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Surface Micro Patterning of Aluminium Reinforced Composite through Laser Peening

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ABSTRACT

Aluminium Composites have universal engineering applications because of their higher strength to weight ratio, ductility, and formability. However, in diverse applications, mechanical properties are the prerequisite at closer surface regions. Such localized changes without impacting various surface treatment approaches can attempt the bulk phase. Laser peening is an advanced surface engineering technique, which has been successfully applied to improve the surface morphology of the material. In this work, the authors focus on improving the surface properties of Al7075 composite through laser peening technique. The hardened layer was evaluated using surface integrity with optical microscopy, EDS, SEM and analysis of microhardness. Process parameters and resulting microstructures of Aluminium composite are summarized, along with the impact of laser peening on surface properties. Research results indicated that laser peening shows a significant influence on the final condition of the surface layer of Aluminium composite.

KEYWORDS

Laser Peening, Mechanical Properties, Metal Matrix Composites, Microstructure Analysis, Stir Casting

INTRODUCTION

Current engineering applications require materials with the broad spectrum of properties like lighter, stronger and less expensive which are rather difficult to congregate using monolithic material systems. Metal matrix composites (MMCs) have been noted to offer such tailored property combinations required in a wide range of engineering applications. The particular benefits exhibited by metal-matrix composites, such as increased specific strength, lower density, increased high-temperature performance limits, stiffness and improved wear-abrasion resistance (Sarkar, Modak, & Sahoo, 2015), are dependent on the properties of the matrix alloy and the reinforcing phase. The applications of MMCs in aerospace, automotive and defense industries can be attributed to its improved thermo-mechanical properties and high strength to weight ratio (Shivanna & Ramamurthy, 2015). Metal Matrix Composites (MMC)(Rajesh, Krishna, Raju, & Duraiselvam, 2014) is sophisticated materials formed by mixing a ductile metal/metallic alloy with hard phases, called reinforcements, to develop the

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advantages of both. Alumina, Boron, Silicon Carbide, etc. are the most commonly used nonmetallic reinforcements, combined with Aluminum, Magnesium, etc., to obtain a unique combination of properties. Discontinuous reinforced aluminium metal matrix composites (DRAMMCs) are a class of composite materials having desirable properties increased fatigue resistance (Zhou et al., 2012), controlled coefficient of thermal expansion, and superior dimensional stability at elevated temperatures, etc.(Rino, Chandramohan, & Sucitharan, 2012) (Seetharaman, 2016). The advantages in some of the physical attributes of MMCs such as non-inflammability, low electrical, no significant moisture absorption properties, resistance to most radiations and thermal conductivities (Yellappa, Puneet, G V Krishnareddy, Giriswamy B, 2014).

The critical shortcomings of MMCs are their cost of manufacturing, which has placed limitations on their actual applications and distressed surface-related properties of aluminium have severely limited its further or direct use. The cost=efficient process for manufacturing composites is essential for growing their use. Particulate-reinforced aluminium metal matrix composites (AMCs) (Malhotra, Narayan, & Gupta, 2013) because of their isotropic properties and relatively low cost are attracting researchers. In recent years, several processing techniques have been designed to prepare particulate reinforced aluminium matrix composites (AMCs). Among the various processing techniques existing for discontinuous or particulate reinforced metal matrix composites, stir casting is one of the best processing methods accepted for the production of large quantity composites. In this study, these disadvantages are overcoming by stir casting technique for fabrication and a laser-based technique is explored to enhance the surface-related properties like microstructure and hardness of aluminium matrix composites. This investigation is to examine the effect of reinforcements (Zirconia plus Silicon Carbide) (Mahamani, Muthukrishnan, & Anandakrishnan, 2012) on mechanical properties of Al 7075 composite samples, processed by stir casting method. Three sets of composites are prepared with fixed percentage of Silicon Carbide (2%) & varying rate of Zirconia (2%, 4% and 6%) by weight fraction. The properties of the samples such as Tensile strength, Impact Strength, Hardness and percentage elongation will be evaluated. From experimental studies, the best combination of matrix and reinforcement sample is further assisted with Laser peening technique for enhancing surface related properties like microstructure and hardness which plays a crucial role in preventing surface crack initiation. Microstructure and SEM analysis were also done to see the distribution and presence of ZrO2 and SiC particles in aluminium alloy (Kumar, Lal, & Kumar, 2013). The hardness test for both laser peened and unpeened the best sample, and the comparison of results are carried out.

