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Properties of $(A384.1)_{1-x}[(SiC)_p]_x$ Composites by Keeping Particle Size at 0.220 μm

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***Abstract*: $(A384.1)_{1-x}[(SiC)_p]_x$ composite containing 0.0%, 0.10%, 0.15% and 0.20% SiC with particle size 0.220 μm were fabricated by modified stir casting technique. The addition of SiC in A.384.1, Al Alloy was found to increase mechanical properties such as hardness, proof stress and ultimate tensile strength with respect to unreinforced Al Alloy. The fabricated composites also showed higher peak hardness and lower peak ageing time as compared. In addition, ageing is found to increase the strength, micro and macro-hardness of the fabricated composites. It is observed from X-ray diffraction that with the increase in percentage of the reinforced particle, the homogeneous and unform distribution of metal in matrix of the composite material increases.**

***Index Terms*—Al Alloys, composites, ageing, X-ray diffraction**

I. INTRODUCTION

THE Metal Matrix Composites, in general, consist of continuous or discontinuous fibers, whiskers or particulates dispersed in a metallic alloy matrix [1] [2]. These reinforcements provide the composite with the properties not achievable in monolithic alloys. Desired improvements in properties including specific strength and modulus, toughness, fatigue, creep, electrical, thermal properties and wear resistance can be achieved by intelligently selecting the reinforcement materials, their size, shape and volume fraction. It is fully established now that MMC's provide a better combination of specific strength and modulus compared to monolithic alloys like aluminum, magnesium, copper, nickel, and steel. There are only a very few materials that are better than reinforced aluminum composites. These include graphite epoxy (along the fiber direction), pure ceramics or diamond but these are much more expensive, anisotropic and very brittle. The specific cost of organic composites is much higher than metal matrix composites for similar specific stiffness [3]. The wear loss of the composite is about 10 times less than that of the Al alloy. The wear resistance of Aluminum composites is also better than that of the Cast Irons that are much heavier [4].

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The most commonly used and economically viable techniques for fabrication of MMC's are solidification processing and stir casting. Another important technique used for the purpose, is infiltration of liquid metal through narrow crevices between fibers or particulate reinforcements that are arranged in a perform. In solidification processing liquid metal is combined with the reinforcement phase and solidified in a mold, however in stir casting the molten metal is stirred with the help of either a mechanical stirrer or high intensity ultrasonic waves. This action disperses the reinforcing phase, which is added to the surface of the melt in the molten metal and solidifies the composite melt, containing reinforcements suspended in the melt. Stir mixing Casting is now used for large-scale production of Metal Matrix Particulate Composites [3] [4] [5].

In the year 1996, the worldwide composite use was around 2.5 Million Kg and is increased to around 5 Million kg by the year 2009 which might have become manifold by now [23]. Aluminum alloys reinforced with very high volume fractions of ceramic particulates or fibers are evincing much interest for structural applications that require high specific modulus, low thermal expansion coefficient and wear resistance. However, the development of these materials has been hindered by difficulties in fabrication and shaping them for end user applications. Studies on as cast and heat treated Si C_p-reinforced A1-4.5%Cu-l.5%Mg composite specimens fabricated by vigorous stirring of the carbide in a semi-solid alloy slurry, followed by remelting and stir-casting showed a substantial increase in the work hardening of the material [5]. This increase became more significant with increasing volume fraction of the carbide. The yield and ultimate tensile strength and the elastic modulus of the material have been reported to increase with heat-treatment and volume fraction of carbide at the expense of ductility [7] [9]. The other aluminum MMC's containing reinforcing particles of B_4C, SiC and Al_2O_3 (0-20 vol %) fabricated by stir casting manufacturing route followed by hot extrusion, which is one of the cost effective industrial methods, also exhibited the similar improvement in properties. The aging behavior of Al Alloy AA2024 with 0, 8, 14, 19, and 24 vol.% SiC_p composites manufactured by stir casting in the semi-solid state of the alloy AA2024 and studied at 177°C for a period of 2-200 hrs, showed precipitation phases present; Al_2CuMg in the unreinforced alloy and $CuAl_2$, Mg_2Si for the reinforced composites. Peak hardness increased as the SiC_p volume fraction increased and appeared almost at the same time after about 14 hr aging in all the materials. The hardness reduction rate in the overage condition is found to

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decrease with increasing Si C_p content [11],[18],[19] & [24].

