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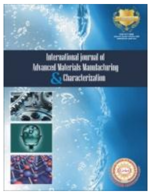

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Application of Taguchi Method in the Optimization of Friction Stir Welding Parameters of an Aeronautic Aluminium Alloy

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The Friction Stir Welding (FSW) process is still an innovative solid state mechanical processing technology enabling high quality joints in materials previously considered with low weldability such as most of the aeronautic aluminium alloys. The Taguchi method was used to find the optimal FSW parameters for improvement mechanical behaviour of AA2024-T351. The Taguchi design is an efficient and effective experimental method in which a response variable can be optimized. The parameters considered were vertical downward forging force, travel speed and pin length. An orthogonal array of L_9 (3^4) was used; ANOVA analyses were carried out to identify the significant factors affecting tensile strength (GETS), bending toughness (GEB) and hardness field. An algebraic model for predicting the best mechanical performance was developed and the optimal FSW combination was determined using this model. The results obtained were validated by conducting confirmation experiments.

Introduction

Significant interest has been shown in the use of advanced welding techniques for aircraft structures, particularly given the design and manufacturing benefits they afford over established mechanical joining methods. Whilst a variety of welding methods have been identified for airframe structures, friction stir welding is an important candidate technique that is distinctive in being a low energy, solid-state process [1]. Although the friction stir welding joints have a better quality compared to the fusion techniques, there are still some defects that may arise and which are very sensitive to small variations in process parameters. Typical defects that may arise in FSW joints result from: imperfect stir of the materials during the processing, inadequate surface preparation, lack of penetration of the pin and non-uniform vertical forging forces along the material thickness. Some characteristic FSW defects are lack of penetration (typically addressed as kissing-bond), root flaw (concerning weak or intermittent linking), voids on the advancing side and second phased particles and oxides alignment under the shoulder [2]. Advanced aerospace aluminium alloys have been required to allow high fracture toughness, higher fatigue performance, high formability, and superplasticity to meet the needs for lower structural weight, higher damage tolerance and durability [3].

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Taguchi method

The method presented in this study is an experimental design process called the Taguchi design method. Taguchi design, developed by Dr. Genichi Taguchi, is a set of methodologies by which the inherent variability of materials and manufacturing processes has been taken into account at the design stage [4]. Although similar to design of experiment (DOE), the Taguchi design only conducts the balanced (orthogonal) experimental combinations, which makes the Taguchi design even more effective than a fractional factorial design. By using the Taguchi techniques, industries are able to greatly reduce product development cycle time for both design and production, therefore reducing costs and increasing profit [5]. Taguchi proposed that engineering optimization of a process or product should be carried out in a three-step approach: system design, parameter design, and tolerance design. In system design, the engineer applies scientific and engineering knowledge to produce a basic functional prototype design.

The objective of the parameter design [6] is to optimize the settings of the process parameter values for improving performance characteristics and to identify the product parameter values under the optimal process parameter values. The parameter design is the key step in the Taguchi method to achieving high quality without increasing cost. The steps included in the Taguchi parameter design are: selecting the proper orthogonal array (OA) according to the numbers of controllable factors (parameters); running experiments based on the OA; analyzing data; identifying the optimum condition; and conducting confirmation runs with the optimal levels of all the parameters [5].

The main effects indicate the general trend of influence of each parameter. Knowledge of the contribution of individual parameters is the key to deciding the nature of the control to be established on a production process. Analysis of variance (ANOVA) is the statistical treatment most commonly applied to the results of the experiments to determine the percentage contribution of each parameter against a stated level of confidence [6]. Taguchi suggests [7] two different routes for carrying out the complete analysis. In the standard approach the results of a single run or the average of repetitive runs are processed through the main effect and ANOVA (raw data analysis). The second approach, which Taguchi strongly recommends for multiple runs, is to use the signal-to-noise (S/N) ratio for the same steps in the analysis.

In the present investigation, only the raw data analysis was performed. The effects of the selected FSW parameters on the selected performance characteristics were investigated through the plots of the main effects based on raw data. The optimum condition for each of the performance characteristics was established through the raw data analysis. An algebraic model for predicting the best mechanical performance was developed. The optimal FSW parameters were verified using a confirmation experiment.

Experimental design

Selection of FS welding parameters and their levels

The welding experiments were carried out on an ESAB Legio FSW 3UL. Plunge and dwell periods (v_x=0) were performed under vertical position control and weld period (v_x>0) was carry out under vertical downward force control.

