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Investigation of Thermal History and Optimization of Thermal Stresses in Friction Stir Welded Copper Sheets

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Abstract

In the present study, thermal history have been determined for joined copper sheets under various welding conditions using Frigaad relation, numerically. The obtained results were compared with the experimental results and it was found that there is a good agreement between them. Also, it was found that the traverse velocity mainly affects the amount of transferred heat and the rotational speed changes the temperature of the welding process. This study cleared that in all welding conditions at first, the thermal history diagrams predicted using Frigaad relation are lower than the diagrams obtained from the experiments and then, the trend of process diagrams reverses and the simulation diagrams place higher than the experiment diagrams. In addition, Signal-to-noise analysis shows that shoulder diameter is a significant factor and plays a major role in affecting the longitudinal tensile thermal stresses.

1. INTRODUCTION

Friction stir welding is one of the new methods of connecting components to each other that compared to other methods is a relatively new one. This method was originally invented for connecting aluminum parts but its use was quickly extended to other materials such as magnesium, copper, steel, titanium, zinc [1] and many polymeric [2] and thermoplastic [3] materials. It was used to connect pieces with different materials as well [4-6]. This method was invented and introduced by The Welding Institute (TWI) in England in 1991 [7]. Recently, by developing the application of copper and its alloys as a structural material, the demand for the use of the method for welding the material is growing [8, 9]. Accordingly, copper has been chosen for the present study. Copper is applied to build pipes and ducts in many industries [10] and due to the corrosion resistance in plumbing [11, 12]. It is also used for water supply at homes [13] in the way that in the world, 80% of water supply systems are made of copper [14].

One of the important issues in FSW is to determine the thermal history and distribution in workpiece during the welding process [15]. This issue is important from two points: first, it can be determined whether welding is possible or not in a particular condition and Second, the thermal history and distribution in a piece affect the residual stress and grain size, thus it affects the weld strength [15]. Hence, a lot of researchers have attempted to provide experimental strategies or analytical models to determine thermal distribution in the workpiece. For example, Hwang et al. could specify the thermal history in the specific parts of workpiece through placing thermometers in aluminum sheets and welding them applying the mentioned method [15]. Also, Xue et al. were able to evaluate the thermal effect on the mechanical properties of obtained welds via FSW on copper in water and air and with different temperatures and determining the maximum temperature [16]. Imam et al. compared the relationship between mechanical and microstructural properties of stir areas and affected by temperature with maximum temperature for aluminum alloys [17].

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Along with the conducted analytical and experimental studies, some researchers used numerical methods for determining the field of thermal distribution and its history in some parts of workpieces. For instance, using DEFORM-3D software, Buffa et al. could specify the thermal field in two parts of AA6060-T4 aluminum pieces connected by FSW [18]. Also, using Euler model, Jacquin et al. determined the thermal history and distribution in AA6060-T4 aluminum sheets and compared them with values obtained from the test [19]. Al-Badour et al. achieved the values of maximum temperature in FSW of AL6061-T6 aluminum through presenting Eulerian – Lagrangian model and compared them with experimental values [20].

Javadi et al. optimized residual stresses produced by friction stir welding of 5086 aluminum plates using Taguchi method. They optimized parameters including feed rate, rotational speed and pin diameter [21]. Also, Ugender studied the effect of friction stir welding parameters such as tool pin profiles, rotational speed and welding speed on the mechanical properties of tensile strength, hardness and impact energy of magnesium alloy AZ31 [22]. In this investigation, the experiments were carried out as per Taguchi parametric design concepts and an L_9 orthogonal array. He found that the important parameters influencing the weld mechanical properties are tool pin profiles and the combination of rotational speed and welding speed.

In the present study, two copper pieces have been welded together by the friction stir welding method under different welding conditions. The thermal history has experimentally been determined in a specific point of these pieces too. Then, using a numerical method and an empirical relation, the thermal history has been determined at the same points and under the same circumstances and has been compared with experimental results. Finally, three important process parameters including tool rotational and traverse speed and shoulder diameter have been optimized using Taguchi method.

2. MATERIALS AND METHODS

To carry out the tests, copper samples with lengths of 135 mm and widths of 50 mm were cut perpendicular to the rolling direction from a large sheet with a thickness of 5 mm. The content of the constituent elements of copper used in this study based on quantitative tests is presented in Table 1.

Table 1. *The weight percentage of constituent elements of copper used in the study*

Cu	Pb	Sn	P	Ni	Ag	Zn
Base Metal (99.86)	0.005	0.0041	0.0224	0.0011	0.0017	0.0092

After smoothing the intended sections, the samples were placed together in a die for the welding process and were fixed towards each other by the die constraints. In addition to keeping the two workpieces fixed towards each other, the die constraints pushed them to the bottom of the die, where a copper plate is embedded. This copper plate at the bottom of the die is responsible for cooling the workpieces. As can be seen in Figure 1, the water enters the die via a hose and flows under the copper plate and into the slots, which are created under the copper plate for this purpose. This has a cooling effect on the copper plate of the die. Also, the copper plate, which is in direct contact with the workpieces, serves to transfer heat from the workpiece to the water, thereby reducing the temperature of the workpieces.

After cooling, the water flow enters into the exit hose from the other side of the die and exists through it. The mass rate of water passing through the die is equal to 0.019 kg/s. Cooling is done to transfer rapidly heat from pieces so that the opportunity of grain growth is taken from their microstructures. In many studies and references, it has been acknowledged that within the FSW process, cooling and removing rapidly heat from pieces lead to improving the properties of most materials [23-25].

