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RESEARCH NOTE

Analysis of Milling Process Parameters and their Influence on Glass Fiber Reinforced Polymer Composites

I. S. N. V. R. Prasanth*[a], D. V. Ravishankar[b], M. Manzoor Hussain[c]

[a] *Department of Mechanical Engineering, St Mary's integrated campus, JNTU, Hyderabad, India*
[b] *Department of Mechanical Engineering, T.K.R.CET, JNTU, Hyderabad, India*
[c] *Department of Mechanical Engineering, J.N.T.U Hyderabad, India*

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ABSTRACT

Milling of fiber reinforced polymer composites is of great importance for integrated composites with other mating parts. Improper selection of cutting process parameters, excessive cutting forces and other machining conditions would result in rejection of components. Therefore, machining conditions are optimized to reduce the machining forces and damages. This work reports practical experiments in milling, to study the effect of machining conditions on cutting force, surface roughness and damage factor of Glass Fiber Reinforced Polymer (GFRP) composites. The experiments were carried out with a designed carbide end mill tool by a random set of milling process parameters. The results showed that machined surface integrity was highly influenced by the spindle speed followed by the feed rate. The results of the experiments were illustrated and analyzed by interaction plots and Scanning Electron Microscope (SEM) images.

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1. INTRODUCTION[1]

Nowadays Glass Fiber Reinforced Polymer (GFRP) composites are alternative products for metals due to their superior characteristics like high specific stiffness, corrosion resistance, fatigue resistance and less weight to strength ratio. Therefore GFRP composites are widely used in automobile, aerospace and other industrial applications. However, composite materials have distinct mechanical behavior compared with other conventional engineering materials. Jahanmir et al. [1] stated that milling is one of the machining operations to produce closed dimensional accuracy with fewer damages on mating parts. The surface finish is an important measure that would be indication for surface quality of machined composites. In this regard Ramulu et al. [2] focused on determination of optimum machining processes to obtain the desirable surface quality. The mechanistic modeling approach is used for predicting cutting forces in the milling process of fiber reinforced polymer composites. The machining force plays a key role in getting desirable machinability indices. Hence, Janarthan and Jeyapaul [3] proposed a specific energy function and it was determined by regression analysis of experimental data and a machining model. The model predictions were concluded to be in good agreement with experimental results. Srinivasulu [4] conducted the experiments by drilling operation using a Taguchi technique with prefixed cutting parameters on GFRP workpiece and the confirmation test was concluded with the analysis of variance (ANOVA). Many researchers conducted turning operations to minimize the machined damages on FRP composites. Kumat and Satsangi [5] developed a procedure to evaluate and optimize the selected input factors to achieve the minimum surface damage. Gopalakannan and Senthilvelan [6] considered that EDM is one of the optimistic machining operations to study the process parameters; conduction of experiments was based on the central composite design and desirability approach. The research papers on milling of composites are few as compared with metals. In order to understand the damage mechanisms in

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*Corresponding Author's Email: prasanth5109@gmail.com (I. S. N. V. R. Prasanth)

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machined surfaces of FRP laminates, some researchers [7, 8] optimized the cutting process parameters for analyzing the surface integrity and chip formation mechanisms. In the literature [9-12] some information have been given to obtain the damage free FRP composites using conventional machining operations like drilling and turning. The damages takes place on the machined surfaces, caused by the tool wear, which may result in the rejection of products. The fiber orientation angle is also one of the important factors to affect the machined texture. In this regard, Azmi et al. [13] conducted the experiments as per DOE's and concluded that the fiber orientation is a highly influential factor. With increase of the fiber angle the tool wear rate increased. Rahman et al. [14] reported that the fluctuations of machining force were well experienced while machining FRP composites relative to process parameters. In this regard, the present research work is to investigate the relation between the cutting process parameters and virtue of surface quality of machined composites.

2. EXPERIMENTAL SETUP AND PROCEDURE

2. 1. The Work Specimen Preparation The workpiece material selected for milling operations was the E-Glass bi-directional $[\pm45^0]_{12}$ fiber reinforced polymer composites. The material was fabricated by hand lay-up compression moulding technique. During the fabrication, 12 layers of E-Glass fiber mats (300 mm × 300 mm) were laid up on flat 10 mm thick mould panel. A mixture of polyester resin and hardener at 10:1 ratio was stirred in a glass mug and the ready mixture was poured into the E-Glass preform under a pressure of about 200 kgf. Once the resin was cured after 5 hours, the composites were cut into 100 mm × 100 mm × 10 mm size with a diamond abrasive wheel cutter. The volume fraction 'V_f' was regulated according to (ASTM D2548-68 [15]). The average value of 'V_f' was approximately 0.60.

