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# Effect of Coolant on Cutting Forces and Surface Roughness in Grinding of CSM GFRP

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***Abstract*****—**This paper presents a comparative study on dry and wet grinding through experimental investigation in the grinding of CSM glass fibre reinforced polymer laminates using a pink aluminium oxide wheel. Different sets of experiments were performed to study the effects of the independent grinding parameters such as grinding wheel speed, feed and depth of cut on dependent performance criteria such as cutting forces and surface finish. Experimental conditions were laid out using design of experiment central composite design. An effective coolant was sought in this study to minimise cutting forces and surface roughness for GFRP laminates grinding. Test results showed that the use of coolants reduces surface roughness, although not necessarily the cutting forces. These research findings provide useful economic machining solution in terms of optimized grinding conditions for grinding CSM GFRP.

***Keywords*****—**Chopped Strand Mat GFRP laminates, Dry and Wet Grinding, Cutting Forces, Surface Finish.

## I. Introduction

THE modern industries have expanded the demand for machining advanced composite materials, irrespective of their hardness, toughness and microstructure, to develop sophisticated products of high precision, high speed, high temperature resistance, wear resistance and low weight, etc. Fibre reinforced polymer is rapidly replacing conventional materials in automotive, marine and aerospace industries. Although drilling and turning are the major machining processes required to produce near-net shape in composites, grinding is particularly necessary to produce high dimensional accuracy for assembly tolerance and excellent surface finish [1-4]**.** However, the fibre particles reinforced in GFRP often pose problems during machining.

The presence of these particles causes rapid tool wear and intermittent cutting forces during machining. Grinding of fibre reinforced polymer composites causes more wear of the wheel compared to that of conventional material. This is due to the heterogeneous property of the material, which in turn leads to variable forces exerted on the grinding wheel. Grinding process requires the largest amount of energy among machining processes for removing a volume of material. Most energy is converted into heat and friction by cutting and rubbing. During grinding cutting edges such as blunt abrasive particles can result in the formation of poor surface finish [5]. Malkin et al [6] reported that, high temperatures in grinding affect work piece quality and productivity.

One common way to protect the work piece and grinding wheel in grinding is by the use of coolant. Cooling is achieved by the application of a cooling and lubricating fluid, as well as by selecting process parameters that reduce heat generation [7]. Choi et al [8] reported that surface roughness was better when grinding took place in the presence of coolant than in compressed cold air. In agreement with this finding, Aurich et al [9] concluded that dry grinding led to higher work piece temperatures and a higher alteration of surface layers in comparison to wet grinding. In addition, they reported that better process behaviours, namely lower grinding power by up to 40% and lower work piece temperatures, may result from wet grinding using wheel with defined pattern. Although higher work piece temperature improves the grindability of the material and decreases process forces and power, it degrades the surface quality. Therefore, many researches were directed at reducing grinding temperature and forces, and improving surface quality by optimizing of the grinding variables. One such effort by Anne et al [10] indicated that feed rate, depth of cut, and grit size are significant parameters which affect the surface integrity of silicon carbide during grinding. The heterogeneous property of composites further complicates the search for optimum grinding conditions for best surface quality. This is confirmed by N.S. Hu et al [4], who reported that the longitudinal surface roughness of ground multidirectional composites varied strongly with the local fibre orientations. In view of the present findings, the effectiveness of coolant in reducing work piece surface roughness of CMS GFRP under varying grinding parameters need to be investigated. Despite the extensive researches, the dynamic mechanics of a grinding process is highly non-linear and very complicated, and the process itself remains insufficiently understood. Grinding wheel wear, performance of the equipment, accuracy and quality of work piece are greatly influenced by grinding forces. Today, it is generally accepted that grinding forces comprise chip formation force, frictional force and ploughing force induced respectively by cutting, rubbing and ploughing actions. These forces are highly dependent on process parameters, so much so that the co-efficient of friction can vary from 0.27 to 0.86 [11]. The relationship of grinding force and surface roughness is further confounded in the presence of coolant. Monici et al [12], for example, reported that reduction of tangential cutting force could be achieved with the use of neat oil. The grinding forces, to a vast extent, affect the machined surface roughness, the work hardening, the power consumption, the heat flux at the contact zone between the abrasive wheel and the work piece, the gradient residual stresses, the surface defects as well as the wear of the abrasive grains [13]. Grinding, if not done correctly, can lead to surface damage to the work material and unsatisfactory process economics due to inadequate removal rates and/or excessive wheel wear. Therefore, a study of the effect of coolant on grinding forces at varying process parameters in grinding CSM GFRP is warranted. This is the main objective of the current research.

