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SUSTAINABLE DEVELOPMENT OF LIGHTWEIGHT RECYCLED ALUMINIUM COMPOSITES

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ABSTRACT

In the present work, three composites have been developed by reinforcing Mild Steel (MS) chips in the amounts of 1 wt. %, 2 wt. % 3 wt. % respectively to recycled Aluminium chips through a manual stir-casting process. The developed composites were hot rolled at 200 °C to 50% reduction to increase the strength further. The microstructure showed that adding MS chips leads to grain refinement in the matrix due to the promotion of instantaneous nucleation. Further, it was observed that the composite developed by reinforcing 2 wt. % MS chips exhibited better grain refinement and the smallest grain size among the others, which also exhibited the highest hardness and compression strength of 83 Hv and 563 MPa, respectively, which are 26% and 15.3%, respectively, compared to the unreinforced alloy. This improvement in the strength can be attributed to the improved grain refinement, uniform distribution of MS powder in the matrix, formation of secondary phase and dispersion strengthening. However, beyond 2 wt. % addition of MS chips, the grain size started to grow, leading to a decline in the hardness and compression strength. Further, all the hot-rolled samples exhibited better properties than their counterparts. However, the variation trend in properties after hot rolling remained the same as the composite with 2 wt% MS chips showing the highest hardness and compression strength of 106 Hv and 722 MPa, respectively.

Keywords: *Aluminium composites; Machining chips; Metal casting; Microstructure; Mechanical Properties; Hot Rolling; Recycling*

1. Introduction

The use of materials has marked the evolution of the human race and civilization [1-3]. With technology changing rapidly, the demand for advanced materials has grown to satisfy the latest needs [4]. Starting from the discovery of copper, the development of metals and composites has come a long way, exhibiting extraordinary properties [5]. Early in the metal age, it was observed that pure metals were too soft for any structural applications. The addition of tin to copper to make Bronze has revolutionized the art of alloying to attain better properties [6-8]. The development of Bronze marked a new age and ended the prolonged Stone Age. However, the arrival of Iron, which is stronger, harder and tougher than Bronze, ended the Bronze Age and this competition and is continued to date [9, 10]. This method of strengthening metals with small amounts of other metals has opened a huge door for developing new alloys with better properties [11]. Metals, alloys, and metal-based composites have been rigorously developed in the past century [12]. Aluminium is used in various economic applications and is vital to various industries and sectors.

In industries, aluminium is used for machinery, automobiles, structural frames, food processing, power transmission, transportation, etc [13,14]. In 2021, it was reported that 68 million tons of aluminium have been consumed globally, estimated to increase by 50% by 2030 [15]. Therefore, over the years, aluminium composites have been developed to improve their mechanical properties by using various fabrication methods [16] and processes [17] and types of reinforcements like ceramics [18], Rare Earths [19], recycled materials [20], non-metals [21], toxic wastes [22], etc. However, recycling aluminium chips has become a challenge in the current scenario. Therefore, thepresent work aims to develop lightweight composites from scrap, evaluate their mechanical properties, and co-relate them with the corresponding microstructures using conventional metal casting and manual stirring.

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2. Materials and Methods

For the present study, aluminium chips and Mild Steel (MS) chips obtained after various machining operations as a by-product were collected from the machine shop of the Mechanical Engineering Department, Geethanjali College of Engineering and Technology, Cheeryal, Hyderabad, India. These chips were collected and catalogued progressively over six months. The collected MS chips were crushed to a smaller size using a hydraulic forging machine and sieved to a size of 50 mesh. On the other hand, aluminium chips were crushed manually to make lumps of 300 grams each. The starting materials, chips of aluminium and MS and the sequence of steps involved in the development of the composites are shown in Fig. 1.

Fig. 1 Steps involved in the development of the composites (a) Aluminium and MS scrap chips/powder, (b) Melting of aluminium, (c) Addition of MS powder and stirring, (d) Molten metal, (e) Ice cool water quenching for solidification and (f) Developed composites.

Initially, an Aluminium lump of 300 grams was put in a crucible and heated in an open-hearth kerosene fueled furnace. The crucible was covered with an air tight lid to avoid any unwanted micro inclusions caused by hot flue gases. A thermocouple was attached to the crucible to monitor the temperature. At 800 °C, the lump started to melt and reached complete liquefaction at around 850 °C. The crucible was removed from the furnace after achieving molten state and the MS powder was introduced to the molten aluminium in three stages. The MS powder was divided into three equal parts and after introducing each part into the crucible, the molten mixture was manually stirred for 5 minutes using a thin Stainless-Steel rod until the mixture starts to solidify and put back into the furnace. Finally, after adding all the amount of reinforcement and stirred, the crucible was kept in a bucket of ice-cold water and the molten metal was allowed to rapidly solidify. In this manner, there composites reinforced with varying amounts of MS powder were developed. Also, an unreinforced pure aluminium sample was also cast as a benchmark to study and evaluate the effects of MS powder addition.

