Microstructural Analysis of Drilled Hole in CFRPs Using a Passive Magnetorheological Elastomer

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Abstract. In recent developments, Carbon Fiber Reinforced Plastics (CFRPs) components have drawn substantial attention in the aviation industry due to their environmental stability and lightweight properties. One of the most common machining operations carried out before the final assembly of any complex component is drilling, and drilling-induced delamination has drawn substantial attention from the research fraternity due to its impact on part rejection. Drilling thrust force plays a vital role in the delamination. In the present research study, the thrust force during the drilling of CFRPs is marginally suppressed using a passive magnetorheological elastomer. To incorporate passive MREs, a novel drilling fixture was designed and developed as per the design restrictions. The study comprises unidirectional and bidirectional fiber orientation to understand the impact of suppression of thrust force using the proposed novel approach. The result demonstrates the reduction of 13% and 16% in the drilling thrust force of unidirectional CFRP and bidirectional CFRP respectively, due to passive back-up provided by an isotropic MRE. Moreover, the present study also incorporates microstructural examination and its impact on reducing thrust force through scanning electron microscope examination. Microstructural examination reveals the layer wise damages and its effect on the unidirectional and bidirectional CFRPs.

Keywords: CFRP, Drilling, Microstructural analysis, Magnetorheological elastomer, Thrust force.

1 Introduction

In recent times, CFRPs have gained significant attention in the aviation and automotive sectors due to their superior properties, low coefficient of thermal expansion, low density, high strength-to-weight ratio, and excellent corrosion resistance [1-3]. These characteristics make CFRP an ideal material for the fabrication of various structural components in commercial aircraft and sports equipment in recent developments [4-5]. Depending on the design requirements, both unidirectional CFRP (UD-CFRP) and bidirectional CFRP (BD-CFRP) laminates are employed. BD-CFRP, offering enhanced stiffness and strength in multiple directions, is particularly suitable for components subjected to complex or multidirectional loading conditions [6-7]. For the various applications, BD-CFRP laminates orders to perform two types of machining process.

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To obtain near net shape from the raw materials, primary machining processes are performed like hand lay-up, autoclave and vacuum assisted resin transfer moulding (VARTM). In recent times, VARTM attracts attention over other primary methods due to its controlled fiber-to-resin ratio, improved overall mechanical properties, and better surface finish [8]. Some secondary operations, including as drilling, milling, and turning operations, are carried out to obtain close dimensional tolerance for the assembly of the complex parts. In the recent study, it was concluded that drilling is one of the most fundamental secondary machining operations, which use more than 40% time compared to other machining operation [9-10]. This drilling operation is very crucial for complicated components assembly. Due to structural inhomogeneity and anisotropic behavior of CFRP leads to various drilling-induced damages like, delamination, burr height, hole shrinkage, cylindricity, fiber pull out, micro cracking, chipping, and spalling [11]. Among these, delamination is the most critical damage and thrust force plays a key role in drilling-induced delamination. Therefore, suppression in thrust force eventually results in suppression in delamination. Thrust force suppression during drilling in CFRP can be obtained through either optimized tool design, high-performance drilling methods, or development of novel drilling conditions [12]. In recent times, numerous researchers have worked on the development of novel drilling conditions like adhesive layer, cryogenic cooling, minimum quantity lubrication, pilot hole, reverse air suctioning, spring-damper mechanism, support plate mechanism, and variable feed strategy and suppressed the thrust force in a range of 4 - 27% to reduce the drilling-induced delamination damages [13].

Wang et al. used a 5 mm solid carbide twist drill with and without mechanical spring-damper support to conduct drilling tests on a 16-layered CFRP laminate. Under spring-damper support, thrust force is reduced by nearly $1/4^{th}$ compared to the maximum value [14]. In recent times, magnetorheological (MR) materials have attracted attention due to their tunable damping and stiffness properties. These materials are extensively used in vibration isolators. Magneto resistor sensors and electromagnetic wave absorbers. MR Elastomer (MRE) has been used instead of MR fluid because of solid-state stability, eliminating issues like leakage and sedimentation while offering tunable mechanical properties under a magnetic field [15]. Patel et al. performed drilling experiments on 14-layered UD-CFRP and 12-layered BD- CFRP using a 4 mm high-speed steel drill with magnetorheological elastomer under different magnetic fields (0 mT to 480 mT), resulting in an overall 45% and 43% suppression in thrust force using MRE with maximum magnetic field, respectively [16].

