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Recycling of Aluminum Alloy from Al-Cu Metal Matrix Composite Reinforced with SiC Particulates

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Abstract In this study, we investigate the recycling of aluminum-based metal matrix composites(AMCs) embedded with SiC particulates. The microstructure of the AMCs is characterized by X-ray diffraction and scanning electron microscopy. The possibility of recycling the composite scrap is attempted from the melted alloy and SiC particulates by re-melting, holding and solidification in crucibles. The recovery percentage of the matrix alloy is calculated after a number of holding times, 0, 5, 10, 15, 20, 25 and 30 minutes and for different particulate sizes and weight fractions in the Al matrix. The results show that the recovery percentage of the matrix alloy, as well as the time required for maximum recovery of the matrix, is dependent on the size and weight fraction of SiC particulates. In addition, the percentage recovery increases with particulate size but drops with the particulate fraction in the matrix. The time to reach maximum recovery falls rapidly with an increase in particulate size and fraction.

Key words recycling, aluminum, composite, particulate, holding time, automotive.

1. Introduction

There is an increasing demand of aluminum-based metal matrix composites(AMCs) in various important applications like automotive, aerospace, military structures, engine pistons, drive shafts and sports goods etc. for last few decades.[1)] An increased amount of aluminum usage in our daily life and surroundings have raised a great concern of accumulating huge Al scraps in near future. It is already reported that energy of recycling waste scraps of aluminum ingots is only around 3 % used in the production of a new ingot.[2)] Therefore, there is a strong fact that necessitates the recycling process of aluminum components. Moreover, it cannot be left ignored by current researchers as it maintains the ecological niche of our environment, reduces scraps and consumption of energy. AMCs can be produced by several manufacturing routes such as melting and casting, powder metallurgy, additive manufacturing, cold spray, mechanical alloying, etc..[3-5)] Various types of reinforcement materials are also available to embed these AMCs, for example, short fibers, particulates, whiskers, carbon nanomaterials with different volume fraction and desired application. After the damage of these components, environmental attack or during casting process of small aluminum parts such as automotive car components, piston, shaft, cylinder block or sports valuables etc. a large amount of scrap is generated.[6)] Hence recycling of these scraps is essential to minimize the wastage of valuable materials. In recent few years, some research results have been reported on recycling of AMCs.[7-9)] Nishida and his co-workers used various complex and toxic chemical electrolytes such as NaCl·KCl·Na_2SiF_6 and KCl·AlF_3·K_3AlF_6 to purify the liquid melt form embedded secondary phases, i.e, Al_2O_3 short fibers, SiC whisker from the composite matrix.[9)] Compared to the other types of reinforcements, particulate reinforced AMCs are quite easy to recover than the fiber reinforced AMCs if a suitable matrix and particulate combination are chosen. Particle reinforced AMCs can be easily manufactured by traditional approaches with better mechanical, creep, fatigue, wear and corrosion resistance, as reported by Hossein et al.[10)] Although a great deal of research efforts have been put forward on AMCs, there is still a scarcity of information on the recyclability of particulate

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reinforced AMCs. The development of suitable approach or tools for recycling of AMCs is crucial to the commercialization of these AMCs products. In this study, recycling of aluminum alloy(Al-4.5 wt% Cu) from SiC particulate reinforced AMCs was carried out by conventional melting and casting approach. The minimum holding time to achieve the percentage recovery of the matrix component from the composite scraps containing various particulates of different size and weight fractions was discussed.

2. Experimental Procedures

The composition of matrix aluminum alloy was Al-4.5 wt% Cu with 99.7 % purity, and the SiC reinforcements were over 99.8 % pure particles. The specific weight of Al-4.5Cu alloy and SiC were 2.783 and 3.125 g/cm^3, respectively. The AMC scrap obtained during synthesis of composites by stir casting route contained SiC particles with various sizes, 95, 125, and 490 μm and weight fractions, 5, 10, and 20 wt%. The melting of the scraps in identical crucibles was done in an electric furnace at 800-850 °C. The height of the crucible was 95 mm with top and base diameter of 80 and 70 mm, respectively.

For each melt, 250 g of scrap was used. After the scrap melted, the molten slurry was manually stirred to remove the oxide layer entrapped inside the molten slurry and then holding time was calculated. The procedure adopted for separation of SiC particulates from the matrix is shown in Fig. 1.

