PREDICTION OF THE TEMPERATURE RECORDED IN LAP JOINT AT DURING THE FRICTION STIR WELDING

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Abstract:

The aim of the present work is to model the parameters influencing the temperature during friction stir welding. The area of physical understanding is the influence of tool pin geometry and material on the temperature field, microstructural refinement, resulting material flow and the influence of flow variations on the subsequent mechanical properties of FSW lap welded joints in aluminium 3003. The results obtained allowed us to propose a mathematical model to study the interactions between the different factors. It was found that the most influential parameters are the rotation speed and the welding speed.

1 Introduction

Friction stir welding (FSW) is definitely a new welding process. FS Lap welding is considered as a competitive joining method that can replace other joining methods such as rivets in many cases [1]. Lap joints are widely used in the assembly of parts and products in the aerospace industry. The FSW process has the following important advantages compared to fusion welding processes: Joining of conventionally non-fusion weldable alloys, lower distortion and improved mechanical properties of weldable alloy joints due to the pure solid state joining of metals [2]- [4]. Lap joints are used for assembling parts in the transportation industry. These process features make the FSW process very practical for joining different alloys. Lately some research work has been carried out on friction stir welding of aluminum lap joints [5]- [7]. When these processes are applied to aluminum workpieces, melting and resolidification is very harmful to the material and is known to cause hot cracking, hydrogen cracking, and liquid cracking, not to mention the loss of strength due to the dissolution of precipitates formed during the heat treatment process.

The best results were obtained for overlapping FSW joints between thin sheets of AA7075-T6 and AA6022-T4 when the welding parameters of tool geometry and welding speed were successfully varied at speeds up to 500 mm/min [10]. In friction stir welding of aluminum alloy AA 3003 with different initial microstructures, the results showed that the size of recrystallized grains and the amount of second phase particles in the weld zone (WNZ) decreased with decreasing ambient welding temperature [11]. Buffa et al [12], studied on the lap joining of AA2198-T4 aluminum alloy blanks by FSW by varying the joint configuration and the tool geometry and rotational speed. They found that the use of cylindrical–conical pin tools and the correct choice of the relative sheet positioning increase the welded nugget extension and integrity improving the mechanical performances of the obtained joints.

The thickness of intermetallic compounds (IMC) layer increases from 7.7 to 58.1 μm with decreasing welding speedsand has a significant effect on the strengths of the joints [13]. Fatigue properties of the welded joints of AA 3003-H14 aluminum alloy were evaluated based on the superior tensile properties for FSW at 1500 rpm rotational speed and 80 mm/min welding speed with 89% welding efficiency. Takhakh et al [14].

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Barlas [15] studied the effect of tool tilt angle on tensile shear failure load and weld zone properties for 1050 aluminum plates at a tool speed of 1200 rpm and a welding speed of 30 mm/min. The results indicated that the best joint performance of about 4.8 kN was obtained at 2.5°. The temperature field around the pin tool is asymmetric, with slightly higher temperatures on the retreating side (RS) of the FSW in aluminum alloys [2]. The forming pressure and mixing of the plasticized material lead to the formation of a solid joint region in friction stir welding (FSSW). In the FSW process, on the other hand, lower temperatures are important because the material undergoes severe plastic deformation due to the tool movement and the mechanical properties decrease less [16]. In the fracture zone, a small increase in hardness is observed due to the recrystallization of a very fine grain structure. Much research has been done to simulate friction stir welding using various software to determine the temperature distribution for a given set of welding conditions.

The objective of this work is to study the effects of the parameters affecting the properties during lap welding of AA 3003 by friction stirring. The Design of experiments technique (DOE) was applied to model and predict the behaviour of the friction stir welded joint of aluminium alloy AA 3003. The response surface method (RSM) was used to develop the model. In addition, this optimization allows the development of experimental results and can help to better understand the complexity of the phenomena resulting from the contact of parts/tool during the stirring process.

