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INFLUENCE OF PROCESS PARAMETERS ON THE MECHANICAL PROPERTIES OF HEAT TREATED ALUMINIUM COPPER MAGNESIUM ALLOY

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Abstract: The current study obtained contributions of individual process factors and optimal factors for hardness and UTS, in the heat treatment process of Al-Cu-Mg alloys, every factor such as Mg content, solution temperature, aging temperature and pre-aging time, has three levels, respectively. The standard experiment layout 3 level orthogonal array (OA) L9 was considered. The interaction between the parameters was neglected. Solutionization is conducted at a temperature high enough to put in solution the alloying elements and obtain a supersaturated solid solution, which, in the case of Cu and Mg, is normally at 510 to 550°C. This is the typically know as the "solution temperature". In recent times, the forming of various automobile body panel parts often involved the application of various temperature 170 °C, 180 °C and 190 °C of ageing which in turn would influence the ageing characteristics of the alloy. Taguchi method puts emphasis on S/N ratio as opposed to simple average of output. Analysis of Variance was used to investigate percentage Contribution of Each process parameters on output Response. Results show that parameters such as % Magnesium addition and ageing duration has significant effect on mechanical properties.

Keywords: Al-Cu-Mg alloy, ageing, hardness, UTS, Taguchi and ANOVA

I. INTRODUCTION

One of aluminum's weaknesses is its lack of strength is its pure form. To get around this and preserve aluminum's low density and lightweight other elements are added to the metal to pin dislocations reducing ductility but increasing strength. By this method some aluminum alloys can be as strong as steel. Adding different elements achieves slightly different effect but almost all alloys are stronger than the original aluminum metal. Adding copper to aluminum increases aluminum's strength and hardness and also makes it heat treatable. Those with copper come in the form 2XXX. Alternatively adding magnesium causes increased tensile strength, resistance to marine corrosion and ease at which welding can occur. The presence of magnesium improves strain, hardenability and enhances the material strength by solid solution [1]. Chemical composition and heat treatment exert an important influence on the mechanical properties. The most applied heat treatment for this alloy is a solution treatment followed by an age-hardening that is required for the precipitation of the Al_2Cu hardening constituent. Solution heat treatment is particularly suitable for alloys with high magnesium content in order to promote the formation of the important strengthening precipitate, Mg_2Si [2]. The aim of age-hardening is to produce a large number of fine precipitates in the aluminium grains. These interfere with the movement of dislocations when the metal yields. This has the effect of increasing the strength of the alloy. The heat treatment used to produce the precipitates involves a high temperature solution treatment, quenching and then ageing. From the phase diagram for the pure aluminium-copper binary system, it can be seen that the solubility of copper in aluminium increases with increasing temperature up to the eutectic temperature of about 550°C. The equilibrium microstructure below the eutectic temperature is a two-phase mixture of aluminium and the Al_2Cu intermetallic phase. The initial solution heat treatment aims to obtain the maximum possible concentration of copper in solution. Rapid quenching from the solution temperature prevents the kinetically slow precipitation, forming a highly supersaturated solid

solution of copper. Rapid quenching also preserves the large number density of vacancies in the aluminium lattice from the high solution temperature. This increases copper diffusion rates at low temperature and accelerates ageing. Care must be taken with commercial alloys where the additional alloying elements reduce the eutectic temperature. This reduces the maximum solution heat treatment temperature since heating above the eutectic temperature causes the growth of a brittle intergranular eutectic.
The Taguchi method is a powerful tool for designing high quality systems based on orthogonal array experiments that provide much-reduced variance for experiments with an optimum setting of process control parameters [13-15]. The method has also been widely used in engineering analysis to optimize performance characteristics through design parameter settings.

II. EXPERIMENTAL DETAILS

The investigated materials consists aluminum as a primary constituent and copper is the major addition with magnesium 0-2wt% varied in steps of 0.5Wt%.

A. Alloy preparation

All experimental alloys were prepared by liquid metallurgy route using pure aluminium (99.8 %), electrolytic copper (99.9 %), and magnesium. The compositions were melted in an electrical resistance furnace, using graphite crucible. The molten metal was poured into permanent cylindrical die of diameter 25 mm having 200 mm long. Die was preheated to 200^{0}C. The composition of the alloy was determined using Optical Emission Spectrometer.
The experimental work was divided in two phases. The first phase consists of specimen preparation such as melting, casting and ageing heat treatment of samples with different compositions in the aluminum-copper-magnesium system. The second phase includes mechanical characterization like hardness, ultimate tensile strength and optimization of results by using taguchi method and ANOVA technique.

