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Original Article

Stainless steel flake-reinforced polymer matrix-woven glass fibre hybrid composite: Mechanical and wear characterization

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ABSTRACT

Woven glass fibre polymer composites are one of the most commonly used materials in manufacturing industries and are widely used in various engineering technologies. However, a common shortcoming of these composites is the failure at the matrix-rich interfacial regions where the load transfer between the load-bearing fibre and weak matrix occurs. As a result, researchers have focused on improving the load transfer capability by strengthening the interfacial regions using secondary reinforcements. The industrial waste of stainless steel scrap is selected as a potential secondary reinforcement to strengthen the interfacial regions of the glass fibre composites. The hybrid composites were manufactured using 2.5, 5 and 7.5 wt% of strain steel (SS) scrap and are expected to improve the mechanical and tribological properties of the final composite materials. Tensile test, Pin on drum wear test and three-point bending tests were performed to investigate the effect of stainless-steel scrap on the mechanical and tribological properties of the composite. Fractographic studies were also carried out to analyze the failure behaviour of the tested composites. The properties of the reinforced composites were compared and reported with the pure sample. The addition of stainless steel scrap up to 2.5 wt% improved the mechanical and wear properties of the glass fibre composite and a further increase resulted in a reduction in the strength of the final composite.

KEYWORDS: glass fibre reinforced composite, stainless steel scrap, pin on drum, hand layup, wear resistance.

1. INTRODUCTION

Polymer composite materials are a combination of matrix and reinforcement with distinctly different physical, chemical, and mechanical properties. The reinforcements can be added in various forms and classified as continuous, discontinuous, particulate etc. Since each type of reinforcement exhibits different properties, the appropriate

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reinforcements must be chosen for various applications to enhance the composite properties [1, 2]. Further, the reinforcements are designed and infused in such a way that the transfer of applied load between reinforcements and matrix occurs, which leads to improvement in composite properties [3].

The matrix typically comprises a large portion of the composite and is used to classify the composites as polymer, metal, ceramic etc. among which the polymer matrix is preferred due to its lightweight, good abrasion and corrosion resistance, high stiffness, and high strength along the direction of their reinforcements [4]. For example, glass fibre-reinforced polymer (GFRP) composite is one form of polymer matrix composite in which woven glass fibres are used as a primary reinforcement with the polymer matrix. The glass fibre reinforcement improves the mechanical properties of the composites. However, the main disadvantage of GFRP composites is a weak interfacial region, where the load transfer between the matrix and glass fibre occurs and the failure at the matrix-rich interfacial region can be catastrophic [5]. To improve the weak interfacial region of the GFRP composites and their properties, secondary reinforcements in the form of particulates and short fibres are used [6, 7] and the final composites are called hybrid composites. The secondary reinforcements provide additional load-bearing capacity, and dimensional stability, and improve the tensile, flexural and wear properties [8]. Several research works confirm that various factors including the selection of secondary fibres and fillers [9, 10], the optimum weight/volume fraction [11], matrix types and strength [12], bonding of interface between the matrix and fibre [13] etc. strongly impact the physical and mechanical properties of hybrid composites.

Ahmedizar *et al.* [14] used the nano and microparticles of aluminum oxide with glass fibre/epoxy composites and confirmed that the mechanical and wear properties have greatly improved due to the addition of particulate reinforcements. The sulphide-coated steel fibre hybrid composites were investigated to obtain the tribological behaviour using a pin and disk machine [15]. The hybrid composites were prepared with 5-25 vol% of steel fibres and the results showed that the increase in fibre content increased the coefficient of friction and wear properties. The flexural properties of glass fibre-reinforced epoxy composite filled with different weight fractions of aluminum oxide (Al_2O_3) particles showed an increase in tensile strength for the addition of 10% of secondary filler content, beyond which the properties decreased [13]. However, the ultimate tensile strength and shear strength of the composites decreased with increasing aluminum oxide reinforcement. Shahinoor Alam *et al.* [16] worked with two different sets of secondary filler materials namely Calcium carbonate-Alumina-Magnesia-Titania ($CaCO_3$-Al_2O_3-MgO-TiO_2) and Calcium carbonate-Alumina-Magnesia-Copper Oxide ($CaCO_3$-Al_2O_3-MgO-CuO) with three different weight fractions of 5, 10 and 15%. The wet layup method followed by compression moulding is used for the fabrication of woven glass fiber-reinforced epoxy hybrid composites. The results showed that, as compared to the hybrid filler group containing titanium dioxide (TiO_2), the inclusion of a cupric oxide-containing filler (CuO) group significantly increased tensile, flexural, and impact strength by 20%, 26%, and 12.93% respectively. The effects of bone and coconut shell powder with E-glass fibre-reinforced epoxy composite were studied by Deshpande *et al.* [17]. The composites filled with 15 vol% of coconut shell powder and bone powder showed improved interlaminar shear strength, flexural strength, tensile modulus, hardness, and impact strength compared with the glass fibre composites.

