Influence of Ultrasonic Vibrations on Grain Size and Mechanical Properties of A-356 by Adding Al-5Ti-1B Master Alloy during Solidification

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Abstract- The refinement of the grain size will improve the mechanical properties of AA-356 alloy by propagating ultrasonic vibrations through the die into the melt and adding Al-5Ti-1B master alloy during solidification. Ultrasonic vibrations produces cavitation effect by reducing pores, degassing and formation of more heterogeneous nucleating sites of AA-356 due to the presence of TiAl3 and Bal2 solutes of master alloy. The melt was vibrated at various frequencies and amplitudes with certain interval of time by adding master alloy (Al-5Ti-1B) at different fractions by using Taguchi Technique. From heterogeneous nucleation experimental results shows that the AA-356 structure was changed from   columnar dendrite structure into equi-axed globular grain structure with reduction in grain size. The experimental results shows that due to reduced grain size, the mechanical properties like hardness, ultimate tensile strength were increased.

Index Terms- AA-356, Grain size, Master alloy, Mechanical properties, Ultrasonic vibrations.

I. Introduction

Aluminum and its alloys plays very important role in engineering applications due to their light weight, low density, easy to fabricate, low thermal expansion, physical properties, low wear rate and its excellent corrosion resistance in most environmental conditions(1). AA-356 alloy is used in Aerospace, automobile, marine industry etc.

AA-356 is a hypoeutectic aluminum alloy containing 6.5-7% of silicon   and contains about 50 volume % of eutectic phases (2). The final microstructure can be found by eutectic reaction (3).AA-356 is used to improve flowability of the melt and interfacial properties. To optimize the mechanical properties it necessary to control the grain size 0f AA-356 which otherwise solidifies with coarse columnar grain structure. So the grain refinement play a vital role to improve the properties of AA-356.This can be achieved by adding grain refiners like Al-5Ti-1B,Al-10Ti,Al-3B,Al-3Ti-3B etc in to AA-356 melt(4) and also by inducing ultrasonic vibrations(5,6,7). The Mechanical vibrations can be obtained by(8),electro magnetic vibrations(9),Magneto hydrodynamics(6),electro magnetic stirring mechanisms(11) etc,in to the melt through die .

In die casting and squeeze casting process it consists of so many defects like shrinkage, porosity, pores, discontinuity ,hot tears, air or hydrogen is trapped while pouring the molten metal in to the die cavity during solidification of metals(8). The ultrasonic vibration waves produce more heterogeneous nucleation in the melt. This is due to cavitations phenomena occur within the melt. This leads to degassing, reduce in hot cracking, reduction in porosities and formation of equi-axed grains in small size (7).

There was so much debate on ultrasonic vibrations that the vibrations are propagates in to the melt produces cavitations with large forces also the temperature variations in the melt (10, 11, 12). These pressure , temperature and force fluctuations induces heterogeneous nucleation and segregation control in the melt with reduced in grain size and formation of globular equi-axed non dendrite structure(13-16).

A fine grain size creates a more uniform distribution of secondary intermetallic interphases in addition to pores which form from the evolution of dissolved in the melt (16). The resultant increase in casting integrity is companied by improvements in both mechanical properties and pressure tightness (17-20).

Ultrasonic vibration treatment was known to induce refining effect in AA-356 alloys (17-22). The basic principle is introduction of acoustic waves with frequency 20 KHz to 30 KHz in to the liquid metal and high amplitude oscillations result in the cavitations of the melt and also promote intense mixing through agitation (23). The reported nucleation through local under cooling and wetting of substrates to fragmentation forming grains.

II. Taguchi Method

Taguchi method offers a powerful tool for design of experiments. This methodology has taken the design of experiments from the exclusive world of the statistician and brought it more fully into the world of manufacturing (24). Taguchi method provides a simple, efficient and systematic approach to optimizing designs for performance, quality and cost. Taguchi proposed that engineering optimization of a process or product should be carried out as a three-step approach viz system design. Parameter design and tolerance design (25, 26).

