DE GRUYTER OPEN

ARCHIVES OF MECHANICAL TECHNOLOGY AND MATERIALS
WWW.AMTM.PUT.POZNAN.PL

Parametric study of friction stir welding using elastic return

Mohamed Serier[a]*, Mohamed Berrahou[a], Amina Chikh[a]
[a] *Institute of Sciences and Technology, University center of Relizane, Relizane 48000, Algeria*
* *Corresponding author, Tel.: +213770924415, e-mail address: moha_serier@yahoo.fr*

ARTICLE INFO
Received 01 March 2020
Received in revised form 30 April 2020
Accepted 21 July 2020

ABSTRACT
Aluminum alloy is a very useful material in light manufacturing. Friction stir welding (FSW) is a solid state assembly process that is achievable for this material. This work aims to characterize the quality of the weld joint by an operation of shaping (folding), it aims to study the rate of elastic return in this weld joint after a folding operation. In this context, the elastic return for the folding process has been modeled using experimental tests under optimal welding conditions.

KEY WORDS
Elastic return
Optimization of experiments
Folding Process
FSW

1. INTRODUCTION

Friction stir welding, better known by its acronym FSW (Friction Stir Welding), is a relatively new, environmentally friendly welding process, considered to be the greatest invention in the field of welding since 1991 [1]. The tool used for the FSW consists of a punch with a shoulder and a pin as shown in Figure 1. During welding, the tool rotates while exerting pressure on the surface of the plates [2]. The friction of the tool with the plates and the significant plastic deformation of the material strongly kneaded by the tool, generate heat, which causes a local increase in the temperature of the plates (between 0.6 and 0.8 of the melting point) and softening of the metal [3]. The softened metal of the two plates is needed by the tool to form the welded joint [4]. The use of this process in the construction of aircraft, naval or automobiles makes it possible to reduce the manufacturing costs and, indirectly, the operating costs thanks to the structural lightening. Copper and its alloys have very interesting specific properties such as very good thermal conductivity, good ductility accompanied by good mechanical [12,13] and corrosion resistance. It is for this reason that these alloys are used in several industrial sectors. Folding is the process of forming by cold deforming, which consists of deforming a flat sheet by changing abruptly the angle [9-10]. Therefore, there is inevitably an elastic deformation that accompanies it, as the elasticity value of the material can be exceeded in the folding processes, but not the limits of elastic force. In other words, the material retains some of its original elasticity and consequently the material tries to return to its original shape and bend slightly, when the load is removed. The aim of this study is to see how two sheets assembled by this type of welding behave after the bending operation and to estimate the stiffness of their joint welding by the phenomenon of elastic return through the selected welding conditions.

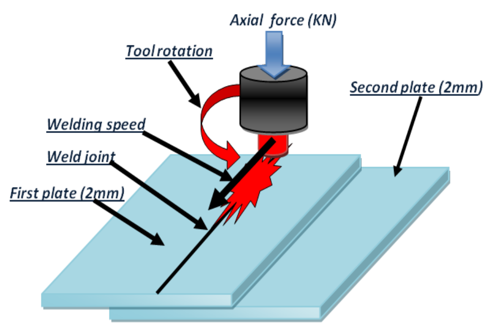


Fig.1. ***FSW process diagram.***

DOI: 10.2478/amtm-2020-0002

2. EXPERIMENTAL PROCEDURES

Two alloy plates of type 7075 - T5, of dimensions 100 mm x 100 mm and thickness of 4 mm are welded in a superimposed manner by friction mixing in eight copies. The tool used during the welding operation is in highly alloyed steel X200 cr12. The folding operation was carried out on the part welded in order to quantify the elastic return of each test piece produced by the conditions of this type of welding [5]. In this study we keep the same bending parameters for the welded sheets and the single sheet.