A rotary tool used for doing the FSW process includes a shoulder with a diameter of 20 mm and a pin with a diameter of 8 mm and length of 4.7 mm. In order to improve the material travels, some threads are created on the pin which lets the material moves better around the instrument and to some extent it will move the axis. The tilt angle is considered as 2.5 degrees on the instrument. The indentation of the shoulder in the pieces (Plunging) is also 0.2 mm.

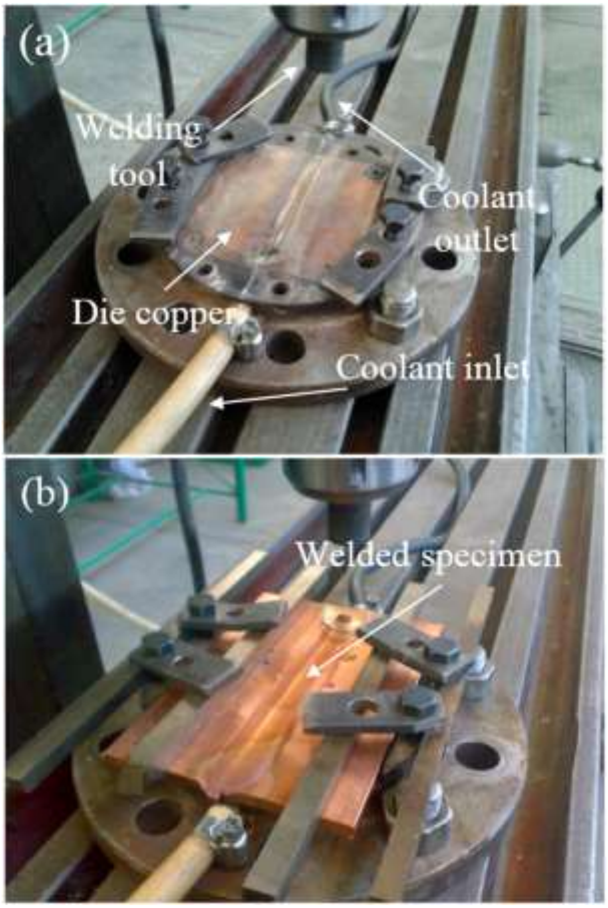

Figure 1. *View of (a) the tools and the die used in the welding process and (b) the pieces fixed to the die after the welding process.*

The appropriate welding conditions for successful welding of the mentioned samples were determined by welding under different conditions (presented in Table 2) and using a trial and error method. Also, the point whose temperature has experimentally and numerically been measured for each welding cases has been indicated in Figure 2.

Table 2. *Different cases used in welding.*

Investigated cases	Rotational speed, N (rpm)	Traverse speed, v (mm/min)
Welding conditions 1	500	56
Welding conditions 2	500	112
Welding conditions 3	710	56

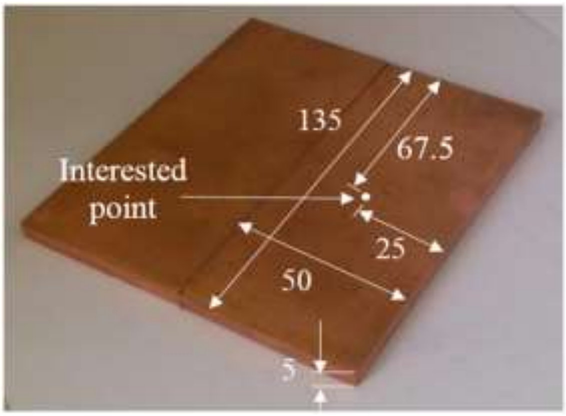

Figure 2. *The point whose temperature has experimentally and numerically been measured for each welding cases.*

An infrared thermometer was used to measure the temperature in the workpiece. The thermometer was fixed on the table of a milling machine and moves with it (Figure 3). The thermometer reads the temperature values for a particular point at any time and instantaneously sends the obtained information to a manual computer to record via a receiver. So, by focusing the thermometer on the specific point of the surface of the workpiece, in the advancing side, its thermal history can be recorded instantaneously on the computer. This particular point is the midpoint of one of the two sheets that should be welded together (Figure 2).

Figure 3. *Thermometer installed on the table of angle grinder for measuring instantaneous temperature.*

In order to determine the stress-strain diagram for the base metal at various temperatures, the standard samples of the tensile test were prepared based on ASTM-E8 standards shown in Figure 4(a) [26]. Also, Figure 4(b) shows the electric furnace used for high-temperature tensile tests. The true stress-strain diagram from the tensile test was obtained at two temperatures of 700°K and 800°K. These temperatures were chosen because they were approximately maximum temperatures that workpieces experienced on the conditions mentioned in Table 2. These temperatures were measured by infrared thermometer exclusively behind the tool in each welding mode during welding processes. Figure 5 shows true stress-strain diagrams of the base metal at two temperatures of 700°K and 800°K.