Time selected for holding the molten slurry was 5, 10, 15, 20, 25 and 30 minutes. The molten metal was top poured carefully in graphite molds so that the flow of high-density slurry(alloy with SiC particulates) from the bottom of the crucible to the mold could be avoided. The alloy was then weighed and percentage recovery of the matrix at different time intervals was evaluated for each composition. The initial weight of the alloy scrap was 250 g which was recovered up to 192.5 g. The percentage recovery of the matrix alloy was defined as:

The percentage recovery of matrix alloy =

$$\frac{W_{RA}(g)}{W_C(g) - W_Z(g)} \times 100$$

where W_{RA} = weight of the recovered matrix alloy, W_C = weight of the composite, W_Z = weight of the SiC in the composite. Amount of SiC in the composite scrap was determined by chemical dissolution method. Microstructural characterization study was accomplished using X-ray diffraction(XRD) and scanning electron microscope (SEM). SEM images were taken from the bottom part of the casting, solidified in the crucible to observe the bed thickness of the matrix alloy with silicon carbide.

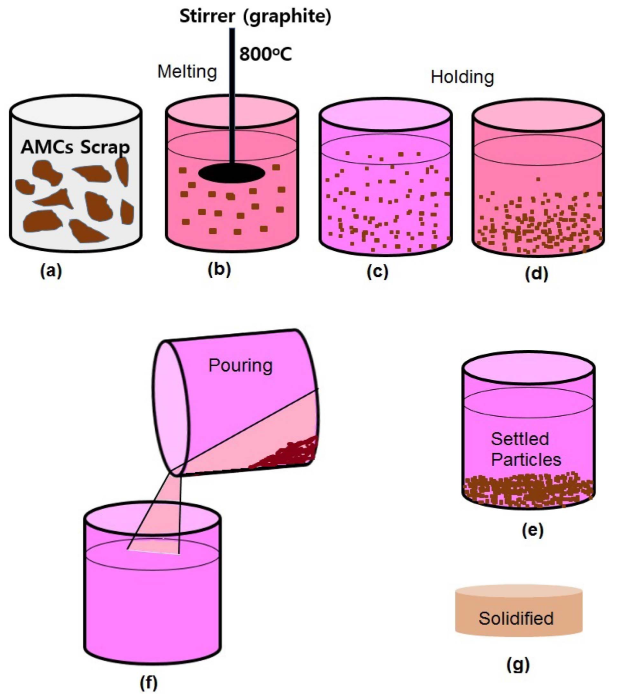

Fig. 1. Schematic diagram for separation of Al matrix and SiC reinforcement.

3. Results and Discussion

Fig. 2(a) is the photograph taken from the bottom of the casting, solidified in the crucible after 10 minutes of holding at 800 °C, for the composite scrap reinforced with 5 wt% SiC particulates of size 125 μm. The dark bottom part of the photograph is the alloy matrix saturated with SiC particulates and the top shining part is the aluminum alloy without the presence of SiC particulate. The further confirmation of phases was attempted by XRD analysis showing Al, SiC and $CuAl_2$ intermetallic compounds, as shown in Fig. 2(b).

Fig. 3 shows the SEM images from the bottom(alloy saturated with SiC particulates), intermediate(the region where pure alloy and composite co-exist) and the top (alloy free from SiC reinforcement) portions of the casting after settling process. It is observed that SiC particulates completely separate from the alloy after holding the scrap in a molten condition and as a result fine SiC particulates are not found in the top part of the casting. However, some loss of matrix alloy occurs as the bottom part of the casting contains a certain amount of matrix alloy saturated with silicon carbide.

Fig. 4 shows the amount of percentage recovery(%) of the matrix as a function of holding time for different size and fraction of reinforcements. It is observed that SiC