B. Mechanical Tests

Mechanical Tests such as Tensile and Hardness were conducted as per the ASTM standards. In the present study, the tensile test was conducted to using a standard 40 ton capacity Servo-hydraulic universal testing machine of model UTES-40. The test was carried out at ambient temperature and in accordance with ASTM A370 standards. Three specimens were tested and average values of the Ultimate Tensile Strength are reported.
In the present study, hardness of the specimens was measured by using a standard Brinell hardness testing machine**.** The hardness test was conducted in accordance with ASTM E10 standards. Three readings were taken for each specimen at different locations to circumvent the possible effect of any alloying element segregation and the average value was considered.

C. Taguchi Method

The Taguchi method puts emphasis on S/N ratio as opposed to simple average of output. It is so because in order to achieve robustness, we must consider standard deviation instead of basing our decisions merely on averages. For higher is better quality characteristic, the S/N ratio used for this type response is calculated according to Eq. (1)

Signal to noise ratio (S/N in db)
$$\frac{S}{N} = -10\log\left(\frac{\bar{x}^2}{\sigma^2}\right) \qquad (1)$$

Where: dB the unit of S/N ratio (decibel), $\bar{x}$ Average value and σ and standard deviation of experimental value of the i^{th} quality characteristic. The standard experiment layout 3 level OA L9 (3^4) for factors is listed for this case and shown in Table 1 and 3.

D. Analysis of Variance

Analysis of Variance (ANOVA) is a powerful analyzing tool which is used to identify significant of each parameter on output response. Study of ANOVA table for a given analysis helps to control the process parameters. The Minitab 15 Software is used to identify various terms in ANOVA. The table 2 and 4 shows the ANOVA for Hardness and UTS. The ANOVA table shows effect individual effect of each parameter and interaction effect of each parameter on output response. Here in ANOVA table, Mg content (A), ageing duration (B), Homogenous temp (C) and Ageing temp (D).

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III. RESULTS AND DISCUSSION

A. Optimization of Mg and heat treatment parameters on Hardness

TABLE 1. EXPERIMENTAL LAYOUT USING L9 (34) ORTHOGONAL ARRAYS

Trail No.	Mg in wt.% (A)	Aging duration in hrs (B)	Solution temp in °C (C)	Aging temp in °C (D)	Hardness, BHN			Average BHN	Standard devotion	S/N ratio
					Trail 1	Trail 2	Trail 3			
1	0.5	1	510	170	57.5	58.0	58.3	57.9	0.391	-43.41
2	0.5	3	530	180	57.4	58.3	58.4	58.0	0.509	-41.14
3	0.5	5	550	190	61.9	61.8	61.9	61.9	0.020	-69.81
4	1	1	530	190	60.3	60.5	59.8	60.2	0.332	-45.18
5	1	3	550	170	61.0	60.7	60.6	60.7	0.210	-49.24
6	1	5	510	180	70.3	70.6	70.7	70.5	0.223	-50.01
7	1.5	1	550	180	64.9	64.5	64.2	64.5	0.334	-45.72
8	1.5	3	510	190	73.1	73.5	73.6	73.4	0.250	-49.36
9	1.5	5	530	170	84.1	84.8	84.4	84.4	0.327	-48.25

Table 1 shows the variations of hardness with Mg, heat treatment parameter for different aging temperatures and time. The hardness variation trend with aging temperature and time will be increased to reduce. For aging temperature, 170°C is the better of the pre-aging parameters. The aging process at 170 °C to increase its hardness over time, also increases mainly in the Al alloy, without the over-aging phenomenon, therefore there is higher alloy stability at this temperature. However, in this study, the overall heat treatment process is not a single-stage aging treatment coupled with aging temperature and time. Therefore, when aging temperature and time increase, hardness will follow the trend.