Taguchi method is structured approach for determining the best combination of inputs to produce product or service. Based on design of experiments (DOE) methodology for determining parameters levels. DOE is important tool and is method for quantitatively identifying the right inputs and parameter levels for Making a high quality product and service (27, 28). The major step in Design of experiments is the evaluation of combination of factors and levels which provide desired information. Analysis of experimental results uses a signal to noise ratio to aid in the determination of the best process design using MINITAB software (29).

In present work the ultrasonic vibrations range from 20Khz, 24Khz and 28Khz were induced in to the melt through die during solidification to refine the grain structure from columnar dendrite structure into equi-axed globular grain structure with reduced in grain size . The ultrasonic vibrations were induced around the die isothermally for different frequencies, amplitudes with certain interval of time for different fractions of master alloy (Al-5Ti-1B) and the effect of grain size and properties have been investigated.

III. EXPERIMENTATION

A. AA-356 alloy

In the present investigation the commercial aluminum AA-356 is used as base material. The composition is as shown in table1.

Table1

Element	Si	Mg	Mn	Fe	Ni	Zn	Sn	Ti	Pb	Al
Wt %	6.5-7	0.3	0.02	0.1	0.05	0.01	0.01	0.02	0.02	Bal

A Teflon coated permanent steel mold die is used in the experimental setup. A cavity is made around the die to supply water for cooling purpose and the cavity can be closed at the top as shown in fig.1and fig.2. Fig.3 shows the experimental setup used to produce ultrasonic vibrations in the range of 1Hz to 100MHz
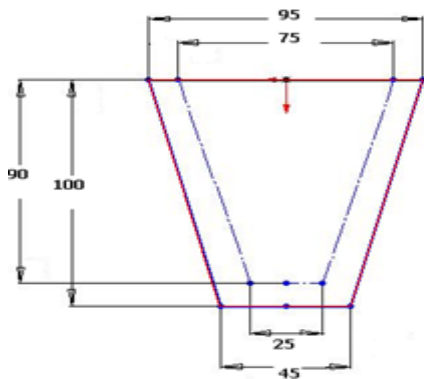

Fig.1 Die (All dimensions in mm)

Fig 2. Die with copper winding

A copper coil having 3Ω resistance was wound around the die and is connected to the functional signal generator through transistor and D.C supply. A sine wave was generated by signal generator in the range of 1Hz to 1MHz and fed in to the coil as shown in fig.3. These Ultra-sonic vibrations around the die were propagate into the melt . The aluminum AA-356 alloy was melted separately using graphite crucible melting furnace, the melt is maintained at liquids temperature of 614◦C and the temperature was increased to 800◦C for 3hrs to melt completely. The primary Fcc structure of aluminum dendrites starts to form at 614◦C and the binary at 574◦C.Tertiary eutectic and complete intermetallics form at the later stages.

B. Master alloy

The master alloy or grain refiner (Al-5Ti-1B) was prepared separately by electrolysis method and it is cut in to required Wt% fraction and add into the AA-356 melt. The master alloy is added to the AA-356 melt and allow to melt for one more hour, the mixer is thoroughly mixed using mechanical stirrer for different fractions 0.4Wt%(Al-5Ti-1B),0.6Wt%(((Al-5Ti-1B), 0.8Wt%(Al-5Ti-1B). The castings were prepared according to taguchi method using L9 orthogonal array by taking the molten metal using ladle and poured into permanent steel mold die and it is solidified without inducing ultrasonic vibrations. Further for next experiments was generated using orthogonal arrays and analysis of parameters was done using ANOVA technique ,the molten metal is poured in to the die and ultrasonic vibrations were induced during solidification with 20Khz.24khz,28Khz at 40µm,60µm,80µm amplitude for 40s,80s,120s respectively for different compositions 0.4Wt%(Al-5Ti-1B), 0.6Wt%(Al-5Ti-1B),0.8Wt%(Al-5Ti-1B) etc.