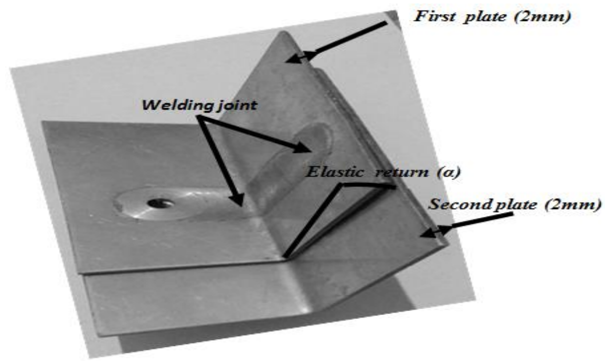


Fig.2. ***Folding of two welded sheets using FSW.***

On the basis of a previous research [4], in this study we will test the weld joint by its elastic return after folding under the effect of the speed of rotation of the tool which is between 1000 and 1400 rpm, the tool feed speed is between 22 and 75 mm / min and the axial penetration force of the tool is between 2 and 4 KN as shown in table 1.

Table 1. Experimental result of elastic return

N	Tool rotation Speed (rpm)	Welding speed (mm/min)	Axial force (KN)	Elastic return (α°)
1	1000	22	2	3,7
2	1400	22	2	3,1
3	1000	75	2	3,5
4	1400	75	2	2,9
5	1000	22	4	3,4
6	1400	22	4	3,3
7	1000	75	4	3,2
8	1400	75	4	3,0

3. MODELING BY DESIGNS EXPERIMENTS

The modeling is done by the complete plan. Calculations can be carried out by a simple matrix calculation as indicated in the expression [6]**.** To avoid the problem of the units of the constituent variables, the regression model of the method of the experimental designs [7–8] requires code on the factors levels - one takes the maximum value coded ‘‘+1”, and the minimum value coded ‘‘-1”.

Table 2. Coded parameters values.

N	Tool rotation Speed (rpm)	Welding speed (mm/min)	Axial force (KN)	Elastic return (α°)
1	-1	-1	-1	3,7
2	+1	-1	-1	3,1
3	-1	+1	-1	3,5
4	+1	+1	-1	2,9
5	-1	-1	+1	3,4
6	+1	-1	+1	3,3
7	-1	+1	+1	3,2
8	+1	+1	+1	3,0

The mathematical analysis consists in estimating by the method of least squares.

$$y_i = a_0 + \sum_{i=1}^{k} x_i a_i + \sum_{i=1}^{k-1} \sum_{i=j=1}^{k} I_{ij} x_i x_j + e_i \qquad (1)$$

The developed form of expression 1 for three parameters is

$$y_i = a_0 + a_1 x_{i1} + a_2 x_{i2} + a_1 x_{i3} + I_{12} x_{i1} x_{i2} + I_{13} x_{i1} x_{i3} + I_{23} x_{i2} x_{i3} + e_i$$

The term e_i is the difference between the experimental value and that given by the polynomial. Applying this to eight experiments that were performed, we find the following matrix system

$$\begin{pmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \\ y_5 \\ y_6 \\ y_7 \\ y_8 \end{pmatrix} = \begin{pmatrix} 1 & -1 & -1 & -1 & +1 & +1 & +1 \\ 1 & +1 & -1 & -1 & -1 & -1 & +1 \\ 1 & -1 & +1 & -1 & -1 & +1 & -1 \\ 1 & +1 & +1 & -1 & +1 & -1 & -1 \\ 1 & -1 & -1 & +1 & +1 & -1 & -1 \\ 1 & +1 & -1 & +1 & -1 & +1 & -1 \\ 1 & -1 & +1 & +1 & -1 & -1 & +1 \\ 1 & +1 & +1 & +1 & +1 & +1 & +1 \end{pmatrix} \begin{Bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \\ I_{12} \\ I_{13} \\ I_{23} \end{Bmatrix} + \begin{pmatrix} e_1 \\ e_2 \\ e_3 \\ e_4 \\ e_5 \\ e_6 \\ e_7 \\ e_8 \end{pmatrix}$$

The coefficients are found by the following expression:

$$\text{Coefficients} = \left({}^{t}XX\right)^{-1} \left({}^{t}X\right)\left(Y\right) \qquad (2)$$

Table 3. Coefficients of models

Factor	coefficients	
overall average	a_0	3,2625
Tool rotation	a_1	-0,1875
Welding speed	a_2	-0,1125
Axial force	a3	-0,0375
Interaction tool rotation/ Welding speed	I_{12}	-0,0125
Interaction tool rotation/ Axial force	I_{13}	0,1125
Interaction Welding speed/ Axial force	I_{23}	-0,0125

