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Effect of Hot Rolling on Al-4.5%Cu Alloy Reinforced Fly Ash Metal Matrix Composite

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Abstract Today's world has an increasing interest in composites containing low density and low cost reinforcements. However, these materials endure from poor distribution of the reinforcement in matrix and increase in porosity level. Fly ash is one of the low density reinforcement available in abundant and going as waste from thermal power plants. This paper is concerned with characterization of samples cast from an Al-4.5wt.%Cu alloy reinforced fly ash particles. The composite materials were casted by liquid metal stirring technique with 10wt.% fly ash were reinforced in the base matrix. The composites fabricated by stir casting were rolled at four different reductions of 20, 40, 60 and 80%. The results showed decreased porosity with improved hardness, tensile strength and wear resistance with increase in percentage of rolling reduction. Optical micrograph indicates uniform distribution of fly ash particles and refined grain structure by increasing the rolling reduction.

Keywords Metal matrix composite, Liquid Stir casting, Fly ash, Wear, Rolling

1. Introduction

Recycling of fly ash, the coal combustion waste product produced by thermal power plants, is an increasingly urgent problem associated with their storage and disposal, which may have negative effect on human and serious environmental issues[1-5]. On the other hand, the high cost of aluminum Metal Matrix Composites (MMCs), reinforced with ceramic particles such as SiC and Al_2O_3 has limited their use in many engineering applications[6]. To reduce this cost and expand their utilization base, Al alloys have been reinforced with low cost reinforcement such as fly ash[7-8]. The inclusion of fly ash in aluminum MMCs has a unique natural source of the particulate material for light-weight and low-cost composites[4]. This is because of the combination of its low price along with low density, attractive physical and mechanical properties, and advantageous spherical shape, which is very expensive to produce it in a simulated way[9]. Aluminium-fly ash (ALFA) composites have been developed in recent years. The use of fly ash as a filler or reinforcement for aluminum alloys is very desirable from an environmental stand point[10]. MMCs produced by casting by means of reinforced by diffusion particles, platelets, continuous fibres and non-continuous fibres[11]. In recent years particulate reinforced composites are being produced by different methods, such as stir casting[12-13], squeeze casting[14], powder metallurgy[15], compo casting[16] spray deposition technique[17] and plasma spraying[18]. Among these methods, stir casting is considered to be flexible and inexpensive due to its low processing cost and high production rate. An added advantage of this process is the near-net shape formation of the composites[19]. Mahendra K.V. et al.[20] reinforced fly ash particles in Al-alloy by stir casting route and stated higher hardness, tensile, compression and impact strength with increase percentage of fly ash. M. Ramachandra et al.[8] showed higher wear resistance by the addition of fly ash to Al-alloy MMCs. Sudarshan et al.[21] have synthesized Al–fly ash particle composites and stated higher damping capacity by reinforcing fly ash particle. P. K. Rohatgi et al.[22] reinforced fly ash in Al-alloy by pressure infiltration and showed lower coefficient of thermal expansion with decrease in air voids. All MMCs produced will have poor plasticity and the plastic deformation is an effective method to refine grains[23]. Many researchers have conducted secondary process for the mechanisms of high temperature deformation of MMCs, including, hot working, hot extrusion, high temperature compression, hot forging and hot rolling[24-27]. Compared with some exclusive and costly methods such as extrusion, forging, rapid solidification, and equal channel angular pressing (ECAP), rolling process was a common way that can fabricate large dimension products[23,28-29]. Shafaat Ahmed et al.[30] rolled Al-4.5Cu-3.4Fe composite to a reduction of 73% and stated increase tensile and ductility with increase in extent of rolling. Mervin A. Herbert et al.

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[31] rolled mushy state Al-4.5Cu-5TiB2 composite to a reduction of 7.5% and concluded that increase in hardness and decrease in wear rates by extension of rolling. S. Kumar et al.[32] rolled Al-4Cu-5TiB2 insitu composite to a reduction of 40% both in ambient and cryogenic temperature and showed improved hardness and wear resistance compared to as cast composites. Sajjad Amirkhanlou et al.[33] reported that rolling Al-SiC composites to 95% reduction increases tensile strength and decreased porosity level with increase in reduction of rolling. However studies on rolling behaviour of Al-fly ash MMCs by stir casting have been rarely conducted and hence an attempt has been made in the present study. The rolling was adopted as a secondary process for refining and to enhance the mechanical properties of Al-Cu alloy reinforced fly ash MMCs. Low cost liquid metallurgy stir casting process is utilized to fabricate the MMCs. The stir cast blanks were subjected for hot rolling process for different reductions. A further objective is to investigate the effect of extend of hot rolling reduction on the microstructure, porosity and mechanical properties of the produced MMCs.