2 Materials and method

The material tested and studied is an AA 3003 alloys of 2 mm thickness. Samples were cut according to the shape shown in the Figure 1. The external sheets were welded parallel to the rolling direction while the central sheet was put in the long transverse direction for FSW process in order to limit potential effect of rolling texture. The chemical composition of the aluminum 3003 sheet is presented in Table1 and the mechanical properties of the sheets are presented in Table 2. Two welding tools used for the single and double overlap joint is made of steel type 42CrMo4 (Figure 2). Mechanical properties of this steel after quenched and tempered (Rm = 750/1300 MPa, A= 10-14 %, Re = 500/900 MPa and E = 210000 MPa). Friction Stir Lap Welding (FSLW) was conducted at selected rotation speeds of 1000, 1400 and 2000 rpm and selected travel speeds of 160, 200 and 250 mm/min.

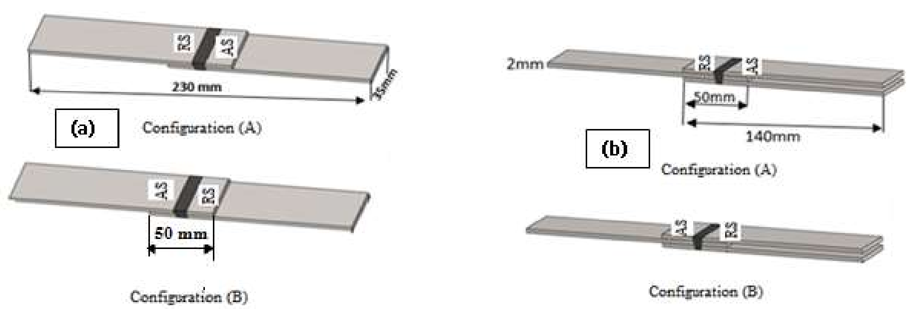

Figure1. Lap shear specimens, a) single lap, b) double lap.

Table 1. Chemical composition of 3003 aluminum alloy.

Element	Al	Mn	Si	Fe	Cu	Ti	Zn
Mass %	96.7	1.3	0.9	0.9	0.13	0.1	0.3

Table 2. Mechanical properties of 3003 aluminum alloy.

Rs (MPa)	UTS (MPa)	A (%)	Micro hardness (HV)	YS (MPa)	Ym (GPa)
127	160	5.6	51	110	60

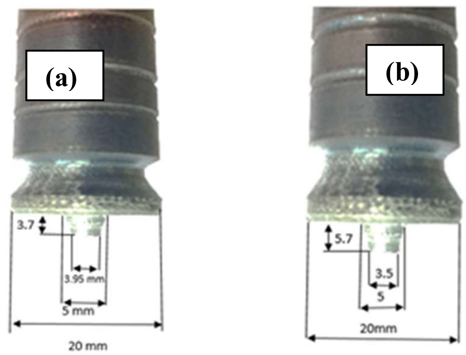

Figure 2. Geometry of the tools used, (a) single lap, (b) double lap.

The welding process was carried out with a FSW machine and a mechanical clamping system along the rolling direction in two different shapes. On the advancing side (AS), the motor velocity resulting from the rotation of the instrument is equidirectional with the translational velocity of the instrument, and on the retreating side (RS), the two velocities (axial and longitudinal) reinforce each other. This leads to an asymmetry of the material flow, which affects the microstructure and mechanical properties. As shown in Figure 3, for each FSW shape (single and double overlap), we distinguish two configurations depending on the direction of rotation and welding (Figure 3.a, 3.b), resulting in an asymmetric metal flow. A leading side and a trailing side are observed in the joining area:

The former is characterized by the "positive" composition of the tool feed and the circumferential speed of the tool, while in the latter case the two velocity vectors are opposite. Moreover, a vertical movement of the material is observed in the section, due to both the angle of inclination and the geometry of the tool pin, mixing the two layers of material [17].

The thermocouples used in this study are placed at distances from the center of the stir zone (SZ) to predict the temperature during the welding operation (Figure 4).

(a) *(b)*

Figure 3. Stir welded Lap joint, (a) Configuration (A), (b) Configuration (B).

Figure 4. Position of thermocouples used in this investigation.

