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An Experimental Investigation of Rotary Ultrasonic Machining and Mechanical Property Evaluation on Hand Layup Fabricated Hybrid Composite

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Abstract: Rotary ultrasonic machining (RUM) is a feasible solution for the cost-effective machining of brittle and hard materials. This study aims to provide new information based on the drilling of hybrid composites of natural fibre and glass fibre using RUM (rotary ultrasonic machining) to improve the quality of machined holes while reducing machining costs, as well as to investigate the effects of machining and tool factors on output variables. To explore the properties of small-diameter drilling for hybrid composite, the surface roughness along the feed direction of the drilled hole is measured. During RUM drilling, the influence of the process parameters (feed rate, depth of cut, tool rotation speed, and ultrasonic power) and output variables (MRR and SR) on the manufactured composites were analysed. In addition, the composite has undergone mechanical testing to analyse and compare its mechanical properties. The results indicate that MRR grows as a function of all process factors, with material combination and feed rate being the most effective and important. SR rises with feed rate, whereas frequency has the opposite effect. All process factors except ultrasonic power have a considerable influence on SR variation. Comparing the mechanical properties of composite materials, it was discovered that the combination material C2 had more hardness and flexural strength than all other composite combinations. But in terms of tensile strength, C3 material is superior to other composite materials.

Keywords: RUM, Natural Fibre, composites, Unconventional machining

1. Introduction

In recent times, not only advanced machining but the trend to fabricate and replace the traditional material usages with new cost-effective hard and brittle composite material is high in demand. The mechanical characteristics of these materials seem to be comparable to those of more conventional materials. The preference for composites made from natural fibres over those made from synthetic fibres is rising for environmental and sustainable grounds. Among the synthetic fibres that are now readily accessible are nylon, rayon, polyester, acrylic, glass, and plastic. Synthetic fibers' non-biodegradability, high production costs, and bulk are its drawbacks[12),13)]. Because their benefits outweigh their drawbacks, natural fibres are employed as reinforcement in both thermosetting and thermoplastic matrices. These plant-based materials are light in weight, inexpensive, poisonous, and difficult to recycle. Numerous fiber-reinforced composites may be made using natural fibres. Examples include sisal, bamboo, banana, flax, kenaf, and coir[6),14)-16)]. Energy may be recovered during cremation by using these non-abrasive, renewable fibres.

Banana fibre is a waste fibre that results from the production of bananas. It is a lingo-cellulosic fibre that has superior mechanical qualities and can be isolated from the pseudo stem of the banana plant[8)]. The inner bark of the banana stem is where banana fibre is found. When bananas are collected from a banana tree, the stem (trunk) is chopped slightly above the soil. Up until a few years ago, these trunks posed a serious problem for growers. These banana trees would often be burned. transporting these trunks to a fibre extraction machine. The banana fibres are in the inner, brown, or cream-colored bark of the trunk[1)]. The outer bark (green portion) of the stem is peeled off by hand. Additionally, it has been discovered that banana composite has better flexural and impact strength than hybrid composite. By combining banana and glass fibres, a composite material with enough stiffness and damping behaviour may be created that is both affordable and simple to utilize. A study of the mechanical qualities of an epoxy composite reinforced with bananas demonstrates that adding glass fibre up to 20–40% leads to an increase in mechanical properties such as tensile, flexural, and hardness strength. On the other side, bamboo fibre is comparable to other fibres, making it a natural option. Bamboo is utilised in furniture, building, and other industries because it grows quickly, self-renews, and has remarkable mechanical characteristics[4)]. As technology has improved, it has expanded to consumer and industrial products, increasing raw material and final product demand. Bamboo may be altered chemically and physically (like acetylation)[5)]. Chemicals destroy natural bamboo's sustainability and recyclability. Bamboo studies are few. Heat treatment may also increase bamboo's lifetime and dimensional stability, enhancing its value. Bamboo fibres have a modulus of 46 GPa and tensile strength of 600 MPa. Because of these properties, plant-based fibres may replace conventional ones. Recent research indicates bamboo and banana as a polymeric composite reinforcement[7),9)].