2. 2. Mechanical Characterization of GFRP Composites According to the standard ASTM D638-03 the gauge length and cross head speeds were chosen. The test was carried out in Universal Testing machine (UTM) at room temperature conditions (30 ^{0}C). The test involved the application of tension in the work piece until it broke. The tensile stress recorded according to the strain. The test was performed on the samples of Bi-directional woven roved type glass fiber reinforced composites and the corresponding graph was drawn. The tensile test for fabricated laminate is presented in Figures 1 (a) and (b). The experiments were repeated at least 3-5 times and the average values are shown in Table 1.

2. 3. End Milling Machinability Tests Under dry conditions, the end milling tests were carried out on a conventional universal milling machine with 10 HP spindle power and 3000 rpm maximum spindle speed as shown in Figure 2. The selected machining process parameters were the spindle speeds of 690, 960, 1153, 1950 and 2500 rpm; feed rates of 1, 2 and 3 mm/s under a constant depth of cut of 3 mm, respectively. These machining conditions were based on the literature [16], where the spindle speed was 20-200 m/min. All machining operations were performed by designing two fluted solid carbide end milling tool of rake angle 30^0 and clearance angle was 12^0 with 10 mm diameter. A vacuum cleaner was used to extract the chips from cutting zone to minimize the chip interference with workpiece.

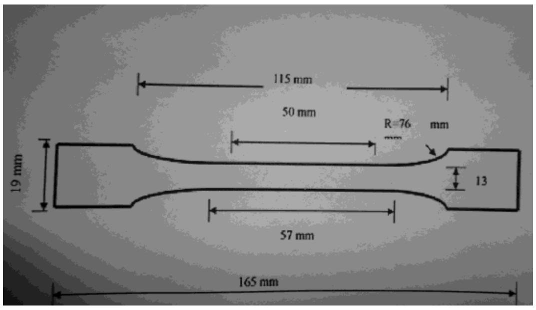

Figure 1 (a). Geometrical dimensions of tensile test specimen as per ASTM D638-03

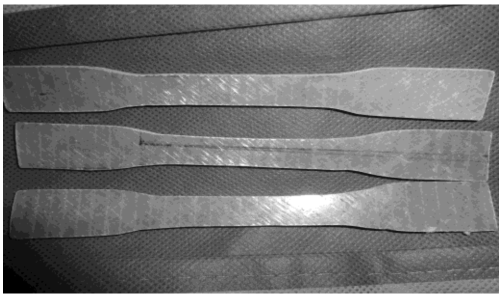

Figure 1 (b). Woven -Roved tensile test specimens

TABLE 1. Mechanical properties of GFRP composites

Typical properties of laminate	Bi-directional laminate values
Ultimate tensile strength in fiber direction	280(±6.84) MPa
Tensile modulud in fiber direction	18(±6.84) Gpa
Tensile modulus in trasverse direction	4.8(±0.11) GPa
Mass density	2.13(±0.0079) g/cm^3

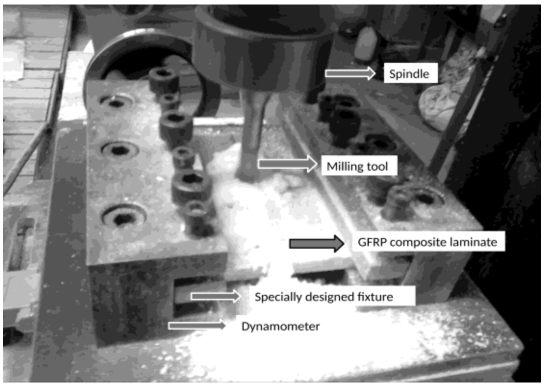

Figure 2. Experimental set up for end milling of GFRP composites

The workpiece is held centrally in the specially designed fixture and vibrations were avoided. The machining forces during milling operations were measured by using a mill tool dynamometer in the range of 0 to 50 kgf (As shown in Figure 2).