2.1 Response surface methodology

Analysis of variance (ANOVA) was performed to determine the process parameters that are statistically significant. The purpose of the ANOVA test is to investigate the significance of the process parameters that affect the temperature of the FSLW compounds. In addition, the rotational speeds used have a significant effect on the temperature. To predict the temperature during the welding process, the response surface method (RSM) is used to develop the nonlinear model of the FSW joints of aluminum alloys AA 3003. The response control factors for the analysis were the rotation speed and the welding speed. These factors and parameters were used to build up the mathematical model that can be used to predict the optimum factor.

2.2 Developing a mathematical model

Response surface methodology is a collection of mathematical and statistical techniques useful for analyzing problems in which several independent variables influence a dependent variable or response and the goal is to optimize the response. For these experimental conditions, the model used has form given below:

$$Y = \emptyset\,(x_1,\ \ x_2, \ldots\ldots\ldots, x_k) \pm\ e_r \qquad (1)$$

The Design of Experiments approach was applied to 12 tests, two replicates are considered for each combination of the input variables, which made it possible to define the coefficients summarized in Table 3.

Table 3. Results of the Design of Experiments.

Test	Rotation speed (rot) (rpm)	Welding speed (wel) (mm/min)	T1 Conf (A) (single lap) (°C)	T2 Conf (B) (single lap) (°C)	T1 Conf (A) (double lap) (°C)	T2 Conf (B) (double lap) (°C)
1	1000	160	230	276	221	206
2	1400	160	225	283	241	249
3	2000	160	270	313	229	351
4	1000	200	191	295	217	198
5	1400	200	239	329	278	212
6	2000	200	274	331	283	366
7	1000	250	229	267	184	174
8	1400	250	225	327	216	184
9	2000	250	268	320	259	222
10	1400	200	239	329	278	212
11	1400	200	239	329	278	212
12	1400	200	239	329	278	212

The temperature of FSLW is a function of the welding parameters such as tool rotational speed (rot) and welding speed (wel) and it can be expressed as,
Temperature = f (rot, wel).
The polynomials help optimize the temperature parameters in order to reach the desired responses. To calculate the coefficients of the models, a regression method based on the least squares criterion is used. The mathematical models suggested by MODDE 5.0 (Modeling and Design) are:

$$(T_1) = 238 + 18.75 * rot - 0.499978 * wel + 21.25 * rot^2 - 11 * wel^2 - 0.25001 * rot * wel \qquad (2)$$

$$(T_2) = 328.13 + 15{,}5798 * rot + 5.19328 * wel - 7.69192 * rot^2 - 11.3592 * wel^2 + 2.19171 * rot * wel \qquad (3)$$

$$(T_3) = 273.209 + 21.1205 * rot - 6.49861 * wel - 8.45218 * rot^2 - 18.5031 * wel^2 + 6.50707 * rot * wel \qquad (4)$$

$$(T_4) = 220.042 + 60.1667 * rot - 37.6667 * wel + 45.875 * rot^2 - 19.625 * wel^2 - 24.25 * rot * wel \qquad (5)$$

3 Results and discussion

The result of RSM design of experiment is displayed in Table 4. The residuals in Figure 5 are falls on a straight line, which depicts that the errors are normally distributed [18], which reveals that there is very good correlation between the experimental value and predicted value of the responses.

Table 4. Design matrix with responses (Temperature).

Test	Rotation speed (rpm)	Welding speed (mm/min)	T1 Conf (A) (single lap) (°C)	T2 Conf (B) (single lap) (°C)	T1 Conf (A) (double lap) (°C)	T2 Conf (B) (double lap) (°C)
1	-1	-1	230	276	221	206
2	0	-1	225	283	241	249
3	1	-1	270	313	229	351
4	-1	0	191	295	217	198
5	0	0	239	329	278	212
6	1	0	274	331	283	366
7	-1	1	229	267	184	174
8	0	1	225	327	216	184
9	1	1	268	320	259	222
10	0	0	239	329	278	212
11	0	0	239	329	278	212
12	0	0	239	329	278	212