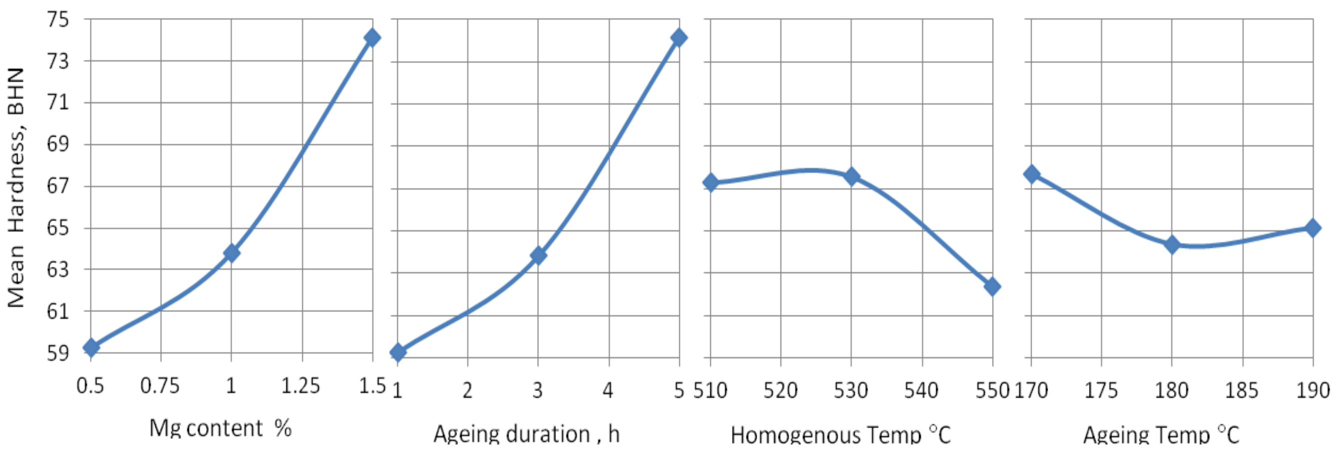

Fig.1: Effect of individual parameters on average hardness value of Al-Cu-Mg alloys

The effect of individual parameters on average hardness values is shown in Fig. 1. The average of the hardness can be calculated by (Ai+Aj+Ak)/3 where I, j and k are the levels of parameters, The range of average responses shown in the Table 1, over the three levels of each experimental factor, is: Mg content (A), ageing duration (B), Homogenous temp (C) and Ageing temp(D). It is observed from the graph that the best parameter are A3 (1.5wt%), B3 (5 hrs), C2 (530 °C) and a D1 (170 °C).

B. Implementation of ANOVA for hardness

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Table 2 shows the process parameters (factors) that were chosen for the development of Al-Cu-Mg alloys. Three levels were specified for each parameter. Table 2 shows the ANOVA for hardness of Al-Cu-Mg alloys.

TABLE 2 RESULTS OF THE ANALYSIS OF VARIANCE FOR HARDNESS

Factors	Mg in wt.% (A)	Aging duration in hrs (B)	Solution temp in °C (C)	Aging temp in °C (D)	Total
Sum of factors	177.8	182.7	201.9	203.1	765.4
	191.5	192.2	202.6	193.1	779.3
	222.3	216.8	187.1	195.5	821.7
Sum of squares difference	3120.1	1863.2	458.5	163.2	5605.1
Degree of freedom	2	2	2	2	8
% of contribution	55.67	33.24	8.18	2.91	100
	1	2	3	4	
Optimal level	A3	B3	C2	D1	
	1.5 %	5 hrs	530 °C	170°C	

From Table 2 the values of sum at factor level, sum of squares of differences and % contribution are found as shown in table, and it can be seen that the third level of factor (A) give the highest summation (i.e. A3, which is 1.5 wt.% of Mg). The highest summation for factor (B) is at the third level (i.e. B3, which is 5 hr of ageing duration), highest summation for factor (C) is at second level (i.e C2 solution temperature is 530 °C) and the highest summation for factor (D) is at the first level (i.e. D1, which is 170 °C ageing temperature). These results have proved the success of Taguchi method in the prediction of the optimum parameters for higher hardness.

