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Experimental Investigation of Mechanical Properties of Al2024-SiC Metal Matrix Composite

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Abstract: **-- Metal Matrix Composites (MMCs) have evoked a keen interest in recent times for potential applications in aerospace and automotive industries owing to their superior strength to weight ratio and high temperature resistance. To achieve these objectives two step-mixing method of stir casting technique has been adopted and subsequent property analysis has been made. Aluminum (Al 2024) and SiC (150 µm) has been chosen as matrix and reinforcement material respectively. The present study was aimed at evaluating the physical properties of Aluminum in the presence of silicon carbide at varying compositions. Consequen tly aluminum metal matrix composite combines the strength of the reinforcement with the toughness of the matrix to achieve a combination of desirable properties not available in any single conventional material. The compositions were added up to the ultimate level and stir casting method was used for the fabrication of aluminum metal matrix composites. Experiments have been conducted by varying weight fraction of SiC (5%, 10%, 15%, 20%, 25%), while keeping all other parameters constant. The results were evaluated by Tensile Test, Rockwell Hardness Test, Charpy Impact Test (including micro-structure), Compression Test and Heat Treatment In terms of a metal-matrix composite, an Aluminum 2024 alloy as the matrix and silicon carbide as the reinforcement is considered to be an excellent structural material used in both the aeronautic/aerospace industry and also the automotive industry. This is due to its high strength-to-weight ratio and its high thermal conductivity.**

Index Terms**—Metal Matrix Composites MMC's, Silicon Carbide SiC.**

I. INTRODUCTION

A composite is combination of two materials in which one of the materials, called the reinforcing phase, is in the form of fibers, sheets, or particles, and is embedded in the other materials called the matrix phase. The reinforcing material and the matrix material can be metal, ceramic, or polymer. Composites typically have a fiber or particle phase that is stiffer and stronger than the continuous matrix phase and serve as the principal load carrying members. Discontinuously reinforced aluminum matrix composites are fast emerging as engineering materials and competing with common metals and alloys. They are gaining significant acceptance because of higher specific strength, specific modulus and good wear resistance as compared to ordinary unreinforced alloys. Reinforcing particles used in this study are silicon carbide particles which are added externally. Aluminum alloy 2024 has good machining characteristics, higher strength and fatigue resistance. It is widely used in aircraft structures, especially wing and fuselage structures under tension. Silicon carbide is a compound of silicon and carbon with a chemical formula SiC. Silicon carbide was originally produced by a high temperature electro chemical reaction of sand and carbon. Any acids or alkalis or molten salts up to 800°C do not attack silicon carbide. In air, SiC forms a protective silicon oxide coating at 1200°C and is able to be used up to 1600°C. The high thermal conductivity coupled with low thermal expansion and high strength gives this material exceptional thermal shock resistant qualities. Silicon carbide ceramics with little or no grain boundary impurities maintain their strength to very high temperatures, approaching 1600°C with no strength loss. Chemical purity, resistance to chemical attack at temperature and strength retention at high temperatures has made this material very popular as wafer tray supports and paddles in semiconductor furnaces. It is an excellent abrasive and has been produced and made into grinding wheels and other abrasive products for over one hundred years. Today the material has been developed into a high quality technical grade ceramic with very good mechanical properties. It is used in abrasives, refractory's, ceramics and numerous high-performance applications.

The objective of the present work is to form the reinforcing phase within the metallic matrix by reaction of silicon carbide and its proportions with aluminum in the metallic melt. Its hardness, tensile behavior and hardness were also evaluated.

objective

- To manufacture a Metal Matrix composite using
- Aluminum-2024, Silicon Carbide
- To determine the mechanical properties of Metal Matrix composites, Such as Tensile Test, Impact Test, Hardness Test and

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Compression Test.

- The effect of loading on Tensile strength, Impact strength and hardness of the Metal Matrix composite.