Devendra *et al.* [18] fabricated different composite panels with the addition of individual filler materials from fly ash, aluminum oxide, magnesium hydroxide and hematite powder with a volume fraction of 10 to 15%. Ultimate tensile tests, Charpy impact test and Brinell hardness tests were conducted and their results concluded that composite with 10 vol.% magnesium hydroxide showed maximum tensile and hardness strength whereas composite filled with 10 vol% volume of fly ash showed maximum impact strength. Wojciech Zurowski *et al.* [19] have investigated the effect of the addition of quartz filler into glass fibre-reinforced composite on the wear properties and confirmed that the wear resistance of the hybrid composite was significantly improved with the addition of 6 wt.% quartz.

However, the use of stainless steel scraps, which are an industrial machining waste and are abundantly available, has not been studied suitably as secondary reinforcement for manufacturing glass fibre hybrid composites. Stainless steel is a commonly used metal for different mechanical parts and is often subjected to machining. These machined scraps are mostly contaminated with different oils and coolants. Also, most of the metal scraps exhibit different properties because of the heat generated during machining which makes the recycling tougher. Hence, the main objective of this project is to utilize stainless metal (SS) scrap as a secondary reinforcement to manufacture woven glass fibre-reinforced polymer hybrid composites. The hybrid composites were experimentally characterized to understand the effect of secondary SS scarp reinforcement on improving the mechanical and wear properties of the composites.

2. MATERIALS AND METHODS

2.1. Materials

Epoxy resin (LY556) with a density of 1.2 g/ml and aliphatic amine hardener (HY-951) with a density of 0.932 g/ml were used to manufacture the composites. The hardener has a high filler addition possibility and can be used to cure epoxy at room temperature. The polymer matrix and the glass fibres were supplied from Herenba Instruments & Engineers, Chennai, India. The woven-type glass fibre with a thickness of 0.5 mm was used as the primary reinforcement. The woven glass fibre mats were cut to the required dimensions using scissors and the weight of the single-ply glass fibre was measured as 37 grams. The secondary reinforcement, stainless steel (SS) scraps was collected from a local supplier in Chennai and cleansed with acetone to remove the oil content. Then the SS scrapes were filtered to have an average length of 1 mm length and a few micron thickness. The dimension of the secondary reinforcement was confirmed with the help of a scanning electron microscope (SEM). The weight percentage was calculated and the composites were fabricated as shown in Table 1. Based on our primary experimental results, the SS scrap addition was limited to 7.5 wt.% due to wettability and impregnating issues.

2.2. Fabrication of composite samples

Hand layup is used as the primary method for the fabrication of composite samples. A digital weighing machine was used to maintain the correct weight percent for the different composite specimens. The individual constituents and the composite manufacturing process are shown in Figure 1. At first, the resin mixture was prepared by mixing epoxy and hardener in the ratio of 10:1 and then degassed. Then an aluminum foil was placed on a flat die and was waxed over the surface. A single layer of the woven glass fibre mat was gently placed and then levelled by a steel roller. The epoxy resin was applied on the levelled glass fibre by brush. Once the epoxy was applied, the cleaned stainless steel scrap was sprinkled onto the surface of the composite. The different weight fractions of stainless-steel scrap were used based on the calculations given in Table 1. The process was repeated for adding 6 layers of woven glass fibre mats. The hand layup process was completed quickly to prevent the curing of the

Table 1. Composition of different composite materials.

Sample/material	Epoxy resin	Glass fibre (vol%)	Stainless steel scrap (wt%)
1	50%	50%	0%
2	50%	47.5%	2.5%
3	50%	45%	5%
4	50%	42.5%	7.5%

