Development of AA2024 Matrix Composites Reinforced with Micro Yttrium through Cold Compaction with Superior Mechanical Properties

C. H. S. Vidyasagar, D. B. Karunakar

***Abstract*—**In this present work, five different composite samples with AA2024 as matrix and varying amounts of yttrium (0.1-0.5 wt.%) as reinforcement are developed through cold compaction. The microstructures of the developed composite samples revealed that the yttrium reinforcement caused grain refinement up to 0.3 wt.% and beyond which the refinement is not effective. The microstructure revealed Al2Cu precipitation which strengthened the composite up to 0.3 wt.% yttrium reinforcement. Upon further increase in yttrium reinforcement, the intermetallics and the precipitation coarsen and their corresponding strengthening effect decreases. The mechanical characterization revealed that the composite sample reinforced with 0.3 wt.% yttrium showed highest mechanical properties like 82 HV of hardness, 276 MPa Ultimate Tensile Strength (UTS), 229 MPa Yield Strength (YS) and an elongation (EL) of 18.9% respectively. However, the relative density of the developed composites decreased with the increase in yttrium reinforcement.

***Keywords*—**Mechanical properties, AA 2024 matrix, yttrium reinforcement, cold compaction, precipitation.

I. Introduction

It is a well-established fact that aluminium is the most commonly used light metals in the world [1]. Due to their low density, high specific strength and resistance to corrosion, and especially low cost, aluminium alloys and its composites are very useful for structural applications in aerospace, military, and transportation [2]. Aluminium Metal Matrix Composites (AMMCs) also called as Aluminium matrix composites (AMCs) in short, were developed as a viable and practical solution to the shortcomings of the alloys. The major advantages of AMCs compared to their un-reinforced counter parts are as follows [3], [4]. AMCs have been noted to offer such tailored property combinations required in a wide range of engineering applications [5], [6]. Some of these property combinations include: high specific strength, low coefficient thermal expansion and high thermal resistance, good damping capacities, superior wear resistance, high specific stiffness and satisfactory levels of corrosion resistance [7]. In AMCs, one of the constituents is aluminium/aluminium alloy. In AMCs aluminium is used as the matrix material and most commonly, the materials such as Al_2O_3, SiC, TiB_2, TiC, TiO_2, B_4C, fly ash, TM, graphite, nano materials, etc., are used as the reinforcements. Properties of AMCs can be tailored by varying the constituents and the amount of volume fraction [8].

In general, over monolithic alloys, the AMCs are reputed to have better elastic modulus, tensile and fatigue strength [9]. When these reinforcements are combined with Al matrix, the resulting composite exhibits significant improvement in its hardness, strength, fracture toughness and wear resistance [10]. cold compaction is a chip less metal-forming process, which employs an incremental compact pressure technique. Type, size, quantity and distribution of the blended reinforcement particles have direct impact on the change of properties. The particle size plays a significant role on the dispersion and distribution of the reinforcement particles in the matrix. Bigger particles tend to have a worse diffusion and densification quality. Moreover, they lead to crack propagation and breaking during the powder compacting stage or after sintering stage [11], [12]. However, the powder metallurgy route has some advantages when compared to liquid metallurgy route. Due to the lower sintering temperatures, there are no chemical reactions between matrix and reinforcements like that in the liquid state [13]-[15]. The composite powders with a high degree of dispersion are produced in the first process step, compacted in the second step and then sintered in the third step. The degree of uniform distribution of the reinforcement particles depend on the method employed for blending the composite powders. High energy milling (HEM) has emerged as an effective method for blending the composite powders [16]. To meet the structural strength requirements, components for aerospace applications are usually manufactured through cold working [17]. The present study investigates the effects of yttrium reinforcement to an AA2024 matrix through cold compaction and conventional sintering.

II. Experimental Procedures

In this section, a batch of composites comprising of five different composite samples were developed by reinforcing varying amounts of micro yttrium ranging from 0.1-0.5 wt% to the AA2024 matrix. An unreinforced sample was also developed as a bench mark to evaluate the effect of yttrium reinforcement. The composite samples were processed through cold compaction. In this work, the materials chosen were the powders of 2024 aluminium alloy and micro yttrium procured from Alfa Aesar, USA. The as-received powders are shown in Fig. 1. The average particle size of as-received

C. H. S. Vidyasagar is with the Metallurgical and Materials Engineering Department, Indian Institute of Technology Roorkee - 247667, India (corresponding author, e-mail: sureshvidyasagar@gmail.com).

