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The Influence of Deep Cryogenic Treatment (DCT) on the Mechanical Behaviour of Aluminium Metal Matrix Composites

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Abstract: ***The outcome of cryogenic treatment (CTT) on the mechanical behaviour of Al alloy LM 25, LM25+5% fly ash and LM25+10%fly ash composites was investigated. Cryogenic treatments were performed with threedifferent soaking periods (0 hr (Untreated), 12hr, 24hr) ata constant cryogenic temperature of -196°C. After the CTT, the mechanical behaviour of the materials was measured. It is obvious that LM25+10% fly ash composites exhibitbetter mechanical properties than the LM25 and LM25+10% fly ash composites.As cryogenic soaking period increases mechanical properties of the MMCs tend to increase too. The effect of fly ash mass percentage and cryogenic soaking period on the mechanical behaviour of materials was studied by using Taguchi and Analysis of Variance (ANOVA).***

Keywords: ***cryogenic treatment, fly ash reinforced LM 25 composites, cryogenic soaking period, mechanical behaviour, Taguchi, ANOVA.***

I. INTRODUCTION

Material researchers arefulfilling the need of the engineering industries in synthesizing materials in order to accomplish the desired properties to enhance efficiency and reduce the cost [1].The usage of aluminum alloys has been gradually increasing in the automotive industry to decrease the weight of vehicles, whichenhances the efficiency and reduces the exhaust pollutants. The shortcomings of Al alloys are lower yield strength and higher wear rate. Deep Cryogenic Treatments (DCTs) can be employed to enhance the mechanical as well as tribological properties of the Al alloys. One of the benefits of deep CTT is that the micro structural changes take place in the whole bulk material instead of merely onthe surface. Deepcryogenic-treated materials can be employed in the manufacture of structural components.Volker Franco Steieret al. [2] examined the impact of CTT on the wear of the Al alloy 6061.The results demonstrated theCTT-enhanced wear resistance of the aluminum alloy. Gu et al. [3] analyzed the influence of CTT on hardness and wear behaviour of Ti-Alalloy for biomedical applications. The hardness of the treated material increased due to the increase of dislocation density and twins.

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Bouzadaet al. [4] examined the effect of DCT on the properties of the AA7075-T6 metal alloy. Various authors have made research and found an increase in the mechanical properties after DCT. Susheel Kalia [5] reviewed It was found composites. Lulayet al. [6] examined the effect of CTTs on 7075 aluminum alloy. It was reported that no considerable
the effect of CTT on some metals, alloys, plastics and
effect was noted on the mechanical properties on account of a 2-hr CTT. A little improvement in tensile strength and a slight drop in hardness wereobserved on account of 48 hr of CTT. Singla et al. [7] assessed the cryogenic processing of the materials and manufacturing.

Jiang et al. [8] examined the influence of CTT on the mechanical properties of Al alloy 3102. DCTcouldenhance the yield strength along withdeclinein the elongation of the Al-alloy. Wang et al. [9] studied the impact of CTT on the mechanical behaviour of Al alloy 2A11. Results showed that cryogenic treatment could improve the mechanical properties of aluminum alloy. Taskesenet al. [10] analyzed the effect of CTT on the ageing behaviour of Al 7075-B_4C composites. The hardness of the cryogenically-treated specimens increases considerably.Kumar et al. [11] analyzed the impact of DCT on the wear rate of AISI D3 Die Steel using statistical tools.

Rasool et al. [12] examined the DCT of Al-SiC Composite. They reported that the treated specimens haddemonstrated an enhanced compressive strength. Lulayet al. [13] evaluatedthe outcome of CTT on Al 7075. Zhang et al. [14] analyzed the tensile strength of 3104 aluminum alloy processed by homogenization and CTT. Slatter and Thornton [15] studied the cryogenic treatment of engineering materials. They reported that the term 'cryogenic' relatedto very low temperatures and hada broad range of applications in medical, electrical and electronic fields. Thornton et al. [16] studied the impact of CTT on the wear behaviour of the materials.Soaking temperature anddurationwere the important factors which decided the quality of the cryotreated materials. The total cost of cryogenic cycle dependedon the soaking time[17].

