Statistical Analysis of Ultimate Tensile Strength of Grain Refined and Modified Al-Si Alloys (LM-25, LM-6 and LM-30) Using ANOVA

Abstract — The fact that Aluminium is used in all sectors of engineering and manufacturing is undisputable. The addition of grain refiners and modifiers to the commercially available aluminium silicon alloys improves the mechanical properties of these alloys and provides technical and economic advantages. Commercially available Al - Si alloys LM25 (hypoeutectic < 12% Si), LM6 (eutectic 12% Si) and LM30 (hypereutectic > 12% Si) are grain refined with 0.2%Al-5Ti-1B, 1%Al-3B and modified with 0.3%Al-10Sr master alloys. The Ultimate Tensile Strength (UTS) of these samples is analysed statistically using ANOVA, to predict the percentage contribution of the independent variables on dependent variable. Al, Si, Grain refiner, Peak load and elongation are the process parameters selected for performing ANOVA for UTS. The analysis concludes that Si content and the peak load has maximum significance.

Index Terms— Al-Si alloy, Hypoeutectic, Eutectic, Hypereutectic, Grain refiners, Modifier, UTS, ANOVA

1 Introduction

THE binary alloy system of Al – Si is extensively used for casting owing to its casting characteristics and excellent fluidity, and the eutectic is formed at 11.7 wt % Si. The addition of grain refiners and modifiers further refines the uniform distribution of eutectic Al and Si in the alloys. The commercially available Al-Si hypoeutectic alloy LM25 with Al-Si < 12wt %, eutectic alloy LM6 with Al-Si 12wt % and hypereutectic alloy LM30 with Al-Si >12wt % is considered for this study. The master alloys Al-5Ti-1B (0.2 wt. %) and Al-3B (1wt. %) are used as grain refiners and the master alloy Al-10Sr (0.3 wt %) is used as modifier. The strength to weight ratio of aluminium is superior to steel, and aluminium is one of the lightest structural metal. An attempt is made in this study to analyse and predict the percentage contribution of the independent variables (Al, Si, Grain refiner, Peak load and elongation) on dependent variable (UTS). Tensile test was conducted on the untreated and treated samples. And the results are analysed statistically with ANOVA.

2 Preparation of Samples

The commercially available eutectic Al-Si alloy LM6 was heated in an induction furnace at 720˚C. The melt was degassed with hexachloroethane. A portion of the Al-Si melt was poured into the graphite mould and remaining molten alloy is placed into the furnace. This is the casting of the untreated specimen. In the next step, the estimated amount of Al-5Ti-1B master alloy chips were added to LM6 alloy melt and stirred approximately for about 30s. After 5 minutes of holding, a part of melt has been poured into the graphite mould as in the earlier case, and the specimen was designated for recognition. The same procedure was repeated by adding calculated amount of Al-3B and Al-10Sr to the melt, and the specimen were designated accordingly. These experiments were conducted without addition of any lubricants or coolant. The same procedure is repeated for LM25 and LM30. A total of 12 specimens were obtained as shown in Table 1.

Table 1 : Prepared Sample Designation

Grain refiners	0.2% Al-5Ti-1B	1% Al-3B	0.3% Al-10Sr
Untreated Alloy	Samples	Samples	Samples
Untreated LM-25	LM-25+0.2% Al-5Ti-1B	LM-25+1% Al-3B	LM-25+0.3% Al-10Sr
Untreated LM-6	LM-6+0.2% Al-5Ti-1B	LM-6+1% Al-3B	LM-6+0.3% Al-10Sr
Untreated LM-30	LM-30+0.2% Al-5Ti-1B	LM-30+1% Al-3B	LM-30+0.3% Al-10Sr

3 Study of microstructure

The untreated Al-Si samples and those treated with various grain refiners were mechanically polished using standard metallographic techniques before the examination. A filtering electron magnifying instrument furnished with Energy Dispersive X-Ray Spectroscopy (EDS) (Model- FEI Quanta-200, scanning electron microscope, NE Dawson Creek Drive, Hillsboro, USA) was used to obtain the SEM micrographs of the samples.