2. Experimental Details

A stir casting setup which consisted of a resistance furnace and a stirrer assembly is used to synthesis the composite. Al-4.5wt%Cu alloy commercially prepared was melted in a resistance heated muffle furnace and casted in a crucible. Table 1 shows the chemical composition of base alloy, analysed by optical emission spectrometer. The density of fly ash measured is 1.9 g/cm^3 with the particle size varying between 28 and 35μm. Initially, Al-Cu alloy was charged into the crucible and heated to about 760°C till the entire alloy in the crucible was melted. The 10wt.% fly ash particles were preheated to 280°C for two hours to remove moisture. The steel mold of size 25mm diameter with 200mm length was used for the preparation of cast blanks. The mold was also preheated to 250°C for 2-3 hours to obtain uniform solidification.

Table 1. The chemical composition of the Al-4.5%Cu matrix alloy (wt. %)

Cu	4.51
Mg	0.061
Si	0.52
Fe	0.59
Mn	0.13
Ni	0.06
Pb	0.03
Sn	0.02
Ti	0.012
Zn	0.12
Al	balance

After the molten metal was fully melted the hexachloroethane degassing tablet was added to reduce the porosity[20]. The stirrer was lowered into the melt slowly to stir the molten metal at the speed of 450 rpm. The preheated fly ash particles were added at the rate of 40 g/min during the stirring time with Mg (0.6wt %) were also added to ensure good wettability of particles[34]. Various stirrer speeds, tilt angles and movement of stirrer from top to bottom in the crucible were used to obtain vortex strong enough to disperse the reinforcements into the melt[21]. The stirring was continued for another 1min even after the completion of particle feeding. The temperature was also monitored simultaneously during stirring. When the temperature remained between 710 and 730°C, the mixture was poured into the mold and the time taken to fill the mold was 6.1 seconds. The maximum duration of mixing was 3min. The clearance of the stirrer from the bottom of the crucible was approximately 10 mm with the melt depth of 120 mm. As the matrix alloy is age hardening, the as-cast composites produced were subjected to T6 heat treatment[35]. The castings were heated to 520°C for 12 hours, quenched in 100ºC water and reheated to 170ºC for 16 hours and cooled in the furnace temperature before hot rolling process[36]. The rolling samples were machined for a dimension of 180mm length, 12mm width and 12mm thickness. The samples were hot rolled with a temperature of 410°C and the thickness reduction of 0.25mm per each cycle into different final reductions of 20%, 40%, 60% and 80% with intermediate heat treating process. The laboratory rolling mill with a loading capacity of 15tons is used for rolling the samples with no lubrications shown in Figure 1.

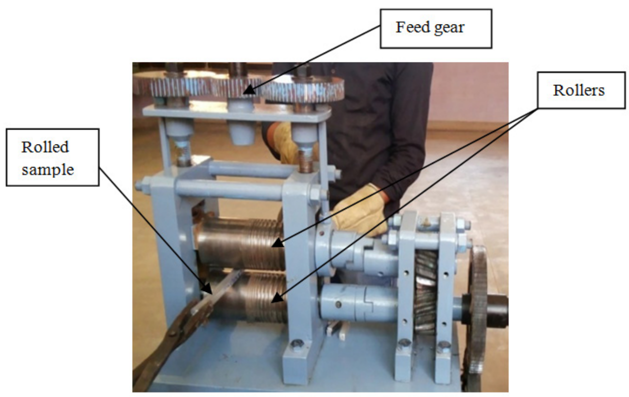

Figure 1. Rolling of composite in a rolling mill

The roll diameter was 85mm and roller speed was set to 45rpm. Experimental density of composites was measured by water displacement technique. According to Archimedes' principle, the buoyant force is equal to the weight of the fluid displaced by the object. Therefore the weight of water is equal to the difference of real weight and apparent immersed weight of specimen. The theoretical density is measured from rule of mixture (ROM) and is given by

$$\rho_T = \rho_m V_m + \rho_r V_r \qquad (1)$$

Where;

ρ_T, ρ_m and ρ_r is the theoretical densities of composites, matrix and dispersed phase respectively.