Taking the milling dynamometer readings as per Langari et al. [17] experimentation model, the steps were: (1) connecting the data analogue device cable to mill tool dynamometer, in which the output readings were displayed on personal laptop. (2) Inserting the end milling tool in the spindle and fixing the laminate in the fixture properly, and setting the spindle speed at 960 rpm and the feed rate at 1 mm/s where the depth of cut was 3 mm for all 15 experiments as mentioned in Table 2. (3) Taking the readings from each of the experiential runs, where the values of F_X-feed force, Fy-cutting force and F_z-thrust force were directly displayed on the data analog lap top. (4) The resultant force 'F' was considered to be machining force and formula used as $F = \sqrt{F_x^2 + F_y^2 + F_z^2}$. The procedure was repeated for all the experiments. Each experimental value for measuring the surface roughness at three places (using the centreline average method) along the direction of fiber ply was calculated using a Mitutoyo profile meter. Here the cut-off value and transfer length were set 0.5 mm/s and 5 mm, respectively. Moreover, the damages of machined slot widths were measured at three different places using a travelling microscope. Hence, the damage factor (F_D) was calculated by taking the average value. Therefore, $F_D = W_{max}/W$; where the W_{max} is the maximum machined slot width and 'W' is the tool diameter in millimeters. The procedure of experimental runs is shown in Table 2. Finally, the experimental work excellence was analyzed by SEM photographs.

3. EXPERIMENTAL EVALUATIONS

The investigation was mainly focused on the machined surface quality of GFRP composites. The milling process parameters correlated under the machining force effects with surface roughness and machined surface damage. Moreover, the experimental work was evaluated by drawing interaction graphs and the machined surface quality was perfectly analyzed by SEM images. The results of the surface roughness (Ra), machining force (F) and damage Factor (F_D) were obtained as a function of the milling process parameters. All the milling operations were performed with a designed carbide mill tool and fifteen trials were carried randomly.

3. 1. Discussion

The results of experiments (related to trial number 1 to 6 as shown in Table 2) are illustrated in Figures 3 (a), (b) and (c) and Table 3. The specimens were machined with a designed carbide mill tool at low spindle speeds of 690 and 960 rpm and at low feed rate of 1 mm/s which resulted in a low induced machining force (F) of 23.5 and 23.1 N. At this stage, low surface roughness (2.56 and 2.42 µm) and less damage factor (1.28 and 1.20) were obtained. But initially 'R_a' and 'F' decreased with increase of the spindle speed from 690 to 1153 rpm. This is because the less compressive force exerted on the tool cutting edge compels less friction and thereby the machining force and consequently 'R_a' is decreased. Whereas at the spindle speeds beyond the 1153 rpm, the machining force enormously increased, thereby intended friction generated heat and consequently damages took place on machined slot (some fibers experienced surface failures like crack growth formation, fiber shear failure, fiber bending are shown in SEM Figures 4(a), (b) and (c)). Besides the above experimental values of machining force measurements, the surface roughness (R_a) and damage Factor (F_D) were analyzed with aid of SEM micrographs.

TABLE 2. Test plan for milling operations

Trial number	Tool type	Spindle speed in "rpm"	Feed rate (mm/s)	Depth of cut (mm)
1 to 3	Solid carbid tool	690	1/2/3	3
4 to 6	Solid carbid tool	960	1/2/3	3
7 to 9	Solid carbid tool	1153	1/2/3	3
10 to 12	Solid carbid tool	1950	1/2/3	3
13 to 15	Solid carbid tool	2500	1/2/3	3

Experiment number	Trial number	Tool type	Spindle speed in "rpm"	Feed rate (mm/s)	Depth of cut (mm)
1	1	solid carbid tool	690	1	3
	2	solid carbid tool	690	2	3
	3	solid carbid tool	690	3	3

similarly 4 other sets of experiments were conducted at spindle speeds of 960, 1153, 1950 and 2500 rpm

