Parametric Study on Grindability of GFRP Laminates Using Different Abrasives

P. Chockalingam, C. K. Kok, T. R. Vijayaram

***Abstract*—**A study on grindability of chopped strand mat glass fiber reinforced polymer laminates (CSM GFRP) have been carried out to evaluate the significant parameters on wheel performance. Performance of Aluminum oxide and c-BN wheels during grinding of CSM GFRP laminate was evaluated in terms of grinding force and surface roughness during grinding. The cubic Boron Nitride wheel experiences higher tangential grinding forces components and lower normal force component than Aluminum oxide grinding wheels. In case of surface finish, Aluminum oxide grinding wheels outdo the cubic Boron Nitride grinding wheels.

***Keywords*—**Grinding, glass fiber reinforced polymer laminates, grinding force, surface finish.

I. Introduction

GRINDING is one of the oldest and most common method for producing accuracy and fine surface finish on materials. Rapid development in the manufacturing industry demands efficient machining process. One of the major limiting factors in grinding production rates is surface finish. Poor surface finish can be reduced by the application of a cutting fluid that removes the friction and heat from the two surfaces [1]. The material removals by finishing process generate forces, which might have effects on the surface finish of the workpiece [2]. For this reason, many research works have been carried out to optimize the ground surface integrity and stock removal.

GFRP composites are stiff and stronger, used for applications where, weight, strength and volume are critical, for example, in automotive and marine applications. CFRP and GFRP composite laminates are by far the most commonly fiber reinforced composite materials used in many industries in view of their high mechanical properties. They are formed by the combination of fibers (carbon or glass) and polymer matrix [3]. GFRP composite laminates are used in fairings, storage room doors, landing gear doors, and passenger compartments, wing boxes, horizontal stabilizers, vertical stabilizers, and wing panels [4].

Grinding process is usually used to meet the required specifications on geometrical, dimensional and surface quality on workpiece [5]. Cubic Boron Nitride grinding wheels have been widely used in high efficiency and high precision grinding [6], [7]. Tonshoff et al. [8] reported that grinding with c-BN wheel provides lower grinding temperatures resulting in lesser thermal damages and undesirable residual stresses.

The ground surface roughness and hardening are mainly controlled by the grinding conditions, i.e. depth of cut, feed, and speed [9]. An overview of the process parameters used to optimize the ground surface quality in the literature shows that the types of workpiece material, the grinding conditions and the grinding wheel specifications [10]. The main purposes of a grinding fluid can be categorized into lubrication, cooling, transportation of chips, cleaning of the grinding wheel and the corrosion reduction [11]. Brahim et al. [12] observed that surface roughness characteristics are increased sharply with increase of depth of cut using alumina grinding wheels. Increasing the cutting speed at constant feed rate reduced the average chip thickness and length thereby decreasing the total grinding forces. Other hand, increasing the feed rate, results in higher chip thickness and lengths, and thus, an increase of grinding forces. Increasing depth of cut increases grinding forces and thermal stresses [13].

II. Materials and Methods

A. Machine, Material, and Wheel

The grinding process was carried out using a vertical spindle CNC (Mazak) machining centre. Fig. 1 shows the machine setup for the grinding process. Chopped strand mat glass fiber [14] (CSM 450 R-glass fiber) and unsaturated polyester (Reesol P9509) glass fiber reinforced polymer laminate have been used as work-piece materials in this investigation. This Chopped strand mat glass fiber laminate has maximum strength and stiffness along all directions. The chemical, physical and mechanical property of material is given in Table I. The laminate specimens of size of 50mm x 15mm x 10mm were cut from a plate of 250mm x 250mm x 10mm and the grinding was performed on 50mm x 10mm face. The experimental has been planned as central composite design with default alpha points with 8 cube points, 4 alpha points and 1 centre point as given in Fig. 2. The central composite design will represent the entire experimental design space and useful to understand the interaction effects of factors in the design space. The cutting speed used in the design space in the range of 2980 rpm to 8025 rpm, feed rate of 830 mm/min to 1670 mm/min and depth of cut of 0.17 to 0.33mm. The grinding process was carried out using pink aluminum oxide (PA46QV), orange aluminum oxide

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(OA46QV) and c-BN (B46QV) profile mounted wheels. The size of the wheel is 25mm diameter x 19mm length x 6mm mandrel. The grinding experiments were carried out with water based emulsion (5%) coolant.

