International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 – 5161
Available at http://inpressco.com/category/ijcet

Research Article

Evaluation of Mechanical Properties of Rolled Cryo treated Al 6061–SiC Metal Matrix Composite (weldment) and Optimization using Design of Experiments (DoE)

Chandrahas M[1], Dr. R Saravanan[2], Dr.B. S Praveen Kumar[3*]

[1]Research Scholar, Mechanical Department, University Visvesvaraya college of Engineering, Bengaluru
[2]Professor, Mechanical Department, University Visvesvaraya college of Engineering, Bengaluru
[3]Associate Professor & Sr TPO, Mechanical Department, Madanapalle institute of technology and Sciences, Madanapalle

Received 15 Nov 2025, Accepted 15 Dec 2025, Available online 17 Dec 2025, **Vol.15, No.6 (Nov/Dec 2025)**

Abstract

This study evaluates the mechanical properties of rolled cryo treated Aluminium 6061 reinforced with Silicon Carbide (SiC) particulates and optimizes process parameters using Design of Experiments (DoE). The composite was fabricated through stir casting and subsequently subjected to rolling under controlled parameters. Mechanical characterization included Yield Strength, Ultimate tensile Strength, Elongation, Hardness, and Impact Energy. Taguchi's L9 orthogonal array was employed to identify optimal parameter settings for maximizing mechanical performance. Results indicate that reinforcement percentage and rolling reduction significantly influence the composite's mechanical behaviour.

Keywords: *Al 6061, SiC, MMC, Rolling, Mechanical Properties, Design of Experiments, Taguchi Method.*

---

1. Introduction

Aluminium Metal Matrix Composites (AMMCs) have gained attention due to their superior strength-to-weight ratio, wear resistance, and enhanced mechanical performance. Aluminium 6061 alloy serves as a widely used matrix material owing to its weldability, corrosion resistance, and mechanical reliability. The inclusion of Ceramic particles such as Silicon Carbide (SiC) improves hardness, stiffness, and thermal stability.

Rolling, as a secondary processing technique, refines the microstructure, improves density, and enhances the mechanical properties of composites. However, the extent of improvement depends on several factors including reinforcement percentage, rolling reduction, and sintering temperature. This research aims to analyze the effect of these parameters and optimize them using Design of Experiments (DoE).

2. Literature Review

Several studies confirm that the mechanical properties of AMMCs improve with the incorporation of reinforcements. Rolling further enhances the bonding between matrix and reinforcement, reducing porosity. Optimization using DoE methods such as Taguchi has proven effective in determining the parametric influence on mechanical properties.

In the continuing quest for improved performance, which may be specified by various criteria including less weight, more strength and lower cost the materials being used currently often reach the limit of their usefulness. This resulted in the emergence of composites. The tailor-made specific properties of materials for better overall performance is so great and diverse that no one material is able to satisfy the conflicting requirements of constructive properties. This has led to the research on materials, which is able to satisfy the varying demands from the different industries. This naturally leads to the resurgence of the ancient concept of combining different materials in an integral composite material to satisfy the user requirement. There are more than eighty thousand materials represented in the market, and this figure is rapidly increasing. Advanced materials are being developed to an increasing extent [1]. Among these materials one finds prominently used composite. The development of composites as a new engineering material has been one of the major innovations in the field of materials in the past couple of decades [2]. The MMCs are a new range of advanced materials used in applications where conventional materials and alloys are not suitable for use.

This outstanding benefit of composite materials is that they can be tailored to produce various combinations of stiffness and strength [3, 4]. It is possible to develop new material with a unique combination of properties previously unattainable

*Corresponding author's ORCID ID: 0000-0000-0000-0000
DOI: https://doi.org/10.14741/ijcet/v.15.6.4

with conventional materials. This ability to engineer materials with specific properties for specific applications represents a great potential advantage of composites.

It is also possible to selectively reinforce particular areas of components, thus providing development of materials properties only in area, which is truly necessary. In material science, composites are described as consisting of at least two discretely separable components. In the broadest sense this may be taken to include even chemically or mechanically engineered products such as duplex phase alloys. However, composites have come to be known as that family of materials resulting from the reinforcement of one component with another [5-9].