Some other authors have also demonstrated that the same Al-Mg alloy could be used to infiltrate into Al_2O_3 and SiC performs and the AlN/Al ratio in the matrix could be varied by controlling the process temperature to yield metal matrices with isolated AlN particles (MMC) and composites with micro-structural gradients. The fracture toughness of the composites was seen to decrease with increase in process temperature, whereas, flexural strength was found to increase with process temperature. The effect of particulate loading on mechanical behavior of Al_2O_3/Al metal matrix composites made by a pressure-less infiltration technique is found to increase the Young's modulus and the rate of increase was observed to be well within the bounds. The measured yield strengths were nominally the same in both tension and compression, although, greater ultimate strengths and strain-to-failure were observed in compression than in tension [11], [12], [16] & [17].

Generally, the composite materials are designed to have suitable physical and mechanical properties when other options are limited. As compared to un-reinforced metals and alloys, the reinforced materials are generally brittle and have small elongation to tensile failure and low fracture toughness [14],[15]&[16]. However, Al/Al alloy based ceramic particulate composites exhibit relatively promising characteristics as compared to others. A number of systemic studies have been done on these MMC's but there are certain gaps that require immediate attention. These include optimized fabrication methodology, interfacial effects between reinforcement and metallic matrix, micro-structural stability aspects versus improvement in composite material characteristics and age hardening impacts on the material [20][21][22][23][25].

II. EXPERIMENTAL

A. Methodology

Keeping in view the above mentioned study, the present research work mainly concentrated on the following:
We have evaluated a number of methods reported in literature for fabricating Al alloys composites but due to high cost of manufacturing many of them have limited use. Melt stir casting technique is found to be the simplest and most economical fabrication method for these materials. In earlier studies, stirring of the melt has been done in open air or using a furnace having provision to create an inert environment. A simple modification of the conventional technique as proposed by Surappa & Rohatgi leads to remarkable improvement in this method [6][8][10]. Besides the other components required in the technique, we have an additional steel cover fitted with glass wool lining to make an inert atmosphere in order to prevent reaction of aluminum with environmental gases[13]. The A384.1 Al alloy is used as the matrix and the reinforcement of SiC with grain sizes of 0.220 µm had been used with varying contents (x=0 to x=20). The grain size was determined using Sigma Scanpro Image Analyser™. The densities of the samples have been determined by standard Archimede's principle. The porosity has been determined by knowing the difference between the theoretical and measured densities. Mechanical Properties like hardness, tensile strength, compressive strength etc. had also been determined.
In order to investigate the microstructure-processing-property correlation the extruded samples of the fabricated MMC's were prepared using hot-extrusion at 420^0C with an extraction ratio of 27:1 at the speed of 2 m/min. For ageing studies, heat treatments of unreinforced and reinforced samples is carried out in air at 530^0C using a convection furnace. After 1.5 hours the samples were taken out and quenched in water at room temperature then the samples were transferred within one minute to a container maintained at a temperature of 162^0C ± 2^0C inside a furnace, to investigate the ageing effect by varying retention time from half an hour to twenty two hours. Mechanical Properties of the composites were then studied using Vickers Micro-hardness tester, MATSUZAWA-MMT-X7, Japan™ at a load of 25 gm and Brinell Macro-hardness (BH) tester, Indentec Hardness Tester™ on the as-cast and peak-aged conditions at a load of 62.5 Kg.

Depending on the need, the fabricated MMC samples were also tested under compressive and tensile stresses using the Universal Testing Machine from M/S. ENKAY Enterprises , New Delhi. . The samples were structurally characterized by using X-Ray Diffractometer (BRUKER-D-8-ADVANCE) in this work. The microstructure and interfaces were studied using Optical microscopy (Radical-RMM-1) Scanning Electron Microscope (METEK FE-I-200F) and Energy Dispersive X-ray Spectroscopy (EDAX).

B. Preparation of samples for studies

In order to fabricate the MMC samples, base Al alloy A384.1 was melted in an alumina crucible in furnace up to 810°C. The steel cover of the setup was then removed to add the preheated (810°C) reinforced particles of SiC in the melt. A protective atmosphere was maintained during stirring by holding a pipe carrying inert gas over the melt. After the addition and through mixing, the metal matrix composites were fabricated by pouring the melt-mix into a die. The un-reinforced and reinforced casted materials were then subjected to hot extrusion described above. Hot extruded composites of 10 mm diameter bars were then heat treated at 400^0C for 3 hours in the furnace. In order to further investigate the effect of aging, the extruded MMC's were then pyro processed as per the pre-decided schedule of aging treatment. For structural, micro-structural and mechanical characterization the sample preparation was done first by polishing the sliced samples with emery paper up to 1200 grit size, followed by polishing with SiC suspension on a grinding machine using velvet cloth. Finally, the samples were polished with 0.5 µm diamond paste.

