Abrasive water jet machining of Sisal/Pineapple epoxy hybrid composites with the addition of various fly ash filler

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Abstract
This research was based on influence of various fly ash filler content in the machining properties of Pineapple (P)/Sisal (S) hybrid fiber reinforcement composites. Fly ash from bio waste materials of Bagasse (BGFA), Banana (BFA) and Coir (CFA) were used. High hardness nature of 3% BFA (22.73 HV) and 3% CFA (23.85 HV) reduces Material Removal Rate (MRR) and increases its surface roughness nature of the composites. Maximum MRR of 376.38 mm³ min⁻¹ was observed in 3% BGFA combinations with 250 MPa Water jet Pressure (WP), 1mm Standoff Distance (SOD) and 20 mm min⁻¹ Traverse Speed (TS) as machining parameters. MRR of 353.64 and 352.76 mm³ min⁻¹ was found out with 1% CFA and 1% BFA combinations. Lower surface roughness of 6.39 μm, 6.71 μm and 6.75 μm was found in 3% BGFA, 1% CFA and 1% BFA based composites. Filler surface created a tight bonding with the matrix, which reduces the erosion of fiber particles at higher WP. Untreated fibers showed lesser machining properties due to low fiber/matrix bonding. SEM results showed reducing of cracks and matrix breakages by the substitution of filler powders.

1. Introduction
In the modern era of generation humans are finding difficult to dispose plastic products due to its non biodegradable nature and environmental problems. As a solution for this researchers are using natural bio wastes from various plants which are eco-friendly. Sisal, cotton, kenaf, cellulosic fibers from various plants, Impomea pescaprae, pineapple, ramie, roselle, coir, flax, jute, bagasse, alovera and hemp are some of the fibers used for various applications. The usage of these can reduce the bio waste accumulation and improve the properties of polymer composites [1–10]. These bio fibers have the property to stick with water content, that will reduce the properties by lesser contact with the matrix resin. Effective surface treatments, filler substitution, hybridization of reinforcement fibers will provide good solution for the reduced properties [11–15].

In the initial researches man-made fibers such as glass, basalt, carbon and aramid were combined with natural fibers such as flax, sisal, coir and kenaf fibers for adding up of properties. The disposal of these synthetic fibers is a big issue, it will produce high CO₂ content and they are non biodegradable. Now natural fiber hybridization was done for the enhancement of properties [16–20]. The addition of filler incorporation with higher inorganic content enhanced the mechanical properties of polymer composites. Sugar cane is used in thermal power plant as a raw material for producing thermal energy and thus to rotate turbines in the plant [21, 22]. Flyash with high silica nature produces maximum flexural and tensile strength at 3% incorporation [23].

Banyan tree saw dust filler (20–40 wt%) reduces the surface roughness and kerf taper angle properties of polypropylene based composites and enhancing the machining nature of natural composites. This saw dust created a stiffer matrix by reducing the porosity and making the polymer composites to withstand with the pressure created by abrasive particles [24]. Standoff distance makes most impact in surface roughness and kerf angle properties of banana reinforced polyester composites. Water pressure, traverse speed and standoff distance increases the surface roughness of this polymer composites [25]. In jute fiber composites, feed rate is the predominant factor for reducing kerf angle and surface roughness property [26].
Natural fillers of coconut shell and palm shell reduces the delamination nature of hemp/kevlar with epoxy matrix composites. Kerf angle and material removal rate is mainly depending on traverse speed \[27\]. Sodium hydroxide treatment at 4% enhanced the machining property of coconut shealth natural composites. It improved the compatibility between filler and polyester matrix \[29\]. Apart from that, natural fillers such as calotropis gigantean stem powder, azadirachta indica seed powder, spent camellia sinensis powder along with graphene powder was used for enhancing the properties of natural fiber composites \[30–32\].

In Southern part of India especially in Tamilnadu production of banana, sugar cane and coconut tree are plenty. The waste materials after the production of these plants were burned to ash and these filler powders were used in machinability study of sisal/pineapple hybrid composites.

2. Materials and methods

2.1. Materials

The natural fibers of Pineapple (P) and Sisal (S) extracted from southern India was taken as main constituent along with matrix substance epoxy resin and hardener grade of LY556 and HY951 mixed in 10:1 ratio. The flyash filler from the waste of Bagasse (BGFA), Banana (BFA) and Coir (CFA) were used. The pineapple and sisal fiber properties were showed in table 1.