The strength and stiffness of composites very much depend on the reinforcing material. Dispersion strengthened metals are a kind of composites in which only the concentration of the strengthening particles is controlled, not their exact dimensions or orientation. In general, a hard dispersoid when used as reinforcement in a soft matrix reduces the impact strength of the matrix, at the same time improves other mechanical properties, whereas a soft dispersoid in a hard matrix improves impact strength and adversely affects other properties [10].

Many processing techniques are available for MMC's but most widely used technique is Stir casting method. Here Stir Casting method is implemented for the fabrication of Aluminum matrix composites [11]In order to change in properties of Metal matrix composite are subjected to under the secondary processing techniques like forging, rolling extrusion etc. here we focusing on effect of Aluminum metal matrix composite when subjected to hot extrusion and it was found that with Equal channel angular extrusion desirable enhancement in material properties is achieved due to ultra-fine grain refinement [12]. For uniform dispersion of material blade angle should be 45° or 60°, For good wet ability we need to keep operating temperature at semisolid stage i.e. 630o for Al (6061). At full liquid condition it is difficult uniform distribution of the reinforcement in the molten metal. Preheating of mould helps in reducing porosity as well as increases mechanical properties. Improved die design and surface treatment will play an important role in the economic production of high-quality composites with excellent structures and properties [13,14]. Two new approaches (Cold Forging and Thixo forging) towards an improvement of the forming behavior of metal matrix composites (MMC) have been investigated. Cold Forming was performed with two aluminum based MMCs (Al6082 with Al2 O3 short fibers and Al6061 with Al2 O3 particles) [15-17]. Some of the work has done on hot rolling and aging due hot rolling one can achieve large plastic deformation and it is found that Tensile strength and hardness have increased and wear rate is decreased [18]. Further the effort was made on Effect of Secondary Processing and Nanoscale Reinforcement on the Mechanical Properties of Al-TiC Composites with an average of 45nm, reinforcement was synthesized using low energy planetary ball mill followed by hot extrusion Microstructural characterization of the materials results uniform distribution of reinforcement, grain refinement. Properties characterization results that hardness nano-TiC particulates has increased, elastic modulus, 0.2% yield strength [19,20]. a) Primary Processing of Composites: Production of composite material by combining ingredient materials (e.g. powdered metal and loose ceramic particles, or molten metal and fibre preforms), but not necessarily to final shape or final microstructure b) Secondary Processing: Processing steps which follow primary processing, and aim to alter the shape or microstructure of the material (e.g. shape casting, forging, extrusion, heat-treatment, machining).

Vickers Indentation (Hardness)

The Vickers' indentation experiment has been carried out in which the diamond indenter is utilized to indent specimen and hardness of the material has been determined. The hardness of the Al6061-SiC composite for different weight fraction of the reinforcement (Fig.1) has been determined and depicted in Fig.2 shows the hardness of Al6061-SiC composite for the different weight fraction of reinforcement. The average of three indentations on the said composite has been taken to plot the graph with standard deviation.

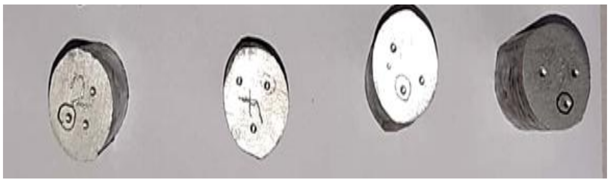

Fig.1 Specimens after Vickers Hardness Test

From the Fig 2 it is clear that as the increment in composition of the SiC, the hardness of the composite increases, up to 7wt%. Further increment in the composition reduces the hardness of the said composite.