II. MATERIALS AND METHODS

The following section will elaborate in detail the experimental procedure carried out. The steps involved are:

1. Specimen Fabrication (Fabrication of FRP).
   - ✓ By Mechanical Stir Casting Method.
   - ✓ Preparation of specimens as per the A.S.T.M (American Standards for Testing and Materials) Standards.
2. Tensile test
3. Impact Test
4. Hardness Test
5. Compression test
6. Shear Test
7. Study of Micro-structure
8. Heat Treatment of MMC

Raw Materials

Raw materials used in this experimental work are:
Al-2024, Silicon Carbide Powder

Table 1: Chemical composition of pure aluminum

Si	Fe	Ti	V	Cu	Mn	Al	others
0.07%	0.34%	0.001%	0.008%	0.001%	0.004%	99.55%	0.002%

Table 2: Chemical composition of Al 2024

Si	Fe	Ti	Zn	Cu	Mn	Al	Mg	Cr
Max 0.5%	Max 0.5%	Max 0.15%	Max 0.25%	3.8-4.9%	0.3-0.9%	90.7-94.7%	1.2-1.8%	Max 0.1%

Aluminum alloy 2024 is an Aluminum alloy, with copper as the primary alloying element. It is used in applications requiring high strength to weight ratio, as well as good fatigue resistance. It is weldable only through friction welding, and has average machinability. Due to poor corrosion resistance, it is often clad with Aluminum or Al-1Zn for protection, although this may reduce the fatigue strength. In older systems of terminology, this alloy was named 24ST.

Weight Fractions

Assuming that the composite material consists of fibers and matrix material, the weight of the composite material is equal to the sum of the weight of the fibers and the weight of the matrix.

Therefore,

$W_C = w_f + w_m$

where, Al 95% SiC 5%

0.500 Kg = 0.500(.95) +0.500(.05) Kg

= 0.475 + 0.025

= 0.500 Kg

w_C - weight of composite material

w_f - weight of fiber

w_m - weight of matrix

The weight fractions (mass fractions) of the fiber and the matrix are defined as

$W_f = w_f/w_C$

Such that the sum of weight fractions is

$W_f + W_m = 1$

Density:

$\rho_c = \rho_f V_f + \rho_m V_m$

= density of Al (0.975) + density of SiC (0.025)

Silicon Carbide

Silicon carbide (SiC is a compound of silicon and carbon with chemical formula SiC

It occurs in nature as the extremely rare mineral moissanite. Silicon carbide powder has been mass-produced since 1893 for use as an abrasive. Grains of silicon carbide can be bonded together by sintering to form very hard ceramics that are widely used in applications requiring high endurance, such as car brakes, car clutches and ceramic plates in bulletproof vests. Electronic applications of silicon carbide such as light-emitting diodes (LEDs) and detectors in early radios were first demonstrated around 1907. SiC is used in semiconductor electronics devices that operate at high temperatures or high voltages, or both. Large single crystals of silicon carbide can be grown by the Lely method; they can be cut into gems known as synthetic moissanite. Silicon carbide with high surface area can be produced from SiO_2 contained in plant material.Because of the rarity of natural moissanite,

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mostsilicon carbide is synthetic. It is used as an abrasive, and more recently as a semiconductor and diamond simulant of gem quality. The simplest manufacturing process is to combine silica sand and carbon in an Acheson graphite electric resistance furnace at a high temperature, between1,600 °C (2,910 °F) and 2,500 °C (4,530 °F). Fine SiO_2 particles in plant material (e.g. rice husks) can be converted to SiC by heating in the excess carbon from the organic material. The silica fume, which is a byproduct of producing silicon metal and ferrosilicon alloys, also can be converted to SiC by heating with graphite at 1,500 °C (2,730 °F).

The material formed in the Acheson furnace varies in purity, according to its distance from the graphite resistor heat source. Colorless, pale yellow and green crystals have the highest purity and are found closest to the resistor. The color changes to blue and black at greater distance from the resistor and these darker crystals are less pure. Nitrogen and Aluminum are common impurities, and they affect the electrical conductivity of SiC.

III. FABRICATION OF METAL MATRIX COMPOSITESTIR CASTING

In a stir casting process, the reinforcing phases are distributed into molten matrix by mechanical stirring. Stir casting of metal matrix composites was initiated in 1968, when S. Ray introduced alumina particles into aluminum melt by stirring molten aluminum alloys containing the ceramic powders. Mechanical stirring in the furnace is a key element of this process. The resultant molten alloy, with ceramic particles, can then be used for die casting, permanent mold casting, or sand casting. Stir casting is suitable for manufacturing composites with up to 30% volume fractions of reinforcement.

