Journal of Engineering Science and Technology
Vol. 13, No. 2 (2018) 515 - 523

PROCESS PARAMETER OPTIMIZATION FOR FRICTION STIR WELDING OF ALUMINIUM 2014-T651 ALLOY USING TAGUCHI TECHNIQUE

RAJEESH J., BALAMURUGAN R., BALACHANDAR K.*

School of Mechanical Engineering, SASTRA University, Thanjavur, 613401, Tamilnadu, India
*Corresponding Author: kbchandar@mech.sastra.edu

Abstract

This work focuses on the joining aluminium alloys (AA-2014 T651) using friction stir welding technique resulting in better mechanical properties within a chosen window of parameters. Experiments were conducted by varying rotational speed (355 rpm, 450 rpm, and 710 rpm), transverse speed (31.5 mm/min, 63 mm/min, 125 mm/min) and tool tilt (0°, 1°, 2°) at three different values. This work presents an approach based on Taguchi technique to establish the optimum conditions resulting in higher weld strengths of the AA-2014 T651 alloy weld joints, within a chosen window of parameters. The optimal parameters were found to be 355 rpm tool rotation speed , 31.5 mm/min traverse speed and a tool tilt of 2°, which resulted in 327.73 MPa tensile strength. From the analysis of variance (ANOVA) it was found that the influence of traverse speed on the tensile strength was 46.6%, while the influence of tool tilt and tool rotation speed were 33.1 % and 18.1 % respectively. Pareto analysis for the combination of parameters have shown more influence on the tensile strength by the traverse speed and tool tilt than that of other combinations. A regression model of the above process along with a regression fit equation was developed for the tensile strength of friction stir welded AA-2014 T651 alloy plates.

Keywords: Friction stir welding, Travel speed, Tool rotation speed, Tool tilt, ANOVA, Taguchi technique.

1. Introduction

Friction stir welding (FSW) is an emerging solid state welding technique. Unlike fusion welding processes, FSW weldments are not melted and recast. Being a recent technology, FSW has opened up a new area of welding research involving

Nomenclatures

RS	Tool rotation speed in rpm
TS	Traverse speed in mm/min
TT	Tool tilt in degrees

Greek Symbols

η	Signal to noise ratio

Abbreviations

AA	Aluminium Alloy
ANOVA	Analysis Of Variance
ASTM	American Standard of Testing of Materials
FEA	Finite Element Analysis
FSW	Friction Stir Welding

metals with low melting point and poor weldability alloys like aluminium [1, 2]. Heat treatable aluminium alloys, AA-2014 in particular has better strength to weight ratio and improved strength are extensively used in aircraft and defence industries.

The FSW joints have replaced the traditional joining processes like mechanical fastening and increased the possibilities of process automation also. This has enhanced defect-free joints with low distortion and lesser residual stresses. The other advantages include better joint efficiency and energy efficient joints of dissimilar alloys also. These reasons make FSW a perfect candidate process of joining AA-2014 plates.

Earlier studies [3-5] have been done on aluminium alloys with steel tool material for achieving significantly higher penetration & better surface appearance. The joint efficiency and higher impact strengths were possible even in ferrous and nickel based alloys, than using other grades of stainless steel [5]. Hence SS-316 was chosen as tool material for this study. Previous research works [6-8] have shown that the traverse speed has more influence on the tensile strength on aluminium alloys, while the tool tilt for low carbon steel alloy. Since many published research publications [9-15] have established optimization using Taguchi technique [16], it is evident that there is scope for optimization study of FSW of AA2014-T651, using a validated thermo-mechanical model. Considering the above fact, FSW trials were carried out in 8 mm thick rolled plates of AA2014-T651 using SS316 tool [17].

2. Experimental procedure

The chemical and mechanical properties of the chosen aluminium alloy (AA2014-T651) as shown in Tables 1 and 2 respectively. The plates with 100 mm length, 75 mm width and 8 mm thick were prepared to suit the friction stir welding. A non-consumable stainless steel (SS 316) tool was used to produce the joints. The tool had 25 mm and Φ10 mm of shoulder and pin diameter respectively. A clockwise threaded tool pin was utilized for joining the aluminium alloy(AA2014-T651) plates.

Table 1. Material composition (in weight %) [18].

Al	Cu	Cr	Fe	Mg	Mn	Si	Ti	Zn	Others
90.4 - 95	3.9 - 5	0.1	0.6	0.2 - 0.8	0.4 - 1.2	0.5 - 1.2	0.15	0.25	0.05-0.15

Table 2. Mechanical properties.