The developed samples were cut into convenient pieces for further characterization and testing. Also, suitable samples were cut for hot rolling. Samples of 30x30x20 mm were cut and hot rolled at 200 °C up to 50% reduction in 10 passes with a 5% reduction and water quenching after each pass. The rolled samples were also characterized and tested; their properties were compared with that of the unrolled samples.

3. Results and Discussion

3.1 Density

The developed samples were cut precisely into 1.5 X 1.5 X 1 cm blocks for density testing. The theoretical density of the composites was calculated through the Rule of mixtures, and the experimental density was measured using the Archimedes principle [23]. The relative density of the developed composites was calculated using Equation (1).

Relative Density (RD) = Experimental density/Theoretical density (1)

The intended composition and relative density of the developed composites are shown in Table 1 below. From Table 1, it can be noticed that as the amount of reinforcement increases, the relative density tends to decrease. It is evident that the theoretical density of the composite increases with an increase in the amount of MS powder, as its density is higher than that of aluminium.

Table 1 Intended compositions and relative densities of the developed composites.

S. No.	Aluminium wt%	MS powder wt%	Relative Density %
1	100	0	98.87
2	99	1	97.42
3	98	2	97.23
4	97	3	97.19

The experimental density constantly decreased with an increase in the reinforcement, resulting in the decrease of RD. This phenomenon is expected because of manual stirring during the addition of reinforcement which would have introduced gas bubbles [24].

Also, the introduction of the reinforcement and stirring in three stages, displacing the crucible in and out of the furnace for adding reinforcement, and quenching the molten mixture in ice-cold water, which did not provide enough time for the entrapped gas bubbles to escape to the surface, could be the main reasons for the formation of pores in the composites [25]. However, the decrease in the RD of the composite samples is significantly smaller and well above 97 %.

3.2 Microstructure Characterization

One piece from each developed composite was cut and prepared for microstructure observations. An Optical Microscope (Make: Upright Microscope) was used for the microstructure observations. The samples were prepared in line with the ASTM standards. The samples were polished on 400, 600, 800, 1200, 1500 and 2000 silicon carbide emery papers. Next, the samples were cloth polished using a diamond paste to get a mirror-polished surface. The polished samples were then etched with modified Keller's reagent for 35-45 seconds and thoroughly washed, air-dried and made ready for microstructure observations [26]. The microstructures of the developed composites are shown in Fig. 2 below. From Fig 2, the microstructure change with increased MS powder addition can be observed. It is also evident from the microstructures that the grain refinement increases from Fig 2 (a) to (c), and after that, abruptly, the grains tend to grow. Moreover, a needle-like secondary phase can be seen in Fig 2 (b) to (d), which get finer and increase in number up to Fig 2 (c) and become coarser in (d).

The change in mechanical properties, such as hardness and compression strength, can be attributed to grain refinement and fine secondary phase development [27]. The mechanical properties of the composites improve as the grain size decreases and the finer secondary phase increases up to 2 wt% addition of MS powder. However, the properties tend to decrease as the grain size increases, and the secondary phase becomes coarser when the amount of MS powder addition increases beyond 2 wt%. This can be due to the fact that finer MS powder particles get agglomerated, and their distribution gets affected as their amount increases [28]. The microstructures of the developed samples hot rolled at 200 °C up to 50% reduction are shown in Fig. 3. Solid red arrows show the rolling direction in Fig 3. As discussed earlier, grain refinement was evident in the composites due to the addition of fine MS powder. During hot rolling, the grains were elongated in the direction of rolling, accommodating themselves to eliminate any pores present during the initial fabrication. It can be observed from Fig 3 that the composites were densified [29]. Also, the secondary phase was uniformly redistributed due to the rise in temperature and pressure applied during rolling.

