APPLICATION OF GREY RELATIONAL GRADE IN OPTIMIZING TENSILE PROPERTIES OF 6061 ALUMINUM ALLOY

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Abstract

The industrial applications of lightweight metals is the driving force for engineers and researchers to find solutions with cost effective to improve the existing lightweight alloys with attractive mechanical properties and service performance levels. The Al-Mg-Si alloy is among those alloys gaining prominence by automotive industry, with an interest to reduce weight, fuel consumption and exhaust emissions of the vehicles. In previous investigations, the application of Taguchi design of experiments (DOE) of the L_9 orthogonal array (OA) with four process variables, namely, quenching media, delay time before stretching, stretching steps, delay time after stretching and three levels for each variable has shown that the strength or ductility values is enhanced by applying DOE for single quality optimization. However, product performance depends on many quality characteristics, which cannot be solved by Taguchi method. Thus, the optimization of multi qualities (yield, tensile, ductility, tensile toughness) of the 6061 aluminum alloy can be resolved by Grey-based Taguchi method. The method combines the Taguchi DOE orthogonal array (OA) with grey relational analysis to find the grey relational grade, which can convert the optimization of multi qualities into single quality optimization that is used to determine the optimal variables levels and their effects on performance of the alloy. The obtained results shows that the most affected process variables to the tensile properties values is stretch steps, followed by quenching media and then delay times and thus the optimal process variable levels are determined more precisely on the overall tensile properties of the alloy.

Keywords: Aluminum alloys, precipitation, stretch, optimization, tensile properties

1. INTRODUCTION

The use of the heat treatable Al-Mg-Si alloys in the automobile vehicles has increased over the past years due to the lightweights and attractive combinations of medium strength, good formability, weldability, machinability, and corrosion resistance. Several studies were reported in the literatures to improve the aging response of this alloy. The effect of heat treatments on AA6061aluminum alloy deformed by cross-channel extrusion (CCE) was reported [1] and found that this method enhanced the mechanical properties of the alloy. The development of high strength Al-Mg-Si alloy through cold rolling and aging has been reported [2], and found that the combination of high strength and ductility could be improved by severe plastic deformation followed by anneal/aging treatment. The tensile properties of AA6061 alloy in different designated precipitation hardening and cold working conditions were investigated [3], and reported that combination of work hardening and precipitation hardening improved mechanical properties and negative or positive effect of pre-aging mainly depend on the amount of cold work.

Taguchi [4] design of experiment (DOE) is a methodology for improving the quality of products and processes. Taguchi method has applied the concept of orthogonal array (OA) to minimize the number of parameters combinations that reduces the number of experiments and to optimize the process parameters of a single performance response at a lower cost and shorter times. Lately, Taguchi method has been applied to several engineering materials issues [5-7] to determine optimum process parameters for single quality characteristics. However, engineering materials performance depend on many characteristics, so it is important to find the best process parameters that can produce the better performance levels for multiple quality characteristics at same time. Deng [8] had proposed grey relational analysis in the grey theory that can handle both incomplete information and unclear problems more precisely. The grey relational analysis [9,10] can convert the optimization of multiple quality characteristics into a single quality optimization called grey relational grade, which can provide an optimum process parameters. Tarng et.al [9] have applied the grey-based Taguchi method to determine submerged arc process parameters in hardfacing. Kopac et. al [11] have studied the effects of the flank milling parameters based on grey – based Taguchi method in the machining of an Al-alloy casting plate for injection moulds. Hatab et al [12] have investigated the effects of RRA heat treatment process parameters on properties of 7079 alloy using grey-based Taguchi method. The use of L_9 orthogonal array with grey relational in optimizing of friction welding AlCuBiPb alloy has been reported by Hatab et. al [13]. The aim of this study is to investigate the influence of quenching media, delay times and stretch steps process variables in optimizing tensile properties of the commercial AA6061 aluminum alloy using Grey-based Taguchi method.

2. EXPERIMENTAL AND DESIGN

2.1 Materials and Procedure

The as-received specimens are in the form of standard tensile specimens made from commercial 6061-T6 aluminum alloy with thickness of ~1.60mm by ~12.6mm width by 50mm gage length. The specimens were solution heat treated at 535^0C, quenched in water, hot-water or ice brine water, delayed time 10, 100 or 1440 minutes before stretch, stretched 3% (single), 1.5% each (double) or 1% each (triple), then delayed time 10, 100 or 1440 minutes, followed by artificially aging in oil bath at 160^0C for 5 hours. The specimens were deformed (stretched) and tested using Electromechanical testing machine Zwick (type-Z050), with load cell of 50 kN capacity; coupled with extensometer type 6336-107; with controlled strain rate of 0.00025 /s. The as-received and initial condition alloys in T6 condition are tested to determine the tensile properties for comparison purposes.