FABRICATION OF ZIRCONIA, SIC REINFORCED AMCS

Selection of Fabrication Method

Until date, various processing techniques (Surendran, Kumaravel, & Vignesh, 2014) have been in use for the fabrication of Zirconia plus SiC reinforced AMCs. Among the variety of manufacturing processes available for discontinuous metal matrix composites, stir casting is accepted and currently practiced commercially its advantages in its simplicity, flexibility and applicability to large scale production and, its principle to allow a conventional metal processing route (Mathur & Barnawal, 2013) to be used and its cheap cost. This liquid metallurgy processing method is the most economical of all the existing routes for metal matrix composite production (Bonollo, Guerriero, Sentimenti, Tangerini, & Yang, 1991), allows large sized components fabrication, and can sustain high productivity rates (see Table 1).

MATERIAL ACQUISITION

AL7075: Aluminium 7075 (Al7075) is chosen as the matrix material since, it is low cost and has better properties like excellent thermal conductivity, high shear strength, abrasion resistance, high-

Table 1. A comparative evaluation of different techniques used for discontinuously reinforced metal matrix composite fabrication

Methods	Range of Shape and Size	Metal Yield	Range of Volume Fraction	Damage to Reinforcement	Cost
Stir casting	Wide range of shapes, larger size to 500 kg	Very high, >90%	Up to 0.3	No damage	Least expensive
Squeeze casting	Limited by preform shape	Low	Up to 0.45	Severe damage	Moderate-expensive
Powder metallurgy	Wide range, restricted size	High	0.3-0.7	Fiber or particle fracture	Expensive
Spray casting	Limited shape, large size	Medium	0.3-0.7	-	Expensive

temperature operation, non-flammability, showing good formability with conventional equipment and minimal attack by fuels and solvents. It possesses excellent casting properties and reasonable strength. This alloy is appropriate for mass production of lightweight metal castings. The chemical composition is shown in Table 2.

Zirconia (ZrO2): Zirconium dioxide (ZrO2) sometimes known as Zirconia is a white crystalline oxide of zirconium. It is chemically un-reactive and slowly attacked by concentrated hydrofluoric acid and sulfuric acid. Zirconia is a very hard material; its hardness is 8–8.5 on Mohr's scale. ZrO2 was monoclinic crystal structure at room temperature and transitions to cubic and tetragonal at elevated temperatures. The volume expansion done by the cubic to tetragonal to monoclinic transformation induces significant stresses, and these stresses cause ZrO2 to crack upon cooling from high temperatures.

Silicon carbide (SiC): It also known as carborundum is a compound of silicon and carbon with chemical formula SiC Silicon carbide is a well-known abrasive in recent years due to the durability and low cost of the material. Its hardness is 9-9.5 on Moh's scale. SiC reinforced AMCs may help in increase the wear resistance (Rahman & Al Rashed, 2014). Mechanical properties of both reinforcements are tabulated in Table 3.

FABRICATION BY STIR CASTING

Composites fabricating by stir casting technique involves melting of the matrix material followed by the adding of preheated reinforcement to the melt with simultaneous stirring, followed by casting in a mold. The schematic diagram of stir casting process is shown in Figure 1. The following features characterize stir casting processing method:

- The content of dispersed phase should not more than 30% vol.;
- Distribution of dispersed phase throughout the volume matrix is not homogeneous;
- The technology is relatively straight forward and inexpensive.

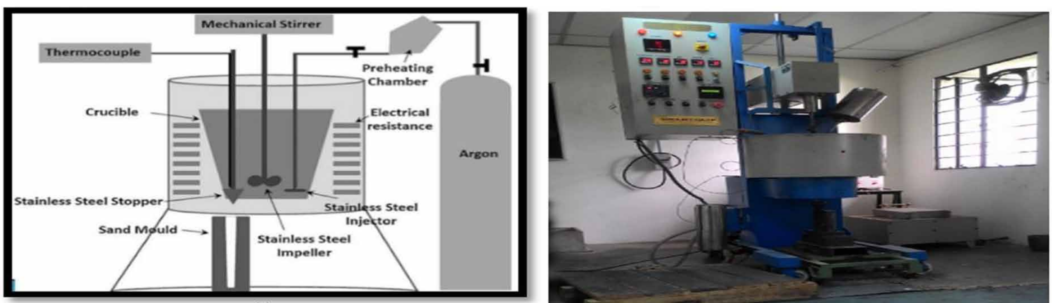
Table 2. Chemical composition of aluminium 7075