The FSW tool that was use to perform all the welds is a patented modular concept of FSW tools. This tool is based on 3 main components: Body; Shoulder and Pin, which enable the easy replacement of any damage component and the combination between different shoulder and pin geometries. Moreover, this tool enables internal forced refrigeration and the setting of any length for the pin. The pin is 9º conical with a bottom diameter of 4mm and LH threads along its length. The shoulder is plane with 2 spiral striates scrolling an angle of 180º with outer and inner diameter of 16mm and 5mm, respectively. Mechanical properties and chemical composition of 2024-T351 aluminium alloy which was used in the experiments are shown in Tables 1 and 2.

Table 1. Mechanical properties of AA2024-T351

Young modulus (GPa)	Yield stress (MPa)	Ultimate Stress (MPa)	Elongation (%)	Toughness (J/mm^3)
75.5	383.8	533.8	22.0	80.7

'

Table 2. Chemical composition of AA2024-T351, % weight

Al	Mg	Cu	Mn
89.87	3.38	6.20	0.55

The initial welding parameters implemented were the following: a rotation speed of 1000 rpm (CW), a travel speed of 250 mm/min, a plunge gap pin-to-anvil plate of 50 m, a vertical downward forging force of 900 kg, a pin length of 4.17 mm and a null tilt angle. The process parameters workable range for the experiments was chosen in order to control the weld seams quality including defects in the root, the type of defect more difficult to eliminate in sound welds. Therefore, three levels of the FS welding parameters were selected as shown in Table 3.

Orthogonal array experiment

To select an appropriate orthogonal array for experiments, the total degrees of freedom need to be computed. The degrees of freedom are defined as the number of comparisons between process parameters that need to be made to determine which level is better and specifically how much better it is. For example, a three-level process parameter counts for two degrees of freedom. The degrees of freedom associated with interaction between two process parameters are given by the product of the degrees of freedom for the two process parameters [8]. In the present study, the interaction between the welding parameters is neglected. Therefore, there are six degrees of freedom owing to the three welding parameters.

Once the degrees of freedom required are known, the next step is to select an appropriate orthogonal array to fit the specific task. Basically, the degrees of freedom for the orthogonal array should be greater than or at least equal to those for the process parameters. In this study, an L_9 orthogonal array was used. This array has twenty six degrees of freedom and it can handle three-level process parameters. Each FS welding parameter is assigned to a column and twenty seven welding parameter combinations are available. A total of nine experimental runs must be conducted, using the combination of levels for each control factor (A–D) as indicated in Table 3.

Table 3. The basic Taguchi L_9 (3^4) orthogonal array

Run	Control factors and levels			
	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

However, this study did not use all the array cells for four factors, because only three factors were considered (vertical downward forging force, travel speed and pin length). Therefore, the last column (for the fourth factor) in the

L_9orthogonal array is left empty for this specific study.

The selected parameters are listed in Table 4 along with their applicable codes and values for use in the Taguchi parameter design study.

Table 4. Friction stir welding parameters and their levels

FSW parameter	Symbol	Level 1	Level 2	Level 3
Variable parameters				
Vertical force (kg)	A	850	900	950
Travel speed (mm/min)	B	120	250	500
Pin length (mm)	C	4.00	4.08	4.17
Constant parameters				
Tilt angle	0			
Rotation speed	1000 rpm			
Rotation direction	CW			
Plunge speed	0.1 mm/s			
Dwell time	8 s			
FSW control	Vertical force control			

Welding performance assessment

In order to conclude about the quality of the welded joint relatively to the base material properties, a coefficient called Global Efficiency to Tensile Strength, GETS (1) was developed by Vilaça [9].

$$GETS = \left(C_E \frac{E_i}{E_{BM}} + C_{\sigma_y} \frac{\sigma_{y_i}}{\sigma_{y_{BM}}} + C_{\sigma_{UTS}} \frac{\sigma_{UTS_i}}{\sigma_{UTS_{BM}}} + C_A \frac{A_i}{A_{BM}} + C_{U_T} \frac{U_{T_i}}{U_{T_{BM}}} \right) \times 100\ (\%) \qquad (1)$$

In analogy with the tensile tests and the GETS coefficient, a Global Efficiency to Bending, GEB (2) was also considered.

$$GEB = \left(C_F \frac{F_i}{F_{BM}} + C_d \frac{d_i}{d_{BM}} + C_{U_B} \frac{U_{B_i}}{U_{B_{BM}}} \right) \times 100\ (\%) \qquad (2)$$

The weights considered in (1) and (2) are shown in *Table 5.These* weights aim at consider the relative importance level of the mechanical properties in design of aeronautic structures.