Taguchi method yields the rank of various parameters with the level of significance of a factor or the interaction of factors on a particular output response. The response table for signal to noise ratio is as shown in table .2. Analysis of varience of th

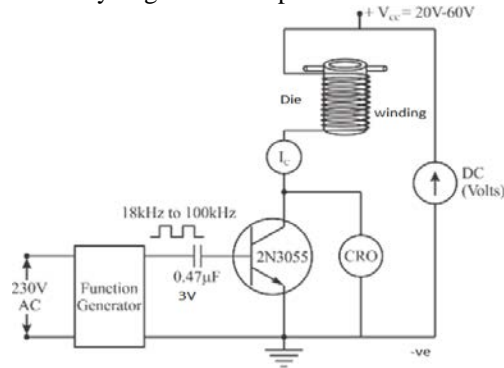S/N ratio is performed to identify the statically significant   parameters.

Fig 3. Circuit diagram of ultrasonic vibration set up

The specimens are prepared using castings according to ASTM standards for grain size, hardness and tensile test, the specimens were polished, etched with use of HCL, HNO3,Cu and water solution for grain size and hardness . On etched specimens , hardness and tensile specimens were conducted. Compare them with and without ultrasonically treated specimens and analyzed using Taghuchi Method using "Larger the better".

$$\text{S/N ratio} = -\log_{10}\left(\frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2}\right) \text{ dB}$$

Where $y_1, y_2, \ldots y_i$ are responses. n is number of observations.

L9 test	A Master alloy	B Frequency (kHZ)	C Amplitude (µm)	D Holding time(s)
1.	A1	B1	C1	D1
2.	A1	B2	C2	D2
3.	A1	B3	C3	D3
4.	A2	B1	C2	D3
5.	A2	B2	C3	D1
6.	A2	B3	C1	D2
7.	A3	B1	C3	D2
8.	A3	B2	C1	D3
9.	A3	B3	C2	D1

Table2 L₉ Orthogonal array of Taguchi

IV. RESULT AND DISCUSSION

The Vickers hardness test carried out in the present investigation and the cast samples before and after the addition of grain refiners with or without ultrasonic vibrations.The main aim of the experimental plan was to find the important factors and combinations of factors influencing the mechanical properties to increase hardness and tensile strength. The experiments were developed based on the orthogonal array with the aim of influence frequency,amplitude and period of time. Taguchi recommends analyzing the S/N ratios using conceptual approach

that involves graphing the effects and visually identifying the significant factors.

The results for various combinations of parameter were obtained by conducting the experiments as per the orthogonal array. The measured results were analyzed using the commercial software MINITAB 14 specially used for design of experiment applications. Table 3 and table 6. Shows the experimental results of average repetitions for hardness and tensile strength.To measure the quality characteristics the experimental values are transformed in to signal to noise ratio. The influence of control parameters such as frequency, amplitude and period of time has been analysed using signal to noise response table.

| EX. No | Process parameter level | | | | Hardness | | | HV | S/N ratio (dB) |
| | A Master Alloy | B Frequency (KHz) | C Amplitude (μm) | D Holding Time (Sec) | Test run | | | | |
					1	2	3		
1	0.4	20	40	40	62	66	63	64	36.12359948
2	0.4	24	60	80	77	74	71	74	37.38463439
3	0.4	28	80	120	74	73	78	75	37.50122527
4	0.6	20	60	120	67	72	71	70	36.9019608
5	0.6	24	80	40	66	70	68	68	36.65017825
6	0.6	28	40	80	70	76	76	74	37.38463439
7	0.8	20	80	80	74	68	74	72	37.14664993
8	0.8	24	40	120	67	69	74	70	36.9019608
9	0.8	28	60	40	67	64	64	65	36.25826713

Table3 S/N ratio for Hardness (HV)

The mean S/N ratio for each level is summarized in the response table 4. The total mean S/N ratio for the nine experiments is also calculated.