V_m and V_r is the volume fraction of matrix and dispersed phase respectively.

The porosity was calculated as according to formula given below:

$$\text{Porosity (\%)} = \frac{\rho_{T-}\rho_E}{\rho_T} \text{ X } 100 \quad (2)$$

Where ρ_T the theoretical density is measured from rule of mixture (ROM) and ρ_E is the density measured by water displacement method.

Hardness measurements were performed using a Brinnel hardness tester with a load of 10kgf as per ASTM-E10-01. Hardness values were averaged over five measurements taken at different points on the cross-section. Tensile tests were carried out using samples prepared according to ASTM-E-8M standard. These tests were conducted using an Instron servo-hydraulic tensile testing machine. Wear test was carried out for rolled composites using a computerized pin on a disc wear testing machine under ambient temperature conditions. Wear specimens of 6mm X 6mm X 3mm were prepared and subsequently, the weight loss of the materials was determined. Optical micro photographs were taken for different reductions to examine the effect of the percentage of particle distribution, porosity present in the composites. Microstructure and fracture surfaces (obtained by wear test) were studied by scanning electron microscope (SEM.).

3. Results and Discussion

3.1. Microstructure

In order to understand the variation of percentage voids with increasing reduction, microscopical investigation was made to examine particle fracture due to successive hot rolling. Optical microphotographs of the composites strip after 0, 20, 40, 60 and 80% reduction during rolling with 10wt% fly ash MMCs are shown in Figure 2.

