A novel machine and method for milling continuous fibers

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Received 22 August 2014; accepted 1 July 2015

A novel machine for milling continuous fibers into discrete lengths is presented. Methodology for milling variety of fibers using present machine is devised. The machine is designed and developed based on the concept of cattle grass cutter. More specifically, it employs the principle of shaving razor, i.e., shearing. The machine chiefly comprises a stationary blade, a moving blade and a feeding roller. The cutting edge design and the usage of novel material for blades enable the minimum contact between stationary and moving blades, which results in highly accurate milling of continuous fibers to very fine lengths of the order of few micrometers. The discrete length milled fibers are characterized through scanning electron microscope (SEM) for the fineness and accuracy. The SEM micrographs show that the machine mills the fibers accurately and efficiently. The machine provides the flexibility of milling variety of fibers with un-interrupted feeding of multiple tows and produces milled fibers of uniform length with square cut ends by achieving close tolerance. The incorporation of the liquid bath, provision of multiple tows feeding and the novel carbide tip at the base of both the stationary blade and moving blade make it an efficient, user friendly and safe machine in milling multiple tows un-interruptedly to uniform length. Lab scale cost analysis of milling strategic fibers like carbon fibers is found very minimal, which shows the good scope of scaling the machine in a cost effective manner for the production of short fibers from continuous fibers.

Keywords: Milling machine, Continuous fibers, Milled fibers, Rollers, Blades, Sagging, Dropping, Winding, Cost analysis

Composites are the advanced materials, which are used for high performance applications where lightweight with competent properties to those of conventional materials is required. Several types of composites have been developed and still being developed. These are mainly classified based upon matrix and reinforcement. Based upon matrix and reinforcement these are further classified into several categories. One of the important category of composites based upon reinforcement is short fiber reinforced composites. In last couple of decades, enormous work on the development of composites has been done1-7. However, more focus was given on continuous fiber reinforced composites. In last few years, the short fiber reinforced composites have attracted researchers, material developers and designers because of ease in their fabrication and low cost of processing8,15. Additionally, the flexibility of moulding short fiber reinforced composites into complex shapes and isotropic properties make them further viable over continuous fiber reinforced composites13,16,17.

The end properties of short fiber reinforced composites depend upon various parameters. However, the critical length of reinforcement and the degree of dispersion are the major factors which greatly dominate their properties18,19. Further, the accurate and uniform aspect ratio of reinforcement helps in predicting the end properties of short fiber reinforced composites. The more accurate and uniform is the aspect ratio; the better is the prediction of end properties. Additionally, to make short fiber reinforced composites commercially viable, easy, cost-effective and versatile; the advanced fiber milling machines are the need of the hour. Though cutting, chopping and milling of fibers is very common in textile industry, the milling of advanced fibers like ceramic and carbon is not much explored. Further, the machines and techniques of milling used in textile industry, don’t give discrete length fibers of micrometer size. Additionally, the control over surface damage is also not so critical in textile industry. On the other hand, both control over surface damage and lower aspect ratios are most important for high end composites16.

Presently, most of the researchers and designers, as reported in literature, use scissor for milling advanced continuous fibers into discrete length fibers. The usage of scissor for milling continuous fibers results in large variation in the length of discrete fibers as well as lack of square cut ends. Further, these

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methods have many limitations in milling fibers to micrometer level. They may cause longitudinal cracking of fibers, rupture of fiber filaments, etc. Additionally, these processes take lot of time. Hardly, any literature is available where milling of high end fibers has been done using milling machines. However, some of the milling machines have been reported for advanced fibers. But, most of these are used for the milling of metal fibers with low level of tolerance and with interrupted feeding. Hence, it is the objective of the present invention to design, develop and install a novel milling machine with a methodology to mill variety of fibers ranging from low modulus polymer fibers to very high modulus carbon fibers. The machine provides the flexibility of milling even flexible to brittle fibers into micrometer size discrete fibers with very fine accuracy.