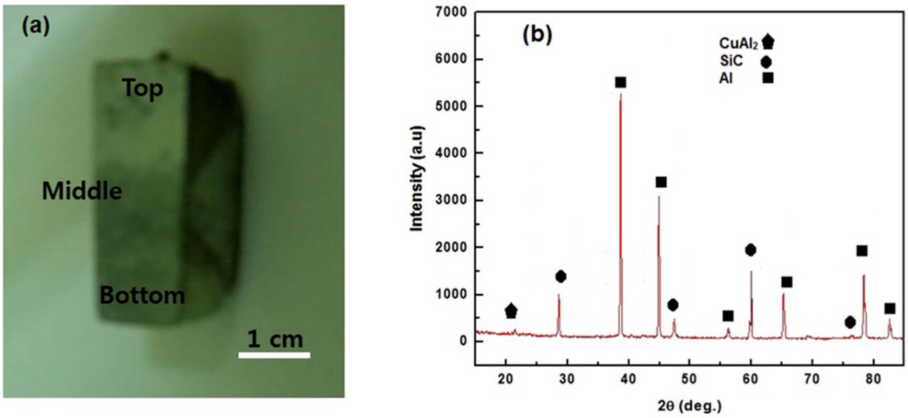

Fig. 2. (a) Image take from the bottom of solidified casting in the crucible after 10 minutes of holding at 800 °C, for the composite scrap reinforced with 5 wt% SiC particulates of size 125 μm, (b) XRD pattern of (a) in the middle region.

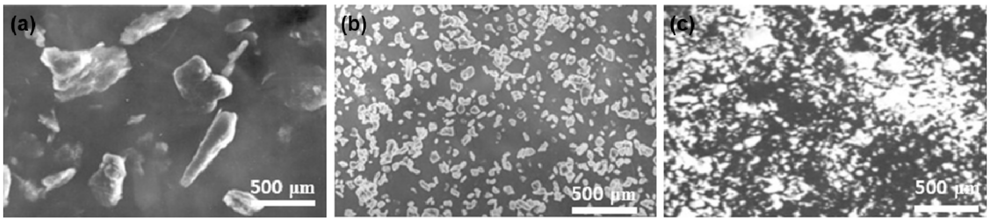

Fig. 3. SEM images of (a) bottom, (b) middle, and (c) top region of the casting solidified in the crucible after 10 minutes of holding at 800 °C, for the composite scrap reinforced with 10 wt% SiC particulates of size 125 μm.

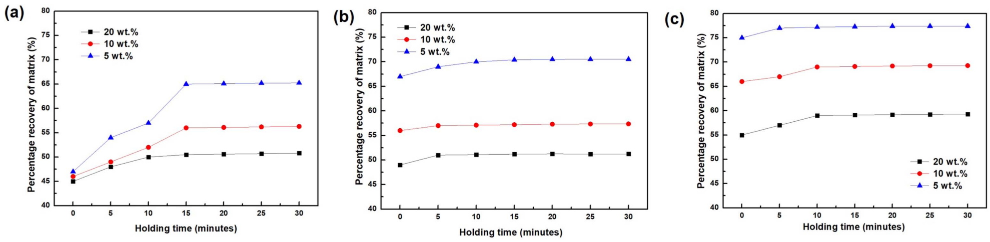

Fig. 4. Relationship between the SiC weight fraction and recovered Al matrix for SiC particulate size, (a) 95, (b) 125, and (c) 490 μm.

particulates immediately settles at a very high rate within first few minutes after melting for all the composite scraps and then the settling rate slows down according to the particle size and weight fraction.

The melt flow behavior of SiC particulates proceed through three steps. (a) Melting and separation of SiC particles and aluminum in the crucible, (b) wetting and buoyancy behavior of the SiC powder particles by the melt, and (c) breaking up of settled or segregated particles in the crucible. The first two steps are dependent upon the size, shape, density as well as the chemistry of the particles and the Al melt and contribute most to the recovery of SiC particles.

Initially, the sedimentation rate is quite high until 5 minutes of holding time irrespective of the composite scrap compositions. This may be related to the high fluidity of the initial melt. However, the sedimentation rate becomes slow beyond 5 minutes of holding time. This may be due to the increased viscosity of the liquid metal at the bottom of the crucible due to the saturation of SiC particulates.[11] The settling of particulates after 5 minutes of holding time is rather gradual when the composite scraps are embedded with smaller particulate size and lower weight fraction.

Fig. 5 demonstrates the effect of SiC particulates size and weight fraction for the maximum recovery of the matrix. It is seen that the percentage recovery of the matrix increases as the particle amount decreases and

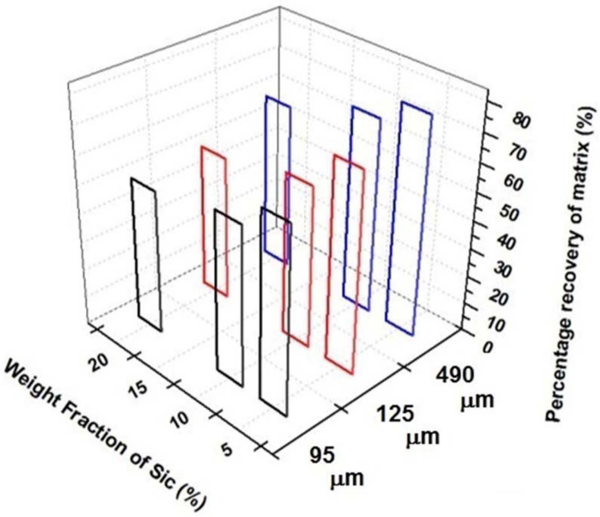

Fig. 5. Influence of SiC particulate size and amount on maximum percentage recovery of Al alloy.