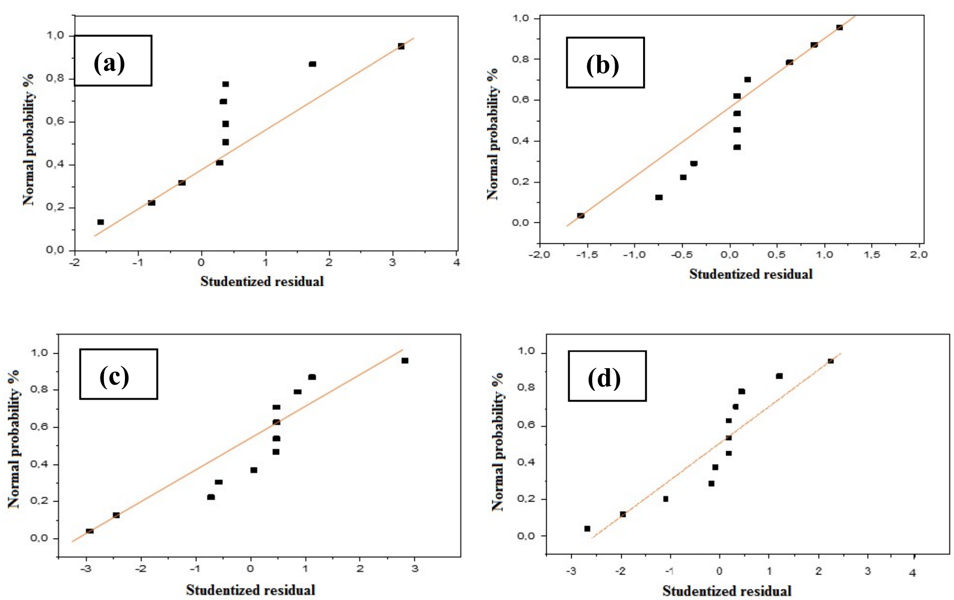

Figure 5. Normal probability plot of regression, a) configuration A (lap joint), b) configuration B (lap joint), c) configuration A (Double lap joint), d) configuration B (Double lap joint).

All of the above considerations indicate excellent fit of the regression models. Figure 6 shows the effects of rotational speed and welding speed on temperature. The experimental treatments performed at different tool speeds: 1000 rpm and 2000 rpm were chosen to study the effect of tool speed variation on the transient temperature distribution inside the weld zone. It can be observed that the temperature gradually decreases with increasing welding speed, which is due to the metallurgical transformation caused by the high rotational speed (Figure 6.b, 6.d, 6.f and 6.h).