4. VALIDATION OF MODEL

4.1. Residual variation

Y observed $=(Y$ predicted $=a_0 + a_1X_1 + a_2X_2 + a_3X_3 + I_{12}X_1X_2 + I_{13}X_1X_{3} + I_{23}X_2X_3) + e$

$$SCER = \sum_{i=1}^{n}\left(Y^{(\text{observed})} - Y^{\text{predicted}}\right)^2 \quad (3)$$

$$SCER = (3{,}7 - 3{,}6875)^2 + (3{,}1 - 3{,}1125002)^2 + (3{,}5 - 3{,}5125002)^2 + (2{,}9 - 2{,}8875)^2 + (3{,}4 - 3{,}4124998)^2 + (3{,}3 - 3{,}2875)^2 + (3{,}2 - 3{,}1875)^2 + (3 - 3{,}0124998)^2$$

SCER= 0, 00125

4.2. Variation due to the linear connection

$$SCEL = \sum_{i=1}^{n}\left(Y^{(pre)} - Y_{(med)}\right)^2 \quad (4)$$

$$scel = (3{,}6875 - 3{,}2625)^2 + (3{,}1125002 - 3{,}2625)^2 + (3{,}5125002 - 3{,}2625)^2 + (2{,}8875 - 3{,}2625)^2 + (3{,}4124998 - 3{,}2625)^2 + (3{,}2875 - 3{,}2625)^2 + (3{,}1875 - 3{,}2625)^2 + (3{,}0124998 - 3{,}2625)^2$$

$$\mathbf{SCEL = 0,4975}$$

***Table 6. Fisher test* [11]**

Variation Source	ddl	Sum of squares	Mean squares	Fabs
Regression (model)	**(k-1) 6**	**SCEL = 0,4975**	**MCF = SCEL/(k-1) 0,0710**	**MCF/ MCR 113,71**
Residuals	**((n-k) 2**	**SCER = 0,00125**	**MCR = SCER/(n-k) 0,000625**	
Total	**(n-1) 7**			

The comparison of the value calculated by our model (Fabs: 113.71) with only one of the tests, drawn from the Fischer table with the degrees of freedom (k-1) and (n-k), Fcri 19,33 shows that Fabs> Fcrit; therefore, this model is globally significant.

This correlation can also be illustrated by plotting the measured responses, based on the estimated responses. This is given by Figure 3, which shows a strong correlation between them.

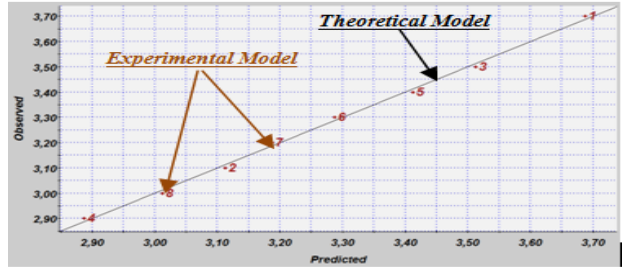
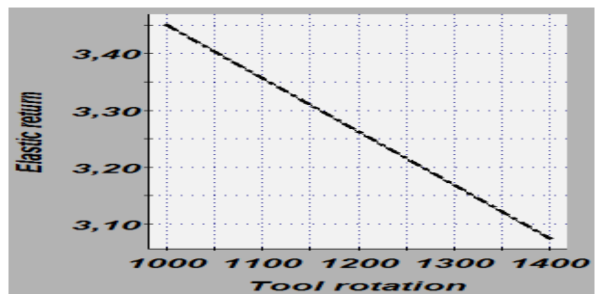


Fig.3. Schematization of both models (experimental and theoretical).