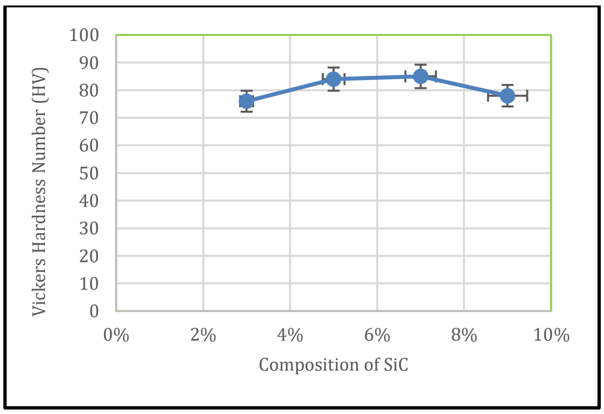

Fig.2 Hardness of the Al6061-SiC composite

From the Vickers' hardness experimental results, the weight percentage of the SiC in the Al6061 matrix increases the hardness of the Al6061-SiC composites. The installment of SiC particles in the matrix and the bonding between the Al6061 and SiC particles act as the barrier to the debonding of the matrix and reinforcement. Thus, the enhanced hardness of the said composites has been obtained. However, at 9wt%, the further increment in the SiC particles will lead to clustering of the particles in aluminum matrix which decreases the hardness. Overall, better bonding between the Al6061 and SiC particles and the uniform distribution of the SiC particles in the Al6061 matrix, the said composite exhibits the high hardness value.

Tensile strength

From the standard tensile test experimentation, the various tensile properties of the materials were determined such as tensile, yield strength and percentage elongation. Tensile test of Cryo treated Al6061-SiC particulate composite for 3wt%, 5wt%, 7wt% and 9wt% of the SiC is carried out using UTM with computerized data acquisition units in a room temperature. From the tensile test experimentation, the load and the deformation values have been recorded and used for the further calculation of stress and strain. The Specimens used for tensile test are shown in Fig.3.Al6061-SiC particulate composite specimens were tested to find the tensile properties like yield strength, percentage elongation and ultimate tensile strength until it fractures. The stress-strain graph is plotted as shown in the Fig.4 of the said composites.

Fig.3 Tensile Test Specimens after Fracture

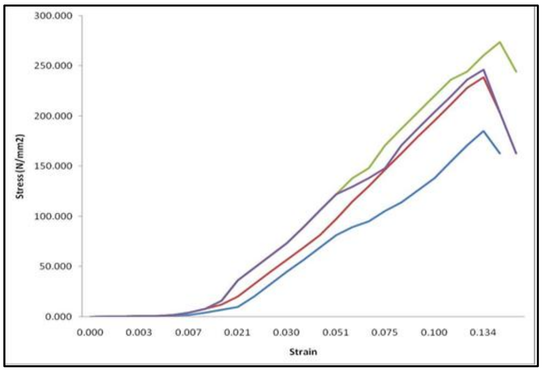

Fig.4 Stress-Strain diagram for the Al6061-SiC composites

From the stress-strain diagram it is observed that the failure of the Al6061-SiC composites is follows the same path. However, the load carrying capacity of the Al6061-7 wt % SiC is higher than the others. Thus, the addition of the silicon carbide increases the load carrying capacity. However, the further increment in the SiC might cause the clustering of the reinforcement in the matrix. Thus, reduces the load carrying capacity.

The ultimate tensile and yield strength and % elongation of the said composites is determined and plotted against the different varying compositions of the SiC is shown in the Fig.5.

From the Fig.5(a) it is observed that the yield strength of the Al6061-7wt%SiC composite is higher than the remaining compositions of the said composites. Adding of SiC particles increases the yield strength up to 7wt% of reinforcement. It is also observed to be 54% increment in the yield strength of the composites. At 12wt% of SiC, the yield strength of the said composite is decreased by 12%.