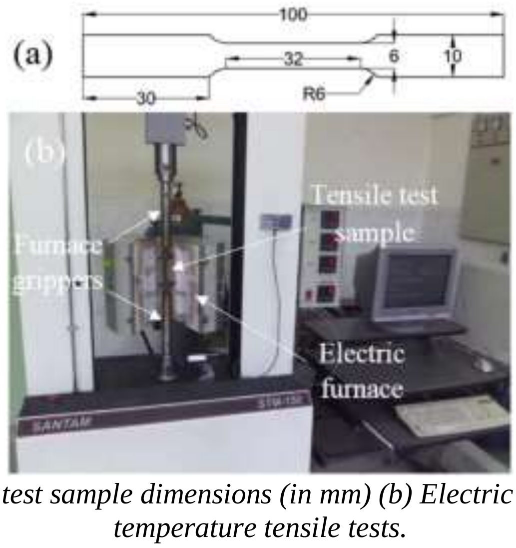

Figure 4. *(a) Tensile test sample dimensions (in mm) (b) Electric furnace used for high temperature tensile tests.*

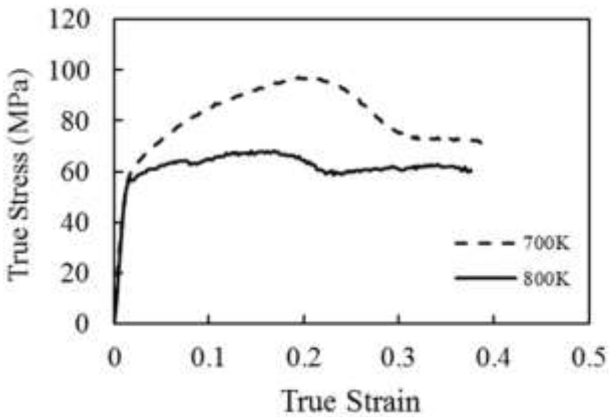

Figure 5. *True stress – strain diagram of the base metal at two temperatures of 700°K and 800°K.*

3. SIMULATIONS

In order to simulate and determine the thermal field numerically in the workpiece, LS-Dyna software was used. For modeling the process of welding in the software, the option of thermal weld was used. This option was particularly included to simulate the process of welding in the mentioned software. Using this option, the rotary tool that is the thermal generator in the process of friction stir can be modeled as a heat source and moved along the surface of the workpiece with the desired speed. By moving this heat source on the workpiece, the heat can transfer to the workpiece and the temperature of the workpiece can increases at various parts of the workpiece, based on the heat transfer rate. To determine the produced heat rate by the rotary tool, within the process of friction stir welding, several relations are presented in various references. One of the important relations is the one provided by Frigadd et al. [27] that is used for calculating the heat generated by the tool. This relation is as follows:

$$\dot{q}=\frac{4}{3}\pi^2\mu P\omega R^3 \tag{1}$$

Where $\dot{q}$, μ, P, ω and R are the rate of net heat input (W), the coefficient of dynamic friction, pressure (Pa), the angular speed (rps) and tool radius (m), respectively. According to Frigadd theorem, the rotational speed of tool and its radius have the most effect in generated heat. Also, Frigadd et al. suggested that the P be considered equal to flow stress at the temperature of the process [27].

In the present study, to obtain the rate of produced net heat, the above relation has been used. In so doing, the dynamic friction coefficient between tool and workpiece has been considered equal to 0.36 [28]. P-Value is equal to the flow stress of the material of workpiece at the temperature at which the process is performed. As we know, the flow stress is the stress in which deformations are of a plastic type. Given Figure 5, it can be found that after crossing from the yield stress and entering to the flow stress area, the true stress-strain diagram of copper at high temperature become first ascending and then descending and thereafter, it will be horizontally and fairly constant. Therefore, given that for using Equation 1 and obtaining the rate of produced heat at the certain temperature and a specified rotation of tool (N), a constant number should be used and this number i.e. the flow stress of workpiece material has been considered in the temperature of the process equal to the stress of horizontal area of the diagram. Thus, P was considered at the temperature of 700 °K equal to 72MPa and 800 °K equal to 61MPa.

According to what was said, to calculate the rate of transferred heat at the rotation of 500 rpm using Equation 1, we can write:

$$\dot{q}=\frac{4}{3}\pi^2\mu P\omega R^3=\frac{4}{3}\pi^2(0.36)\left(72\times10^6\text{Pa}\right)\left(\frac{500}{60}\text{rps}\right)\left(10\times10^{-3}\text{m}\right)^3 = 2842.45\text{W} \tag{2}$$

Also, to calculate the rate of transferred heat at the rotation of 710 rpm using Equation 1, we have:

$$\dot{q}=\frac{4}{3}\pi^2(0.36)\left(61\times10^6\mathrm{Pa}\right)\left(\frac{710}{60}\mathrm{rps}\right)\left(10\times10^{-3}\mathrm{m}\right)^3 = 3419.62\mathrm{W} \tag{3}$$

To consider boundary conditions, it is assumed that 10% of the heat created by the tool is wasted through the tool itself and the thermal conductivity [28]. Therefore, it is assumed that 90% of the heat created by the tool is spent to do the process. So, for the two mentioned states, the net heat transferred to the workpiece will be equal to:

At the rotation of 500 rpm:

$$\dot{q}_{net}=0.9\times2842.45\mathrm{W}=2558.2\mathrm{W} \tag{4}$$

and at the rotation of 710 rpm:

$$\dot{q}_{net}=0.9\times3419.62\mathrm{W}=3077.65\mathrm{W}. \tag{5}$$

It is also assumed that water with the ambient temperature passes through two channels of copper sheet and exchanges the heat through (convective) transmission with the copper sheet and therefore with the workpiece. All of the other cases of heat exchange during the process performance are negligible and were ignored; for example, the heat transferred by the workpiece to air or small components of the die.
If the specific heat capacity of water is considered as c = 4200 J/kg $^{\circ}$K [29] to obtain the outlet water temperature of the die, we can write:
At the rotation of 500 rpm:

$$\dot{q}_{net}=\dot{m}c\Delta T\Rightarrow2558.2\mathrm{W}=0.019\frac{\mathrm{kg}}{\mathrm{s}}\times4200\frac{\mathrm{J}}{\mathrm{kg}\,^{\circ}\mathrm{K}}\times\Delta T\Rightarrow\Delta T=32\,^{\circ}\mathrm{K} \tag{6}$$

