R Keshavamurthy
Department of Mechanical Engineering
Dayananda Sagar College of Engineering
India

Vijay Tambrallimath
Department of Automobile Engineering
Dayananda Sagar College of Engineering
India

Abhinandan Badari
Department of Automobile Engineering
Dayananda Sagar College of Engineering
India

Anand Krishna R
Department of Mechanical Engineering
Dayananda Sagar College of Engineering
India

Pradeep Kumar G S
Department of Mechanical and Automobile Engineering
CHRIST (Deemed to be University), Bangalore
India

M C Jeevan
Department of Mechanical Engineering
Sapienza University of Rome
Italy

Friction and Wear Behaviour of Copper Reinforced Acrylonitrile Butadiene Styrene based Polymer Composite Developed by Fused Deposition Modelling Process

This paper focuses on the development of copper filled Acrylonitrile Butadiene Styrene (ABS) composites by fused deposition modelling (FDM) and to characterize its friction and wear behaviour. Twin screw extrusion technique was employed to extract copper-ABS composite filament. Three different materials were tested, i.e. pure ABS, ABS+2.5wt% Cu and ABS+5wt% Cu. Friction and wear characteristics of pure ABS and copper filled ABS composites were tested under various loads and sliding velocities. Addition of Copper powder has significantly improved the friction and wear properties of the developed composites. Further, it is also observed that friction and wear behaviour increased with increase in copper content in ABS. Worn out surfaces were subjected to scanning electron microscopy studies to analyse and identify the possible wear mechanisms involved.

Keywords: *ABS, Copper, FDM, friction, Wear, Scanning Electron Microscopy*

1. INTRODUCTION

Interest in the development of polymer composites has gained greater interest compared to metals due to their applicability in wide range of mechanical parts. The reasearch to establish greater applicability of these composites is increasing rapidly [1]. Polymers are widely used due to the demand of low weight and less cost in various engineering application such as bushes, gears and in electrical appliances [2,3]. Virgin polymers have restricted applications but they can be further extended by reinforcement of the polymer matrix with metals, carbon fiber, fibreglass and many more reinforcing materials. Reinforcing using fibres or fillers in a polymer matrix can modify the polymer's properties (tribological, mechanical and thermal), although the particle size and quantity of the filler material added into the polymer matrix affects its strength and fracture toughness [4,5]. Studies of tribological variations were analyzed for PTFE and its composites by addition of different filler materials like glass fibres, graphite flakes, carbon, bronze or combination. Coefficient of friction was seen to be slightly less for composites. There was considerable wear reduction by addition of filler and PTFE+bronze exhibited greater wear resistance [1]. Many new technologies have been developed for preparation of parts in sustainable manner. Additive Manufacturing (AM) relatively a new technology being used for development of parts of any complex shape. Additive manufacturing (AM) techniques allow the production of geometrically complex parts from three-dimensional (3D) model data, usually layer upon layer, without the need for additional moulds or tools. Keshavamurthy et. al. have stated the classification of additive manufacturing process into 7 ways by using numerous materials. The process generally involves development of 3D model in any applicable software, slicing it and then feeding into the process to develop a part. The sustainable approach of using additive manufacturing process over conventional manufacturing process is widely accepted and this new method is contributing the reduction of carbon foot print. Numerous case studies have been reported and applicability by various industries are also in exponential rise in global scenario [6]. The process of AM is expected to achieve substantial societal impact on various sectors such as healthcare, transportation, aerospace, electronics and construction [7]. Besides additive manufacturing, there are traditional manufacturing technologies for preparation of parts, where roughness parameters is very important [8]. Despite the diversity of AM techniques only a few seem to meet the practical requirements of industrial manufacturing of small series. Fused deposition modelling (FDM) or fused filament fabrication (FFF) is identified as one of these. The process involves motor pressurized filament pull through a heated nozzle and depositing the molten extruded filament onto the bed as a vertical series of horizontal two-dimensional (2D) slices of the 3D part being manufactured. Compared to other AM techniques, FDM involves lower costs, user-friendly, requires less post-processing and can use a multitude of materials. FDM process comes

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Correspondence to: Vijay Tambrallimath, Assitant Professor, Dayananda Sagar College of Engineering, Bangalore, India.
E-mail: vijay.tambrallimath@gmail.com
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with its advantages when compared to traditional manufacturing techniques. One of the biggest advantages of 3D printing over traditional manufacturing is that the 3D printing process generally doesn't require any special new tooling to make a part. When making a prototype, this can save a lot of time, money, and effort that would normally be spent on tooling the production line and getting an assembly process set up. Another key advantage of using 3D printing over many traditional production processes is that it is incredibly resource-efficient. On the other hand, major limitations with the parts built by FDM process are poor functionality as fully functional and load bearing components. Lower stiffness and poor wear resistance of FDM parts further limits their application as functional parts for many engineering uses. Further, meagre information is available as regards friction and wear behaviour of copper filled ABS composites developed by fused deposition modelling process. In the light of the above, present investigation is aimed to develop copper powder reinforced ABS filaments by Fused Deposition Modelling technique. Filament suitable for FDM process was developed using twin screw extrusion for various percentage of copper in ABS.