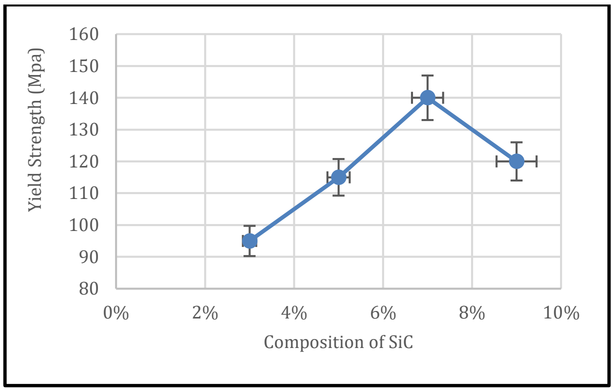

Fig.5(a): Variation in yield strength of Al6061-SiC composite

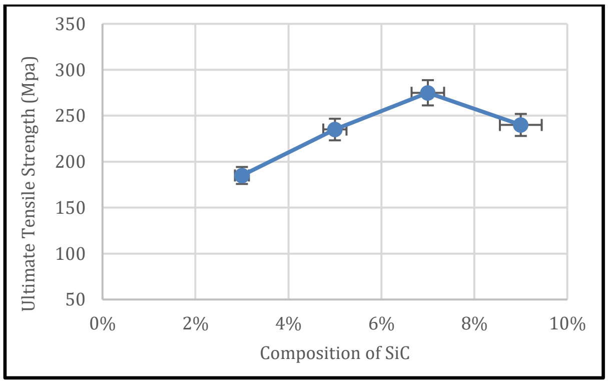

Fig.5(b): Variation in ultimate tensile strength of Al6061-SiC composite

From the Fig.5.3(b) it is seen that the ultimate tensile strength of the Al6061-7wt%SiC composite is higher than the remaining compositions of the said composites. Thus, the load carrying capacity of said composite increases by addition of SiC reinforcement. The addition of SiC particles increases the ultimate tensile strength up to 7wt% of reinforcement. It is also observed to be 47% increment in the ultimate tensile strength of the composite. At 9wt% of SiC, the yield strength of the said composite is decreased by 10%.

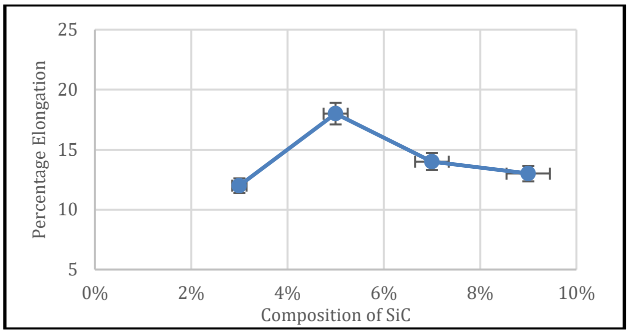

Fig.5(c): Variation in percentage elongation of Al6061-SiC composite

From the Fig 5(c) it is observed that the percentage elongation of the composite, initially increased up to 6wt% of SiC in the aluminum matrix and further decreases. It is obvious that the addition of hard particles of SiC increases the hardness and thus ductility of the said composite decreases. The initial increment in the ductility is 14% whereas the overall decrement in the ductility is 10% at 12wt% of SiC.

Hence the addition of SiC to the Al6061-SiC composites increases the yield strength, ultimate strength of the composite with the loss of ductility. It is also obvious that the silicon carbide material is identified to be the one of the hardest substances, adding of which in the ductile material like aluminum increases the strength of the composite and as a consequence of which the percentage of elongation decreases.

Fig 6 demonstrates the interface of the SiC reinforcement in the aluminum matrix, obtained from the fractured surfaces of the Al-SiC composite. The SEM micrographs of the Al-SiC also indicates the uniform distribution of the SiC reinforcement in the Al6061 matrix. Thus, the increased values of the mechanical properties such as hardness, tensile strength, yield strength has been obtained.

SEM Analysis

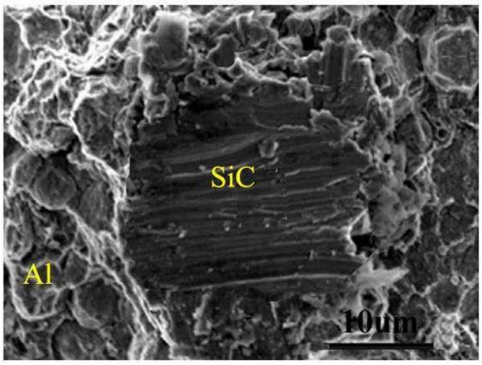

Fig.6 SEM micro-graph showing the clear interface between matrix and reinforcement

From the scanning electron microscopy, Fig.6, it is clear that the matrix and the reinforcement exhibit the good bonding. The liquid metallurgy route of preparation of the MMC brings the improved bonding and distribution of the reinforced particles. From the Fig.6 it is also observed that the reduction of porosity along the grain boundaries and residual porosity within grains.