The micrographs of the untreated samples and the samples treated with 0.2 wt % Al-5Ti-1B, 1 wt % Al-3B, 0.3 wt % Al-10Sr are shown in Fig.1 to Fig.3. When a liquid alloy is cooled, nuclei or seed will begin to form in many parts of the melt simultaneously. Heterogeneous nucleation provides a method for control of the grain size of the solidified casting. By creating numerous sites for heterogeneous nucleation a fine grain size can be obtained.

With the inoculation of the grain refiners and the modifier into the Al-Si alloy melt heterogeneous nucleation sites are created for solid α-Al and this results in finer grain size.

The presence of primary silicon structures in as-cast untreated sample can be noted, and it is observed that the Si in the treated samples has undergone spheroidization. Among the samples of LM-25 alloy, the sample modified with 0.3wt% (Al-10Sr) has maximum UTS of 275MPa, owing to the spheroidization of Si particles. Also, among the 12 samples tested in this study, the sample LM25+0.3wt% (Al-10Sr) is the sample with the maximum UTS value of 275MPa.

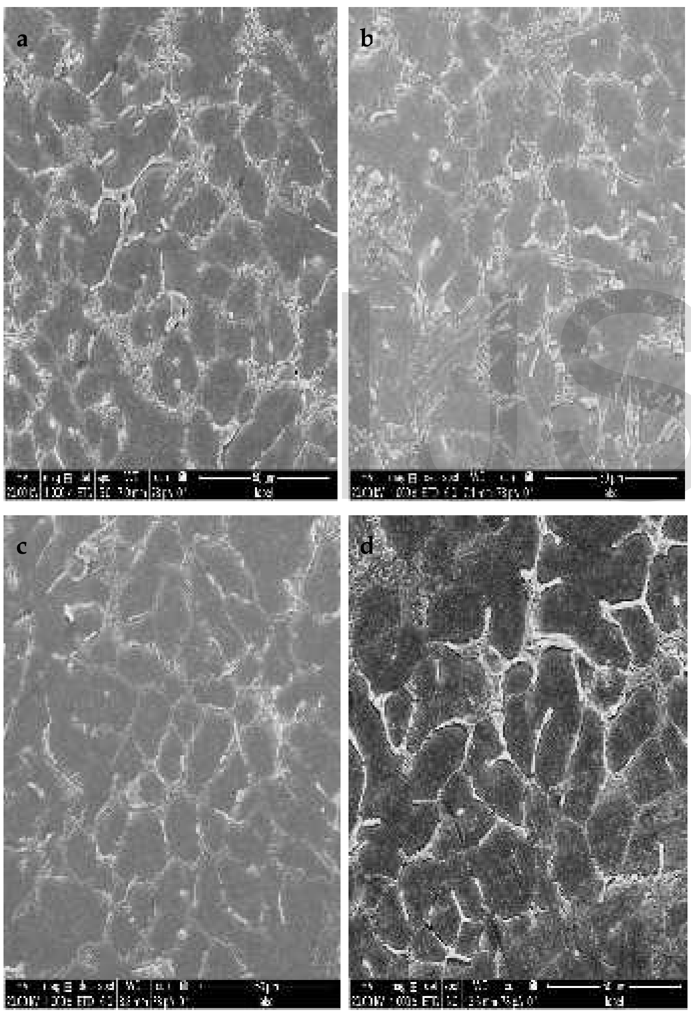

Fig.1 : LM-25 samples (a) Untreated alloy, (b) Al-5Ti-1B, (c) Al-3B & (d) Al-10Sr

Among the samples of LM-6 alloy, the sample modified with 0.3wt% (Al-10Sr) has maximum UTS of 219MPa, due to modification of Si particles.