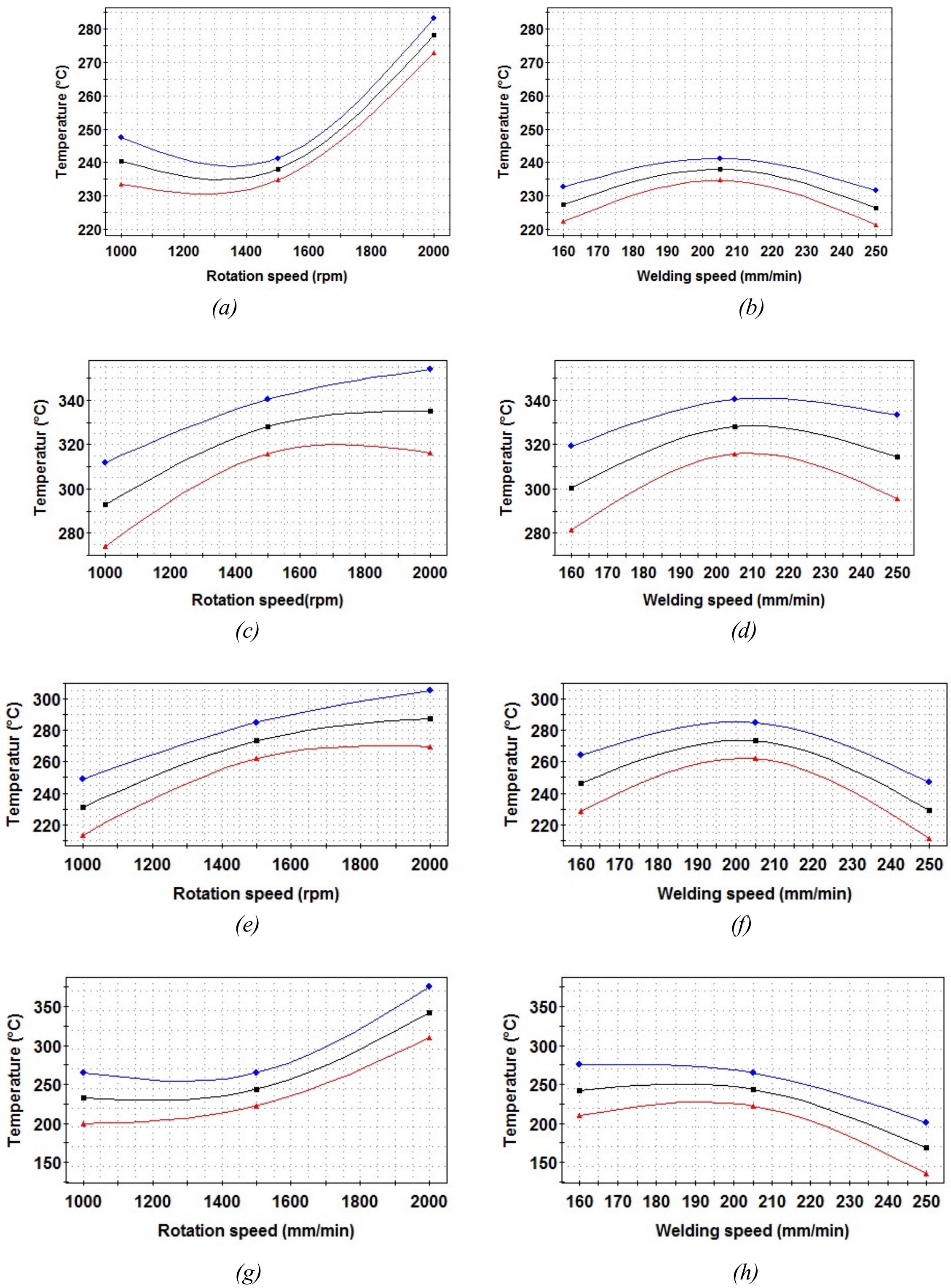

Figure 6. Analysis of thermal profile measured at the welding, a) and b) configuration A (lap joint), c) and d) configuration B (lap joint), e) and f) configuration A (Double lap joint), g) and h) configuration B (Double lap joint).

In Figure (6c) and Table 3, maximum temperature of the experimental test that it was detected for a rotational speed of 2000 rpm was approximately 366 °C for the sample with tool speed of 200 mm/min and the minimal is detected with 1000 rpm at 184 °C.

The temperature profiles have a uniform plot during the welding process which is trending symmetrically toward the peak of thermal cycles, and dropping axisymmetrically after passing through the maximum temperature. In this analysis step, it was decided to broaden the scope of our study by taking into account the interaction between two factors. This allows viewing the output parameters on a three dimensional (3D) graph (Figure 7); this graph depicts the variation of the temperature as a function of the two factors (Rotation speed and welding speed). In Figure 8, it is observed that the value of the temperature was 337.1°C at the rotational speed of 1900 rpm and the welding speed of 210 mm\min (Figure 8.b), whereas the value of the temperature decreases to (272.9 °C) at the rotational speed of (2000 rpm) and the welding speed of 210 mm\min (Figure 8.a). It is also observed that for the double lap joint the highest value of the temperature was 360 ° C at a rotation speed of 2000 rpm (Figure 8.c) and a welding speed of 160 mm / min and decreases at 270 ° C for a rotation of 1600 rpm and a welding speed of 220 mm \ min (Figure 8.d).