2. MATERIALS AND METHODLOGY

2.1 Raw materials

The ABS pellets utilized in this study were procured from M/s J P Polymers, Bangalore, India. Copper was used in the form of powder and size varied from 5 microns to 20 microns, SEM and EDAX of the copper powder which was acquired from M/s ACE Rasayan, Bangalore. ABS was used as matrix and copper powder was used as filler. The matrix is a tough, but relatively weak plastic that is reinforced by stronger and stiffer reinforcing agents. Before processing, ABS chips were dried under vacuum at 80^{o}C for at least 2 hours [9].

2.2 Twin screw extrusion

The process of mixing the ABS matrix and copper reinforcement after removing moisture was carried out using compounding machine. The temperature set was noted to be around 200^{0}C inside the chamber. The developed composite was then fed to twin screw co-rotating extruder followed by water cooling bath, counter-current air dryer and rotating knife. The temperature maintained at the end of wire extruder was set to 230^{0}C, which was considered to be optimal [10].

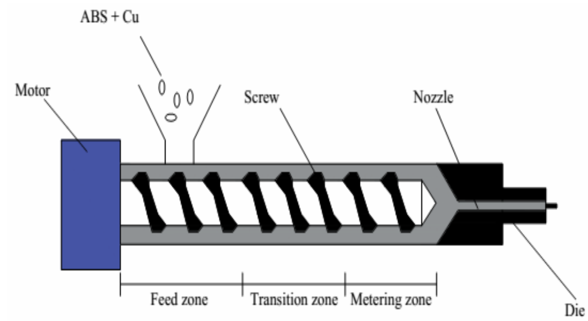


Figure 1. Schematic diagram of twin screw extruder

The filaments were extruded with a diameter of 1.75mm at a rate of 2m/min in M/s GLS Polymers, Bangalore. Figure 1 shows the schematic diagram of twin screw extruder. The dispersion was fairly homogenous with good bond between matrix and reinforcement as observed from the scanning electron microscopy of the developed filament shown in figure 2.

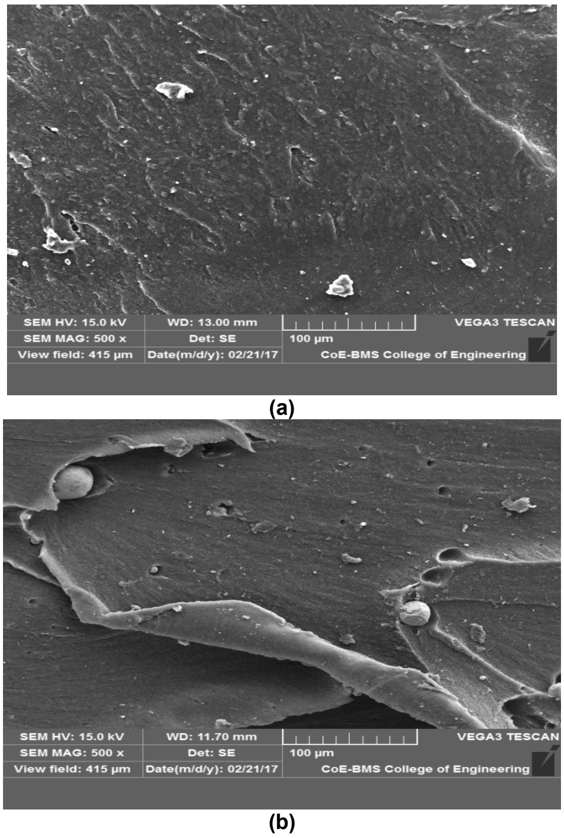


Figure 2. SEM of filament surface (a) ABS (b) ABS+5wt% Cu

2.3 Fused deposition modelling (FDM)

The development of requisite parts were carried out in layer wise form by extracting out the filament from the nozzle and laying on the print bed is the principle of working of FDM. The three dimensional model data is fed into the system after slicing, which prints the material on the defined parameters like angle of orientation, layer thickness, width, raster angle and built direction. The nozzle makes its movement in x and y direction and the bed moves in z direction [11]. Pramaan prusa i3 technology printer was used for the development of parts available at Global 3D labs, Bangalore. Each and every parameter plays an important role in determining the various properties [12]. For the developed filament the optimal nozzle temperature was chosen to be 240^{0}C with bed temperature of 90^{0}C. The layer thickness was chosen to be 0.2mm with an orientation angle of 45^{0}.

