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Effect of MR Fluid Damping during Milling of CFRP Laminates

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ABSTRACT
Machining of fiber reinforced composites is an essential activity taken up in order to integrate them with other components. Carbon fiber reinforced polymer (CFRP) composites are difficult to machine owing to the non-homogeneity of their constituent materials and abrasive nature. As these materials involve more than one phase, the variation of cutting forces is rather large, which leads to tool chatter and poor surface finish. Therefore the proper selection of the tool, process parameters and the ability to control the machining forces would result in better tolerances and improved surface finish. In this study, multiple slots are machined in CFRP laminates under different machining conditions of spindle speed, feed and depth of cut. A comparative study is made by conducting the same set of experiments under the influence of the magneto- rheological (MR) damping in order to assess the tool deflection. It is observed that the MR fluid damping reduces the tool deflection and thus improves the quality of machined surfaces.

Keywords: Carbon Fiber Reinforced Polymer (CFRP), End milling, Magneto-Rheological (MR) fluid damping, Tool deflection

I. INTRODUCTION

Carbon Fiber Reinforced Polymer composites are widely used in aerospace, automotive and aviation industry due to their excellent structural and thermal properties. These advanced materials are light in weight; hence their specific strength, stiffness and hardness are high. Generally the composite laminates/components are produced to their near net shape by various methods. As these components have to be integrated with other components made from conventional materials, it requires them to be joined in various ways due to which the machining of these laminates becomes inevitable. Close dimensional tolerances and surface finish are the essential requirements for various applications. Whenever the laminated components are assembled together then the performance of the joint or the fit obtained depends critically on the quality of the mating machined surfaces. Milling is one of the most common machining operations performed in industries. Many recent advancements in controls and machining technologies have lent support to popularize the use of this operation. Researchers have studied the dynamics of end milling process in which instantaneous cutting position of the cutter was found to affect the metal cutting forces. A.I.Azmi et al. [1] discussed the machinability of glass fiber reinforced composites (GFRP) during end milling by using Taguchi's method of design of experiments. The machinability of GFRP laminates was studied with respect to surface roughness, tool life and machining forces. Experiments were conducted under different cutting conditions by considering cutting speed, feed rate and depth of cut as factors at three levels according to the Taguchi design of experiments method. Karpat et al. [5] proposed a mechanistic force model for milling of CFRP by collecting cutting force data during slot milling of CFRP using polycrystalline diamond cutters. The model is shown to be capable of predicting cutting force during milling of multidirectional CFRP laminates. The relationship was represented with simple sine functions. Hocheng and Puw [7] investigated the cutting of unidirectional CFRP composites using a single square carbide insert. The researchers found that work piece fiber orientation had a significant effect on the formation of burrs and surface roughness. Good quality surface finish was obtained on the machined surface when the tool was fed along the fiber orientation. Paulo Davim et al.[6] evaluated the cutting parameters for milling of GFRP composite laminates with the aim to minimize the delamination factor and to maximize the surface finish. ANOVA technique was utilized to obtain the set of optimum cutting parameters for the two objectives. Rahman et al.[9] studied the machinability of CFRP composites with various cutting parameters with three types of cutting tool materials, namely uncoated carbides, ceramics and Cubic Boron nitride(CBN). The CFRP specimens had short (discontinuous) and long (continuous) fiber reinforcements. It was reported that the carbide tool performed better at low cutting speeds, whereas the performance of CBN tool was better than that of the others at high cutting speeds. Koplev et al.[8] contributed the first chip formation studies through orthogonal cutting of CFRP composites in the 0^o and 90^o fiber orientations. Devi Kalla et al. [5] developed a methodology for predicting the cutting forces by transforming specific cutting energies from orthogonal cutting to oblique cutting of CFRP composites. R.Madoliat, S.Hayati et al., [10] investigated the suppression of chatter of slender end mill via a frictional damper. It was shown that the friction damper improved the quality of surface finish during the end milling process .Palani Kumar et al., [11],[12] studied the delamination factor in case of drilling and chatter in boring of GFRP composites.