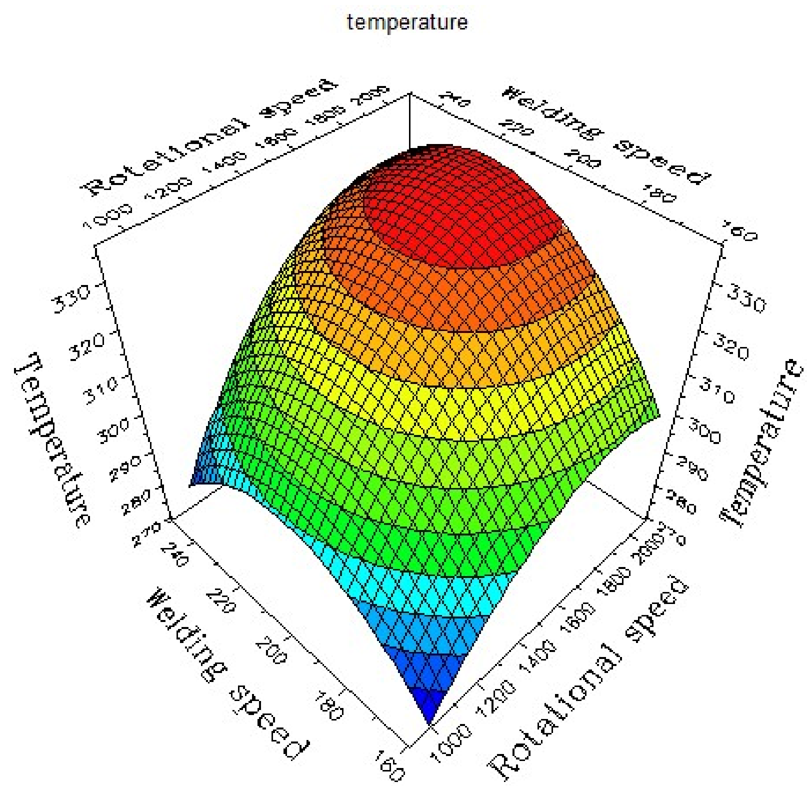

Figure 7. Three-dimensional (3D) variation of Temperature as a function of rotation speed and welding speed.