2.4 FRICTION AND WEAR TEST

The friction and wear experiments on the FDM printed parts as shown in figure 3, was carried out using a pin-on-disk equipment at room temperature. The developed ABS-Cu specimens were used as test samples in two bodies wears and EN 31 was used as disk material.

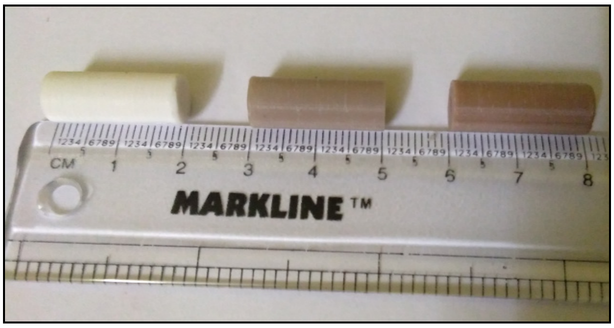


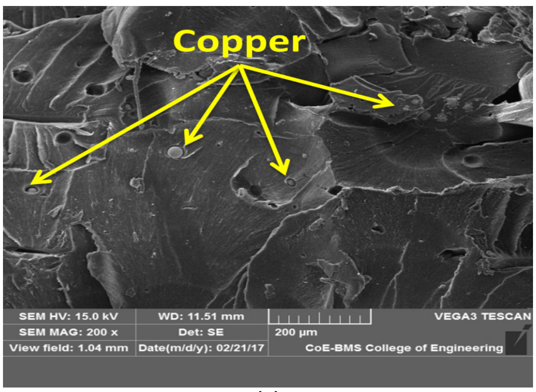
Figure 3. Dimension of wear testing parts (b)Photograph of parts for wear test

The track radius for test was 100mm and test duration was 5 minutes. Samples of size 8mm diameter and 20mm length was used as test samples. The experiments were performed on samples with distinct copper weights. Results for all samples were recorded by varying load and sliding velocities and the findings acquired were mapped on a graph. Two samples were considered for each test condition. Normal load was varied from 5N(0.1Mpa) to 20N(0.4Mpa) in steps of 5N. Whereas sliding velocity was varied from 0.262 m/s(sliding distance: 78.6m) to 1.048m/s(sliding distance: 315m) in steps of 0.262m/s. All tests were carried out under dry conditions using EN31 (60HRC) disc material. The initial surface finish (Ra) of the steel disk 1 micron whereas for all test samples surface finish of 0.5 micron was maintained. Test duration for each sample was 10 minutes. Wear loss was measured using Linear Variable Differential Transducer (LVDT) whereas load cell of 0.1N accuracy was used to record frictional force. After the wear test, worn-out surfaces were subjected to scanning electron microscopy studies to explore the various wear mechanisms involved. Figure 3 shows the photograph of wear test specimens built by FDM process.

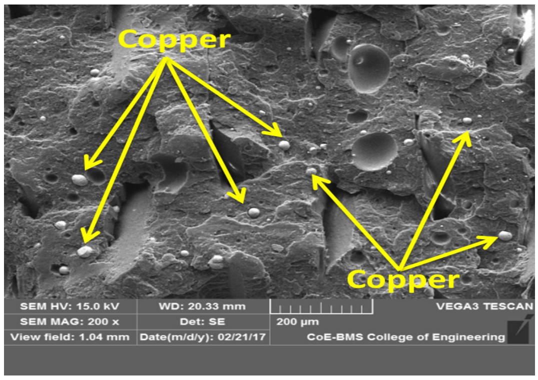
3. RESULTS AND DISCUSSION

3.1 MICROSTRUCTURE

Figure 4 (a-b) shows the scanning electron micrographs of ABS+2.5wt%Cu and ABS+5wt%Cu, figure 4 (c-d) shows the cross section images ABS and ABS+5wt%Cu composite developed by fused deposition modelling process. It is observed that there are no visible flaws seen in both ABS+2.5wt%Cu and ABS+5wt%Cu composite.