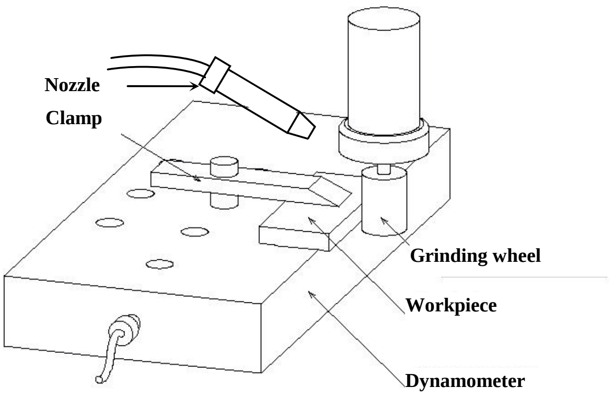

Fig. 1 Experimental set-up

TABLE I
PROPERTIES OF GFRP COMPOSITE

Tensile strength	80-90 MPa
Tensile modulus	1.55 – 1.65 GPa
Density	1600 kg/m^3
Hardness	53-56 HRB
Elongation at break	5.5-5.7 mm
Coefficient of thermal expansion	5.3-7.5 x 10^{-6} K^{-1}

B. Force and Surface Roughness Measurement

Grinding force was measured using Kistler 9257BA type dynamometer and recorded with the help of DWETRON software. The data's are recorded at the rate of 100sample/sec. The ground surface roughness has been measured using MAHR Perthometer S2 PGK surface roughness tester measuring instrument. The resolution of the equipment is ±25μm and repeatability is 5%. The experimental design table and measured responses are given in Table II.

III. Results and Discussion

The rate of grinding operation carried out depends on the power which is applied in the process and material removal rate. Basically a sharp abrasive particles and effective coolant will reduce the forces and energy required. In this study, the influence of forces, and surface roughness carried out to increase the grinding rate. In grinding, two important forces acts between abrasive and workpiece. They are tangential force, Fy and normal force, Fx.

In empirical relationship of grinding behaviour with basic grinding process parameters, was observed that either grinding forces (normal or tangential), F, can be approximated by a power function such that

$$F = ch_{eq}{}^{f} \tag{1}$$

where, c and f are empirical constants [5]. Where, equivalent chip thickness, h_{eq}, is defined as

$$h_{eq} = a_e \frac{v_w}{v_s} \tag{2}$$

where, a_e is the depth of cut, v_w is the feed, and v_s is the wheel speed.

A. Observation on Grinding Force

Grinding experiments have been carried out with pink aluminum oxide, orange aluminum oxide wheel and c-BN wheel. Relative parametric influence on normal (Fx) and tangential components (Fy) of grinding force for all three wheels are illustrated in Figs. 3 and 4, respectively. Higher order of forces recorded for P-Al_2O_3, followed by O- Al_2O_3 and c-BN wheels. Higher forces are results of abrasive grain flattening.

1. Effect of Speed

A significant effect of speed on cutting forces is observed in this work. At constant low feed, as speed is varied from low to high (i.e. runs 1 to 2), grinding with all the three wheels namely pink aluminum oxide, orange aluminum oxide and c-BN grinding wheel, shows decrease in forces due to average chip formation factors are reduced. An increase of depth of cut increases grinding forces for P-Al_2O_3 wheel and c-BN wheel. On the contrary, there is a decrease in normal and tangential grinding force observed for O-Al_2O_3 grinding wheel, regardless of depth of cut.

At high feed rate, increasing wheel speed results in decreased the tangential force for all grinding conditions except for O-Al_2O_3 grinding at low depth of cut. Normal forces increasing for P-$Al_2O_3$and O-Al_2O_3 but for c-BN it is decreased. At higher depth of cuts normal forces decreased for all three grinding wheel.