Density, g/cc	Brinell hardness number, BHN	Ultimate tensile strength, MPa	Yield strength, MPa	Poisson's ratio
2.8	135	483	414	0.33

The chosen plates were joined using 3000 rpm spindle speed, 22 kVA PC based position controlled friction stir welding machine. The weld parameters considered were tool rotation speed, traverse speed and tool tilt angle. Three different values were considered for each of the above. While the other parameters were kept constant, a constant axial force of 5KN was applied, for all the experiments. Taguchi's L9 orthogonal array was used to design the number of experiments, as shown in Table 3. Uniaxial transverse loading tensile test specimens were prepared, as per ASTM E-084 [19] using wire-cut electrode discharge machining.

Table 3. Weld parameter matrix.

Level	Trial No.	Tool rotation speed, rpm	Traverse speed, mm/min	Tool tilt, degrees
I	**I**	355	31.5	0
	II	355	63	1
	III	355	125	2
II	**IV**	450	31.5	1
	V	450	63	2
	VI	450	125	0
III	**VII**	710	31.5	2
	VIII	710	63	0
	IX	710	125	1

3. Results and Discussion

Taguchi analysis using MINITAB 17® was conducted considering maximum tensile strength and hence the larger-the better criterion was used. In this experiment, the signal to noise ratio reflects the measure of variation of tensile strength under different combinations of the FSW parameters and for j^{th} experiment, it is given as in Eq. (1).

$$S/N \text{ ratio } (\eta) = -10 \log_{10} ((1/n)\, \Sigma\, (1/\, (Y_{ij})^{\,2})) \quad (1)$$

where n is the number of experiments. The tensile results of the nine different specimens are as shown in Table 4.

Table 4. Predicted results from Taguchi analysis.

Trial No.	Tool rotation speed, rpm	Traverse speed, mm/min	Tool tilt, degree	S/N ratio	Tensile Strength, MPa
I	355	31.5	0	48.0418	252.40
II	355	63	1	49.0238	282.61
III	355	125	2	46.2652	205
IV	450	31.5	1	49.7481	307.19
V	450	63	2	50.3143	327.73
VI	450	125	0	41.1045	113.56
VII	710	31.5	2	49.6740	304.58
VIII	710	63	0	39.5937	95.43
IX	710	125	1	40.1354	101.57

The mean of the S/N ratio and the tensile strengths for the chosen parameters at all the levels are as tabulated in Table 5 and 6. The respective ranks obtained were calculated considering maximum delta values. From Fig. 1, the decrease in the mean of S/N ratio was observed for increase in tool rotation speed and traverse speed, while for the tool tilt, it was increasing. The same trend was also observed in the mean of tensile strength values.

Table 5. Taguchi response table for S/N ratios.

Level	Tool rotation speed, rpm	Traverse speed, mm/min	Tool tilt, degrees
1	**47.77**	**49.15**	42.91
2	47.05	46.31	46.30
3	43.13	42.49	**48.74**
Delta	4.63	6.66	5.83
Rank	**3**	**1**	**2**

Table 6. Taguchi response table for tensile strength.

Level	Tool rotation speed, rpm	Traverse speed, mm/min	Tool tilt, degrees
1	246.7	288.1	153.8
2	249.5	235.3	230.5
3	167.2	140.0	279.8
Delta	82.3	148.1	125.3
Rank	**3**	**1**	**2**

Figure 2 shows the trend of the various mean values of S/N ratios for different tool rotation speed (RS), traverse speed (TS), tool tilt (TT). No much change in the tensile strength values were observed for the change in the tool rotational speed up to 450 rpm, beyond which drastic reduction in the mean values were observed.

The Pareto chart (Fig. 3) shows the individual and combined effect of the chosen three parameters viz. tool rotation speed, tool traverse speed and tool tilt. The order of impact on the tensile strength is travel speed, followed by tool tilt and tool rotation speed respectively at 95% confidence level. The combined effect of tool tilt and traverse speed (BC) taking next position is a testimonial that both traverse speed and tool tilt have more influence on the tensile strength.

Figure 4 shows the normal probability chart with tensile strength response. The normal probability plot of residuals shows no severe deviation from the normality. The analysis is done considering the centre points, since it is impractical to check the existence of a non-linear element in the relationship between process parameters and the tensile strength of the weldments. The maximum of the S/N ratio and the tensile strength were observed at 355 rpm, 31.5 mm/min traverse speed and 2° tilt. Metallurgically, the effect of the tool rotational speed, traverse speed and tool tilt could be attributed to the churning effect along the weld nugget at higher tilt angles. Further, at higher speeds, churning effect improves the grain fineness along the weld nugget, as described in the literature [20, 21].