(a)



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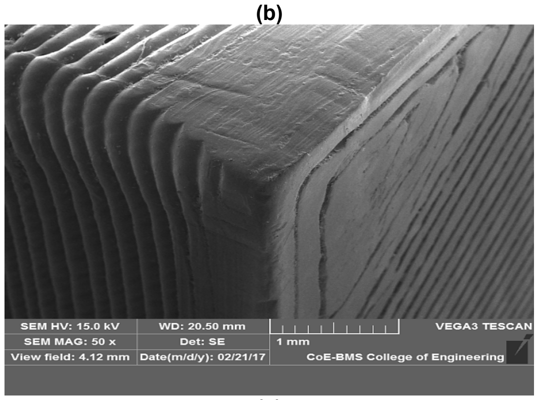
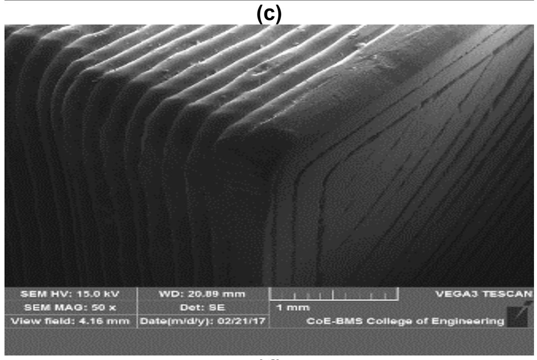


(c)



(d)

Figure 4. SEM of specimens built by FDM process (a) ABS+2.5wt%Cu (b) ABS + 5wt% Cu (c) cross section image of ABS (d) cross section image of ABS+5wt%Cu

The studies of microstructure of the developed parts by Fused Deposition Modelling indicate that the addition of Copper particles shows good wet ability in the ABS matrix which results in minimal porosity. There is also no visibility of formation of the aggregates or agglomerates of the copper fillers in the ABS matrix. This clearly demonstrates the uniform distribution and bonding of spherical shape copper particles throughout the ABS matrix. Homogeneity in dispersion of copper particles in ABS polymer matrix adds to enhancement in the mechanical properties of FDM parts by augmenting the load bearing capacity of FDM part in engineering applications. Further, it is also seen from the scanning electron micrographs that there exists an exceptional union between ABS matrix and copper particles in ABS-Cu composite synthesized by FDM process. The bond between filler material and polymer materials is another important aspect which plays a vital role in dictating the final properties of FDM parts. In addition, micrographs do not show any visible sign of debonding or pull-out of copper particles from ABS matrix. SEM images of the parts at different proportion of Copper addition are shown in the Figure 4 (a-b). The images were captured in the build direction and it shows consistent dispersion of the Copper particles in the matrix without any major defect as mentioned earlier. It is also important to note that addition of Copper particles did not hamper the structural geometry of the ABS matrix instead, amalgamated well with the matrix to form proper polymer chains which contributes to improved characteristic properties. The cross-section of SEM images of the developed samples of ABS and ABS+5wt% Cu composite is shown in Figure 4 (c-d).Formation of flawlessly bonded and defect free layers in the build direction is clearly visible in both cases of pure ABS and ABS-Cu FDM parts. Vijay et. al. made a similar study on understanding the dispersion of graphene nanoparticles in PC-AS matrix and has found the dispersion of the reinforcement to be uniform without formation of any agglomeration or aggregation. The density of the samples increased with increase in graphene content [13].

3.2 WEAR

The characteristic analysis of wear behaviour of the parts developed by fused deposition modelling process is studied with variation in load. Fig.5 shows variation of wear loss with respect to different loads. Fig.6 shows variation of wear rate with respect to different sliding velocities. The virgin polymer parts see incremental wear behaviour with increase in load and sliding velocity. However, for the polymer part reinforced with copper particles, the wear behaviour saw a decrement compared to ABS under both varied loads. With increase in sliding velocity the wear rate of both pure ABS and copper filled ABS decreases remarkably. Under all slding conditions studied, the wear rate of copper filled ABS was significantly lower than vergin ABS. Further, it is also noticed that with increase in the percentage of copper filler in ABS matrix the wear loss is found to decrease under varied load conditions. Thus, increase in the copper content in the ABS matrix leads to decrease in the wear loss when compared with the pure ABS under identical test conditions. Even distribution of shear stress over the surface of the test specimen due to the presence of copper particles mainly contributes to reduction of wear with addition of the filler material. Further, presence of copper metal filler in ABS matrix material increases the shear strength of FDM parts which results in the formation of tiny particles during the wear process from the composite surface. These tiny particles get mechanically bonded with counter surface and form a protective transfer film layer at the interface and plays vital role in reducing the wear loss of the composite parts [14]. The decrease in wear loss with increase in the copper content may also be attributed to the fact that during the wear test the FDM parts experience the shearing forces. Due to this, the copper particles present in the test specimen modify the counter surface by forming transfer film and minimizes the wear loss. Increased copper content in FDM part leads to the formation of more homogenous and stable transfer film between counter surface and test specimen. This results in further reduction of wear in case of composite parts [15].