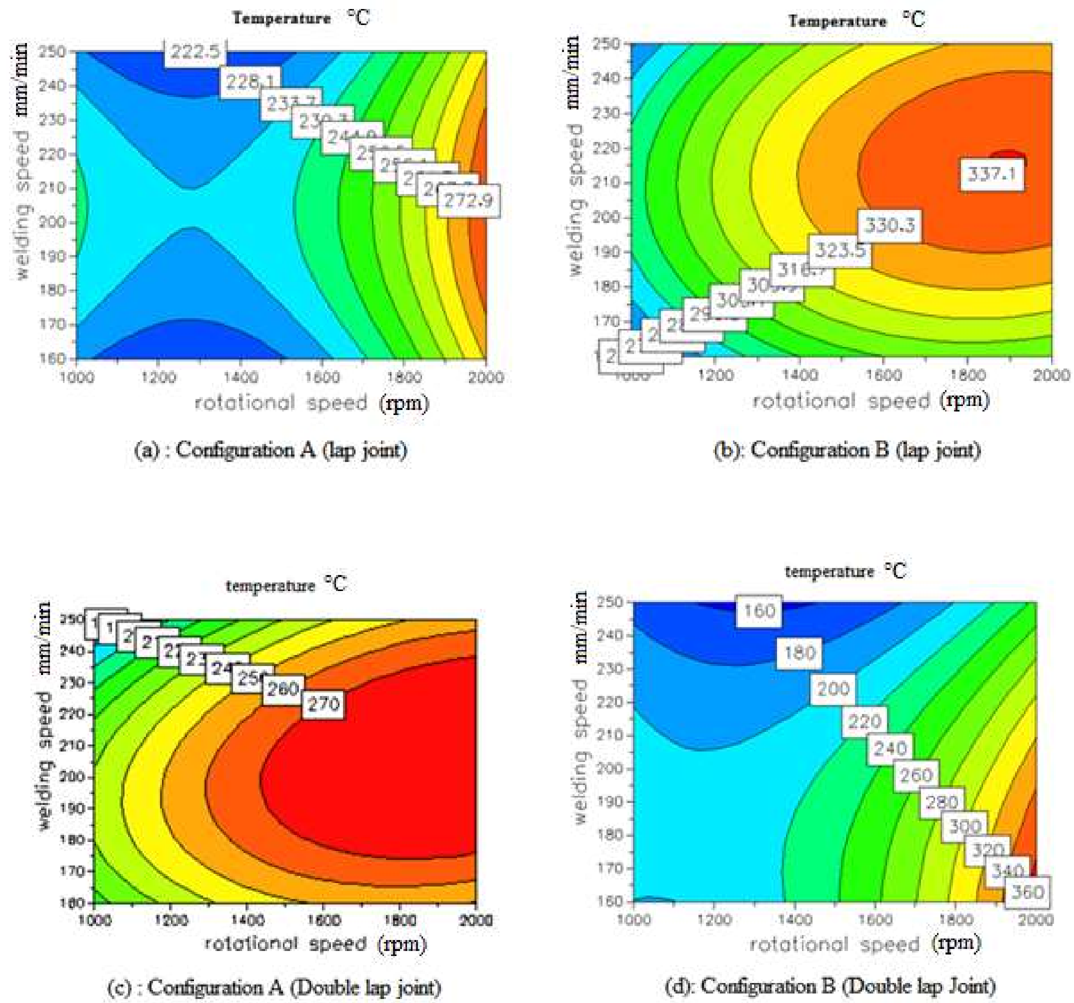

Figure 8. Variation of Temperature as a function of the two factors.

Figure 9 shows the most influential parameters on temperature. The effects of the factors are shown using a bar graph. This diagram gives the effects in decreasing order of their importance in absolute value. This figure clearly shows the sensitivity of the rotational speed and the welding speed respectively to temperature. A small change in rotational speed causes large temperature changes as the welding speed increases.

The results obtained by this study show that the temperature is more sensitive to the speed of rotation than to the speed of welding. After a thorough analysis, these figures show that the classification of the dominant factors on the maximum temperature is as follows: (rot) and (rot * rot). (Figure 9a). On the other hand, for (Figure 9b), the order of dominant factors are as following: (rot) and (wel*wel). Sensitivity analysis, a method to identify critical parameters and rank them by their order of importance, is paramount in model validation where attempts are made to compare the calculated output with the measured data [19].