III. RESULTS AND DISCUSSIONS

A. Analysis of Density and Porosity

In this work, the $(A384.1)_{1-x}[(SiC)_p]_x$ composite system has been investigated by taking SiC as reinforcement and Al alloy (A384.1) as matrix. With particle size 0.220µm SiC up to 10-20 % by weight can be successfully added to Al

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alloy matrix. The modified stir casting method as described above is employed to produce composite samples with 'x' from 0.0 to 0.20. The micro-structural characterization of MMCs and unreinforced alloy exhibited lower amount of porosity as compared to any other similar composite system. No interaction layer or any other reaction product was found at the interface. Further, the extruded MMC's were studied for the effect of extrusion ratio on microstructure, mechanical properties, and fracture behavior. The composites reinforced with x=0.10 Si C with an average size of grain sizes of 0.220μm had considerably lower porosity contents, good strength and increased ductility. From TABLE I it is observed that a change in density from as-cast to extruded conditions is found to be 5.546%, 6.444%, 8.086% and 9.304% for 'x' values of 0.0, 0.10, 0.15 and 0.20 respectively. Accordingly, the reduction in porosity from as-cast to extruded conditions was also observed for the different values of 'x' (94.4% for x=0 and 67.05% for x=0.20).

Optical microscopy observations revealed that the as-cast specimens have brittle fracture behavior; promoted by cracking of the large SiC particle clusters, whereas, the fracture surfaces of extruded composites showed extensive tear ridge formation by initiation and growth of shallow dimples around the cracked particles, which is a characteristic feature of ductile fracture process. Moreover in TABLE II, the values of macro- and micro-hardness of the samples exhibited a trend of variation. The extruded samples were found to have low values of micro-hardness as compared to the as-cast and peak aged conditions. The reduction ranges for macro-hardness from 6.603% (for x=0.20) to 7.766% (for x=0.10) and 9.969% for matrix alloy. The reduction observed in case of macro-hardness is less as compared to the micro-hardness, however, in both the cases the reduction in the values of hardness is found to decrease with increasing 'x'. From this characteristic trend, it is clear that drastic changes in macro- and micro-hardness are observed with the amount of reinforcement in matrix.

B. Effect of Aging

In order to investigate the effect of aging on mechanical properties, the hardness versus ageing time characteristics of matrix and its aged composites were investigated. The observed changes in micro-hardness for the composites for the different values of 'x' (0.0, 0.1, 0.15 and 0.20) from as-cast to peak aged condition are 56.6% , 74.4%, 70.2% and 70.9% respectively. The corresponding changes observed in macro-hardness are 9.969%, 7.766%, 7.611% and 6.603% respectively. After the peak ageing time, the values of both micro- and macro-hardness were found to decrease drastically probably due to the larger precipitates that grow at the expense of smaller ones, as revealed by SEM studies.

From the Figure 1, the peak micro-hardness values observed in the alloys with the reinforcements of x=0.10, 0.15 and 0.20 are, respectively, 185 at 7.0 hours, 189 at 7.1 hours and 188 at 7.3 hours as compared with 166 at 6.5 hours in the unreinforced alloy (x=0.0). The higher values of micro-hardness observed in case of peak-aged composites can be explained in terms of higher dislocation density near the particle–matrix interface due to the large difference in thermal expansion coefficient between the matrix and reinforcement as compared to unreinforced alloys.

