again the drilling speed, the chip is discontinuous and enormously reduced in size. In the considered range for the drilling speed and feed rate, a continuous chip was never observed for the 2.5 mm drill. At drilling speed of 2500 rpm, the chip is already discontinuous and, increasing the drilling speed, the heat generation is so severe to cause the chip agglomeration in a cluster. This cluster can remain fixed to the drill or to the workpiece, affecting significantly the surface quality of the hole.

In Figure 3 the thrust is reported as a function of the distance from the disk center for both drills. In this case the drilling speed was fixed at 2500 rpm and the feed rate at 100.5 mm/min. In these machining conditions, a continuous chip was observed for the 5 mm drill and a discontinuous chip for the 2.5 mm drill.

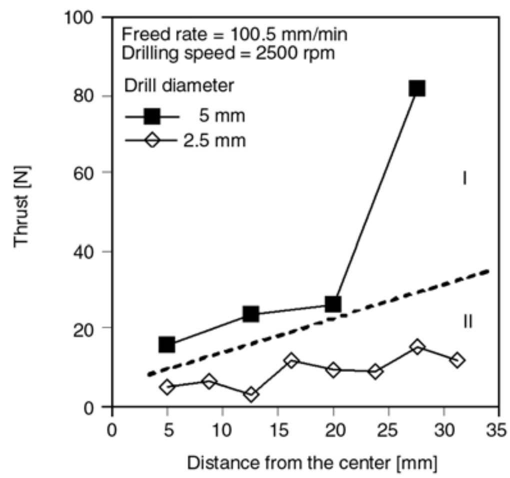

Figure 3. Drilling test results: thrust dependence on the distance from the disk center

DSC test results are summarized in Figure 4 where the scans are compared (Figure 4a) and the peak temperature and melting heat are extracted (Figure 4b). Finally, in Figure 5 the indentation results are shown. A comparison is given between two curves for which a high difference was observed (Figure 5a). Moreover, the trends of the indentation load at 1 mm and the indentation curve slope are both presented (Figure 5b and 5c).

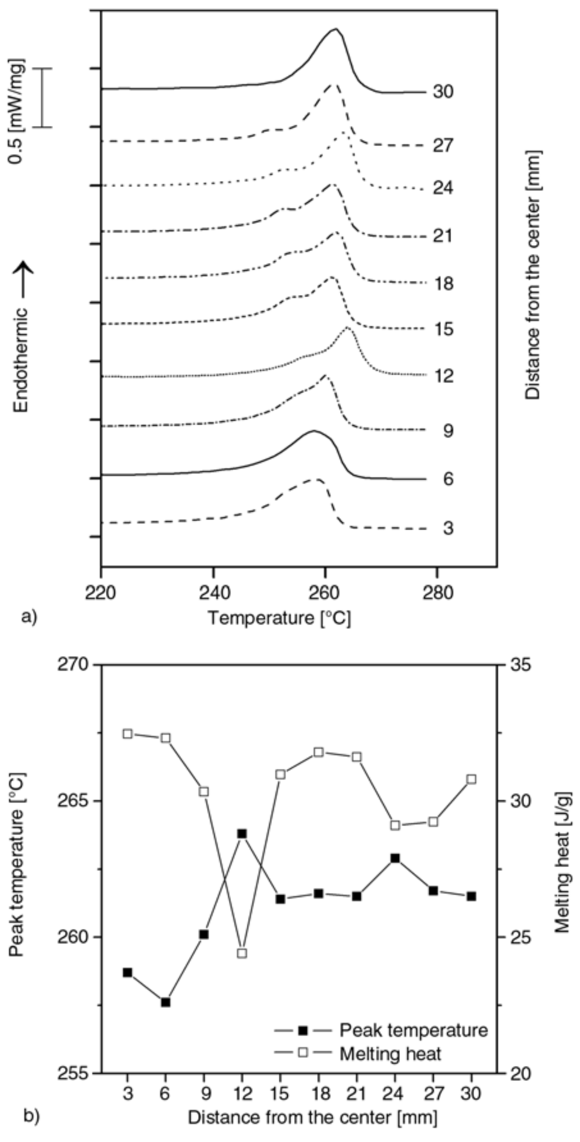

Figure 4. DSC test results: effect of the distance from the center on a) the melting peak shape and b) the peak temperature and area

Drilling and indentation tests were performed also on the unfilled PA disk. The disk was drilled along the radius at the drilling speed of 5000 rpm and the feed rate of 100.5 mm/min by using a drill of 5 mm. The cutting conditions were chosen to have a continuous chip but a significant trend was not observed. A thrust of 25.4 ± 0.5 N was measured (for 4 holes), and an indentation load of 465 ± 7 N (for 23 indentations).