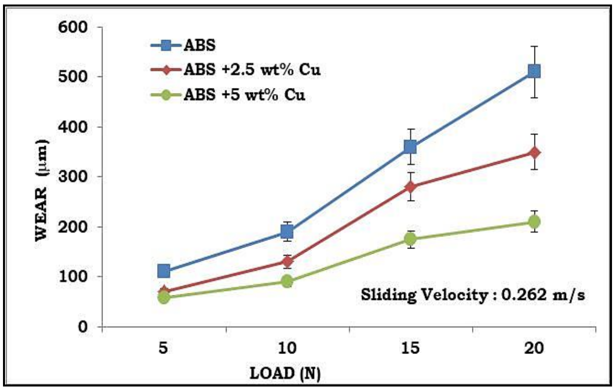


Figure 5. Variation of wear with respect to load

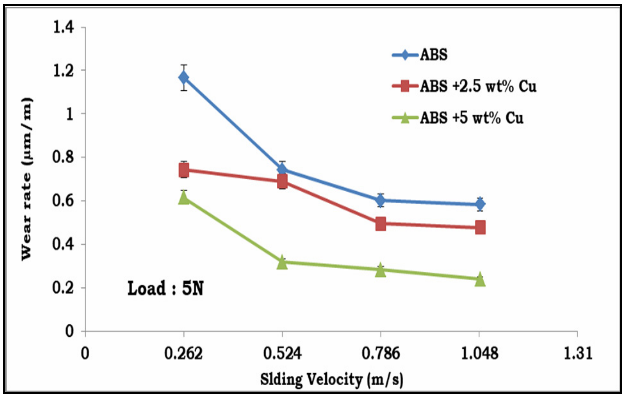


Figure 6. Variation of wear rate with respect to sliding velocity

FDM parts built with 5wt% addition of copper particles exhibited lowest wear loss when compared with 2.5wt% copper reinforced ABS and pure ABS parts. Increase in sliding velocity leads to increase in temperature at the surface, which leads to softening of the parts and hence deteriorates the material surface. The variation of wear loss with load is shown in Figure 5. Load was varied between 5N to 20N and constant sliding velocity of 0.262 m/s was adopted. It is observed that there is an increasing trend in wear loss with increase in load for all the materials studied. However, when compared with pure ABS composite parts filled with copper particles exhibited significantly lower wear loss. For pure ABS the average wear loss recorded was 110,190, 360 and 510 microns for the load values of 5N, 10N, 15N and 20N respectively. On the other hand, for 5wt%copper filled ABS composite the wear loss was found to be 58, 90, 175 and 210 microns for the load values of 5N, 10N, 15N and 20N respectively. Comparatively an incredible decrease in wear loss is observed in case of composite. The variation of wear rate with sliding velocity is shown in Figure 6. It is realized from the graph that pure ABS part shows decrease in wear rate with increase in sliding velocity. Initially for 0.262 m/s of sliding velocity the wear rate value of pure ABS is found to be 1.16 microns/m, whereas for sliding velocity of 1.048m/s the wear rate of 0.63 microns/m was recorded. In case of 5wt% copper reinforced FDM parts, 0.61 microns/m and 0.28 microns/m was recorded for sliding velocity of 0.262m/s and 1.048m/s respectively. This clearly demonstrates that wear rate of copper filled FDM parts are significantly lesser when compared with pure ABS parts both at lower and higher loads. It is also seen that for a given load and sliding velocity, increase in copper content in ABS matrix contributes to reduction in wear loss. The presence of copper particles in ABS matrix material suppresses the formation of cracks on the surface by acting as load bearing elements. This aspect is the main reason for reduction in wear loss in composite FDM parts, especially at higher loads and sliding velocities. Abra–sion and adhesion are the common mechanisms involved in the process of wear. Friction and wear are very complex and often interconnected phenomena [16]. As the load increases the enhancement of plastic defor-mation increases and results in formation crack over the surface of the FDM parts. The crack initiation leads to the removal of higher volume of the material with increase in load. However, the higher load carrying capacity of the composites is attributed to the presence of Copper particles as discussed earlier. The obser–vations are in line with fellow researchers [17, 18].