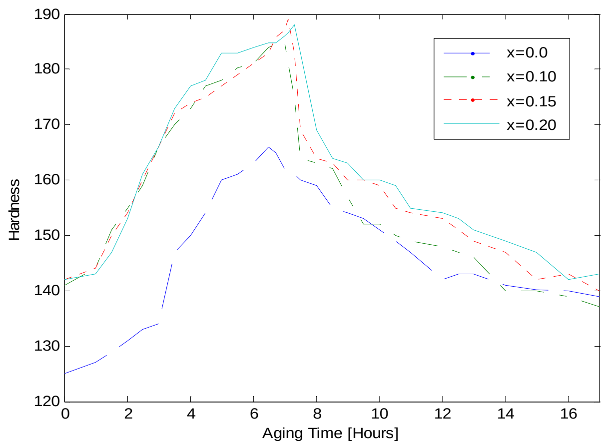

Figure 1: Variation in micro-hardness with time for ageing of the composites

C. Effect of compressive and tensile stresses

The mechanical testing of the fabricated composites was also done under compressive and tensile stresses. In the TABLE III, the compressive properties of the Al alloy and MMC's revealed that the values of 0.2% proof stress, compressive strength and e_f % increase with composition from x=0 to x=0.15 and decrease for x>0.15. While moving from as-cast to extruded, an increase in compressive strength and 0.2% proof stress is observed, however, the peak-aged materials were found to have low values of these parameters as compared to as-extruded samples. The micro-structural investigations revealed that the interface between the reinforcement and matrix plays a determining role in mechanical properties of these composites. Main strengthening in these materials comes from the particle clustering and porosity in the interfacial regions.

With respect to the tensile measurements in TABLE IV, as-cast composite x=0.15 exhibits highest values of 0.2% proof stress (399 MPa) and UTS (441 MPa) among all the as-cast composites fabricated. The as-cast reinforced samples were found to have 0.2% proof stress and UTS values larger than the unreinforced alloy, however, for x=0.20 composite the values are found to be lower than those of x=0.10 and 0.15 samples but higher as compared to x=0.0. For extruded composites the values of these parameters are found to decrease in general with an exception of x=0.1 MMC for which values remain nearly unchanged. Under peak aged condition the composite x=0.15 is found to have UTS and 0.2% proof stress values (476 MPa and 397 MPa respectively) highest among all the samples fabricated.

This composite exhibits a significant increase in 0.2% proof stress and UTS over that of the unreinforced alloy but shows marginal improvement over x=0.10 sample. The micro-structural studies on these composite materials have revealed that the samples having lower values of UTS and 0.2% proof stress were free from the micro-cracks as noticed in alumina reinforced materials. It is obvious from this discussion that the SiC reinforced materials have better mechanical properties as compared to their other counterparts.

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D. X-Ray Diffractions

The scanning electron micrographs of the samples were taken on electron microscope, equipped with energy dispersive X-ray microanalyser. From the figure 2, X-ray diffraction studies on the reinforced Al Alloys indicated that samples 0.220microns particle size of SiC with varying percentage i.e. for x=0.10, 0.15,0.20, showed peaks corrosponding to orthorhombic symmetry and the metallurgical reaction takes place. With the increase in percentage of the reinforced particle, the homogeneous and unform distribution of metal in matrix of the composite material increases. The EDX analysis, however, revealed the presence of the elements Al , Si , Mg and C at the interface layer. SiC particles are found to get wetted by Al Alloys melt in a better way as compared to other ceramic reinforcements and thus the interfacial structure bonding is comparatively strong in this system as evidenced by the improved mechanical properties of these materials.

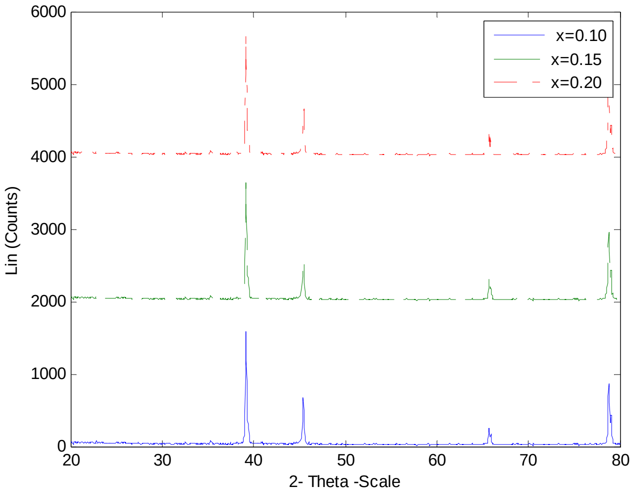

Figure 2: SiC-220 X-Ray Diffraction; Type: 2Th/Th Locked Start: 5.000^0 –End: 80.000^0 – Step: 0.050^0 – Step time : 3 s – Temp.: 25^0(Room) Time started : 1196320768 sec- 2-Theta: 5.000^0- Operation: Smooth 0.150| Y Scale Mul 0.750| Import

The X-Ray Diffraction and SEM studies showed that the addition of SiC reinforcement in different amounts and varying particle sizes in the casting is also found to produce Aluminum Nitride (AlN). The observed formation of AlN might have come from aluminum nitridation probably taking place during cooling at lower temperatures. Both the friction coefficients and the wear rates decrease significantly with the incorporation of SiC as reinforcement in Al alloys melt. The observed strengthening of composite can be explained in terms of dispersion strengthening due to SiC particle reinforcement.