And at the rotation of 710 rpm:

$$3077.65\mathrm{W}=0.019\frac{\mathrm{kg}}{\mathrm{s}}\times4200\frac{\mathrm{J}}{\mathrm{kg}\,^{\circ}\mathrm{K}}\times\Delta T\Rightarrow\Delta T=38.6\,^{\circ}\mathrm{K}. \tag{7}$$

The water temperature at the inlet to the die was 298 $^{\circ}$K. Therefore, the water temperature at the outlet will be 330 $^{\circ}$K at the rotation of 500 rpm and 336.6 $^{\circ}$K at the rotation of 710 rpm. To perform the simulation, the average temperature of the inlet and outlet has been considered as cooling water temperature i.e. temperatures of 314 $^{\circ}$K and 317.3 $^{\circ}$K for rotations 500 rpm and 710 rpm, respectively.
To calculate the convective heat transfer coefficient (h), the relation of convective heat transfer has been used:

$$\acute{q}=Ah\Delta T \tag{8}$$

In the Equation 8, $\acute{q}$ is the rate of heat transferred to the cooling water and A is the area of the die channel moistened by water (Figure 6), so we have:

$$A=2\times[(6+30+6)\times100]\mathrm{mm}^2=8.4\times10^{-3}\mathrm{m}^2 \tag{9}$$

Now, given that the heat that the copper sheet at the bottom of die takes from the workpiece is directly transferred to cooling water, we have:

$$\acute{q}=\dot{q}\Rightarrow Ah\Delta T=\dot{m}c\Delta T\Rightarrow h=\frac{\dot{m}c}{A}=\frac{0.019\frac{\mathrm{kg}}{\mathrm{s}}\times4200\frac{\mathrm{J}}{\mathrm{kg}\,^{\circ}\mathrm{K}}}{8.4\times10^{-3}\mathrm{m}^2}=9500\frac{\mathrm{W}}{\mathrm{m}^2\,^{\circ}\mathrm{K}} \tag{10}$$

However, it should be noted that h coefficient is not often a constant value and depends on parameters such as the length of the pipe (channel) and Nusselt number, etc., but the value obtained from the above relation can be accepted as average h in the channel.

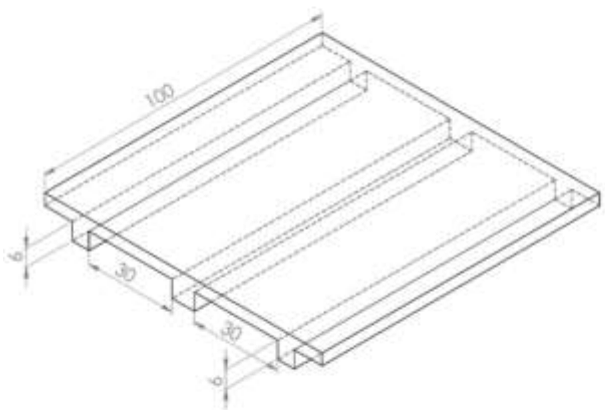

Figure 6. *Dimensions of two die channels.*

Given that the specific heat capacity and thermal conductivity coefficient of copper have different values at various temperatures, these two quantities were introduced to software in terms of temperature, according to Table 3 [30].

Table 3. *Specific heat capacity and thermal conductivity coefficient of copper at various temperatures [30].*

Temperature (ºK)	Thermal conductivity (W/mºK)	Heat capacity (J/KgºK)
200	412	343
350	396	391
500	387	403
650	376	425
800	365	437
950	355	455
1100	345	468
1250	334	478

For the more similarity of simulations to the conducted experiments, the thermal source has been considered as a fixed point of space and just above of the two half pieces and at the beginning of their intersection. Two half workpieces are passed completely similar to the test across their intersection, beneath and tangent to it and with constant speeds. Each half of workpiece has been meshed by 2700 cubic elements.

As it was explained in the section of experiments, two halves of the workpieces and the copper sheets of the bottom of die do significant heat exchange. So, this exchange should be considered in the simulation. Therefore, in addition to the two halves of workpiece, copper sheet of the die and its two water passing channels, have been modeled using 2800 cubic elements. Given that the workpiece became practically tight on the die copper by the die constraints and completely contacted with it at any moment, meshing of the workpieces and die copper was done in the way that nodes of their elements (in their contact plane) overlapped at each other. In the next step, the nodes consistent with each other were merged to desirably do the heat exchange between two halves of the workpieces and die copper. So, there is no need to define the contact between various components of the issue. In this simulation, due to its high accuracy, the model of piecewise linear plasticity material has been used since using this model, the parts of stress – strain diagram of the material are identically presented to the software without the need for the curve fitting. The copper density has been considered equal to $8900\frac{kg}{m^3}$ and the initial temperature of all components equal to 298 $^{\circ}$K.

4. RESULTS AND DISCUSSION

4.1. Thermal History and Field

Through simulations, the thermal field can easily be achieved at any time and for any welding mode. Figure 7 shows the thermal field in three different welding conditions and when welding tool is located in the middle of the weld line. Also, Figure 8(a) indicates the thermal history for the point of workpieces whose thermal history has experimentally been measured and Figure 8(b) reveals the thermal history for the point which the heat source passes and places in the middle of the weld line.

