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ORIGINAL ARTICLE

Influence of cutting tool and conditions on machinability aspects of polyphthalamide (PPA) matrix composite materials with 30 % glass fiber reinforced

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Abstract Despite the importance of the polyphthalamide (PPA) composites in many industrial applications, especially for automotive industry, very little is known about the machinability of these composites. This paper presents the drilling characteristics of PPA matrix composite materials having glass fiber of 30 % reinforced by using HSS, TiN-coated HSS, and carbide drills. The influence of cutting parameters, for example cutting speed and feed rate, on the delamination factor and surface roughness of the composites has been examined during the drilling operations. Experimental results have demonstrated that as cutting speed increases, surface roughness decreases, and as feed rate increases, surface roughness increases as well. Higher cutting speeds and lower feed rates generate better surface quality. The drilling test results have demonstrated that the delamination factor increases through the increase of feed rate and decreases through the increase of cutting speed. It is obtained the best results of the delamination factor at higher cutting speeds and lower feed rates. The machined surface is examined by means of scanning electron microscopy (SEM). SEM images of the machined surfaces show the presence of cracks, fiber pullout, and shearing of fibers.

Keywords PPA matrix · Glass fiber · Drilling · Machinability · Surface roughness · Delamination factor

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1 Introduction

Machining of glass fiber-reinforced polymer (GFRP) composite materials has always been difficult because of multitude of difficulties encountered suchlike fiber pulling out, fiber fuzzing, matrix burning, and fiber-matrix detachment, which result in subsurface damage, reduced strength, and short product service life. Drilling has a very important role in the cutting process because more than 40 % of material removal processes are drilling. [1].

The improvement of the drilling process of fiber-reinforced polymers (FRPs) is important not only for decreasing the manufacturing costs but also for improving the part quality [2]. It should be kept away from the delamination phenomenon as its well-known negative effect on mechanical behavior [3]. Delamination is a major problem with respect to drilling fiber-reinforced composite materials and also reducing the structural integrity of the material. Moreover, it causes poor assembly tolerances, and it has the potential for long-term performance deterioration [4]. Delamination occurs both at the entrance and the exit planes of the hole [5].

Davim et al. [6] have examined the influence of cutting parameters and the matrix on the specific cutting force, delamination factor, and surface roughness. It has been determined that the feed rate is the most influencing parameter on delamination factor. Hocheng and Tsao [7], in their study on drilling of composite materials with various drill bits, have submitted a comprehensive analysis of delamination in use of various drill types, such as saw drill, candle stick drill, core drill, and step drill. In their analysis, the delamination is predicted and compared by twist drill.

Many researchers have carried out studies on drilling of composite materials. Ogawa et al. [8] examined the relation between the cutting force and the surface roughness of a drilled hole. They have found that the major cutting edge of the drill has more influence than the chisel edge of the drill on the quality of the drilled hole. Lin and Chen [9] have carried out a wide range of experiment in order to examine the influences of cutting speed and also other cutting parameters on drilling features, including cutting forces and tool wear when drilling CFRP composites are at high spindle speed. It has been determined that the mean thrust force increases as cutting speed increases for both multifaceted drill and twist drill.

Polyphthalamide (PPA, high-performance polyamide) is a thermoplastic synthetic resin of the polyamide (nylon) family that is used to renew metals in the high-temperature automotive applications, as the housing for high-temperature electrical connectors and multiple other uses. It has demonstrated a degree of advantage to use in cutlery [10]. The current study is an attempt to examine experimentally the significance of the drill materials and the operating variances (the cutting speed and feed rate) on the surface roughness and delamination factor of the work piece hole.

2 Experimental setup

2.1 Materials

In this investigation, a commercially available short glass fiber-reinforced PPA high-performance polymer composite material supplied by Akromid T1GF30, Akro Plastics (Germany) was used. Samples with 60 × 80 × 5 mm^3 dimension were prepared by using injection molding method. The physical and mechanical properties of the short glass fiber-reinforced PPA matrix are illustrated in Table 1.

2.2 Drilling

The cutting experiments have been carried out by drilling in dry cutting conditions on a HAAS TM1 three axis CNC milling machine, which is equipped with a maximum spindle speed of 4.000 rpm and a 5.6-kW drive motor. Figure 1 illustrates the CNC milling machine where the actual drilling is operated.