For their intended usage, components created from these materials require precise machining. Conventional machining processes cannot shape these materials in most circumstances. This permits sophisticated "advanced machining procedures" to be used. Combining USM with CG creates the RUM material creation technique[10)]. A rotary ultrasonic machine converts low-frequency electric impulses into high-frequency signals, which are provided to a transducer and turned into a mechanical back-and-forth motion before being transmitted to a tool via a horn. Diamond-coated tools work as abrasives by hammering, extracting, and eroding. Changing machining process parameters might hurt output quality. To obtain the desired outcome, process parameters must be tuned. Spindle speed, feed rate, and ultrasonic power determine RUM machining qualities and application[3), 11)]. In the literature, material removal rate, surface quality, tool wear, cutting force, and edge chipping are analysed. Edge chipping, which occurs when fractures grow uncontrolled at the end of machining and cause the material to break apart at the edges, is particularly damaging to RUM-drilled holes. This complicates correct work. RUM must eliminate or decrease edge chipping. These RUM variables affect end-product quality. In RUM, process parameters are optimized to provide the highest-quality machined component. Literature is lacking on the use of contemporary technologies for experimental design, despite the need to analyse the machining capabilities of float glass. It seems sensible to explore how RUM processing parameters affect edge chipping.

Despite the widespread implementation of RUM for purposes such as slot cutting and surface milling, there is still room for improvement in drilling via RUM in terms of the workpiece (product) design and machining optimization[2),24)]. This work aims to improve the parametric parameters for producing the highest quality RUM by identifying the essential process variables that have the greatest impact on the machining qualities of the fabricated composite and analysing the mechanical property exhibited by the fabricated hybrid composite made from banana, bamboo, and glass fibre. To cover the current knowledge vacuum in the field of process optimization in RUM of the manufactured composites, the present study has also included the use of relatively modern statistical methods like Taguchi and ANOVA, which provide meaningful process optimization through the desirability function.

2. Material and Methodology

2.1 Material Selection

Both plant and animal-based natural fibres are commonly available worldwide. The choice of natural fibre for NFRCs is highly influenced by the desired properties of composites as stated by their application[17)-19)]. Although there are certain restrictions, they mostly include moisture absorption, variation, and dimensional stability[22),23)]. Several industrial uses for these eco-friendly composites include load-bearing and outdoor applications, such as car exterior components, sports equipment, transit facilities, and maritime constructions[25)]. In this experimental study, banana fibre mat, bamboo fibre mat, glass fibre mat, epoxy resin, silicon spray, and hardener were considered raw materials. Separate banana and bamboo composites are constructed from these basic materials by adhering them layer by layer. Table 1. indicates the composites' material composition in the composition, varied proportions of banana, bamboo, and glass fibres are combined with epoxy and hardener. Composites are produced by the hand layup method, which requires physically inserting fabric layers, or plies, in the mould and then adding resin matrix to make a laminate stack. In the composition three fibres of banana (b), bamboo (B), and glass (G) are used, 3B shows the three layers of bamboo fibre, 1G indicates one layer of glass fibre and so on.

Table 1 Chemical composition of the composites.

S. No.	Designation of composites	Composition	Fibre used
1.	C1	2B-1G-2B-1G-2B-1G	Bamboo
2.	C2	3B-1G-3B-1G-3B-1G	Bamboo
3.	C3	3b-1G-3b-1G-3b-1G	Banana
4.	C4	2b-1G-2b-1G-2b-1G	Banana

2.2 Experimental parameters and optimization considered

The exhaustive literature review and trial experiment aid in evaluating the process parameters and their values.

Material combination, feed rate, frequency, and ultrasonic power, which are listed in Table 2, are the process parameters considered for the tests during the drilling of the composites. In addition, it was possible to accept other process factors as experimental variables, but machine limitations prevented this. So, certain parameters, such as spindle speed (1000 RPM) and tool diameter, were held constant: (6mm). This study will provide the following machining qualities and mechanical properties: tensile strength, flexural strength, hardness, material removal rate, and surface roughness. Taguchi optimization using ANOVA analysis for the most effective machining configuration and significance of machining factors[20),21)]. The L16 orthogonal array was used for experiment performance in this research. Before optimization, all Taguchi DOE factors are established in MINITAB 19.0, and the interactions between factors AB, AC, and BC are considered during the generation of orthogonal array tables and the sequencing of trials. A considered significance threshold of 5% for this research.

Table 2 Control variables and their levels.