According to Figure 8, it is evident that the effect of rotational speed of tool on the maximum rate of temperature is much more than the effect of its traverse velocity. Figure 8(b) reveals that 100% increase in the traverse velocity from 56 mm/min to 112 mm/min has led to decrease the maximum temperature from 715 $^{\circ}$K to 693 $^{\circ}$K which is by no means a significant value. On the other hand, if the rotational speed increases from 500rpm to 710rpm that is 24% rises, the maximum temperature will increase from 715 $^{\circ}$K to 802 $^{\circ}$K. Also, according to diagrams of Figure 8 although, increasing in traverse velocity hasn't a significant effect on the thermal history of different points of the workpiece, it causes to decrease the duration of welding time i.e. transferring less heat to the workpiece. Moreover, Figure 8(a) shows that with increasing the rotational speed of the tool, the interested point of workpiece bear more temperature and an increasing in the temperature is significant. Therefore, in summary, it can be said that the traverse velocity change mainly affects the transferred heat rate and the change in the rotational speed dramatically change the temperature of the process.

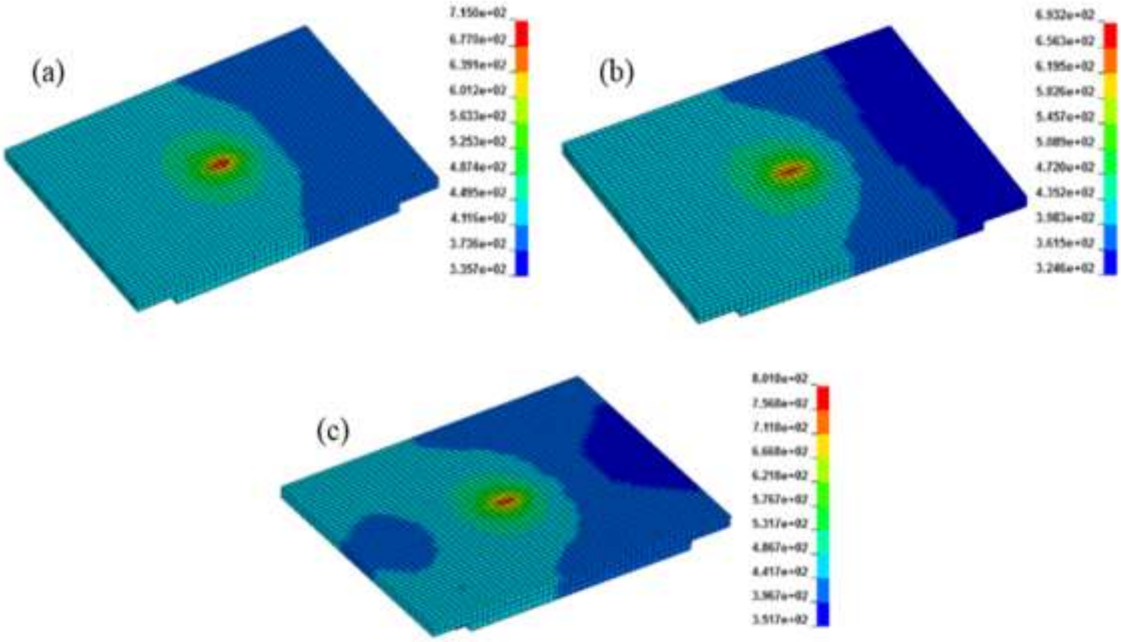

Figure 7. *Temperature field in three different welding conditions (according to Table 2) of welding: (a) welding conditions 1, (b) welding conditions 2 and (c) welding conditions 3.*

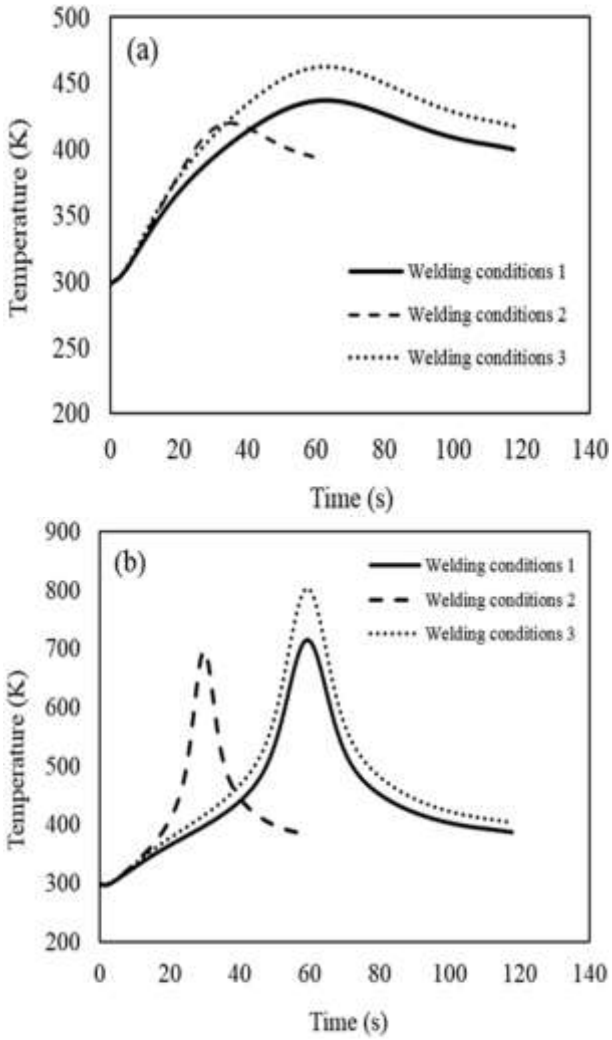

Figure 8. *(a) The thermal history in the point of workpieces whose thermal history has experimentally been measured and (b) the thermal history in the point on which the heat source passes and places in the middle of the intersection line of two pieces.*