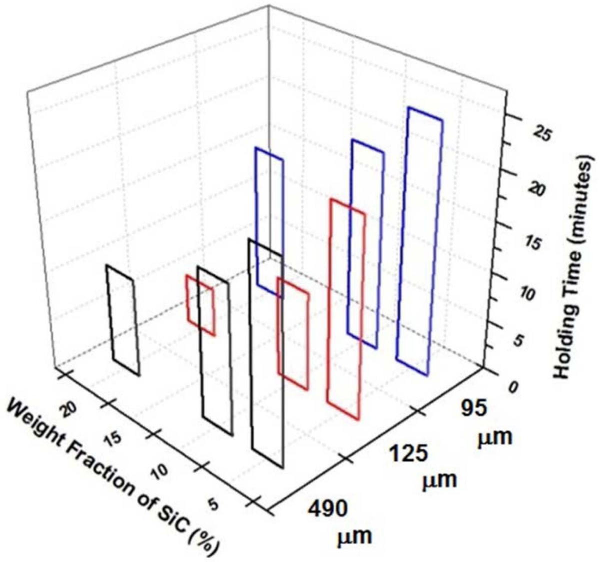

Fig. 6. Influence of SiC particulate size and amount on minimum holding time required to achieve maximum recovery of Al alloy.

particle size increases. The scrap with 5 wt% SiC particulates of 125 µm size shows maximum percentage recovery of ≈77 wt%. The percentage recovery of the matrix alloy was found to be 50 wt% for composite scrap embedded with a particle size of 95 µm, and the amount of 20 wt%. The SiC particulates settled at the bottom for composite scrap embedded with a low amount of SiC retains less matrix alloy with it. On the contrary, for composite scrap with high SiC particulate weight fraction retains a higher amount of aluminum matrix alloy.

Therefore, a higher particulate amount indicates a poor percentage recovery and vice versa. Small SiC particles stay in suspension for a longer time and settle at a slow rate compared to larger SiC particulates. This can be related to the buoyancy force of the liquid alloy, which is more effective on small SiC particulates.[11-12] The bed thickness of the matrix alloy with smaller SiC particulates at the crucible bottom is higher as compared to that with larger particles, which decrease the amount of matrix alloy recovery. Thus, it can be inferred that when the particle size decreases, the percentage recovery of the matrix alloy also decreases as a consequence.

Fig. 6 displays the effect of SiC particulate size and weight fraction in the matrix on minimum holding time required to achieve maximum recovery of matrix alloy. It is noticed that increase in particulate size and weight fraction degrades the minimum time to get maximum percentage recovery. It can be observed that time taken for the complete settling of composite scrap containing SiC particulate of size 125 µm and weight fraction of 20 wt% is only 5 minutes. Whereas composite scrap reinforced with SiC particulate size of 95 µm and amount of 5 wt% took 25 minutes for complete settling. A rapid settling of SiC particulates occurs when the composite is embedded with larger SiC size when added in higher weight fraction, can be correlated to the velocity gradient during the settling of the larger particulates.[12]

The big sized particulates led to the accelerated agitation of the melt and drag the nearby particulate in motion and subsequent improvement in settling rate was observed. As already described in earlier sections, smaller SiC particulates have lightweight and can remain in the melt for a longer period of time without settling. Therefore, the time required for obtaining maximum percentage recovery of the matrix is higher as compared to that with bigger SiC particulates.

4. Conclusions

The following conclusions can be drawn from the present investigation.

1) Al matrix alloy can be successfully recycled from composite scraps into the molten metal alloy and SiC particulates by re-melting, holding and casting approach.

2) It can be concluded that about 50-77 % of the Al alloy matrix can be regained from the composite scraps embedded with SiC particulates of different particle size and weight fraction.

3) The percentage recovery of the Al alloy improves with an increase in particulate size and the decrease in particulate weight fraction

4) Higher particulate and weight fraction cause a minimum time to achieve maximum recovery of Al alloy.

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