S. No.	Parameters	Level 1	Level 2	Level 3	Level 4
1.	Material of composite (Combination)	C1	C2	C3	C4
2.	Feed rate (mm/min.)	4	5	6	7
3.	Frequency (kHz)	20	21	22	23
4.	Ultrasonic power (Watt)	0.2	0.7	1.2	1.7

3. Fabrication, Experimentation and Result Measurement

3.1 Composite material fabrication

The hand layup process, which simply entails manually placing fabric layers, or plies, in the mould and then applying resin matrix to produce a laminate stack, is the most traditional and fundamental way to manufacture composites. Using hand rollers, the wet composite is then rolled, brushed, or pressed to evenly distribute the resin, release trapped air, and solidify the composite layers to improve the interaction between the reinforcement and matrix and achieve the required thickness as represented in Figure 1. The quality of the laminate, the mixing of the resin, and the amount of laminate resin depend greatly on the operator's expertise because not much fibre loading is achievable with this labour-intensive technique. To achieve flawless surface quality, thin plastic sheets are employed at the top and bottom of the mould plate. Banana, bamboo, and glass fibres mat were sliced into length and width measurements of 150*150 mm and the lamination was created using a 4 mm thick material. The composite laminate is made up of many layers of glass fibre and natural fibres that are used to create various samples. By adding the necessary amount of epoxy glue, the fibre layers were created. 4 composites (C1, C2, C3, C4) has created dimension (10 cm*20 cm) by a natural fibre sheet and glass fibre sheet.

Fig. 1: Addition of fibres layer for composite fabrication

3.2 Experimentation

For this experiment, a CNC rotary ultrasonic drilling and a slot-cutting machine are used. A revolving ultrasonic horn removes material from the workpiece to operate the machine. This rotation transforms the equipment from a standard ultrasonic device into a rotational ultrasonic device. The linear interpolation offered by G&M code programs governed the movement of the tools. Figure 2 depicts the setup for cutting C1 and C3 polymers using RUM. For analytical reasons, the second workpiece C2 and C4 are drilled using the same setup. All input parameters are the same as C1 drilling. After the bamboo fibre-reinforced polymer has been drilled, the machining setup, tool, and parameters for the banana fibre workpiece are prepared (C3&C4).