2.2. Fabrication

The pineapple and sisal reinforcements were surface treated with 5% NaOH and after the alkali treatment and these fibers were cropped into a approximate length of 5mm using chaff cutter also called as Animal ration shredder. Compression moulding method with temperature and pressure of mould at 90° C and 14 MPa were the conditions followed in this experimentation. Flyash powders were grinded with high end ball milling equipment having 800 rpm for 360 min with 3:1 ball to filler ratio. Filler powders from 1–4% was mixed with SP fiber combinations at 30 wt%. The compression mould was placed with SP fiber combination and resin/fly ash combinations were mixed with that and provided with suitable temperature and pressure as above mentioned.

3. Experimental details

3.1. Characterization of fly ash powders

Flyash fillers were undergone with X-Ray Fluorescence spectroscopy (XRF), ash content and organic substance experimentation.

3.1.1. X-Ray Fluorescence spectroscopy (XRF)

The XRF testing was undergone with S4 Bruker model equipment with X ray tube with 4 Kw Rh. Collimators with 0.25°–0.46° was having property for beam narrowing and to detect particles in the components (table 2).

3.1.2. Organic substance and ash content

It was followed by using ASTM D2974 standard and muffle furnace was used in detecting the organic and ash substance in it (table 2).

3.2. Mechanical testing

Tensile, flexural, impact, hardness and density testing was carried out here. ASTM standards of D790, D638 was followed in flexural and tensile properties. Impact test and hardness testing followed D256 and E384 ASTM.
standards. UTM machine (Tinius Olsen H10KL) was used for flexural and tensile property testing followed by Charpy Impact hammer test in Impact testing. Impact, tensile and flexural testing was taken in 5 samples of same combination and the average values are taken as the results. Hardness properties were detected using micro hardness tester with load and time of 100 g and 15 sec. All the readings from 10 different portions were used as the results called as Vickers Pyramid Number (HV).

3.3. Density calculations
Initially the hybrid natural fiber composite samples are properly cleaned. In density calculations five trials were taken from each composite combinations. In the first step specimen weight was calculated in air (dry condition), then the same sample is dipped in distilled water at weight is again measured, then applying the Archimedes principle density was calculated using the below mentioned formula.

$$\rho = \frac{\text{Mass at Atmosphere}}{\text{Mass at Atmosphere} - \text{Mass at wet conditions}}$$  \hspace{1cm} (1)

3.4. Abrasive Water Jet Machining (AWJM)
DWJ1313/FB model jet cutter was used for abrasive water cutting using garnet erodent abrasive particles. It has a nozzle diameter of 0.76 mm and machining accuracy of \( \pm 0.01 \) mm. Machine is operated using alpha numerical systems. The input factors such as water pressure, traverse speed and standoff distance were applied in different ranges. The machining response such as material removal rate and surface roughness were taken from this experiment.

To improve the machining characteristics, the composite needs to have larger material removal rate and smaller surface roughness. The initial response Material Removal Rate (MRR) is influenced by traverse speed, drilling depth and nozzles kerf width. Formula for material removal is given below. Here \( h_i \) is drilling depth (mm), \( d \) is the nozzle diameter (mm) \( [d_i = (\text{Top Width} + \text{Bottom Width})/2] \), \( v_r \) is Traverse speed (mm/min). The top and bottom widths were calculated using optical microscope after the machining.

$$\text{Material Removal Rate(MRR)} = h_i d_i v_r$$  \hspace{1cm} (2)

The next response is Surface Roughness (Ra), it is calculated with Surftest SJ-401 model profilometer having a top range of 350 \( \mu \)m and 0.25 mm sec\(^{-1}\) of measuring speed. The probes used for surface roughness detection needs to be in contact with work piece, calculations were taken from 6 to 7 locations and the mean values were taken as the results.