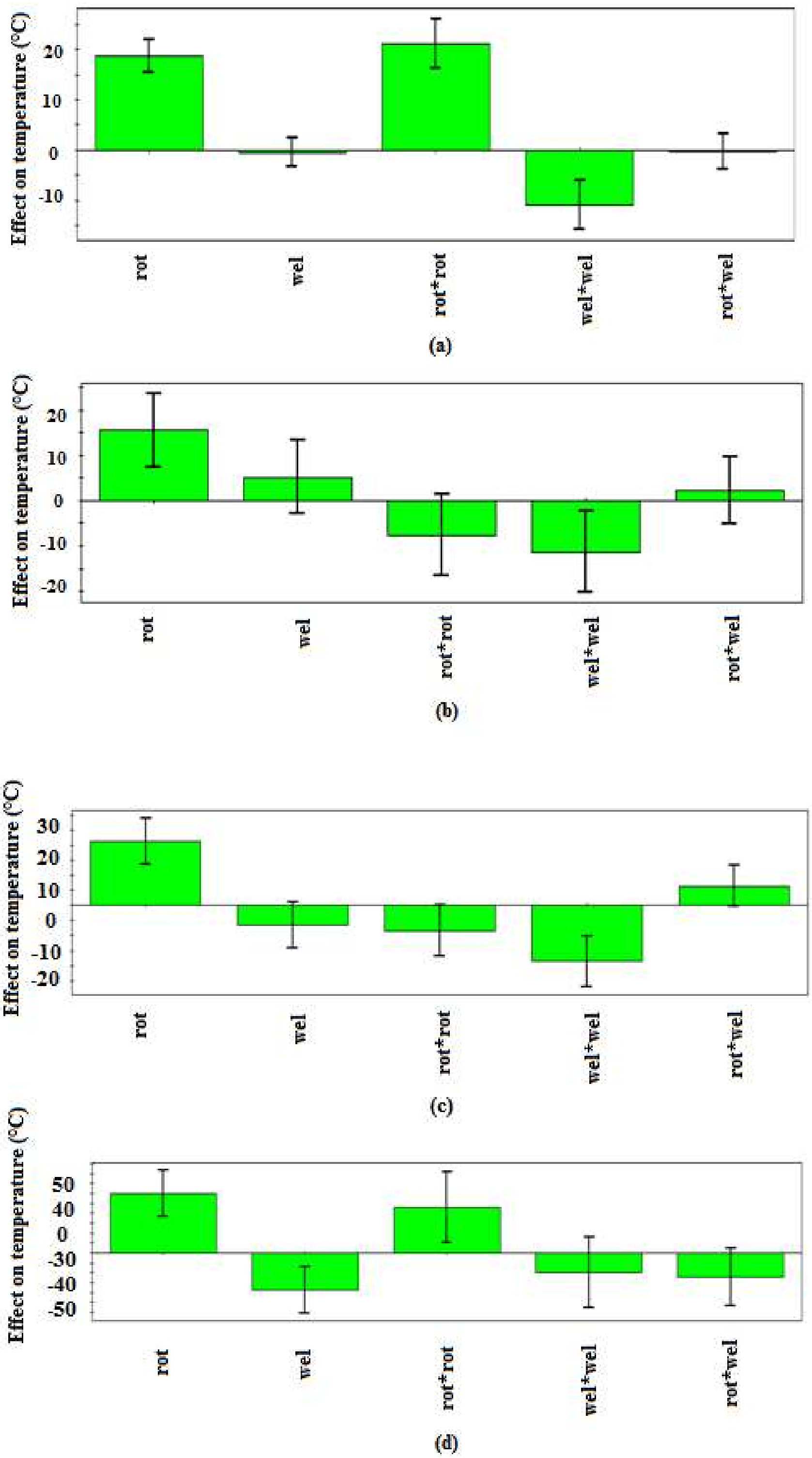

Figure 9. Effects of factors on temperature and their interaction, a) configuration A (lap joint), b) configuration B (lap joint), c) configuration A (Double lap joint), d) configuration B (Double lap joint.

4 Conclusion

The present work was developed to determine the main influential and optimum process parameters of friction stir welding on temperature during FSLW of AA3003 aluminium alloy using Design Expert software. Different combinations of process parameters were favoured to investigate the optimum values of temperature in the nugget zone. Obviously, the height temperatures are higher near the weld and decrease towards the HAZ. In addition, a systematic approach to develop an empirical method to predict the temperature by including friction stir welding (FSLW) process parameters such as tool speed and welding speed was presented.
The following important conclusions are derived from this investigation.

1. The model developed by the Design of Experiments approach made it possible to obtain a better prediction of the temperature of a welded joint. This model provides an effective tool for selecting the optimal parameters of the friction stir lap welding (FSLW) process.
2. The maximum values (278.012 °C , 337.245 °C) were found at tool rotation speeds (1999.99 rpm, 1892.19 rpm), welding speed (203.698 mm/min, 216.167 mm/min), whereas minimum temperatures (222.475°C, 269.094°C) were observed at tool rotation speeds(1282.47 rpm, 1000 rpm) traverse speeds (249.997 mm/min, 160 mm/min) for single lap joint (Configurations A and B) respectively.
3. For the double lap joint, the maximum values (286.44 °C , 368.369 °C) were found at tool rotation speeds (1968.25 rpm, 1999.98 rpm), welding speed (206.282 mm/min, 160.001 mm/min), whereas minimum temperatures (174.465 °C, 155.72 °C) was observed at tool rotation speeds(1000 rpm, 1304.3 rpm) traverse speeds (250 mm/min, 250 mm/min) for configurations A and B respectively.

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