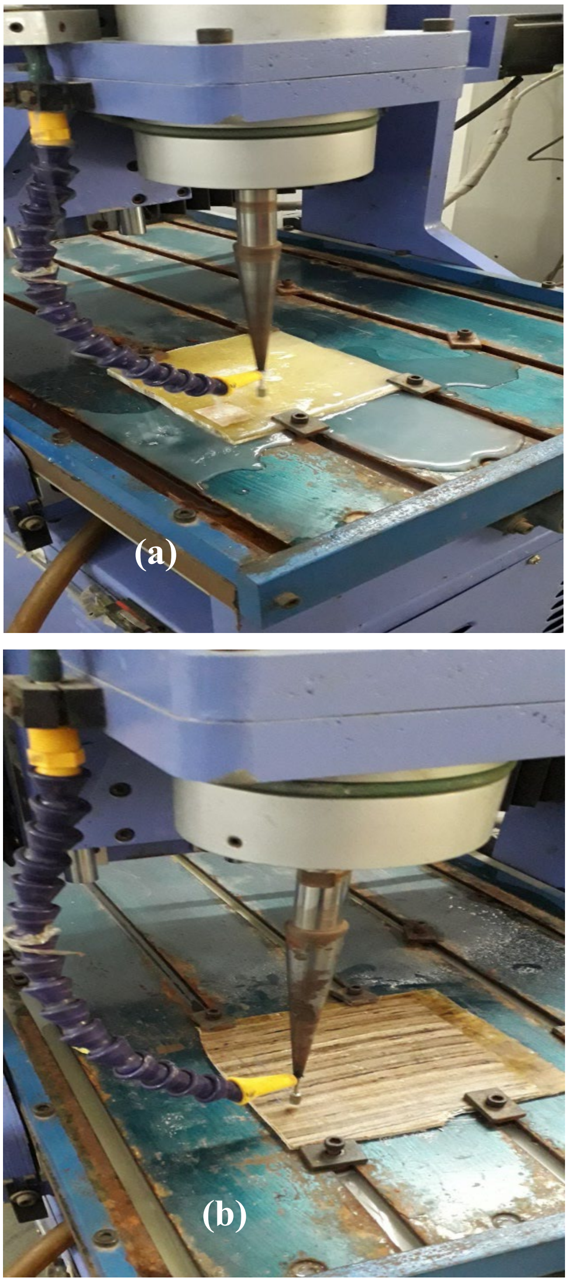

Fig. 2: Drilling process on C1 (a) & C3 (b) fabricated composite using RUM

3.3 Result measurement

The result of the experiments was obtained by various mechanical testing machines and specific equipment for the machining characteristics measurement like surface roughness and MRR. MRR was calculated by using a stopwatch and the mathematical calculation for the volume removed during the drilling. While the surface roughness of the inner surface of the hole was measured by using a portable surface roughness tester from the SURFTEST SJ-210 series, shown in Figure 3. The tensile test is performed on the Universal Testing Machine (UTM) KIC-2-300-C capacity 30KN. For mechanical testing, the manufactured hybrid composite material is saw-cut to the necessary dimensions. In a tensile test, the specimen is mounted in a device and put under tension as shown in Figure 4 (a). The most used flexural test for composite materials is the three-point test. The crosshead location is used to calculate specimen deflection. Flexural strength and displacement are test outcomes. The test specimen is put in the universal testing machine, and force is applied to it until it fractures and breaks. The specimen and machining setup used for conducting the flexural test is presented in Figure 4 (b). Brinell Scale Comparison of Hardness For testing reasons, an indentation is formed with a 10 mm-diameter ball indenter, which is often made of hardened steel or carbide steel. After applying weights of 60 kgf, 100 kgf, 150 kgf, 187.5 kgf, and 250 kgf at different places for each load, the smaller dial was changed to 3. The bigger dial's indication stops after 30 seconds, releasing the weight.

Fig. 3: Surface roughness measurement using SURFTEST SJ-210

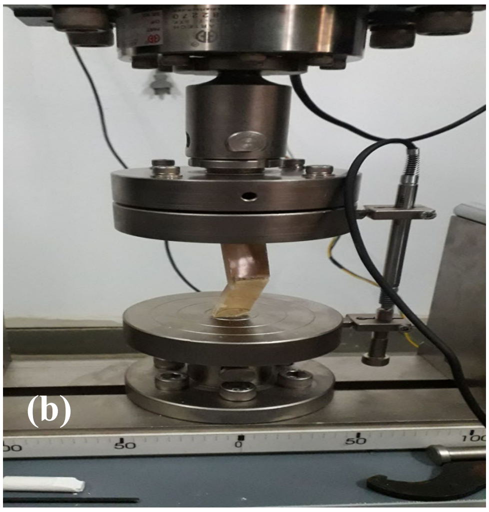

Fig. 4: Tensile (a) and Flexural (b) test on the fabricated composite material

4. Results and Discussion

Table 3 shows the overall experiment of the research which includes mechanical properties of fabricated composite and machining output parameters results.

4.1 Effect of process parameter on MRR and SR during drilling

The main effects plot for means for MRR and SR variation during RUM is shown in Figure 5. Feed rate was found the most effective parameter on MRR variation followed by material combination, frequency, and least effective ultrasonic power Figure 5 (a). Combination C4 of material, 7 mm/s of feed rate, 23 Hz of frequency and 1.7 watts of ultrasonic power show the highest value can be considered as the optimum point for material removal rate. On the other side, the material of the fabricated composite found to be the most effective on surface roughness variation followed by feed rate, frequency and last is ultrasonic power. Combination C2 of material, 4 mm/s of feed rate, 23 Hz of frequency and 1.7 watts of ultrasonic power show the lowest value can be considered as the optimum point for surface roughness.