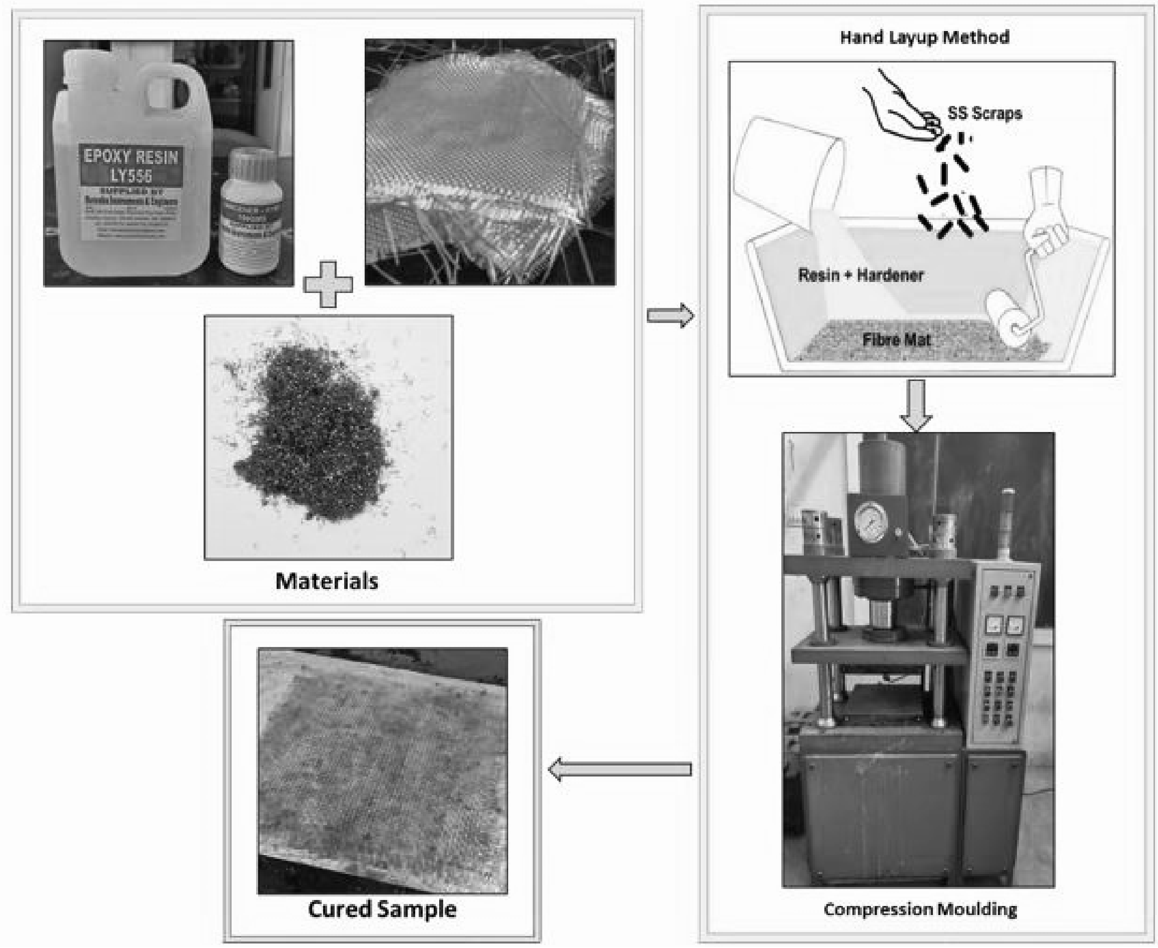


Figure 1. Schematic diagram of composite preparation.

resin mixture. The assembled prepregs were allowed to be partially cured at room temperature for 90 minutes before transferring the samples to a compression moulding machine.

The semi-cured sample covered with aluminum foil was then placed on a compression machine moulding platen. This process was necessary to remove all the entrapped air bubbles present between the layers. During this process, the sample was kept at a temperature of 80 ºC for 45 minutes and with a pressure of 20-30 MPa. The compressed sample was then allowed to cure for 8 hours at room temperature before cutting the test specimens. The thickness of the final glass fibre hybrid composite panel was in the range of 2.9~3.1 mm. The fabricated specimens were removed from the aluminum foil and the composite test specimens were accurately cut as per ASTM D638 standards with the dimensions of 160 mm x 12.5 x ~ 3 mm.

2.3. Testing procedure

An Instron universal testing machine with a load cell of 50 kN was used for the tensile tests and the data was acquired by the computer in-built software. The tensile test was performed with a cross-head speed of 0.5 mm/min as per ASTM D638 standard. An extensometer was used to measure the displacement during testing and the stress-strain curve was built to obtain the ultimate tensile strength and modulus of elasticity. The three-point bending test was carried out as per ASTM D790 standards using the test rig attached to the Instron testing machine. The sample with the dimensions of 60 mm × 12.5 mm × 3 mm was used for the three-point bending and the flexural strength was obtained and compared for the different weight fractions. Wear tests were carried out using the pin-on drum test as per ASTM A514 standard.

The pin-on drum apparatus (refer Figure 2) consists of a rotating drum covered with an emery sheet and a composite pin. The drum rotates at the speed of 40 rpm and the composite pin is allowed to run over the drum with a load of 1 kg acting on the pin. The composite pin's abrasion end was smoothened by the 1000-grit SiC sheets to avoid excess wear during the initial stage. Through a system of gearing, a single motor drives the entire machine, which automatically stops after completing a pre-set number of drum revolutions. The end of a composite pin specimen is forced to drag over the rolling drum covered by abrasive paper. The stimulated wear due to the crushing and grinding caused high-stress abrasive wear. The initial and final weight of the composite specimen and worn-out particles were measured for different wt.% SS scrapes after completing a certain number of revolutions. For the wear test, the composite pin's width, thickness and height were selected as 7 mm, ~3 mm and 15.7 mm, respectively.

2.4. Morphological characterization

The morphological studies were carried out using a JEOL JSM-6010 scanning electron microscope (SEM) with an accelerated voltage of 5 kV. Before the SEM test, the composite samples were sputter-coated with gold to make them conductive. Images of the tested composite specimens were taken and were used to analyze the wear and fracture behaviour of the composite material.

3. RESULTS AND DISCUSSION

3.1. Tensile strength

The stress-strain curves of the glass fibre steel scrap hybrid composite are shown in Figure 3. As can be seen, the addition of stainless steel scraps gradually increases the mechanical properties of the glass fibre composites. Figure 4 shows the tensile strength of the SS scrap-strengthened glass fibre hybrid composites. The experimental results show the highest tensile strength of 209 MPa for the addition of 5 wt% SS scraps. Further, an increase in SS scraps of 7.5% SS scraps reduces the tensile strength of the hybrid composites to 163 MPa. The main reason for the reduction in tensile strength at a higher percentage of 7.5 wt% of SS scrap is due to the debonding of scrap particles from the matrix. These debonded scraps create voids and act as a potential site for stress concentration. A similar trend of reduction in tensile strength for the addition of a higher amount of metal particles was shown by Onitiri and Akinlabi [20].