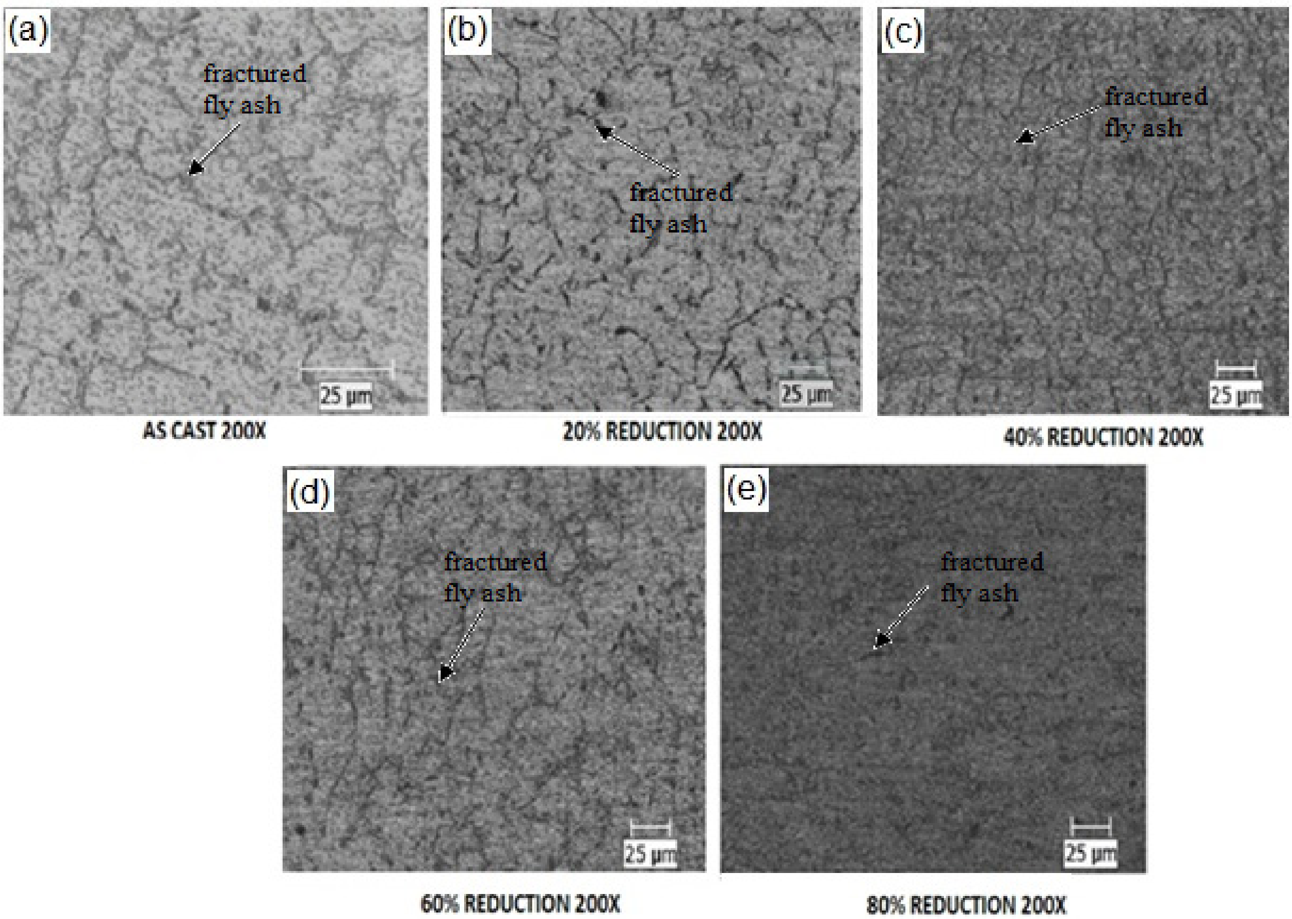

Figure 2. Optical microphotographs of Al-4.5% Cu/10fly ash composite microstructure: a) 0% as cast, (b) 20%, (c) 40%, (d) 60% and (e) 80% reduction

In the cast composites, uniform distribution of grain structure in the matrix alloy is influenced by many factors including particle reinforcement method, particle mixing, rheological behaviour of materials melting point and reactions during solidification. Stir casting exhibit improved dispersion of fly ash[20] up to 15wt% and confined between the growing and continuously run over solid particles of the primary phase in the partly solid state. From Figure 2(a), the grain structure is still not improved by using stir casting. As the reduction of rolling starts from 20% to 40% (Figures 2(b) & 2(c)), the declustering phenomenon begins to occur. In spite of the particulate damage where the fracture strain along the transverse direction was observed to increase significantly with increase in reduction of rolling, the dispersion of fly ash particle obtained will minimize the stress concentration at the particulates resulting in minimal particle damage leading to larger plastic deformation of the matrix and fly ash. After the 60% reduction (Figure 2(d)) of as cast composite, the declustering improves in large trend and particle free zones are large with further refining the grain structure is possible between matrix and reinforcements. Finally after 80% reduction during hot rolling (Figure 2(e)) complete dynamic recrystallization occurred and no free zones formed. The mechanism for evolution of grain structure in the hot rolled as cast composite have shown bimodal grain size distribution in which the formation of fine grains is believed to be caused by successive reduction of composites by rolling. During last roll pass, all the clusters disappear so well that almost no particle free zones remain in the composite and a homogeneous particle distribution is observed (Figure 2(e)).

Although a large part of porosities is expected to be eliminated after 80% reduction indicating that the remaining micro voids decrease by increasing the number of reduction due to the rolling pressure.

3.2. Hardness

Figure 3 shows the variation in hardness with the extent of rolling. The hardness of a material is a physical parameter indicating the ability of resisting local plastic deformation. The hardness of Al-fly ash composites was found to increase gradually with an increase in the extent of reduction during rolling. This increase was observed from 73 to 109 BHN of Al-Cu/10% fly ash composite. This can be attributed primarily to the refined grain structure of matrix, presence of harder fly ash reinforcement and harder $CuAl_2$ phase in the matrix, and also the higher constraint to the localized matrix deformation during indentation as a result of the presence of reinforcement. Also, fly ash, like other reinforcements strengthens the matrix by creation of high density dislocations during cooling to room temperature due to the difference of coefficients of thermal expansions between the fly ash and matrix. Mismatch strains developed between the reinforcement and the matrix obstructs the movement of dislocations, resulting in improvement of the hardness of the composites.