4. Discussion

The behavior of a polymer under machining is quite complex and the addition of a structural filler is a further complication. Generally for metals, cutting forces increase when the feed rate increases and the drilling speed decreases, as a higher amount of material is removed. For the reinforced PA considered in this study, the chip formation mechanism seems to play a significant role in determining the cutting forces, in disagreement with metals. Drilling at the same distance from the center, the same mechanical properties are expected in the workpiece material, therefore it is possible to assume that the observed differences in thrust are only dependent on the process parameters. Using a 5 mm drill, at low drilling speeds (up to 5000 rpm), the thrust dependence on the feed rate and drilling speed is in agreement with metals (Figure 2a). The thrust increases by increasing the feed rate or by decreasing the cutting speed. In these machining conditions, a continuous fluent chip is obtained. Increasing the drilling speed over 5000 rpm, the thrust suddenly increases and higher values are obtained at lower values of feed rate. In these conditions the chip is small and discontinuous. Evidently, the chip is too small to provide a good heat

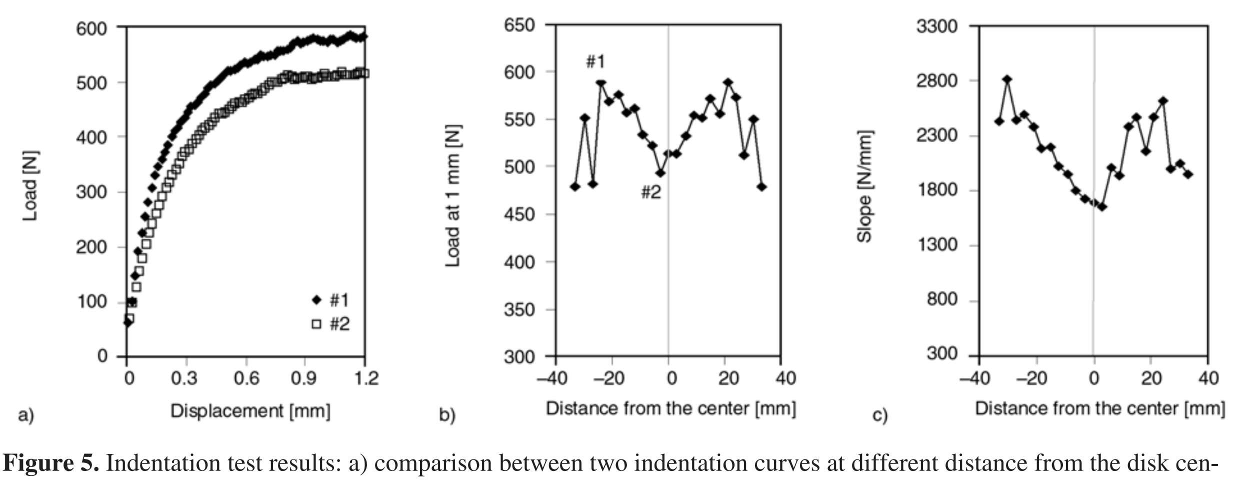

Figure 5. Indentation test results: a) comparison between two indentation curves at different distance from the disk center; b) indentation load at 1 mm and c) indentation curve slope as a function of the distance from the disk center

removal from the machining zone and the cutting mechanism is significantly affected by the excessive temperature increase. It is possible to recognize two main chip formation mechanisms: (I) a continuous chip and (II) a discontinuous chip. The transition between the two mechanisms is not sharp as the chip appears, in some cases, highly stretched and with some melted filaments. At very high drilling speeds, the temperature increase in the machining zone can be so severe to generate a cluster of melted chips that damages the hole quality.

