Available online at www.sciencedirect.com
SCIENCE DIRECT®

Trans. Nonferrous Met. Soc. China 18(2008) 548−554

Transactions of Nonferrous Metals Society of China

www.csu.edu.cn/ysxb/

# Process parameters optimization for friction stir welding of RDE-40 aluminium alloy using Taguchi technique

A. K. LAKSHMINARAYANAN, V. BALASUBRAMANIAN

Centre for Materials Joining Research (CEMAJOR), Department of Manufacturing Engineering, Annamalai University, Annamalai Nagar−608 002, Tamil Nadu, India

Received 17 September 2007; accepted 29 November 2007

**Abstract:** Taguchi approach was applied to determine the most influential control factors which will yield better tensile strength of the joints of friction stir welded RDE-40 aluminium alloy. In order to evaluate the effect of process parameters such as tool rotational speed, traverse speed and axial force on tensile strength of friction stir welded RDE-40 aluminium alloy, Taguchi parametric design and optimization approach was used. Through the Taguchi parametric design approach, the optimum levels of process parameters were determined. The results indicate that the rotational speed, welding speed and axial force are the significant parameters in deciding the tensile strength of the joint. The predicted optimal value of tensile strength of friction stir welded RDE-40 aluminium alloy is 303 MPa. The results were confirmed by further experiments.

**Key words:** aluminium alloy; friction stir welding; tensile strength; Taguchi technique; analysis of variance

## 1 Introduction

Friction stir welding(FSW) has become a technology of widespread interest because of its numerous advantages, most important of which is its ability to weld otherwise unweldable alloys[1]. Compared with many of the fusion welding processes that are routinely used for joining structural alloys, FSW is an emerging solid state joining process in which the material that is being welded does not melt and recast[2]. Defect free welds with good mechanical properties have been made in a variety of aluminium alloys, even those previously thought to be not weldable. Friction stir welds will not encounter problems like porosity, alloy segregation and hot cracking, and welds are produced with good surface finish and thus no post weld cleaning is required[3]. There have been a lot of efforts to understand the effect of process parameters on material flow behavior, microstructure formation and hence mechanical properties of friction stir welded joints.

The effect of some important parameters such as rotational speed, traverse speed and axial force on weld properties is major topics for researchers[4−6]. In order to study the effect of FSW process parameters, most workers follow the traditional experimental techniques, i.e. varying one parameter at a time while keeping others constant. This conventional parametric design of experiment approach is time consuming and calls for enormous resources. Taguchi statistical design is a powerful tool to identify significant factor from many by conducting relatively less number of experiments. However, this design fundamentally does not account for the interaction among processing parameters. In view of cost and time saving, occasionally these interactions can be neglected. If mandatory, the missing interactions can be analyzed by further running the required experiments.

Though research work applying Taguchi methods on casting methods and fusion welding processes have been reported in literatures[7−10], it appears that the optimization of FSW process parameters of RDE-40 aluminium alloy using Taguchi method has not been reported yet. Considering the above facts, the Taguchi L9 method is adopted to analyze the effect of each processing parameters (i.e. rotational speed, traverse speed and axial force) for optimum tensile strength of friction stir welded joints of RDE-40 aluminium alloy.

## 2 Taguchi method

Taguchi method is an efficient problem solving tool,

**Corresponding author:** V. BALASUBRAMANIAN; Tel: +91-4144-239734(O); +91-4144-241147(R); Fax: +91-4144-238080/238275; E-mail: visvabalu@ yahoo.com

which can upgrade/improve the performance of the product, process, design and system with a significant slash in experimental time and cost[11]. This method that combines the experimental design theory and quality loss function concept has been applied for carrying out robust design of processes and products and solving several complex problems in manufacturing industries. Further, this technique determines the most influential parameters in the overall performance. The optimum process parameters obtained from the Taguchi method are insensitive to the variation in environmental condition and other noise factors[12]. The number of experiments increases with the increase of process parameters. To solve this complexity, the Taguchi method uses a special design of orthogonal array to study the entire process parameter space with a small number of experiments only. Taguchi defines three categories of quality characteristics in the analysis of (Signal/Noise) ratio, i.e. the lower-the-better, the larger-the-better and the nominal -the-better. The S/N ratio for each of process parameter is computed based on S/N analysis. Regardless of the category of the quality characteristics, a larger S/N ratio corresponds to better quality characteristics. Therefore, the optimal level of process parameter is the level of highest S/N ratio. Furthermore, a statistical analysis of variance (ANOVA) can be performed to see which process parameter is statistically significant for each quality characteristics.