2.2 Taguchi Design of experiments

Taguchi design of experiments [4] can be used to optimize a complicated precipitation process that has several variables. Hence, the quenching media (Q_m), delay time (natural aging) before stretch (t_B), stretch steps (S_p), delay time after stretch (t_A) are considered to affect the precipitation process and thus the mechanical properties of the alloy. A standard Taguchi experiment of L_9 (3^4) orthogonal arrays with four variables and three levels for each variable is selected to study the effect of process variables combinations and to determine the effects of each variable on quality characteristics of the alloy. Tables 1 and 2 show the process variables and their levels, and Taguchi DOE respectively. After selecting the appropriate OA, the next steps in Taguchi DOE are to run the experiments and then to evaluate the results of experiments by applying statistical analysis (signal -to- noise ratio, S/N ratio) in order to determine which variable are influential the quality response.

Table 1 Process variables and their levels for 6061 aluminum alloy.

Process variables		Level 1	Level 2	Level 3
A	Quenching media, Q_m	Water	Hot-water	Ice-brine water
B	Delay time before stretch, t_B, min.	10	100	1440
C	Stretch steps, S_p	Single (3%)	Double (1.5% each)	Triple (1% each)
D	Delay time after stretch, t_A, min.	10	100	1440

Taguchi [4] has proposed the signal-to-noise (S/N) ratio as a response of the experiment, which is a measure of the amount of variation present within a trial when noise factors are presented. Three categories may be used to perform analysis of S/N ratios as response: lower-is-better (LB), nominal-is-better (NB), and higher-is-better (HB). In this study, the S/N ratio for the higher-is-better characteristic is given by Taguchi as follows:

$$S/N\ (dB) = -10 \log \left(\frac{1}{r} \sum_{i=1}^{r} \frac{1}{y_i^2} \right) \tag{1}$$

where dB is the unit of S/N ratio (decibel), y_i is the experimental value of the i^{th} quality response, r is the number of measurements in the trial in a row.

Table 2 A standard Taguchi Experimental of L_9 (3^4) orthogonal arrays [4]

Experiment Number	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

The tensile properties are treated as quality response using the higher is the better and can be calculated according to the following equations:

$$\mathrm{YS}^* = -10 \log \frac{1}{r} \sum_{i=1}^{r} \left(\frac{1}{\mathrm{YS}_i^2} \right) \tag{2}$$

$$\mathrm{TS}^* = -10 \log \frac{1}{r} \sum_{i=1}^{r} \left(\frac{1}{\mathrm{TS}_i^2} \right) \tag{3}$$

$$\%\mathrm{El}^* = -10 \log \frac{1}{r} \sum_{i=1}^{r} \left(\frac{1}{\%\mathrm{El}_i^2} \right) \tag{4}$$

$$\mathrm{U}^* = -10 \log \frac{1}{r} \sum_{i=1}^{r} \left(\frac{1}{\mathrm{U}_i^2} \right) \tag{5}$$

where YS^*, TS^*, El^*, U^* are the signal-to-noise (S/N) ratios for yield, tensile, ductility and tensile toughness respectively. YS_i, TS_i, $\%El_i$, and U_i are the experimental values of the i^{th} in the row. The optimal level can be determined from the largest value of the calculated S/N ratio among all other levels of the process variables.

3. RESULTS AND DISCUSSION

3.1 Single Property Using Taguchi Method

Table 3 shows the experimental results for measured yield strength (YS), tensile strength (TS), ductility (%El) and tensile toughness (U) and the calculated signal to noise ratios using equations (2, 3, 4 and 5).