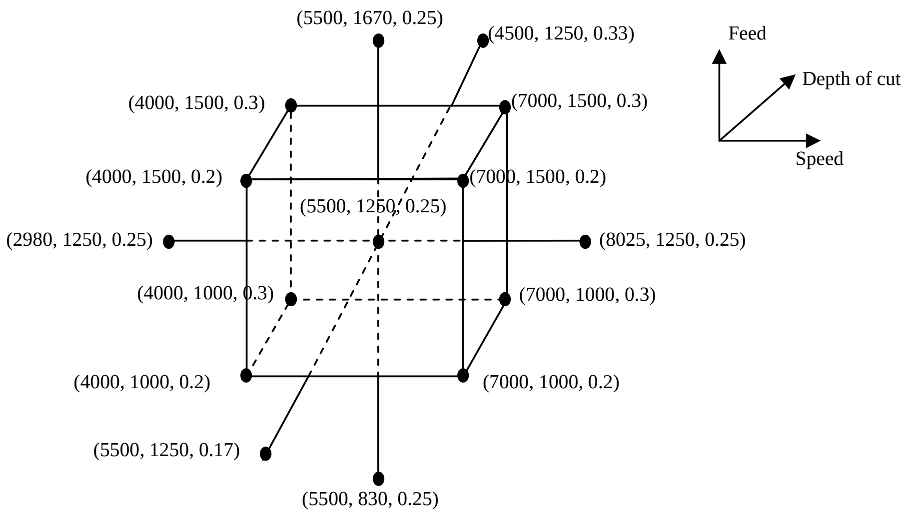

Fig. 2 Experimental design space with selected parameters

TABLE II
EXPERIMENTAL DESIGN TABLE WITH MEASURED RESPONSE

Run	Speed	Feed	Depth of cut	Normal force, Fx (N)			Tangential force, Fy (N)			Surface roughness, Ra (µm)		
	rpm	mm/min	mm	Pink	Orange	c-BN	Pink	Orange	c-BN	Pink	Orange	c-BN
1	4000	1000	0.2	94.28	94.77	91.85	24.18	26.63	31.51	0.82	0.87	1.13
2	7000	1000	0.2	76.70	60.34	78.40	23.20	15.14	21.99	0.87	0.609	0.90
3	4000	1500	0.2	126.08	76.70	66.68	34.69	20.03	33.95	1.04	0.90	1.45
4	7000	1500	0.2	140.40	88.42	58.38	32.49	22.22	25.89	1.06	1.07	0.90
5	4000	1000	0.3	50.07	122.86	84.27	11.97	23.70	27.11	1.07	0.94	0.83
6	7000	1000	0.3	122.84	51.29	102.58	30.05	18.81	22.47	0.96	0.89	0.86
7	4000	1500	0.3	116.56	160.92	156.36	34.93	29.07	38.59	1.07	1.02	0.90
8	7000	1500	0.3	107.71	113.34	129.19	30.28	22.72	27.35	0.95	0.96	0.88
9	2980	1250	0.25	206.40	174.87	141.21	58.62	32.24	34.69	1.08	0.90	0.99
10	8025	1250	0.25	86.96	77.92	93.06	23.44	19.30	25.16	1.09	0.93	0.83
11	5500	830	0.25	113.09	71.564	206.93	29.31	20.03	43.47	1.03	0.80	0.82
12	5500	1670	0.25	150.73	105.74	120.69	40.30	23.70	31.26	1.12	1.18	1.15
13	5500	1250	0.17	104.06	98.44	108.21	30.53	22.96	27.11	0.93	0.81	0.85
14	5500	1250	0.33	161.18	107.25	124.38	39.33	24.67	28.82	1.19	1.13	0.94
15	5500	1250	0.25	37.86	60.82	71.57	15.14	18.32	24.18	0.98	0.83	1.10

2. Effect of Feed

Increasing the feed, increasing the material removal rate and generate significantly higher order of both forces. At constant low speed, as feed is increased (i.e. runs 1 to 3), P-Al_2O_3 grinding shows increased normal and tangential forces due to higher undeformed chip thickness (18% higher) and increased material removal rate. P-Al_2O_3 abrasive grains flatten quickly and sliding over the surface increases the grinding forces. However, grinding with O-Al_2O_3 shows marginal reduction in normal force and tangential force. But, CBN grinding, recorded lower normal and higher tangential forces. Sharper abrasive grains cutting the material effectively cut the material and reduced the forces.