In the present study, an innovative method of MR damping has been utilized in order to suppress the deflections of the end mill during machining. Investigations are carried out by cutting multiple slots in CFRP laminates by considering all the combinations of different process parameters like speed, feed and depth of cut. The effect of the variation of these parameters on tool deflection is investigated under the influence of MR damping.

II. MATERIALS AND TOOLS

Work piece material: Bi directional ($0^0/90^0$) CFRP laminates were fabricated by using woven carbon fiber cloth, epoxy resin (LY556) and hardener (LY551) to a size of 330mm x 170mm x 8 mm by hand layup process as shown in figure 1. These laminates were first tested for their tensile strength, flexural strength and hardness. All these characterisation tests are performed as per ASTM standards.

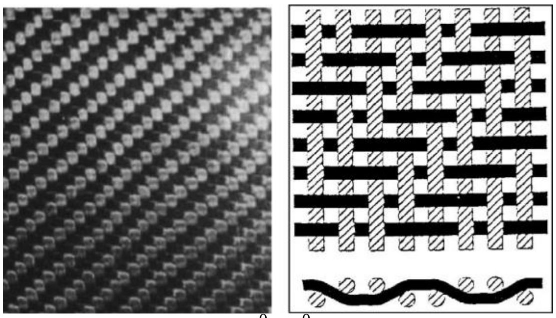

Fig.1 Bi-directional ($0^0/90^0$) woven carbon fiber [6]

Cutting Tool: A four fluted tungsten Carbide end mill (K20) of diameter 6mm and having equal shank and flute lengths of 50mm is selected for machining. Its helix, relief and clearance angles are 30^o, 9^0 and 16^o respectively. Forces during machining (F_m) are measured in the x direction (F_x – feed force), y direction (F_y – cutting force) and z direction (F_z – thrust force) by means of a 3-axis piezoelectric dynamometer. The resultant machining force machining force is obtained by using the relationship $F_m=\sqrt{F_x^2+F_y^2+F_z^2}$. The milling process involving the up and down cuts along with the feed direction is shown in figure 2.

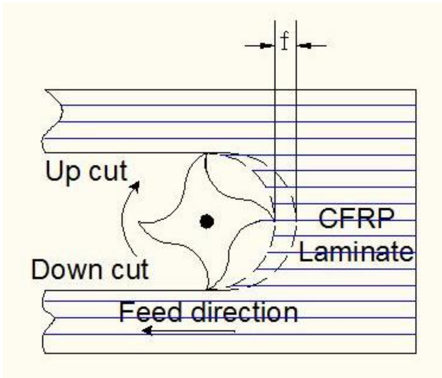

Fig.2 Milling operation

Magneto rheological fluid and MR Damper:

Magneto Rheological (MR) fluids are colloidal suspensions which exhibit large reversible changes in flow properties such as the apparent viscosity when subjected to sufficiently strong magnetic fields. They usually consist of micron-sized magnetizable solid particles dissolved in a non-conducting liquid like mineral or silicone oil. MR fluid acts like a Bingham fluid and the variation of yield stress with respect to magnetic field intensity is non-linear as shown in figure 3.

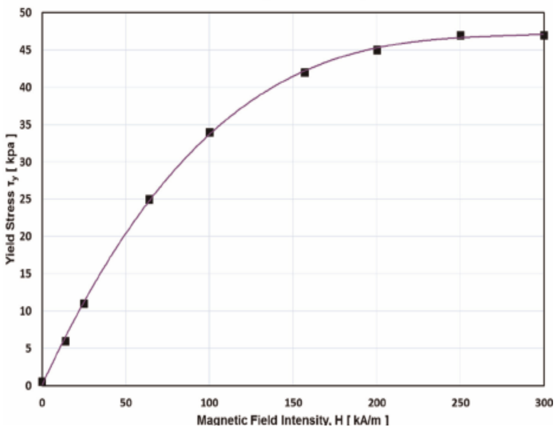

Fig.3 Yield stress Vs Magnetic field intensity [13]