Element	Al	Zn	Cu	Si	Mn	Mg	Cr	Ti	Fe
% wt	87.1-91.4	5.1 – 6.1	1.2 – 2	Max 0.4	Max 0.3	2.1 – 2.9	0.18-0.28	Max 0.2	Max 0.5

Table 3. Mechanical properties of silicon carbide and zirconia

Properties	SiC (in Wt. %)	Zirconia (in Wt. %)
Density g/cm^3	3.2	6.04
Compressive Strength (MPa)	1395	2500
Tensile Strength (MPa)	240	248
Melting Point (°C)	2200	2715
Hardness (Moh's scale)	9-9.5	8-8.5
Fracture toughness(MPa-m$^{1/2}$)	4.6	13
Crystal structure	Hexagonal	Tetragonal

Figure 1. (a) Schematic diagram of stir casting process; (b) Bottom pour type stir casting facility



(a) (b)

This technique has been used by many research groups to fabricate and to study the different combinations of Al-based alloys (Kumar et al., 2013) with Zirconia plus SiC(Singla, Dwivedi, Singh, & Chawla, 2009) (Suryanarayanan, Praveen, and Raghuraman, 2013) reinforcement. Fabricating test specimens, casting with Zirconia with SiC reinforcement by stir casting (Dinesh Pargunde, Prof. Dhanraj Tambuskar, 2013). Composites were prepared in an induction furnace by melting weighed quantity of Al (7075) alloy at ≈850°C along with mixing and then adding weighed amounts of preheated at 450°C & 600°C reinforcements Zirconia plus SiC wt% (refer Table 4) of particles respectively for three specimens. After complete stirring, the melt was poured into a rectangular mould for the preparation specimen.

TESTING OF ZIRCONIA SIC REINFORCED AMCS SAMPLES

The following tests are conducted on base metals and the prepared samples.

Table 4. Composition of reinforcement used

Sample No.	SiC (in Wt %)	Zirconia (in Wt %)
S1	2	2
S2	2	4
S3	2	6

Tensile Test

Tensile testing is a fundamental material science test in which a sample is exposed to a controlled tension until failure. Uniaxial tensile testing is the frequently used for obtaining the mechanical characteristics of isotropic materials. The results of the test could commonly utilize in the selection of equipment material for appropriate application and to forecast how a material will react under other types of forces. Properties that are instantly measured through a tensile test are the ultimate tensile strength, maximum contraction, maximum elongation and reduction in area. The tensile test was performed using computerized Instron tensile testing machine. The test was conducted using strain rate of 2mm/min at room temperatures. As cast composite tensile test specimens were prepared using WEDM according to the dimensions 100mmx10mmx10mm. Tensile test sample is shown in Figure 2.

The results of the tensile test conducted on AMCs samples revealed an increasing tendency in the tensile strength of the composite with maximum reinforcement content (see Table 5). The composite S3 is a combination of 6% Zirconia particles shows better tensile strength as compared to composite S1&S2 which is composite S1 having 2% Zirconia and composite S2 having 4% Zirconia. Dual particles have a different role in the matrix; silicon carbide particles refine the eutectic silicon whereas Zirconia particles provide excellent bonding characteristics to the composite. Aluminum alloy 7075 had measured the tensile strength of 275MPa which is enhanced to a maximum of 324MPa by optimum reinforcement weight percentage.

Hardness Test

The resistance of materials against surface indentation is termed as hardness. A hard material surface resists indentation or scratching and can indent or cut other materials. The hardness of the three stir casted samples is tested on Rockwell Hardness Tester. The images of hardness samples are shown in Figure 3.