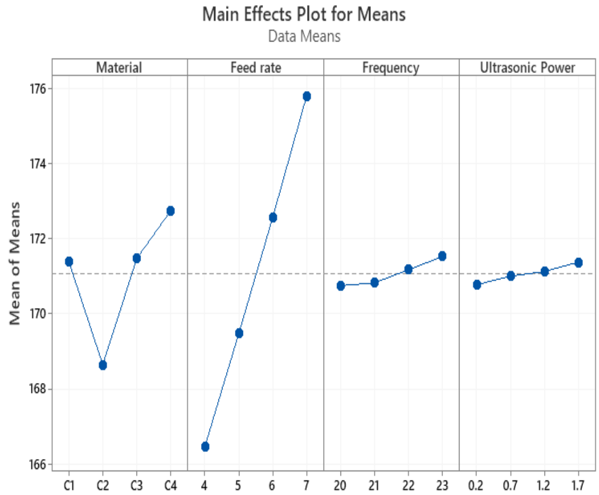

Fig. 5: Main effect plot for means of MRR variation

Table 3 Machining and mechanical property result

S. No.	Material	Feed rate (mm/s)	Frequency (Hz)	Ultrasonic Power (*250 W)	MRR (mm^3/ min.)	SR (µm)	Tensile Strength (N/mm^2)	Bending Strength (MPa)	Hardness (kgf)
1.	C1	4	20	0.2	166	4500	10.60	16.02	47
2.	C1	5	21	0.7	169.6	4620			
3.	C1	6	22	1.2	173	4727			
4.	C1	7	23	1.7	177	4796			
5.	C2	4	21	1.2	164	3505	9.37	75.94	78.7
6.	C2	5	20	1.7	167	3613			
7.	C2	6	23	0.2	170.4	3632			
8.	C2	7	22	0.7	173.2	3707			
9.	C3	4	22	1.7	167.4	5082	36.41	33.22	52.3
10.	C3	5	23	1.2	170.2	5155			
11.	C3	6	20	0.7	172.7	6266			
12.	C3	7	21	0.2	175.6	6254			
13.	C4	4	23	0.7	168.5	8186	7.82	56.38	44.7
14.	C4	5	22	0.2	171.1	8738			
15.	C4	6	21	1.7	174.1	9613			
16.	C4	7	20	1.2	177.3	10469			

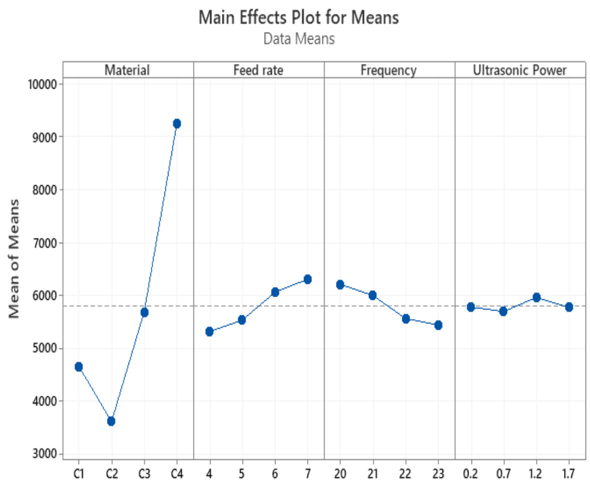

Fig. 6: Main effect plot for means of SR variation

4.2 Analysis of Variable for MRR and SR

Material and feed rate are significant factors for MRR variation, where frequency and ultrasonic power are insignificant for material removal rate. Feed rate contributes the most (83.22%) followed by material (15.65%), frequency (0.72%) and ultrasonic power (0.29%), refer to Table 4. While, for SR, material and feed rate and frequency were found significant factors, where ultrasonic power is insignificant for surface roughness of the inner surface of the hole. Material of the fabricated specimen contributes the most (~95%) followed by feed rate (~3%), frequency (~ 1.5%) and ultrasonic power (~0.2%).

4.3 Mechanical Property analysis on the fabricated specimen

A section from the fabricated specimen is cut out to perform all the mechanical testing. All the mechanical testing was performed at normal ambient temperature and the results can relay with the same condition with ±10% change in environmental condition. The tensile and bending moment strength was calculated on the ultimate strength value, where hardness was calculated in kgf unit, mentioned in Table 3.

Table 4 ANOVA (means) for MRR and SR

ANOVA (mean)		For MRR				For SR			
Source	**DF**	**Seq SS**	**Adj MS**	**F**	**P**	**Seq SS**	**Adj MS**	**F**	**P**
Material	3	35.807	11.9356	131.70	0.001	72001798	24000599	479.48	0.000
Feed rate	3	191.942	63.9806	705.99	0.000	2511983	837328	16.73	0.022
Frequency	3	1.522	0.5073	5.60	0.095	1571213	523738	10.46	0.043
Ultrasonic power	3	0.752	0.2506	2.77	0.213	155394	51798	1.03	0.489
Residual Error	3	0.272	0.0906	_	_	150167	50056	_	_
Total	15	230.294	_	_	_	76390555	_	_	_