IV. CONCLUSIONS

- $(A384.1)_{1-x}[(SiC)_p]_x$ composites are fabricated by a simple and cost effective stir casting technique.
- Composites show higher 0.2% proof stress and higher modulus compared with unreinforced Al alloys.
- The higher values of micro-hardness observed in case of peak-aged composites can be explained in terms of higher dislocation density near the particle–matrix interface due to the large difference in thermal expansion coefficient between the matrix and reinforcement as compared to unreinforced alloys.
- SiC particles are found to get wetted by Al Alloys melt in a better way as compared to other ceramic reinforcements and thus the interfacial structure bonding is comparatively strong in this system as evidenced by the improved mechanical properties of these materials.

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TABLE I

Density and Porosity of $(A384.1)_{1-x}[(SiC)_p]_x$ Al alloys at un reinforced, as-cast, extruded conditions keeping particle size 0.220µm

X	As-Cast		Extruded Conditions		Change in density from as-cast to extruded condition	Change in porosity from as-cast to extruded condition
	Density *gm/cm*^{3}	Porosity	Density *gm/cm*^{3}	Porosity		
0	2380	2.01	2512	0.11	5.55%	94.40%
0.1	2421	3	2577	0.19	6.44%	93.60%
0.15	2462	3.1	2661	0.99	8.09%	68.06%
0.2	2460	3.4	2689	1.12	9.30%	67.05%

TABLE II

Micro and Macro hardness of $(A384.1)_{1-x}[(SiC)_p]_x$ Al alloys at as-cast, extruded and peak aged conditions keeping particle size 0.220µm

x	*Micro hardness (25 gm)*				*Macro hardness (62.5Kg)*			
	As-Cast	Extruded	Peak aged conditions	Change in micro hardness from as-cast to peak aged conditions	As-Cast	Extruded	Peak aged conditions	Change in macro hardness from As-cast to peak aged conditions
0	106	86	166	56.6%	97.3	92	107	9.969%
0.10	106	95	185	74.5%	103	98	111	7.766%
0.15	111	103	189	70.2%	105	101	113	7.611%
0.20	110	119	188	70.9%	106	110	113	6.603%

TABLE III

Compressive properties of $(A384.1)_{1-x}[(SiC)_p]_x$ Al alloys at as-cast, extruded and peak aged conditions keeping particle size 0.220µm

x	As-cast composites			Extruded composites			Extruded composites at peak aged conditions		
	0.2% Proof stress (MPa)	Compressive strength (MPa)	e_f (%)	0.2% Proof stress (MPa)	Compressive strength (MPa)	e_f (%)	0.2% Proof stress (MPa)	Compressive strength (MPa)	e_f (%)
0	271.2	521	22.3	345	511	23.8	378	523	23.95
0.10	377	533	23.3	396	551	24.3	392	549	24.4
0.15	379	536	23.6	391	554	23.6	389.4	549	24.1
0.20	388	529	21.2	402.1	557	23.19	399.7	552	22.87

TABLE IV

Tensile properties of $(A384.1)_{1-x}[(SiC)_p]_x$ Al alloys at as-cast, extruded and peak aged conditions keeping particle size 0.220µm

x	As-cast composites			Extruded composites			Extruded composites at peak aged conditions		
	0.2% Proof stress (MPa)	UTS (MPa)	e_f (%)	0.2% Proof stress (MPa)	UTS (MPa)	e_f (%)	0.2% Proof stress (MPa)	UTS (MPa)	e_f (%)
0	267	333.1	7.9	256	355	9.8	280	399	9.7
0.1	391	429	9.9	397	428.1	10.3	392	447	9.2
0.15	399	441	9.2	394	432	10.4	397	476	9.9
0.2	305	315	8.29	289	336	10.6	299	347	8.4

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