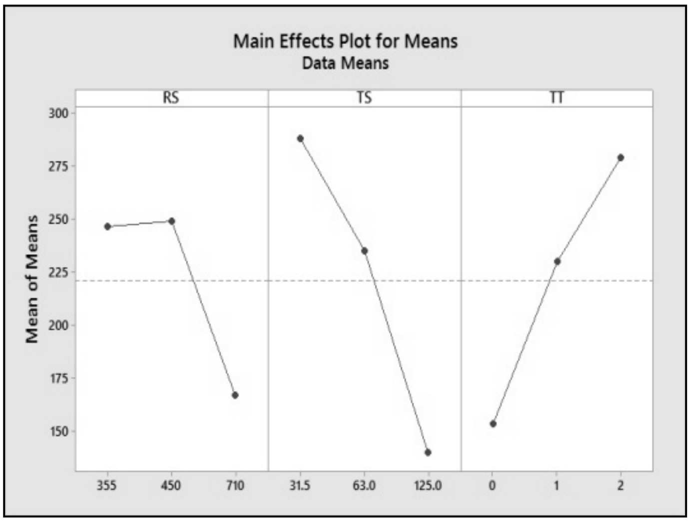

Fig. 1. Means vs. tool rotational speed (RS), traverse speed (TS), tool tilt (TT).

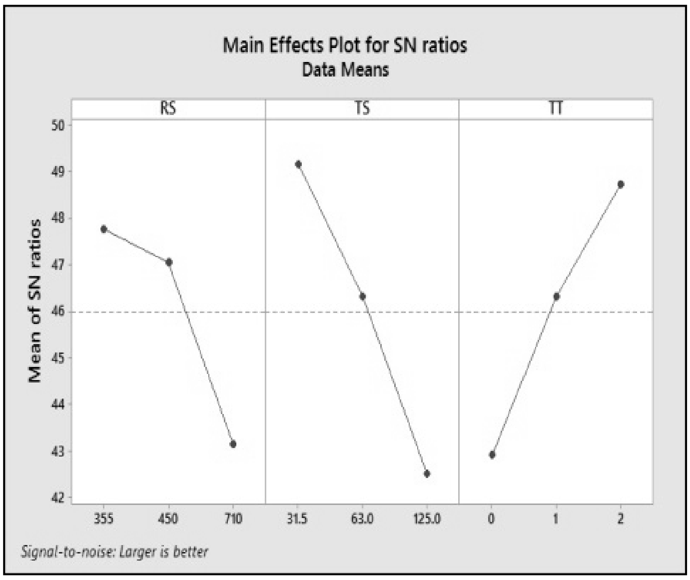

Fig. 2. S/N ratios vs. tool rotational speed (RS), traverse speed (TS), tool tilt (TT).

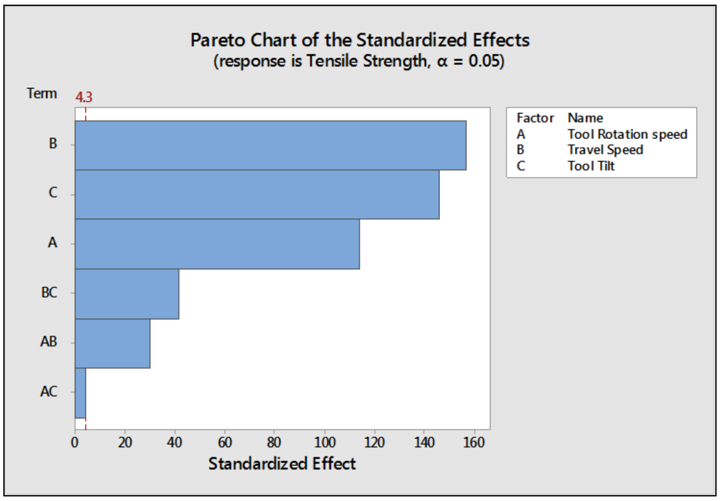

Fig. 3. Pareto chart at 95% confidence.

