Optimization of Heat Treatment Parameters with the Taguchi Method for the A7050 Aluminum Alloy

Chin- Chun Chang, Ji-Gang Yang, Chi Ling and Chang-Pin Chou

***Abstract*—this paper describes a heat treatment process using dual aging for the A7050 aluminum alloy with the Taguchi method to optimize process parameters. The current study considers micro hardness and electrical conductivity as optimization criteria. Pre-aging temperature, pre-aging time, re-aging temperature, and re-aging time are important factors influencing these optimization criteria. Experiment results show that re-aging temperature is the most significant parameter for electrical conductivity, and both aging times are important influence factors for micro hardness performance. The optimal hardness for A7050 heat treatment conditions are pre-ageing temperature 120℃, pre-ageing time 12hrs., re-aging temperature140℃, and re-aging time 8 hrs., respectively. The best electrical conductivity parameters are pre-ageing temperature 120℃, pre-ageing time 4 hrs., re-aging temperature180℃, and re-aging time 24 hrs., respectively. The current study obtained contributing individual parameters for hardness, and electrical conductivity in dual aging of heat treatment.**

***Index Terms*—Taguchi method, heat treatment, micro-hardness, electrical conductivity**

I. INTRODUCTION

The Al-Zn-Mg-Cu series age hardening super-high strength aluminum alloys have been widely used as aircraft structural materials due to their specific set of characteristics, namely, high strength, good corrosion resistance, high resistance to repeated loads, and low rate of fatigue-crack propagation [1-3]. These materials have been indispensable for developing a high performance system of critical technologies in lightweight carrier structures and in energy saving designs. New generations of aircraft and structural carriers are made of novel alloys, materials and related processes [4-5].

Manuscript received January 21, 2010.
This project is supported by the Ministry of Economic Affairs of R.O.C. (No. 98-EC-17-A-05-S2-0012).
Chin- Chun Chang is a Ph.D Candidate at the Department of Mechanical Engineering, National Chiao Tung University, Taiwan. (Corresponding author to provide phone: +886-3-578-0281 Ext.6205; fax: +886-3-578-3890; e-mail: chinchun@ nsrrc.org.tw).
Ji-Gang Yang is a Ph.D at the Chung Shan Institute of Science and Technology, Taiwan. (e-mail: yang.jg123@msa.hinet.net).
Chi Ling is a Master and engineer at the Chung Shan Institute of Science and Technology, Taiwan. (e-mail: lingchi7070@yahoo.com.tw).
Chang-Pin Chou is a professor at the Department of Mechanical Engineering, National Chiao Tung University, Taiwan. (e-mail: cpchou@mail.nctu.edu.tw).

Many investigations [6-8] have studied the effects of parameters in heat treatment and their process on precipitation. Aluminum alloy heat treatments, which include various aging methods, are widely used for precipitation hardening behavior such as single aging, duplex aging, retrogression and re-aging, RRA, and thermo-mechanical treatment, TMT and so on[6,9-12]. Aluminum alloy heat treatment parameters are important factors for obtaining the best mechanical and electrical performance. Heat treatment process parameters such as aging temperature and aging time operate differently according to different conditions. Therefore, to obtain parameter optimization in the heat treatment process, this study investigated with the Taguchi method to optimize 7050 aluminum alloy heat treatment process parameters, pre-aging temperature, pre-aging time, re-aging temperature, and re-aging time.

II. TAGUCHI METHOD

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. The Taguchi method is based on orthogonal arrays and analysis of variance (ANOVA) to minimize the number of experiments and to effectively improve product quality [18-20]. Some of its many advantages include: (1) Designs Orthogonal arrays (OA) to balance process parameters and minimize test runs. (2) Employs signal-to-noise (S/N) ratio to analyze experiment data, and conclude more information. Taguchi recommends using the S/N ratio for determining quality characteristics implemented in engineering design problems. (3) Estimates individual parameter contributions. Since the purpose of this study is to maximize hardness and the electrical conductivity index within optimal levels of process parameters, the higher the better quality characteristic is selected. Each parameter has three levels. The current study considered hardness and electrical conductivity as optimization criteria and also analyzed the influence of each heat treatment parameter on the quality of the research object. The current study obtained contributions of individual process parameters and optimal parameters for hardness, and electrical conductivity in the heat treatment process of aluminum alloys, respectively. In this way, the optimal levels of process parameters can be estimated. The following sections give the analysis results related to the subjects discussed above.