The elongation and elastic modulus of the SS scrap-strengthened hybrid composites are shown in Figure 5. Both the elongation and ductility increased for the addition of SS scraps up to 2.5 wt%, which can also be confirmed from the stress-strain graphs. The highest elastic modulus of

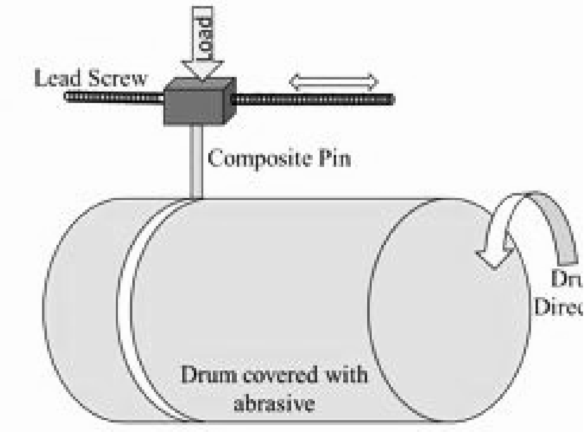


Figure 2. Schematic diagram of pin-on-drum apparatus.

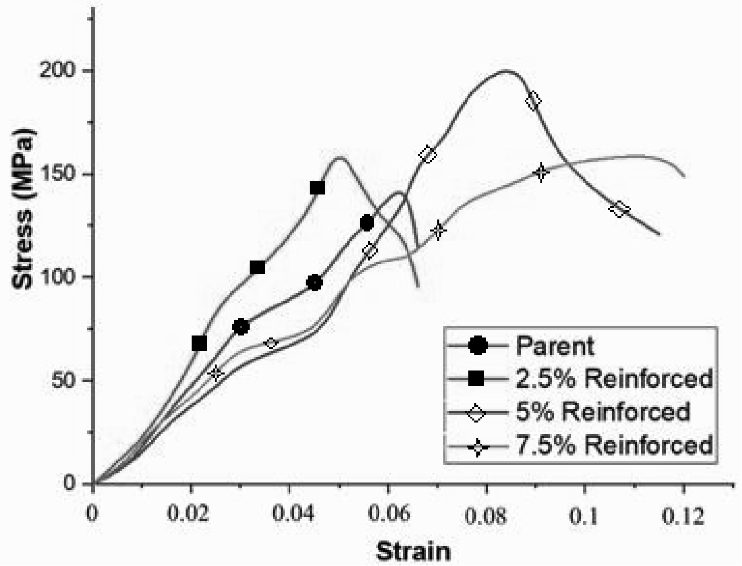


Figure 3. Stress-strain curves of SS scrap-reinforced glass fibre composites.

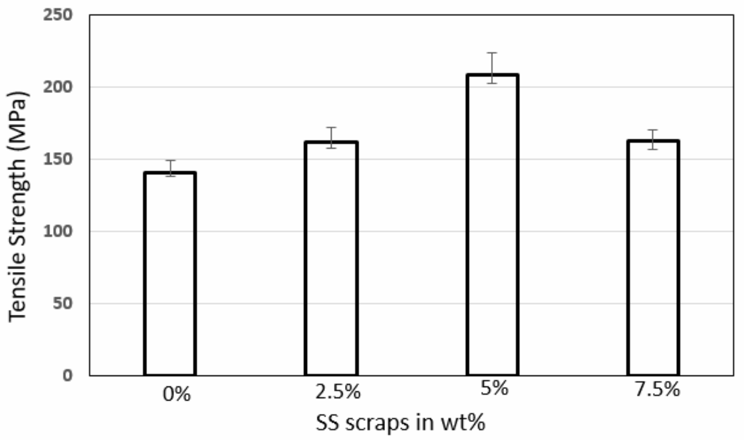


Figure 4. Tensile strength of SS scrap-reinforced glass fibre hybrid composites.

27.5 GPa was observed for the hybrid composites with 2.5 wt.% SS scraps, which provided significant stiffness and rigidity along with the glass fibre; so the elastic modulus was increased by about 20% when compared to the neat glass fibre composite. However, the elongation is found to be improved with the addition of 5 wt%. SS scrap as shown in Figure 5. A further increase in SS scraps to 7 wt% drastically reduced both the elastic modulus and elongation. The reason behind the reduction in properties is due to the poor bonding between the matrix and secondary reinforcement as discussed before.

3.2. Flexural strength and flexural modulus

Figure 6 shows the flexural strength and flexural modulus of the SS-strength glass fibre hybrid composites. The hybrid composites with 2.5 wt% SS scrap reinforcement showed a maximum bending strength of 123.4 MPa and the sample with 5 wt% of SS scrap gave the maximum flexural strength of 100 MPa. With a further increase (greater than 5%) the flexural strength of the hybrid composite reduced drastically due to the debonding of SS scraps as observed before. The flexural modulus also showed similar behaviour as can be seen in Figure 6.