The basic motive of the current research is to suppress the thrust force induced during the drilling of UD-CFRP and BD-CFRP using MRE, where magnetic field is passively developed using permanent magnet. To incorporate MRE in the drilling experiment, a specially designed fixture is fabricated and incorporated into drilling setup. A fixture was attached with a 4-component dynamometer to obtain real real-time thrust force recording.

2 Methods and materials

In this research, UD-CFRP and BD-CFRP specimens have been prepared using the same fabrication method. Using the VARTM technique, 14 layers of CTC1-FUD100 carbon fiber and CT/E 556 industrial grade epoxy resin were used to create a UD-CFRP laminate. Figure 1 shows the schematic of VARTM process. The thickness of 4.8±0.1 mm was obtained after curing of UD-CFRP laminate under room temperature and the volume fraction was maintained 59%. In contrast, a BD-CFRP laminate was created utilizing the VARTM technique with 12 layers of CTC1-FBD120 carbon fiber and CT/E 556 industrial grade epoxy resin. The thickness of the BD-CFRP laminate was 4.9±0.1 mm after curing at room temperature, with a volume fraction of 61%.

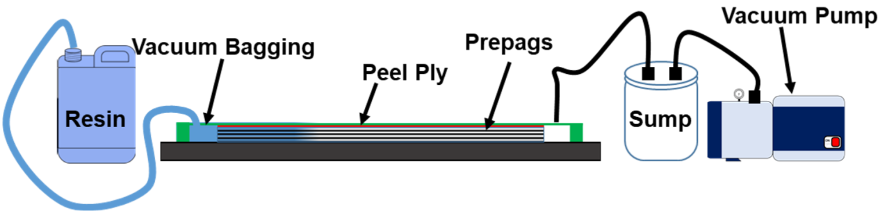


Fig. 1. Schematic representation of VARTM process

At the same time, an isotropic magnetorheological elastomer (MRE) had been developed utilizing irregularly shaped electrolyte iron particles (EIP) bought from Industrial Metal Powders, Pune and silicone rubber (SR) RTV-1010 purchased from Aditya Silicone in Delhi. The weight fraction was maintained 60/40 %w/w respectively and curing of an isotropic MRE was performed at ambient temperature and in the absence of a magnetic field. The figure 2 shows schematic of fabrication process.

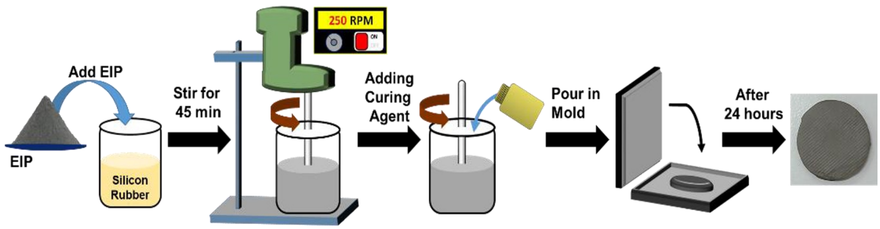


Fig. 2. Schematic representation of isotropic MRE fabrication

Various rheological properties like loss factor, storage modulus, and loss modulus of the prepared MRE were studied using a rotational rehometer Physica MCR 301 (Anton Paar, Graz, Austria) at Charotar University of Science and Technology, Changa, INDIA. The magnetic intensity was varied from 0A to 4A and the results were recorded at 310 K constant temperature. Figure 3 shows the storage modulus and loss modulus at different magnetic intensities. The graph shows that when magnetic intensity increases, the magnetic particles align in the direction of the field, resulting in enhanced energy storage.