At higher depth of cut (i.e. runs 5 to 7) and increasing feed, similar observations can be made on P-Al_2O_3. Contrary to previous observation, grinding with O-Al_2O_3 and c-BN grinding shows an increase in the normal force and tangential force with increased feed because higher depth of cut leads to more cutting and more material removal. At constant high speed with feed varied from low to high (i.e. runs 2 to 4), P-Al_2O_3 grinding shows increased normal and tangential forces. This is because high feed contributes to increased cutting and high speed leads to more rubbing. Similar trend happens to grinding in O-Al_2O_3 grinding. However, CBN grinding cut the material effortlessly and shows decrease in normal force and increase in tangential force. At higher depth of cuts, (i.e. runs 6 to 8) grinding with O-Al_2O_3 shows higher normal forces and higher tangential forces.

Figs. 5 (a) and (b) show the normal and tangential forces in the case of constant middle speed and middle depth of cut. Varying speed from lowest level to highest level (i.e. DOE run 9 to 10) both normal and tangential forces decreasing for all three grindings. Varying feed from lowest level to highest level (i.e. DOE run 11 to 12) increases force level for all grinding conditions except c-BN grinding.

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Nomenclature

Fx :	Radial force	HtS:	Highest speed
Fy:	Tangential force	LtS:	Lowest speed
LS:	Low speed	HtF:	Highest feed
HS:	High speed	LtF:	Lowest feed
LF:	Low feed	HtD:	Highest depth of cut
HF:	High feed	LtD:	Lowest depth of cut
MS:	Medium speed	MD:	Medium depth of cut
MF:	Medium feed		

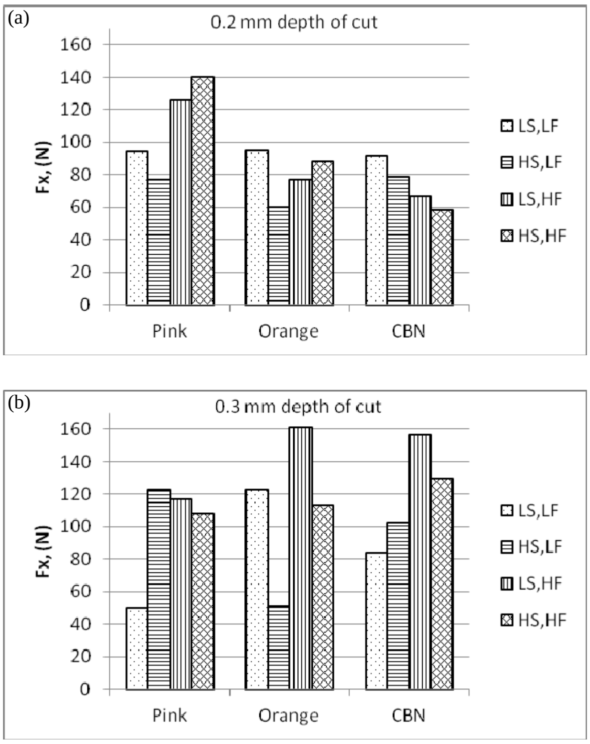

Fig. 3 Parametric influence on normal force (Fx) compared between pink, orange aluminum oxide and c-BN grinding wheels with high and low values of speed and feed; (a) 0.2mm depth of cut, (b) 0.3 mm depth of cut

3. Effect of Depth of Cut

Figs. 6 (a) and (b) show that as depth of cut is increased from lowest level to highest level (i.e. runs 13 to 15), normal and tangential forces increase due to increased undeformed chip thickness for all three grinding conditions. At middle, speed, feed and depth of cut (i.e. run 15), however, contact sliding and subdue cutting, resulting in lower forces for grinding.