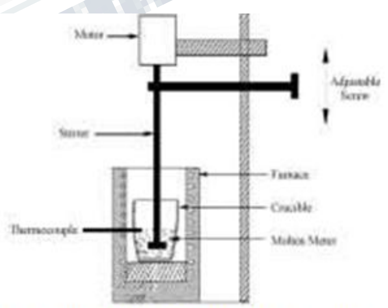

Figure-1: Stir Casting Mechanism

The cast composites are sometimes further extruded to reduce porosity, refine the microstructure, and homogenize the distribution of the reinforcement. A major concern associated with the stir casting process is the segregation of reinforcing particles which is caused by the surfacing or settling of the reinforcement particles during the melting and casting processes. The final distribution of the particles in the solid depends on material properties and process parameters such as the wetting condition of the particles with the melt, strength of mixing, relative density, and rate of solidification .The distribution of the particles in the molten matrix depends on the geometry of the mechanical stirrer, stirring parameters, placement of the mechanical stirrer in the melt, melting temperature, and the characteristics of the particles added.

An interesting recent development in stir casting is a two-step mixing process. In this process, the matrix material is heated to above its liquids temperature so that the metal is totally melted. The melt is then cooled down to a temperature between the liquids and solidus points and kept in a semi-solid state. At this stage, the preheated particles are added and mixed. The slurry is again heated to a fully liquid state and mixed thoroughly. This two-step mixing process has been used in the fabrication of aluminum. Among all the well-established metal matrix composite fabrication methods, stir casting is the most economical. For that reason, stir casting is currently the most popular commercial method of producing aluminum based composites.


Figure-2: induction furnace


Figure-3: stirring mechanism

Figure-4: Graphite crucible

Mixing Ratio's

For the preparation of the metal matrix composite we calculate the percentage of matrix and reinforcement required from the table we come to know about the amounts accurately.

Table 3: Mixing Ratios

Sample No.	Aluminium matrix (%)	Silicon carbide reinforcement (%)
1	95	5
2	90	10
3	85	15
4	80	20
5	75	25

Mould Preparation

First of all the mould for the metal matrix composite is prepared. We have to prepare moulds of below sizes for the preparation of required composite

1. 300x100x100 mm for tensile test specimens
2. 100x300x100 mm for hardness test specimens
3. 100x100x100 mm for impact test specimens

The mixture composites are poured by the stir casting method and molten metal is poured in the moulds and allowed to solidify for 24 hours. According to the ASTM Standards the various Samples are prepared and tests are conducted.

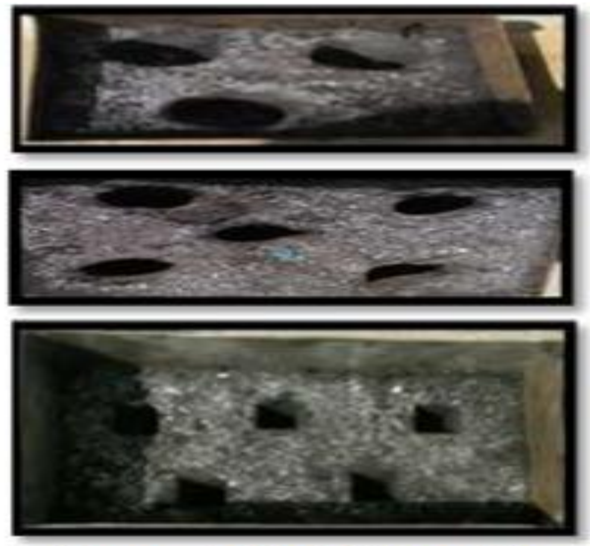

Figure-5: Mould Preparation Casting Samples

Figure-.6: casting samples

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Final Preparation Of Specimens

The specimens are finally prepared as per the ASTMstandards

Figure-7: Final Preparation of Specimens

IV. TESTS CONDUCTED

1. TENSILE TEST
2. HARDNESS TEST
3. IMPACT TEST
4. SHEAR TEST
5. COMPRESSION TEST
6. HEAT TREATMENT
    - Annealing
    - Age-Hardening

Tensile Test

Figure-8: actual specimens of tensile test

Tensile test report

Table-4: representation of tensile strength in n/mm²

S. No	Metal matrix composite		Area of the specimen (m^2)	Applied load (KN)	Tensile strength (σ) (MPa)
	Matrix (Al-2024) %	Particle reinforcement (SiC) %			
MMC-1	95	5	45.28 $x10^{-3}$	9.5	0.209
MMC-2	90	10	45.28 $x10^{-3}$	12.5	0.276
MMC-3	85	15	45.28 $x10^{-3}$	13	0.287
MMC-4	80	20	45.28 $x10^{-3}$	14	0.309
MMC-5	75	25	45.28 $x10^{-3}$	14.5	0.320