III. Experimental

The aluminum alloy 7050 with the composition mentioned in Table 1 was received as 6.35 mm thick plates from an Alcoa commercial product. The samples of 100 mm *x* 60 mm *x* 6.35 mm were prepared and subjected to solid solution heat treatment at 477± 1°C for 1 hour followed by water quenching. This study chose three levels for the four factors. The standard experiment layout 3 level OA L9 (3^4) for factors is listed for this case and shown in Table 2[13-14]. The interaction between the parameters was neglected. Table 3 gives the factors and their levels. Table 4 gives the details of the experiment design and approach. The factors under consideration, including pre-aging temperature, pre-aging time, re-aging temperature, and re-aging time are listed in the first three columns (A, B, C and D) of the OA L9 (3^4). The outputs, hardness and electrical conductivity values are the test results.

All experiments were conducted on commercial furnaces and conformed to AMS2770H in this study. The Vickers hardness measurement was performed on the SHIMADZU-HMV instrument with 25gf waiting for 10 seconds on specimens aged under different conditions. A number of measurements for hardness and electrical conductivity were taken and the average was determined. An electrical conductivity test was used for heat treating the aluminum alloy by the eddy current method, which determines its conductivity according to the percentage of the International Annealed Copper Standard (%IACS) for verifying aluminum alloy heat treatment. This measurement method in this experiment conforms to the criterion of the ASTM E 1004 and MIL-STD-1537C.

Table 1 Chemical composition of the 7050-T7451 aluminum alloy (wt-%)

Alloy	Zn	Mg	Cu	Zr	Cr	Al
7050	5.7-6.7	1.9-2.6	2.0-2.6	0.08-0.15	—	REM

Table 2 Experiment layout using L9 (3^4) orthogonal arrays

Trial No.	Heat treatment parameters				Test results
	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	

Table 3 Heat treatment parameters and their levels

Level	Heat treatment parameters			
	A: Pre-aging temp. (℃)	B: Pre-aging time (Hrs)	C: Re-aging temp. (℃)	D: Re-aging time (Hrs)
1	100	4	140	4
2	120	12	160	8
3	130	24	180	24

Table 4 Experiment design for each heat treatment process and their results

Trial No.	Heat treatment parameters				Hardness (Hv)	*Hv	EC (%IACS)	*EC
	A	B	C	D				
1	100	4	140	4	217.2	46.74	31.18	29.88
2	100	12	160	8	228.6	47.18	36.82	31.32
3	100	24	180	24	155.6	43.84	45.32	33.12
4	120	4	160	24	189.6	45.56	40.38	32.12
5	120	12	180	4	217.2	46.75	40.5	32.14
6	120	24	140	8	255.6	48.15	32.38	30.20
7	130	4	180	8	188.4	45.50	42.32	32.53
8	130	12	140	24	240.6	47.63	34.62	30.78
9	130	24	160	4	221.6	46.91	35.12	30.91

*Hv: Results of the S/N ratio for micro hardness

*EC: Results of the S/N ratio for electrical conductivity

IV. Results And Discussion

A. *Effect of heat treatment parameter on micro hardness performance*

Table 4 shows the micro hardness for various trial runs at three levels of pre-aging temperature, pre-aging time, re-aging temperature, and re-aging time, respectively. Based on this information, the S/N values can be calculated and are also shown. Fig. 1 shows the average effect of each parameter level on micro hardness, respectively. The optimal conditions are those that obtain high micro hardness. Fig. 1 shows that A2B2C1D2 are the best results for micro hardness. The optimal conditions are the following: pre-aging temperature 120 ℃, pre-aging time 12 hours, re-aging temperature 140℃, and re-aging time 8 hours, respectively.