Table 5. Weights considered for GETS and GEB

GETS	GEB
0.30	
0.25	0.50
0.20	0.25
0.20	0.25
0.05	

Because the hardness results are important in assessing the relative mechanical properties between the different zones resulting from the thermo-mechanical FSW cycle it was established the following expression (3) as a welding performance parameter:

$$HARD = \frac{Minimum\ hardness}{BM\ hardness} \qquad (3)$$

where HARD means HArdness Ration Drop, *minimum hardness*is the lowest hardness value measured at themid-thickness of the cross section of the weld seam and *BM hardness* is the base metal hardness value.

Experimental set-up and procedure

After the orthogonal array has been selected, the second step in Taguchi parameter design is running the experiment. The 2024-T351 aluminium alloy was used in this investigation for being one of the most popular materials in aeronautic applications. All the welds were performed in plates rolled to 4 mm thick perpendicular to the rolling direction in a butt joint arrangement with straight edge preparation.

Plates of 200 mm x 145(RD) mm were welded along their long edge. The FSW equipment used was an ESAB Legio FSW 3UL as mentioned in *Section 3.1*. After welding, specimens were produced and mechanical tests were carried out. Both the uniaxial tensile and bending tests were performed on an Instron 1342, with a load cell of 250kN and high resolution biaxial extensometers. Specimens were taken from each welded plate for tensile tests, with geometry according to the EN-895-2002. Bending tests of 90º were carried out. The average distance between supports (distance between the centres of support rolls) is 30 mm. Support rolls diameter is 10 mm and mandrel radius is 5 mm. Mandrel velocity used throughout the trial is 1 mm/min. From each welded condition two specimens were taken and one of them was bended with the root of the weld seam under tensile stress. All mechanical trials were performed at room temperature. The hardness field was established in the mid-thickness (middle level) of the cross section of the weld seam in according to the ISO 6507-2 with 0.5 kg and about 26 measured points.

Analysis of experimental data

Computation of average performance

The procedures after the experimental runs are analyzing data and identifying the optimal levels for all the control factors. The results of GETS, GEB and HARD of each sample are shown in Table 6. There are three categories of performance characteristics, i.e., the lower-the-better, the higher-the-better, and the nominal-the-better. To improve the mechanical behaviour of AA2024-T351, the higher-the-better performance characteristic for GETS, GEB and HARD should be taken for obtaining optimal welding performance.

Table 6. Experimental results

Experiment number	FSW parameter level			GETS	GEB	HARD
	A	B	C			
1	850	120	4.00	0.585	0.518	0.656
2	850	250	4.08	0.627	0.362	0.773
3	850	500	4.17	0.598	0.470	0.736
4	900	120	4.08	0.585	0.629	0.742
5	900	250	4.17	0.685	0.592	0.779
6	900	500	4.00	0.530	0.277	0.871
7	950	120	4.17	0.585	0.506	0.712
8	950	250	4.00	0.555	0.329	0.755
9	950	500	4.08	0.576	0.318	0.798

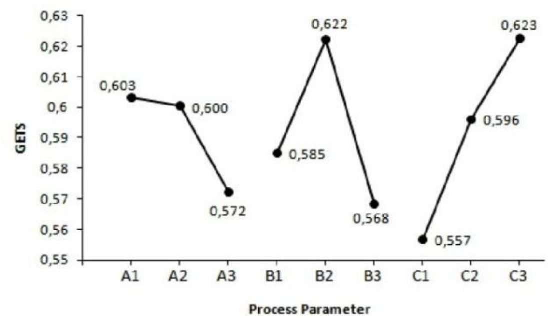

Figure 1.Effect of process parameters on GETS coefficient.

All three levels of every factor are equally represented in 9 experiments. Since the experimental design is orthogonal, it is possible to separate out the effect of each factor at each level [6]. Mean response is the average of quality characteristic for each parameter at different level. For example, the mean percentage GETS for travel speed at level 1 can be calculated by averaging GETS from the experiments 1, 4 and 7. GETS, GEB and HARD for each of the parameter at each level are calculated. These are also called as main effects. Figures 1-3 show the GETS, GEB and HARD response (main effects), respectively.