A very limitedquantum of work has been reported about the cryogenic treatment of Al alloys and metal matrix composites. From the literature review, it is observed that there is no apparent understanding regarding the contribution of cryogenic soaking period on the mechanical behaviour of the materials.Various research findings show that a systematicprocedure has to be carried out in cryogenic treatment.

In this study, the effect of CTT on the mechanical behaviour of LM25 aluminum alloy,LM25+5% fly ash and LM25+10% fly ash compositeshas beenstudied by using Taguchi and Analysis of Variance (ANOVA).

II. MATERIALS AND METHODOLOGY

A. Materials

Commercial LM25 aluminum alloy, LM25+5% fly ash and LM25+10% fly ash compositeswerechosen for this study.LM25 casting alloy was mainly used where the high strength and resistance to corrosion are important considerations.Thechemicalcompositionof the untreated as-cast LM25 sample is representedinTable1.

Table- 1: Chemical Composition of LM25 Aluminium Alloy

Element	Actualvalue (%)	Element	Actual value (%)
Silicon	6.5	Zinc	0.06
Iron	0.4	Titanium	0.012
Copper	0.1	Tin	0.01
Manganese	0.2	Lead	0.1
Magnesium	0.05	Aluminium	Remainder
Nickel	0.09		

B. Fabrication of composites

Al alloy LM25 was selected as the matrix and fly ash particles (100 microns) were used as the reinforcement.LM25+5% fly ash and LM25+10% fly ash MMCs were manufactured through combined stir and squeeze casting techniqueas shown in figure 1.

Composites were fabricated through squeeze casting process, which has the advantages of both stir casting and gravity die casting.Squeeze casting process eliminatedthe shrinkage and gas porosities. High dimensional accuracy, near net shaped,couldbe obtained. Composite melt was prepared by stirring and poured into the mould which was maintained at a temperature of 350°C. Pressure (50 MPa) was applied by preheated diefor 60 seconds till solidification was finished.

Fig. 1. Schematic of Squeeze casting setup

C. Cryogenic treatment

Test specimens of LM25 aluminum alloy, LM25+5% fly ash and LM25+10% fly ash compositeswere subjected to deep cryogenic treatment. It was done by keeping the specimens in a liquid N_2 chamber as shown in figure 2 for two different lengths of time: untreated (0 h), 12hr and 24hr. Cryogenic treatment was performed to assess the soaking effects on the mechanical behaviour of the materials. No post-processing was done after the cryogenic treatment. Figure 2 shows the cryogenic liquid storage tank and Figure 3 the processing chamber where the work piece is soaked in liquid nitrogen at -196 °C.

Fig. 2. Storage tank

Fig. 3.Processing chamber

D. Micro structural Examination

A micro-structural change was observed using standard metallography test. Microstructuresof the LM 25 alloy before and after the DCT areshown in figure 4 and 5 respectively at 500X magnification. It can be seen from Fig.4 that the grainsofuntreated specimen werefiner. It can be observed from the figure 5 that a lot of irregularitiesare visible on the surface of the deep cryogenic treated specimen, which impedes the movement of slipping system, and the hardness tends to increase and the elongation decrease.

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Fig. 4. Microstructure of the LM 25 alloy before deep cryogenic treatment

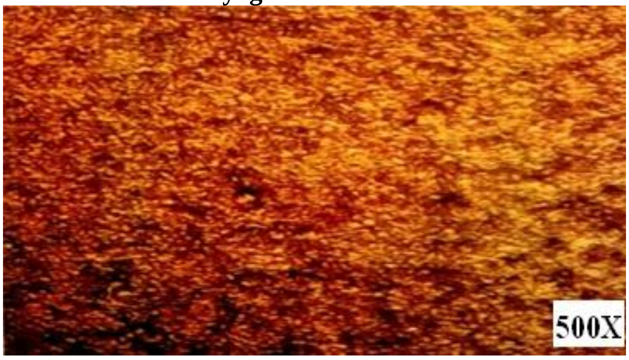

Fig. 5. Microstructure of the LM 25 alloy after deep cryogenic treatment

E. Mechanical Properties

Mechanicaltestingwasdone in line with ASTME8-82 at a room temperatureemploying universal testing machine. Tensile, yield, hardness, and elongation of cryogenic treated LM 25 and LM 25 fly ash MMCs are given in Figures. 7, 8, 9 and 10respectively.A few samples are shown in fig. 6.