Table 4 shows variations of micro-hardness with heat treatment parameters for different aging temperatures and times. The hardness variation trend with aging temperature and time will be increased to reduce. For pre-aging temperature, 120 ℃ is the better of the pre-aging parameters. This result with the data reported in the literature is consistent with [16].The pre-aging process at 120 ℃ to increase its hardness over time, also increases mainly in the A7050 alloy, without the over-aging phenomenon, therefore there is higher alloy stability at this temperature [17-18]. However, in this study, the overall heat treatment process is not a single-stage aging treatment coupled with re-aging temperature and time. Therefore, when re-aging temperature and time increase, hardness will follow the trend.

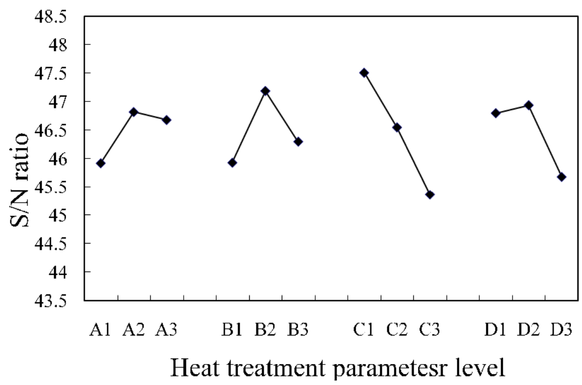

Fig. 1 S/N ratios showing the effects of each parameter level on micro hardness

B. Effect of heat treatment parameter on EC performance

Table 4 shows electrical conductivity for various trial runs at three levels of the four parameters, respectively. Based on this information, the S/N values can be calculated and also shown. Fig. 2 shows the average effect of each parameter level on electrical conductivity, respectively. The optimal conditions are those that give the best electrical conductivity and A2B1C3D3 is the best result. The optimal conditions are: pre-ageing temperature 120 ℃, pre-aging time 4 hours, re-aging temperature 180℃, and re-aging time 24 hours, respectively.

According to Wallace and Ohnishi etc., scholars found that [19-20], RRA heat treatment of the aluminum alloy specimen increases electrical conductivity and obtain a higher performance for stress corrosion resistance, SCR. Therefore, appropriate heat treatment parameters obtain a better result for electrical conductivity of the aluminum plate, and a further understanding of aluminum after heat treatment of the SCR. From Fig. 2 the S/N results show that in pre-aging temperature and time, the degree of influence on electrical conductivity changed little. The initial aging stage provides more nucleation energy for matrix precipitates to supply the supersaturated solid solution to generate a vacancy-rich cluster, and also precipitates more precipitation than the critical nucleation radius of G. P. zone coherence. Therefore, these precipitations have a slight effect on electrical conductivity for pre-aging temperature and time. Fig. 2 and Table 4 show that the heat treatment process experiences a higher re-aging temperature and longer re-aging time to obtain a higher electrical conductivity. Mainly on the grain boundary of the precipitate free zone, PFZ of the solute diffuses to the grain boundary and further interfuses with grain boundary precipitation. Therefore, precipitation has a coarse and large size in the re-aging stage and its precipitate spacing is also larger [21]. The re-aging stage also allows solution heat treatment and quenching produced by the dislocation network to reduce and eliminate. The temperature of re-aging increases the alloy's SCR but also directly decreases the mechanical strength of alloys [22], as shown in Fig. 1.