## 3 FSW process parameters

An Ishikawa diagram (cause and effect diagram)[13] was constructed as shown in Fig.1 to identify the FSW process parameters that may influence the quality of FSW joints. From Fig.1, the welding process parameters such as tool rotational speed, traverse speed, axial force, play a major role in deciding the weld quality. In the present investigation, three level process parameters, i.e. rotational speed(RS), traverse speed(TS) and axial force(AF) were considered. Trail experiments were carried out using 6 mm thick rolled plates of RDE-40 aluminum alloy to fix the working range of FSW process parameters. The chemical composition and mechanical properties of the base metal (RDE-40) used in this investigation are given in Table 1 and 2, respectively.

**Table 1** Chemical composition of base metal (mass fraction,%)

| Zn | Mg | Mn | Fe | Si | Cu | Cr | Ti | Al |
|---|---|---|---|---|---|---|---|---|
| 3.62 | 2.49 | 0.18 | 0.28 | − | 0.1 | − | − | Bal. |

**Table 2** Mechanical properties of base metal

| Yield strength/ MPa | Ultimate tensile strength/ MPa | Elongation/ % | Reduction in cross sectional area/% | Hardness at 0.5 kg load/ VHN |
|---|---|---|---|---|
| 304 | 383 | 15.0 | 10.25 | 130 |

When the rotational speed was lower than 1 200 r/min, wormhole at the retreating side of weld nugget was observed and it may be due to insufficient heat generation and insufficient metal transportation; when the rotational speed was higher than 1 600 r/min, tunnel defect was observed and it may be due to excessive turbulence caused by higher rotational speed. Similarly, when the welding speed was lower than 22 mm/min, pin holes type of defect was observed due to excessive heat input per unit length of the weld and no vertical movement of the metal; when the welding speed was higher than 75 mm/min, tunnel at the bottom in retreating side was observed due to insufficient heat

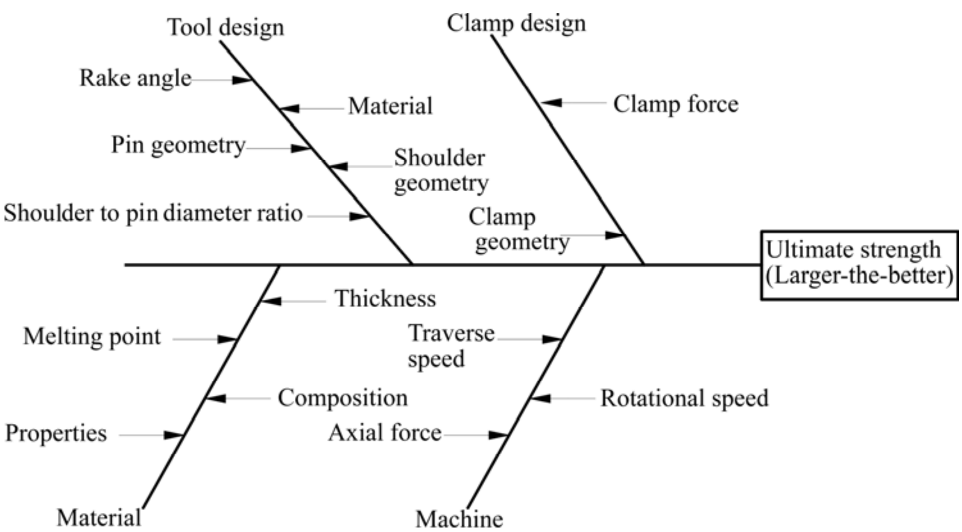


**Fig.1** Cause and effect diagram

input caused by inadequate flow of material. When the axial force was lower than 4 kN, tunnel and crack like defect at the middle of the weld cross section in retreating side were observed since insufficient downward force causes no vertical flow of material; when the axial force was increased beyond 8 kN, large mass of flash and excessive thinning were observed due to higher heat input.