Using a 2.5 mm drill (Figure 2b), a drilling speed of 2500 rpm is already too high to have a continuous chip and only the chip formation mechanism (II) is observed. In this case, thrust increases with the drilling speed and decreases with the feed rate, in opposition to metals.

The effect of the workpiece fabrication process is not negligible in the definition of the cutting forces. Making holes along the disk radius, a higher thrust is measured far from the center (Figure 3). This result was obtained for both drills, even if in the case of the 2.5 mm drill the trend is probably altered by the poor chip formation mechanism. Using the 5 mm drill, the dependence is clear and the thrust can be 8 times higher in the disk periphery compared to the center. A similar trend was not observed for the unfilled PA for which thrust seems to be not dependent on the distance from the center. The higher homogeneity of the unfilled PA was also shown by the indentation results. This occurrence suggests that the thrust mainly depends on the fiber distribution.

In order to investigate the experimental evidence of the thrust increase along the radius, DSC and indentation tests were carried out. Moving from the center toward the periphery, the melting peak is significantly different in shape (Figure 4a). A double melting peak is generally present in all the scans, but the peaks are more separated in the half radius zone. The melting temperature is lower near the center and increases toward the periphery, even if a plateau is already reached at half radius. As the material was extruded through a very thick die, a large difference in crystallization speed between the core and the skin is expected. This phenomenon, together with the local concentration and orientation of fibers, affects the DSC results.

The lack of homogeneity observed by means of DSC was confirmed by the indentation tests. In Figure 5a, a comparison is given between two indentation curves: the first performed near the disk periphery and the second near the center. In detail, the penetration load at 1 mm (Figure 5b) and the initial curve slope (Figure 5c) were taken into account. The indentation load shows a symmetric distribution along the diameter with the maximum toward the half radius; the curve slope trend is similar, even if the symmetry of the results is affected by data scattering. Because of the heterogeneous nature of the material and because of the small dimension of the indenter, data scattering is not eliminable. However, from the comparison between Figures 5b and 5c a clear trend in mechanical properties can be extracted, with a minimum toward the center and a maximum toward the half radius. The trend of the indentation load is probably dependent on the fiber distribution and orientation. In fact reported data are in agreement with the distribution orientation discussed in [13] except for the sudden drop near the disk periphery.

In the external periphery, in the last 10 mm, another minimum is observed. Considering that this external part was not completely involved in drilling, the trend of the thrust in Figure 3 is analogous to the trend of the indentation load in Figure 5b.

The typical approach for modeling is not able to predict the thrust dependence on cutting speed and feed rate in the case of chip formation (II). This occurrence was never discussed in the scientific literature and depends on the combination of several factors: the viscoelastic behavior of the material, the temperature increase during machining and its effect on the material viscosity, the fiber orientation and distribution. However, Equation (1) can be used for the prediction of thrust in the case of continuous chip (I). In fact Figure 6 shows the comparison between experimental and numerical predicted data by means of (1). Only 6 experimental points are present as in the other cases a discontinuous chip was observed. In Figure 6, the equation used for the prediction of the thrust is also reported; the correlation coefficient between experimental and numerical data is 0.93.

5. Conclusions

Polymers behave unlike metals and this difference has to be considered in all the aspects of their processing, also for machining. Performing drilling tests, it was obtained that the dependence of the thrust on the process parameters is significantly affected by the chip formation mechanism. If the

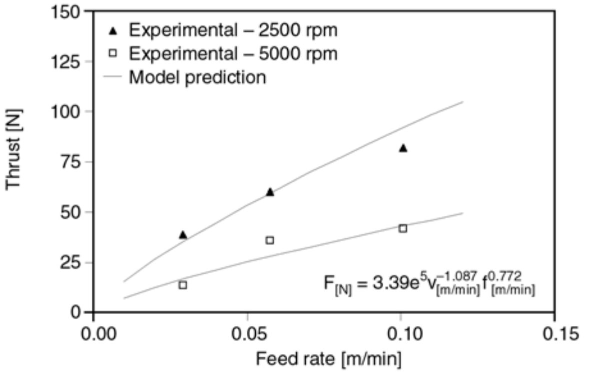

Figure 6. Experimental results and numerical predictions in the case of continuous chip (drill of 5 mm)

chip is discontinuous, thrust increases with drilling speed and decreases with feed rate. This occurrence was never discussed in the scientific literature. Unlike metals, increasing cutting speed does not result in a better machining process. In such conditions, i. e. for a continuous chip, a traditional model (typical of metals) can be used for the prediction of cutting forces. If a different mechanism of chip formation is activated, the traditional approach can lead to significant errors.