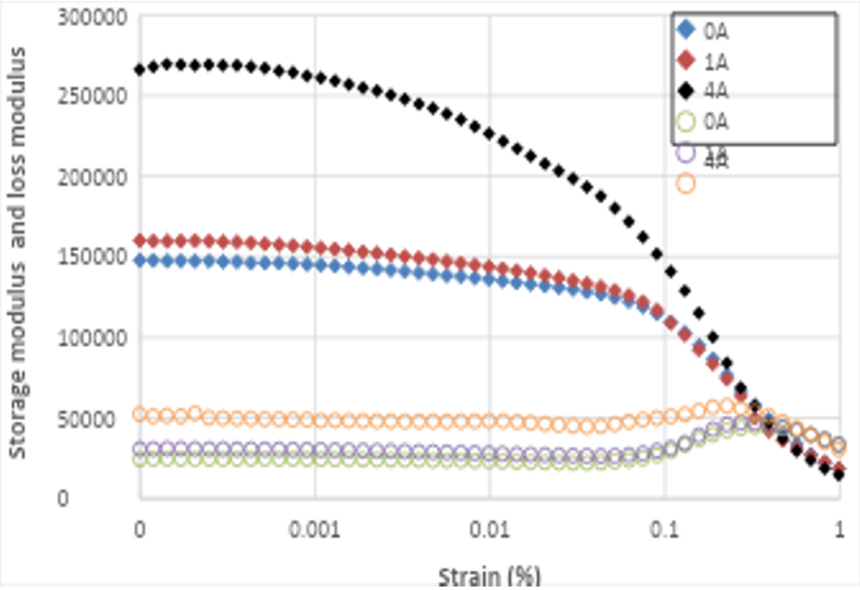
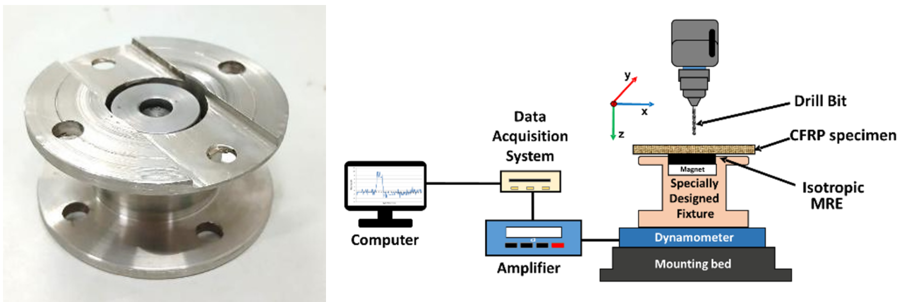


Fig. 3. Variation of storage modulus (◆) and loss modulus (○) verses strain under different magnetic field intensity

2.1 Development of drilling fixture and drilling set up

The specially designed and developed drilling fixture was used to incorporate isotropic MRE during drilling experiments as shown in Fig. 4(a). Drilling experiments were carried out on a three-axis CNC machining center (JYOTI PX10) using standard procedures. The composite laminates were loosely fastened with clamp plate, and a vacuum extraction system was used to remove fiber particles. The clamping fixture was mechanically connected to a piezoelectric dynamometer (Kistler 9272) using threaded connections, and a specially designed drilling fixture was rigidly mounted on the dynamometer. The experimental setup is shown in fig 4(b).



(a) (b)

Fig. 4: (a) A special designed fixture, (b) Experimental setup

All drilling experiments were performed using fixed and variable machining parameters. Fixed drilling parameters were taken as 4 mm standard HSS drill bit with constant federate and cutting speed of 0.07 mm/rev and 7500 rpm respectively [17], whereas to study the effect of the magnetic field on MRE, without and with effect of magnetic field test condition was selected as a variable parameter. To create passive magnetic field, a neodymium rare earth permanent magnet with 1500 gauss magnetic field was used. All drilling tests were repeated twice under exactly same conditions to guarantee reproducibility of results, and the average of the data was used for further analysis.

3 Results and discussion

The prime objective of the current research was to suppress thrust force during drilling of UD-CFRP and BD-CFRP using MRE under passive magnetic field. To check the reliability of the test data, twice experiments had been performed under same test conditions and then average value had been taken into consideration. Figure 5 shows comparative studies of maximum thrust force both types of CFRPs specimen.

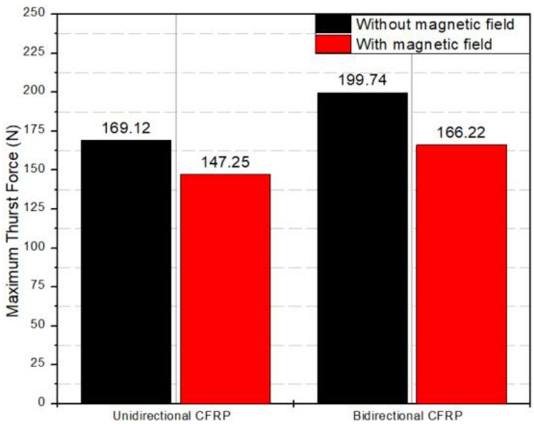


Fig. 5. Comparison of thrust force for difference CFPRs

Along with that, to evaluate microstructural morphology of a drilled hole, Scanning electron microscope (SEM) experiments were performed using JEOL-JSM6010LA at Charotar University of Science and Technology (CHARUSAT), Changa, INDIA on the UD-CFRP and BD-CFRP. The detailed discussion about thrust force suppression and microstructural analysis is briefly discussed in the subsection.