3.5. SEM testing
Hitachi SU660 SEM tester was used for identifying the surface nature of the composites after the machining process.

| Chemical Composition | BFA% | CFA% | BGFA% | [35] | [36] |
|----------------------|------|------|-------|------|------|
| SiO\(_2\)            | 60.64| 63.75| 50.4  | 75.46| 50.40|
| CaO                  | 6.19 | 5.86 | 7.37  | 4.42 | 18.90|
| Fe\(_2\)O\(_3\)      | 4.97 | 3.71 | 4.43  | 1.62 | 6.87 |
| Al\(_2\)O\(_3\)      | 7.83 | 6.82 | 9.68  | 3.35 | 7.48 |
| P\(_2\)O\(_5\)       | 3.97 | 3.76 | 5.26  | 2.18 | 2.47 |
| K\(_2\)O             | 6.35 | 5.89 | 7.27  | 4.16 | 7.29 |
| SO\(_3\)             | 2.74 | 2.88 | 4.27  | 2.99 | 1.94 |
| MgO                  | 2.20 | 2.65 | 6.76  | 3.04 | 1.61 |
| TiO\(_2\)            |     | 0.32 | 0.65  | 0.19 | 1.28 |
| Na\(_2\)O            | 0.15 | 0.19 | —     | 0.30 | 0.33 |
| Cl                   | 0.21 | —    | —     | —    | 0.59 |
| MnO                  | —    | 0.34 | 0.24  | 0.06 | 0.23 |
| Organic Materials%   | 4.59 | 3.02 | 3.25  | 2.15 | 25.33|
| Inorganic Materials% | 95.45| 96.98| 96.75 | 97.85| 74.67|
| Density g cm\(^{-3}\) | 0.55 | 0.73 | 0.93  | 0.74 | 0.53 |
| Loss on Ignition %   | 1.86 | 3.25 | 4.34  | 2.15 | —    |
2. Abrasive Water Jet Machining

4.2. Machinability properties

4.2.1. Material removal rate at varied water jet pressure (WP)

In the initial trial, hybrid SP fiber composites with various % of BFA, CFA and BGFA fillers were machined using varying water jet pressure from 150, 200 and 250 MPa and standoff distance, traverse speed were fixed at 1mm, 20 mm min \(^{-1}\). Material Removal Rate (MRR) improved with Water Pressure (WP) from 150–250 MPa. High pressure erodent with high kinetic energy colliding with the fiber surface provides higher MRR in the specimen. At lower pressure due to small kinetic energy, material removal rate will be lesser negatively influence the machining properties of hybrid composites [24]. The higher filler addition at 4% BFA

4. Results and discussion

4.1. Mechanical properties

In the mechanical testing 13 combinations were used for detecting flexural, impact, tensile, density and hardness properties (table 3). Hybrid fibers of sisal and pineapple composites observed lesser flexural, impact and tensile properties of 64.14 MPa, 53.28 J m \(^{-1}\) and 20.45 MPa when compared to filler added hybrid composites. The maximum properties in BFA was observed with 3% addition having 29.63 MPa, 60.56 J m \(^{-1}\) and 78.32 MPa of tensile, impact and flexural properties. Similarly CFA and BGFA fillers showed maximum property enhancement at their 3% substitution. Tensile properties reaches up to 33.79 MPa and 30.83 MPa by the coir and bagasse flyash addition. Flexural strength showed enhancement up to 70.28 MPa and 73.53 MPa by the filler additions up to 3%. Hardness and density also showed same path with maximum improvement at 3% flyash addition. The better bonding strength of hybrid composites enhanced the density and hardness nature of the composites. The filler addition was introduced to reduce the porous nature of composites and to improve the properties of natural fiber composites [33].

The results clearly proved that positive improvement with the flyash addition. Ball milling has also a major role in reducing the size and improve the compatibility with polymer matrix [17]. In the previous studies baggase flyash added to the mechanical properties of the flax hybrid fiber epoxy matrix composites [36]. The untreated fibers observed lesser mechanical properties than alkali treated natural fibers. Treatment provides rough surface in the sisal pineapple fibers thus enabling rein to pass through these fibers surface and making good bonding with in the composites. The SEM analysis results of BFA, CFA and BGFA is showed in figure 1.

4.2. Machinability properties

Abrasive Water Jet Machining (AWJM) was used for investigating the material removal rate and surface roughness of the hybrid composites. The effect of BFA, CFA and BGFA filler additions in the fiber combination of 30wt% SP were observed in this machining study. All the machining results were taken from 5 locations of the samples to validate the results.