D. B. Karunakar is with the Mechanical and Industrial Engineering Department, Indian Institute of Technology Roorkee - 247667, India.

aluminium and yttrium are 60 microns and 400 microns respectively.

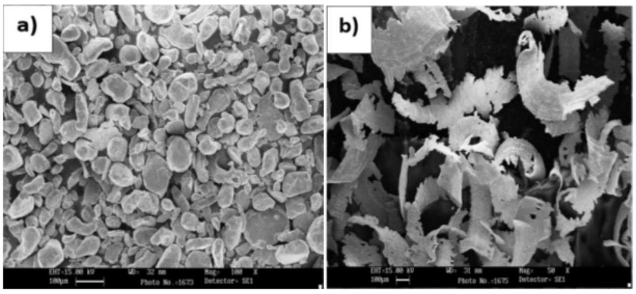

Fig. 1 As-received starting powders (a) AA2024 and (b) yttrium

Yttrium particles of average size 400 microns were used as the reinforcement. This yttrium powder (99.6% purity) was also procured from Alfa Aesar, United States. Five AA2024+Y composite samples with varying amounts of yttrium addition were developed through cold compaction. The as-received AA2024 sample was also sintered as a benchmark to compare with the composite samples and to evaluate the effect of yttrium reinforcement. The composite powder was blended by a ball mill at slow speed with a ball to powder ratio 1:1 for 2 hours. The powder blend was heated to 100 ºC to remove the moisture and make the powder free from humidity. Then, the powder was poured in a hardened steel die and the upper and lower punches were inserted by applying initial hand pressure and the die-punch assembly was placed in a hydraulic press. A pressure of 20 tons was applied gradually and once the desired pressure was applied, it was left to dwell for 1 minute before the pressure was gradually withdrawn. After gently removing the green compact from the die, it was sintered in a tubular furnace at 550 ºC under flowing nitrogen gas for four hours.

III. Results

A. Investigation of Microstructure

The specimens for investigating microstructure were polished and etched prepared according to the standard procedure. The microstructure shows clear grain boundaries and good packing of grains. The FE-SEM microstructures of unreinforced/cold compacted composite samples reinforced with varying amount of yttrium addition is shown in Fig. 2.

B. Density Measurement

The properties of the composite samples mainly depend on the density and percentage of porosity. The green density, densification parameter and relative densities were calculated for each unreinforced/composite sample reinforced with varying amount of yttrium, using standard methods and formulae. Relative green density is the ratio of green density of the compact (calculated after compaction) to experimental density. Fig. 2 shows the variation of green density and relative sintered density of the composite samples with an increase in the reinforcement of micro yttrium.

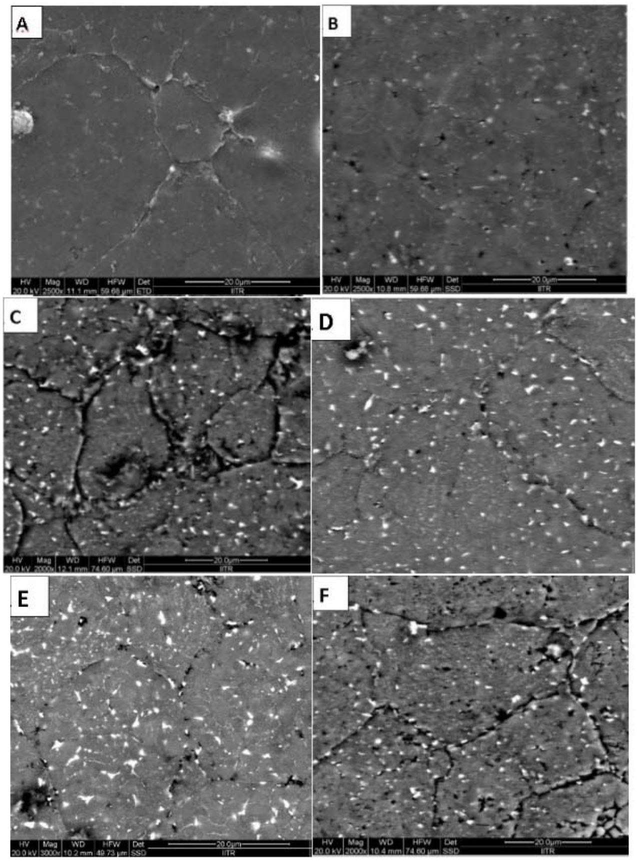

Fig. 2 FE-SEM microstructures of unreinforced/cold compacted composite samples reinforced with (a) 0.0 wt% micro Y, (b) 0.1 wt% micro Y, (c) 0.2 wt% micro Y, (d) 0.3 wt% micro Y, (e) 0.4 wt% micro Y and (f) 0.5 wt% micro Y