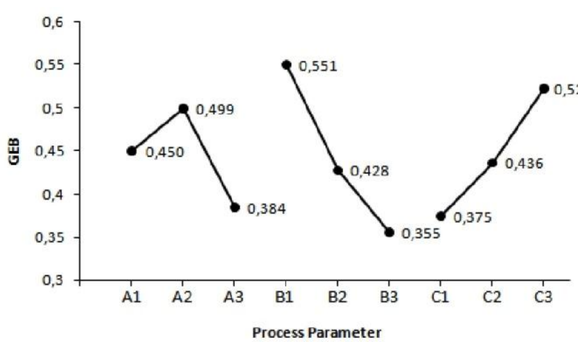

Figure 2.Effect of process parameters on GEB coefficient.

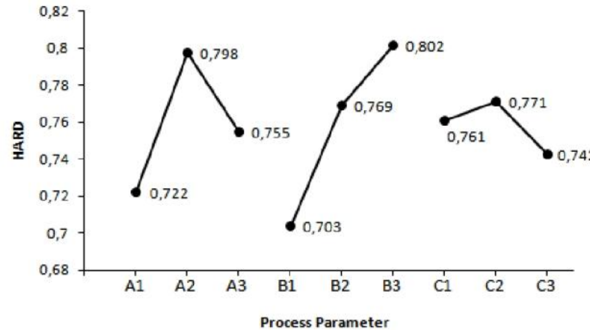

Figure 3.Effect of process parameters on hardness profile.

From Figure 1 it is observed that the GETS is highest at level 1 of vertical downward forging force (A1), level 2 of travel speed (B2) and level 3 of pin length (C3). Increase vertical downward forging force causes decrease in GETS while increase pin length causes increase in GETS. Both are related with the gage area and as such increase vertical downward forging force decrease gage area (because it reduces the thickness) and decrease pin length decrease gage area because there is no total penetration of the pin.

From Figure 2 it is observed that the GEB is highest at level 2 of vertical downward forging force (A2), level 1 of travel speed (B1) and level 3 of pin length (C3). Increase travel speed causes decrease in GEB. The higher travel speed contributes for reducing the processing on the root zone due to the insufficient visco-plastic flux. Increase pin length causes increase in GEB. Increasing pin length inhibits the formation of defects at the root and therefore improves the bending strength of FSW joints.

From Figure 3 it is observed that the HARD is highest at level 2 of vertical downward forging force (A2), level 3 of travel speed (B3) and level 2 of pin length (C2). Increase travel speed causes increase in HARD because it decreases the process' calorific energy input.

Analysis of variance (ANOVA)

ANOVA is a standard statistical technique to interpret the experimental results. The percentage contribution of various process parameters to the selected performance characteristic can be estimated by ANOVA. Thus information about how significant the effect of each controlled parameter is on the quality characteristic of interest can be obtained. ANOVAs for raw data has been performed to identify the significant parameters and to quantify their effect on the performance characteristic. The ANOVA based on the raw data identifies the factors which affect the average response rather than reducing variation. In ANOVA, total sum of squares (SS_T) is calculated by [10]:

$$SS_T \quad \sum_{i=1}^{N}(Y_i \quad \bar{Y})^2$$

Where N is the number of experiments in the orthogonal array, N=9, is the experimental result for the ith experiment and is given by:

$$\bar{Y} = \frac{1}{N}\sum_{i=1}^{N} Y_i \quad (5)$$

The total sum of the squared deviations SS_T is decomposed into two sources: the sum of the squared deviations SS_P due to each process parameter and the sum of the squared error SS_e. SS_P can be calculated as:

$$SS_P = \sum^{t} \frac{(SY_j)^2}{t} - \frac{1}{N}\left[\sum_{i=1}^{N} Y_i\right]^2 \quad (6)$$

Where *p* represent one of the experiment parameters, j the level number of this parameter *p*, *t* the repetition of each level of the parameter *p*, SY_j the sum of the experimental results involving this parameter *p* and level *j*. The sum of squares from error parameters SSe is:

$$SS_e = SS_T - SS_A - SS_B - SS_C \quad (7)$$

The total degrees of freedom is $D_T = N - 1$, and the degrees of freedom Of each tested parameter is $D_P = t - 1$. The variance of the parameter tested is $V_P = SS_P/D_P$. Then, the *F*-value for each design parameter is simply the ratio of the mean of squares deviations to the mean of the squared error ($F_P = V_P/V_e$).
The percentage contribution ρ can be calculated as:

$$\rho_P = \frac{SS_P}{SS_T} \quad (8)$$

Tables 7-9 show the results of ANOVA for GETS, GEB and HARD, respectively.