Total mean S/N ratio = 36.98465462

Symbol	Process parameter	Level 1	Level 2	Level 3	Optimum level (max. S/N ratio)
A	Master Alloy	37.00	36.98	36.77	A_1
B	Frequency (KHz)	36.72	36.98	37.05	B_3
C	Amplitude (μm)	36.80	36.85	37.10	C_3
D	Holding Time (S)	36.34	37.31	37.10	D2

Table4 Response table for mean S/N ratio for hardness and significant interaction

A response graph is drawn using the values from the response table 4. The response graphs exhibit a pictorial view of variation of each parameter and describe what the effect on system performance would be, when a parameter shifts from one level to another. Fig.4 shows the response graph for hardness.
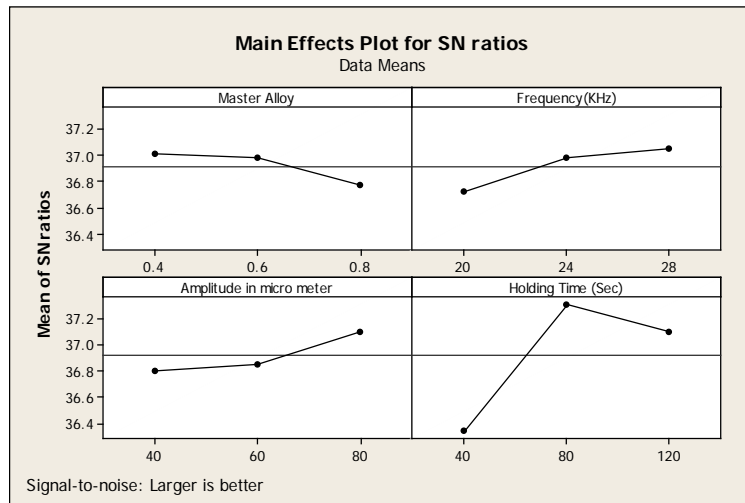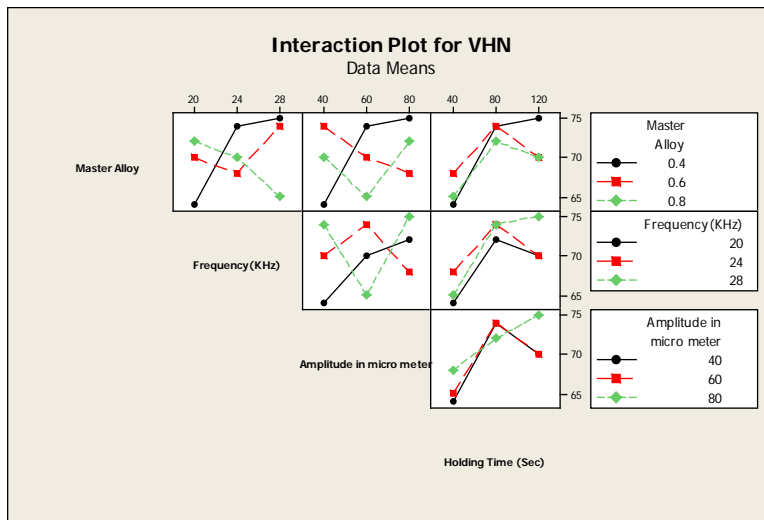
Fig. 4.   Response graph for hardness

Fig. 5. Interaction plot for hardness

From the response graph, the optimal parameters for maximum hardness are:

- Master Alloy at level 1, A_1 = 0.4wt%(Al-5Ti-1B)
- Frequency at level 3, B_3= 28Khz
- Amplitude at level 3, C_3 = 80(μm)
- Holding Time at level 2, D2 = 80s

A.   Analysis of variance (ANOVA)

The contributing ratio of the control factors in getting the maximum as brought out by ANOVA is shown in table 3 and the corresponding Pareto ANOVA diagram is shown in Fig. 4. It is seen that the F ratio values of parameters A, B , C and D are all greater than F-ratio values at 76% significance level drawn from table . The Pareto analysis shows that the weight fraction of master alloy at 0.4wt% has contributed higher impact on hardness. It is concluded that the weight fraction is the major contributing factor and frequency at 28Khz,amplitude at 80(μm) and holding time 80s were   influencing higher imact factor(77.69%)on hardness . The weight fraction of master alloy at 0.4wt% has contributed higher impact on hardness.