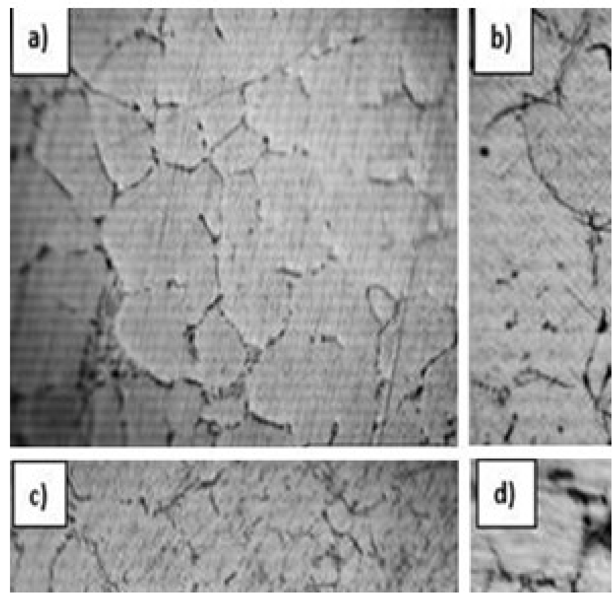

Fig. 2 Optical microstructures of the developed composites reinforced with MS powder (a) 0 wt.%, (b) 1wt.%, (c) 2 wt. % & (d) 3 wt. %.

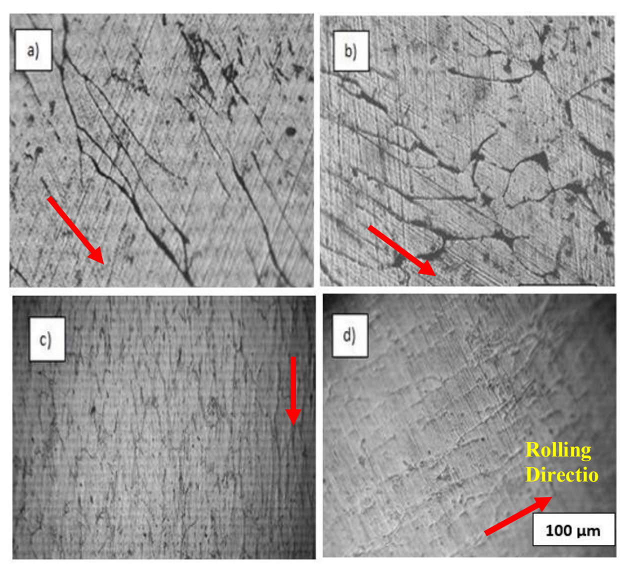

Fig. 3 Optical microstructures of cross-sections of samples hot rolled at 200 °C up to 50% reduction reinforced with MSpowder (a) 0 wt.%, (b) 1 wt.%, (c) 2 wt. % & (d) 3 wt. %.

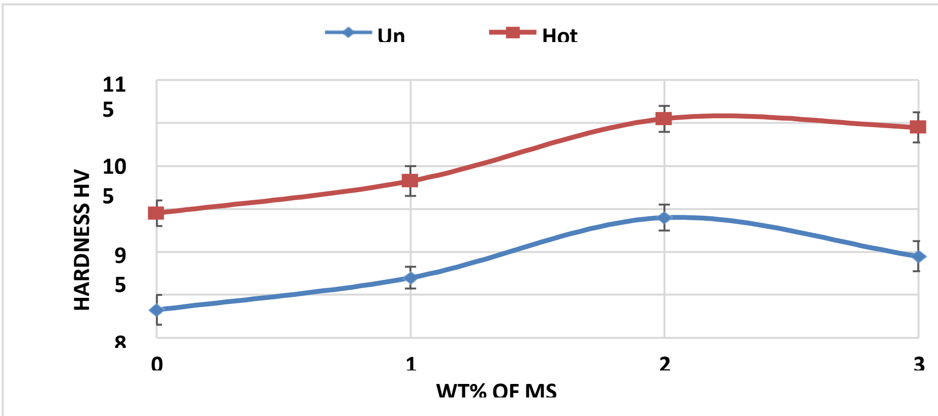

Fig. 4 Microhardness variation of the developed composites with varying amounts of MS powder before and after hot rolling