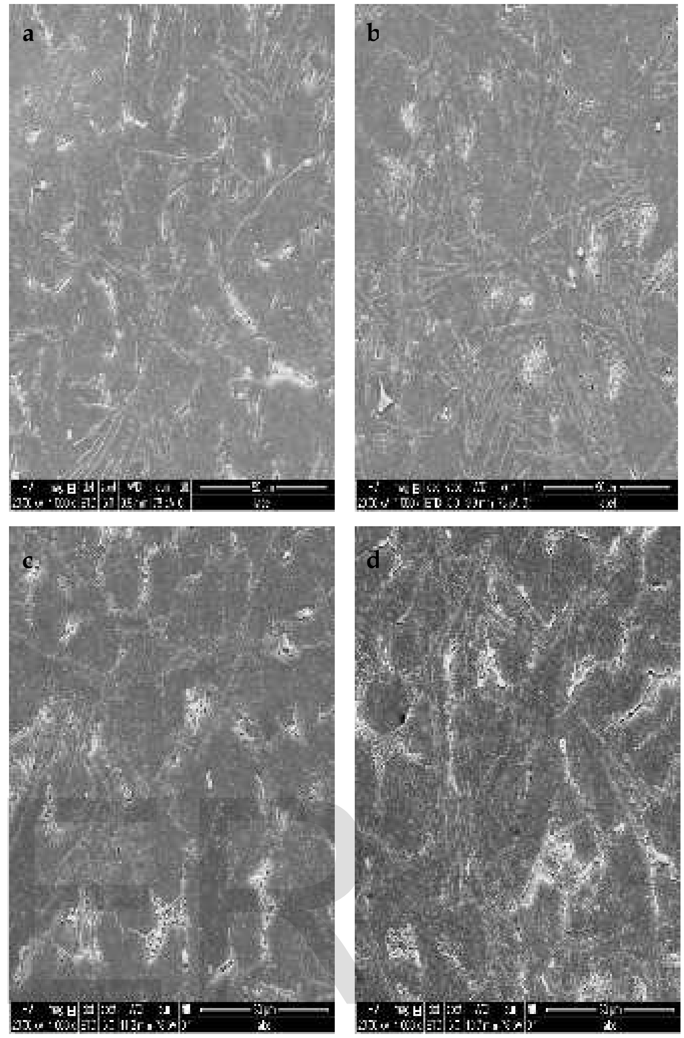

Fig. 2: LM-6 samples: (a) Untreated alloy, (b) Al-5Ti-1B, (c) Al-3B & (d) Al-10Sr

Correlating the UTS readings of LM-30 with the micrographs of LM30, the sample treated with 0.2wt% Al-5Ti-1B has good response to the tensile strength, which may be due to the presence of Ti in the master alloy. May be due to over modification of Si, the addition of 0.3wt% (Al-10Sr) to LM-30 does not show much improvement in the UTS.