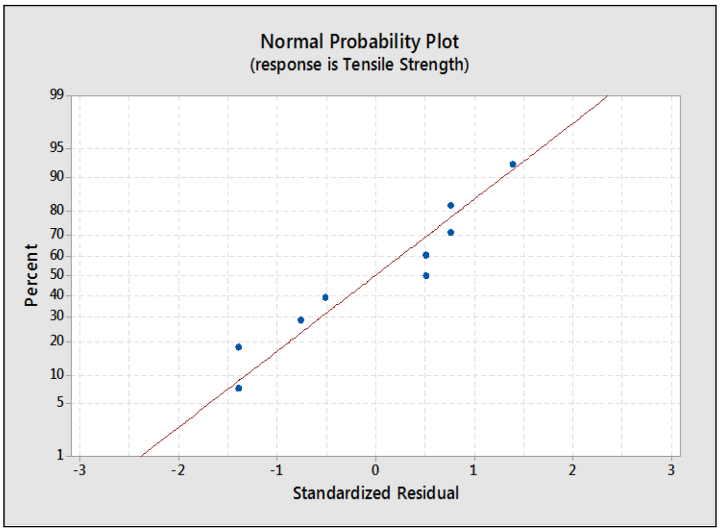

Fig. 4. Normal probability plot.

Considering the above combinations of parameters, a confirmation test was conducted for validating the expected increase in the tensile strength. The confirmation test resulted with 377.5 MPa tensile strength of the friction stir welded AA-2014 T651 plates, being the maximum for the chosen set of parameters considered.

Analysis of variance (ANOVA)

The analysis of variance, ANOVA was carried out following the Taguchi analysis. The total degrees of freedom considered were 8 (2 for each factor and rest for error estimation). Analysis of variance was utilized to determine the contribution of the individual process parameters on the tensile strength of FSW joints. The results obtained were tabulated in Table 7.

From the analysis, it can be construed that at the lower tool rotational speeds, the tensile strength were more robust. The tensile strength is more sensitive to change at higher temperatures. From the sum of squares value, it is evident that the traverse speed values are not closer to the best fit line (ideal case). This indicates that the change in traverse speed has a more impact towards varying tensile strength (response) and it is more sensitive to the change in traverse speed when compared to the other factors. The F-value from the Fischer test also gives the same order of the impact. The R^2 value is the measure of the level of errors in a statistical analysis. The R^2 value was very high (98.85%) suggesting that this to be a reliable model and has less errors.

Table 7. ANOVA table.

	Degree of freedom	**Adjacent sum-of squares**	**Adjacent Mean-of Squares**	**F-Value**	**% Contribution**
Tool rotation speed	2	13098	6549	8.12	18.08
Traverse speed	2	33761	16880.7	20.92	46.61
Tool tilt	2	23945	11972.5	14.84	33.06
Error	2	1614	806.9	-	2.22
Total	8	72418	-	-	100

The analysis of variance and the maximum influence of contribution of the parameters on the tensile strength were found to be traverse speed, tool tilt and tool rotation speed respectively. A regression model of the above process was developed and the regression fit equation was found to be as shown in Eq. (2),

$$\text{Tensile Strength} = 351.3 - (0.1064 \times RS) - (1.576 \times TS) + (62.7 \times TT) \qquad (2)$$

which resulted in 389.17 MPa tensile strength for the optimum values (355rpm, 31.5 mm/min and 2° tool tilt) within a chosen window of parameters

4. Conclusions

Optimal conditions for the improved tensile strength of the friction stir welded Al-2014 T651 alloy has been assessed under different processing conditions using fractional factorial Taguchi design and the following conclusions were arrived.

- From the ANOVA, it is found that the tool rotational speed has 18.08 % influence, traverse speed has 46.62 % influence and tool tilt has 33.06 % influence on the tensile strength of welded joints.
- Pareto analysis also resulted in the same order of impact similar to that of analysis of variance(ANOVA).
- The optimum value of tool rotational speed, traverse speed and tool tilt are found to be 355 rpm, 31.5 mm/min and 2° respectively.
- A non-linear regression model was developed to predict the tensile strength at optimal conditions and the value obtained from the model is within the range when compared to that of experimental value.

Acknowledgements

The authors are grateful to the Welding Research Institute (WRI), BHEL, Trichy, and Metal Joining Laboratory, School of Mechanical Engineering, SASTRA University, Thanjavur, India for extending the facilities to carry out this investigation.