While comparing the tensile stress of all 4 fabricated composites, the C3 combination composite found the highest value flowed by C1, C2 & C4. The graph load applied on the specimen vs the elongated length is represented in Figure 6. the green colour line which is representing the C3 combination varies for long elongation length and is highest in load value, which mathematically gives the highest value in stress calculation compared to the other combination of the specimen. The flexural strength was calculated for the fabricated specimen conspired at the 3-point concept. In comparison, the C2 combination of the fabricated composite specimen is found more flexural strength than all others. The graph load applied on the specimen vs the length of testing considered is represented in Figure 7. the violet colour line which is representing the C2 combination shows the pick point or curve corresponding to the load compared to the other line of material.

The hardness test of the fabricated specimen is tested by using Brinell hardness test equipment. The hardness of specimens was observed by measuring 4 times the result for each type of material composite combination for the error removal, the average value was finally considered as the hardness value of the specimen. Refer Table 3, shows that the material combination C2 is a harder material than the other combination of the material.

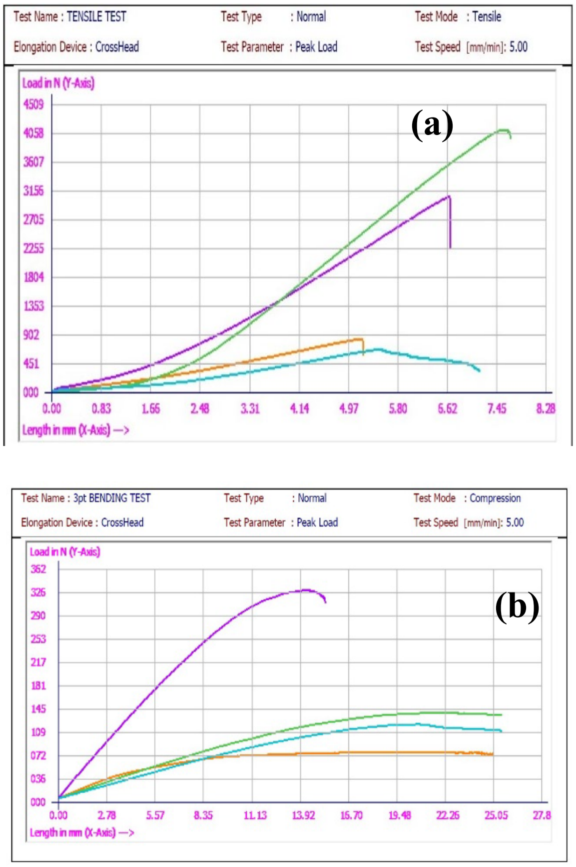

Fig. 7: Load vs effective length of the specimen during (a) tensile (b) bending test

5. Conclusions

Fabrication (Hand-Lay composite fabrication), experimentation and investigation during rotary ultrasonic machining (RUM) were successfully done. mechanical property and optimization with process parameter effect were also performed using Taguchi and ANOVA method in Minitab 19.0 software. These are the conclusions made after the complete study:

I. MRR increases with feed rate, frequency, and ultrasonic power during RUM on all four materials. Ultrasonic power and frequency always show very less effect on MRR variation compared to feed rate. Material combination and feed rate parameters were found significant during RUM for MRR variation where frequency and ultrasonic power were insignificant.

II. SR during RUM does not show a uniform and similar variation with all process parameters. SR increases with feed rate but shows a reverse effect with frequency. Also, the SR value was found lowest with the C2 combination of materials. Another side, very less effect has been shown with ultrasonic power on SR variation. Also, the range of variation of SR with ultrasonic power, frequency and feed rate was less than the material combination. Also, all process parameters have a significant effect on SR variation except ultrasonic power.

III. While comparing the mechanical property of fabricated composite material, it was found that C2 the combination material was found more harder and flexural strength than all other combinations of composite. But for tensile strength, C3 material shows more tensile strength than other composite materials.

3.1 Limitations and Future scope

The research consists of two separate fabrications of composite materials using natural fibre. The researcher can contribute more innovation by fabricating a single matrix composite by using both fibres which can be experimentally compared with the individual property and performance. Also, cutting forces, and machining accuracy can be considered machining characteristic investigations for further study.

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