Hence, the range of process parameters such as tool rotational speed was selected as 1 200−1 600 r/min, the traverse speed was selected as 22−75 mm/min and axial force was selected as 4−8 kN. The FSW process parameters along with their ranges are given in Table 3.

**Table 3** Process parameters with their range and values at three levels

| Level | Rotational speed, $R$/(r·min$^{-1}$) | Traverse speed, $T$/(mm·min$^{-1}$) | Axial force, $F$/kN |
|---|---|---|---|
| Range | 1 200−1 600 | 22−75 | 4−8 |
| Level 1 | 1 200 | 22 | 4 |
| Level 2 | 1 400 | 45 | 6 |
| Level 3 | 1 600 | 75 | 8 |

## 4 Selection of orthogonal array(OA)

Before selecting a particular OA to be used as a matrix for conducting the experiments, the following two points must be considered: 1) The number of parameters and interactions of interest; 2) The number of levels for the parameters of interest.

The non-linear behavior, if exists among the process parameters, can only be studied if more than two levels of the parameters are used. Therefore, each parameter was analysed at three levels. To limit the study, it was decided not to study the second order interaction among the parameters. Each three level parameter has 2 degrees of freedom (DOF=number of levels−1), the total DOF required for 3 parameters each at three levels is 6 (=3×(3−1)). As per Taguchi's method, the total DOF of selected OA must be greater than or equal to the total DOF required for the experiment. So an L9 OA having 8(=9−1) degrees of freedom were selected for the present analysis.

## 5 Experimental work

The rolled plates of RDE-40 aluminium alloy were used as the base material in this investigation. RDE-40 aluminium alloy (Al-Zn-Mg alloy) was basically developed by Research & Development Engineers, Pune, India, and it is closely confirming with the specifications of AA7039 alloy. It is the most widely used high strength aluminium alloy, and has gathered wide acceptance in the fabrication of light mass structures requiring high strength to mass ratio, such as transportable bridge girders, military vehicles, road tankers and railway transport systems. The rolled plates of 6 mm in thickness were cut into the required size (300 mm×150 mm) by power hacksaw cutting and milling. Square butt joint configuration was prepared to fabricate FSW joint. The initial joint configuration was obtained by securing the plates in position using mechanical clamps. The direction of welding was normal to the rolling direction. Single pass welding procedure was used to fabricate the joints. Threaded cylindrical pin profiled, non-consumable tool made of high carbon steel was used to fabricate the joints. An indigenously designed and developed machine (15 h; 3 000 r/min; 25 kN) was used to fabricate the joints.

The welded joints were sliced (as shown in Fig.2(a)) using a power hacksaw and then machined to the required dimensions as shown in Fig.2(b). The American Society for Testing of Materials (ASTM E8M-04) guidelines were followed for preparing the test specimens. The smooth tensile specimens were prepared to evaluate ultimate tensile strength. At each experimental level three specimens were prepared to minimize the noise factor. Tensile test was carried out in 100 kN, electromechanical controlled universal testing machine (Make: FIE-Bluestar, India; Model: UNITEK-94100).

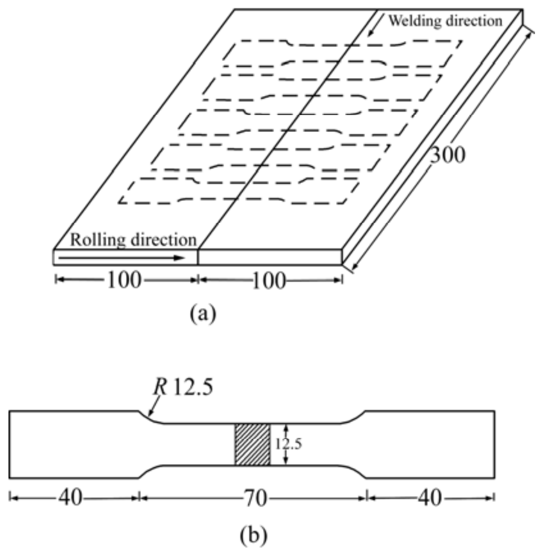


**Fig.2** Scheme of welding with respect to rolling direction and extraction of tensile specimens (a) and dimensions of flat smooth tensile specimen (b)