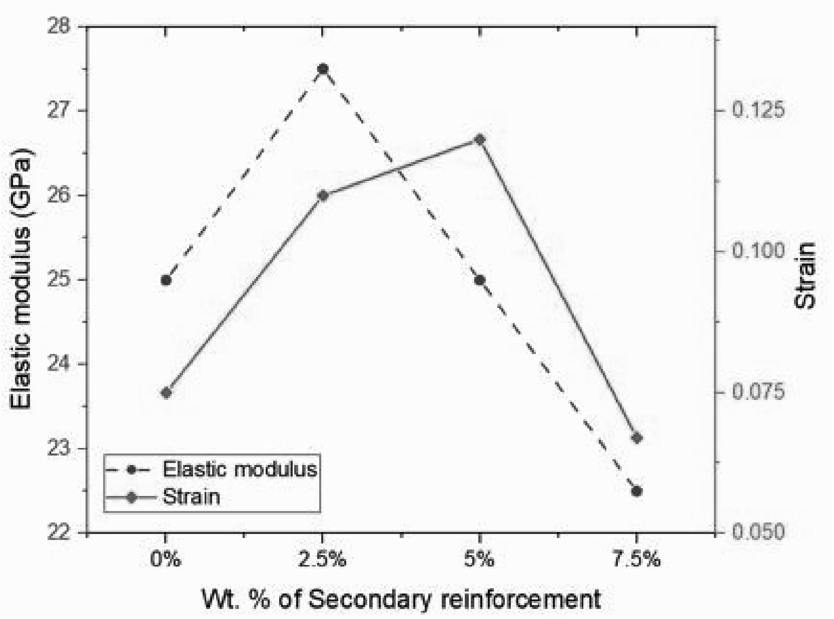


Figure 5. Elastic modulus and strain of the SS scraps (wt.%).

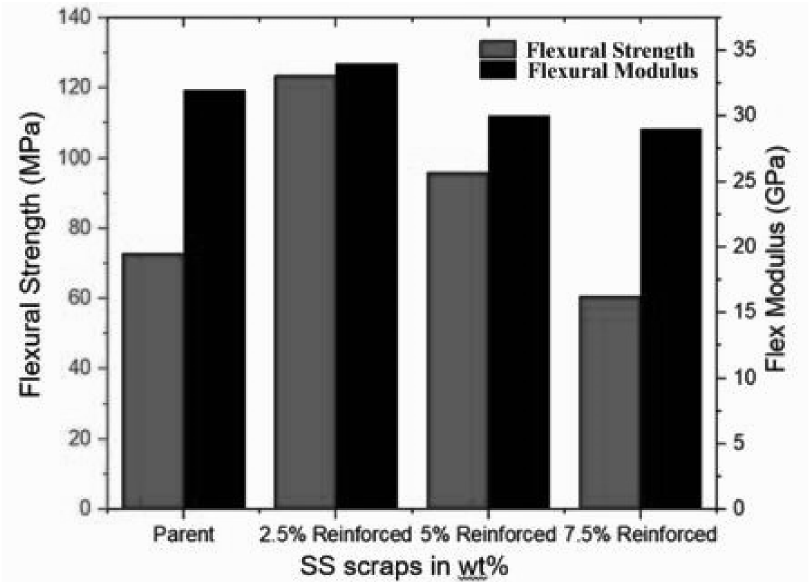
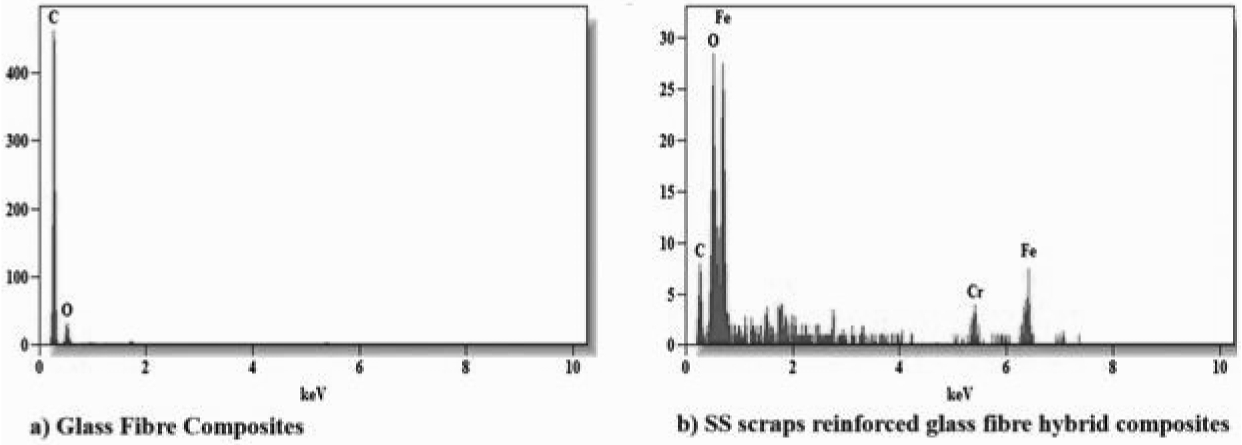


Figure 6. Flexural strength and modulus of SS scrap-reinforced glass fibre hybrid composites.