Figure 2. (a) Tensile test specimen dimensions; (b) Computerized Instron tensile testing machine; (c) Tested tensile samples

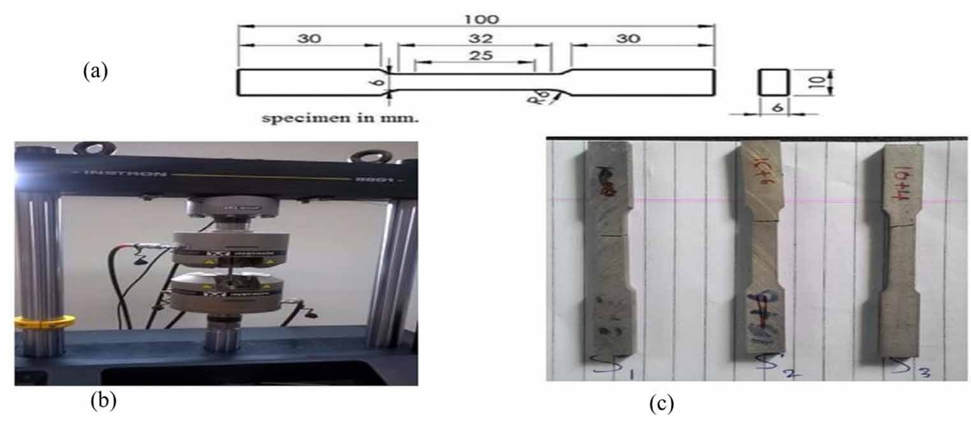


Table 5. Comparing tensile test result of AMC sample

Sample No.	Tensile Strength (MPa)	Percentage Elongation (%)
S1	296	1.18
S2	304	2.08
S3	324	2.78

Figure 3. Tested hardness samples

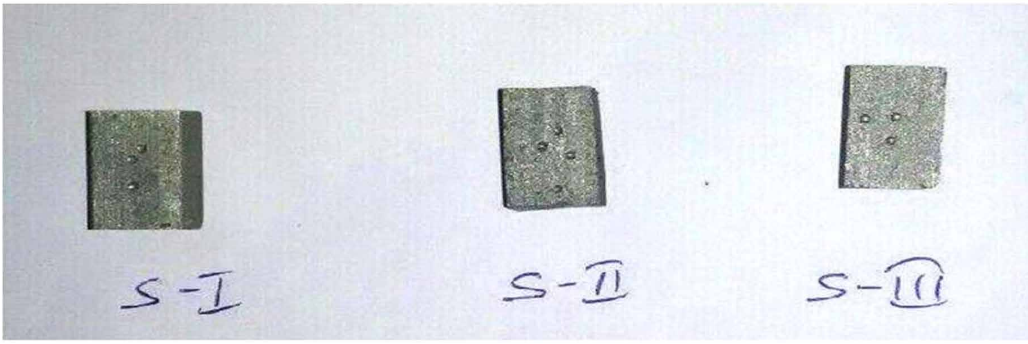


Table 6 shows the Rockwell hardness values of AMCs containing varying wt. % of Zirconia reinforcements. The table demonstrates that addition of Zirconia and SiC particles in Al matrix composites enhances the hardness of AMCs when compared with unreinforced Al. When unreinforced Al has Rockwell hardness value of 84 HRC, hardness value increases with increasing Zirconia content, and maximum obtained hardness value is 96 HRC for 6 wt. % Zirconia-reinforced AMC. The presence of harder and well bonded Zirconia and SiC particles in Al matrix that impede the movement of dislocations increase the hardness of AMCs.

Impact Tests

For conducting impact test a notched bar of AMCs, arranged either as a simply supported or as a cantilever beam, is wrecked by a wedge in a single blow in such a way that the total force required to fracture it may be determined. The energy needed to break AMCs is of importance in cases of shock loading when a structure or component may be necessary to absorb the K.E of a moving body. The energy consumed can be found with the help of Charpy impact tests. The standard specimen size for Charpy impact testing is 10mm x 10mm x 55mm is shown in Figure 4(b). It has been found that from Table 7 as a percentage of reinforcement increased in the Al7075 alloy there is an increase in the impact strength of the AMC samples. When unreinforced Al has Charpy impact strength value of 162 J/m2, Charpy impact strength value increases with increasing Zirconia content and maximum obtained impact strength value is 355.5 J/m2 for 6 wt% Zirconia-reinforced AMC.