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## II. Experimentation

### *A. Experimental Conditions*

A central composite design with default alpha was used to produce the experimental design of grinding process with three controllable process factors: speed, feed and depth of cut, with and without coolant. Thus 15 experimental runs were needed. Table I indicates the grinding process parameters and their levels.

The independent parameter values are chosen based on machine and grinding wheel specifications. The experimental design of grinding conditions is and measured values are summarized in Table II.

TABLE I
PROPERTIES OF GFRP COMPOSITE

| Parameters | Lowest | Low | Centre | High | Highest |
|---|---|---|---|---|---|
| Speed, (rpm) | 2980 | 4000 | 5500 | 7000 | 8025 |
| Feed, (mm/min) | 830 | 1000 | 1250 | 1500 | 1670 |
| Depth of cut, (mm) | 0.17 | 0.2 | 0.25 | 0.3 | 0.33 |

TABLE II
EXPERIMENTAL TABLE WITH MEASURED RESPONSES

| No | Speed (rpm) | Feed (mm/ min) | Depth of cut, (mm) | Normal force, Fx (N) | | | Tangential force, Fy (N) | | | Grinding force ratio, µ | | | Surface roughness, Ra (µm) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Dry | Syn | Emu | Dry | Syn | Emu | Dry | Syn | Emu | Dry | Syn | Emu |
| 1 | 4000 | 1000 | 0.2 | 50.07 | 74.98 | 94.28 | 21.99 | 23.20 | 24.18 | 0.44 | 0.31 | 0.26 | 3.19 | 0.795 | 0.815 |
| 2 | 7000 | 1000 | 0.2 | 23.21 | 91.35 | 76.70 | 15.14 | 20.77 | 23.20 | 0.65 | 0.23 | 0.30 | 3.694 | 0.731 | 0.872 |
| 3 | 4000 | 1500 | 0.2 | 143.86 | 73.53 | 126.08 | 50.32 | 24.91 | 34.69 | 0.35 | 0.34 | 0.28 | 2.479 | 1.079 | 1.041 |
| 4 | 7000 | 1500 | 0.2 | 42.02 | 104.29 | 140.40 | 19.06 | 23.94 | 32.49 | 0.45 | 0.23 | 0.23 | 3.96 | 0.661 | 1.06 |
| 5 | 4000 | 1000 | 0.3 | 85.98 | 83.29 | 50.07 | 34.68 | 24.91 | 11.97 | 0.40 | 0.30 | 0.24 | 3.819 | 0.94 | 1.065 |
| 6 | 7000 | 1000 | 0.3 | 31.51 | 129.45 | 122.84 | 16.61 | 23.20 | 30.05 | 0.53 | 0.18 | 0.24 | 2.865 | 1.077 | 0.956 |
| 7 | 4000 | 1500 | 0.3 | 99.66 | 92.57 | 116.56 | 36.64 | 24.18 | 34.93 | 0.37 | 0.26 | 0.30 | 2.568 | 1.531 | 1.072 |
| 8 | 7000 | 1500 | 0.3 | 89.16 | 126.73 | 107.71 | 21.01 | 29.31 | 30.28 | 0.24 | 0.23 | 0.28 | 4.808 | 1.012 | 0.951 |
| 9 | 2980 | 1250 | 0.25 | 144.08 | 143.11 | 206.40 | 51.29 | 36.89 | 58.62 | 0.36 | 0.26 | 0.28 | 2.952 | 1.138 | 1.079 |
| 10 | 8025 | 1250 | 0.25 | 26.87 | 103.28 | 86.96 | 16.13 | 24.18 | 23.44 | 0.60 | 0.23 | 0.27 | 2.786 | 1.137 | 1.09 |
| 11 | 5500 | 830 | 0.25 | 48.12 | 112.35 | 113.09 | 25.64 | 24.92 | 29.31 | 0.53 | 0.22 | 0.26 | 2.791 | 0.92 | 1.027 |
| 12 | 5500 | 1670 | 0.25 | 146.29 | 128.98 | 150.73 | 35.66 | 31.99 | 40.30 | 0.24 | 0.25 | 0.27 | 3.382 | 1.129 | 1.118 |
| 13 | 5500 | 1250 | 0.17 | 37.86 | 64.97 | 104.06 | 22.71 | 21.01 | 30.53 | 0.60 | 0.32 | 0.29 | 3.226 | 1.233 | 0.925 |
| 14 | 5500 | 1250 | 0.33 | 133.34 | 113.35 | 161.18 | 29.55 | 28.09 | 39.33 | 0.22 | 0.25 | 0.24 | 2.404 | 1.004 | 1.192 |
| 15 | 5500 | 1250 | 0.25 | 59.09 | 90.38 | 37.86 | 27.60 | 20.03 | 15.14 | 0.47 | 0.22 | 0.40 | 4.154 | 1.126 | 0.978 |