The fractured surface of the Al6061-SiCp composite for different weight fractions of the SiC is shown in Fig.7. From the scanning electron microscopic fractographs it is seen that the fractured surfaces of said composites have the micro cracks and voids. It is also observed that the cracks were propagated only in the matrix and not in the reinforcement. The voids and micro cracks are formed at the interface of the matrix and reinforcements. Thus, the propagations of the crack is away from the SiC particles in the matrix and hence will take the higher time to get fractured. As a result, the strength of the Al6061-SiC composite increases. However, for 9wt%SiC, there observed the presence of voids, larger cracks at the vicinity of the interfaces of the matrix and reinforcement. Thus, the tensile strength decreases at 9wt%SiC.

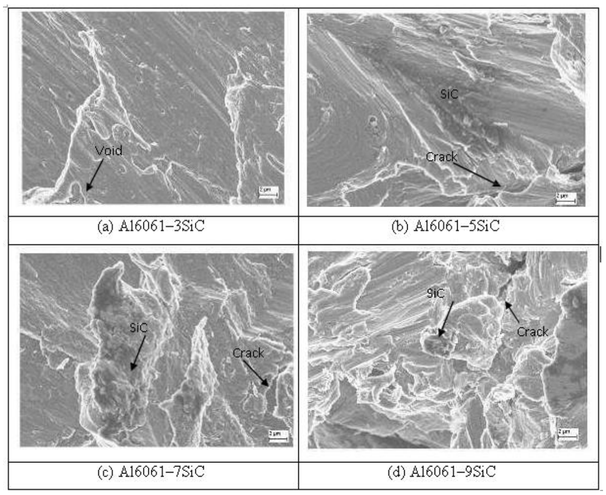

Fig.7 SEM fractographs showing the fractured surfaces for different SiC weight fractions

The higher yield, tensile strength and load carrying capacity of the said composites is because of the uniform distribution of the SiC particles, and there bonding with the aluminum, lesser voids, material's resistance to crack propagation and great bonding between them.

Impact strength

Energy required to fracture the specimen can be determined utilizing the standard impact testing. Charpy V-notch experiment is utilized to determine the material characteristics for the impact loading conditions. Thus, the Charpy impact test experimentation has been conducted for all the compositions of Al6061-SiC particulate composite to investigate their impact strength in the room temperature. The energy absorbed (J) to fracture the specimen has been recorded from the test.

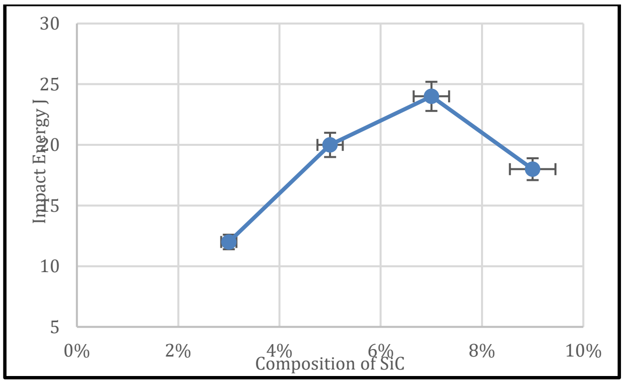

Fig.8 Impact energy absorbed by the Al6061-SiC composite

Since the Al6061 is tough material, the energy absorption capacity the aluminum 6061 is higher. Also, the Al6061-SiC composite is prepared using the liquid phase method, i.e stir casting route, will exhibits higher impact toughness. From the Fig.8, it is observed that, as the percentage compositions increases the in the composites, its impact strength increases. The increased impact toughness of the composite is due to its capability to hold the ductility, with respect to the increment in the reinforcement. Thus, it absorbs the more energy to rupture. The maximum energy absorbed by the Al6061-7wt% SiC composite is 41.5 Nm.

The reduction in the tensile strength and impact strength, at 9wt% of SiC, is may be due to the clustering of SiC particles which fails the uniform distribution in aluminum matrix, cracks at the interfaces of matrix and reinforcements which reduces the load transfer, reduction in ductility of composite due to addition of more SiC particles.

The failure strain decreases after 6wt% of SiC, however the impact strength increases upto 7wt% of SiC. However, this result is may be because of machining operation carried out in preparation of tensile and impact testing specimens.