3.3. Fractography

Scanning electron microscopy was used to analyze the fractured specimen. The energy-dispersive X-ray spectroscopy (EDAX) was also carried out during the SEM analysis at different places to confirm the presence of the SS scraps on the composite specimen. Figure 7a depicts the neat composite specimen without Iron (Fe) and chromium (Cr) peaks whereas the SS scrap-reinforced hybrid composites confirm both Fe and Cr peaks (refer Figure 7b).

Further, the fractured specimen showed different modes of failure such as matrix failure, breaking of continuous fibre, and debonding of secondary



a) Glass Fibre Composites

b) SS scraps reinforced glass fibre hybrid composites

Figure 7. SEM-EDAX analysis.

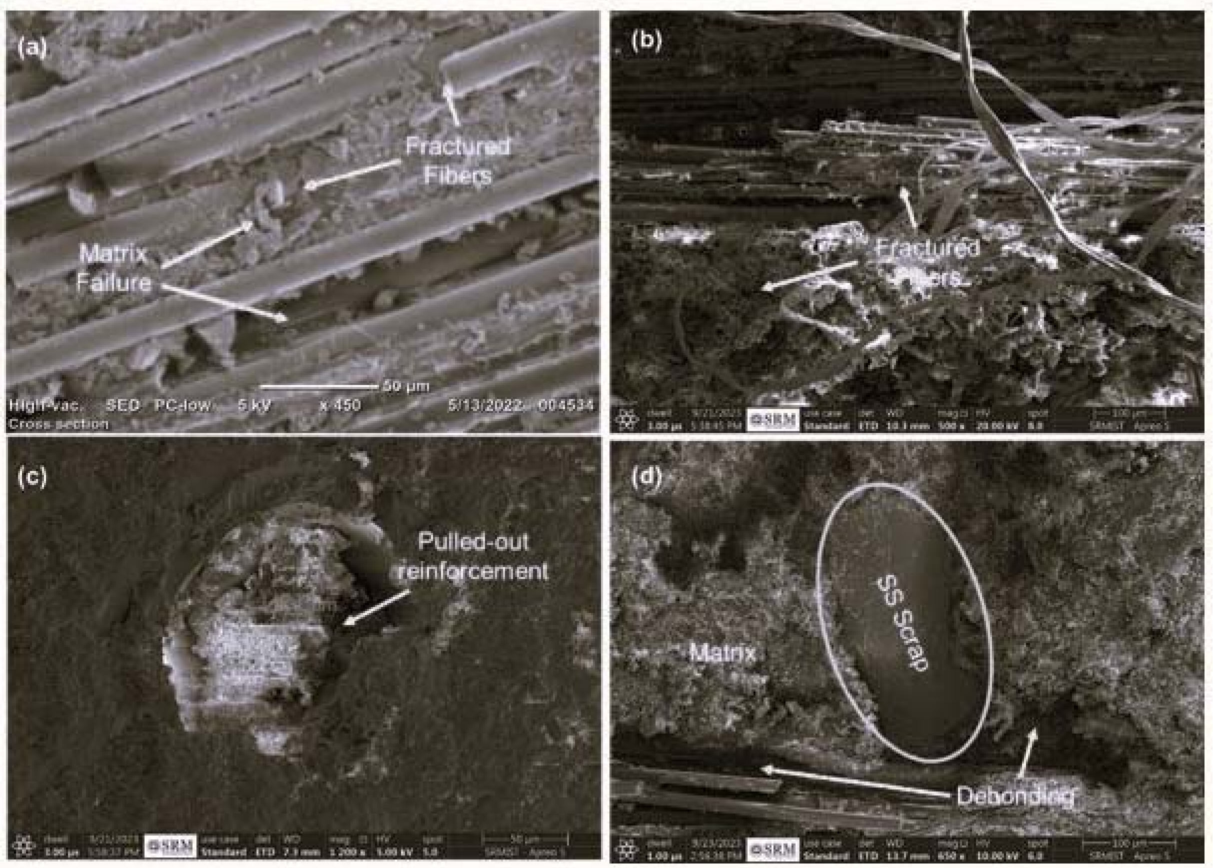


Figure 8. Fractography of SS-reinforced glass fibre hybrid composites.

SS scrap (Figure 8). The poor adhesion between the matrix, fibre and filler can be confirmed by using the SEM images. According to the sectional view from SEM images, the SS scrap was found to have a thickness of a few hundred microns (Figure 8 c & d) and also the debonding and fibre pull-out occurs easily when the SS scraps wt% increase. From the above results, it can be concluded that the mechanical properties of the glass fibre composites could be increased with the addition of up to 5 wt.% SS scraps.