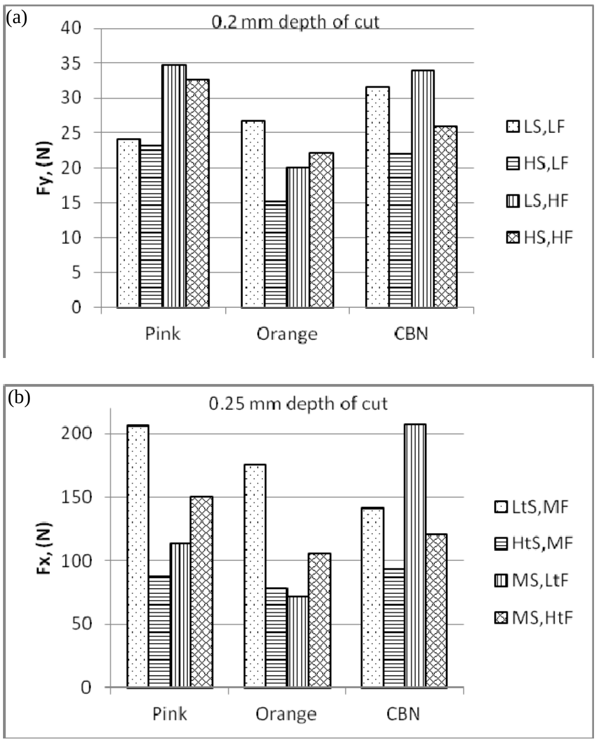

Fig. 4 Parametric influence on tangential force (Fy) compared between pink, orange aluminum oxide and CBN grinding wheels with high and low values of speed and feed (a) 0.2mm depth of cut, (b) 0.3 mm depth of cut

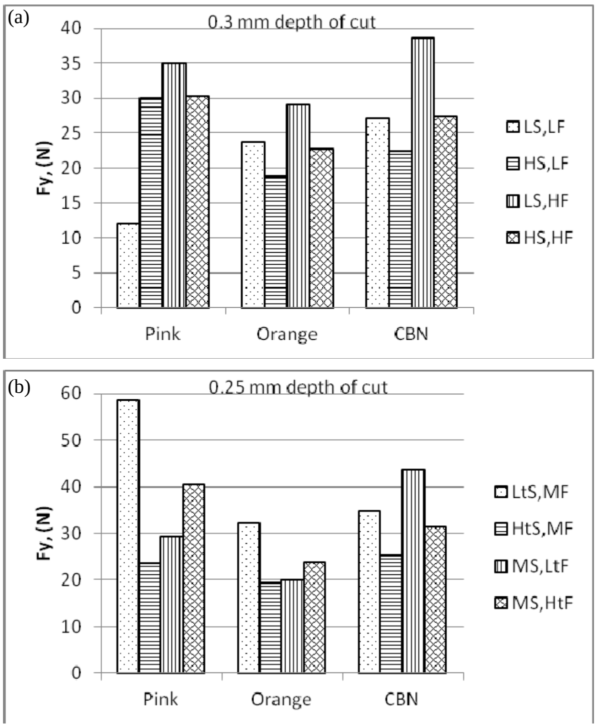

Fig. 5 Parametric influence on forces compared between P-Al_2O_3 and O-Al_2O_3, and c-BN grinding wheels with lowest and highest speed and feed; (a) Normal force, Fx, (b) Tangential force, Fy