3.1 Thrust force comparison in UD-CFRP

The change in thrust force for UD-CFRP was investigated under with and without the passive magnetic effect. Figure 6 shows the thrust force plot against thickness of the laminate. The graph reveals that thrust force fluctuates without any specific pattern which advocates the presence of magnetic field absorb the thrust force and thrust force fluctuation is nearly reduced and the slope of the graph is also reduced.

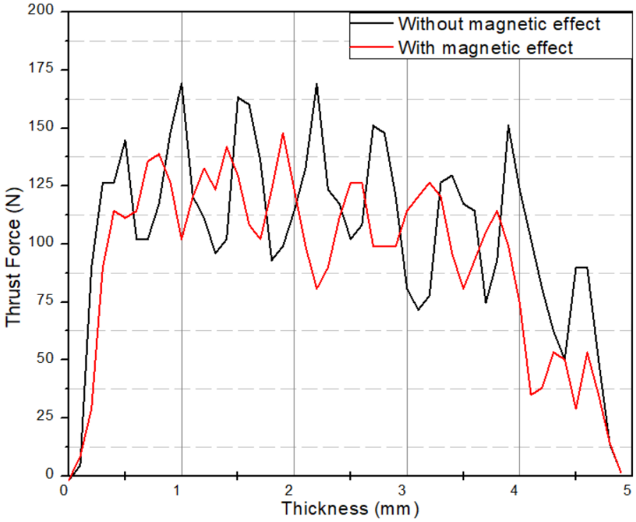
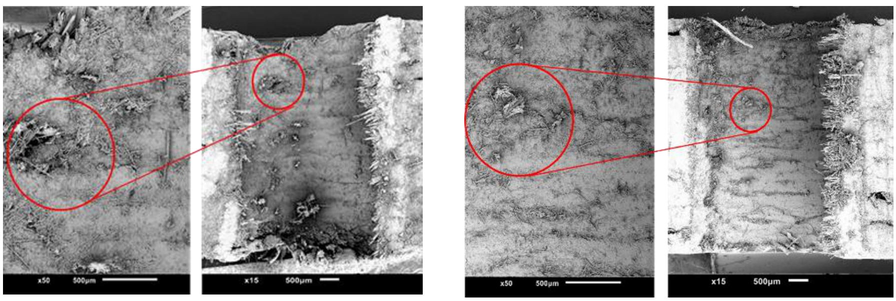


Fig. 6. Thrust force verses thickness plot for UD-CFRP under different test conditions

Meanwhile, in the presence of the 0.15 T magnetic field intensity the maximum thrust force value was suppressed by 13% from 169.12 N to 147.25 N for the same composite material. The suppression in thrust force is obtained due to magnetic properties of the iron particles were tuned in the presence of magnetic field which eventually worked as a passive back-up support.

3.2 Microstructural damage analysis in UD-CFRP

The preceding analysis of thrust force provides a macroscopic view of the end results. However, it is critical to comprehend the microscopic damage in each layer of the laminate that occurred during the drilling procedure. To further understand the micro-level drilled quality and region-wise damage of the drilled hole, a SEM examination was performed on UD-CFRP laminate samples.



(a) (b)

Fig. 7. Microstructural analysis of UD-CFRP drilled hole (a) without magnetic field, (b) with magnetic field

Figure 7 compares the microstructural morphology of a drilled hole of UD-CFRP without and with presence of passive MRE. It is clearly observed that, high impact of the thrust force is not absorbed during drilling operation and which eventually shows layer separation as shown in fig, 7 (a). On the other hand, the thrust force absorbed due to passively tuned MRE and separate layers are shown in fig 7 (b). Also tuned MRE reduced push-out delamination which occurs on the last lamina of the UD-CFRP specimen.