MR fluid dampers enable active and semi-active vibration control systems with reaction times in the range of milliseconds with lower power requirements. The damper consists of a cylinder filled with MR fluid and a piston over which a coil is wound. The gap between the cylinder and piston is kept at a constant value of 0.4 mm. When the current is supplied to the coil, the suspended particles in the MR fluid form chains and hence there is an apparent increase in its viscosity. This help in developing variable damping which is useful for many applications like vehicle suspension, earth quake mitigation, suppression of the vibrations during machining, prosthetics etc.

III. EXPERIMENTATION

The experimentation is performed on a conventional vertical milling machine with the provision of attaching a magneto-rheological damper to the end mill. A dial gauge was used to test the run out of the machine spindle. The CFRP laminate is taken and a sample is prepared in accordance with the size of fixture available on the milling machine. The damper assembly comprises of clamps, T-shaped welded plate to support the damper and ball bearing of 6mm inner diameter through which the end mill shank passes. The MR damper with the associated fittings is attached to the machine as shown in figures 3 and 4. A vibration tester is employed as a diagnostic tool for preventive maintenance of the system involving the measurements of the RMS value of tool deflection. The magnetic probe is attached to the rotating end mill cutter covered by an assembly which is provided to prevent the abrasion of the contacting probe. A regulated current is supplied to the damper coil by using an ammeter.

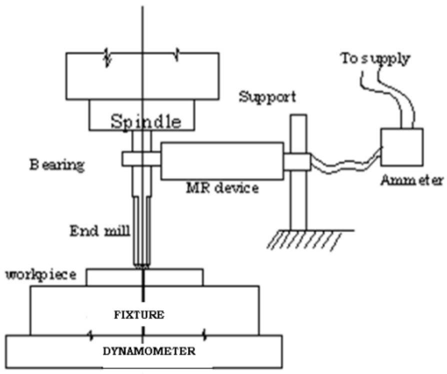

Fig. 3: Schematic diagram of Milling setup

Fig. 4: Experimental setup for milling

The experiments were carried out at three different spindle speeds of 315, 400 and 500 rpm; three different feeds of 32, 40 and 50 mm/min at three depths of cut of 0.3, 0.4, 0.5 mm. As there are three factors involved at three levels, the total numbers of experiments is 27 as per the full factorial experimental design. The machining of CFRP laminates involves the interaction between the tool and its various phases i.e. carbon fibers and epoxy resin. Chatter arises due to the continuous variation in the cutting forces as a result of which the tool in contact with work piece is deflected. Multiple slots are produced as per the design of experiments without the use of MR damper. The same set of experiments is repeated under the influence of the magneto rheological damping. The coil current is incremented from 0.2A to 2.0A in order to increase the damping force. The coil current cannot be increased beyond 2.0A as the properties of MR fluid reach the saturation value. The deflection of the tool in both the cases is compared.

IV. RESULTS AND DISCUSSIONS

When the damper is connected to the tool and the coil current is increased, the deflections are reduced gradually. The maximum effect of damper is observed at the saturation current 2A as shown in figure 5. This behavior is observed when milling is carried out at different combinations of process parameters.