Nomenclature:

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

### *B. Machine, Material and Grinding Wheel*

Grinding was carried out using a vertical spindle CNC (Mazak) machining centre. Fig. 1 shows the experimental setup for the grinding tool. Glass fibre reinforced polymer composite made of Chopped strand mat glass fibre [14] (CSM 450 R-glass fibre) and unsaturated polyester (Reesol P9509) was taken as work-piece materials for the present set of experimental investigation. This type of materials is used in marine and automotive applications and manufacturing of chemical containers. The chemical, physical and mechanical property of the material is given in Table 3. The composite specimens of size of 50 mm x 15 mm x 10 mm were cut from a plate of 250 mm x 250 mm x 10 mm, and grinding was performed on the 50 mm x 10 mm face. The experimental test has been conducted with cutting speed range of 2980 rpm to 8025 rpm, feed rate between 830 mm/min to 1670 mm/min and depth of cut between 0.17 and 0.33 mm. The grinding process was carried out using a pink aluminium oxide profile mounted wheel (PA46QV), 25 mm diameter x 19 mm length x

6 mm mandrel. Dry and wet grinding were conducted, the latter with synthetic and emulsion coolants.

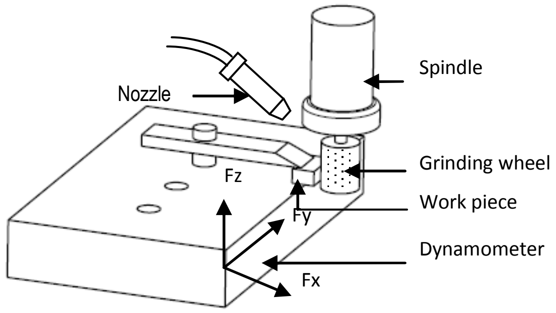


Fig. 1 Experimental set-up

TABLE III
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$^{-1}$ |

*C. Coolant*

The properties of commercial coolants used in this research, Yushiroken SC95 and Aeroil cutting oil emulsion are listed in Table 4.

TABLE IV
PROPERTIES OF COOLANT

| | | |
|---|---|---|
| Name | Yushiroken SC95 | Koolcut C-300 |
| Type | Synthetic 5% | Emulsion 5% |
| Colour | Light yellow transparent | Clear amber liquid |

*D. Force and surface Roughness Measurement*

Grinding force was measured using Kistler 9257BA type dynamometer and recorded with the help of DWETRON software. The ground surface roughness was measured using MAHR Perthometer surface roughness measuring instrument.

## III. RESULTS AND DISCUSSION

The experimental results of dry and wet grinding, cutting force and surface roughness were analysed for the optimal grinding conditions of CMS GFRP. The calculated force ratio values are given in Table I. The results of the measured forces and surface roughness values are shown in Fig. 2 to Fig. 5.

*A. Grinding Force*

It is observed that forces are non-uniform for all three grinding conditions namely dry, synthetic and emulsion grinding. In dry metal grinding, material emerged as a solid extruded sheet has a thickness corresponding to equivalent chip thickness. Equivalent chip thickness, $h_{eq}$, is defined as

$$h_{eq} = a_e \frac{v_w}{v_s} \quad (1)$$

where, $a_e$ is the depth of cut, $v_w$ is the work piece speed (which in this case the feed), and $v_s$ is the wheel speed. In cylindrical plunge grinding, it was observed that either grinding forces (normal or tangential), F, can be approximated by a power function such that

$$F = ch_{eq}{}^{f} \quad (2)$$

where, c and f are empirical constants [5].