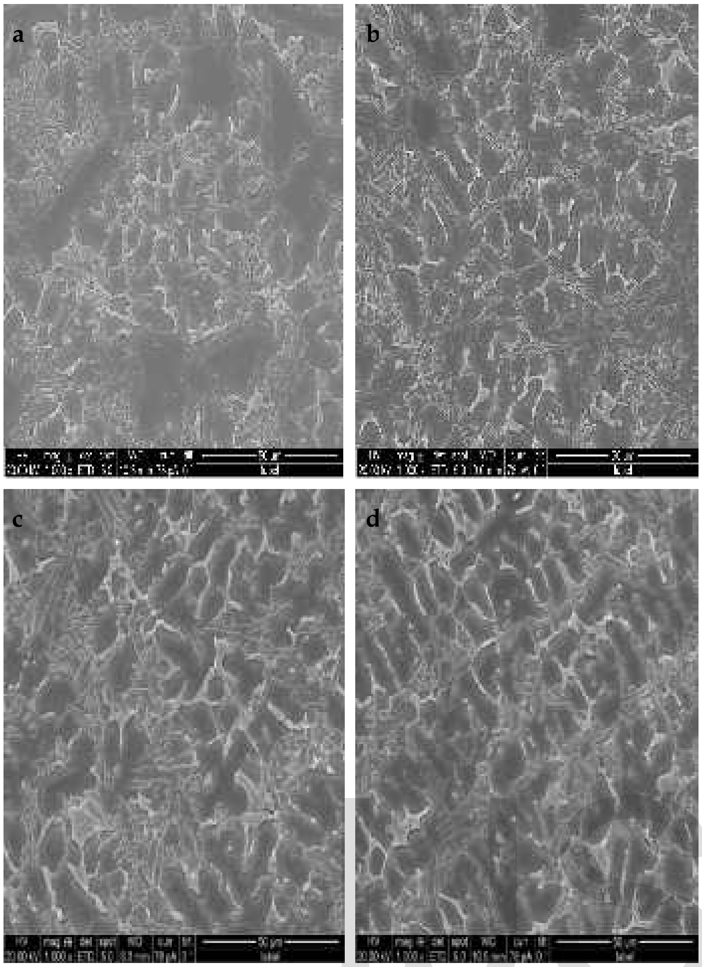

Fig. 3: LM-30 samples: (a) Untreated alloy, (b) Al-5Ti-1B, (c) Al-3B & (d) Al-10Sr

4 Tensile Test

The tensile test of the samples was conducted on the Universal Testing Machine (Model: UNITEK 9450PC Instron Industrial Products).

- *Satya Prema, Mechanical Engineering Department, J N N College of Engineering, Shivamogga-577204, Karnataka, India. E-mail: spabraham1@yahoo.co.in*
- *T M Chandrashekharaiah, Research centre, Department of Mechanical Engineering, Kalpataru Institute of Technology,Tiptur - 572 202, Karnataka, India. E-mail: chandrtm@gmail.com*
- *Srinivasa Murthy M K, Mechanical Engineering Department, J N N College of Engineering, Shivamogga-577204, Karnataka, India. E-mail: murthynivas007@jnnce.ac.in*

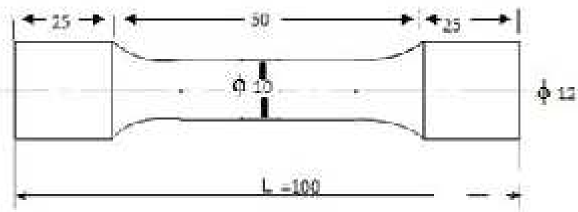

Fig. 4 Tensile test specimen

Fig. 5 Tensile test specimen

The Fig.4 shows the dimensions of the tensile test specimen which is as per the ASTM E8 standard, and Fig.5 shows the tensile test specimen. Tensile tests are conducted with a crosshead speed of 2mm/min, and data is obtained by induced programming for further assessment.

4.1 Study of UTS Results

Table 2 shows the peak load and the percentage elongation and ultimate tensile strength values for different samples. As shown in Fig 6 tensile strength of untreated samples of all the three alloys (LM25, LM6 and LM30) has significantly increased after grain refinement with 0.2wt %Al-5Ti-1B, 1wt%Al-3B and 0.3wtwt %Al-10Sr. The maximum UTS for LM25, LM6 and LM30 is noted for samples LM-25+0.3wt% (Al-10Sr), LM-6+0.3wt% (Al-10Sr) and LM-30+0.2wt% (Al-5Ti-1B) respectively.

Grain refining and alloying modifies the microstructure and improves the mechanical properties of Al. This can be observed in the UTS values of untreated and treated samples of LM-25, LM-6 and LM-30.

Table 2. Ultimate Tensile Strength for Different Alloys with Grain Refiners

Sample	Peak load in KN	Elongation %	UTS (MPa)
Untreated LM-25 (Alloy 1)	18.835	3.093	240
LM-25+0.2wt% (Al-5Ti-1B) (Alloy 2)	19.945	3.093	254
LM-25+1wt% (Al-3B) (Alloy 3)	20.365	3.093	259
LM-25+0.3wt% (Al-10Sr) (Alloy 4)	21.575	5.155	275
Untreated LM-6 (Alloy 1)	16.258	3.093	209
LM-6+0.2wt% (Al-5Ti-1B) (Alloy 2)	16.748	4.167	213
LM-6+1wt% (Al-3B) (Alloy 3)	16.78	3.093	215
LM-6+0.3wt% (Al-10Sr) (Alloy 4)	17.078	4.082	219
Untreated LM-30 (Alloy 1)	17.678	3.093	225
LM-30+0.2wt% (Al-5Ti-1B) (Alloy 2)	19.418	4.167	247
LM-30+1wt% (Al-3B) (Alloy 3)	18.325	2.128	233
LM-30+0.3wt% (Al-10Sr) (Alloy 4)	17.883	3.093	228