In order to compare the experimental and numerical results, the diagrams of the thermal history of each method have been obtained for various welding conditions mentioned in Table 2, are shown in Figure 9. According to these diagrams, it can be found that at first, the simulation diagrams are lower than the diagrams obtained from the experiment because the estimated heat rate is slightly less than the true heat rate. This is because in estimating the heat rate, flow stress has been considered equal to the flow stress of the horizontal part of the diagram; while, the overall flow stress is slightly higher than this value. However, in large strains which occur in the friction stir process, this part of the diagram is not quite noticeable. Afterward, the trend of process diagrams reverses and the simulation diagrams place higher than the experiment diagrams, that is because of the effect of ignored heat loss. Over time, their values in experiment increase while, there is no loss in the simulation. But it should be noted that the values of these differences are not significant compared to temperatures on which the process is done and with a little ignorance, the obtained diagrams can be considered to be coincide.

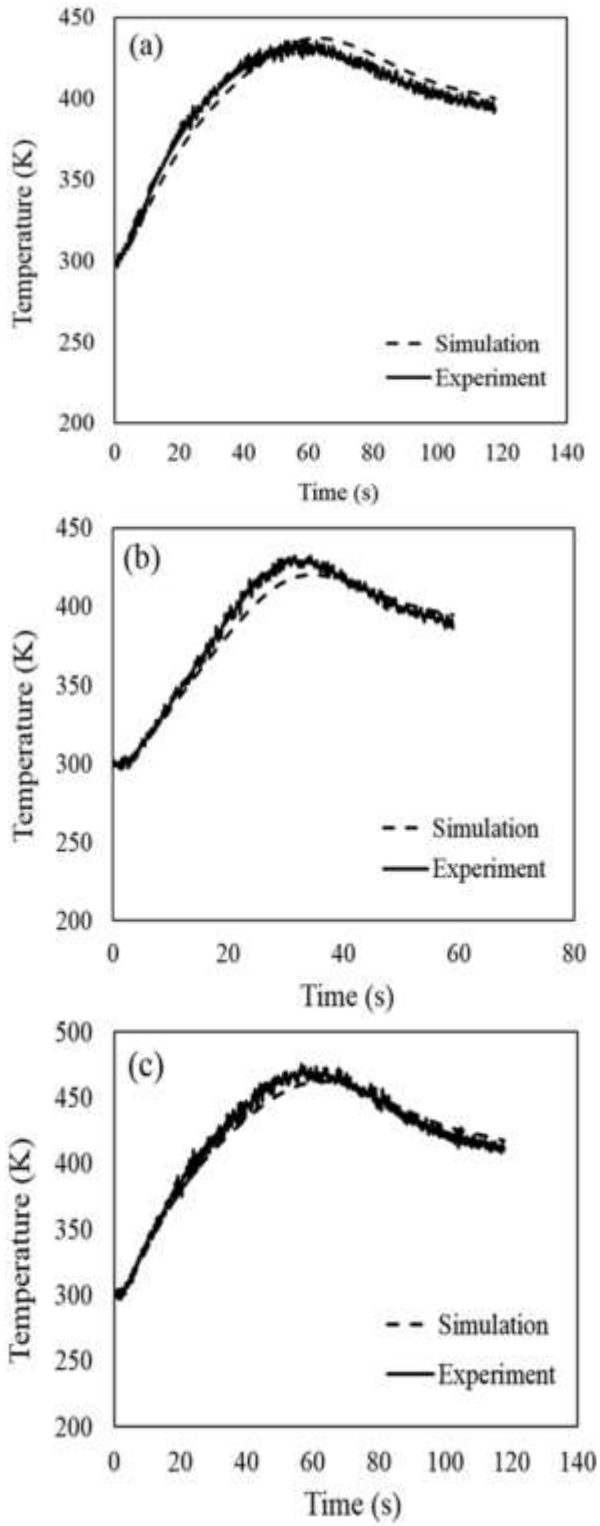

Figure 9. *Comparing the experimental and simulation results (a) Welding conditions 1; (b) Welding conditions 2 and (c) Welding conditions 3.*

This matter demonstrates that the thermal history and field can be predicted by doing a tension test on samples prepared from the intended material and using LS-Dyna software and its thermal weld option. So, it is clear that using the advantages of the numerical method, many time and cost can be saved and the thermal history and field at any moment in workpieces such as complex pieces can be predicted correctly no need to practical weld.

In addition, this study shows that the relation proposed by Frigadd et al. has been successful to estimate the rate of heat transferred to the workpiece within FSW and thus, the relation is valid for the copper workpiece.

4.2. Thermal Stresses Optimization

Thermal stress line profiles from the upper-plate thickness are provided in Figure 10 for the FSW sample sets produced with different welding conditions. Figure 10(a) shows the longitudinal thermal stresses profiles and Figure 10(b) shows the transversal thermal stresses profiles. The gold of this study is the minimization of thermal stresses because thermal stresses are the main reason of created residual stresses in the welded plates. Residual stresses are an important issue in FSW, particularly in fatigue loading because, large tensile residual stresses can be produced during welding processes which can lead to premature fatigue failure. So, the tensile residual stresses should be minimized. For this purpose, it is essential to understand how the welding parameters influence the thermal stress distribution.