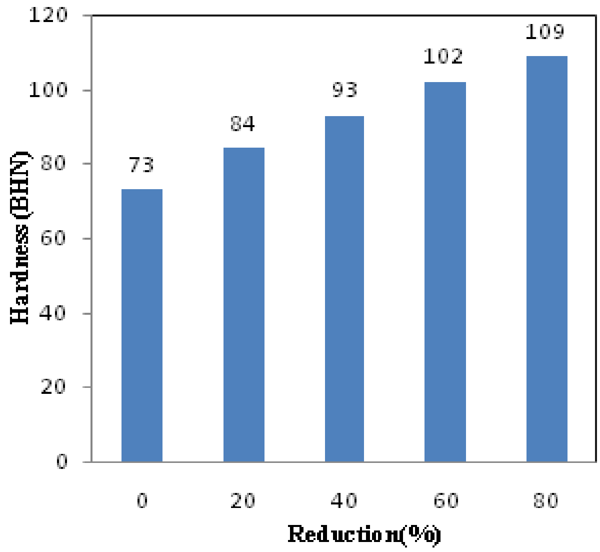

Figure 3. Variations of hardness for as-rolled, 20%, 40%, 60% and 80% reduction composites

This is also confirms that the result reported by I. Narasimha Murthy et al.[37] illustrated the hardness values for 50% deformed of Al-Cu alloy fly ash composites under compressive loading. The increased hardness values were observed for all the tested samples during reduction (0 -80%) deformed condition which is due to the progressively finer dispersion of the fragmented particles and this is in par with literature[30].

3.3. Porosity

The inclusions of gas entrapment during stirring the molten metal, air bubbles entering the slurry at the time of reinforcing particles, solidification shrinkage and water vapour on the surface of the particle are some of the parameters influence the formation of porosity in cast MMCs[38, 39]. The reinforcement of fly ash particles in Al-4.5%Cu alloy by liquid metal stir casting has resulted in agglomeration of particles and porosity (Figure. 2(a)). The fly ash particles are spherical in shape with assorted sizes and agglomerated fines, some of which sticking to the surfaces of the superior ones. These agglomerates have also aided in the formation of high level of porosity. The effect of the rolling process on the measured porosity of the composites in the as cast composite and after rolling is illustrated in Figure 4 as a function of the reduction content. From Figure 4, the as cast composite posses a higher level of porosity than rolled ones and the application of the heavy reduction (80%) during hot rolling results in approximately 0.8% porosity. The trend of the chart shows, as the rolling reduction increases the porosity level decreases. The reduction of porosity during rolling is in agreement with the available literature[39] and the decreased porosity of MMCs during rolling is due to applied shear and compressive force which will fill the voids[40]. It has been observed that the strain hardening or dislocation strengthening play a main role in increasing the strength in the initial reductions (up to 40%), and further reduction leads to the formation of submicron which also contribute to strength. These results are in agreement with the measured porosity and micro structural observations. It has been widely shown that crack formation in the cast MMCs is preferably associated with porosity and clusters of reinforcement, which result in lower mechanical properties [41]. After sufficient reductions, almost all clusters of fly ash particles are eliminated (Figure 2(d) and 2(e)) and almost no porosity remains in the composites. As can be seen from the results of this investigation, the rolling process can be a useful procedure to improve the properties of the as-cast composite and obtain highly uniform MMCs with high-mechanical properties. Although no investigations have been reported about the influence of the rolling process on the properties of any as-cast Al-fly ash composite, the obtained results suggest that the rolling process can be used as excellent technique for eliminating the as-cast composite related problems.

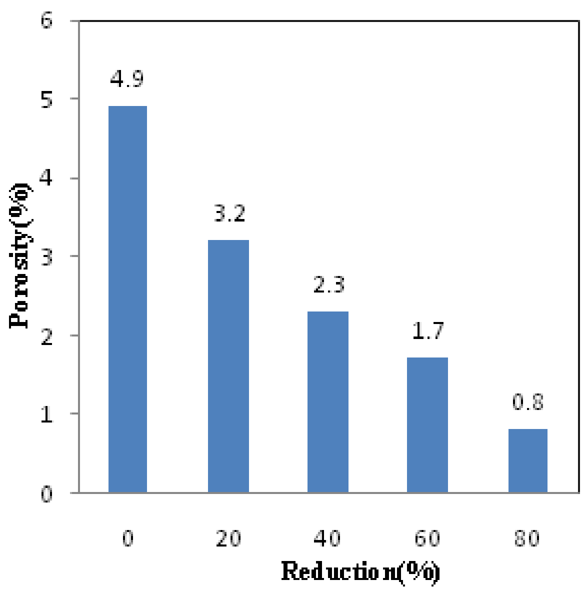

Figure 4. Variations of porosity percentage for as-rolled, 20%, 40%, 60% and 80% reduction composites

The increased rolling reduction provides easier flow of the matrix alloy and hence results in decreased porosity. In fact, rolling process is more effective in the distribution of fly ash particles shown in Figure 4 also demonstrates that a large part of porosity is eliminated. The reduction of porosity obtained here is in agreement with the literature[42], i.e., mechanical working can reduce the porosity and it can be eliminated if the amount of the applied deformation is over eighty percent.