3.3 COEFFICIENT OF FRICTION

Figures 7 and 8 show the variation of coefficient of fric-tion with respect to load and sliding velocities respec-tively. It is observed that coefficient of friction increases with increase in load and sliding velocity for both pure ABS and copper filled ABS parts. However, under all the loads and sliding velocities studied the coefficients of friction of copper filled ABS parts are remarkably lower than pure ABS. Under constant sliding velocity of 0.262m/s the pure ABS has an average coefficient of friction of 0.64, 0.73, 0.85 and 0.94 for the load values of 5N, 10N, 15N and 20N respectively. Whereas copper filled ABS part shows the coefficient of friction values of 0.12, 0.18, 0.43 and 0.69 for the load value of 5N, 10N, 15N and 20N respectively. Similarly, under constant load of 5N the pure ABS has an average coefficient of friction of 0.64, 0.8, 0.81 and 0.89 for the sliding velocity of 0.262m/s, 0.524m/s, 0.786m/s and 1.05m/s respectively. Whereas copper filled ABS part shows frictional values of 0.1, 0.21, 0.48 and 0.65 for the sliding velocity of 0.262m/s, 0.524m/s, 0.786m/s and 1.05m/s respectively. The increase in coefficient of friction with increase in the sliding velocity may be attributed to increased interaction between the particles of the transferred layer and particles in the test specimen.

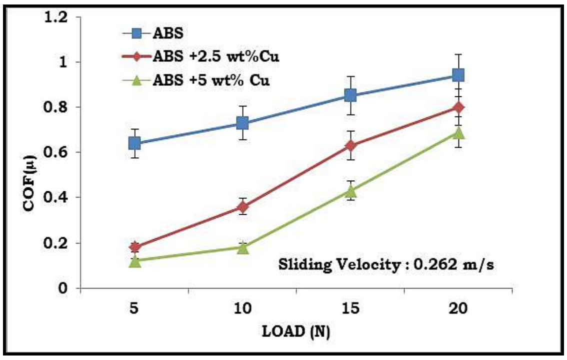


Figure 7. Variation of coefficient of friction with respect to load

The increased rubbing action between particles increases the coefficient of friction with increase in sliding velocity. Higher coefficient of friction with increase in the load may be due to change in the wear mechanism. As the load increases the transfer film at the interface exhibits stick-slip behaviour and leads to hig-her frictional values. Under all the test conditions studied the copper filed composite part offers lowest coefficient of friction owing to improved thermal con-ductivity and stiffness of FDM parts. Enhanced thermal conductivity of copper filled FDM part increases the heat dissipation rate at the and hence reduces the coefficient of friction [19-20].

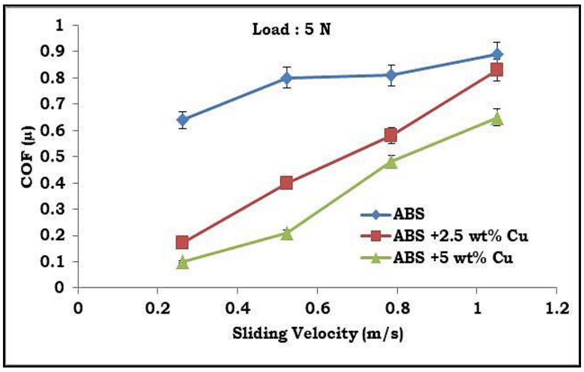
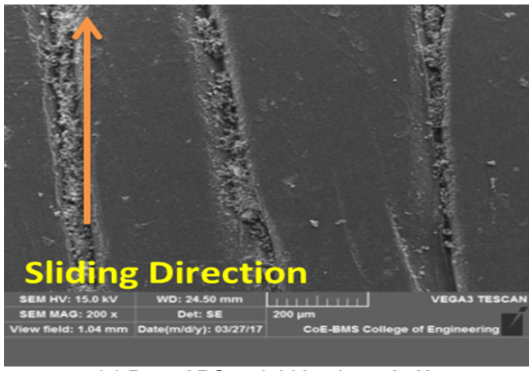


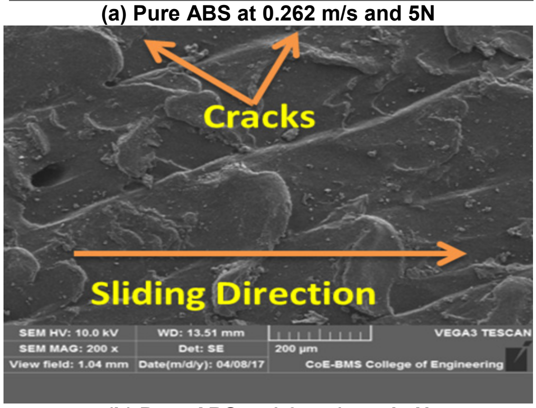
Figure 8. Variation of coefficient of friction with respect to sliding velocity