**Experimental Procedure**

A schematic representation of fiber milling machine (16) is shown in Fig. 1. Based on this general scheme, a fully functional milling machine has been designed, developed and tested. The machine, as installed, is depicted in Fig. 2. The close-ups of front view and side view of the milling assembly comprising moving blade, stationary blade and moving roller along with other accessories of the machine are shown in Fig. 3. The continuous fibers (14) to be milled are bounded over the first fiber spool holder (1) and the second fiber spool holder (2). The number of these fiber spool holders can be increased or decreased depending upon the number of continuous fiber tows to be milled. A set of three aligning rollers (3) aligns the continuous fiber tows (14). The continuous fiber tows (14) are zigzag till they reach the set of three aligning rollers (3). The continuous fiber tows (14) need to be aligned before passing to the horizontal roller (4). The distance between the three aligning rollers (3) can be increased or decreased depending upon the size of the continuous fiber tows (14) to be milled. If the

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**Fig. 1 — Schematic representation of the milling machine**

1. The first fiber spool holder
2. Second fiber spool holder
3. A set of three aligning rollers
4. Horizontal roller
5. Tension roller
6. Liquid bath
7, 8. Pair of guiding rollers
9, 10. Pair of moving rollers
11. Rectangular fixed head
11A. First side of the rectangular fixed head
11B. Second side of the rectangular fixed head
12. Stationary blade
12A. First side of the stationary blade
12B. Second side of the stationary blade
13. Moving blade
13A. First end of the moving blade
13B. Second end of the moving blade
13C. Carbide tip of the moving blade
14. Continuous fiber tow
15. Moving head
15A. First end of the moving head
15B. Second end of the moving head
16. Fiber milling machine

**Fig. 2 — The machine as installed**
continuous fiber tows (14) to be milled are of very less thickness, then the distance between the aligning rollers (3) shall be decreased. Or else the zigzag continuous fiber tows (14) will not get aligned or straighten before they reach the horizontal roller (4). If the continuous fiber tows (14) to be milled are of thickness comparatively higher than the standard distance between the vertical rubber rollers (3), then the distance between the aligning rollers (3) shall be adjusted in such a way that the thickness of the continuous fiber tows (14) remains slightly more than the distance of aligning rollers. The thickness of the tows and distance between aligning rollers is most important for getting flawless milled fibers. Hence, it shall be adjusted judiciously. If the distance maintained is very less, then the continuous fiber tows (14) may undergo undue stress. Hence, to avoid undue stress and to get proper alignment or straightening it is indispensable to maintain proper distance between the aligning rollers (3). Maintaining proper distance between the aligning rollers depends upon the size of the fiber tow and types of the fiber to be milled.

The horizontal/junction roller (4) is positioned immediately after the set of three rollers (3). The horizontal roller (4) further aligns the continuous fiber tows (14). Further, all the continuous fiber tows (14) to be milled travel separately in the form of individual fiber tow as it comes out from fiber spool till they reach the moving blade (13). However, all the continuous fiber tows (14) get in touch at this horizontal/junction roller (4) if fiber tows have lower $K$, where $K$ is number of filaments. In case of higher $K$ fiber tows, the individual fiber tow is fed to individual circular slit (Fig. 4). A tension roller (5) is immersed in liquid bath (6) to tense the continuous fiber tows (14). The liquid bath (6) is provided to
keep the fiber filaments intact together and to avoid fur generation. The fur generation is more in abrasive fibers due to their brittle nature. This fur causes safety issues due to inhalation by the operator. Apart from it, the major issue involved with this fur is the interruption in the continuous feeding of the continuous fiber tows (14) to the slits (Fig.4) of the feeder or fixed head (11). Due to this interruption, the fiber tows start sagging/dropping down in between the feeder (11) and the moving rollers (9, 10). The complete process of fiber sagging/dropping is shown in Fig. 5. The sagging/dropping of the continuous fiber tows (14) can be controlled by stopping the adieu of fur/broken filaments from the continuous fiber tows (14). It is done by passing the continuous fiber tows (14) through the liquid bath (6) prior to feeding the slits of the feeder. The main motive of this liquid treatment is to provide the energy to the continuous fiber tows (14) so that the interaction of inter filament level can increase. The increase in the filament interaction keeps the broken filaments intact with the continuous fiber tows (14) so that the feeding will not get interrupted. Various types of liquid are available for this purpose. However, selection of suitable liquid among these available liquids for particular fiber system is very complex and critical. Hence, due care shall be given for the purpose.