TABLE 3. Experimental results

	Machining force in Newtons			Surface roughness (µm)			Damage factor		
Spindle speed "rpm"	Feed rate at 1 mm/s	Feed rate at 2 mm/s	Feed rate at 3 mm/s	Feed rate at 1 mm/s	Feed rate at 2 mm/s	Feed rate at 3 mm/s	Feed rate at 1 mm/s	Feed rate at 2 mm/s	Feed rate at 3 mm/s
690	23.5	21.7	22.9	2.56	2.56	2.80	1.28	1.21	1.30
960	23.1	22.3	22.6	2.42	2.48	2.70	1.20	1.16	1.23
1153	22.6	21.9	21.8	2.32	2.41	2.66	1.18	1.15	1.20
1950	23.2	23.2	23.1	2.54	2.57	2.68	1.25	1.18	1.23
2500	24.1	23.5	23.8	2.68	2.68	2.92	1.28	1.19	1.25

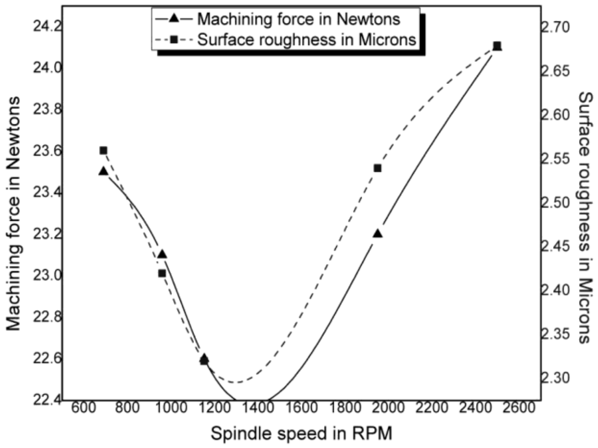

Figure 3 (a). The effect of the spindle speed on the surface roughness and machining force when the feed rate is 1 mm/s

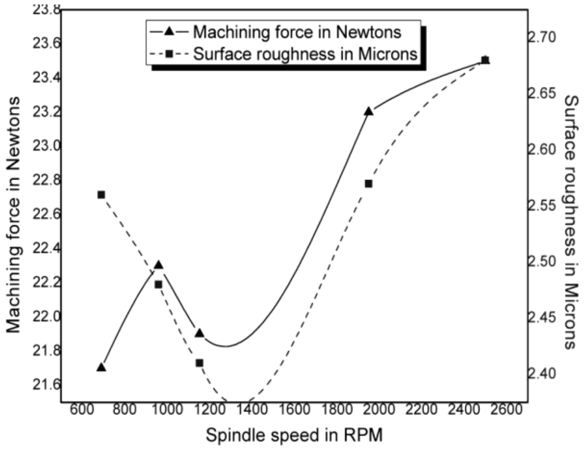

Figure 3 (b). The effect of a spindle speed on the surface roughness and machining force when the feed rate is 2 mm/s

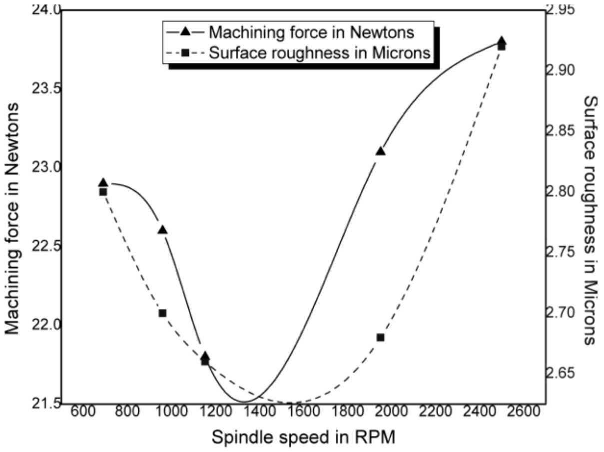

Figure 3 (c). The effect of the spindle speed on the surface roughness and machining force when feed rate is 3 mm/s

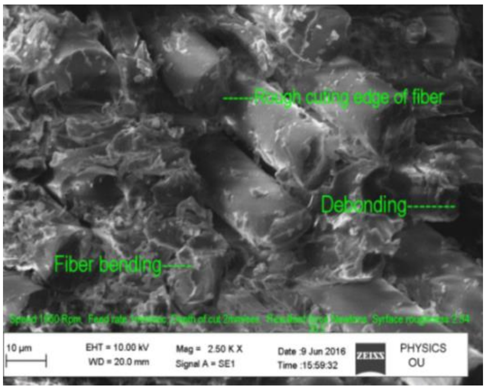

Figure 4 (a). SEM image, when the spindle speed is 1950 rpm and the feed rate is 1 mm/s