Fig. 6. Tested specimens after deep cryogenic treatment

1. Hardness

Fig. 7illustrates the effect of fly ash weight percentage and cryogenic soaking period on the hardness of LM25 fly ash composite. The increase in hardness was found to be 7.84% when the fly ash weight percentage was increased from 5 to 10wt% at the cryogenic soaking period of 24 hrs. The enhanced hardness was due to the addition of fly ash particles, which acted as hurdle to the travel of dislocation with the Al matrix. The hardness also increasedwith the increase in cryogenic soaking period toa significant extent. When the cryogenic soaking period was increased from 0 hrs (untreated) to 24 hrs,the hardness of the LM 25+10% fly ash composite increased by 14.5 % i.e., from96 BHN to 110 BHN. It can be attributed to the fact that cryogenic thermal treatment results in fine and well-distributed precipitates[18].

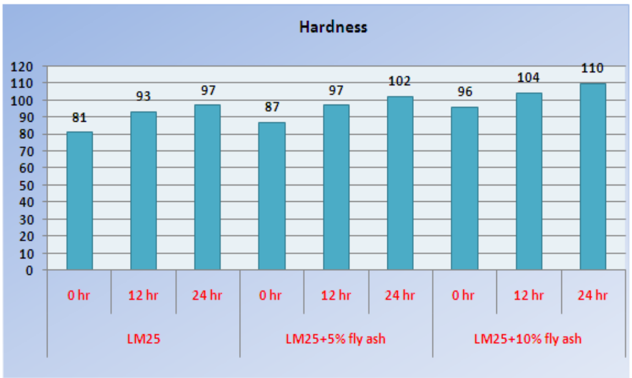

Fig. 7. Effect of cryogenic soaking period on the hardness of LM 25 and MMCs

2. Tensile strength

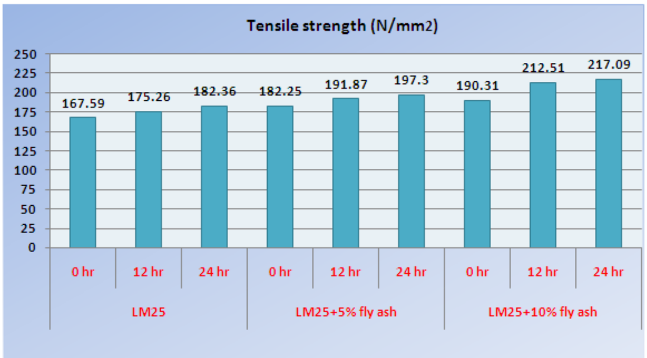

Fig. 8. Effect of cryogenic soaking period on the tensile strength of LM 25 and MMCs

From Fig. 8, it is evident that the LM 25 +10% fly ash composite exhibits higher tensile strength than the base alloy and LM 25 + 5% fly ash composite irrespective of cryogenic soaking period. Theimprovement in the tensile strength is highly influenced by the incorporation of reinforcement particles and formation of magnesium oxide and magnesium silicide at the interface between the phases of matrix and reinforcement [19-20].

The tensile strength of the material tends to increase when the cryogenic soaking period isincreased to 24 hours. It was observed from our earlier work that longercryotreatment(36 hrduration)was not much effective. The ultimate tensile strength tends to drop slightly when the cryogenic soaking period exceeds 36 hours. Hence the enhancement of tensile strength isdirectly related to the cryogenic soaking period. If the cryogenic soaking period is increased from 0hrs (untreated) to 24hrs,the tensile strength of the LM 25 – 10% fly ash composite increases from 190.31 to 217.09 N/mm^{2}i.e., an increase of14%.