## 6 Results and discussion

### 6.1 Signal to noise ratio

Tensile strength is the main characteristic considered in this investigation describing the quality of FSW joints. In order to assess the influence of factors on the response, the means and Signal-to-Noise ratios (S/N) for each control factor can be calculated. The signals are indicators of the effect on average responses and the noises are measures of the influence on the deviations from the sensitiveness of the experiment output to the noise factors. The appropriate S/N ratio must be chosen using previous knowledge, expertise, and understanding of the process. When the target is fixed and there is trivial or absent signal factor (static design), it is possible to choose the signal-to-noise (S/N) ratio depending on the goal of the design[14]. In this study, the S/N ratio was chosen according to the criterion of the larger-the-better, in order to maximize the response. In the Taguchi method, the signal to noise ratio is used to determine the deviation of the quality characteristics from the desired value. The S/N ratio $\eta_j$ (larger-the-better) in the $j_{\mathrm{th}}$ experiment can be expressed as

$$\eta_j = -10\lg\left(\frac{1}{n}\sum Y_{ijk}^2\right) \quad (1)$$

where $n$ is the number of tests and $Y_{ijk}$ is the experimental value of the $i$th quality characteristics in the $j$th experiment at the $k$th test.

In the present study, the tensile strength data were analyzed to determine the effect of FSW process parameters. The experimental results were then transformed into means and signal-to-noise (S/N) ratio. In this work, 9 means and 9 S/N ratios were calculated and the estimated tensile strength, means and signal-to-noise (S/N) ratio are given in Table 4. The analysis of mean for each of the experiments will give the better combination of parameters levels that ensures a high level of tensile strength according to the experimental set of data. The mean response refers to the average value of performance characteristics for each parameter at different levels. The mean for one level was calculated as the average of all responses that were obtained with that level. The mean response of raw data and S/N ratio of tensile strength for each parameter at level 1, 2 and 3 were calculated and are given in Table 5. The means and S/N ratio of the various process parameters when they changed from the lower to higher levels are also given in Table 5. It is clear that a larger S/N ratio corresponds to better quality characteristics. Therefore, the optimal level of process parameter is the level of highest S/N ratio[15]. The mean effect (Fig.3) and S/N ratio (Fig.4) for tensile strength were calculated by statistical software[16], indicating that the tensile strength was at maximum when rotational speed, welding speed and axial force are at level 2, i.e. rotational speed at 1 400 r/min, welding speed at 22 mm/min and axial force at 6 kN. The comparison of mean effect and S/N ratio are presented in Fig.3.

### 6.2 Analysis of variance (ANOVA)

Analysis of variance(ANOVA) test was performed to identify the process parameters that are statistically significant. The purpose of the ANOVA test is to investigate the significance of the process parameters which affect the tensile strength of FSW joints. The ANOVA results for tensile strength of means and S/N ratio are given in Tables 6 and 7 respectively. In addition, the F-test named after Fisher can also be used to determine which process has a significant effect on tensile strength. Usually, the change of the process parameter has a significant effect on the quality characteristics, when $F$ is large. The results of ANOVA indicate that the considered process parameters are highly significant factors affecting the tensile strength of FSW joints in the order of rotational speed, traverse speed and axial force.

### 6.3 Interpretation of experimental results

6.3.1 Percentage of contribution

The percentage of contribution is the portion of the total variation observed in the experiment attributed to each significant factors and/or interaction which is reflected. The percentage of contribution is a function of the sum of squares for each significant item; it indicates

**Table 4** Orthogonal array for L9 with response (raw data and S/N ratio)

| No. | Input parameter | | | Response | | | Mean value | S/N ratio |
|---|---|---|---|---|---|---|---|---|
| | $R$ | $T$ | $F$ | T1 | T2 | T3 | | |
| 1 | 1 200 | 22 | 4 | 190 | 202 | 200 | 197.333 | 45.894 6 |
| 2 | 1 200 | 45 | 6 | 265 | 260 | 268 | 264.333 | 48.441 0 |
| 3 | 1 200 | 75 | 8 | 209 | 205 | 211 | 208.333 | 46.373 3 |
| 4 | 1 400 | 22 | 6 | 266 | 269 | 261 | 265.333 | 48.473 8 |
| 5 | 1 400 | 45 | 8 | 298 | 290 | 286 | 291.333 | 49.284 0 |
| 6 | 1 400 | 75 | 4 | 240 | 236 | 242 | 239.333 | 47.578 6 |
| 7 | 1 600 | 22 | 8 | 220 | 228 | 225 | 224.333 | 47.015 0 |
| 8 | 1 600 | 45 | 4 | 234 | 238 | 230 | 234.000 | 47.381 8 |
| 9 | 1 600 | 75 | 6 | 239 | 230 | 241 | 236.667 | 47.477 3 |