Table 7. Results of the analysis of variance for GETS

Source	DOF	Sum of squares	Mean square	F ratio	Contribution (%)
A	2	0.00176	0.00088	0.70138	11.35
B	2	0.00463	0.00231	1.84158	29.79
C	2	0.00663	0.00331	2.63852	42.68
Error	2	0.00251	0.00126		16.18
Total	8	0.01553			100

It can be seen from Table 7 that pin length and travel speed are the most significant parameters for GETS.

Travel speed and pin length are the most significant parameters affecting the GEB coefficient as given in Table 8. Travel speed and vertical downward forging force are the most significant parameters for HARD (Table 9).

Table 8. Results of the analysis of variance for GEB

Source	DOF	Sum of squares	Mean square	F ratio	Contribution (%)
A	2	0.02003	0.01001	1.12742	15.43
B	2	0.05880	0.02940	3.31042	45.31
C	2	0.03318	0.01659	1.86799	25.57
Error	2	0.01776	0.00888		13.69
Total	8	0.12977			100

Table 9. Results of the analysis of variance for HARD

Source	DOF	Sum of squares	Mean square	F ratio	Contribution (%)
A	2	0.00864	0.00432	2.5825	30.60
B	2	0.01499	0.00749	4.4800	53.08
C	2	0.00126	0.00063	0.3775	4.47
Error	2	0.00335	0.00167		11.85
Total	8	0.02824			100

Prediction of the optimum performance

After the optimum condition has been determined, the optimum performance of the response at the optimum condition is predicted. For the "higher-the-better" quality characteristic, the study of the main effect shows that the optimum condition for GETS is $A_1B_2C_3$. Then the optimum performance (optimum value of the response characteristic) is estimated as follows [7]:

$$Y_{opt} = \frac{T}{N} + \left(\bar{A}_1 - \frac{T}{N}\right) + \left(\bar{B}_2 - \frac{T}{N}\right) + \left(\bar{C}_3 - \frac{T}{N}\right) \quad (9)$$

where T is the total of all results, N the total number of results and $\bar{A}_1$, $\bar{B}_2$ and $\bar{C}_3$ are the average values of the responses at the first, second and thirst levels of parameters A, B and C, respectively.

In analogy with the procedure for GETS, the optimum performance for GEB and HARD coefficients can be predicted.

Table 10 shows the results of the optimum performance for GETS, GEB and HARD.

Table 10. Results f the optimum performance

GETS	GEB	HARD
0.6645	0.6840	0.8541

Algebraic model

The algebraic model (10) presented here was developed in order to obtain a more robust parametric combination that would improve the whole properties of FSW joints and give them to greater resistance to fatigue. For this, were considered the three different combinations predicted by Taguchi method and the percentages contribution of each parameter, obtained by ANOVA. Table 11 shows the percentages contributions which were used in algebraic model:

Table 11. Percentages contribution

	Force	Travel Speed	Pin Length
GETS	**11.35**	**29.79**	**42.68**
GEB	**15.43**	**45.31**	**25.57**
HARD	**30.60**	**53.08**	**4.47**
TOTAL	**57.38**	**128.18**	**72.72**

This combination will be considered the optimal FSW combination.

Confirmation test

Once the optimal level of the process parameters is selected, the final step is to verify the improvement of the performance characteristics using the optimal level of the process parameters. Therefore, confirmation experiment was carried out to validate the developed algebraic model. Table 12