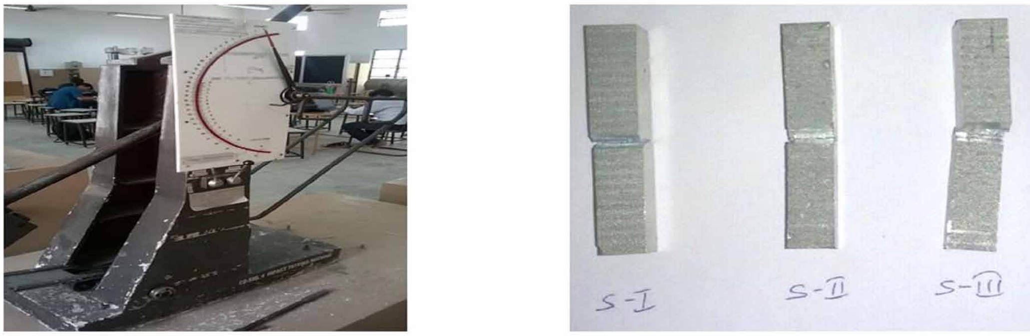
Microstructure Analysis

For microstructure analysis, the samples are polished and cleaned with Keller's regent. Microstructure taken at 20x magnification discloses a reasonably homogeneous distribution of Zirconia and SiC particles in the casted composite. The Microstructures of samples are shown in Figure 5(a), (b), (c) microstructure of 2% SiC and 2, 4, 6%ZrO2 reinforcement. SiC is present in dendritic structure and is uniformly distributed in the aluminum matrix.

Table 6. Comparing hardness test result of AMC sample

Sample Name.	Hardness Values (HRC)			
	Trail 1	Trail 2	Trail 3	Average
S1	87	88.1	89.2	88
S2	88.2	94.3	91.1	91
S3	94.2	96	98.3	96

Figure 4. (a) Impact strength testing facility; (b) Impact tested AMC specimens

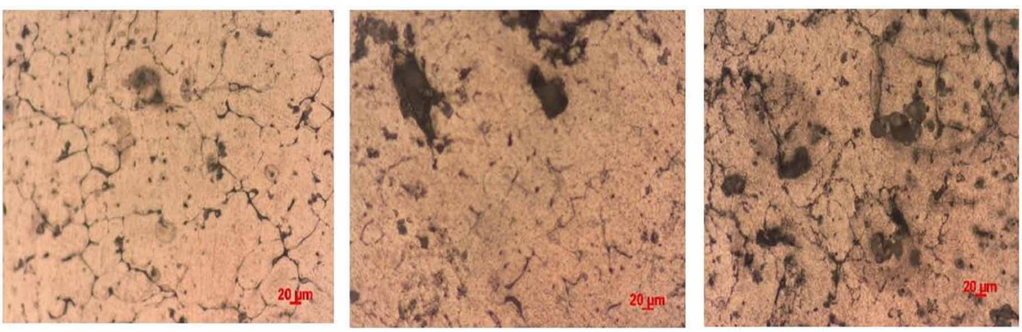


(a) (b)

Table 7. Comparing tensile test result of AMC

Sample Name	Impact Strength (J/m^2)
S1	351.9
S2	352.8
S3	355.5

Figure 5. (a) 20x magnified microstructures of sample 1; (b) Sample 2; and (c) Sample 3



(a) (b) (c)

From micro structures of Figure 5(b), (c) it was observed that Silicon Carbide and Zirconia composite having a cluster of particles and some places are identified with SiC inclusions. Inter dendritic structure of SiC was uniformly distributed in the Al matrix surrounded the Zirconia particles. The microstructure of 2% SiC and 6%ZrO2 is shown in Figure 5(c) containing a cluster of SiC inclusions, ZrO2 particles and Al-Si dendritic phase. From the microstructure it was clear that these clusters are increasing with increase in the weight percentage of ZrO2 in the Al metal matrix. Due these clusters the percentage elongating of the composite is slightly increased.

LASER ASSISTED SURFACE ENGINEERING

A laser beam with a high energy is capable of intensely heating and melting most of the refractory metals and ceramics and deposits them on metallic substrates or simply hardening the surface of metallic substrates up to micro level, which possesses high hardness and excellent wear and corrosion resistance (Yang, Zhou, Zhang, Yang, & Lu, 2004). The distinctive feature of laser beam confined to a small area of melting and solidification within a little depth and hence makes it achievable to modify the surface layer without affecting the volume of the as-received sample. Laser assisted surface engineering offers high cooling rates (103-108 K/s) can give rise to extremely fine grain structures and enhanced mechanical properties blades (Nie, He, Zhou, Li, & Wang, 2014). The advantage of laser assisted surface engineering is that laser beam can be carried to any remote corner of functioning components through fiber optics. Laser peening technique involves the generation of tamped plasmas at the component surface. Laser shock peening (Eberle, Schmidt, Pude, & Wegener, 2016) can induce residual compressive stresses on the surface to a level comparable to that produced by conventional peening without any significant change in surface finish. Deep residual stress is necessary for the safety of critical items such as compressor and turbine (Karbalaian, Yousefi-koma, Karimpour, & Mohtasebi, 2015). A significant additional benefit of laser shock peening is the prevention of crack growth.