Table 1 The properties of PPA composite used (Akromid T1GF30/Akro Plastics)

Properties	Standard	PPA + 30 % GFR
Density, g/cm^3	ISO 1183	1.4
Water absorption, %	ISO 62	1.25
Tensile strength at break, MPa	ISO 527	215
Tensile modulus, MPa	ISO 527	12,500
Elongation at break, %	ISO 527	2.2
Flexural strength, MPa	ISO 178	300
Flexural modulus, MPa	ISO 178	11,000
Ball indentation hardness, MPa	ISO 2039	290

Fig. 1 Experimental setup view

The coolant liquid is not used in all the drilling tests. The experiments have been carried out at different cutting speeds of 7, 9, and 11 m/min and feed rates of 0.05, 0.10, and 0.15 mm/rev. All experimental conditions are summarized and then illustrated in Table 2. Each test has been repeated twice. Three drill geometries are illustrated in Fig. 2.

The surface roughness (Ra) of the hole is measured by surface roughness tester (Mahr-Surf PS1), surface tester having a sampling length (cutoff) of 0.8 mm. The surface roughness is measured by using profilometry, which is illustrated in Fig. 3.

2.3 Delamination factor

Delamination factor (F_{del}) around the holes is measured by using a Nikon Eclipse L150 toolmaker's microscope having 20× magnification and 1-mm resolution. In order to specify the machining parameters with regards to minimal damage of the laminates, digital analysis has been employed in order to measure the adjusted delamination factor (F_{del}) for the drill geometry, which is responsible for the best results concerning the delamination factor. Maximum diameter (D_{max}) in the delamination zone has been measured (Fig. 4) in order to determine the delamination factor around the holes. The value of delamination factor (F_{del}) can be determined by the following equation:

Table 2 The experimental parameters and their values

Parameters	Values
Drill type	HSS, TiN-coated HSS, carbide
Feed rate (mm/rev)	0.05, 0.10, 0.15
Spindle speed (m/min)	7, 9, 11

Fig. 2 Drills used in the experimental work

$$F_{del} = \frac{D_{max}}{D_{drill}}, \quad (1)$$

where D_{max} is the maximum diameter of the delamination zone in mm and D_{drill} is the diameter of the drill in mm [5].

The experimental results of the measured delamination factor and surface roughness are illustrated in Table 3.

3 Results and discussion

Figure 5 illustrates a scanning electron microscope (SEM) micrograph of fracture surface GFRP composite that was prepared using the fiber absorption process. It can be seen that the glass fibers are strongly bonded and homogeneously impregnated with the PPA matrix material.

Figure 6 illustrates the images, which are observed by means of scanning electron microscope (SEM) of the glass fiber-reinforced polymer composite material work piece in drilling. The images are observed at the cut sections of the drilled holes. The micrograph in Fig. 6 is cut section of the hole in which the sheared fibers and matrix materials are seen. Because of the heat generation in drilling, the matrix materials are turned into the lumped masses along with the fibers.

Figure 7 illustrates the images observed by means of scanning electron microscope (SEM) of the glass fiber-reinforced polymer composite material work piece in drilling. Because of the thrust force formed during the drilling operation, the fiber and matrix materials are pulled out and the surface is presented like in figure. The reason is high abrasiveness of the glass fibers that make the tool encountered fluctuation of forces, and it results in the peeling and fiber pullout [11].

3.1 Influence of cutting speed and feed rate on delamination factor

Figure 8a–c illustrates the influence of feed rate and cutting speed on delamination factor when drilling glass fiber-reinforced composite by using the three tool materials. It can be seen that the cutting speed and the feed rate affect the delamination factor. The delamination factor decreased due to an increase in the cutting speed for all the cutting tools, as you see in Fig. 8a. The result shows that an increase of cutting speed raises the temperature produced in drilling of composites, which softens the matrix material and shearing, and in turn, the delamination is decreased. These findings comply with previous works of Palanikumar et al. [12] and Rajamurugan et al. [13] who examined the machinability of glass fiber-reinforced plastic (GFRP) composite materials.