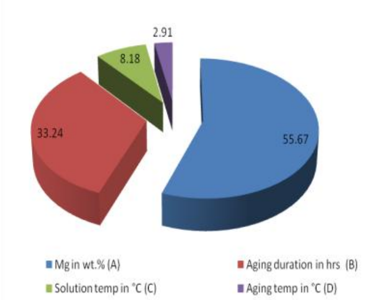

Fig. 2 Contribution of each factor on hardness

Taguchi's and S/N ratio methods used to determine the optimal process parameters which minimize the number of experimentations to be conducted to determine the hardness of Al-Cu-Mg alloy surface were found fruitful. To know the influence of process parameters ANOVA technique is employed. Percentage magnesium addition contributed to hardness is 55.67%, ageing duration contributed to hardness is 32.24%, and solution temperature contributed to hardness is 8.18% and ageing temperature contributes 2.91 %. From the analysis it was evident that the volume fraction of Magnesium is a major contributing factor for improving hardness.

C. Optimization of Mg and heat treatment parameters on UTS

TABLE 3. EXPERIMENTAL LAYOUT USING L9 (34) ORTHOGONAL ARRAYS FOR UTS

Trail No.	Mg in wt.% (A)	Aging duration in hrs (B)	Solution temp in °C (C)	Aging temp in °C (D)	UTS, MPa			Average UTS, MPa	Standard devotion	S/N ratio
					Trail 1	Trail 2	Trail 3			
1	0.5	1	510	170	213	210	210	211	1.732	-41.71
2	0.5	3	530	180	225	225	224	225	0.577	-51.80
3	0.5	5	550	190	238	238	240	239	1.155	-46.31
4	1	1	530	190	224	225	226	225	1.000	-47.04
5	1	3	550	170	220	219	219	219	0.577	-51.59

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6	1	5	510	180	256	255	256	256	0.577	-52.92
7	1.5	1	550	180	259	258	257	258	1.000	-48.23
8	1.5	3	510	190	293	292	290	292	1.528	-45.62
9	1.5	5	530	170	314	312	311	312	1.528	-46.21

Table 3 shows the variations of UTS with Mg, heat treatment parameter for different aging temperatures and time. The UTS variation trend with aging temperature and time will be increased to reduce. For aging temperature, 170°C is the better of the pre-aging parameters. The aging process at 170 °C to increase its UTS over time, also increases mainly in the Al alloy, without the over-aging phenomenon, therefore there is higher alloy stability at this temperature. However, in this study, the overall heat treatment process is not a single-stage aging treatment coupled with aging temperature and time. Therefore, when aging temperature and time increase, UTS will follow the trend.

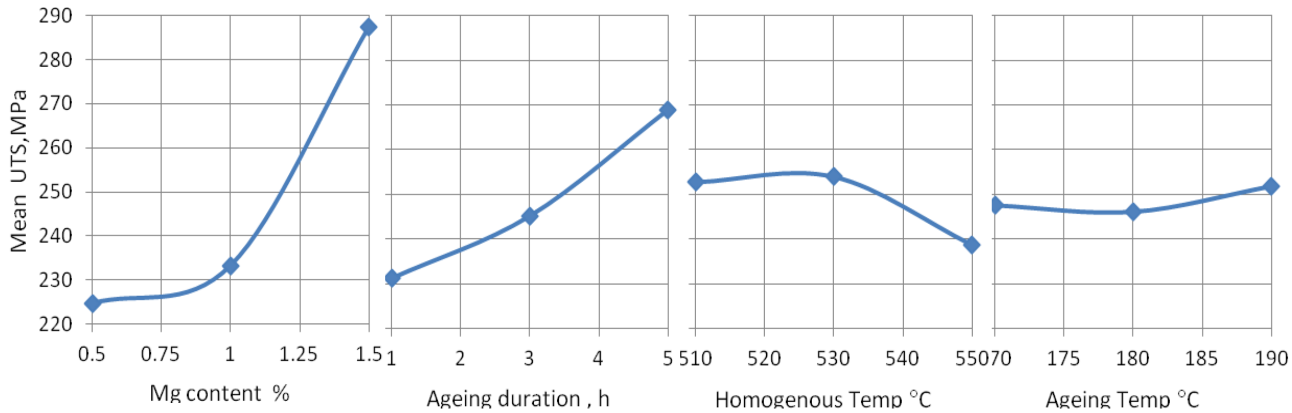

Fig.3: Effect of individual parameters on average UTS value of Al-Cu-Mg alloys

The effect of individual parameters on average UTS values is shown in Fig. 3. The average of the UTS can be calculated by (Ai+Aj+Ak)/3 where I, j and k are the levels of parameters, The range of average responses shown in the Table 3, over the three levels of each experimental factor, is: Mg content (A), ageing duration (B), Homogenous temp (C) and Ageing temp(D). It is observed from the graph that the best parameter are A3 (1.5wt %), B3 (5 hrs), C2 (530 °C) and D3 (190 °C).