Laser Shock Peening of AMC Sample

Laser shock peening (Kibria, G., B. Doloi, 2014) is carried out only for the best sample (S3) by using Nd-YAG Laser setup is shown in Figure 6. Laser Shock Peening (LSP) and Laser Shocked Peened without Coating (LSPwC) experiments are performed at ambient conditions (25°C) using Nd-YAG laser (Litron, UK) with a fundamental wavelength of 1064nm.

The energy consumed for the experiment is 300mJ with a pulse duration of 10ns.The experiment used 10Hz of repetition rate (Karbalaian, Yousefi-koma, Karimpour, & Mohtasebi, 2015) and for the industrial applications; the higher repetition rate may suggest increasing the process speed without the adverse effect on the results for the industrial applications. In general, LSP and LSPwC process (Prabhakaran & Kalainathan, 2016) (Kalainathan & Prabhakaran, 2016), the metal target surface is mirror polished, and water or transparent glass confinement medium is used. The thickness of water confinement layer (1–2 mm) is maintained uniformly by employing water jet setup. The 2D XY translation motorized stage is used to perform LSP and LSPwC experiments in transverse and longitudinal directions.

Surface Roughness of AMC Sample

The average surface roughness is increased from 0.4361μm to 2.3759 μm for LSP specimen due to laser ablation layer on the metal surface and 3.2472μm for LSP specimen due to without ablation layer on a metal surface. As compared to shot peening, LSP with coating produces minimal roughness as shown in Table 8.

Figure 6. (a) Schematic representation of LSP processing setup; (b) LSP processed AMC Sample 3

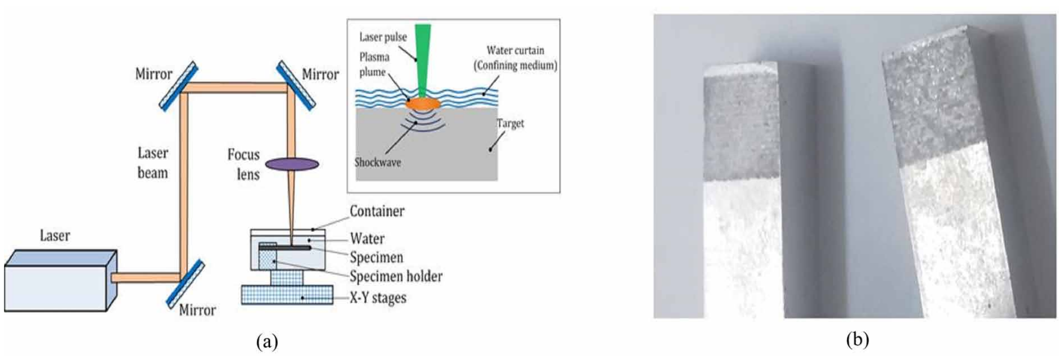


Table 8. Comparing surface roughness of AMC sample 3

Sample Name.	Average Roughness (Ra) µm	Maximum Height of the Profile (Rmax)µm	Root Mean Square Roughness (Rq)µm
S3	0.4361	4.8573	0.5904
LSP with coating S3	2.3759	18.1703	2.9357
LSP without coating S3	3.2472	21.2127	3.9331

Vickers Micro Hardness of AMC Sample

The depth-wise microhardness was measured for AMC Sample 3 as well as Sample 3 laser peened with and without coating is shown in Figure 7(a). The maximum microhardness of casted sample 3 specimens is 152 HV. The laser peened sample 3 with and without ablation layer exhibits a maximum surface hardness of 186 HV and 251HV respectively. The LSP-treated specimens' hardness profile indicates the multiplying effect of work hardening by constructing compressive residual stresses with progressing hardness about 20.42% from the unpeened specimen. The maximum hardness is shown at 50 µm depth and gradually decreased from laser peened surface. From this, it was clear that the work hardening took place on the surface layer and subsurface layers.