3. Yield strength

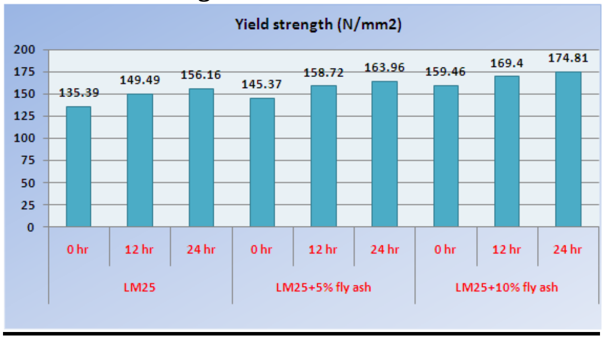

Fig. 9. Effect of cryogenic soaking period on the yield strength of LM 25 and MMCs

Fig.9illustrates the yield strength of LM25 and LM 25- fly ash composites with two different and varying compositions of fly ash and cryogenic treatment soaking periods.It may be inferred from the figure that, when the fly ash weight %is increased from 5 wt% to 10 wt%, the yield strength increasesfrom 163.96 N/mm^2 to 174.81N/mm^{2}withthe soaking period ofabout 24 hrs.

If the cryogenic soaking period is increased from 12 hrs to 24 hrs,the yield strength of the LM 25+10% fly ash composite increasesfrom 163.96 to 174.81N/mm^{2}an increase of6.62%.

4. Elongation

Fig.10 shows the elongation of LM25 and LM 25- fly ash composites with two different and varying compositions of fly ash and cryogenic treatment soaking periods. It can be noted that when the fly ash weight % is increased from 5 wt% to 10 wt%, elongation tends to decrease from 2.65 to 2.60 % with thesoaking duration of about 24 hrs.

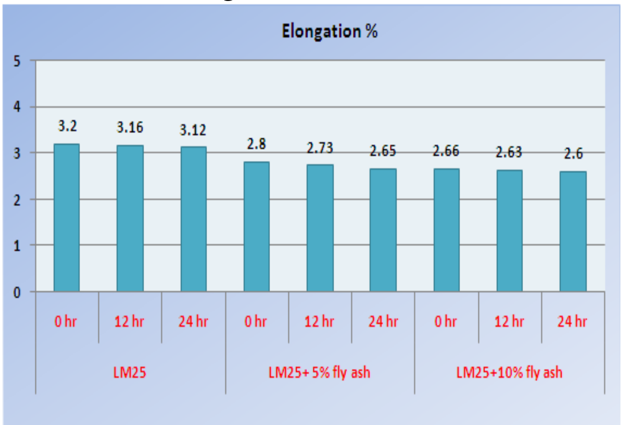

Fig. 10. Effect of cryogenic soaking period on the elongation of LM 25 and MMCs

On the otherhand, the elongation of the LM25 and LM 25- fly ash composites tends to drop when the specimens are subjected to cryogenic treatment. The elongation of LM 25-10% fly ash composite is the lowest (δ=2.60%) when the soaking period is about 24 hrs compared to untreated specimens. However,its tensile and yield strengths are significantly higher than those of the untreated specimens. The increase in thetensile and yield strengths of the LM 25-10% fly ash compositespecimens donot enhance at the expense of drop in the elongation as it decreases by2.25%.

III. STATISTICAL ANALYSIS

A. Taguchi Method

Taguchi's technique is a capable method forfinding the optimum level of process factors that have an effect on the performance of the process. Mathematical relation of the S/N ratio for "Larger is better" is given in the equation (i).

$$\frac{S}{N} = -10\log\left(\frac{1}{n}\sum_i \frac{1}{y_i^2}\right) \qquad \text{Eq. 1}$$

Where, y is the measured data and n is the number of tests.