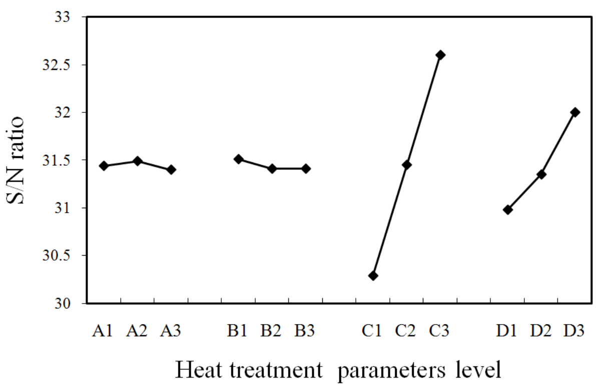

Fig. 2 S/N ratios showing the effects of each parameter level on electrical conductivity

C. Analysis of variance (ANOVA)

This study decomposed the total sum of the squared deviations SST into four sources: the sum of the squared deviations SS_A, SS_B due to pre-aging temperature, pre-aging time factor and the sum of the squared deviations SS_C, SS_D due to re-aging temperature, and re-aging time factor. The percentage contribution by each heat treatment parameter to the total sum of the squared deviations SST can be used to evaluate the importance of the heat treatment parameter change on the performance characteristic.

The hardness results of the ANOVA, as shown in Table 5 indicate that pre-aging and re-aging time are the most significant heat treatment factors affecting hardness performance characteristics. Based on the previous discussion, the optimal heat treatment parameters for hardness are pre-aging temperature at level 2, pre-aging time at level 2, re-aging temperature at level 1, and re-aging time at level 2. The electrical conductivity results of the ANOVA (Table 6) indicate that re-aging temperature and re-aging time are the most significant heat treatment factors affecting electrical conductivity performance characteristics. Based on the previous discussion, the optimal heat treatment parameters for electrical conductivity are pre-aging temperature at level 2, pre-aging time at level 1, re-aging temperature at level 3, and re-aging time at level 3.

Table 5 Results of the analysis of variance for hardness

Symbol	Heat treatment parameter	Sum of squares	Contribution %
A	Pre-ageing temp.	3.56	19.73
B	Pre-ageing time	6.05	33.53
C	Re-aging temp.	3.47	19.24
D	Re-aging time	4.96	27.50
Total		18.04	100

Table 6 Results of the analysis of variance for electrical conductivity

Symbol	Heat treatment parameter	Sum of squares	Contribution %
A	Pre-ageing temp.	0.01	0.1
B	Pre-ageing time	0.02	0.21
C	Re-aging temp.	8.00	82.82
D	Re-aging time	1.63	16.87
Total		9.66	100

V. Conclusions

Taguchi's robust design method can be used to analyze optimal heat treatment parameters for the 7050 aluminum alloy described in the paper. The current study draws the following conclusions based on the experimental results:

1) The Taguchi method efficiently obtains optimal heat treatment parameters for the 7050 aluminum alloy, minimizes the number of experiments, and analyzes the influence of each heat treatment parameter on the experiment results and the contributions of individual parameters.
2) In the heat treatment process of the 7050 aluminum alloy, the optimal conditions for better hardness value are: pre-aging temperature 120℃, pre-aging time 12hrs., re-aging temperature140℃, and re-aging time 8 hrs., respectively. The best electrical conductivity parameters are, pre-aging temperature 120℃, pre-aging time 4 hrs., re-aging temperature180℃, and re-aging time 24 hrs., respectively.
3) In the heat treatment process of the 7050 aluminum alloy, the contributions by percentage of hardness, pre-aging temperature, time and re-aging temperature, time are 19.7%, 33.53%, 19.24% and 27.5%, respectively. The

contributions of electrical conductivity are 0.1%, 0.21%, 82.82% and 16.87%, respectively.

4) The important sequence of optimal conditions for hardness are pre-aging time > re-aging time > pre-aging temperature > re-aging temperature, and the important sequence of optimal conditions for electrical conductivity are re-aging temperature > re-aging time > pre-aging time > pre-aging temperature.