Wetability is the most important parameter in the selection of the liquid to avoid the adieu of broken filaments from the fiber tow. The wetting liquid used, in the bath to keep most of the broken filaments intact with the continuous fiber tows, is selected based upon its wettabiliy with the fibers to be milled. It can vary with fiber to fiber. But for carbon fibers, water is found most suitable compared to other wetting liquids. The carbon fibers are of three types such as rayon based carbon fiber, pitch based carbon fiber and PAN based carbon fiber. The rayon based carbon fiber is obsolete now a day because of inferior properties. The remaining two fibers are different to each other. In addition to this, other fibers like ceramic, polymer, etc., also have different wettabiliy with water and other liquids.

A pair of guiding rollers (7,8) and a pair of moving rollers (9,10) are incorporated in the present milling machine for guiding and moving the continuous fiber tows (14). In the pair of moving rollers (9,10), the roller (10) is driven by the geared motor whereas roller (9) acts as guiding roller. The material of construction of rollers plays a very crucial role in damage free un-interrupted fiber feeding. If the rollers are made from materials like steel or ceramic then, higher tightening is required to avoid slippage. Slippage free higher tightening causes damage to filaments’ surface, which lowers down the properties of fiber products such as short fiber reinforced composites. The guiding rollers (7,8) and the moving rollers (9,10) which are made from rubber alone resulted in damage free fiber surface. However, winding of fiber filament over the moving roller (10) is observed with rubber rollers. This winding mechanism of fibers and then fiber tows over moving roller is shown in Fig. 6. Finally, these guiding rollers (7,8) and the moving rollers (9,10) are made up of a combination of rubber and steel. One roller from each of the set is made from steel and other one from rubber. The rollers (guiding rollers and moving rollers) with rubber and steel are selected to avoid slippage and filament surface damage. As the guiding rollers (7,8) and the moving rollers (9,10) are made of rubber and steel, the continuous fiber tows (14) are found with correct interaction with the rollers thereby avoiding the slippage of the continuous fiber tows (14) from the guiding rollers (7,8) and the moving rollers (9,10). The guiding rollers (7,8) and the moving rollers (9,10) which are made from rubber and steel materials protect the continuous fiber tows (14) from filament surface damage at higher
tightening. By protecting the filament surface from damage, the properties of the continuous fibers are maintained without any degradation.22

A rectangular fixed head (11) is designed to have circular slits at its center. The two slits and three slits systems are shown in Fig. 4. The number of slits can be further multiplied as per the requirement. The circular slits are used to feed the continuous fiber tows (14). The first side (11A) of the rectangular fixed head (11) is exposed for the feeding of continuous fibers. The second side (11B) of the rectangular fixed head (11) is exposed to hold stationary blade (12). The stationary blade (12) of the present system, as depicted in Fig. 4a, has two circular slits which coincides with the slits of the rectangular fixed head (11). The slits of the stationary blade (12) and the rectangular fixed head (11) are designed to coincide with each other to avoid any friction due to different size and type of stationary blade’s (12) slits and rectangular fixed head’s (11) slits. The first side (12A) of the stationary blade (12) is attached to the rectangular fixed head (11) through bolt mechanism. The second side (12B) is exposed to milling operation by moving blade (13). The first end (13A) of the moving blade (13) is attached to the moving head (15). The second end (13B) of the moving blade (13) is used for milling the continuous fiber tows (14). The first end (15A) of the moving head (15) is connected to the electric motor. The second end (15B) of the moving head holds the moving blade (13) through conventional means.

The circular slits (Fig.4) present in the rectangular fixed head (11) feeds the fiber with the help of the moving rollers (9,10). The feeder slits’ shape and size play an important role in the feeding of the continuous fiber tows (14). The horizontal rectangular slits are suitable for the higher $K$ fiber tows whereas circular slits are suitable for the lower $K$ fiber tows. The higher $K$ fiber tows are like a strip/tape, hence horizontal rectangular slits with 1.45 times of the width and 1.55 times of the height of the higher $K$ fiber tows are found optimum with respect to uniform milled length of discrete fibers and smooth feeding. Circular slits with 1.5 times the diameter of the lower $K$ tows are found suitable.