3.4 WORN OUT SURFACE ANALYSIS

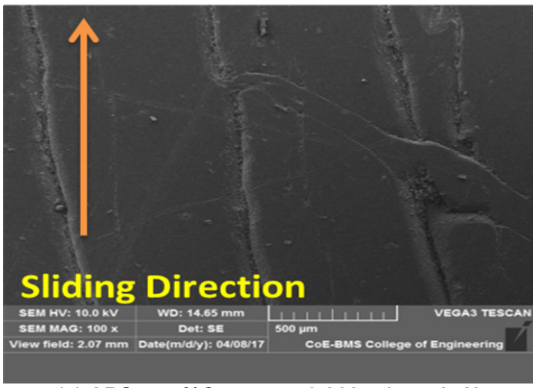
Figure 9 shows the scanning electron micrographs of pure ABS and copper filled ABS composites tested under various load and sliding velocities. It is observed that the morphology of worn-out surface of non-reinforced FDM part is completely different from morphologies of parts filled with copper at all the loads and sliding velocities. Pure ABS shows the presence of microcracks, microcutting and ploughing on the worn out surfaces. As the load and sliding velocities increase the extent of microcracks and ploughing marks increases.



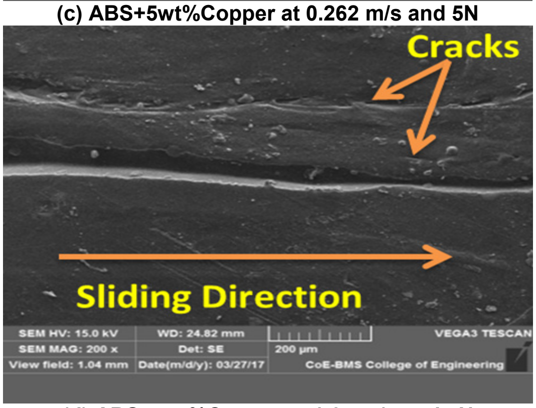
(a) Pure ABS at 0.262 m/s and 5N



(b) Pure ABS at 1.05 m/s and 5N



(c) ABS+5wt%Copper at 0.262 m/s and 5N

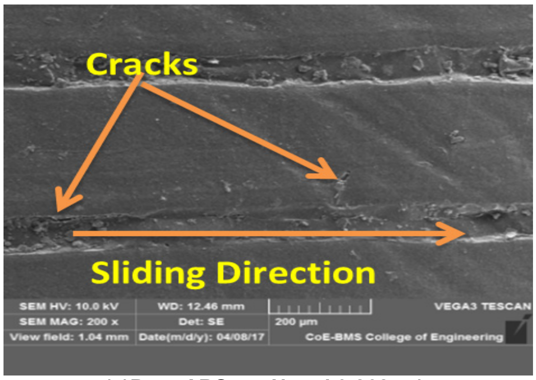


(d) ABS+5wt%Copper at 1.05 m/s and 5N

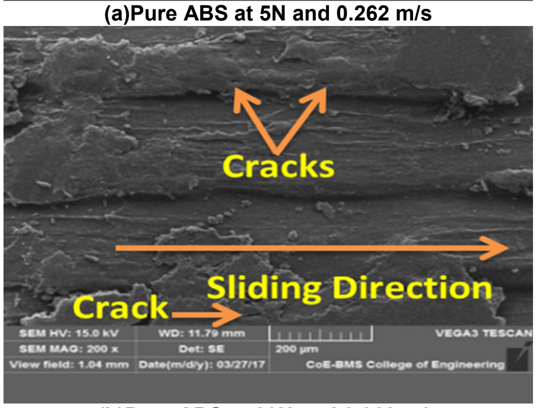
Figure 9 (a-d). SEM of worn-out surfaces at different sliding velocities

On the other hand, copper filled ABS composites show lesser cracks and ploughing marks. With increase in the copper content, these marks appear to be diminished. The surface of the pure ABS depicts brittle fracture and clearly accounts the higher wear loss in case of unfilled ABS, incorporation of copper particles modifies the surface and depicts relatively ductile fracture. Further, it is also noticed that loads and sliding velocities have a significant impact on the surface damage of both unfilled and copper filled FDM parts as shown in figure 9 and 10 respectively.