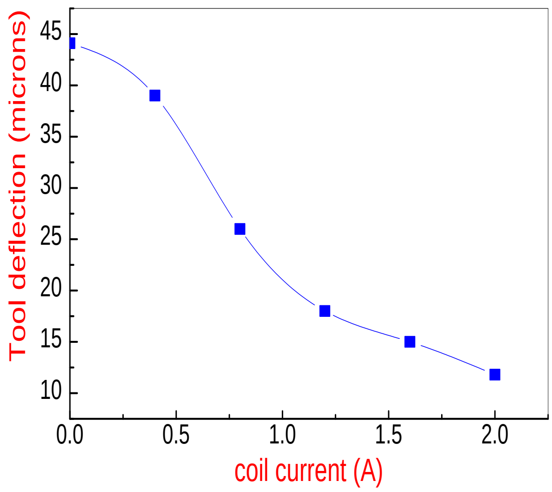

Fig.5 Tool deflection Vs Coil current

The behavior of the tool without (w/o) and with damper assembly is shown in figure 6. It is observed that the tool deflection increases with an increase in feed rate for a given spindle speed and depth of cut. . An increase in the feed rate causes an increase in cross section area of the undeformed chip thereby resulting in an increase in machining force and hence the tool deflection. Under the influence of MR damper at maximum current, it is observed that the deflection decreases though the feed is increased at different speeds.

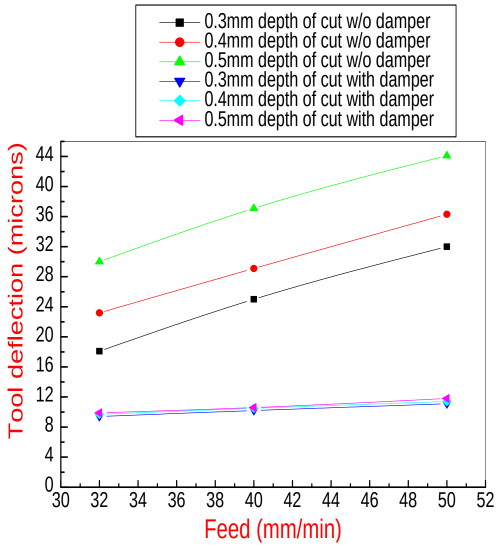

Fig.6.Tool deflection Vs feed at 800 rpm

It is also observed that as depth of cut is increased, the deflections also increased for a given feed and speed as shown in figure 7. The effect of increase in speed on the deflection was lesser when compared to that of feed and depth of cut. A similar trend is observed at higher speeds but the deflections reduce at higher speeds for a given feed and depth of cut It is clearly evident from this figure that the tool deflections are reduced due to MR damping. When the machining is performed under the influence of MR damping, it is observed that the tool deflections are reduced by 71%, 70% and 68% as the coil current is increased to a maximum of 2A at 315, 500 and 800 rpm respectively.

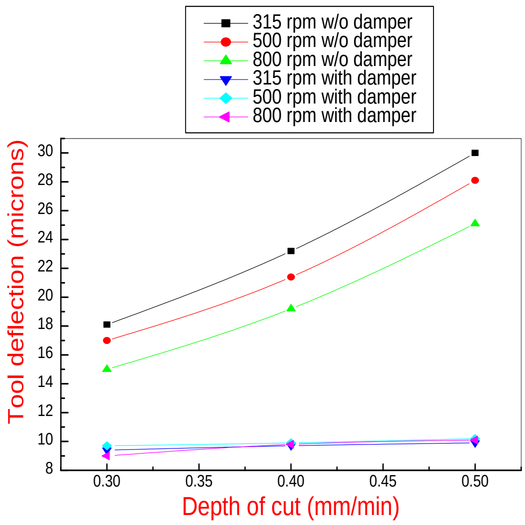

Fig.7. Tool deflection Vs depth of cut at feed 50mm/min

V. REGRESSION ANALYSIS

The regression equation for the tool deflection (δ) in the absence of the MR damper is given by

$$\delta = -15.9 - 0.00955\ N + 0.696\ f + 51.7\ doc$$

Predictor	**Coef**	**SE Coef**	**T**	**P**
Constant	-15.917	2.141	-7.43	0.000
Speed (N)	-0.00954	0.00135	-7.06	0.000
Feed (f)	0.69627	0.03671	18.97	0.000
Depth of cut (doc)	51.667	3.310	15.61	0.000