D. Implementation of ANOVA for UTS

Table 4 shows the process parameters (factors) that were chosen for the development of Al-Cu-Mg alloys. Three levels were specified for each parameter. Table 4 shows the ANOVA for UTS of Al-Cu-Mg alloys.

TABLE 4: RESULTS OF THE ANALYSIS OF VARIANCE FOR UTS

Factors	**Mg in wt.% (A)**	**Aging duration in hrs (B)**	**Solution temp in °C (C)**	**Aging temp in °C (D)**	**Total**
Sum of factors	674	694	758	743	2869
	700	736	762	738	2936
	862	807	716	755	3140
Sum of squares difference	62119	19472	3922	468	85981
Degree of freedom	2	2	2	2	8
% of contribution	72.25	22.65	4.56	0.54	100
	1	2	3	4	
Optimal level	A3	B3	C2	D3	
	1.5 %	5 hrs	530 °C	190°C	

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From Table 4 the values of sum at factor level, sum of squares of differences and % contribution are found as shown in table, and it can be seen that the third level of factor (A) give the highest summation (i.e. A3, which is 1.5 wt.% of Mg). The highest summation for factor (B) is at the third level (i.e. B3, which is 5 hr of ageing duration), highest summation for factor (C) is at second level (i.e C2 solution temperature is 530 °C) and the highest summation for factor (D) is at the first level (i.e. D3, which is 190 °C ageing temperature). These results have proved the success of Taguchi method in the prediction of the optimum parameters for higher UTS.

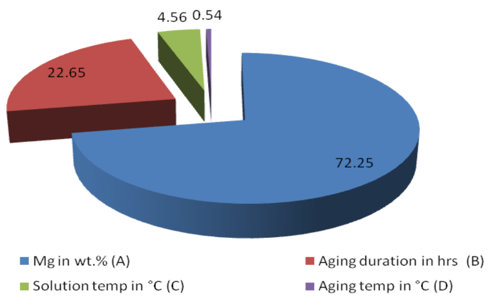

Figure. 4 Contribution of each factor on UTS of Al-Cu-Mg alloys

Taguchi's and S/N ratio methods used to determine the optimal process parameters which minimize the number of experimentations to be conducted to determine the UTS of Al-Cu-Mg alloy surface were found fruitful. To know the influence of process parameters ANOVA technique is employed. From the figure 4, it is clear that Percentage magnesium addition contributed to UTS is 72.25%, ageing duration contributed to UTS is 22.65%, solution temperature contributed to UTS is 4.56% and ageing temperature contributes 0.54 %. From the analysis it was evident that the volume fraction of magnesium is a major contributing factor for improving UTS.

IV. CONCLUSIONS

Taguchi's robust design method can be used to analyze optimal heat treatment parameters for the aluminum copper magnesium alloy described in the paper. The current study, it is observed from taguchi analysis that hardness value is optimized at 1.5% Mg addition, 5hr ageing duration, 530^0c solution temperature and with ageing temperature of 170^0c. UTS value is optimized at 1.5% Mg addition, 5hr ageing duration, 530^0c solution temperature and with ageing temperature of 190^0c. From ANOVA technique it is clear that %Magnesium Contributed to hardness is 55.67%, ageing duration contributes 32.24%, solution temperature contributed to hardness is 8.18% and ageing temperature contributes 2.91%. From the analysis it was evident that the volume fraction of magnesium is a major contributing factor for improving hardness. It also observed for UTS, Mg % contributes 72.25%, ageing duration contributed to UTS is 22.65%, solution temperature contributed to UTS is 4.56% and ageing temperature contributes 0.54 %. From the analysis it was evident that the volume fraction of magnesium is a major contributing factor for improving UTS.

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