SEM Analysis

The Casted AMC specimens is polished and etched as per the metallographic standards. The microstructures of etched specimens were examined using a scanning electron microscope (SEM). Aluminum matrix, Zirconia and Silicon Carbide (SiC) analyzed by scanning electron microscope with average size of less than 5 microns and variation in peened and unpeened portion of sample 3 as shown in Figure 8.

Therefore, at the interface, the laser-modified region is jig-jag. It can be seen that the dendritic phase mixture has been selectively melted on the laser treated portion. In sample3 laser-peened with coating shown in Figure 8(a) the clear boundary of peened and unpeened region as of coating the shock waves are confined to the area at which the laser beam strike. But in sample3 laser peened without coating as shown in Figure 8(b) there is gradual change in the dendritic phase that ensures good bonding and easy load transfer from the laser-melted layer into the substrate. As illustrated in Figure 8(a), the dendrite structure is highly refined within the laser-modified region. The microstructures of the examined sample3 have four distinct micro phases, (as marked) which are as follows: the aluminum matrix (grey area), the SiC particles (dark particle), the dendritic phase of aluminium and silicon (white area) and Zirconia (dark particle surrounded with white line). In sample3 laser peened

Figure 7. Depth-wise microhardness profile of Sample 3

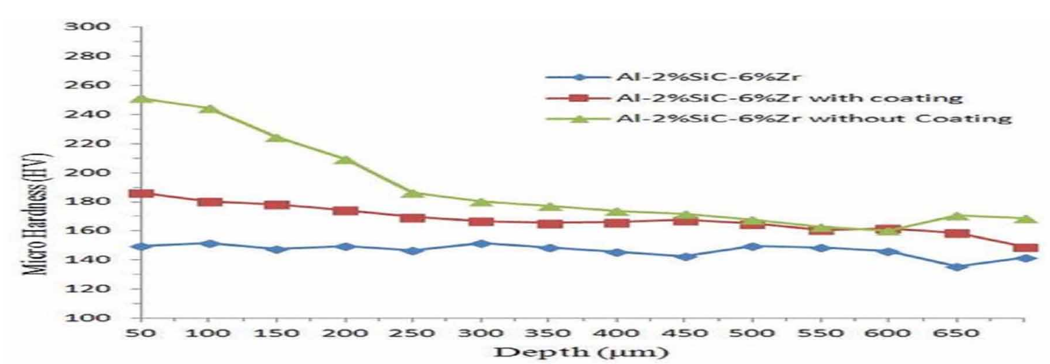
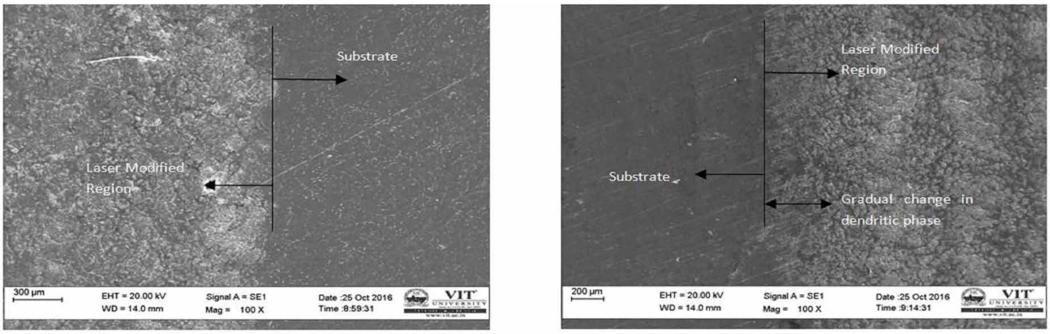


Figure 8. (a) SEM Sample 3 laser peened with coating; (b) SEM Sample 3 laser peened without coating