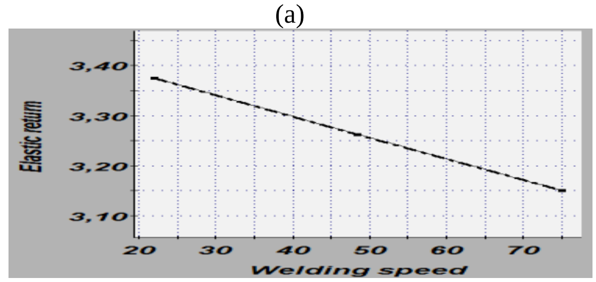
5. DISCUSSION

5. 1. *Analysis of a single factor effect*

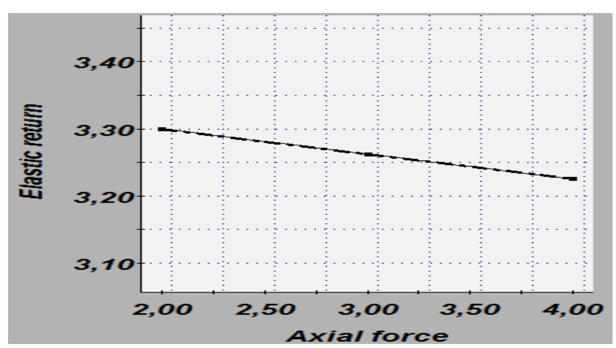
This analysis consists in maintaining a variable factor and fixing the other two in the model (1).



(a)



(b)



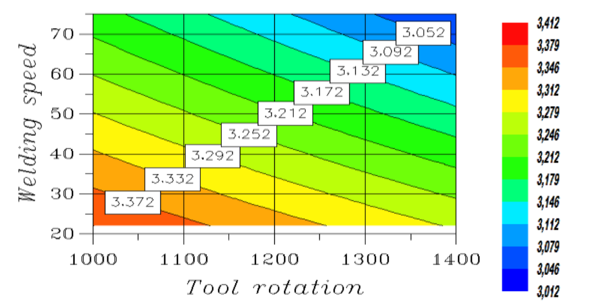
(c)

Fig.4. ***Effect of the factors separately***

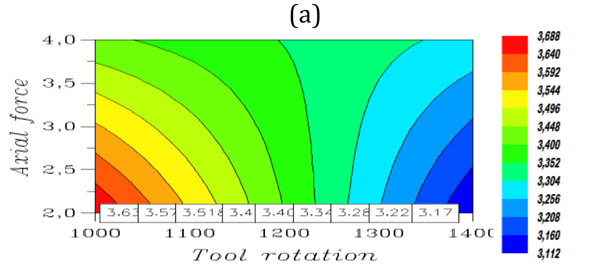
The importance of the effects caused by the main factors on the objective function can be estimated from Fig. 4. The first remark concerns the slopes which show that the factors have the meaning of influences. The second remark sets up the quantification of the degree of influence of each factor on the response and it is as follows: the elastic return is low if the weld is made under a high tool rotation speed. A high welding speed also gives a good quality of weld joint which elastic return is minimized. The axial force is almost without effect since the transition from its low level to its high level does not give a considerable change on the elastic return.

5.2. Analysis of simultaneous effect of two factors

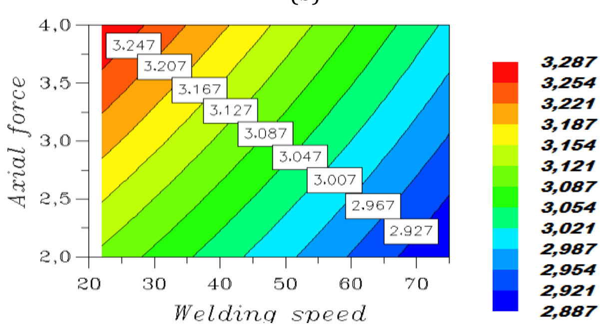
The characterization of the welded joint by the elastic return after folding under the effect of secondary factors (I12, I13 and I23), is based on the variation of two factors on the response at the same time.



(a)



(b)



(c)

Fig.5. Interaction of one factor with the other.

And since in this study we are looking for lowest value attracted by the elastic return, therefore the remarks will be based on the lowest value in each interaction in the figure below and it is commented as follows:

In figure 5 (a) the elastic return is at 3.012 ° if the speed is at its high level and the axial force is at 4 KN. In the interaction I13, the elastic return attains a value of 3.112 ° if the speed of rotation is at its high level and the axial force at its low level (figure 5b).

The interaction between the welding speed at its high level and the axial force at its low level with the fixing of the rotation speed at 1400 rpm results in a low elastic return of 2,887 ° (figure 5c). Note that this is the best result for the three interactions.