Source of variation	Degrees of freedom	Sum of squares	Variance	Pure variation	F-ratio	Contribution %
Weight fraction Master Alloy % - A	2	6.89	3.44	0.934	0.07*	5.48
Frequency (KHz) - B	2	11.56	5.78	0.894	0.12*	9.20
Amplitude (µm)- C	2	9.56	4.78	0.911	0.10*	7.62

| Holding Time (S)-D | 2 | 97.56 | 48.778 | 0.011 | 10.45 | 77.69 |
| Total | 8 | 125.56 | | | | 100 |

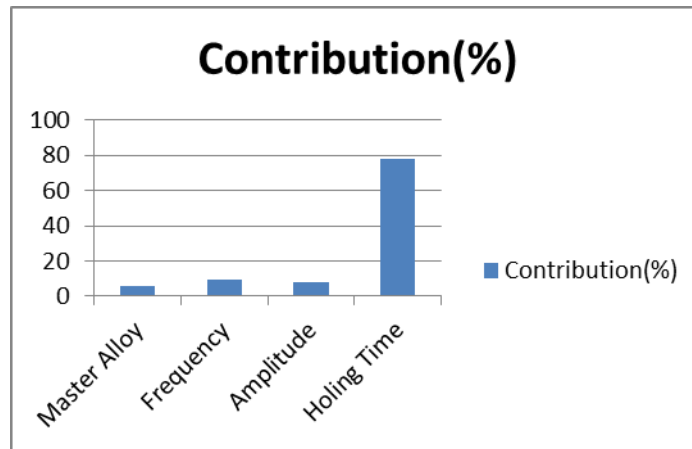**Table 5: Results of analysis of variance for hardness**

Fig. 6. Pareto analysis for Hardness

B. Prediction of optimum performance

At the optimum setting condition, the optimum hardness is estimated using following Eq.

Predicted optimal hardness = $(A'_1 - T) + (B'_3 - T) + (C'_3 - T) + T$

where A'_1 is the average hardness value for first level weight fraction, B'_3 is the average hardness value for third level of frequency combination, C'_3 is the average hardness value for third level of amplitude and T is the mean hardness value from all experimental data. In calculating the estimate, we use only strong effects.

Predicted optimum value of hardness = $(71 - 70.22) + (69 - 70.22) + (70.66 - 70.22) + 70.22 = 70.22$

C. Confidence interval

From Eq. 1, the confidence interval of the above predicted estimate at 76% significance = ±1.22 i.e., the experimental values should lie within the predicted range of 70.22±1.22 = 71.44.

D. Confirmation test

A confirmation test was carried out at the optimum settings of the process parameter recommended by the investigation, i.e., 0.4wt% weight fraction, 28Khz frequency, 80 □m amplitude and 80s of holding time. The hardness value obtained at the optimum setting is 70.95

EX. No	Process parameter level				Tensile strength (N/mm^2)	S/N ratio (dB)
	A Master Alloy	B Frequency (KHz)	C Amplitude (μm)	D Holding Time (Sec)		
1	0.4	20	40	40	175.5	44.8855
2	0.4	24	60	80	173.7	44.796
3	0.4	28	80	120	175.7	44.8954
4	0.6	20	60	120	191.5	45.6434
5	0.6	24	80	40	187.5	45.46
6	0.6	28	40	80	177.8	44.9986
7	0.8	20	80	80	192.8	45.7021
8	0.8	24	40	120	186.7	45.4229
9	0.8	28	60	40	191.7	45.6524

Table 6: S/N ratio for Tensile strength

The mean S/N ratio for each level is summarized in the response table 4. The total mean S/N ratio for the nine experiments is also calculated.

Total mean S/N ratio = 45.2484

Symbol	Process parameter	Level 1	Level 2	Level 3	Optimum level (max. S/N ratio)
A	Master Alloy	44.86	45.37	45.59	A_3
B	Frequency (KHz)	45.41	45.23	45.18	B_1
C	Amplitude (μm)	45.10	45.36	45.35	C_2
D	Holding Time (S)	45.33	45.17	45.32	D1