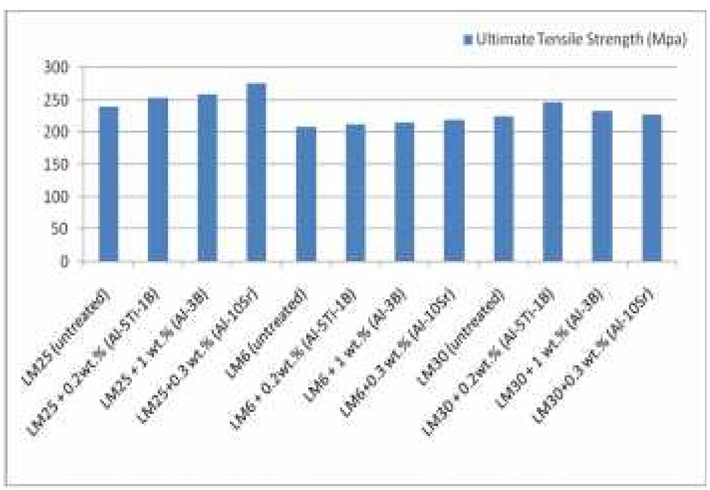

Fig. 6 UTS (MPa) for all the types of alloy samples of LM-25, LM-6 and LM-30

Fig. 7-9 shows the variation in UTS for individual untreated and treated Al alloys of LM-25, LM-6 and LM-30 respectively. The maximum UTS of 275MPa is recorded for LM-25+0.3wt% (Al-10Sr). Correlating this with the microstructure of the sample in Fig.1(d), it can be seen that the eutectic Si has changed structure, and Sr contributes for the same. For the LM-6 alloy also the addition of 0.3wt% (Al-10Sr) gives the maximum UTS of 219MPa.