3.4. Tensile Strength

It is well known factor that under tensile straining condition the ductility of the composite is highly affected by the progressive of reinforcement damage[43, 44]. Figure 5 shows the tensile strength of as cast is lower and as the reduction of rolling progress, the tensile strength increases to the peak value of 346MPa for 80% reduction. The highest strength and ductility was obtained at higher reduction during rolling. The longitudinally sectioned samples tested for composite of showed that restoration during hot rolling with dynamic recovery increases the ductility as well as slight improvement in strength brought about by lower damage sensitivity induced by hot rolling and higher reductions. It is expound that the rise in ductility with increase in reduction corresponds to a alter in damage behaviour, crack nucleation induced by particle cracking and due to superior decohesion of fly ash from matrix at interface sites. There is a comprehensible correlation exists between the evolution of damage in composites and the achievable tensile strength[45]. The presence of fly ash particle in Al-Cu matrix and their role in improving the microstructure leads to increase in strength. The rolled tensile fracture surface of Al-4.5Cu/10fly ash at room temperature is shown in Figure 7. The two regions are visible on the surface where a flat surface located around fly ash particles and on area in the matrix including fine dimples and fly ash particles were broken by brittle mechanism. It is the combination of soft mechanism in matrix due to which formation of dimples and a cleavage mechanism around and inside of fly ash precipitates.

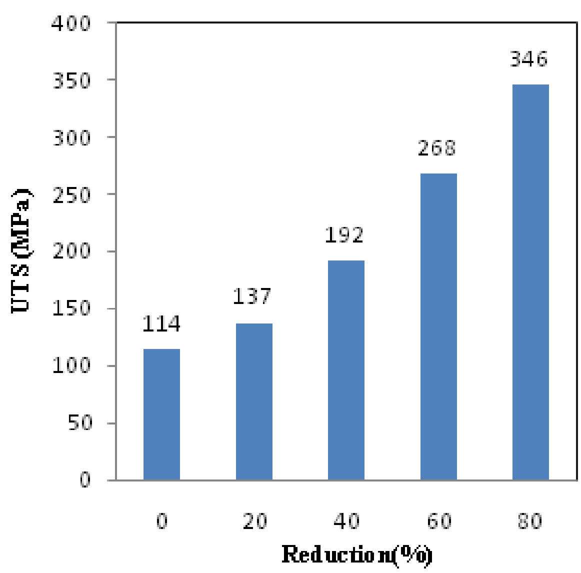

Figure 5. Variations of tensile strength for as-rolled, 20%, 40%, 60% and 80% reduction composites

There are still some cracks visible inside the fly ash fracture and during tensile test, more than one crack is formed in the bulk of fly ash particle and one of them leads to breakdown of fly ash particles. The formation of flat area around the fly ash particle on fracture surface is due to the growth of cracks in fly ash particle into the matrix[46].

From Figure 6, it is clear that the maximum value of tensile elongation is obtained for the maximum reduction of (6.8%), which is 2.19 times higher than that of the as-cast composite (3.1%). Improving the tensile strength and elongation by increasing the rolling reduction is attributed to the uniformity of the fly ash particles has an important effect on the strength and elongation of the MMCs. A consistent particle distribution provides a longer average distance for the propagation of cracks in the matrix. By increasing the number of reductions during rolling, the distribution of fly ash particles in the aluminum matrix changes to yield a more uniform product. This causes the strength and ductility to improve.