REFERENCES

[1] Dumony D, Deschamps A. Characterization of precipitation microstructures in aluminium alloys 7040 and 7050 and their relationship to mechanical behavior[J]. Materials Science and Technology, 20(5): 567-576, 2004
[2] T. S. Srivatsan, S. Sriram, D. Veeraraghavan, V. K. Vasudevan, "Microstructure, tensile deformation and fracture behaviour of aluminium alloy 7055", Journal of Materials Science 32, 2883-2894, 1997
[3] Chen K H, Liu H W, Zhang Z, Li S, Tood R I. "The improvement of constituent dissolution and mechanical properties of 7055aluminum alloy by stepped heat treatments", Journal of Materials Processing Technology, 142(1): 190-196, 2003
[4] J. R. Davis, "ASM Specialty Handbook-Aluminum and Aluminum Alloys", ASM, April, 395, 2002
[5] I. N. Fridlyander, "Aluminum alloys in aircraft in the periods of 1970 - 2000 and 2001 - 2015", Metal Science and Heat Treatment, 43, 1 - 2, 2001
[6] B. M. Cina: U. S. Patent No. 3856584, Dec. 24, 1974
[7] T. Engdahl, V. Hansen, P. J. Warren, K. Stiller, "Investigation of fine scale precipitates in Al-Zn-Mg alloys after various heat treatment", Mater. Sci. Eng. A., 327, 59-64, 2002
[8] R. G. Song, Q. Z. Zang, M. K. Tseng, "The application of artificial neural networks to the investigation of aging dynamics in 7175 aluminum alloy", Mater. Sci. Eng. C., 3, 39-45, 1995
[9] F. Viana, A. M. Pinto, H. M. Csantos, A. B. Lopes, "Retrogression and re-aging of 7075 aluminum", J. Mater. Proc. Tech., 92, 54-59, 1999
[10] C. G. Yang, PhD thesis, Graduate Institute of Mechanical Engineering, National Central University, Taiwan, 2001
[11] Ber L. B. "Accelerated artificial aging regimes of commercial aluminum alloy", Mater. Sci. Eng., A280, 91-96, 2000
[12] K. Ural, "A study of optimization of heat treatment conditions in retrogression and re-aging treatment of 7075-T6 aluminum alloy", J. Mater. Sci. Letter, 13, 383, 1994
[13] G.Taguchi: Introduction to Quality Engineering, Asian Productivity Organisation, Tokyo, 1990
[14] P.J.Ross: Taguchi Techniques for Quality Engineering, McGraw-Hill, Newyork, 1988
[15] Taguchi G. Taguchi on robust technology development methods. New York, NY: ASME Press;1–40, 1993
[16] J. Iqbal, M. A. Shaikh, M. Ahmad and K. A. Shoaib, "Aging effect on hardness and microstructure of Al-Zn-Mg alloys, J. Mater. Sci. Technol., Vol.16 No.3, 2000
[17] Lin C K, Yang S T. "Corrosion fatigue behavior of 7050 aluminum alloys in different tempers" J. Engineering Fracture Mechanics, , 59 (6) : 779-795, 1998
[18] Gang S, Alf red C. Early2stage precipitation in Al2Zn2Mg2Cu alloy (7050) J. Acta Materialia, 52 (4) : 503 4516, 2004
[19] W. Wallace, J. C. Beddoes, M. C. demalherbe, "A New Approach to the problem of Stress Corrosion Cracking in 7075-T6 Aluminum", Aero. And Space J., Vol. 27, pp. 222-232, 1981
[20] Ohnishi and Shiota, "Heat Treatment to Reduce the Susceptibility Al-Zn-Mg-Cu Alloy to Stress Corrosion Cracking", Light Metal, Vol. 36, pp. 647-656, 1986.
[21] M. O. Speidel, "Stress Corrosion Cracking of Aluminum Alloy", Metallurgical Transaction A, Vol. 6A, pp. 631-642,1975
[22] B. M. Cina, "Aluminum Industrial Products", NASA Contractor Reports, U. S. Patent 3856584, 1974