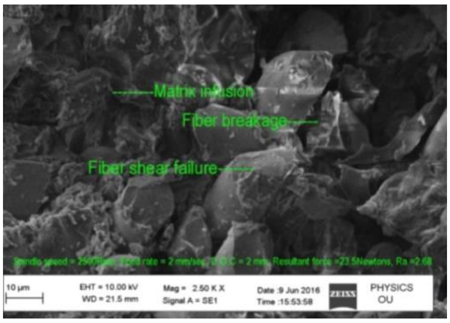

Figure 4 (b). SEM image, when the spindle speed is 2500 rpm and the feed rate is 2 mm/s

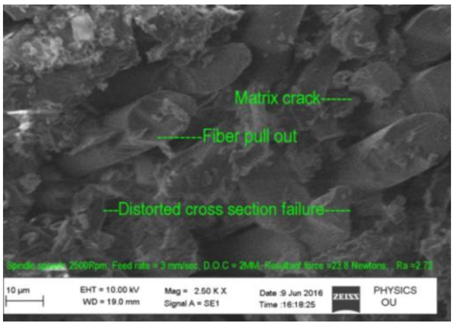

Figure 4 (c). SEM image, when the spindle speed is 2500 rpm and the feed rate is 3 mm/s

Figures 5 (a) and (b), show the SEM micrographic area of machined slot. The specimens were machined at spindle speeds of 690 and 960 rpm and the feed rate is 1 mm/s which concludes the cutting of fibers become smooth, free from cracks and no notable damage was found on the machined slot. Consequently, the experimental runs from 7 to 9 were conducted as usual (as shown in Table 2) and no more distinct results were found as 1 to 6 and 10 to 15 trial runs.

Two different sets of experiments were conducted (trials numbers 10 to 15 in Table 2) and the results were depicted in Table 3, there were three specimens machined at a spindle speed of 1950 and 2500 rpm, the feed rate was 2 and 3 mm/s and depth of cut was constant as 3 mm for all experiments.

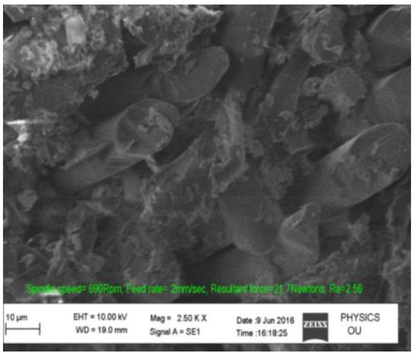

Figure 5 (a). SEM image, when the spindle speed is 690 rpm and the feed rate is 2 mm/s

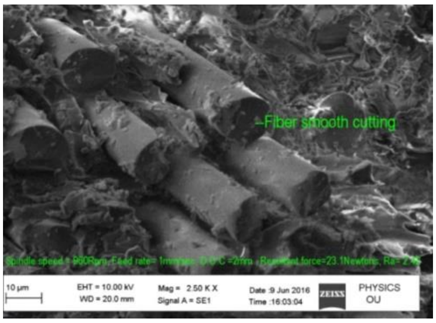

Figure 5 (b). SEM image, when the spindle speed is 960 rpm and the feed rate is 1 mm/s

At this stage the machining forces were maximized (23.5 and 23.8 N) and thereby induced surface roughness (2.68 and 2.92 µm) and damage factor (1.19 and 1.25) were maximized.

Significantly, the visibility of damages on three machined laminates was clearly examined by SEM Figures 4 (a), (b) and (c). Figure 4 (a) shows the details of fiber bending, de-bonding and rough cutting on fibers at a spindle speed of 1950 rpm and the feed rate of 1 mm/s. Figure 4(b) shows the details of matrix infusion, fiber breakage and fiber shear failure at a spindle speed of 2500 rpm and the feed rate is 2 mm/s. Figure 4 (c) displays the details of matrix crack, negative fiber pull out and distorted cross section failure, when the spindle speed is 2500 rpm and the feed rate is 3 mm/s.