S = 1.40450 R-Sq = 96.6% R-Sq(adj) = 96.2%

The regression equation for the tool deflection (δ') in the presence of the MR damper is

$$\delta' = -15.3 - 0.00827\ speed + 0.566\ feed + 35.6\ doc$$

Predictor	**Coef**	**SE Coef**	**T**	**P**
Constant	-15.327	2.604	-5.89	0.00
Speed (N)	-0.0082	0.00164	-5.03	0.00
Feed (f)	0.5655	0.04464	12.67	0.00
Depth of cut (doc)	35.556	4.026	8.83	0.00

S = 1.70821 R-Sq = 92.0% R-Sq(adj) = 90.9%

The deflection of the tool can be minimized in the absence of MR damping to less than 20µm when the feed is maintained at 34 mm/min along with depth of cut of 0.34mm as shown in the contour plot of the response surface analysis, figure 8. When machining is carried out at 40mm/min and 0.4 mm depth of cut, the deflections are reduced to less than 15µm under the influence of damping as shown in figure 9 at the same speed. The figure 10 shows the residuals plot of tool deflection in the presence of MR damping.

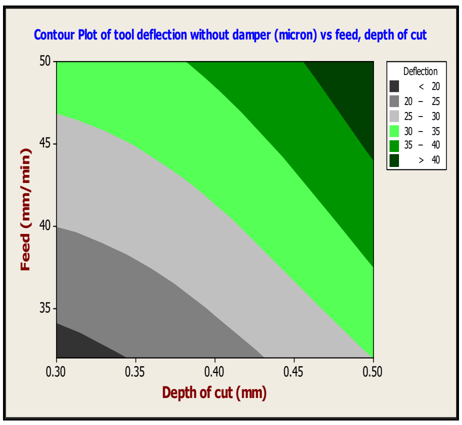

Fig.8. Contour plot of tool deflection without damper

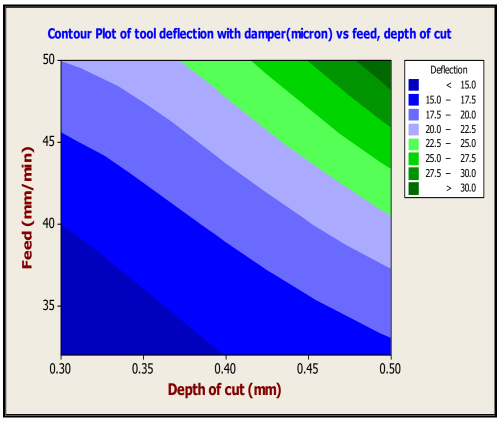

Fig.9. Contour plot of tool deflection with damper

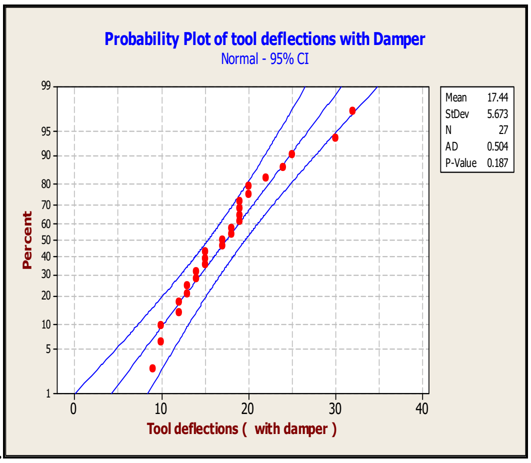

Fig.10. Probability distribution plot for tool deflection

VI. CONCLUSIONS

Milling of CFRP laminates was performed using tungsten carbide tool by varying the process parameters and it was observed that feed and depth of cut were the dominant factors that affected the tool deflection. In order to investigate the effect of magneto-rheological damping, the same set of experiments of milling was done in the presence of MR damper. It is observed that the MR damper reduced the tool deflection up to a maximum of 71% at 2A current. This reduction of tool chatter helps to maintain the dimensional accuracy, improve the material removal rate and surface finish of the machined surface.

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