Design Of Experiment (DoE)

The design of experiments is conducted using special matrices called orthogonal arrays, consists of set of experiments with various process parameters as variables to study from one experiment to another and allows the effect of several parameters to be determined efficiently. The effects of various factors can be determined by computing simple averages. Estimates of factor effects are then used to determine the optimum factor setting. An orthogonal array is a fractional factorial experimental matrix that is orthogonal and balanced.

The number of experiments to analyze the factor effects of a process through DOE is denoted by for example; 33= 27 experiments, where 3 represents the number of levels and 3 represents the number of factors involved. In general, an experiment in which all-possible combinations of the factor levels are realized is called a full factorial experiment. The numbers of trials in a factorial experiment are considerably high and sometimes impracticable in actual use. In fact, orthogonal array evolved through the concept of fractional replication. In practical scenarios, it is usually tedious and expensive to conduct full factorial experiments. For this reason, orthogonal array method provides techniques where in reducing the full factorial to a fractional factorial which reduces the number of experiments, we can still arrive at the factor effects provided, the layout is such that the factors are kept orthogonal to each other. This outcome eliminates the time and additional costs that are involved in carrying out full factorial experiments.

Steps involved in Design of Experiments.

It usually consists of the following steps

- Deciding the number of factors and levels
- Counting the degrees of freedom (DOF).
- Selecting a standard orthogonal array.
- Preparing the experimental layout based on the standard orthogonal array.

In many cases, it is difficult to fit a standard orthogonal array to the combinations of factors and levels a process has and even if one can the number of experiments still maybe large. For this reason, there are a number of modifications which may be employed to tackle these problems. Some of the modifications are column merging methods, compound factor methods, dummy level technique, etc.

Selection of Factors and levels

In order to observe the influencing degree of cryogenic process parameters on the mechanical properties of Al6061-SiC MMCs, three parameters namely; (1) cryogenic temperature in C; (2) treatment duration in hours and (3) particle wt. %, each at three levels were considered and are listed in Table 1.

Table 1: Cryogenic treatment control parameters

Factors	Control factor	DOF	Level 1	Level 2	Level 3
A	Cryogenic temperature, °C	02	-100	-150	-196
B	Duration of treatment, h	02	0	25	50
C	Wt. % of SiC	02	0	10	20

Maintain the cryo-treatment parameters as constants to enable the 1) study of the effect of cryogenic temperature; (2) treatment duration and (3) particle wt. %, on the mechanical properties result. The degrees of freedom for three parameters in each of three levels were given in Table 1.

Taguchi model for tensile properties

Table 2 indicates the parameters used and the results of tensile test. Three levels L9, 33 orthogonal arrays with nine experimental runs were selected. The total degree of freedom is computed. In this research nine experiments were conducted at different cryogenic parameters, and then the specimens were machined and tested for tensile behaviour. The S/N ratios were computed for tensile strength in each of the nine trial conditions and their values are given in Table .2.

Table 2: Experimental observations for tensile test data as per DOE

Exp. NO.	Factors			Tensile results			Average	Standard deviation	S/N ratio
	A	B	C	1	2	3			
1	-100	0	0	120.37	117.18	118.88	118.81	1.5936	37.45
2	-100	25	10	167.00	164.09	165.79	165.63	1.4634	41.08
3	-100	50	20	205.64	205.09	205.56	205.43	0.2991	56.74
4	-150	0	20	190.79	188.49	191.15	190.14	1.4439	42.39
5	-150	25	0	191.06	189.17	190.68	190.31	0.9977	45.61
6	-150	50	10	161.50	159.99	161.74	161.08	0.9478	44.61
7	-196	0	10	195.70	192.52	194.71	194.31	1.6305	41.52
8	-196	25	20	193.55	191.92	193.35	192.94	0.8897	46.72
9	-196	50	0	184.65	183.44	184.40	184.16	0.6380	49.21

The experimental results are shown by using orthogonal array including the tensile strength calculations whereby taken with three levels of observations of cryogenic temperature, cryogenic duration and percentage of SiC. Taguchi method is used to optimize the parameters to get the effectiveness of this approach for engineering as well as research purposes. An experiment during the product design stages involves the materials used in manufacturing the experimental product which affects the final quality outcome. A more effective method for these situations is to study their effect simultaneously by setting up experiments following the design of experiment technique. This step should lead to some understanding of the basic design of experiment principles. As far as the benefits from the technique are concerned, experimental planning is the most important.