This observation on grinding of metal is very much applicable to dry grinding of CSM GFRP in the current study, although not equally applicable to wet grinding.

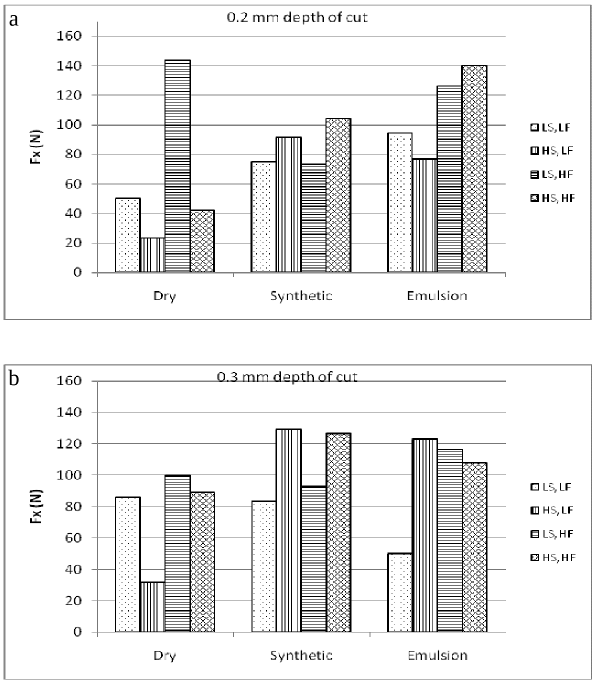


Fig. 2 Normal force, Fx for dry, synthetic and emulsion coolant with high and low values of speed and feed (a) 0.2mm depth of cut, (b) 0.3 mm depth of cut

*1. Effect of Speed*

At constant low feed, as speed is varied from low to high (i.e. DOE runs 1 to 2), dry grinding shows low normal and tangential forces due to lower chip formation, and similar trend is observed for dry grinding at higher depth of cuts. On the contrary, there is a rise in normal grinding force when synthetic coolant is present, regardless of depth of cut. The same is also true for grinding in emulsion coolant except at low feed. Water-based emulsion coolant is more effective in cooling the work piece, but its lower viscosity often translates to its inferior performance in lubrication compared to synthetic oil-based coolant. In this case, as speed is increased, emulsion coolant shows decrease in grinding forces due to the breakdown of lubricant, resulting in an increase of grinding force ratio as rubbing predominates material removal. Grinding force ratio is largely reduced in the presence of synthetic coolant, as higher normal forces related to cutting is achieved at higher speed accompanied by lower tangential force.

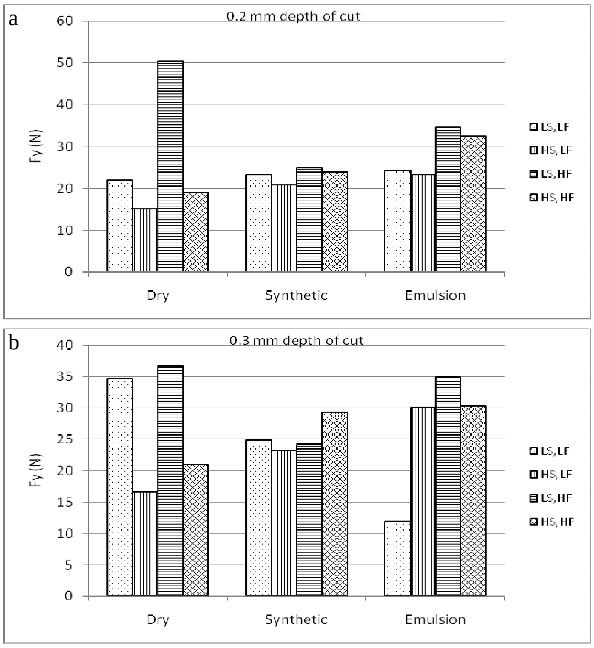


Fig. 3 Tangential forces, Fy for dry, synthetic and emulsion coolant with high and low values of speed and feed (a) 0.2mm depth of cut, (b) 0.3 mm depth of cut

At higher depth of cut, similar observations can be made on dry and wet grinding in synthetic coolant with regard to the effects of increased speed. Grinding in emulsion coolant shows high forces due to reduced lubricating effect and increased grit to work piece contact.