**Table 5** Main effects of tensile strength (means and S/N ratio)

| Process parameter | Level | Means | | | S/N ratio | | |
|---|---|---|---|---|---|---|---|
| | | A | B | C | A | B | C |
| Average value | L1 | 223.3 | 229.0 | 223.6 | 46.90 | 47.13 | 46.95 |
| | L2 | 265.3 | 263.2 | 255.4 | 48.45 | 48.37 | 48.13 |
| | L3 | 231.7 | 228.1 | 241.3 | 47.29 | 47.14 | 47.56 |
| Main effects | L2−L1 | 42.0 | 35.1 | 31.9 | 1.54 | 1.24 | 1.18 |
| | L3−L2 | −33.6 | −35.1 | −14.1 | −1.16 | −1.23 | −0.57 |

**Table 6** ANOVA for tensile strength (means)

| Source | S/N Ratio | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | DF | Seq SS | Adj SS | Adj MS | SS’ | F | P | Percentage of contribution |
| RS | 2 | 2 966.89 | 2 966.89 | 1 483.44 | 2 885.44 | 36.44 | 0.027 | 41.30 |
| TS | 2 | 2 404.74 | 2 404.74 | 1 202.32 | 2 323.34 | 29.54 | 0.033 | 33.25 |
| AF | 2 | 1 532.07 | 1 532.07 | 766.04 | 1 450.67 | 18.82 | 0.050 | 20.76 |
| Error | 2 | 81.41 | 81.41 | 40.70 | 326.2 | − | − | 4.67 |
| Total | 8 | 6 985.65 | | | | | | 100.00 |

**Table 7** ANOVA for tensile strength (S/N ratio)

| Source | S/N Ratio | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | DF | Seq SS | Adj SS | Adj MS | SS’ | F | P | Percentage of contribution |
| RS | 2 | 3.862 2 | 3.862 2 | 1.9311 2 | 3.753 86 | 35.65 | 0.027 | 41.25 |
| TS | 2 | 3.043 3 | 3.043 3 | 1.5216 5 | 2.934 96 | 28.09 | 0.034 | 32.25 |
| AF | 2 | 2.085 8 | 2.085 8 | 1.0428 8 | 1.977 46 | 19.25 | 0.049 | 21.73 |
| Error | 2 | 0.108 3 | 0.108 3 | 0.0541 7 | 0.433 42 | − | − | 4.77 |
| Total | 8 | 9.099 7 | | | | | | 100.00 |

DF—Degrees of freedom, Seq SS—Sequencial sum of squares, Adj SS—Adjusted sum of square, Adj MS—Adjusted mean square, SS’—Pure sum of squares, F—Fisher ratio, P—probability that exceeds the 95 % confidence level.