Palanikumar et al. have concentrated on the use of Grey relational analysis in order to optimize the drilling parameters for the delamination factor and the thrust force in the drilling of GFRP composites. They observed that the machining performance in the composite machining process can be enhanced at optimal drilling conditions. Rajamurugan et al. have examined, in their study, relations between the drilling parameters suchlike fiber orientation angle, tool feed rate, rotational speed, and tool diameter with regard to delamination in drilling of GFR-polyester composites. The results of this investigation have demonstrated that the increase in feed rate and

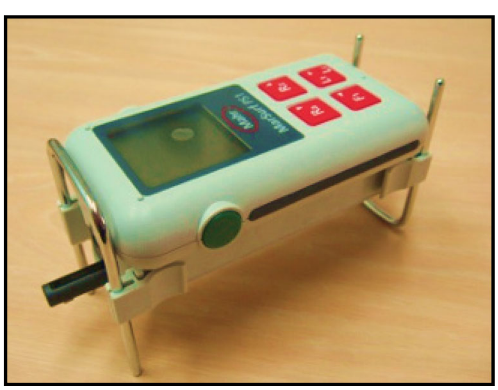

Fig. 3 Surface roughness tester

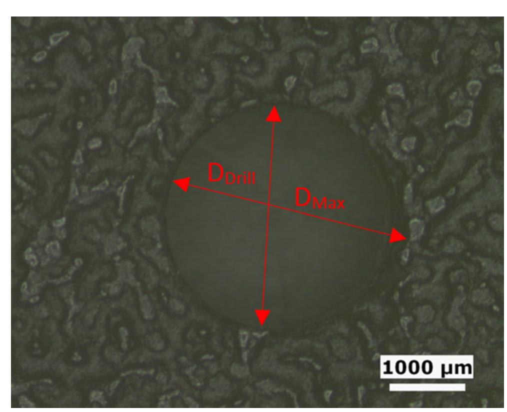

Fig. 4 Photographs illustrating of the delamination factor around the drilled hole using optical microscope

Table 3 Experimental results of delamination factor and surface roughness in drilling PPA composites

Cutting tool	Spindle speed (m/min)	Feed speed (mm/rev)	Delamination factor	Surface roughness (μm)
HSS	7	0.05	1.091	0.98
HSS	7	0.10	1.117	1.04
HSS	7	0.15	1.123	1.11
HSS	9	0.05	1.072	0.81
HSS	9	0.10	1.076	0.82
HSS	9	0.15	1.082	0.86
HSS	11	0.05	1.065	0.74
HSS	11	0.10	1.069	0.79
HSS	11	0.15	1.070	0.80
HSS + TiN	7	0.05	1.048	0.71
HSS + TiN	7	0.10	1.060	0.72
HSS + TiN	7	0.15	1.064	0.73
HSS + TiN	9	0.05	1.040	0.68
HSS + TiN	9	0.10	1.044	0.69
HSS + TiN	9	0.15	1.045	0.70
HSS + TiN	11	0.05	1.037	0.64
HSS + TiN	11	0.10	1.038	0.65
HSS + TiN	11	0.15	1.039	0.67
Carbide	7	0.05	1.030	0.61
Carbide	7	0.10	1.035	0.62
Carbide	7	0.15	1.039	0.63
Carbide	9	0.05	1.023	0.57
Carbide	9	0.10	1.025	0.58
Carbide	9	0.15	1.029	0.59
Carbide	11	0.05	1.009	0.49
Carbide	11	0.10	1.016	0.52
Carbide	11	0.15	1.021	0.55