Taguchi method is one of the popular optimization techniques that could be used to optimize welding parameters. Optimization of process parameters is a key step in the Taguchi technique to reach high quality without increasing the cost. This is because optimization of FSW process parameters can decrease the tensile thermal stress (TTS), which leads to improvement of performance characteristics [21].

Generally, classical process parameter design is complex and not easy to solve. This is mainly true when the number of the process parameters increases, leading to a large number of simulations have to be carried out. To solve this problem, the Taguchi method with a special design of orthogonal arrays can be employed to study the entire process parameter space with a small number of simulations only. The optimum combination of the process parameters can then be predicted.

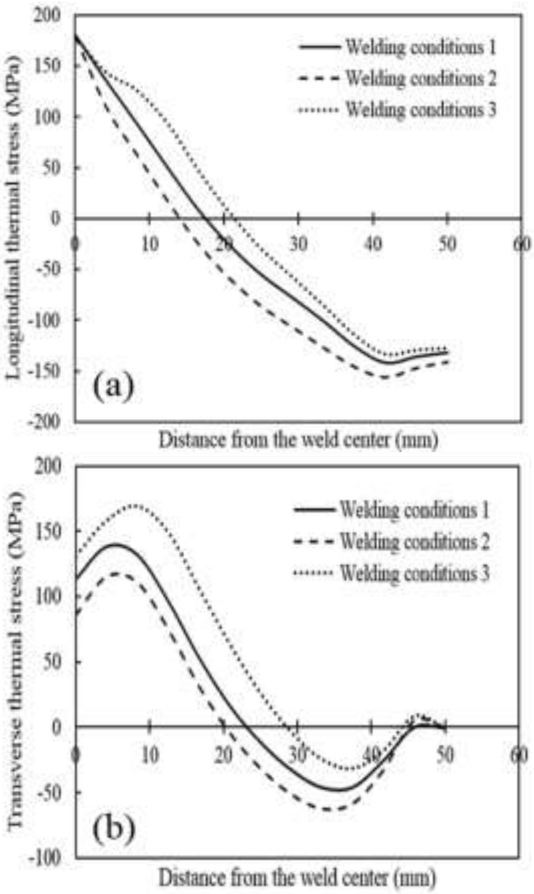

Figure 10. *(a) Predicted longitudinal thermal stresses profiles and (b) Predicted transversal thermal stresses profiles for a half of welded copper plates under different welding conditions.*

As mentioned, the goal of this section is the optimization of thermal stresses produced by the FSW process on copper sheets using simulation method. By using the Taguchi method, the DOE is employed to optimize welding parameters including rotational speed and traverse velocity of tool and shoulder diameter.

The process parameters are considered in five levels each as shown in Table 4. In order to minimize the number of simulations, Taguchi's L_{25} factorial design of simulation was adopted in this work, the design matrix is given in Table 5.

Table 4. *Process parameters at five levels.*

parameters	Level 1	Level 2	Level 3	Level 4	Level 5
Rotational speed (rpm)	500	552	605	657	710
Traverse speed (mm/min)	56	70	84	98	112
Tool shoulder (mm)	20	21	22	23	24

Table 5. *Taguchi's L_{25} design matrix.*

Sim. No.	Rotational speed (rpm)	Traverse speed (mm/min)	Tool shoulder (mm)
1	500	56	20
2	500	70	21
3	500	84	22
4	500	98	23
5	552	112	24
6	552	56	21
7	552	70	22
8	552	84	23
9	552	98	24
10	552	112	20
11	605	56	22
12	605	70	23
13	605	84	24
14	605	98	20
15	605	112	21
16	657	56	23
17	657	70	24
18	657	84	20
19	657	98	21
20	657	112	22
21	710	56	24
22	710	70	20
23	710	84	21
24	710	98	22
25	710	112	23

It is clear that owing to process parameters changes, the transferred heat rate to the sheets changes and therefore, the temperature of coolant water, induced residual stresses and flow stress of workpiece change. So, for every welding cases, these quantities should be determined using the corresponding formula and numerical method. For determination of transferred heat rate to the sheets in all 25 welding conditions mentioned in Table 5, Equation (1) was used.

Simulation results show that the amounts of longitudinal thermal stresses are more than the amounts of traverse residual stresses. Other researchers have obtained the same conclusion [31, 32]. In addition, the maximum of longitudinal tensile thermal stresses has occurred on the weld line. Thus, in this study, the maximum of longitudinal TTS which is created on the weld line is considered as an objective function that is the most longitudinal tensile thermal stress. Table 6 presents the transferred heat rate to the sheets, the flow stress, the temperature of water at the outlet and the induced longitudinal TTS for 25 considered welding conditions in Table 5.

Table 6. *Transferred heat rate to the sheets, the flow stress, the temperature of water at the outlet and the induced longitudinal TTS for 25 considered welding conditions in Table 5.*

Sim. No.	Transferred heat rate (W)	Flow stress (MPa)	temperature of water at outlet (ºK)	longitudinal TTS (MPa)
1	2842.45	72.00	330.00	142.05
2	3081.83	67.43	332.76	143.01
3	3312.17	63.04	335.35	139.68
4	3532.80	58.84	337.84	136.92
5	3742.16	54.85	340.20	134.22
6	3245.30	64.32	334.60	147.72
7	3476.11	59.92	337.20	134.88
8	3694.91	55.75	339.67	131.57
9	3901.71	51.81	342.00	128.60
10	3003.64	68.92	331.87	149.10
11	3627.02	57.05	338.91	130.37
12	3844.03	52.92	341.35	126.53
13	4047.15	49.03	343.64	123.52
14	3154.90	66.04	333.58	144.40
15	3397.02	61.43	336.31	141.46
16	3976.00	50.39	342.84	122.47
17	4175.93	46.58	345.09	118.77
18	3291.25	63.44	335.12	140.06
19	3533.48	58.83	337.85	136.91
20	3761.66	54.48	340.42	133.85
21	4294.29	44.33	346.43	114.61
22	3419.62	61.00	336.56	136.21
23	3660.59	56.41	339.28	132.16
24	3886.95	52.09	341.84	129.04
25	4098.19	48.07	344.22	126.21