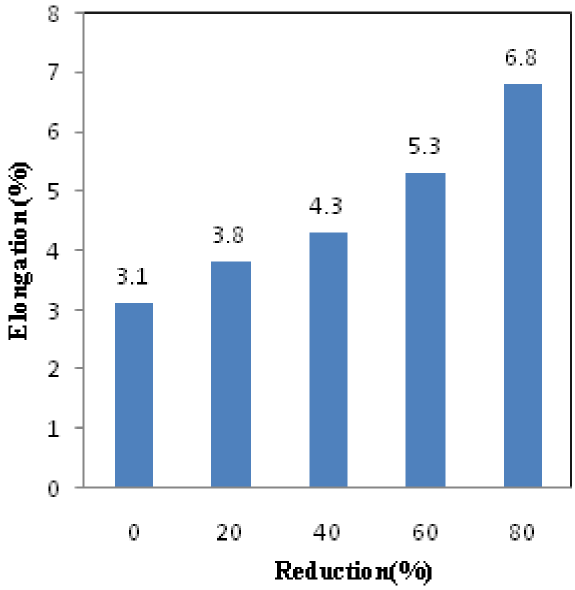

Figure 6. Variations of tensile elongation for as-rolled, 20%, 40%, 60% and 80% reduction composites

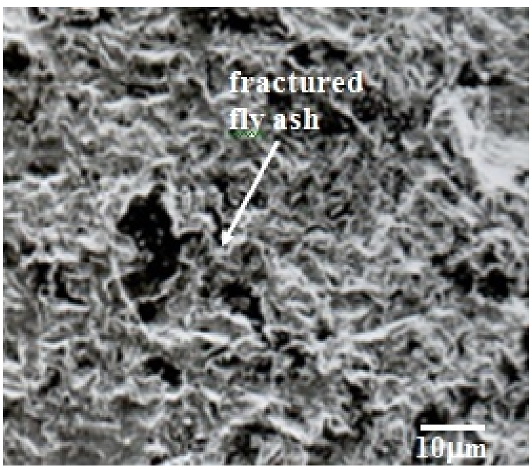

Figure 7. SEM microphotographs of tensile fracture of Al-4.5%Cu/10fly ash composite after 80% reduction

The porosity has a major effect on the strength and ductility of the MMCs. Porosities in MMCs can act as preferential crack initiation sites and propagation paths for the cracks. As shown in Figure 4, by increasing the reduction, the porosity content in the composites decreases due to high formability of the aluminum matrix and rolling pressure, thus enhancing the strength and elongation again and also the bonding quality between the aluminum layers is another important factor for determining the strength and ductility. The experimental works[47] have shown that by increasing the number of cycles, a stronger bonding is created between the aluminum layers, imparting a higher strength and elongation to the product. The grain refinement and strain hardening by dislocations may also contribute to increasing the strength by increasing the rolling reduction.

3.5. Wear Testing

The rolled composites were machined to a square pin of 6mmX6mm with height of 7 mm for perfect match in the wear testing specimen holder (separate arrangement) for the wear study. The tests were carried out using a computerized pin on a disc wear testing machine under ambient temperature conditions on specimens for normal load of 15N, and for a constant track velocity of 80 m/sec. A hardened steel disc (60 HRc) was used as the counter body. The duration of the test was 60 minutes. For each experiment, a new pin and a new disc were used. Before the tests were conducted, both the pin and disc were degreased, cleaned and dried with acetone. The wear tracks on the specimen were observed under a SEM to examine the effect of the percentage of particulate on the wear behaviour of the MMCs.

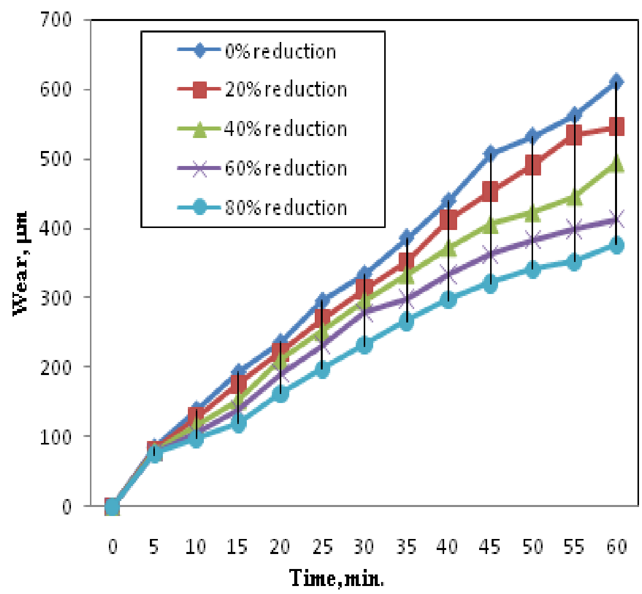

Figure 8. Wear behaviour of Al-4.5%Cu/10fly ash composite under normal load of 15KN

Figure 8 shows the results of dry sliding wear behaviour of MMCs with 10% fly ash content. It was observed that wear decreases with increase in reduction in rolling as found by other researchers[48, 49]. This is due to the increase of hardness of the respective composites with the extent of rolling and also the abrasive nature of fly ash. The finer dispersion of the fragmented particles strengthens the composite. Since the average particle size of fly ash lies in the range 28-35μm, the extent of particles pulled out from the surface was smaller. With increase in reduction, the amount of particle present strengthens the matrix and hence more wear resistance is observed.