Moreover, the fabrication effect of the workpiece can influence the cutting forces more than the process parameters. The thrust increases by a factor of 8 from the center of the considered disk toward the external circumference, due to fiber orientation and distribution. If turning tests are used for the definition of a cutting load, this occurrence could significantly affect results. However, local indentation tests can help to enhance the effectiveness of modeling procedures and machining processes. If the material behavior under machining is not taken into account, poor tolerances would be obtained and the total cost of the part production would be unacceptable.

Acknowledgements

The authors are grateful to Dr Gianluca Palazzo for his support in experimentation.

References

[1] Kobayashi A.: Machining of plastics. McGraw-Hill, New York (1967).

[2] Roy P. K., Basu S. K.: Evaluation of processing factors on turning of thermoplastics. Polymer Engineering and Science, **17**, 751–757 (1977).

[3] Ferry J. D.: Viscoelastic properties of polymers, 3rd edition. Wiley, New York (1980).

[4] Hocheng H., Pwu H. Y., Yao K. C.: On drilling characteristics of fiber-reinforced thermoset and thermoplastics. Materials and Manufacturing Processes, **8**, 653–682 (1993).

[5] Hocheng H., Puw H. Y.: Machinability of fiber-reinforced thermoplastics in drilling. Journal of Engineering Materials and Technology, **115**, 146–149 (1993).

[6] Alauddin M., Choundhury I. A., El Baradie M. A., Hashmi M. S. J.: Plastics and their machining: a review. Journal of Materials Processing Technology, **54**, 40–46 (1995).

[7] Eriksen E.: Influence from production parameters on the surface roughness of a machined short fibre reinforced thermoplastic. International Journal of Machine Tools and Manufacture, **39**, 1611–1618 (1999).

[8] Eriksen E.: The influence of surface roughness on the mechanical strength properties of machined short-fibre-reinforced thermoplastics. Composites Science and Technology, **60**, 107–113 (2000).

[9] Xiao K. Q., Zhang L. C.: The role of viscous deformation in the machining of polymers. International Journal of Mechanical Sciences, **44**, 2317–2336 (2002).

[10] Kim D., Ramulu M., Doan X.: Influence of consolidation process on the drilling performance and machinability of PIXA-M and PEEK thermoplastic composites. Journal of Thermoplastic Composite Materials, **18**, 195–217 (2005).

[11] Mata F., Reis P., Davim J. P.: Physical cutting model of polyamide composites (PA66 GF30). Materials Science Forum, **514–516**, 643–647 (2006).

[12] Davim J. P., Mata F.: A comparative evaluation of the turning of reinforced and unreinforced polyamide. International Journal of Advanced Manufacturing Technology, **33**, 911–914 (2007).

[13] Sanomura Y., Kawamura M.: Fiber orientation control of short-fiber reinforced thermoplastics by ram extrusion. Polymer Composites, **24**, 587–596 (2003).

[14] Tagliaferri V., Caprino G., Diterlizzi A.: Effect of drilling parameters on the finish and mechanical properties of GFRP composites. International Journal of Machine Tools and Manufacturing, **30**, 77–86 (1990).

[15] Di Ilio A., Tagliaferri V., Veniali F.: Cutting mechanisms in drilling of aramid composites. International Journal of Machine Tools and Manufacturing, **31**, 155–165 (1991).

[16] Di Ilio A., Tagliaferri V., Veniali F.: Tool life and hole quality in drilling aramid and fibrous composites. Composite Material Technology, **37**, 203–207 (1991).

[17] Cheng L., Xia X., Yu W., Scriven L. E., Gerberich W. W.: Flat-punch indentation of viscoelastic material. Journal of Polymer Science, Part B: Polymer Physics, **38**, 10–22 (2000).

[18] Benabdallah H. S., Bui V. T.: Indentation of poly(formaldehyde), reinforced nylons and poly(ethyl terephthalate). Polymer Engineering and Science, **44**, 1439–1447 (2004).