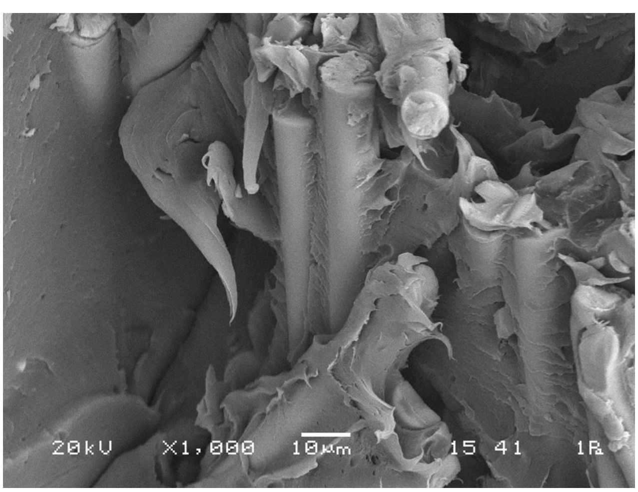

Fig. 5 SEM micrograph of fracture surface of GFRP composite materials

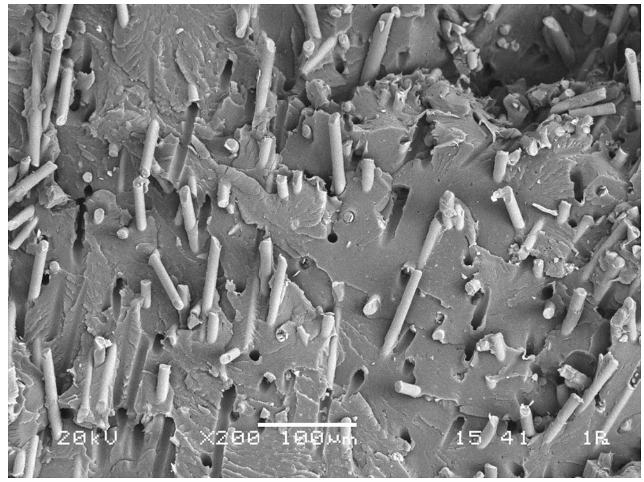

Fig. 6 The images observed through scanning electron microscope

drill diameter raises the delamination size; however, there is no clear effect observed for fiber orientation angle.

Figure 9a–c illustrates the influence of feed rate on delamination factor for all the cutting speeds. It can be seen on Fig. 9a that the delamination factor has increased by an increase in the feed rate because of the increase of thrust force in drilling. The study of Kilickap [4] submits, as a similar finding with that of the current study, that increasing the feed rate deteriorates the surface quality of glass fiber-reinforced plastic (GFRP) composite as in most other materials. Sunny et al. [14] and Rubio et al. [15] have argued that the feed rate is determined to be the most significant parameter, which has an influence on the delamination factor. The result presented by the researchers is well suited for this study in which role of the feed rate is significant.

Gaitonde et al. [16, 17] reported that increase in feed rate increases the delamination factor because of the increased thrust as well as chatter and was reduced at higher cutting speeds in drilling of wood panels.

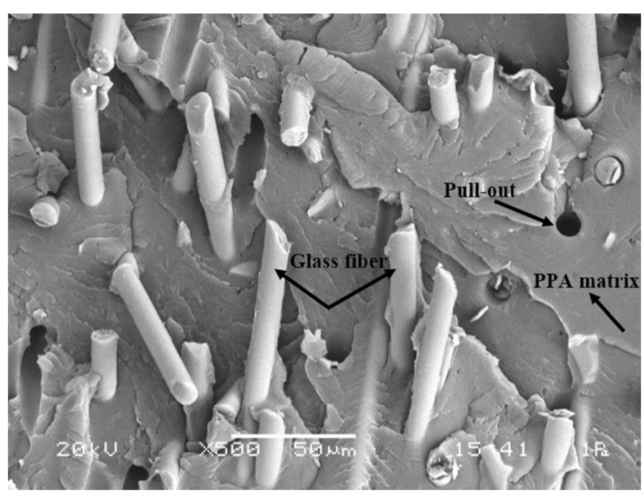

Fig. 7 Typical machined surface profile observed during machining GFRP composite material