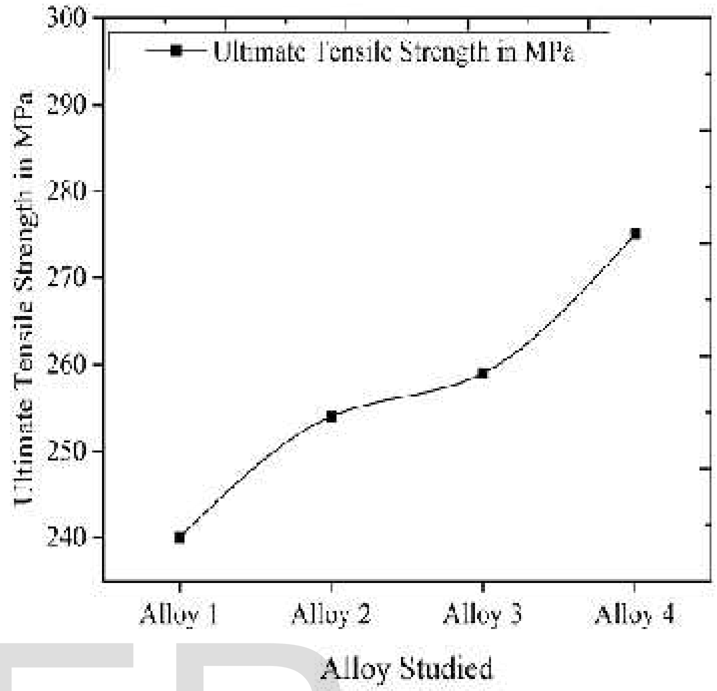

Fig. 7 Ultimate Tensile Strength of LM-25 for all grain refiners

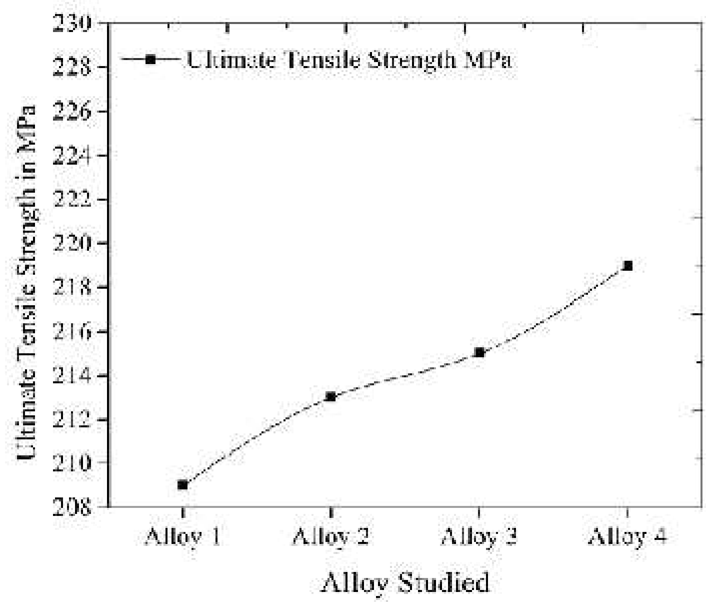

Fig. 8 Ultimate Tensile Strength of LM-6 for all grain refiners

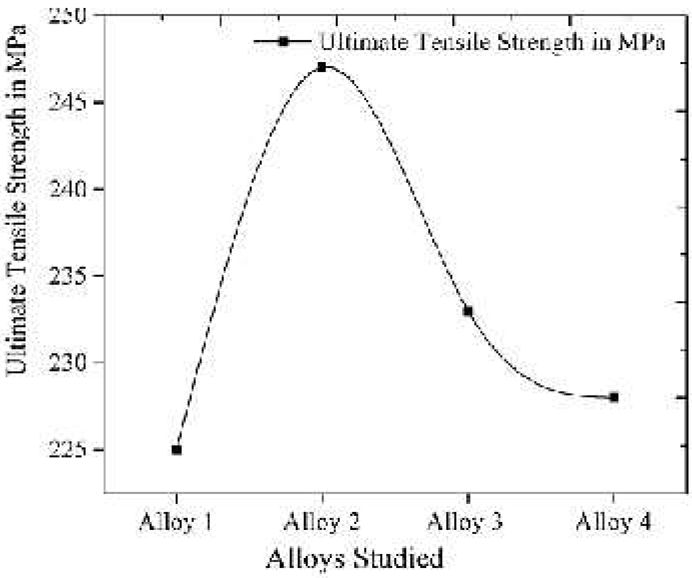

Fig. 9 Ultimate Tensile Strength of LM-30 for all grain refiners

Results indicate that there is improvement in yield strength, UTS and elongation percentage. The test results invariably suggest that addition of grain refiner (mix) enhances the UTS. But, there is variation of Si content in the three alloys considered for this study. Hence, to further determine the significant factor influencing the UTS a statistical analysis was conducted.

4.2 Statistical Analysis of Ultimate Tensile Strength

The purpose of ANOVA is to investigate the significant factors which influence the dependent variable. Basically experience or literature determines these factors, but, they may or may not be the significant factor. Hence ANOVA helps in finding these factors. H.M.Somashekhara et al used the Taguchi Technique and ANOVA to optimize surface roughness in turning operation, and Taguch's parameter design was used to obtain optimum condition with lowest cost, minimum number of experiments and industrial engineers can use these method for decision making. Taguchi methods are successfully applied to Al-Si composites to optimize process parameters. In the present study, statistical analysis of ultimate tensile strength of LM-25, LM-6 and LM-30 was carried out to predict the percentage contribution of the independent variables on dependent variable. The process parameters selected for performing ANOVA for UTS are Al, Si, Mix(Grain refiner), Peak load (KN) and elongation.

Table 3 depicts the ANOVA analysis of ultimate tensile strength for the LM-25, LM-6 and LM-30 respectively. It is seen that Si and Peak load has maximum significance due to F ratio value of 98.56 and 70.56.