Table 3 - Experimental results, YS, TS, %El, and U and calculated S/N ratios for 6061 aluminum alloys

Experiment Number	[1]YS MPa	[2]YS*	[1]TS MPa	[2]TS*	[1]%El	[2]%El*	[1]U, Joule	[2]U*
1	307	49.7310	338	50.5670	11.4	21.0169	37.03	31.1691
2	271	48.6630	313	49.8980	12.6	21.8377	36.47	31.0987
3	232	47.3170	288	49.1920	14.8	23.3241	38.67	31.5933
4	248	47.8750	298	49.4710	13.8	22.8068	37.77	31.5139
5	269	48.5830	310	49.8340	12.4	21.8521	35.93	31.0928
6	238	47.5180	291	49.2870	15.5	23.7993	39.97	31.0013
7	274	48.7580	314	49.9350	11.6	21.0275	34.07	30.3909
8	243	47.7110	293	49.3470	15.1	23.5294	40.30	32.0700
9	236	47.4530	288	49.1920	14.5	22.7123	38.00	30.9962

[1]Average of three tests   [2]Calculated S/N ratios

It is clearly indicated that the calculated signal-to-noise (S/N) ratios of experiment numbers 1, 6, and 8 give the better strength, ductility, and tensile toughness respectively among the nine running experiments, e.g., running experiment number 1 with process levels of water quenching, 10 minutes delay time before stretching, 3% single stretch, 10 minutes delay time after stretching, and then artificial aged at 160°C for 5 hours gives average tensile properties of 3 tests: 307 MPa yield strength, 338 MPa tensile strength and 11.4%El (ductility), and 37.03 tensile toughness. The combinations of process variables levels produce different values of tensile properties as given in Table 3. It is obvious that Taguchi method enables us to investigate a single tensile property as indicated by the obtained results, which shows high strength of alloy can be obtained by running experiment number 1, while running experiments 6 and 8 give high ductility and toughness respectively. However, the aim of the study is to determine which experiment of the alloys that produce high strength and toughness, and this can be accomplished by applying the grey relational method which can convert the optimization of multiple qualities into single quality optimization that will give the optimal process variables to produce the best combination of tensile properties of the alloy.

3.2 Multiple Properties Using Grey Method

The grey relational analysis [9,10] is a method to convert multiple optimization into a single optimization called grey relational grade. The First step in this method is to perform data processing called generation of grey relation. This can be accomplished by normalizing the experimental results in the range of zero to one. In this investigation, the S/N ratio is normalized for the higher-is-better quality response; and the equation used to calculate this response is given by equation (6):

$$x_{ij} = \frac{x_{ij} - x_{min}}{x_{max} - x_{min}} \tag{6}$$

where x_{ij} is the normalized S/N ratio for the j^{th} performance quality in the i^{th} experimental run. X_{ij} is the S/N ratio for the j^{th} performance quality in the i^{th} experimental run. X_{min} and X_{max} are the minimum and the maximum of the S/N ratios for the j^{th} performance quality in all the experimental runs.

Table 4 shows the normalized experimental results (generation of grey relation). The higher the value of the normalized S/N ratio indicates the better property when compared with the ideal value of one. After calculating the normalized S/N ratio, then the grey relational coefficient (γ_{ij}) is determined using equation (7):

$$\gamma ij = \frac{\min_i \min_j | x_i^o - x_{ij} | + \beta * \max_i \max_j | x_i^o - x_{ij} |}{| x_i^o - x_{ij} | + \beta * \max_i \max_j | x_i^o - x_{ij} |} \tag{7}$$

where x_i^0 is the ideal normalized S/N ratio for the j^{th} performance quality in the i^{th} experimental run, and β is the distinguish coefficient which is defined in the range $0 \le \beta \le 1$. The general used value for β is 0.5. Note that the (γ_{ij}) is to express the relationship between the ideal and the actual x_{ij} of the experimental results.

Table 4 – Normalized S/N ratio (x_{ij}) and calculated grey relational grade (Γ) for 6061 aluminum alloys

Experiment Number	Normalized value of x_{ij}, for YS	Normalized value of x_{ij}, for TS	Normalized value of x_{ij}, for %El	Normalized value of x_{ij}, for U	Grey relational grade, (Γ)	Ranking order
Ideal	1	1	1	1	1	-----------
1	1	1	0.3333	0.4824	0.7039	1
2	0.5305	0.5068	0.4149	0.4636	0.4790	6
3	0.3333	0.3333	0.7454	0.6378	0.5124	4
4	0.3940	0.3840	0.5836	0.6015	0.4911	5
5	0.5125	0.3855	0.4167	0.4621	0.4688	7
6	0.3529	0.4840	1	0.9244	0.6567	2
7	0.5537	0.5210	0.3342	0.3333	0.4355	8
8	0.3740	0.3604	0.8375	1	0.6430	3
9	0.3464	0.3333	0.5614	0.4388	0.4200	9