Table7 Response table for mean S/N ratio for Tensile strength and significant interaction
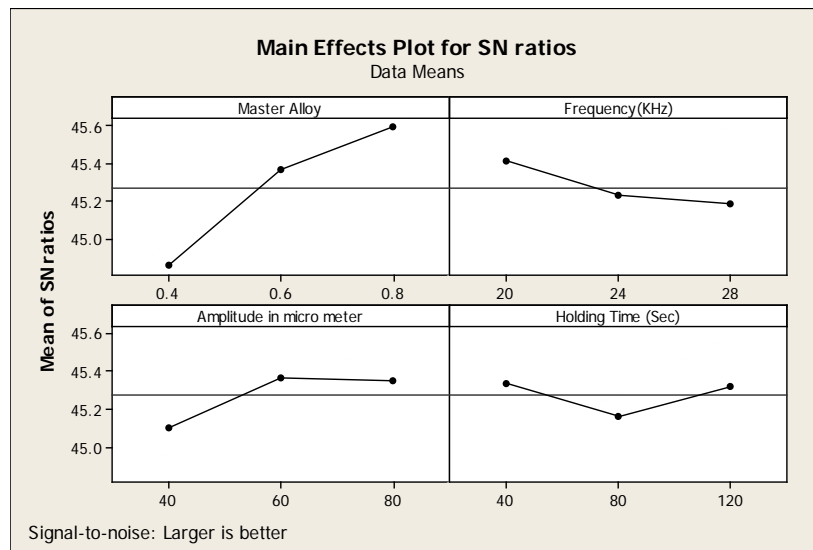

Fig. 7.   Response graph for tensile strength.

A response graph is drawn using the values from the response table 8. The response graphs exhibit a pictorial view of variation of each parameter and describe what the effect on system performance would be, when a parameter shifts from one level to another. Fig.7   shows the response graph for tensile strength.

From the response graph the optimal parameters for maximum tensile strength are,

- Master Alloy at level 3, A_3 = 0.8wt%(Al-5Ti-1B)
- Frequency at level 1, B_3= 20Khz
- Amplitude at level 2, C_2 = 60(μm)
- Holding Time at level 1, D1 = 40s
- *E. Analysis of variance (ANOVA)*

The contributing ratio of the control factors in getting the maximum as brought out by ANOVA is shown in table 9 and the corresponding Pareto ANOVA diagram is shown in Fig. 8. It is seen that the F ratio values of parameters A, B , C and D are all greater than F-ratio values at 76% significance level drawn from table . The Pareto analysis shows that the weight fraction of master alloy at 0.8wt% has contributed higher impact on tensile strength. It is concluded that the weight fraction is the major contributing factor (75.29%) and frequency at 20Khz, amplitude at 60(μm) and holding time 40s are second influencing factors (12.13%). The weight fraction of master alloy at 0.8wt% has contributed higher impact on tensile strength.

Source of variation	Degrees of freedom	Sum of squares	Variance	Pure variation	F-ratio	Contribution %
Weight fraction Master Alloy % - A	2	374.3	187.17	0.056	16.76*	75.29
Frequency (KHz) - B	2	40.23	20.11	0.357	1.8*	8.09
Amplitude (μm)- C	2	60.27	30.13	0.270	2.7	12.13
Holding Time (S)-D	2	22.33	11.16	0.270	2.7	4.49
Total	8	497.13				100

Table 8: Results of analysis of variance for tensile strength

F. Prediction of optimum performance

At the optimum setting condition, the optimum tensile strength is estimated using following Eq.

Predicted optimal hardness = (A'3 – T) + (B'1 – T) + (C'$_2$ – T) + (D'1-T) + T

where A'3 is the average tensile strength value for third level weight fraction, B'$_1$ is the average tensile value for first level of frequency combination, C'$_2$ is the average tensile strength value for second level of amplitude, D'1 is the average tensile strength of first level and T is the mean tensile strength value from all experimental data. In calculating the estimate, we use only strong effects.