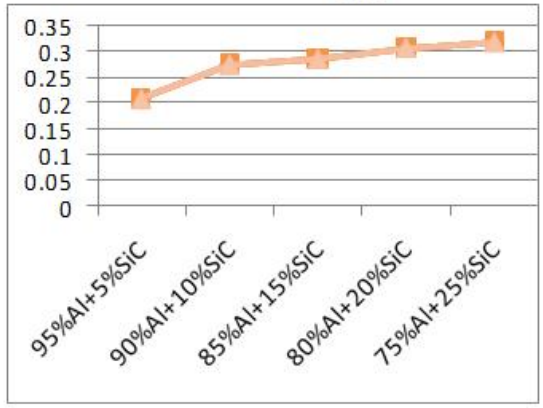
Radius of specimen = 12 mm

Height of the specimen = 180 mm

Area of the specimen $= \pi r^2 = 45.28 \times 10^{-3}\ m^2$

Tensile strength $= \frac{\text{tensile load}}{\text{area of the cross section}}$ MPa

Tensile strength for sample-1$=\frac{9.5}{45.28}$=0.209 MPa

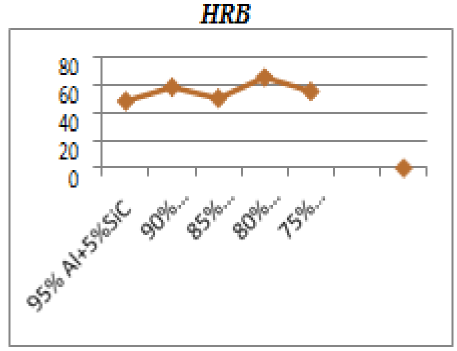


Graph-1: representation of tensile strength in N/mm²

Hardness Test

Figure-9: specimens of hardness test

Table-5.2: representation of Hardness in HRB



Graph- 2: representation of Hardness in HRB

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Impact Test

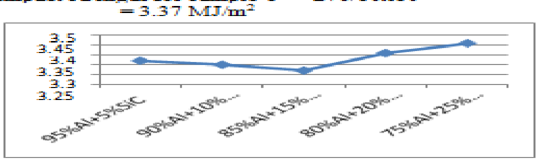
Table-5.3: representation of impact strength in MJ/m²

S.No	Metal matrix composite		L x b Area of the Notch (m^2)	Impact Energy Absorbed (J=Nm)	Impact strength (Ks) (MJ/m²)
	Matrix (Al-2024) %	Particle reinforcement (SiC) %			
MMC-1	95	5	$80x10^{-6}$	270	3.37
MMC-2	90	10	$80x10^{-6}$	268	3.35
MMC-3	85	15	$80x10^{-6}$	265	3.32
MMC-4	80	20	$80x10^{-6}$	273	3.41
MMC-5	75	25	$80x10^{-6}$	277	3.46

Width of notch = 8 mm
Thickness of the notch = 10 mm
Area of the notch = L x b $= 80x10^{-6} m^2$

Impact strength = $\frac{\text{impact energy absorbed}}{\text{area of the notch}}$ MJ/m^2

Impact strength for sample-1 $= 270/80x10^{-6}$ $= 3.37 MJ/m^2$



Graph-3: representation of impact strength in MJ/m2

S.No	Metal matrix composite		Type of scale	Rockwell Hardness Number (RHN)
	Matrix (Al-2024) %	Particle reinforcement (SiC) %		
MMC-1	95	5	[illegible]	[illegible]
MMC-2	90	10	[illegible]	[illegible]
MMC-3	85	15	[illegible]	[illegible]
MMC-4	80	20	[illegible]	[illegible]
MMC-5	75	25	[illegible]	[illegible]

II. Shear Test

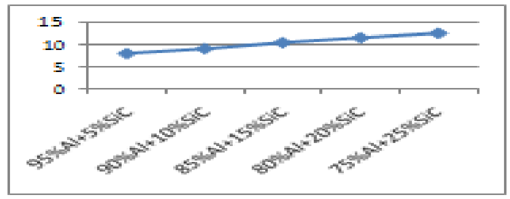
Table-5.4: representation of shear strength in KPa