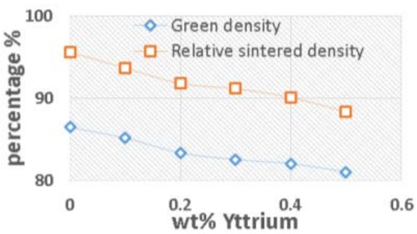

Fig. 3 Variation of green density and relative sintered density of the cold compacts unreinforced/ reinforced with varying amounts of micro yttrium

After the cold compaction, the green compacts were sintered to promote diffusion between the powder particles. From Fig. 3, it can be observed that the green density as well as the sintered density decreases with an increase in yttrium addition. However, the sintered density is higher than the green density for each case of the reinforcement. The densification parameter was calculated as 0.9.

C. Evaluation of Mechanical Properties

The mechanical properties of the composite samples like hardness, UTS, YS and EL were tested by a computerized Vicker's hardness testing machine and Universal Testing Machine (UTM). Ten measurements were taken for each sample in the case of hardness and three measurements in the case of tensile strength and the average values of the readings are furnished with error bars, showing highest and lowest values. Fig. 3 shows the variation of hardness with an increase in the reinforcement of yttrium wt%. From Fig. 4, it can be seen that the hardness increased with the reinforcement of yttrium up to 0.3 wt% and decreased with further reinforcement. There is a clear trend of increase and decrease in the hardness for the composite samples with the reinforcement of yttrium.

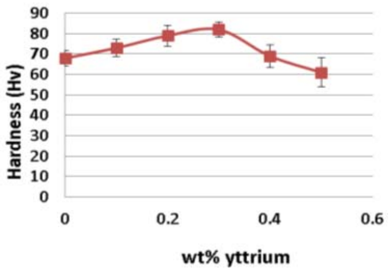

Fig. 4 Variation of hardness in the cold compacted unreinforced/composite samples reinforced with varying amounts of micro yttrium

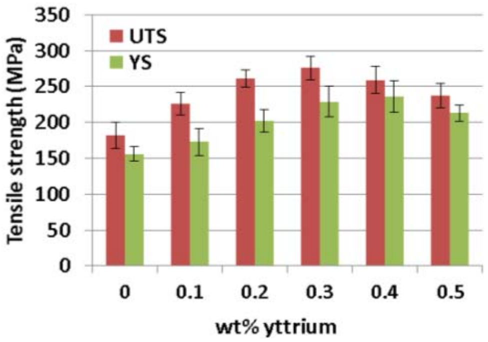

Fig. 5 Variation of UTS and YS of the cold compacted unreinforced/composite samples reinforced with varying amounts of micro yttrium

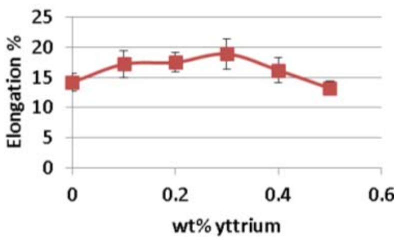

Fig. 6 Variation of EL in the cold compacted unreinforced/composite samples reinforced with varying amounts of yttrium

Fig. 5 shows the variation of UTS and YS in the sintered composite samples with an increase in the reinforcement of yttrium. The UTS and YS also followed the same trend of variation as the hardness. Obviously, UTS and YS increase up to 0.3 wt.% yttrium reinforcement and decreased with further reinforcement. However, the average difference between UTS and YS decreased when the yttrium reinforcement increased beyond 0.3 wt.%.

Fig. 6 shows the variation of EL at fracture with the reinforcement of yttrium. EL at fracture is a measure of the composite's ductility. Poor sintering causes the samples to fail at much lower loads with less EL. The EL of the composite samples in the present case also followed the same trend as the other mechanical properties.

IV. Discussion

A. Density

The reinforcement of yttrium decreased the relative green density. The morphology of AA2024 powder particles could be the reason for such low green densities. As the void spaces increased, the density decreased. The increase in void spaces may be due to the irregular and random alignment of matrix powder particles. In addition to that, aluminium powder got oxidized forming an oxide layer when exposed to atmosphere. Each aluminium alloy powder particle was covered with an oxide layer leading to an increase in the deviation from theoretical density. Although the reinforcement of yttrium is very less, its reinforcement might have decreased the green density as its powder particles were larger than the matrix powder particles, moving the matrix particles much apart while accommodating themselves, creating more void spaces and thus decreasing the relative green density.