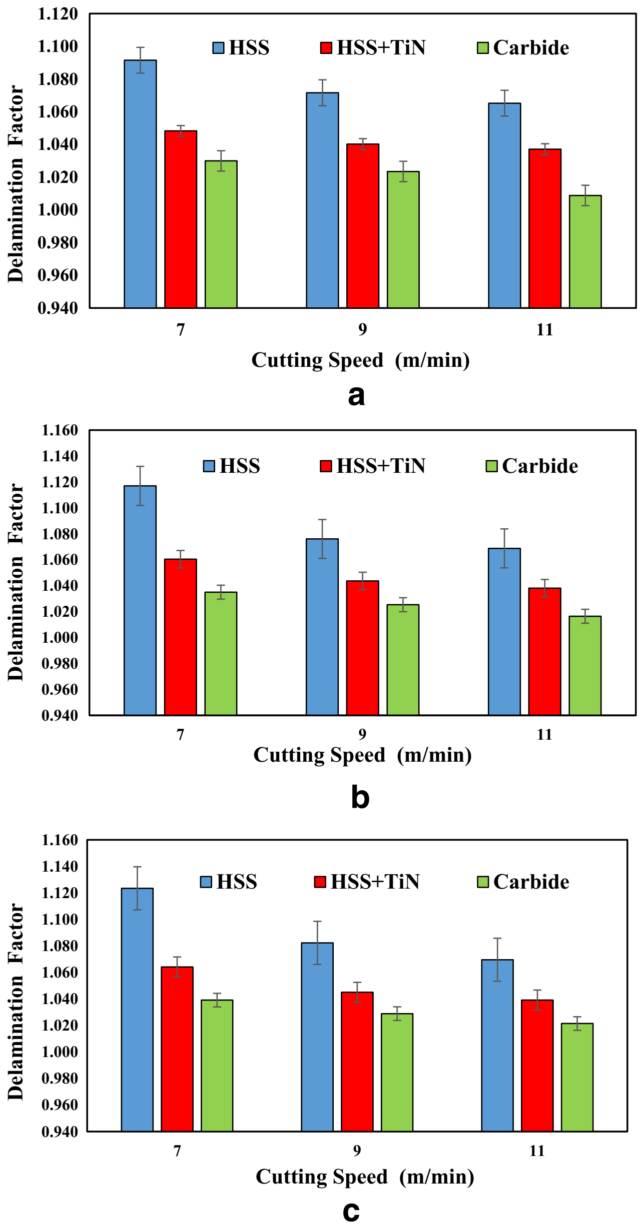

Fig. 8 Effect of feed rate on surface roughness cutting speed: 7 (**a**), 9 (**b**), and 11 (**c**) m/min

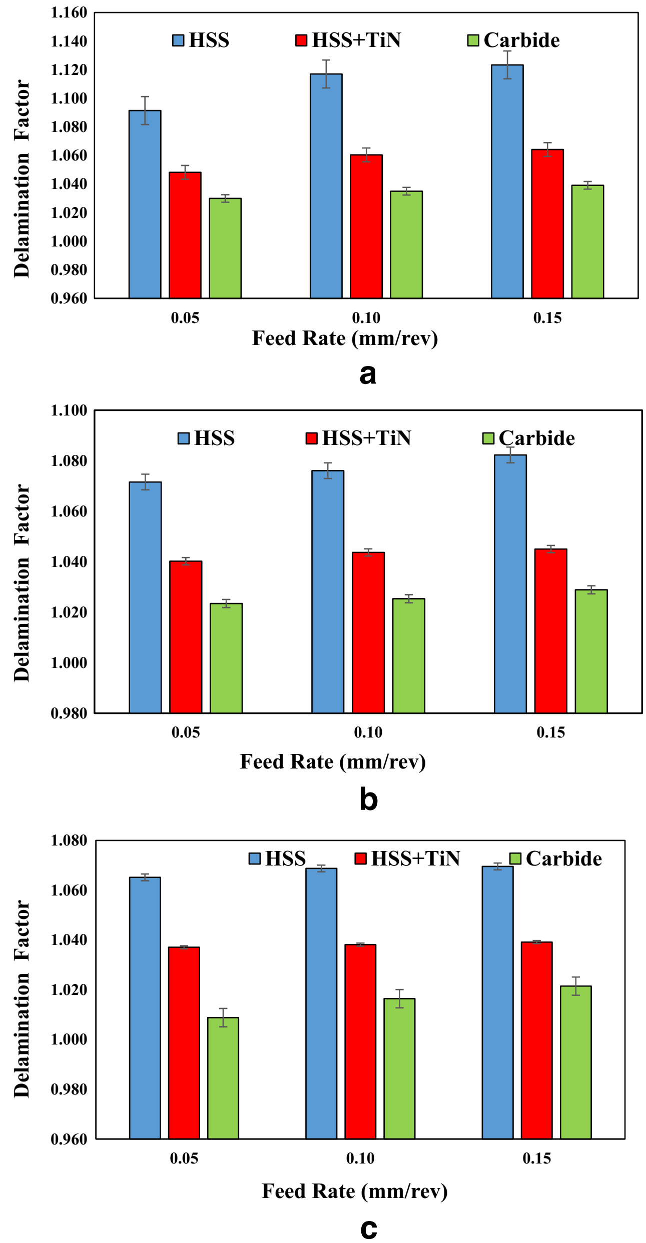

Fig. 9 Variation of delamination factor with respect to feed rate and cutting tools: 0.5 (**a**), 0.10 (**b**), and 0.15 (**c**) mm/rev

3.2 Influence of cutting speed and feed rate on surface roughness

Surface roughness is one of the main requirements for drilling processes, and it defines the quality of the final product. While drilling glass fibers composite with drill, the crack generates in deformation zone and it reproduces downward. From time to time, fibers are pulled out and they flow with the cutting tool edge, and others remain with the top part protruding from the cutting surface, since the fiber materials are usually fragile in nature [18–20].