4.2.1. Material removal rate

| SL NO | Combinations | Material removal rate (MRR) | Hardness (Hv) | Density (g/cm\(^3\)) |
|-------|--------------|-----------------------------|---------------|---------------------|
| 1     | 30% SP       | 20.45                       | 19.26         | 1.161               |
| 2     | 30% SP/1% BFA| 23.78                       | 20.37         | 1.183               |
| 3     | 30% SP/3% BFA| 29.63                       | 22.73         | 1.188               |
| 4     | 30% SP/4% BFA| 30.89                       | 21.24         | 1.185               |
| 5     | 30% SP/1% CFA| 36.75                       | 21.12         | 1.173               |
| 6     | 30% SP/3% CFA| 33.79                       | 23.85         | 1.190               |
| 7     | 30% SP/4% CFA| 29.53                       | 22.73         | 1.184               |
| 8     | 30% SP/1% BGFA| 27.83                     | 20.24         | 1.184               |
| 9     | 30% SP/3% BGFA| 30.83                     | 20.38         | 1.198               |
| 10    | 30% SP/4% BGFA| 28.82                   | 19.85         | 1.192               |
| 11    | Untreated 30% SP/1% BFA| 20.27               | 19.21         | 1.175               |
| 12    | Untreated 30% SP/1% CFA| 21.35               | 20.27         | 1.165               |
| 13    | Untreated 30% SP/3% BGFA| 27.88              | 19.79         | 1.193               |
reduces the MRR due to agglomeration effect, which damages the matrix properties. Agglomeration reduced the load carrying and stress transfer capacity, which ultimately reduces the machining nature of the epoxy based composites [29]. Hybrid fiber composites with out filler showed brittle failure at higher WP and it also severely damage the fiber/matrix bonding [27]. Material removal rate at varied water jet pressure is showed in figure 2.
At higher WP surface striations occurs due to dynamic property of water jet, which increases the energy fluctuation [24]. In the second set of combinations with varied WP (150-250 MPa), constant SOD (1 mm) and TS (20 mm min⁻¹) in 30 wt% SP with CFA composites (figure 2(b)) showed good machining properties in higher WP. Maximum MRR of 353.64 mm³ min⁻¹ was produced in 30 wt% SP with 1% CFA combination. Low hardness and good compaction with fiber and matrix enhanced its machining properties. Higher hardness of 23.85 HV (3% CFA) than 21.82 HV (1% CFA) reduces the MRR at 3% filler addition. Filler addition will provide improvement to brittle nature of epoxy resin matrix. Filler surface created a tight bonding with the matrix, which reduces the erosion of fiber particles at higher WP [28].

Third set of combinations with varied WP also showed similar MRR results. Agglomeration of higher BGFA addition at 4% reduced the MRR from 174.43 to 324.97 mm³ min⁻¹ (figure 3(a)). These combinations possess maximum MRR at 3% BGFA addition, it is mainly due to similar hardness properties of 20.38 HV (3% BGFA) and 20.24 HV (1% BGFA) filler substitution.

4.2.1.3. Material removal rate at varied Traverse Speed (TS)
In these combinations TS was varied from 20, 30 and 50 mm min⁻¹, SOD and WP are fixed constants at 1mm and 150 MPa. The initial hybrid combinations of SP enhanced the MRR from 183.25-319.93 mm³ min⁻¹ with 20-50 mm min⁻¹ TS. Increase in feed rate enhanced MRR in each BFA filled composites (figure 5(b)). Maximum MRR (199.14-352.76 mm³ min⁻¹) was observed in BFA with 1% substitution. Similarly in third set of combination with BGFA maximum MRR of 321.78 mm³ min⁻¹ was produced at 3% BGFA, 1mm SOD. The substitution of CFA at 1% enhanced the MRR from 293.74-303.23 mm³ min⁻¹. The substitution of CFA at 1% enhanced the MRR from 293.74-303.23 mm³ min⁻¹ and similarly 3% BGFA improved the MRR from 293.74-303.23 mm³ min⁻¹.

Figure 3. MRR at varied WP and SOD.
Filler addition is due to the hydrogen bond between them which enhances the stress and load transferring capacity of the polymer matrix composites. Increase in hardness makes lesser machining properties for 3% CFA addition (324.95 mm³ min⁻¹). In the third set of combinations 3% BGFA showed maximum MRR of 349.14 mm³ min⁻¹ (figure 6(a)). Agglomeration reduced MRR at 4% CFA and BGFA addition in hybrid SP composites.