Table 3 ANOVA analysis of Ultimate Tensile strength

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-value	Remarks
Regression	5	4671.43	4671.43	934.286	1986.15	0.000	Insignificant
Al	1	571.07	0.81	0.805	1.71	0.239	Insignificant
Si	1	3140.43	0.73	0.734	98.56	0.008	Significant
Mix	1	59.03	0.41	0.412	0.88	0.385	Insignificant
Peak load (KN)	1	900.55	174.31	174.312	70.56	0.000	Significant
Elongation %	1	0.35	0.35	0.349	0.74	0.422	Insignificant
Error	6	2.82	2.82	0.470			
Total	11	4674.25					

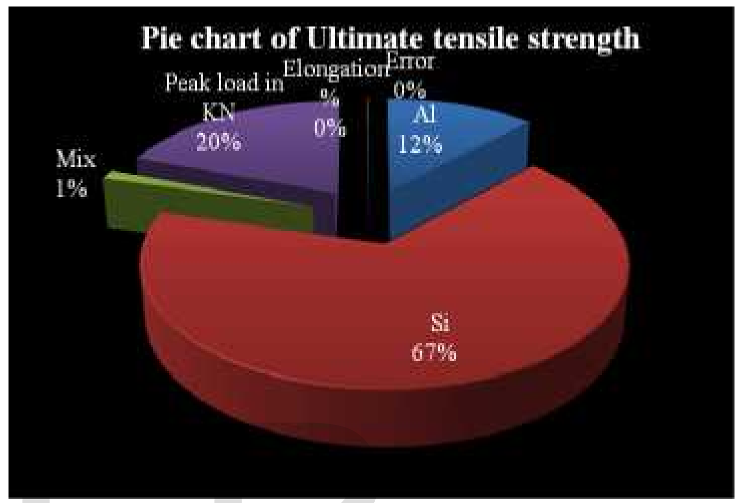

Fig. 10 Pie of UTS and percentage contribution of the independent variables

Fig. 10 shows the percentage contribution of the process parameters and the percentage contribution of Si is 67% and peak load is 20% compared to other process parameters such as Al (12%), Mix(1%) and elongation (0.02%) respectively. Si followed by Peak load is the major influencing parameter on ultimate tensile strength (UTS) of the alloys. Similarly the mix of grain refiner has the least effect on UTS. Fig. 11 clearly depicts that the residual plots are equally distributed on either side of the reference points.

Multiple linear regression model of Ultimate tensile strength :

Ultimate tensile strength = -122.6 - 1.142 Al + 1.65 Si - 0.900 Mix + 13.213 Peak Load -0.598 % elongation (1)

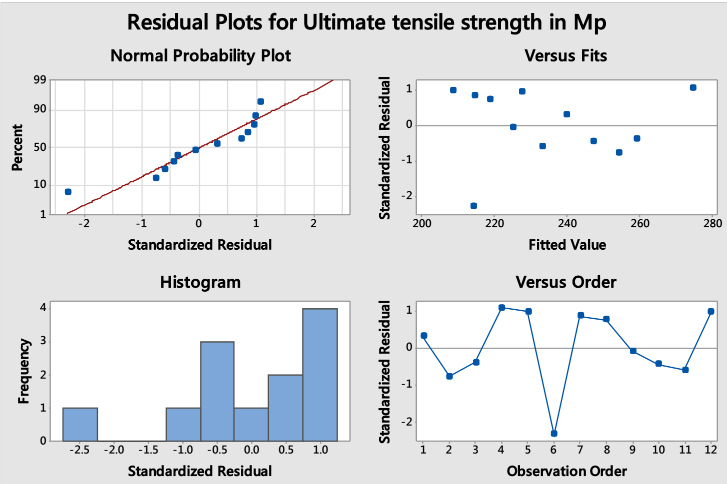

Fig. 11 Residual and observation plots of Ultimate tensile strength

The general regression equation for Ultimate tensile strength (UTS) is as shown in the Equation 1. It shows the influence of independent variables on dependent variable of ultimate tensile strength. Table 4 and 5 shows the coefficient of determination of 99.02% with a T-value is more for Peak load and the Si. It indicates that both the process parameters are more influencing on other parameters.

Table 4 UTS Model summary

SS	R^2	R^2 (adj)
0.736182	99.02%	98.81%

Table 5 Coefficients of UTS

Terms	Coefficients	T-value	P-value
Constant	-122.6	-1.23	0.265
Al	-1.142	1.31	0.239
Si	1.65	1.25	0.258
Mix	-0.900	-0.94	0.385
Peak load in KN	13.213	19.25	0.000
Elongation %	-0.598	-0.86	0.422

Table 6 shows the measured and the predicted values of the UT strength.