The base of the moving blade (13) is made up of harden steel. The milling tip of moving blade (13) is made up of indigenously developed ultra high hardness carbide. This carbide tip (13C) is joined with the base of the moving blade (13) with brazing technology. The electric motor used to move the blade is a variable speed geared motor. Its rpm varies from 0-120. The stationary blade’s (12) base is made up of harden steel. However, its surface exposed for shearing mechanism with moving blade (13) is made up of indigenously developed ultra high hardness carbide which is again joined with base of stationary blade (12) with brazing technology.

The reciprocating speed of the moving blade (13) is variable and it operates in three modes, i.e., 120, 60 and 30 stocks/min. The maximum reciprocating speed of the moving blade (13) is 120 stocks/min and minimum 1 stock/min. But as per the required length of the milled fibers, it operates in three modes, i.e., 120, 60 and 30 stocks/min. It changes its mode automatically depending upon the input milled length of fibers. For a length of 100-1500 µm milled fibers, it operates @ 120 stocks/min. For a length of 1500-5000 µm milled fibers, it operates @ 60 stocks/min. For a length of 5000-10000 µm milled fibers, it operates @ 30 stocks/min. At mode-1 (120 stocks/min), the speed of the moving roller (10) varies from 0.2 to 4 rpm as per the preset length...
of the milled fibers. At mode-2 (60 stocks/min), the speed of the moving roller (10) varies from 1.5 to 6 rpm as per the preset length of the milled fibers. At mode-3 (30 stocks/min), the speed of the moving roller (10) varies from 3 to 6 rpm as per the preset length of the milled fibers. The length of the milled fibers is controlled by the mode of the moving blade (13) and the rpm of the moving roller (10). The entire operation of controlling length of the fibers is made automatic. The required milled length of the fibers is fed to the controller and the modes of moving blade and the feeding roller are adjusted accordingly.

Results and Discussion

Experimental trials are conducted using variety of carbon fibers, silicon carbide fibers, etc. The continuous fiber spools are fed to the spool holder and milling into different lengths is done. The performance of the milling machine is further clarified by the trials conducted with variety of fibers.

Trial — 1

High modulus pitch based continuous carbon fiber tows (P-75 grade) comprising 2000 filaments are milled into discrete fiber lengths of 3 mm. Two fiber tows are milled simultaneously and milled fiber lengths are inspected visually as well as microscopically. The digital image of milled carbon fibers is depicted in Fig. 7b. The SEM micrographs of milled carbon fibers are shown in Figs 7c and 7d. From SEM micrographs of the milled carbon fibers, it can be seen that the milled length of carbon fibers is very accurate. Though some breakage of fibers to lower length has occurred, the ends of milled carbon fibers are perfectly square cut. It shows the excellent performance of the milling machine for high modulus carbon fibers.

Trial — 2

High strength and low modulus PAN based continuous carbon fiber tows (T-800 grade) comprising 24000 filaments are milled into discrete fiber lengths of 3 mm. Here also, two fiber tows are milled simultaneously. The inspection of the cut lengths is again done through visual and SEM. The digital image of the milled carbon fibers is shown in Fig. 8b. The SEM micrographs are shown in Figs 8c and 8d. Here also, from SEM micrographs, it can be observed that the level of cut length accuracy is very high and the ends are perfectly square cut. Further, the breakage of fine fibers is very less in this as compared to pitch based high modulus P-75 grade carbon fibers’ milling. The main cause behind the less breakage of PAN based carbon fibers into small lengths is the higher elongation of the PAN based carbon fibers.