Predicted optimum value of tensile strength = (190.4 – 183.65) + (174.96 – 183.65) + (185.6 –183.65) + 183.65 = 183.66

G. Confidence interval

From Eq. 1., the confidence interval of the above predicted estimate at 77.7% significance = ± 1.22 i.e., the experimental values should lie within the predicted range of 183.66 ± 1.22 = 184.88 N/mm^2.
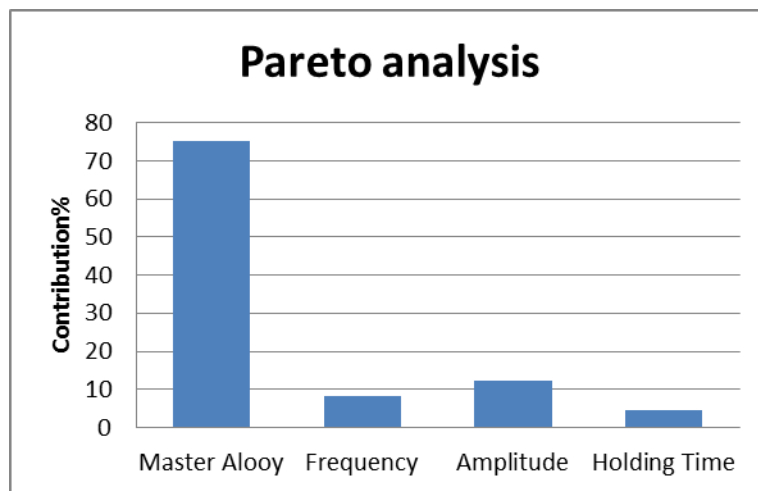

Fig. 8 Pareto analysis for Tensile strength

H. Confirmation test

A confirmation test was carried out at the optimum settings of the process parameter recommended by the investigation, i.e., 0.8wt% weight fraction, 20Khz frequency, 60 ☐m amplitude and 40s of holding time. The tensile strength value obtained at the optimum setting is 185.01

I. Tensile strength

The results for various combinations of parameters were obtained by conducting the experiments as per the orthogonal array. The data on the Tensile stength was analyzed by using Taguchi method by using MiniTab-15 software. The contributions of the input variables and their interaction are shown in main effects plot fig 4. According to Signal to-noise ratio for larger is the better, the higher mean value of ultimate tensile strength is given by 0.8wt%(Al-5Ti-1B), 28KHz,60μm and 40s holding time as shown in fig 7.

From the interaction plot it is concluded from fig 9. it can be seen that the higher mean values of ultimate tensile strength given by 0.8wt % (Al-5Ti-1B), 28KHz,80μm and 80s of holding time. From overall results the ultimate tensile strength is increased by around 16% compare to pure AA-356 according the standards given in ASTM hand book.

V. CONCLUSION

In present investigation high intensity ultrasonic vibrations eliminate coarse grains and forms globular equi-axed grains small grains approximately 25µm, which shows that the grains are refined is related to nucleation (hetrogeneuos) and survival of small nuclei or embryos of grains formation by improving mechanical properties like hardness and ultimate tensile strength. From the confirmation test it is concluded that the optimum settings of the process parameter recommended by the investigation, for hardness i.e., 0.4wt% weight fraction, 28Khz frequency, 80☐m amplitude and 80s of holding time. The hardness value obtained at the optimum setting is ----

Again from the confirmation test it is concluded that the optimum settings of the process parameter recommended by the investigation, for tensile strength i.e., 0.8wt% weight fraction, 28Khz frequency, 80 ☐m amplitude and 40s of holding time. The tensile strenth value obtained at the optimum setting is ----

The experimental result shows that the overall results the hardness and ultimate tensile strength is increased by around 13% and 16% respectively compare to pure AA-356 when it is treated ultrasonically when it is compare with the pure aluminum AA-356 without ultrasonic treatment.

It can be seen that for hardness 0.4wt % (Al-5Ti-1B), 28KHz,80µm and 80s of holding time is more effective and for ultimate tensile strength 0.8wt%(Al-5Ti-1B)grain refiner is more effective when it is treated 20KHz frequency with amplitudes 80µm for 80 se. This is due to cavitations assisted fragmentation is the main contributor to grain refinement to produce small grain size to increase tensile strength.

The microstructure shows that the porosities are reduced to larger extent under ultrasonic treatment which leads to better flow properties for fluidity of complex mold designs.

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