Table 6 shows that the minimum of TTS is 114.61 and belongs to welding conditions 21. In welding conditions 21, the rotational speed is 710rpm, traverse speed is 56mm/min and tool shoulder is 24mm. in this welding conditions, the maximum heat transfers to the workpiece. So, the welding conditions 21 is the optimal welding conditions, of course from the point of view of the minimum longitudinal TTS. It should be noted that in welding conditions 21, the amount of the maximum of TTS is optimal (minimum) respect to other welding conditions that is because of thermal softening that means the more the heat transferred to the workpiece, the less the pick of induced thermal stress. Of course, if the objective of optimization was the optimizing of longitudinal TTS in the whole of the workpiece, the welding conditions that transferred the least heat to the workpiece (welding conditions 1) was the best.

In the present study, thermal stress had been investigated as the main parameter in order to achieve a joint with minimum longitudinal TTS. In order to better analysis, signal to noise analysis was used to minimize longitudinal TTS values. Since the objective of this study is to maximize longitudinal TTS through optimum process parameters in friction stir welding, “Smaller is better” quality characteristic is applied in this study. For this purpose, the S/N ratio is calculated using the below formula:

$$\frac{S}{N} = -10Log\left(\frac{1}{n}\sum\nolimits_{i=1}^{n} Y_i^2\right) \tag{11}$$

Where Y_i is the value of longitudinal TTS for the *i*th simulation, *n* is the number of simulations and *N* is the total number of data points.

According to Table 6, 25 main values for longitudinal TTS and 25 corresponding values of S/N were obtained. The optimal combination of factors and levels were obtained by analyzing each calculated main values, in order to achieve the minimum longitudinal TTS. As it is clear, higher values of S/N ratio of a simulation, corresponds to the better quality of the welded joint. Therefore the optimal condition is a condition with the maximum S/N ratio. Values of S/N ratio of longitudinal TTS in different levels of used parameters are shown in Figure 11. The analyses are made using the popular software known as MINITAB 16.

As Figure 11shows, value of longitudinal TTS is minimum when rotational speed, traverse speed and shoulder diameter were in 710rpm, 56mm/min and 24mm levels respectively, because, values of S/N ratios in these levels are maximum. Also, to determine that which FSW process parameters have the maximum effect on the longitudinal TTS, it is needed to investigate the S/N ratio. Figure 11 gives a clear picture as to how far the process parameter affects the longitudinal TTS and the level of significance of each factor involved in the analysis. In fact, the main effects for S/N ratio are plotted in Figure 11. The high S/N ratio value indicates that the factor is highly significant in affecting the response of the process. In this investigation, shoulder diameter is a highly significant factor and plays a major role in affecting the longitudinal TTS.

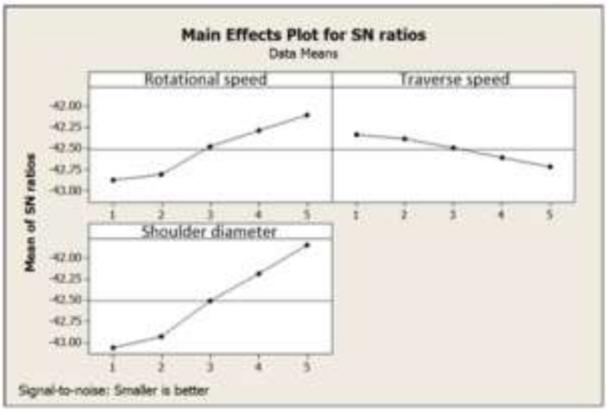

Figure 11. *Values of S/N ratio of longitudinal TTS in different levels of used parameters.*

5. CONCLUSIONS

In this study, the thermal histories in copper sheets were determined experimentally and numerically during a Friction Stir Welding butt joining process and were compared with each other. The following conclusions can be drawn based on the results:

1- The traverse velocity change mainly affects the transferred heat rate and the change in the rotational speed dramatically changes the temperature of the process. For example 100% increase in the traverse velocity from 56 to 112mm/min has led to decrease in the maximum temperature from 715 to 693°K which is by no means a significant value, while the rotational speed increasing from 500 to 710 rpm, accordingly 24-percent rise, increases the maximum temperature from 715 to 802°K.
2- The relation proposed by Frigadd et al. has been estimated successfully the rate of heat transferred to the workpiece within FSW, thus the relations valid for the copper workpiece.
3- In all welding conditions, at first, the simulation diagrams are lower than the diagrams obtained from the experiment because the estimated heat rate is slightly less than the true heat rate. Afterward, the trend of process diagrams reverses and the simulation diagrams place higher than the experiment diagrams, that is because of the effect of ignored heat loss occurred in the experiment.
4- Signal-to-noise analysis shows that shoulder diameter is a significant factor and plays a major role in affecting the longitudinal tensile thermal stresses.

CONFLICT OF INTEREST

No conflict of interest was declared by the authors

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