In this, larger is better concept is used to represent the main effect graph. The average values of levels L1, L2, L3 at given cryogenic temperature are 163.3, 180 and 190 shown in Fig.9.1(level 3 is best combination). The quality characteristics investigated in this study that the combination of parameters and their levels make the best combination, say optimal quality characteristic to be achieved for third level. The average effects of cryogenic exposure duration at level 1, 2, and 3 respective values as average at the point are 167, 183 and 182 and the main effect graph is shown in Fig. 9.2 (level 2 is best combination). The average effects of particle size at level 1, 2, and 3 respective values as average at the point are 157, 179 and 196 and the main effect graph is shown in Fig. 9.3 (level 3 is best combination).

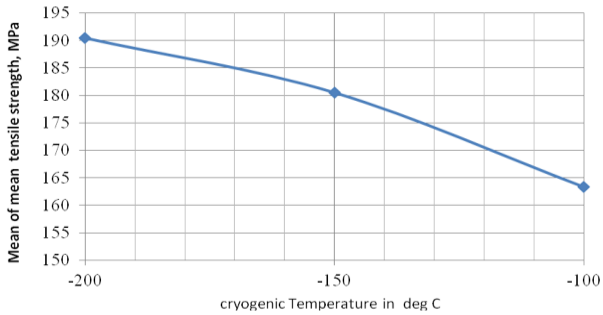

Fig. 9.1 Effect of cryogenic temperature on mean of mean tensile strength of SiC composites

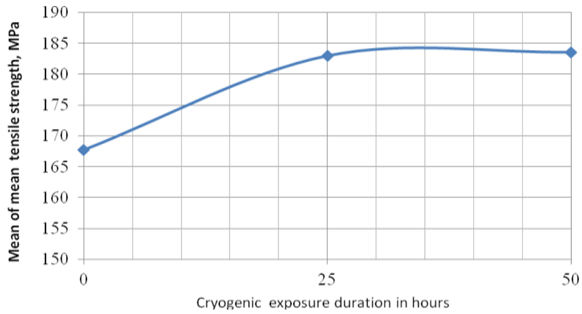

Fig. 9.2 Effect of cryogenic exposure duration on mean of mean tensile strength of SiC composites

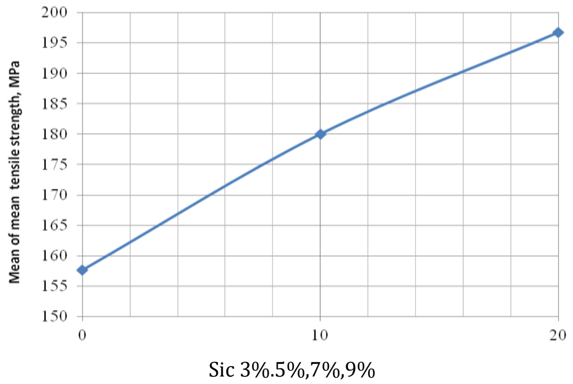

Fig. 9.3 Effect of SiC particulate on mean of mean tensile strength of Al6061-SiC composites

This step was utilized to review a number of standard analyses to build the confidence in interpreting the experimental results. By the analysis of variance (ANOVA) it is clear that the percentage contribution of cryogenic temperature is 54.23%, cryogenic exposure duration is 23.01 % and wt. % SiC is 22.77 %.

Table.3: ANOVA design table for tensile strength of cryogenic treated Al 6061-SiC composites

Factor		A	B	C	Total
Sum at factor level	1	489.9	503.3	548.9	1602.8
	2	541.5	548.9	539.9	
	3	571.4	550.7	590.1	
Sum of square difference		10210.3	4332.1	4287.1	18829.5
Degree of freedom		02	02	02	06
% Contribution		54.23	23.01	22.77	100.0
Optimum Level		03	02	03	
		-200 °C	50h	20 wt.%	

The ANOVA table represents the predictive equation for performance of the optimum condition and or any other possible condition. The numbers shown are computed for the optimum condition. The optimum condition is determined based on the quality characteristic selected for the analysis. It is a common practice to only include the significant factor (not pooled) in calculating the expected performance. At level 1, 2 and 3, the percentage contribution is more significant for the optimum outcome of the factors. The optimum condition and performance can be obtained by these results and which can participate and contribute a significant task while working on various tests.