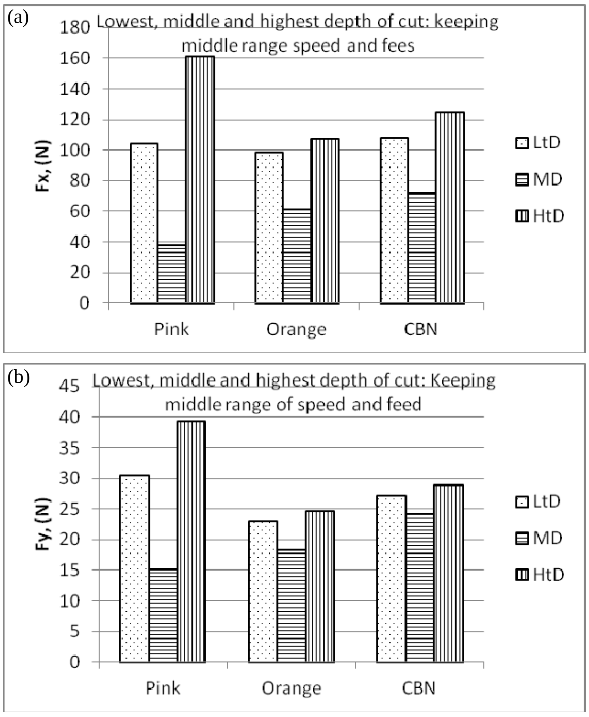

Fig. 6 Effect due to depth of cut; (a) normal force (b) tangential force

B. Observation on Surface Finish

The influence of cutting speed on the surface finish during machining of CSM GFRP using different grinding wheel at designed parameters with combination of speed, feed and depth of cut is shown in Fig. 7. The ground surface roughness is characterised by average surface roughness, Ra (µm). From the experimental results, it is concluded that the grain flattening effects in the Al_2O_3 grinding wheels produces lower surface roughness. However, for c-BN, grinding wheels micro-fracture acts as a new cutting edge produces higher surface roughness at lower depth of cuts.

Empirically relating surface roughness to the grinding parameters is to assume a direct correlation with the equivalent chip thickness, which, as suggested by Malkin;

$$Ra = c_3 h_e^{\,x}$$

where R_a is the average roughness, and C_3 and x are coefficients. According to this equation the depth of cut and feed have the same effect on roughness.

1. Effect of speed

Generally, for all grinding conditions, increase in speed produces a significant variation in the surface roughness. At low feed and 0.2mm depth of cut, increasing grinding speed (i.e. runs 1 to 2) decreases surface roughness in all three grinding. Indeed, surface roughness, increases sharply with the increase of depth of cut. With feed maintained and the depth of cut increased to 0.3mm (i.e. runs 5 to 6), a similar trend is observed except for c-BN grinding.