After determining the (γ_{ij}) the weighting method is used to determine the grey relational grade (Γ), and is given by equation (8):

$$\Gamma = \frac{1}{n}\sum_{i=1}^{n} w_i \times \gamma_{ij} \tag{8}$$

where w_i is the weighting factor for the j^{th} performance quality, and n is the number of performance. In the present study, the weighting factor for yield strength, tensile strength, %El, and tensile toughness are taken as equal weighting factors (0.25). Table 4 shows the calculated grey relational grade (Γ) gives that experiment number 1 is the optimal combinations of tensile properties, namely, 37.03 joule tensile toughness, 307 MPa yield strength, 338 MPa tensile strength, and 11.4%El. The calculated mean grey relational grade response data shown in Table 5 (see rank column) indicates that the tensile properties values are influenced by the stretching process, followed by quenching media, delay time after stretch, and the least influence variable is the delay time before stretch. Thus, the optimal process variables (Table 5) are level 1 for quenching media, level 1 for delay time before stretch, level 1 for stretch steps and level 3 for delay time after stretch or A1B1C1D3.

Table 5 Grey relational grade response (Γ) data

Process variables	Level 1	Level 2	Level 3	Max.-Min.	Rank
A Quenching media, Q_m	0.5651	0.5389	0.4995	0.0656	2
B Delay time before stretch, t_B, min.	0.5435	0.5303	0.5297	0.0138	4
C Stretch steps, S_p	0.6679	0.4634	0.4722	0.2045	1
D Delay time after stretch, t_A, min.	0.5309	0.5237	0.5488	0.0251	3
Total mean value of grey relational grade = 0.5345					

3.3 Experiment Verification

The confirmation of experiment is the final step to verify the multiple quality characteristics using the optimal levels of the process variables. If the results of the confirmation test do not agree with the results of the experiment runs, then new experiments are required. The predicted grey relational grade (Γ) for optimizing tensile properties is given by equation (9):

$$\Gamma_{conf} = \Gamma_{mean} + \sum_{i=1}^{n} [(\Gamma_{opt})_i - \Gamma_{meam}] \tag{9}$$

A comparison between predicted properties using equation (9) and actual experiment are shown in Table 6,

Table 6 Results of verification test for optimal process variables for tensile properties

Conditions	Level	Yield strength, MPa	Tensile Strength, MPa	Ductility, %El	Tensile Toughness Joule
Prediction	A1B1C1D3	306.6	347.7	13.15	38.94
Experiment	A1B1C1D1	307	338	11.4	37.03
*Initial		288	327	8.61	26.5
As received T6		303	323	11.7	36.62
**Improvement		19	11	2.79	10.53

*Initial condition, the specimens are solution heat treated at 535°C, water quenched, 10 minutes delayed, and then artificial aged at 160°C for 5 hrs.
**Improvement, the obtained results of experiment number 1 is compared to initial condition specimens.

indicating that the predicted experiment using process variables of level 1 for quenching media, level 1 for delay time before stretch, level 1 for stretch steps and level 3 for delay time after stretch or A1B1C1D3, will give better tensile strength, ductility (%El) and tensile toughness when compared with experiment number 1 (AB1C1D1). Thus the grey method can estimate the process variables affects on the overall tensile properties, can be used to determine the tensile properties of alloy at any other combinations of process variables for this range of experiments.

4. CONCLUSION

The present study is demonstrated the application of Grey – based Taguchi method for optimizing multiple equalities response to efficiently establish process variables for the commercial 6061 aluminum alloys. The grey relational analysis using S/N ratios provide a solution to convert the optimization of multiple quality characteristics into a single quality optimization called grey relational grade for determining the optimal process variables of the tensile properties. The optimal process variable levels for determining tensile properties of the alloy are water quench, 10 minutes delay time before stretch, 3% single stretch, 1440 minutes delay time after stretch and then aged at 160°C for 5hrs. The calculated tensile properties are 306.6 MPa yield strength, 347.7 MPa tensile strength, 13.15% El, and 38.94 joule tensile toughness, while the running experiment number 1 gives 307 MPa yield strength (~19MPa increase); 338 MPa tensile strength (~11MPa increase), 11.4%El (~2.79%El increase), and 37.03 joule tensile toughness (~10.53 joule increase) when compared with initial condition of the alloy aged at 160°C for 5hrs. The stretch steps is the most influence variable, followed by quenching media, delay time after stretch, and the least affected variable is the delay time before stretch in this set of the experiments.

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