Figure 9 shows the worn surface of 10% fly ash composite under the normal load of 15N. It can be seen that the ploughing and scoring along the sliding direction is enhanced. When compared to the base alloy, the wear scars are smaller due to the presence of fly ash particulates. This shows that the presence of fly ash in the matrix offers a resistance to wear. The fractured fly ash particles are seen in the SEM photomicrographs.

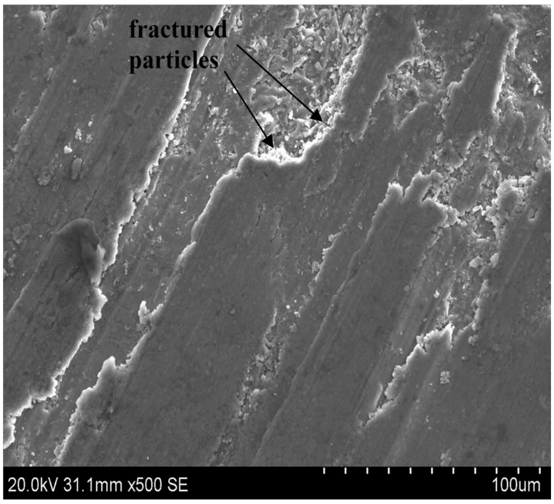

Figure 9. SEM microphotographs of 80% reduction during rolling of Al-4.5%Cu/10fly ash composite after wear

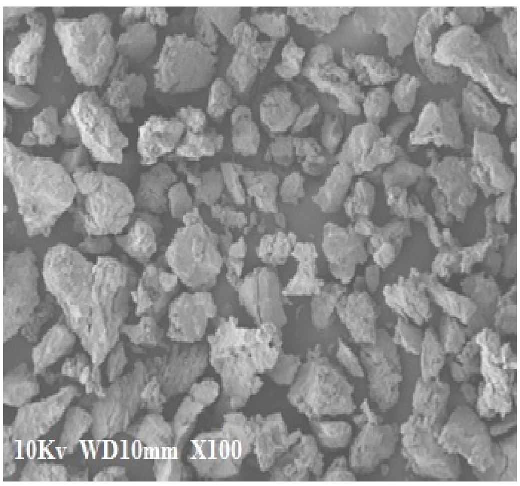

Figure 10. SEM microphotographs of wear debris of Al-4.5%Cu/10fly ash composite

Figure 10 shows the wear debris of MMCs. The worn debris particles are likely to act as third body abrasive particles. The fly ash particles trapped between the specimen and counterface cause micro-ploughing on the contact surface of the composite. The continuous longitudinal lines parallel to the sliding direction on the worn surfaces of the composites probably result from the ploughing action of the fly ash particles. At normal loads, composites show delamination, due to which the material loss in the form of plate-like debris takes place.

4. Conclusions

The Al-4.5wt%Cu/10fly ash composite can be successfully hot rolled to maximum of 80% reduction without edge cracking. The hardness and UTS of the composites gradually increased with an increase in extent of rolling. Porosity on the other hand decreases with increase in reduction of rolling. The cracking of particles controls ductility of the as cast composite but for rolled samples void, nucleation growth and linkage control ductility. With rolling reductions, the amount of particle strengthens the matrix and hence more wear resistance is observed. The Al-Cu/fly ash composite in rolled condition has better properties than as cast MMCs. The major features of micro photographs suggest that the fly ash particles and their distribution might have led to the increase in mechanical properties of the composites due to fine grain structure during rolling reduction. Optical micrograph indicates uniform distribution of fly ash particle and refined grain structure by increasing the rolling reduction. One can optimally indenture the properties of such materials by making MMCs with proper substitute of secondary process such as rolling for better life of the component.

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