3.3 Thrust force comparison in BD-CFRP

The change in thrust force for BD-CFRP was investigated under with and without the passive magnetic effect. Figure 8 shows the thrust force plot against thickness of the laminate. The graph reveals that thrust force fluctuates without any specific pattern which advocates the presence of magnetic field absorb the thrust force and thrust force fluctuation and the slope of the graph is reduced marginally.

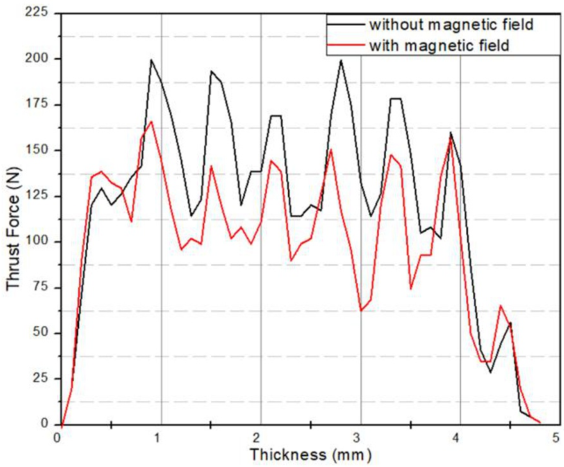
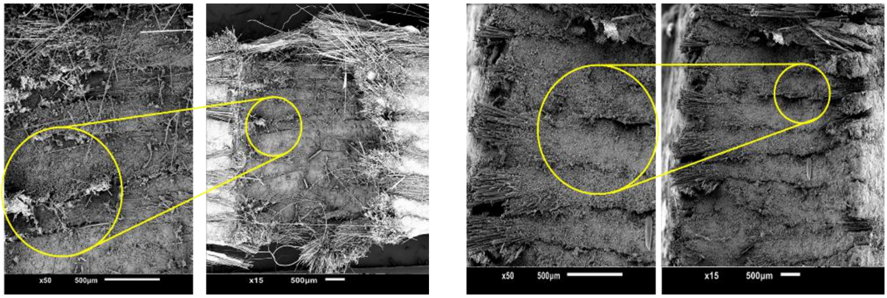


Fig. 8. Thrust force verses thickness plot for BD-CFRP under different test conditions

Meanwhile, in the presence of the 0.15 T magnetic field intensity the maximum thrust force value was suppressed by 13% from 199.74 N to 166.22 N for the same composite material. This thrust force suppression is obtained due to magnetic properties of the iron particles were tuned in the presence of magnetic field which eventually worked as a passive back-up support.

3.4 Microstructural damage analysis in BD-CFRP

Similarly, to study the influence of the macroscopic observation of the BD-CFRP sdrilled hole on microscopic damages in each layer of the laminate, a SE analysis were carried out on the samples of BD-CFRP laminate.



(a) (b)

Fig. 9. Microstructural analysis of BD-CFRP drilled hole (a)without magnetic field, (b) with magnetic field

Figure 9 compares the microstructural morphology of a drilled hole of BD-CFRP without and with presence of passive MRE. It is clearly observed that, layer separation and fiber debonding affected the overall microstructure of the drilled hole as shown in fig, 9 (a). On the other hand, passively tuned MRE helped to maintain strong fiber structure and less lateral damage throughout the depth of the drilled hole shown in fig 9 (b). Also tuned MRE reduced push-out delamination which occurs on the last lamina of the BD-CFRP specimen.

4 Conclusion

The present work emphasizes on the microstructural analysis of drilled hole in UD-CFRP and BD-CFRP using a passive magnetorheological elastomer. An isotropic 60/40 % w/w MRE was developed using electrolyte iron particles to sustain impact of the thrust force due to aligned particle strength. The thrust force during drilling was recorded using 4-component dynamometer. Thrust force for UD-CFRP was reduced by 13% with the presence of magnetic field compared to without magnetic field test condition. Similarly, 16% thrust force was suppressed for BD-CFRP under the same test conditions. This macroscopic observation advocates the influence of the tuned MRE under the effect of the passive magnetic field.

For microscopic evaluation of the each layer for UD-CFRP and BD-CFRP, SEM imaged were observed under 50x zoom condition. It is clearly observed that, MRE behaves as a back-up support, when its magnetic properties were tuned in the presence of the passive magnet. This not only absorb thrust force, but also reduces the microstructural damage occurred in the layers of the CFRP laminate.

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