$$\begin{bmatrix} Force & x & x \\ x & Speed & x \\ x & x & Pin \end{bmatrix} = \begin{bmatrix} A_1 & A_2 & A_2 \\ B_2 & B_1 & B_3 \\ C_3 & C_3 & C_2 \end{bmatrix} \begin{bmatrix} \frac{\rho_{A_{GETS}}}{\rho_{A_T}} & \frac{\rho_{B_{GETS}}}{\rho_{B_T}} & \frac{\rho_{C_{GETS}}}{\rho_{C_T}} \\ \frac{\rho_{A_{GEB}}}{\rho_{A_T}} & \frac{\rho_{B_{GEB}}}{\rho_{B_T}} & \frac{\rho_{C_{GEB}}}{\rho_{C_T}} \\ \frac{\rho_{A_{HARD}}}{\rho_{A_T}} & \frac{\rho_{B_{HARD}}}{\rho_{B_T}} & \frac{\rho_{C_{HARD}}}{\rho_{C_T}} \end{bmatrix}$$

$$\begin{bmatrix} Force & x & x \\ x & Speed & x \\ x & x & Pin \end{bmatrix} = \begin{bmatrix} 850 & 900 & 900 \\ 250 & 120 & 500 \\ 4.17 & 4.17 & 4.08 \end{bmatrix} \begin{bmatrix} 0.1978 & 0.2324 & 0.5869 \\ 0.2690 & 0.3535 & 0.3516 \\ 0.5333 & 0.4141 & 0.0615 \end{bmatrix}$$

$$Force = 168.13 + 242.10 + 479.97 = 890\ kg$$

$$Speed = 58.1 + 42.42 + 207.05 = 308\ mm/min$$

$$Pin = 2.45 + 1.47 + 0.25 = 4.17\ mm$$

shows the results of the confirmation experiment using he optimal FS welding parameters. Based on the result of the confirmation test, the GETS coefficient increased 4.9% and the GEB coefficient increased 0.8%. The experimental results confirm the algebraic model parameter design for the optimal FS welding parameters.

Table 12 . Results of the confirmation experiment

	Optimal FS welding parameters		
	Prediction for GETS	Prediction for GEB	Experiment
Level	$A_1B_2C_3$	$A_2B_1C_3$	^{A}AM^{B}AM^{C}AM
GETS value	66.4 %		71.3 %
GEB value		68.4 %	69.2 %

Conclusion

This paper has presented an application of the parameter design of the Taguchi method in the optimization of FS welding parameters. The following conclusions can be drawn based on the experimental results of this study: Taguchi's robust orthogonal array design method is suitable to analyze this problem as described in this paper. It is found that the parameter design of Taguchi method provides a simple, systematic, and efficient methodology for the optimization of the FS welding parameters. The improvement of GETS from initial FS welding parameters to the optimal parameters is about 2.8%and the improvement of GEB from initial FS welding parameters to the optimal parameters is about 10%.

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References

1. R. Pedwell, H. Davies and A. Jefferson, 1999, Proc. 1st Int. symposium on Friction Stir Welds, Thousand Oaks, California, 14th – 16th June.
2. T. Santos, P. Vilaça, L. Reis, L. Quintino, M. Freitas, *Advances in NDT Techniques for Friction Stir Welding Joints of AA2024*, TMS 2008 Annual Meeting &Exhibition, Symposium, New Orleans, USA, March 2008.
3. Manabu Nakai, TakehikoEto, *New aspects ofdevelopment of high strength aluminum alloys for aerospace applications*, Materials Science andEngineering, pp. 62-68, 2000.
4. G.S. Peace, Taguchi Methods, *A Hands-on Approach*, Addision-Wesley, MA, 1992.
5. Julie Z. Zhang, Joseph C. Chen, E. Daniel Kirby, *Surface roughness optimization in an end-milling operation using the Taguchi design method*, Journal ofMaterials Processing Technology 184, pp. 233–239, 2007.
6. Ross, P.J., *Taguchi Technique for Quality Engineering*, 1988 (McGraw-Hill: New York).
7. Roy, R.K., *A Primer on the Taguchi Method*, 1990 (Van Nostrand Reinhold: New York).
8. M. Nalbant, H. Gokkaya, G. Sur, *Application of Taguchimethod in the optimization of cutting parameters for surface roughness in turning*, Materials and Design 28, pp. 1379–1385, 2007.
9. Vilaça, P., *Fundamentos do Processo de SoldaduraporFricção Linear – Análise Experimental e ModelaçãoAnalítica*, PhD Thesis, Instituto Superior Técnico,UniversidadeTécnica de Lisboa, Setembro 2003.
10. W.H. Yang, Y.S. Tarng, *Design optimization of cuttingparameters for turning operations based on the Taguchi method*, Journal of Materials Processing Technology 84,