References

[1] Introduction to Composites and History of Composites, 2001. Composites, Volume 21 of ASM Handbook,

[2] Jatitz, Whittenberger,J.D. 1990, in Solid State Powder Processing, ed. A.H.Clauer & J.J. deBarbadillo. The Minerals, Metals and Materials Society, Warrendale, PA,,p. 137.

[3] Berghezan, Stoloff, N.S. & Alman, D.E., 1990, In Intermetallic Matrix Composites vol.194, ed. D.L. Anton et al. Materials Research Society, Pittsburgh, PA, p. 31.

[4] J.A.E. Bell, A.E.F Warner, and T.F. Stephenson, 1996, Processing, Properties, and Applications of Cast Metal Matrix Composites, P. Rohatgi, Ed., TMS, , p 247.

[5] D.M. Miller, Glass Fibers, Composites, Vol 1, 1987, Engineered Materials Handbook, ASM International, p 45–48.

[6] K. Shariq, E. Anderson, and M. Yamaki, "Carbon Fibers," July 1999, Chemical Economics Handbook Market Research Report, SRI International, Menlo Park, CA.

[7] E.I. Du Pont de Nemours & Co., Inc., Oct 1998. "Kevlar and Nomex Specialty Additives for Enhanced Performance".

[8] T.W.Clyne, 1993, An Introduction to Metal Matrix Composites. Cambridge University.

[9] A.Needleman, 1993, Fundamentals of Metal Matrix Composites, Butteroorths, Bostan Page 80-85.

[10] V.I. Kostikov,1995, Fibre Science and Technology, Chapman & Hall, London,

[11] Rajeshkumar Gangaram Bhandare, Parshuram Sonawane M (2013) Preparation of Aluminium Matrix Composite by Using Stir Casting Method 3: 148-155.

[12] Naik Sachin Ashok, Ravi Kumbar T, Madhusudhan (2016) Investigation on Mechanical and Tribological Properties of 6061 Aluminium - SiC Alloy Fabricated by Stir Casting Method and Equal Channel Angular Extrusion: The Review. IRJET 3(4): 2771-2774.

[13] (2001) Aluminium mmc extruded products with high stiffness and wear resistance. Seco Aluminium Ltd United Kingdom.

[14] Honnaiah C, Satyabodh Raichur, Madhusudan M (2016) A Study on Mechanical Behaviour of Hot Extruded Aluminium based MMC Reinforcedwi th Varying Alumina Particles (A356 Al2 O3). IJRET 5(3): 2278-0181.

[15] Rabindra Behera, Das S, Chatterjee D, Sutradhar G (2011) Forgeability and Machinability of Stir Cast Aluminum Alloy Metal Matrix Composites. JMMCE 10(10): 923-939.

[16] Ezatpor Hr, Torabi Parizi M, Sajjadi S A (2013) Microstructure and mechanical properties of extruded Al/Al2 O3 composites fabricated by stir-casting process. Trans Nonferrous Met Soc China 23(5): 12621268.

[17] Ramesh CS, Adarsha Hirianiah, Harishanad KS, Naveen PrakashNoronha (2014) A review on hot extrusion of Metal Matrix Composites, (MMC's).

[18] Reddappa HN, Suresh KR, Niranjan HB, Satyanarayana KG (2014) Effect of Aging on Mechanical and Wear Properties of Beryl Particulate Reinforced Metal Matrix Composites. Journal of Engineering Science and Technology 9(4): 455-462. 006 This work is licensed under Creative Commons Attribution 4.0 Licens DOI: 10.19080/JOJMS.2018.04.555642.

[19] Deborah DL, Chung (2010) Composite Materials Science and Applications (2nd edn.), Springer, New York, USA.

[20] Senthilkumar V, Balaji A, Hafeez Ahamed (2011) Effect of Secondary Processing and Nanoscale Reinforcement on the Mechanical Properties of Al-TiC Composites. Journal of Minerals & Materials Characterization & Engineering 10(14): 1293-1306.