Fig. 7—Schematic representation of milling of continuous fibers (a) High modulus P-75 grade carbon fiber spool, (b) digital image of milled fibers of 3 mm length, (c) low magnification SEM micrographs of milled fibers, (d) higher magnification SEM micrographs of milled fibers
In order to check the performance of milling the continuous fibers to micrometer lengths, the pitch based continuous carbon fiber tows (P-75 grade) comprising 2000 filaments are milled into discrete fiber lengths of 400 µm. In this case also, two fiber tows are milled simultaneously and milled fiber lengths are inspected by visual inspection and SEM. The digital image of milled carbon fibers is shown in Fig. 9b. The SEM micrographs of milled carbon fibers are depicted in Figs 9c and 9d. From the digital image of the milled carbon fibers, it can be seen that the milled fibers are almost like a powder. It reflects the ability of the machine to mill the fibers to a finer length. Further, performance validation can be done by seeing the SEM micrographs. The SEM micrographs show that almost all the milled fibers have a square cut ends. The square cut ends of the milled fibers are desirable. Some fibers of length shorter than the milled lengths are also seen in the SEM images. This has happened due to slight breakage of fibers due to brittleness. However, the length of the milled fibers is not found more than the set length. This shows the excellence of the milling machine even for finer cut lengths. Further, various types of short fiber composites fabricated by the usage of the milled fibers of the milling machine of the present invention and the product made thereafter are shown in Fig.10.

**Cost analysis**

The cost analysis of the lab scale version of the milling machine with two tows milling is done. The basic cost of electricity, labor input and consumables is taken into consideration for computing the milling cost. Since the machine is fully automatic, the actual man hour required to run the machine for 10 h is only taken into consideration. Further, the typical length of milled carbon fibers is taken 3 mm. Based upon the above mentioned conditions, the typical milling cost, as depicted in Table1, is worked out. The unit cost depends upon various parameters and the one most important parameter is the length of the milled fibers. Based upon the length of milled fibers, cost may vary. For longer length milled fibers, the unit cost may come down whereas for shorter length milled fibers, the unit cost may go up. Though the unit milling cost of the lab scale machine, as shown in Table 1, is very minimal, it may further come down many folds for the industrial version of the milling machine.
Fig. 9—Schematic representation of milling of continuous fibers (a) High modulus P-75 grade carbon fiber spool, (b) digital image of milled fibers of 400 µm length, (c) low magnification SEM micrographs of milled fibers, (d) higher magnification SEM micrographs of milled fibers.

Fig. 10 — Schematic representation of the various short fiber composites and their products and SEM micrographs (a) C/SiC composite, (b) C/C composite, (c) C/Al composite, (d) C/SiC composite bipolar plate, (e) C/C composite pressure transducer fixture, (f) SEM micrograph of C/SiC composite, (g) C/C composite fastener, (h) higher magnification SEM micrographs of C/C composite.
Table 1 — Milling cost analysis

<table>
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<th>Fiber type</th>
<th>Milling length (mm)</th>
<th>Milling/10 h (g)</th>
<th>Milling cost/10 h (Rs)</th>
<th>Milling cost/g (Rs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-300</td>
<td>3</td>
<td>42.12</td>
<td>105</td>
<td>2.49</td>
</tr>
<tr>
<td>T-800</td>
<td>3</td>
<td>209.52</td>
<td>105</td>
<td>0.50</td>
</tr>
<tr>
<td>P-75</td>
<td>3</td>
<td>75.6</td>
<td>105</td>
<td>1.39</td>
</tr>
</tbody>
</table>

Conclusions
The milling machine with a flexibility to mill multiple fiber tows without any kind of interrupted feeding is designed and developed. The entire operation, setting of the length of the milled fibers to milling, is made fully automatic. Further, the milling of fibers using the machine is done effectively with a very fine tolerance and perfect square cut ends, and without damaging the fiber surface. The milling machine is found suitable for milling variety of fibers like ceramic, carbon, polymer, etc., with very fine tolerance. The milling machine is designed in such a way that it can be scaled up to mill fibers on mass production basis by increasing the number of slits in stationary blade and blade holders, and accordingly enhancing the size of milling blade.

Acknowledgments
Author is grateful to the testing divisions of Vikram Sarabhai Space Centre for rendering their humble and timely support in characterizing the milled carbon fibers. Author is thankful to Mukesh Bhai, Hentry, V K Vineeth, Omendra Mishra, S Babu, A Prabhakaran Pillai, V Viswabaskaran, C Simon Wesley, V Chandrasekaran, S C Sharma and P P Sinha for their valuable suggestions and assistance in the design and development of the milling machine and the trials thereafter.

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