4.2.2. Surface Roughness (SR)

4.2.2.1. Surface roughness at varied Water Jet Pressure (WP)
Surface roughness of the composites must be reduced for improving the machining properties of the composites. In the combinations with constant SOD of 1 mm and TS with 20 mm min⁻¹, varied WP (150–250 MPa) surface roughness increased with increase in the WP (figures 6(b), 7(a) and (b)). The filler
addition of BFA, CFA and BGFA showed decrease in surface roughness nature of the natural composites. In the hybrid combinations of SP fibers minimum surface roughness of 7.53 μm was produced at low WP, surface roughness increases with increase in pressure up to 250 MPa. This increase in the surface roughness may be due to jet divergence effect, this causes erodent particles to be found in the end portions of the jet. This creates lesser erodent material in unit time/unit area hitting the specimen target. Multiplication effect of water jet causes erodent particles to be scattered up to jets critical deployment distance. Increase in the scattering of abrasive particles increases surface roughness in the specimen [25]. At higher pressure divergent jet gets required energy to machine the work piece which increased the composite specimens’ surface roughness and irregularity. Increase in the WP, increased the kinetic energy of abrasive particles and improved the MRR. During this high kinetic energy inter-particles get collide and abrasive particles with enormous energy hit the target specimen that increases the surface roughness [26]. Lower surface roughness of 6.54 and 6.73 μm is observed in BFA and CFA at 1% with 150 MPa WP. Similarly BGFA at 3% showed lesser surface roughness of 6.39 μm at same WP (figure 7(b)).

Figure 6. MRR at varied TS and SR at varied WP.

Figure 7. SR at Varied WP.
The filler substitution produces a protective layer from the high kinetic energy abrasive particles hitting the work piece. This reduces flush off the fiber composite materials thus improving the machining nature of the composites [29].

4.2.2.2. Surface roughness at varied Standoff Distance (SOD)

The increase in TS also increased the surface roughness of the hybrid fiber composites. In the combinations SOD (1–3mm), constant WP and TS of 150 MPa and 20 mm min$^{-1}$ were the working parameters used (figures 8(a), (b) and 9(a)). In the initial trial, hybrid fiber composites of SP showed 7.65–8.13 $\mu$m of surface roughness. Increase in the filler addition up to 1% reduces the surface roughness to 6.85–7.29 $\mu$m. Similarly 1%, 3% addition of CFA and BGFA (figures 8(a) and (b)) reduces the surface roughness up to 6.82 and 6.68 $\mu$m. Higher substitution of filler addition increased the surface roughness of the hybrid composites due to the agglomeration effect. At high SOD, kinetic energy of water jet will be higher, thus it cracks the fiber/matrix bonding and increases the surface roughness properties.

Figure 8. SR at varied SOD.

Figure 9. SR at varied SOD and TS.
4.2.2.3. Surface roughness at varied Traverse Speed (TS)
In these combinations, TS (20–50 mm min⁻¹), constant WP and SOD of 150 MPa and 1 mm working parameters were used (figures 9(b), 10(a) and (b)). Traverse speed also increases surface roughness of the hybrid combinations and reducing the machining properties of the composites. Initial hybrid composites of SP observed with surface roughness of 7.68–8.24 μm by the increase in traverse speed up to 50 mm min⁻¹. The hybrid composites of SP showed lesser surface roughness by the filler substitution of BFA (7.14 μm) and CFA (6.71 μm) at 1%. BGFA observed its lesser surface roughness (7.23 μm) at 3% incorporation. At high feed rate, more amount of fiber composites were cut from the target point, thus increasing the surface roughness in the composites [24]. In these combinations 20 mm min⁻¹ traverse speed, constant SOD and WP of 1mm and 150 MPa with filler mixing of 1% (for BFA and CFA) and 3% (BGFA) showed good machining properties.

4.2.3. Machining properties of untreated fibers
Material removal rate of untreated SP fibers with varied WP from 150–250 MPa, constant SOD and TS of 1 mm and 20 mm min⁻¹ showed reduced properties while comparing with treated fibers. Untreated hybrid fibers with 1% BFA (figure 11(a)) showed MRR with 167.03–301.02 mm³ min⁻¹, which is lesser than treated hybrid fibers with 189.14–335.29 mm³ min⁻¹ MRR. Similarly untreated fibers with 1% CFA (figure 12(a)) observed with maximum MRR of 315.54 mm³ min⁻¹, which is lower than treated fibers with 353.64 mm³ min⁻¹. Hybridization of untreated SP fibers with 3% BGFA fillers (figure 13(a)) also showed lower machining
Figure 12. MRR and SR of Untreated and Treated Fibers in 1% CFA/SP Hybrid Composites.