At high feed, increasing wheel speed in dry grinding generally increases the grinding efficiency regardless of the depth of cut. This is because the cutting grains tend to rub over the work piece surface, resulting in less material removal per wheel revolution, and consequently lower grinding forces at greater material removal rate by increased feed. Similar trend happens to grinding in emulsion at high feed and high depth of cut.

It is interesting to note that tangential force in the presence of synthetic coolant does not seem to vary much in most of the experiment runs. At low feed and high depth of cut (i.e. DOE runs 5 & 6), increasing speed increases the normal forces in wet grinding tremendously. This leads to sharp drop of grinding force ratio in the case of synthetic coolant, making the grinding wheel behave like a blunt wheel. The same is not true for emulsion coolant. Except in cases where the lubricating effects of emulsion coolant break down, such as at low feed and high speed, dry grinding and wet grinding in emulsion coolant tend to show similar trend.

Referring to Fig. 4, at constant mid feed and mid depth of cut, varying speed from lowest to highest (i.e. DOE runs 9 & 10) reduced both normal and tangential forces significantly by almost 60% for all three grinding due to reduced undeformed chip thickness.

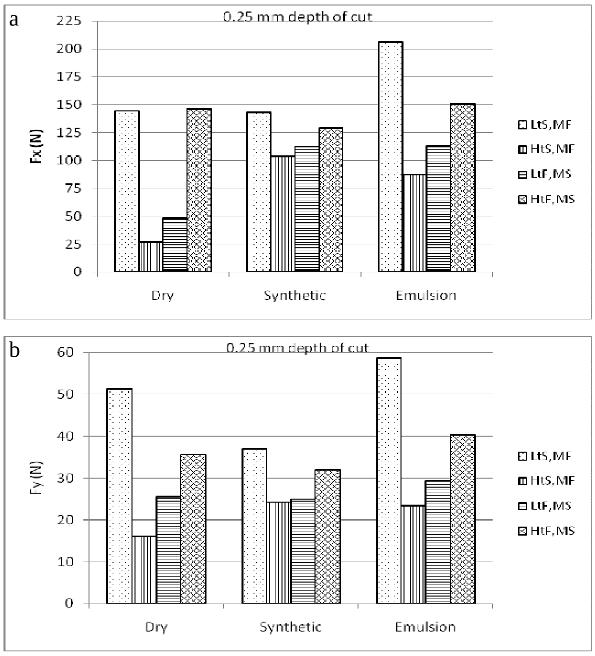


Fig. 4 Grinding forces for dry, synthetic and emulsion coolant at medium depth of cut with lowest and highest speed and feed; (a) Normal force, Fx, (b) Tangential force, Fy.

2. *Effect of Feed*

At constant low speed, as feed is increased (i.e. DOE runs 1 to 3), dry grinding shows increased normal and tangential forces due to higher undeformed chip thickness (18% higher) and increased material removal rate. However, grinding with synthetic coolant shows marginal reduction in normal force and increase in tangential force. This phenomenon indicates that the presence of synthetic coolant between work and wheel has inhibited cutting and promoted rubbing (force ratio increased 3%). Grinding with emulsion coolant recorded higher normal and tangential forces than that with synthetic coolant, but lower forces than dry grinding, indicating possibly a breakdown of lubrication. At higher depth of cut (i.e. DOE runs 5 to 7) and increasing feed, similar observations can be made on dry and grinding with emulsion coolant. Contrary to previous observation, grinding with synthetic coolant at higher depth of cut shows a marginal increase in the normal force and reduction in tangential force with increased feed because higher depth of cut leads to more cutting.

At constant high speed with feed varied from low to high (i.e. DOE runs 2 to 4), dry 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 synthetic coolant and emulsion coolant. However, at higher depth of cuts, grinding with synthetic and emulsion coolants at high speed show lower normal forces and higher tangential force indicating the coolant effect.

Fig. 4a and 4b show the normal and tangential forces in the case of constant middle speed and middle depth of cut. Varying feed from lowest level to highest level (i.e. DOE run11 to 12) increases force level for all grinding conditions due to increased undeformed chip thickness at higher material removal rates.