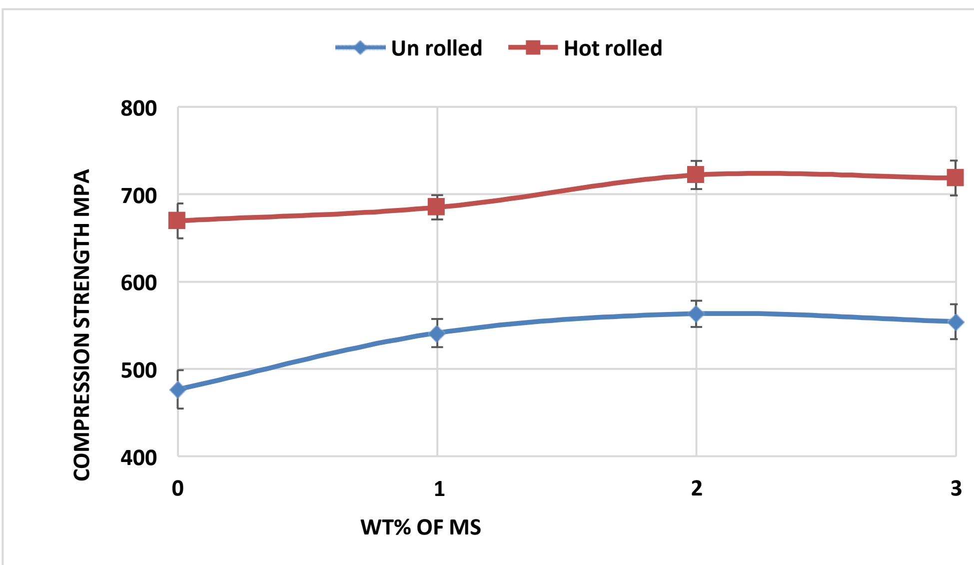

Fig. 5 Compression strength variation of the developed composites with varying amounts of MS powder before and after hotrolling

Moreover, due to severe plastic deformation, it can be observed from Fig 3 (c) that the elongated grains were further broken along their length, decreasing the grain size and, thus, increasing the number of grains and grain boundaries [30]. Initially, the secondary phase was concentrated between the elongated grains. However, with 2 wt% MS powder reinforcement, it can be observed that the secondary phase is broken into smaller amounts and distributed uniformly.

3.3 Mechanical Properties

The developed composites were cut into appropriate shapes and sizes according to ASTM standards for mechanical testing. Micro hardness testing was conducted on the prepared samples using a computerized Vikers hardness testing machine, while the compression test was done on a Universal testing machine according to ASTM E8 standards. Ten readings were taken on each sample at points spread across the surface and the average is reported along with the maximum and minimum values. Similarly, three samples from each composite were compressed and the average value is reported. The micro hardness of the composites before and after hot rolling is showed in Fig. 4.

From Fig 4, the trend followed by the microhardness with an increase in the amount of MS powder can be seen. With an increase in the amount of MS powder addition, hardness gradually increases up to 2 wt%. However, hardness tends to drop beyond 2 wt% addition of MS powder. On the other hand, hot-rolled samples also followed a similar trend as that of unrolled samples. However, there is an average increase of around 20 Hv between the both. The gradual increase in the hardness can be attributed to the occurrence of grain refinement, Al-Fe secondary phase formation and uniform distribution in the matrix with the addition of MS powder [31].

Similarly, the grains elongated due to hot rolling, and the secondary phase was redistributed within the matrix at the grain boundaries. Moreover, with a further increase in the amount of MS powder, the fracture of elongated grains resulted in an increase in the number of grains and grain boundaries within the matrix, as seen in Fig 3. Also, severe plastic deformation induced by rolling plays a major role in improving the hardness as it promotes the number of dislocations within the matrix. The decrease in the hardness beyond 2 wt% addition of MS powder can be attributed to the agglomeration of particles and secondary phase in the matrix. Fig 5 shows the variation of compression strength with an increase in the addition of MS powder. The variation in compression strength also follows a similar trend as that of the hardness, as seen in Fig 4. This variation trend can be explained on similar lines as that of hardness. The increase in compression strength, both before and after hot rolling, can be attributed majorly to the grain refinement, increase in the number of dislocations due to rolling, further grain size reduction due to rolling, size reduction and uniform distribution of Al-Fe secondary phase [32].

4. Conclusions

In the present study, three composites reinforced with varying weight percentages of MS scrap were successfully developed. The microstructure revealed the high intensity of grain reinforcement up to 2 wt% of MS powder, beyond which the refinement is insignificant.

The developed composite mechanical properties were improved compared to the unreinforced sample. The sample reinforced with 2 wt% of MS powder exhibited the highest hardness andcompression strength of 83 Hv and 563 MPa, which are 26% and 15.3%, respectively, compared to theunreinforced alloy.

Hot rolling further improved the mechanical properties of the composites and followed a similar trend asthat of unrolled samples. The microstructures showed elongated grains, grain fracture, decreased size and uniform distribution of secondary phase within the matrix.

The sample reinforced with 2 wt% of MS powder exhibited the highest hardness and compression strength of 106 Hv, which is 21% and 42% compared to the sample without rolling and unrolled and unreinforced samples, respectively. Similarly, the sample reinforced with 2 wt% of MS powder exhibited the highest compression strength of 722 MPa, which is 22% and 34%, compared to the sample without rolling and unrolled and unreinforced samples.

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