6. THE OPTIMUM RESULT

We know that a sheet of thickness of 4 mm is more rigid than two welded sheets whose thickness is 4 mm, so logically the elastic return in the first case is lower compared to the second case. The optimum in this operation is to find an elastic return close to that of a 4 mm sheet among the eight test pieces

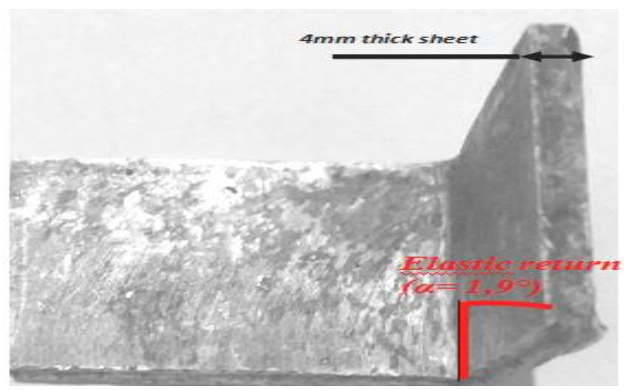


Fig.6. Elastic return in a thick sheet 4mm after folding

as shown in the figure, the 4 mm thick sheet metal feels an elastic return of 1.9° after folding and by comparison by the tests made, we find that the good result is that welded with a rotation speed of 1400 rpm and a welding speed of 75 mm / min under the effect of an axial force of 4KN gives a value of 2.9°. Therefore the sheets welded by these conditions give better resistance to elastic return.

7. CONCLUSIONS

In this article, we carried out an experimental study to test the rigidity of the FSW type weld joint by the elastic return after folding, since both processes are essential in the industry of aluminum alloys and pure aluminum material. We hope that this work will have contributed to a modest extent to the development of a more unified welding operation. It would be desirable that the remarks will be as follows:

- The advantage of this study is the power to bend two welded sheets by friction mixing;
- The model developed by this method can better predict the results of combining FSW welding with bending;
- Confirmation that the classification of the effects of the factors in order of significance is the rotation speed, then the welding speed, then the axial force;
- After this study we can bend welded sheets by this technique without risk of delaminating.

REFERENCES

[1] **José, F., Lindolfo, F., Ricardo, I.,** Thermomechanical Modelling of FSW Process Using a Cylindrical Tool in an Aluminum Alloy Alclad AA 2024-T3. journal of Materials Research,. (2018).

[2]**Khodaverdizadeh, H,. Mahmoudi, A, Heidarzadeh A., and E. Nazari,** Effect of friction stir welding (FSW) parameters on strain hardening behavior of pure copper joints, Materials and Design,. 330–334,(2012).

[3]**Oliveira, Miranda, A, C., Gerlich, A., Walbridge, S.,** Aluminum friction stir welds: Review of fatigue parameter data and probabilistic fracture mechanics analysis. Engineering Fracture Mechanics, (2015). 243–260.

[4] **Serier ,M, Berrahou,M, Tabti, A, Bendaoudi ,S,** Effect of FSW welding parameters on the tensile strength of aluminum alloys, ARCH. MECH. TECH. MATER, 41-45, (2019).

[5] **Serier ,M, Bendaoudi ,S, Benmansour , D-L, and Tabti, A** Numerical modelling of springback behavior in folding process, Advances in Materials Research, 75-81, (2019).

[6] **Fisher, R,** The design of experiments. Oliver and Boyd 1935.

[7] Designs of Experiments, Expérimentique Edition, in: François Louvet, Luc Delplanque (Eds.), French Edition, 2005.

[8] Pratiquer les plans d'expériences, in Jacques Goupil (Ed.), Edition Dunod, French Edition, 2005.

[9] **Andersson, A.** Information exchange within the area of tool design and sheet-metal-forming simulations, J. Eng. Des.,283-291, (2001)

[10] **Lepadatu, D,** Optimisation du procédé de pliage, Thèse de doctorat ; Université d'Angers, Angers, France. (2006).

[11] **Goupy J, Creighton, L. D**, Introduction aux plans d'expériences (2006).

[12] **Rakesh R, Antonio C- O-M, ShiHui G, Scott W, Adrian, G** Fatigue analysis of friction stir welded butt joints under bending and tension load "Engineering Fracture Mechanics, 34-45 (2019).

[13] **Schneider D.H., Stafford J.P.B, Varner T.W.** Optimizing weld quality of a friction stir welded aluminum alloy, Journal of Materials Processing Technology, 188-196,(2015).