Table- 2: Parameters and levels

Level	A- Material	B- Cryogenic Soaking time (hrs)
I	LM25	2
II	LM25+10% fly ash	12
III	LM25+10% fly ash	24

Table- 3: Response table for Signal to Noise Ratios – Larger is better (Hardness)

Level	A- Material	B-Cryogenic Soakingperiod (hrs)
1	39.09	38.87
2	39.57	39.82
3	40.27	40.25
Delta	1.18	1.38
Rank	2	1

Table- 4: Response table for Signal to Noise Ratios – Larger is better (Tensile strength)

Level	A- Material	B-Cryogenic Soaking period (hrs)
1	44.86	45.1
2	45.59	45.69
3	46.29	45.95
Delta	1.43	0.86
Rank	1	2

Table- 5: Response table for Signal to Noise Ratios – Larger is better (Yield strength)

Level	A- Material	B- Cryogenic Soaking period (hrs)
1	43.33	43.31
2	43.85	44.03
3	44.49	44.34
Delta	1.16	1.03
Rank	1	2

Table- 6: Measured values and S/N ratios for mechanical properties

Exp.No	A- Material	B- Cryogenic Soaking period (hrs)	Measured Values			Signal to Noise ratio		
			Hardness	TS (N/mm^2)	YS (N/mm^2)	Hardness	TS	YS
1	1	0	81	167.59	135.39	38.1697	44.48496	42.6317
2	1	12	93	175.26	149.49	39.3697	44.87366	43.4922
3	1	24	97	182.36	156.16	39.7354	45.21859	43.8714
4	2	0	87	182.25	145.37	38.7904	45.21335	43.2495
5	2	12	97	191.87	158.72	39.7354	45.66014	44.0126
6	2	24	102	197.3	163.96	40.172	45.90254	44.2948
7	3	0	96	190.31	159.46	39.6454	45.58923	44.053
8	3	12	104	212.51	169.4	40.3407	46.54759	44.5783
9	3	24	110	217.09	174.81	40.8279	46.7328	44.8513

1. Results of S/N Ratio

The Signal/Noise ratio for the factors level is computed by considering the mean value the S/N ratios at the related level. Parameter with the maximum S/N ratio gives the desired quality.Computed values and Signal/Noise ratios for the mechanical properties are specified in the table.3.

The ranking of selected factors is given for the hardness of the materials in Table 4,showing thatcryogenic soaking period is the principal parameter followed by the material. Ranking of parameters is presented in Tables 5 and6 revealing that the material is the principalparameter followed by cryogenic soaking period in obtaining the enhancedtensile strength and yield strength.

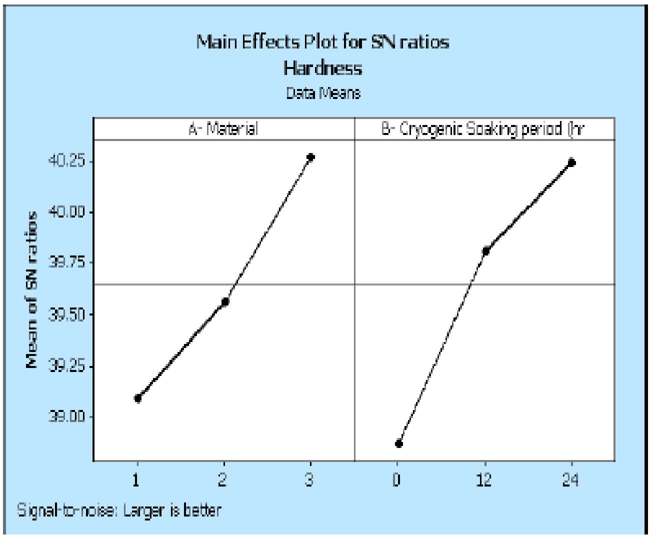

Fig. 11. Response diagram of S/N ratios for hardness

Figure 11 shows that optimum levels of the parameters in attaining the maximum hardness areLM25+10% fly ash MMC (material) and cryogenic soaking period (24hrs). A similar tendencyis seen for the tensile strength (figure 12) and yield strength (figure 13) of the materials.