The relative densities of the green compacts were increased after sintering. However, the composites did not attain full theoretical density. It can also be observed that the reinforcement of yttrium had a negative influence on the relative density of the composites even after sintering. Many factors can be held responsible for the failure of composite samples to attain full theoretical density. Firstly, the oxide layer that forms on each aluminium powder particle due to atmospheric exposure hinders the particle-particle contact and decreases the diffusion and densification during sintering. During compaction, the applied pressure breaks the oxide layers on the particle surfaces, favoring good particle-particle contact. Secondly, the broken oxide layers escape from the compact in the form of gas with the application of heat during sintering. As the temperature increases, necking starts at particle-particle contact points and grows with an increase in the temperature, leading to the densification of the composite sample. The decrease in relative density of the sintered composites can be explained by the inability of the applied pressure to completely break the oxide layers. Moreover, the gases generated from the broken layers might have failed to escape completely from the composite sample during sintering, giving a way to higher number of voids. Thirdly, the morphology of the aluminium alloy powder particles and their random orientation, which create void spaces at triple and quadruple points.

B. Hardness

The variation in the trend of hardness as seen in Fig. 4 can be explained by the dispersion strengthening caused by the yttrium particles. Reinforcement of yttrium caused a strain field in the matrix around it due to the huge difference in their co-efficient of thermal expansion. The strain fields caused an increase in dislocation density and the yttrium particles hindered the dislocation motion (dispersion strengthening) when a load is applied on the composite sample and hence increase the hardness. Solid solution hardening also plays a role as the solid solution containing dissolved copper creates a strain field around it because of the difference in their atomic sizes. Since copper atoms are smaller than aluminium atoms, a tensile strain field is caused in the lattice. The dislocations have a strain field at their core due to the distortion in lattice. The copper solute atoms with a tensile strain field will diffuse to the dislocation core to nullify a part of compressive strain field and hence reduces the strain field. This hinders the dislocation motion and hence hardness is increased. However, the hardness falls beyond 0.3 wt.% yttrium. This can be explained by the tendency of yttrium particles to agglomerate as its wt.% increases. The agglomerated yttrium acts as a grain itself and its dispersion hardening effect decreases. However, the solid solution hardening remains same for all the samples.

C. Tensile and EL

The tensile strength also followed a similar trend as the hardness as seen from Fig. 5. Multiple mechanisms control the strength of a composite. While the strength achieved by grain size and solid solution strengthening is the same for all the composite samples, the variation caused in the strength can be attributed to yttrium reinforcement and cumulative effect of the strengthening mechanism. Yttrium particles offer dispersion strengthening by obstructing the movement of dislocations when a load is applied. Reinforcement of yttrium also causes an increase in dislocations density, which further increases the strength by causing hindrance to the motion of neighboring dislocations. Apart from the strengthening mechanisms discussed, decrease in sintering parameters and relative density also played a part in the decrease in EL of the composite samples as seen in Fig. 6. Hence, a specific amount of yttrium reinforcement (0.3 wt%) to AA2024 matrix could create optimum conditions in the composite sample and achieve superior mechanical properties.

V. Conclusions

Based on the aforesaid investigations and results, the following conclusions can be drawn.

Five different composite samples reinforced with varying amounts of yttrium reinforcement along with unreinforced AA2024 sample were successfully developed through hydraulic cold compaction and subsequent conventional sintering. Reinforcement of yttrium decreased the relative green density, relative sintered density and densification parameter. Hardness, UTS, YS and EL of the composite samples were improved up to 0.3 wt.% yttrium reinforcement and then decreased with further yttrium addition. The hardness, UTS, YS and EL were found to be 68 HV, 182 MPa, 156 MPa and 14.2% respectively for the unreinforced AA2024 sample. The highest hardness, UTS, YS and EL were found to be 82 HV, 276 MPa, 229 MPa and 18.9% respectively for the composite sample with 0.3 wt.% yttrium addition. It was observed that the reinforcement of 0.3 wt.% yttrium to the AA2024 matrix creates favorable conditions for the strengthening mechanisms and to show its best effect on the composite sample, leading to superior mechanical properties.

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