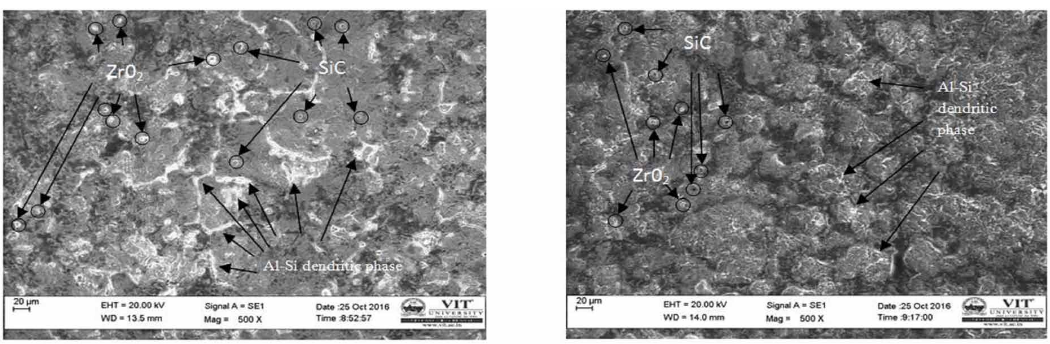


(a) (b)

with coating shown in Figure 9(a) clearly dendritic phase, Zirconia and SiC are observed because of coating the heat absorbed is little when compared to sample3 laser peened without coating. The heat observed by sample3 composite of laser peened without coating is little high and it is reason for refinement of grains.

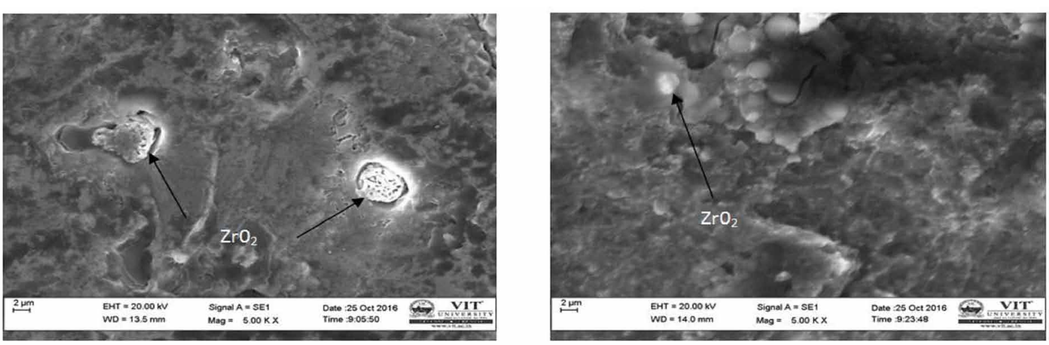
The microstructure of sample3 is examined by SEM at 5.0K X magnification. In sample3 laser peened with coating shown in Figure 10(a) Zirconia particles are surrounded by the Al-Si dendritic

Figure 9. (a) SEM Sample 3 laser peened with coating at 500X; (b) SEM Sample 3 laser peened without coating at 500X



(a) (b)

Figure 10. (a) SEM Sample 3 laser peened with coating at 5.0KX; (b) SEM Sample 3 laser peened without coating at 5.0KX



(a) (b)

phase is clearly noticeable. But in Sample 3 laser-peened with coating shown in Figure 10(b) at same magnification the Zirconia particles can't be noticeable because the surface is modified with direct contact of laser beam pulse.

CONCLUSION

In order to strengthen the engineering usage of AMCs several challenges need to be addressed such as impact of reinforcement, processing technique, corresponding applications and effect of reinforcement on the mechanical properties. Al-SiC-Zr02 composites were produced by stir cast processing method with different weight percentage of reinforcement and the mechanical properties such as Microhardness, Roughness and SEM analysis were evaluated:

- The results of various tests conducted on AMCs samples revealed an increasing trend in matrix properties with increased reinforcement content. Composite containing 2wt. % of SiC and 6wt. % of Zirconia fabricated showed the maximum value of the hardness, tensile strength and impact strength in comparison with other specimens which could be attributed primarily due to the presence of harder Silicon Carbide and Zirconia particles;
- Hardness is an important property of a component which is subjected to heavy load. The surface micro hardness of the composites was increased from 148 HV to 251 HV for 2wt%SiC and 6wt%ZrO2 after laser peening without coating. The reinforcement of particles has enhanced the micro hardness of aluminum matrix and composites;
- Even though LSP produce surface roughness it was minimum compared to shot peening. The surface roughness further controlled by using LSP with a coating using optimal laser parameters;
- SEM analysis discloses the micro phases formed during laser peening and even distribution of reinforcement in the matrix is the reason for increase surface micro hardness.

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