References

1. Liu, H.J.; Fujii, H.; Maeda, M.; and Nogi, K. (2003). Mechanical properties of friction stir welded joints of 1050-H24 aluminium alloy. *Science and Technology of Welding and Joining*, 8(6), 450-454.
2. Colligan, K. (1999). Material flow behaviour during friction stir welding of aluminum. *Welding Journal Supplement*, 229-s-237-s.
3. Thomas, B.; Matthew, C. (2016). Study on the effect of tool material on mechanical properties and microstructures of friction stir welded AA6061 aluminum alloy. *International Journal of Latest Trends in Engineering and Technology* (*IJLTET*), 6(4), 537-543.
4. Karthick, K.R.; Samuela, L.C.; Saravanan, M.; and Balachandar, K. (2014). An experimental investigation on friction stir welding of dissimilar aluminium alloys AA2014-T6 and AA6063-O. National Weld Meet, NWM-2014, Kilakarai, India.
5. Sorensen, C.D.; and Nelson, T.W. (2007). *Friction stir welding of ferrous and nickel alloys*. ASM International, Chapter 6, 111-120.
6. Arun Kumar, N.; Elanchezhian, C.; and Ramnath, B.V. (2014). Investigation of process parameters of friction stir welded AA7075 aluminium alloys. *International Journal of Engineering Research*, 3(Special 1), 148-150
7. Pradeep, A.; and Muthukumaran, S. (2013). An analysis to optimize the process parameters of friction stir welded low alloy steel plates. *International Journal of Engineering, Science and Technology*, 5(3), 25-35.
8. Grujicic, M.; Arakere, G.; Pandurangan, B.; Hariharan, A.; Yen, C.-F.; Cheeseman, B.A.; and Fountzoulas, C. (2011) Statistical analysis of high cycle fatigue behaviour of friction stir welded AA5083-H321. *Journal of Materials Engineering and Performance*, 20(6), 855-864.
9. Devaiah, D.; Kishore, K.; and Laxminarayana, P. (2016). Optimization of process parameters in friction stir welding of dissimilar aluminium alloys (AA5083 and AA6061) using Taguchi technique. *International Journal of Industrial Engineering Computations*, 5(8), 15303-15310.
10. Shinde, R.D.; and Rathi, M.G. (2016), Optimization of FSW process parameter to achieve maximum tensile strength of aluminum alloy AA6061. *International Research Journal of Engineering and Technology*, 3(2), 936-943.
11. Bayazid, S.M.; Farhangi, H.; and Ghahramani, A. (2015). Investigation of friction stir welding parameters of 6063-7075 Al-alloys by Taguchi method. *Procedia Materials science*, 11, 6-11.
12. Kashyap C.G.K., Harinarayana K.; and Kumar, N.J. (2016). Process optimization of friction stir welded silicon carbide composites by Taguchi methodology. *International Conference on Recent Innovations in Civil & Mechanical Engineering*, *IOSR Journal of Mechanical and Civil Engineering* (*IOSR-JMCE*), 50-54.

13. Lakshminarayanan, A.K.; and Balasubramanian, V. (2008). Process parameters optimization for friction stir welding of RDE-40 aluminium alloy using Taguchi technique. *Transactions of Nonferrous Metals Society of China*, 18(3), 548-554.
14. Jayaram, M.; Sivasubramanian, R.; Balasubramanian, V.; and Lakshminarayanan, A.K (2009). Optimization of process parameters for friction stir welding of cost aluminium alloy A319 by Taguchi method. *Journal of Scientific & Industrial Research*, 68(01), 36-43.
15. Lee, C.-Y.; Lee, W.-B.; Kim, J.-W.; Choi, D.-H.; Yeon, Y.-M.; and Jung, S.-B. (2009). Lap joint properties of FSW dissimilar formed 5052 Al and 6061 Al alloys with different thickness. *Journal of Material Science*, 43(9), 3296-3304.
16. Varun, K.A.; and Balachandar, K. (2012). Effect of welding parameters on metallurgical properties of friction stir welded AA 6063-O. *International Conference on Intelligent Manufacturing Systems* (*ICIMS2012*), SASTRA University, Thanjavur, India.
17. Elangovan, K.; Balasubramanian, V.; and Valliappan, M. (2008). Influences of tool pin profile and axial force on the formation of friction stir processing zone in AA6061 aluminium alloy. *The International Journal of Advanced Manufacturing Technology*, 38(3-4), 285-295.
18. ASM international handbook committee (1997). *Metals handbook*, 4, 17-51.
19. ASTM E8 / E8M-15a (2015). Standard test methods for tension testing of metallic materials, ASTM International, West Conshohocken, PA, www.astm.org
20. Ghosh, M.; Kumar, K.; and Mishra, R.S. (2010). Analysis of microstructural evolution during friction stir welding of ultrahigh-strength steel. *Scripta Materialia*, 63(8), 851-854.
21. Venkateswaran, P.; and Mishra, A.K. (2013). Friction stir surfacing of cold sprayed bainitic steel . *International Journal of Applied Research in Mechanical Engineering* (*IJARME*), 31(1), 6-14.