Table 6 Model summary of Ultimate Tensile Strength

Sl. No.	Measured UTM	Predicted UTM	Error
1	240	240.214	-0.21407
2	254	253.274	0.72638
3	259	259.193	-0.19289
4	275	274.819	0.18095
5	209	208.162	0.83792
6	213	214.019	-1.01855
7	215	214.604	0.39631
8	219	218.379	0.62118
9	225	225.824	-0.82363
10	247	247.227	-0.22725

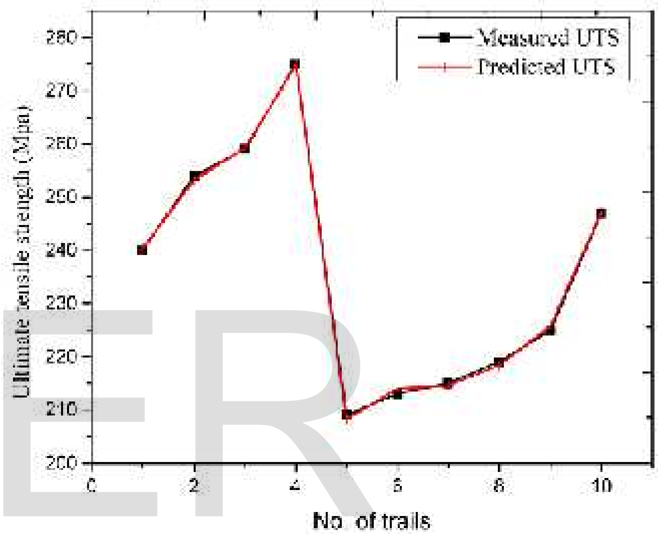

Fig. 12 Measured and predicted values of Ultimate tensile strength

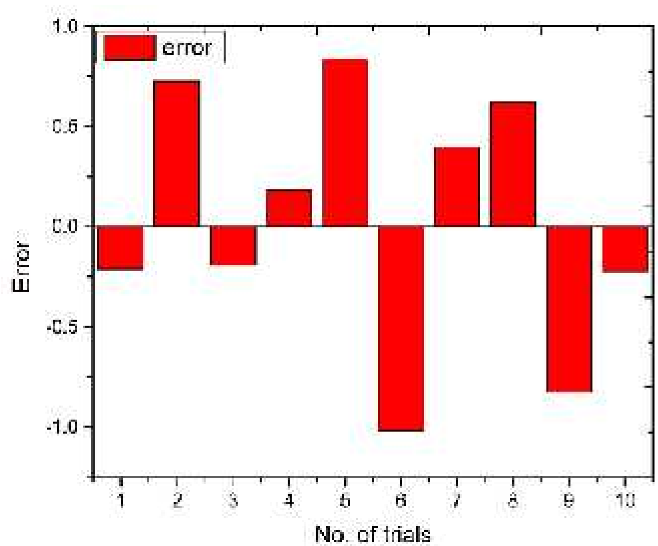

Fig. 13 Error graph of Ultimate tensile strength

A graph of experimental values against predicted values is drawn for all LM-25, LM-6 and LM-30 as depicted in Fig. 12.

Fig. 13 shows the error between the variables from the predicted equation. It clearly shows that the error is less than 5% and the predicted points are very close to the measured values. Hence the predicted equation is good predictive capability with the acceptable accuracy. Finally results clearly show that addition of grain refiners / modifier improves the Ultimate tensile strength.

5 Conclusion

The samples of LM-25, LM-6 and LM-30 treated with 0.3wt% Al-10sr, 0.3wt% Al-10sr and 0.2wt%Al-5Ti-1B have UTS of 275 MPa, 219MPa and 247MPa respectively. The corresponding increase in UTS values of these samples being 14.5%, 4.8% and 9.8% respectively. The overall significant sample being LM-25+0.3wt% Al-10sr (275MPa) with a increase in UTS by 14.5 %. Si content and Peak load has maximum significance for Ultimate Tensile Strength.

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