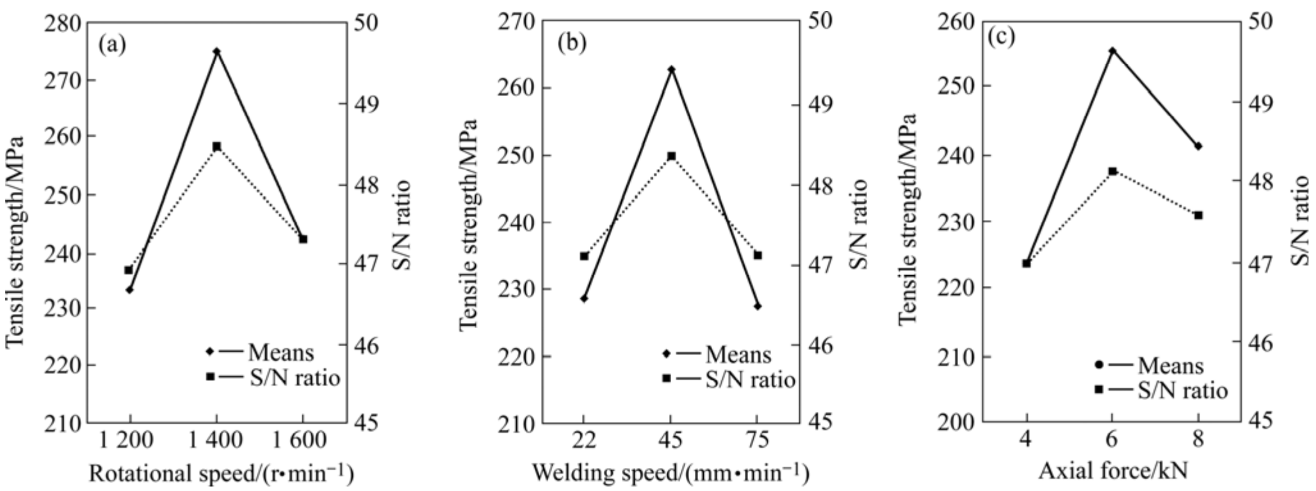


**Fig.3** Comparison of mean effect and S/N ratio of tensile strength

the relative power of a factor to reduce the variation. If the factor levels are controlled precisely, then the total variation could be reduced by the amount indicated by the percentage of contribution. The percentage of contribution of the rotational speed, welding speed and axial force is shown in Fig.4.

6.3.2 Estimation of optimum performance characteristics

The methods described in this paper for tensile

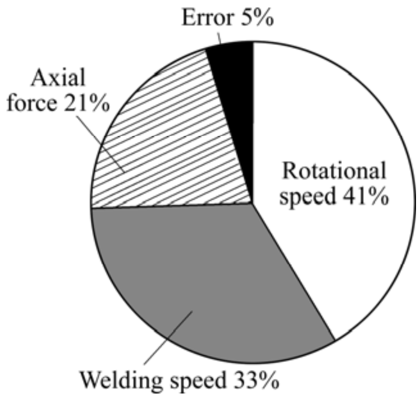


**Fig.4** Percentage of contribution of factors (Means)

strength prediction and optimization can eliminate the need for performing experiments on the basis of the conventional trial and error method which is time consuming and economically not justifiable. The present study is aimed at to identify the most influencing significant parameter and percentage contribution of each parameter on tensile strength of friction stir welded RDE-40 aluminium joints by conducting minimum number of experiments using Taguchi orthogonal array. Based on the highest values of the S/N ratio and mean levels (Fig.3) for the significant factors A, B and C the overall optimum condition thus obtained were $A_2$, $B_2$ and $C_2$. Similar results were obtained by Vijan and Arunachalam studied on optimization of squeeze casting process parameters using taguchi analysis ($A_3$, $B_2$, $C_2$).

Once an experiment is conducted and the optimum treatment condition within the experiment is determined, one of two possibilities exists:

1) The prescribed combination of factors level is identical to one of those in the experiment;

2) The prescribed combination of factors level is not included in the experiment.

It must be noted that the above combination of factor levels $A_2$, $B_2$, $C_2$ are not among the nine combinations tested for the experiment. This is expected because of the multifactor nature of the experimental design employed (9 from $3^3$=27 possible combinations). The optimum value of tensile strength is predicted at the selected levels of significant levels of significant parameters. The estimated mean of the response characteristics (tensile strength) can be computed as

$$\text{Tensile strength(TS)} = \overline{RS}_2 + \overline{TS}_2 + \overline{AF}_2 - 2\overline{T} \qquad (2)$$

where $\overline{T}$ is the overall mean of tensile strength, MPa (Table 2); $\overline{RS}_2$ is the average tensile strength at second level of rotational speed, 1 400 r/min; $\overline{TS}_2$ is the average tensile strength at second level of welding speed, 45 mm/min, $\overline{AF}_2$ is the average tensile strength at second level of axial force 6 kN. Substituting the values of various terms in Eqn.(2), then

Tensile strength=265.3+263.2+255.4−2×238.37= 303.16 MPa

### 6.4 Confirmation test

The final step is verifying the improvement in tensile strength by conducting experiments using optimal conditions. Three confirmation experiments were conducted at the optimum setting of process parameters. The rotational speed, traverse speed and axial force were set at level 2 and the average tensile strength of friction stir welded RDE-40 aluminium alloy was found to be 311 MPa, which was within the confidence interval of the predicted optimal of tensile strength.