The influence of spindle speed at three different feed rates on machining force and surface roughness is clearly illustrated in Figures 3 (a), (b) and (c). In general cutting force increases with increasing the spindle speed. The high machining force of 23.8 N was noticed at a spindle speed of 2500 rpm. At this denture highest value of the surface roughness of 2.92 µm and damage factor of 1.25 is presented. It is noticed from experimental results that where the spindle speed is maximum, the cutting force will be maximized and there is a possibility of surface damages on machined slot.

From the previous researcher Sakma and Seto [18] found that when the feed rate is increased, the friction is created between tool and workpiece, consequently the surface damages increases. The experimental evaluation from Table 3 and tribological properties of workpieces is clearly illustrated in SEM Figures 4(a), (b) and (c). When the feed rate increases from 2 to 3 mm/s, the machining force (23.8 N) and surface roughness (2.92 µm) are increased. At this stage, compressive force exerted by the tool cutting edge compels the chip to bend upwards (fiber bending) and leading to a fiber peeled up, and it was substantiated from SEM Figure 4 (a). There is a possibility of machining vibrations which tends to damage the top layer of machined surface. Subsequently more cracks (matrix infusion, matrix crack) are formed on the machined surface due to the ability of brittleness of matrix material, and it can be seen from SEM Figures 4(b) and 4(c).

4. CONCLUSIONS

The effect and critical analysis of milling process parameters on the surface quality of GFRP composite laminates was thoroughly conducted with a designed carbide end mill tool. The machined surface integrity was evaluated by interference plots and SEM micrographs and the following conclusions were made:

1. From the interaction graphs and SEM micrographic observations, it is found that the optimized milling process parameters are spindle speed of 690 rpm and the feed rate of 1 mm/s. Hence the induced surface roughness and damage factor are minimized as 2.32 μm and 1.18, where the surface quality was better.

2. The following data were observed from the values of spindle speed and the feed rates beyond the optimum levels:

a. The machining force on composites increases with increased spindle speed from 1153 to 2500 rpm and the feed rate from 2 to 3 mm/s, where the machined slot produces more surface damages.

b. From the SEM observations it is found that the surface roughness and damage factor increases with increasing the spindle speed and the feed rate, where the surface failure mechanism is dominated.

c. The machining force, surface roughness and damage factor are significantly influenced by the spindle speed followed by the feed rate.

3. The interaction effect between the spindle speed and machining force is highly influenced by machinability characterization when compared with other interactions.

4. The machined surface quality of composites is highly influenced by the spindle speed and followed by the feed rate.

5. From the results of experimentation, it is evident that the machinability of GFRP composites is strongly dependent on the machining force as the intermediate factor.

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RESEARCH NOTE

I. S. N. V. R. Prasanth[a], D. V. Ravishankar[b], M. Manzoor Hussain[c]

[a] *Department of Mechanical Engineering, St Mary's integrated campus, JNTU, Hyderabad, India*
[b] *Department of Mechanical Engineering, T.K.R.CET, JNTU,Hyderabad, India*
[c] *Department of Mechanical Engineering, J.N.T.U Hyderabad, India*

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چکیده

فرزکاری کامپوزیت‌های پلیمری تقویت شده برای تولید کامپوزیت‌های یکپارچه با سایر قطعات بسیار مهم است. انتخاب نامناسب پارامترهای فرآیند برش، نیروهای برش بیش از حد و سایر شرایط ماشینکاری منجر به رد اجزاء می شود. بنابراین، شرایط ماشینکاری برای کاهش نیروهای ماشینکاری و آسیب رساندن بهینه‌سازی شده است. دراین پژوهش اثر شرایط ماشینکاری بر روی نیروی برشی، زبری سطح و عامل آسیب فیزیکی ترکیبات پلیمری فایبر گلاس (GFRP) بررسی شده است. آزمایشها با استفاده از یک ابزار تصادفی کاربید طراحی شده با استفاده از مجموعه تصادفی از پارامترهای فرایند انجام شد. نتایج نشان داد که یکپارچگی سطح ماشین به شدت تحت تاثیر سرعت چرخش و نرخ تغذیه است. نتایج آزمایش ها با استفاده از نمودارهای تعاملی و تصاویر میکروسکوپ الکترونی اسکن (SEM) تجزیه و تحلیل شد.

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