S.No	Metal matrix composite		Cross sectional Area of the specimen (m^2)	Shear load (N)	Shear strength (t) (KPa)
	Matrix (Al-2024) %	Particle reinforcement (SiC) %			
MMC-1	95	5	2.86x [illegible]	23	8.04
MMC-2	90	10	2.86x [illegible]	26	9.09
MMC-3	85	15	2.86x [illegible]	30	10.48
MMC-4	80	20	2.86x [illegible]	33	11.53
MMC-5	75	25	2.86x [illegible]	36	12.58

Radius of specimen = 12 mm
Height of the specimen = 70 mm
Area of the specimen $= 2\pi r^2 = 2.86x10^{-3} m^2$

Shear strength = $\frac{\text{shear load}}{\text{area of the specimen}}$ KPa

Shear strength for sample-1 $= 23/2.86x10^{-3} = 8.04$ KPa



Graph-4: representation of shear strength in KPa

Compression Test

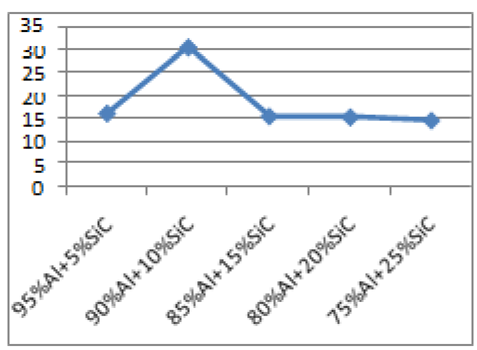
Table-5.5: representation of compression strength in MPa

S.No	Metal matrix composite		Area of cross section (m^2)	Compression load applied (KN)	Compression Strength (MPa)
	Matrix (Al-2024) %	Particle reinforcement (SiC) %			
MMC-1	95	5	3.455x [illegible]	55.1	15.93
MMC-2	90	10	3.455x [illegible]	105.1	30.42
MMC-3	85	15	3.455x [illegible]	52.8	15.28
MMC-4	80	20	3.455x [illegible]	52.1	15.09
MMC-5	75	25	3.455x [illegible]	49.7	14.38

Radius of specimen = 10 mm
Height of the specimen = 45 mm
Area of the specimen $= \pi r^2 = 3.455x10^{-4} m^2$

Compression strength = $\frac{\text{compression load}}{\text{area of the specimen}}$ MPa

Compression strength for Sample-1 $= 55.1/455x10^{-4} = 15.93$ MPa



Graph-5: representation of compression strength in MPa

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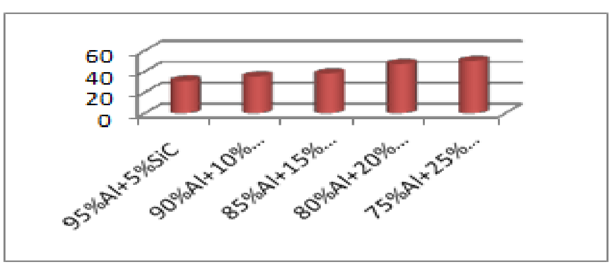
Heat Treatment

Annealing

The distorted, dislocated structure resulting from cold working of aluminium is less stable than the strain-free, annealed state, to which it tends to revert. Lower-purity aluminium and commercial aluminium alloys undergo these structural changes only with annealing at elevated temperatures. Accompanying the structural reversion are changes in the various properties affected by cold working. These changes occur in several stages, according to temperature or time, and have led to the concept of different annealing mechanisms or processes.

Table-7: representation of hardness number in HRB

S.No	Metal matrix composite		Type of scale	After Annealing Rockwell Hardness Number (HRB)
	Matrix (Al-2024) %	Particle reinforcement (SiC) %		
MMC-1	95	5	Red(B)	31
MMC-2	90	10	Red(B)	35
MMC-3	85	15	Red(B)	38
MMC-4	80	20	Red(B)	47
MMC-5	75	25	Red(B)	50



Graph-6: representation of hardness number in HRB

Compression strength test report

Table-8: representation of compression strength in MPa after heat treatment

S. No	Metal matrix composite		Area of cross section (m^2)	Compression load applied (KN)	Compression Strength (MPa)
	Matrix (Al-2024) %	Particle reinforcement (SiC) %			
MMC-1	95	5	$5.11x10^{-3}$	250	48.92
MMC-2	90	10	$5.11x10^{-3}$	275	53.81
MMC-3	85	15	$5.11x10^{-3}$	285	55.77
MMC-4	80	20	$5.11x10^{-3}$	300	58.7
MMC-5	75	25	$5.11x10^{-3}$	310	60.66