## 7 Conclusions

1) The percentage of contribution of FSW process parameters was evaluated. It is found that the tool rotational speed has 41% contribution, traverse speed has 33% contribution and axial force has 21% contribution to tensile strength of welded joints.

2) The optimum value of process parameters such as rotational speed, traverse speed and axial force are found to be 1 400 r/min, 45 mm/min and 6 kN respectively.

## Acknowledgements

The authors are grateful to the Department of Manufacturing Engineering, Annamalai University, Annamalainagar, Tamil Nadu, India for extending the facilities of Metal Joining Laboratory and Materials Testing Laboratory to carry out this investigation. The authors also wish to express their sincere thanks to Naval Research Board (NRB), Ministry of Defence, New Delhi for the financial support to carry out this investigation through sponsored project No.DNRD/05/4003/NRB/67. The authors also acknowledge the help rendered by Mr. Subbiah, Manager, LTM, Chennai, India to procure the base material.

## References

[1] COLLIGAN K. Material flow behaviour during friction stir welding of aluminum [J]. Welding Journal, 1999, 7: 229s−237s.

[2] LIU H J, FUJI H, MAEDA M, NOGI K. Mechanical properties of friction stir welded joints of 1050-H 24 aluminum alloy [J]. Science and Technology of Welding and Joining, 2003, 8: 450−454.

[3] BARCELLONA A, BUFFA G, FRATINI L, PALMERI D. On microstructural phenomena occurring in friction stir welding of aluminum alloys [J]. Materials Processing Technology, 2006, 177: 340−343.

[4] LEE W B. Mechanical properties related to microstructural variation of 6061 Al alloy joints by friction stir welding [J]. Material Transactions, 2004, 45(5): 1700−1705.

[5] ELANGOVAN K, BALASUBRAMANIAN V. Influences of pin profile and rotational speed of the tool on the formation of friction stir processing zone in AA2219 aluminum alloy [J]. Journal of Materials Science Engineering A, 2007, 459: 7−18.

[6] ELANGOVAN K, BALASUBRAMANIAN V. Effect of tool pin profile and axial force on the formation of friction stir processing zone in AA6061 aluminum alloy [J]. International Journal of Advanced Manufacturing Technology. DOI: 10.1007/s00170-007-1100-2.

[7] CASALINO G, CURCIO F, MEMOLA F, MINUTOLO C. Investigation on Ti6A14V laser welding using statistical and Taguchi approaches [J]. Journal of Material Processing Technology, 2005, 167: 422−428.

[8] GUHARAJA S, NOORAL HAQ A, KARUPPANNAN K M. Optimization of green sand casting process parameters by using Taguchi's method [J]. International Journal of Advanced Manufacturing Technology, 2006, 30: 1040−1048.

[9] VIJIAN P, ARUNCHALAM V P. Optimization of squeeze casting process parameters using Taguchi analysis [J]. International Journal of Advanced Manufacturing Technology, 2006, 30: 1122−1127.

[10] KUMAR S, KUMAR P, SHAN H S. Parametric optimization of surface roughness castings produced by evaporative pattern casting process [J]. Materials Letters, 2006, 60: 3048−3053.

[11] MONTGOMERY D C. Design and analysis of experiments [M]. IV Edition. NY: John-Wiley & Sons, Inc, 2006.

[12] ROSS P J. Taguchi techniques for quality engineering [M]. NY: Tata McGraw Hill, 1988.

[13] Factory Management and the Asian Productivity Organization. Industrial engineering and technology−Japan quality control circles, quality control case studies [M]. Tokyo: Serasia Limited, 1982.

[14] PHADKE M S. Quality engineering using Robust design [M]. NJ, USA: PTR, Prentice Hall, Englewood Cliffs, 1989.

[15] SHARMA P, VERMA A, SIDHU R K, PANDAY O P. Process parameter selection for strontium ferrite sintered magnets using Taguchi L9 orthogonal design [J]. Material Processing Technology, 2005, 168:147−151.

[16] MINITAB$^{TM}$ Statistical software Release 15.

**(Edited by YUAN Sai-qian)**