Figure 10a–c illustrates the influence of cutting speed on surface roughness for all drills. The results of these figures indicate that the surface roughness is raised by increasing feed. The best surface quality of composite materials has been observed at 0.05-mm/rev feed rate. The figure illustrates almost the same trend as discussed before. In the previous study from the authors [21], they have discussed thickness of the specimen instead of fiber orientation angle. Even in this case, feed rate has been the dominant factor, which affects the surface roughness in drilling of composites. Among the factors analyzed, feed rate is the most significant factor, which affects the surface roughness of holes. This finding is close to the findings submitted by Ogawa et al. [22].

Davim and Mata have examined an optimization study of surface roughness in turning FRP tubes manufactured by

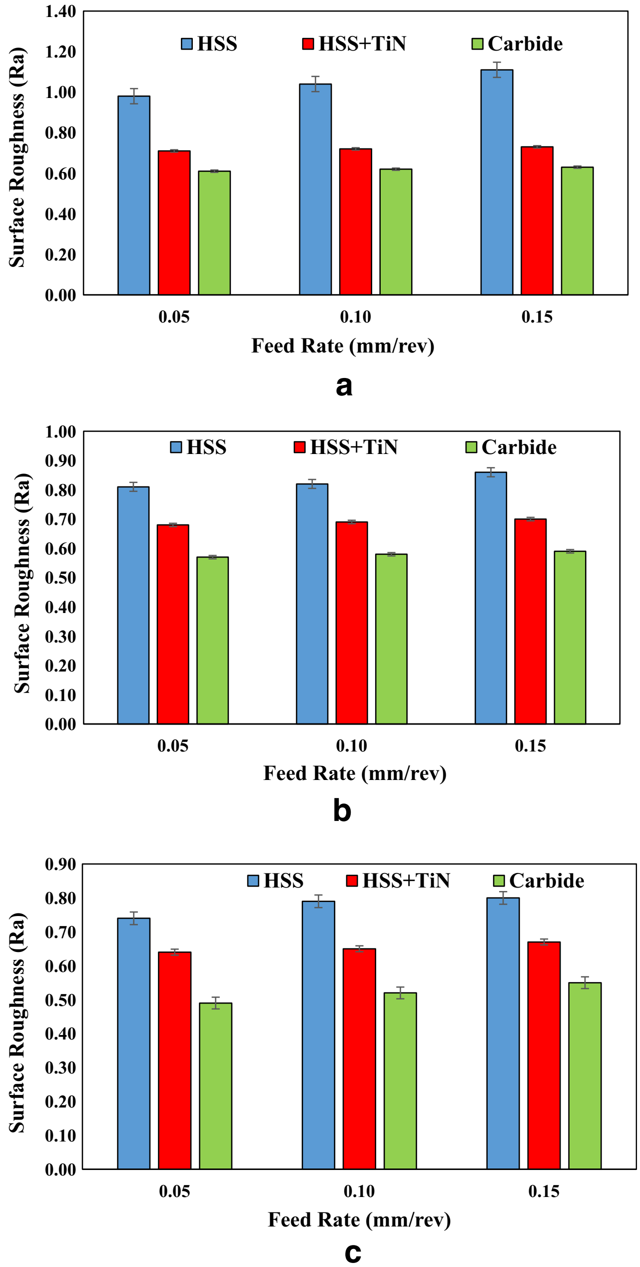

Fig. 10 Effect of cutting speed and feed rate on surface roughness: 7 (**a**), 9 (**b**), and 11 (**c**) m/min