*3. Effect of depth of cut*

Figure 5a and 5b shows that as depth of cut is increased from lowest level to highest level (i.e. DOE runs 13 to 15), normal and tangential forces increase tremendously due to increased undeformed chip thickness (11%) for all three grinding conditions. At middle, speed, feed and depth of cut (i.e. DOE run 15), however, the presence of coolants tends to promote contact sliding and subdue cutting, resulting in lower forces for grinding in both coolant. This effect of coolant in promoting sliding ceases at high depth of cut.

*B. Surface Finish*

The influence of cutting speed on the surface finish during machining of CSM GFRP using different coolant at designed parameters with combination of speed, feed and depth of cut is shown in Fig. 6.

From the experimental results, it is concluded that during dry grinding, higher speed and higher feed produces poor surface finish among other combinations of experiments. On the contrary, it can be seen that better surface finish is produced at high speed and high feed when grinding with synthetic coolant, and at low depth of cut, low speed and low feed when grinding in emulsion coolant. In general, it can be easily concluded wet grinding, either with synthetic or emulsion coolant, is effective in producing significantly improved surface finish compared to dry grinding.

*1. Effect of speed*

At low feed and 0.2 mm depth of cut, increasing grinding speed (i.e. DOE runs 1 and 2) increases surface roughness in dry grinding due to increased rubbing of the abrasive grains at high wheel speed. On the contrary, under similar grinding condition, surface roughness values decreases slightly in the presence of synthetic coolant due to lubrication effect as grinding force ratio drops to 0.22. Compared to the use of synthetic coolant, slightly higher surface roughness is recorded with the use of emulsion coolant due to higher friction in the contact surface (force ratio of 0.3). With feed maintained and the depth of cut increased to 0.3 mm (i.e. DOE runs 5 and 6), a reverse trend is observed in dry grinding due to higher removal of material by cutting rather rubbing; while grinding in synthetic coolant led to a minimal increase in roughness due to oil-smothened cutting action. In the case of emulsion coolant, again higher surface roughness results as compared to that of synthetic coolant owing to less effective lubrication and the corresponding increased rubbing (i.e. force ratio increased from 0.25 to 0.3). At high feed (i.e DOE runs 3, 4 and 7, 8), regardless of the depth of cut, increasing wheel speed in dry grinding will only worsen the surface finish. In general, wheel speed does not seem to be of much influence in wet grinding as it is in the case of dry grinding, except in the cases of synthetic coolant at high feed, which feature significantly improved surface finish with increased wheel speed.

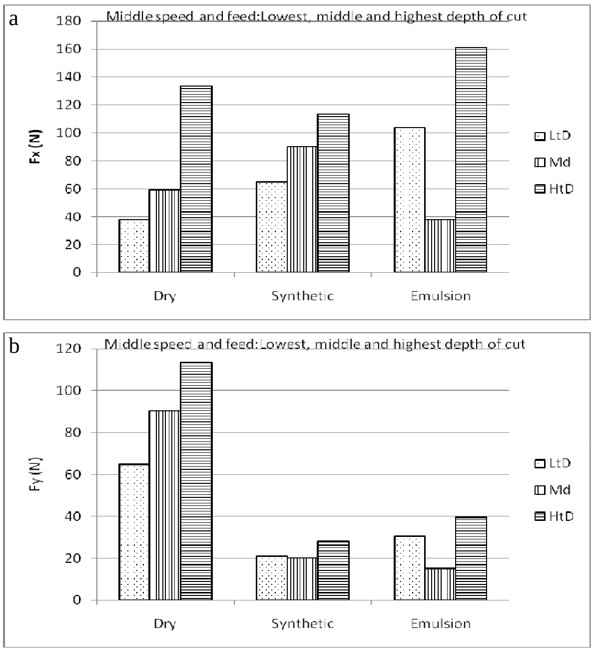


Fig. 5 Effect due to depth of cut a) normal force b) tangential force

At middle range of feed and depth of cut, as speed is varied from lowest level to highest level (run such as 9 to 10), surface roughness reduced except for grinding in emulsion. In this case, a slight increase in roughness observed due to reduced lubricating effects.

*2. Effect of Feed*

Regardless of the depth of cut, at constant low speed, as feed is increased from low to high (i.e. DOE runs 1 and 3), surface roughness decreases in dry grinding due to larger uncut chip thickness, which in turn causes self-sharpening of the wheel surface and smoothening of the work surface. In grinding with synthetic coolant, surface roughness values increase due to coolant layer preventing the effective abrasive work contact. As the lubrication effect of emulsion coolant reduces with increasing feed, surface roughness is increased when grinding in this coolant.