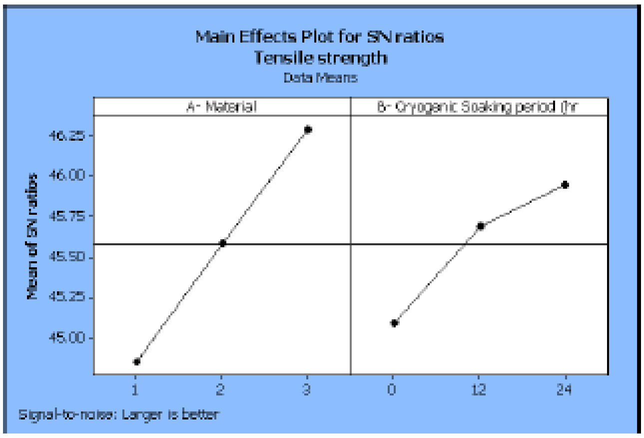

Fig. 12. Response diagram of S/N ratios for Tensile strength

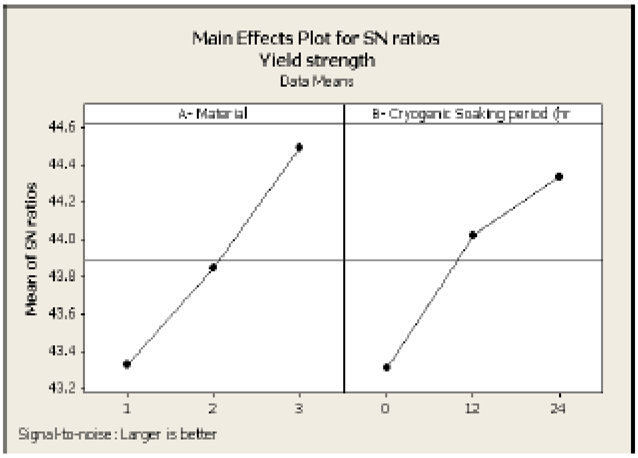

Fig. 13. Response diagram of S/N ratios for Yield strength

Table- 7: ANOVA analysis for Hardness

Parameter	DoF	SS	F-Value	P value	Pc
A- Material	2	258	129	0	42.15
B-Cryogenic soaking period (hrs)	2	350	175	0	57.19
Error	4	4	1		0.65
Total	8	612			100

2. Results of ANOVA

Table- 8: ANOVA analysis for Tensile strength

A- Material	2	1494.97	40.47	0.002	70.16
B- Cryogenic soaking period (hrs)	2	561.75	15.21	0.014	26.36
Error	2	73.88			3.46
Total	8	2130.61			

Table- 9: ANOVA analysis for Yield strength

A- Material	2	657.87	152.24	0.000	55.38
B- Cryogenic soaking period (hrs)	2	521.24	120.62	0.000	43.88
Error	2	8.64			0.72
Total	8	1187.76			100.00

Analysis of variance was carried out for determining the percentage contribution of the parameters using the software package MINITAB. The analysis is presented for hardness, tensile strength and yield strength in tables 7, 8, and 9 respectively. The value of P (probability value) is given for each parameter. If the P-value is below 0.05, the factoris statistically important.

P values for materials and cryogenic soaking period are below 0.05, which are significant factors. In Anova table, the contribution of each parameter on the mechanical properties of the specimens is given in terms of percentage. Anova table 7 shows that the cryogenic soaking period (57.19%) is the major contributing parameter followed by the material (42.15%) influencing the hardness of the specimens. It isconcluded from Anova table 7 that material (70.16%) is the major contributing parameter followed by cryogenic soaking period (26.36%) forinfluencing the tensile strength of the specimens.A similar tendencyis observed for the yield strength.

IV. CONCLUSION

The outcome of cryogenic treatment on the properties of the materials was analyzed and the following outcomes were obtained.The results indicate that deep CTT specimens led to an improved hardness and tensile strength. The increase in the hardness of the LM 25- 10% fly ash composite was found to be approximately 14.5% after the cryogenic treatment.The materials processed by the cryogenic treatment exhibited consistent tensile strength. In other words, both the tensile and the yield strength of the LM 25- 10% fly ash composite improved withcryogenic treatment without the sacrifice of elongation. Material (70.16%) was the major contributing parameter followed by cryogenic soaking period (26.36%) for influencing the tensile strength of the specimens. A similar trend was observed for the yield strength. Hence, it can be concluded that cryogenic soaking period has to be optimized to attain the desired mechanical properties.

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