3.4. Wear test

Variation of the wear rate of composite for the addition of different wt.% of SS scrap is given in Table 2 and Figures 9 and 10. The results revealed that the wear rate of the hybrid composite pin was reduced by increasing the SS scrap into glass fibre-reinforced composite up to 5 wt.% (Figure 10). The presence of SS fillers improved the thermal stability of glass fibre-reinforced composite and also reduced the contact asperities between the pin and drum. So the wear rate of the composite with the addition of filler materials (up to 2.5% and 5 wt.%) has slightly increased. The composite with the highest filler (7.5 wt.%) addition showed poor wear resistance, which is due to an increase in SS particles that reduced the wettability between glass fibre and epoxy followed by the reduced interfacial strength. Also, the difference in coefficient of thermal expansion increases with increased filler material and causes premature failure. SS fillers easily detach from the composite due to the reasons stated above.

3.5. Scanning electron microscopy

Scanning electron micrographs of the worn and fractured specimen with 2.5% wt. steel scraps are

Table 2. Experimental results of wear tests for the specimens.

SS scrap (%)	Sample id	Initial weight (g)	Final weight (g)	Abrasion loss (g)	Abrasion loss %	Wear resistance (g^{-1})	Wear rate (g/s)
0	S1	1.0074	0.8446	0.1628	16.16	6.1425	1.2921e^{-3}
2.5	S2	1.2074	1.0543	0.1531	12.68	6.5317	1.2151e^{-3}
5	S3	0.8648	0.7035	0.1613	18.65	6.1996	1.2801e^{-3}
7.5	S4	0.9231	0.7234	0.1997	21.63	5.007	1.5829e^{-3}

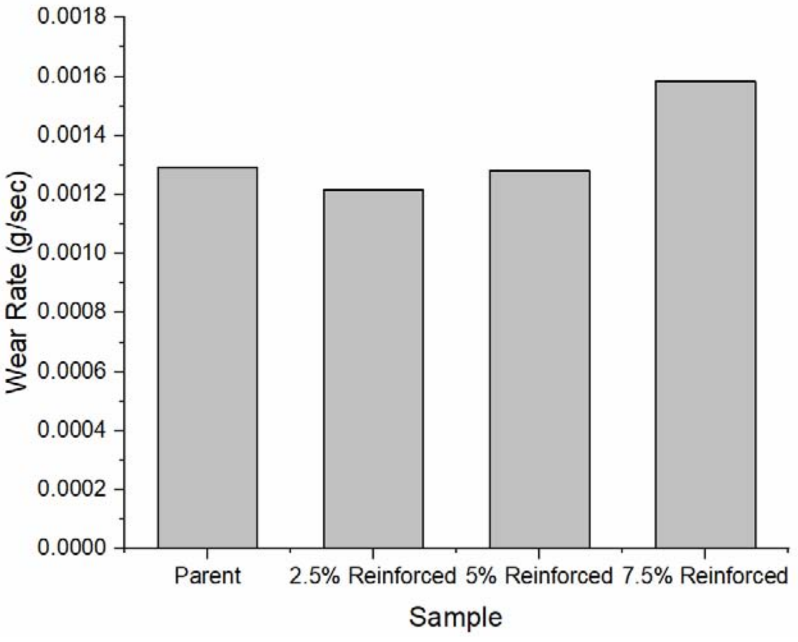


Figure 9. Wear rate of different composites.

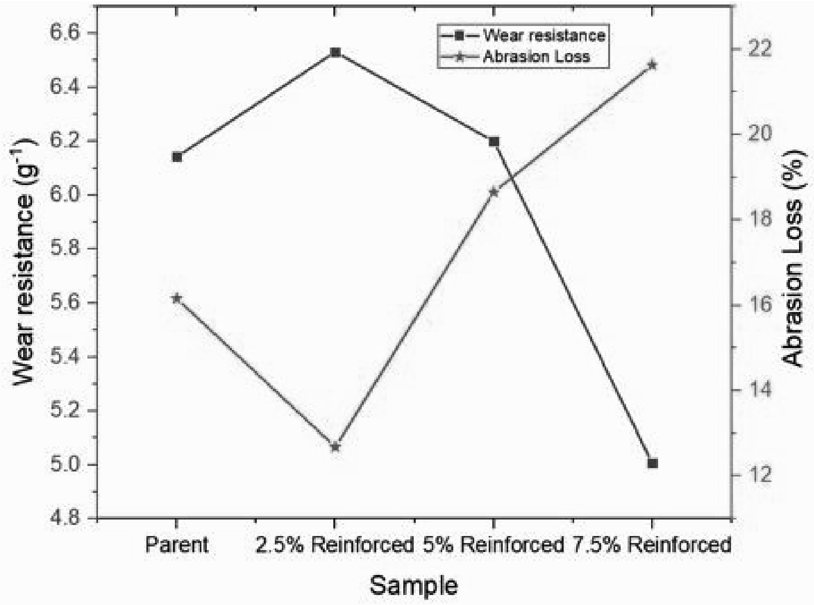


Figure 10. Wear resistance of different composites.