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

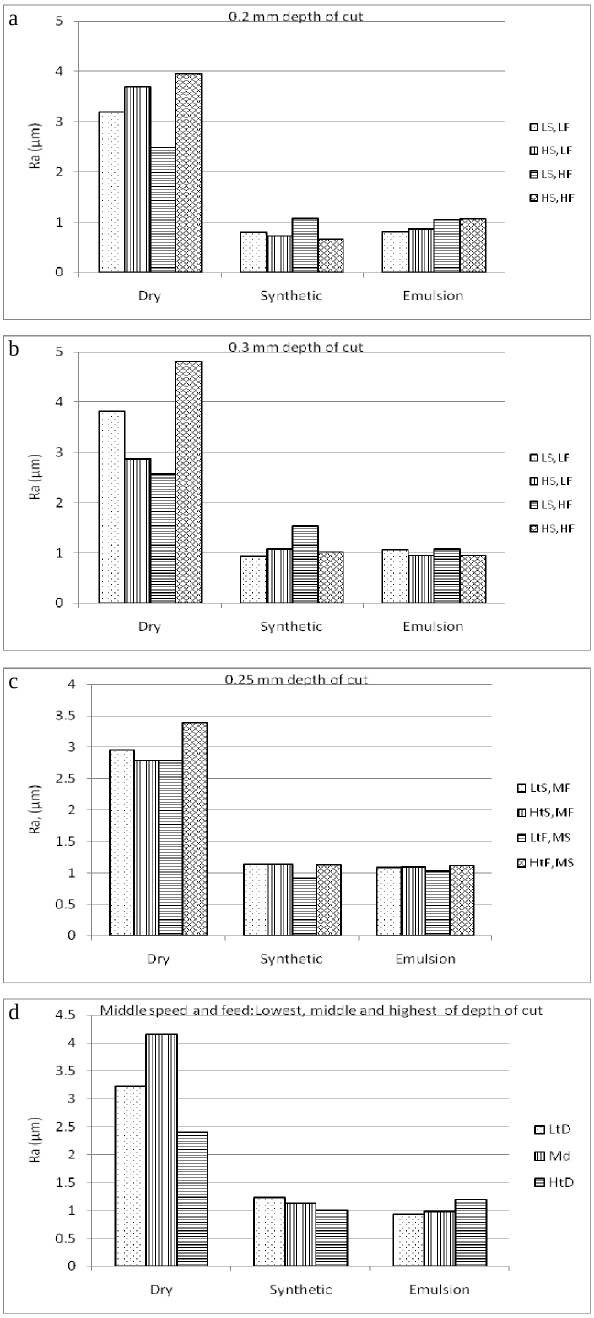


Fig. 6 surface roughnesses, Ra, for low and high, speed and feed conditions. (a) 0.2 mm depth of cut, (b) 0.3 mm depth of cut (c) Middle (0.25 mm) depth of cut with lowest and highest speed and feed, (d) Lowest to highest depth of cuts with middle speed and feed

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 speed and depth of cut, varying feed from low to high (DOE 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*

At constant middle range of speed and feed, as depth of cut is increased from lowest level to highest level (i.e. DOE runs 13 to 15) surface roughness is reduced for synthetic coolant grinding but increased for dry grinding and emulsion coolant grinding due to lack of lubricating effects.

## IV. CONCLUSION

In this paper, a study on CSM GFRP grinding to investigate the effects of grinding forces and surface roughness was conducted. The design of experiment with a central composite design with 8 factorial, 6 axial points and 1 centre points was adopted. The speed, feed and depth of cut were chosen as process factors. The variables recorded are normal, tangential grinding forces and surface roughness.

Based on the test results, the following points are concluded:

(i) Dry grinding exhibits lower grinding forces at low feed and high speed with all depth of cuts due to lower chip formation factor. Grinding in synthetic coolant exhibits lower grinding forces at high feeds and low speed due to increased cutting and increased lubricating effect. Whereas, grinding in emulsion coolant exhibits lower forces, at lower speed, feed and higher depth of cuts.

(ii) Higher feed and lower speed minimize surface roughness for dry grinding. On the other hand, higher speed and higher the depth of cut improves surface finish when grinding in synthetic coolant. With emulsion coolant, better surface finish is obtained at higher speed and higher feed.

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