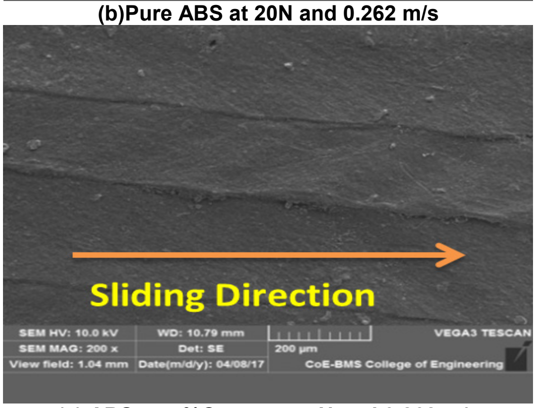
The extent of damage at higher loads and sliding velocities are severe when compared at lower loads and sliding velocities. However, even at higher loads and sliding velocities copper filled FDM parts show relatively minimum surface damage when evaluated with unfilled surfaces. Thus, the presence of copper particles made a remarkable influence on morphology of worn-out FDM parts. This clearly supports improved friction and wear performance of the FDM parts reinforced with copper powder.The smooth surfaces seen in composites are due to the load shared by copper particles which is not seen in unfilled ABS matrix. When pure ABS slides against the steel counter surface FDM parts undergo excessive fatigue with excessive surface damage. This is characterized by disintegration of top surface of the pure ABS with formation of wear debris along with deep grooves in the direction of sliding (Figure 10). Under similar test conditions the surfaces of the copper filled ABS composites has less wear with minimum scars. Thus, it is clearly evident from the worn surface analysis that there is significant change in wear mechanism from severe wear to mild wear with addition of copper particles in ABS matrix. This supports the friction and wear trend observed in the pure ABS and copper filled ABS parts.



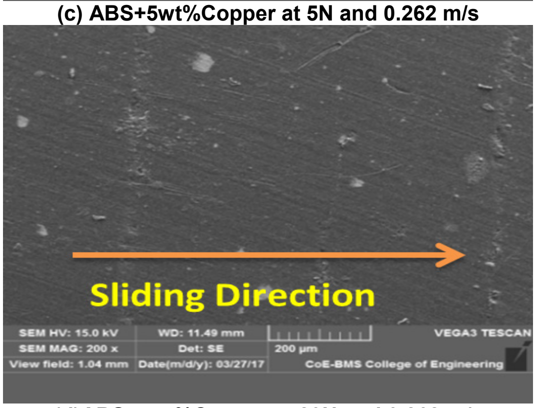
(a)Pure ABS at 5N and 0.262 m/s



(b)Pure ABS at 20N and 0.262 m/s



(c) ABS+5wt%Copper at 5N and 0.262 m/s



(d)ABS+5wt%Copper at 20N and 0.262 m/s

Figure 10 (a-d). SEM of worn-out surfaces at different loads

4. CONCLUSION

The friction and wear behaviour of pure ABS and copper filled ABS composites developed by FDM process was studied. Copper filled ABS composite exhibit lower wear loss and lower coefficient of friction compared to pure ABS. The coefficient of friction and wear loss decreases with increase in copper content. Wear loss increases with increase in the load. Wear rate decreases with increasing sliding velocity, whereas Coefficient of friction decreases with increase in load and sliding velocity. Under all the loads and sliding velocities studied, copper filled ABS composite exhibits superior friction and wear performance compared to pure ABS parts.

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КАРАКТЕРИСТИКЕ ТРЕЊА И ХАБАЊА КОД ПОЛИМЕРНОГ КОМПОЗИТА СА ABS МАТРИЦОМ ОЈАЧАНОМ БАКРОМ ДОБИЈЕНОГ КОРИШЋЕЊЕМ FDM ПРОЦЕСА

Р. Кешавамурти, В. Тамбралимат, А. Бадари, А. Кришна Н., П. Кумар Г.С., М.Ц. Јеван

Рад приказује добијање ABS композита ојачаног бакром помоћу FDM процеса и описује карактерис-

тике трења и хабања код таквог полимерног композита. Техником двоструке екструзије добијено је композитно влакно од бакра и ABS. Испитивање је обухватило три различите врсте материјала: чист ABS, ABS + 2,5 wt% и ABS композите ојачане бакром који су били изложени различитим оптерећењима и брзини клизања. Додавање прашкастог бакра значајно је побољшало карактеристике трења и хабања код композита. Степен трења и хабања се повећао са повећањем садржаја бакра у ABS. Површине изложене хабању су испитане SEM техником и идентификовани су могући механизми који учествују у хабању.