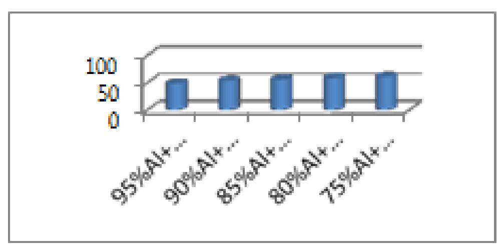
Radius of specimen = 10 mm

Height of the specimen = 50 mm

Area of the specimen $= \pi r^2$

$= 5.11x10^{-3}\,m^2$

Compression strength $= \frac{\text{compression load}}{\text{area of the specimen}}$ MPa



Graph-7: representation of compression strength in MPa

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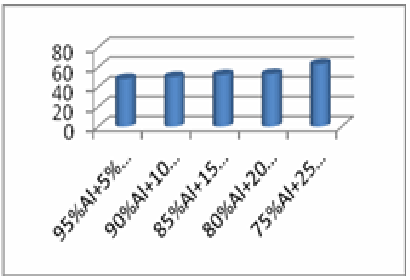

Graph-.8: representation of hardness number in HRB

Proposed Applications based on observing results

- Aircraft fittings
- Gears and shafts
- Bolts and nuts
- Clock parts
- Computer parts
- Couplings
- Fuse parts
- Hydraulic valve bodies
- Missile parts, munitions
- Pistons
- Rectifier parts
- Worm gears
- Fastening devices
- Veterinary and orthopedic equipment
- Aircraft structures.

Adopting SiC/Al composites to make the optical mirror substrates for a satellite would be expected to cut weight down by10 kg. Reduction in the weight of supporting structures and savings of fuel

For aerospace optoelectronic detecting systems working in a severe vibration environment, such as airborne optoelectronic platform, a high natural frequency is always required for long-term mechanical reliability. The multi-functional SiC/Al composites have a very high resonance frequency which is expected to be about 70% higher than Al alloys and Ti alloys

Advantages

- No limited properties compare to alloys
- Easy availability of Matrix and fiber
- Reusable and refurbishment is possible
- Higher temperature capability
- Higher toughness and strength
- High hardness
- Density reduces compared to base metal
- No moisture absorption
- Ability to fabricate into desired shape under metal working application

Disadvantages

- Defects may rise during casting
- High skilled labour is required to fabricate
- Cost of MMC's are relatively high compared to base metal
- Brittleness increases as the MMC's have high hardness
- Properties of MMC's variation is high compare to base Metal

V. CONCLUSION

Al-SiC of various concentrations(5%,10%,15%,20%,25%) composites were successfully fabricated by stir casting process. Based on the experimental observations the following conclusions have been drawn:

- Density of the composites decreased by increasing the content of the reinforcement.
- The present study shows that the tensile strength of metal matrix composite increases to the certain level of addition of reinforcement. The maximum value of tensile strength is obtained at 25%wt of Silicon Carbide loading and having the tensile strength of 2.07 MPa
- The present study reveals that the Rockwell Hardness Number of Metal Matrix composite increases to the certain level of addition of reinforcement and then starts decreasing on further fiber loading. The value of maximum RHN is 65 is obtained at 20%wt of Silicon Carbide reinforcement.
- The present study reveals that the Compression Strength of Metal Matrix composite increases to the certain level of addition of reinforcement and then starts decreasing on further fiber loading. The value of maximum Compression strength is 30.42 MPa is obtained at 10%wt of Silicon Carbide reinforcement.
- The present study reveals that the Impact Strength of Metal Matrix composite increases to the certain level of addition of reinforcement. The value of maximum Impact strength is 3.46 MJ/m2 is obtained at 25%wt of Silicon Carbide reinforcement.
- The present study reveals that the Shear Strength of Metal Matrix composite increases to the certain level of addition of reinforcement. The value of maximum Impact strength is 12.58 MPa is obtained at 25%wt of Silicon Carbide reinforcement.

- The compression strength and hardness values of the metal matrix composites has been increased after the Annealing and Age-hardening heat treatment process and the maximum values of 60.66 MPa and 63 RHN are obtained at 25% wt of Silicon Carbide reinforcement.
- With the addition of SiC with higher percentage the rate of elongation of the hybrid MMCs is decreased significantly. From the above results we can conclude that instead of Al-SiC composites could be considered as an exceptional material in sectors where lightweight and enhanced mechanical properties are essential.

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