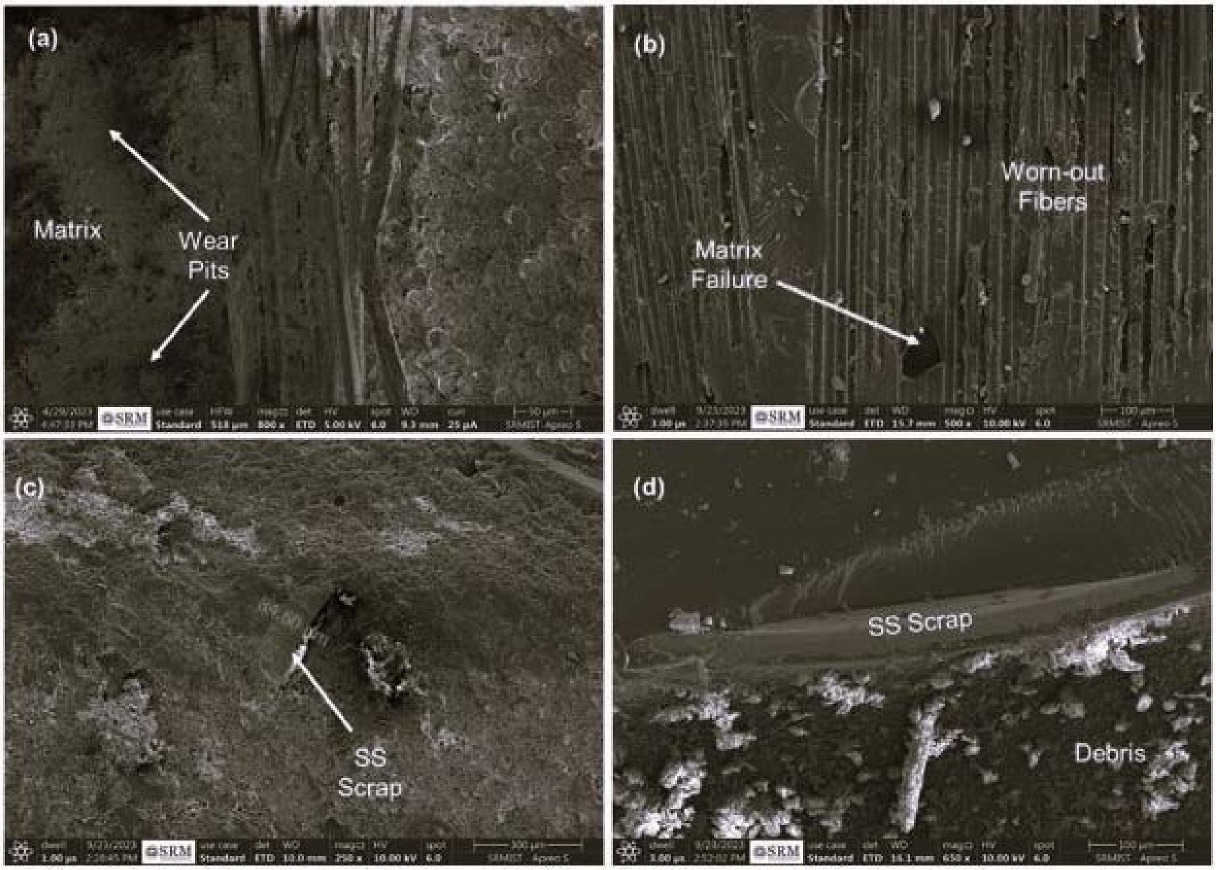


Figure 11. SEM image of composite with 2.5% SS scrap (a) wear pits; (b) worn-out fibres; (c) & (d) filler pull out.

shown in Figure 11. The composite sample subjected to wear shows the wear pit, filler pull out and worn-out fibres. During the wear test, the composite pins were pushed against the drum in a normal direction to the fibre, which resulted in worn-out matrix and wear pits as shown in Figure 11(a).

However, with the addition of 2.5 wt.% SS scrap, the wear resistance increased considerably and on further addition, the wear resistance reduced due to filler pull out, which can be noticed from the SEM images shown in Figure 11 c & d.

4. CONCLUSION

Machined SS scraps were used as the filler for the fiber-reinforced composites and the following conclusions were drawn from the test results.

1. The tensile strength of the material increases till 5 wt% addition of SS scarp and shows a decrease with further addition. The decrease in tensile strength is the result of weak interfacial bonding and strength between the SS scraps and the matrix within the interfacial region.
2. The sample with 2.5 wt% SS scraps has higher flexural strength and modulus compared to other samples, which decreases with further addition above 5 wt% addition.
3. In the wear test with a pin-on drum method, the wear resistance of the composites initially increased with the addition of 2.5 wt% SS scraps compared to other samples. Further, an increase in SS scrap beyond 2.5 wt% affected the wettability between the fibre and matrix material resulting in increased wear rate and reduced wear resistance.

From the experimental results, it can be concluded that the SS scrap waste could be used as secondary reinforcement to improve the mechanical and wear properties of the glass fibre-reinforced epoxy hybrid composite materials.

CONFLICT OF INTEREST STATEMENT

There is no conflict of interest.

ABBREVIATIONS

SS : Stainless steel
SEM : Scanning electron microscope
wt% : Weight fraction
vol% : Volume fraction

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