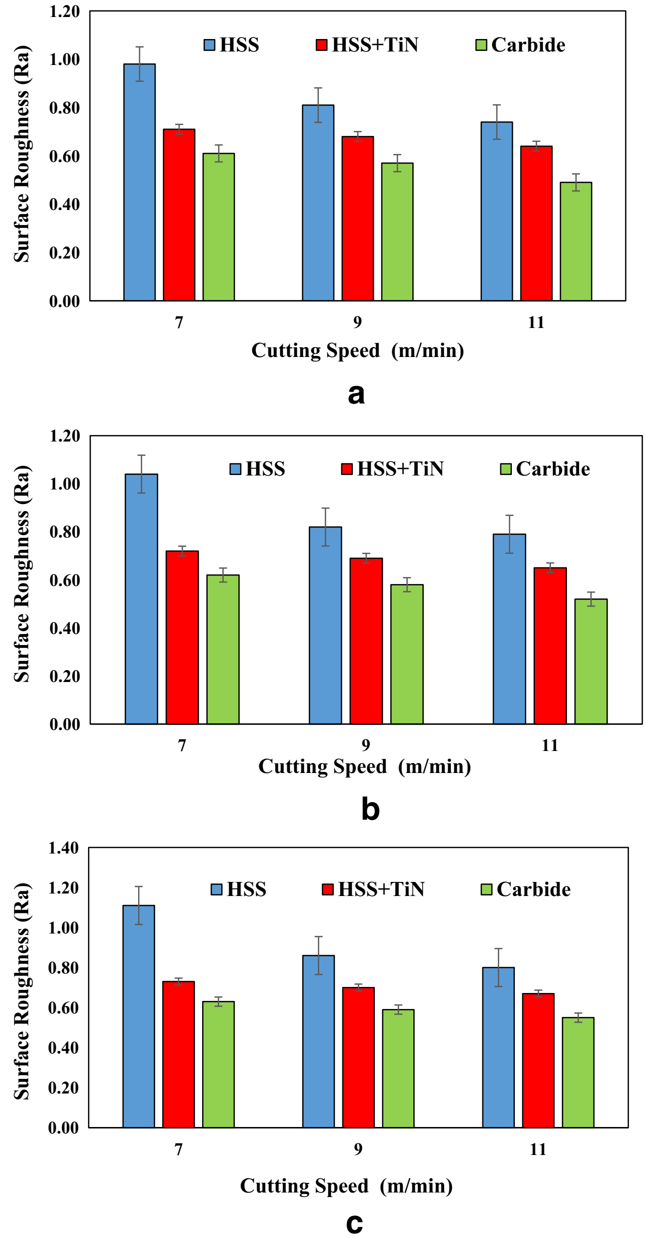

Fig. 11 The effect of cutting speed on surface roughness: 7 (**a**), 9 (**b**), and 11 (**c**) m/min

filament winding and hand lay-up, using polycrystalline diamond cutting tools. They found that the surface roughness (*Ra*) increases with the feed rate [23].

Davim et al. investigated the machinability of PA 66 polyamide with and without 30 % glass fiber reinforcing, when precision turning at different feed rates and using four distinct tool materials. They reported that the surface roughness of composite materials produced by the four cutting tools was not significantly affected by feed rate within the range tested [24].

Figure 11a–c illustrates the influence of cutting speed on surface roughness in drilling of glass fiber-reinforced polymers. The figure indicates that the increase of spindle speed decreases slightly the surface roughness in drilling of composites. Many researchers have well documented the fact that the cutting speed factor has the critical influence on surface roughness of glass fiber-reinforced polymer composites [25–28]. Petropoulos et al. have examined that the influence of cutting conditions on surface roughness in machining of polyethertherketone composites. They have submitted that the lower surface roughness is observed at the highest cutting speed [28].

Davim and Reis have expressed opposite trend. They studied machinability of polyetheretherketone composite reinforced with 30 % glass fiber using polycrystalline diamond and cemented carbide (K20) tools. They concluded that the surface roughness of composite materials decrease with the cutting velocity [29].

4 Conclusions

From this study, the following conclusions were reached:

- The drilling test results demonstrated that the delamination factor increases as the feed rate increases.
- The delamination factor decreases as the cutting speed increases.
- The surface roughness values decrease as the cutting speed increases.
- The surface roughness values increases as the feed rate increases.
- Lower *R*a surface roughness values are acquired by means of carbide tools in drilling operations.
- At low feeds, the surface roughness of the GFRP is affected by fiber fracture or pullout; however, it is controlled by the feed rate at higher feeds.
- Analysis of drilled surface demonstrates the existence of cracks, fiber pullout, and shearing of fibers.

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