Figure 13. MRR and SR of Untreated and Treated Fibers in 3% BGFA/SP Hybrid Composites.
properties while comparing with treated hybrid fibers. Fiber treatment improved the crystallinity of the fibers, thereby increasing the dimensional stability of the natural reinforced composites [26].

The surface roughness property increases with untreated fiber composites, which reduces the machining properties. The operating conditions with SOD varied from 1-3 mm, constant WP and TS of 150MPa and 20 mm min$^{-1}$ was used (figures 11(b)–13(b)). Untreated SP fiber with 1% BFA and CFA showed higher surface roughness when compared to treated SP fibers. Alkali treatment provides wet resistant and rough fiber which improves the compatibility between fiber/matrix and decreases the surface roughness in the natural hybrid composites [29]. Similarly untreated SP fiber with 3% BGFA showed higher surface roughness than treated fibers.

4.2.4. SEM Analysis after AWJM

In the initial combination (Figure 14(a)) with treated fibers of 30 wt% PS/3% BFA showed lesser cracks and abrasive particle were seen near the drilled holes. Good adhesion between fiber/matrix reduces the interface crack and crack network. The composites (Figure 14(b)) with treated fibers of 30 wt% PS/1% BFA showed lesser cracks than untreated fibers with 3% BFA. Filler particle reduces the flush off and pullout of hybrid fibers and improved the machinability of the natural composites [24].

The figure 14(c) and (d) showed EDX images of 30 wt% PS/3% BFA and 30 wt% PS/1% BFA composites. The 3% BFA composites showed K, Ca, C, Ti, O, Mn, Fe, Mg, Al, Si, P elements and 1% BFA composites with Cl, K, Ca, O, Mg, Al, Si, P in their combinations. All these elements in BFA form inorganic compounds which improved the machinability of natural composites.

In the second set of combinations with treated 30 wt% PS/3% CFA (figure 15(a)) showed crack network and fiber breakages in their combinations. Hardness of this combination produced lesser machining properties with fiber deformations. The EDX image of same combination showed (figure 15(b)) K, Ca, Ti, O, Fe, Mg, Si and P elements in its composition.
In the final combination of composites (figure 16(a)) with untreated 30 wt% PS/3% BGFA showed interface crack and other heavy cracks. Untreated fibers possess lesser adhesion between fiber and matrix due to -OH content in the fiber surface causing surface deformations during the machining. The second combination with (figure 16(b)) treated 30 wt% PS hybrid composites were observed with erosion of fiber reinforcement due to no filler substitution. Filler enter into the void gaps of fiber/matrix interface and improved the machining characteristics of the natural composites (figure 16(c)), treated 30 wt% PS/3% BGFA showed this properties. The elements in the treated 30 wt% PS/3% BGFA composites were showed in EDX with figure 16(d), the
combinations contains S, K, Ca, O, Mn, Fe, Na, Mg, Al, Si and P elements in their composite surfaces which enhances the machining properties of composites.

5. Conclusions

- The addition of flyash fillers such as BFA, CFA and BGFA at 3% enhanced the mechanical properties of hybrid sisal/pineapple fiber composites
- In the machining characteristics using AWJM, filler substitution increases the MRR and decreased the surface roughness nature of hybrid PS composites.
- Maximum MRR was observed at 1% BFA and 1% CFA mixing due to lesser hardness compared to 3% BFA and 3% CFA combinations.
- The increase in WP and TS increased the MRR and surface roughness of the composites.
- Maximum MRR of 376.38 mm³ min⁻¹ was observed in 3% BGFA combinations with 250 MPa WP, 1mm SOD and 20 mm min⁻¹ TS. Slightly similar MRR of 353.64 and 352.76 mm³ min⁻¹ was found out in 1% CFA/250 MPa WP/1mm SOD/20 mm min⁻¹ TS and 1% BFA/150 MPa WP/1mm SOD/50 mm min⁻¹ TS.
- Lower surface roughness of 6.39 μm, 6.71 μm and 6.75 μm was found in 3% BGFA, 1% CFA and 1% BFA based epoxy composites. Untreated fibers showed lesser machining properties due to low fiber/matrix bonding.

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