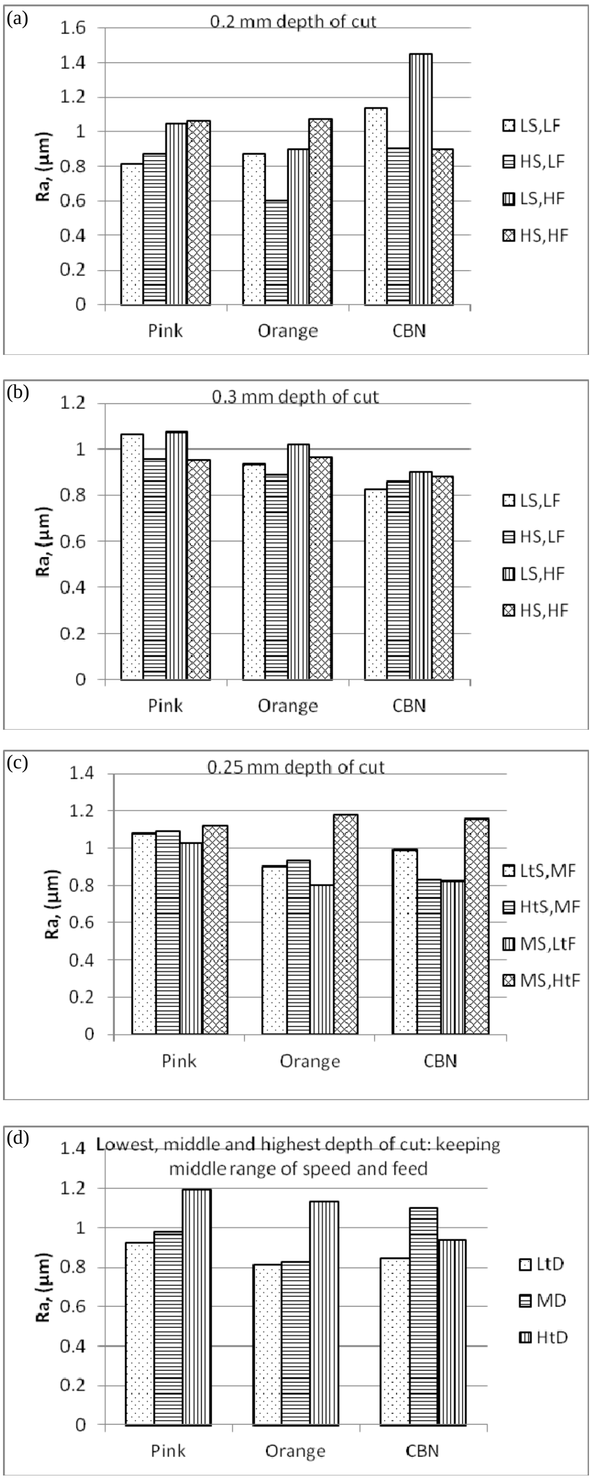

Fig. 7 Parametric influence on surface finish compared between P-Al_2O_3 and O-Al_2O_3, and c-BN grinding wheels (a)0.2 mm depth of cut (b) 0.3mm depth of cut (c) 0.25 mm depth of cut (d) lowest, highest and middle depth of cut

At high feed and 0.2mm depth of cut (i.e. runs 3 to 4) surface roughness value increased for Al_2O_3 wheel however for c-BN grinding shows lower surface roughness. At high feed (i.e. runs 7 to 8), 0.3mm depth of cut, increasing wheel speed reduce the surface roughness.

2. Effect of feed

It is evident from Fig. 7 that a significant increase in the surface roughness value when feed is increased. Basically excessive forces acting on surface produced lower surface roughness. Regardless of the depth of cut, at constant low speed, as feed is increased from low to high (i.e. runs 1 to 3), surface roughness increases for all three grinding condition.

At constant high speed, as feed is varied from low to high (i.e. runs 2 to 4 and 6 to 8), abrasive particles cut the material at high speed in dry grinding, leaving scratch marks on the material, which increases its surface roughness, except for c-BN grinding.

Under similar conditions, grinding in synthetic coolant marginally reduces surface roughness due to reduced friction effect while grinding in emulsion coolant results in slightly higher surface roughness due to less lubrication effect than in synthetic coolant. Similar observations can be made for dry grinding at higher depth of cut; whereas for wet grinding marginal variations in surface roughness remain.

At middle range of middle feed and depth of cut, varying speed from lowest to highest (i.e. run 9 to 10) leads to increase in surface roughness except for c-BN grinding. At middle range of middle speed and depth of cut, varying feed from lowest to highest (i.e. run 11 to 12) leads to increase in roughness values for all grinding conditions due to increased cutting and smoothing by abrasive grains.

3. Effect of depth of cut

Fig. 7 shows variation of surface roughness, Ra on depth of cut. At constant middle range of speed and feed, as depth of cut is increased from lowest level to highest level (i.e. runs 13 to 15) surface roughness is increased for Aluminum oxide grinding but decreased for c-BN grinding.

IV. Conclusion

In this work the effects of abrasive types, grinding wheel speed, feed and depth of cut on surface roughness and cutting forces on the grindability of chopped strand mat glass fiber reinforced polymer laminates were investigated. Within the experimental trials conducted in this research work, indicate that grinding with c-BN wheel experience relatively higher order tangential grinding force components and lower order normal grinding force components. Comparative study on the performance of Al_2O_3 girding wheels and c-BN grinding wheels indicate better performance of O-Al_2O_3 wheel in terms of surface finish in the regime of high speed, low feed and low speed high feed conditions. C-BN grinding wheels shows better performance at high depth of condition of all possible experimental conditions with relatively smooth texture, compared to surface ground with Al_2O_3 wheel. As a whole, c-BN wheel performed better than Al_2O_3 wheel.

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