EXPERMENTAL INVESTIGATION OF TEMPERATURE FOR STIR FRICTION WELDING DISTRIBUTION

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ABSTRACT

Friction stir welding (FSW) is a solid state joining method for metal and is widely used for Al-Alloys. In the present work ,temperature distributions were investigated for Aluminum alloy (7008), the effect of the main welding parameters such as rotational speed (tool speed) and liner speed (welding speed) on the temperature distribution were investigated .The results show that the rotational speed has a strong effect on the temperature distribution and this effect increases with temperature increase, but the linear speed has an (inverse proportion) with the temperature increase. This effect was less than the rotational speed. Peak temperature was estimated theoretically by using (Bakingham π) theorem to derivate the relationship between the dimensionless heat input and dimensionless peak temperature. In this study a mechanical test (tensile test) for welded specimen was investigated to study the effect of temperature distribution on the mechanical properties of the alloy, results show that Aluminum alloy (7008) was weldable on the (FSW) process and obtain an maximum weld efficiency (81%) with parameters (880 rpm) rotational speed and (1 mm/sec) welding speed. By comparing test results with peak temperature to the Al-Alloy the obtained result was that the welding process is successful when welding temperature be (75-80%) of melting point of the used material.

الخلاصة

اللحام بالاحتكاك والدعج هي إحدى طرق اللحام الحديثة وتعتبر من طرق لحام الحالة الصلبة للمعادن حيث تستخدم بشكل واسع لسبائك الألمنيوم.في هذا البحث تمت دراسة عملية توزيع الحرارة لسبيكة ألمنيوم (7008) ودراسة تأثير متغيرات اللحام مثل (السرعة الدورانية) التي تمثل سرعة أداة اللحام والسرعة الخطية التي تمثل سرعة اللحام على توزيع درجات الحرارة للسبيكة باستخدام ماكنة التفريز الميكانيكي العمودية ومن هذه الدراسة أتضح انه للسرعة الدورانية تأثير كبير على درجات الحرارة ويكون

هذا التأثير ذو علاقة طردية مع ارتفاع درجات الحرارة. اما السرعة الخطية فلها علاقة عكسية مع ارتفاع درجات الحرارة وتاثيرها اقل مما هو عليه في السرعة الدورانية. وتم أيضاً استقراء درجات الحرارة القصوى للسبيكة لقيم مختلفة من السرعة الدورانية والسرعة الخطية عملياً.تمت دراسة نظرية من خلال اشتقاق العلاقة بين كمية الحرارة الداخلة ودرجة الحرارة القصوى للسبيكة ورسمها بيانياً للحصول على معادلة يتم الحصول منها على درجة الحرارة القصوى نظرياً . تم بعد ذلك إجراء فحص ميكانيكي (فحص الشد) للعينات لدراسة تاثير درجات الحرارة على الخواص الميكانيكية للسبيكة بعد لحامها بهذه الطريقة وبناءاً على النتائج التي تم الحصول عليها وجد ان السبيكة قابلة للحام بهذه الطريقة مع الحصول على كفاءة قصوى (81%) باستخدام متغيرات لحام (880 دورة / دقيقة سرعة دورانية مع 1 ملم/ثا سرعة لحام) ومن خلال مقارنة نتائج الفحص مع درجات الحرارة القصوى للسبيكة تم الحصول على نتيجة عملية اللحام نجحت عند وصول درجة حرارة اللحام بما يعادل (75-80%) من درجة انصهار السبيكة.

- **KEYWORD**: Friction stir welding, Temperature Distribution, Peak Temperature.

INTRODUCTION

Welding is a materials joining process in which two or more parts are coalesced at their contacting surfaces by suitable application of heat and/or pressure (Groover, 2002) . The welding processes are devided into three major groups: Fusion welding ,Solid state welding And Adhesive bonding: (Serope, 1997). Friction Stir Welding is a relatively new joining process, invented at the welding institute (Cambridge, UK) in 1991 and developed initially for aluminum alloys, it is a solid-state joining technique. The weld is made in the solid phase, that is no melting. Since its invention, the process has received world-wide attention and today companies in Scandinavia, Japan and the USA are using the technology in production, particularly for joining aluminum alloys. High quality weld can generally be fabricated with absence of solidification cracking, porosity, oxidization and other effects resulting from traditional fusion welding (Hemanth,2006). NASA is using this kind of welding on the space shuttle. This kind of welding can help the shuttle be strong, but light (NASA,2002). FSW has been successfully used to weld similar and dissimilar cast and wrought aluminum alloys, steels as well as titanium, copper and magnesium alloys, dissimilar metal group alloys and metal matrix as well as to weld hollow objects such as tanks and tube/pipe, and parts with 3-dimentional contours (Terry Khaled,2005). Friction Stir Welding method of joining is based on the fact that the metal is subjected to heavy plastic deformation at high temperatures, but lower than the melting point, so the basic concept of FSW is remarkably simple, a rotating tool with pin and shoulder is inserted in the material to be welded, and traversed along the line of interest as shown in Fig.1.

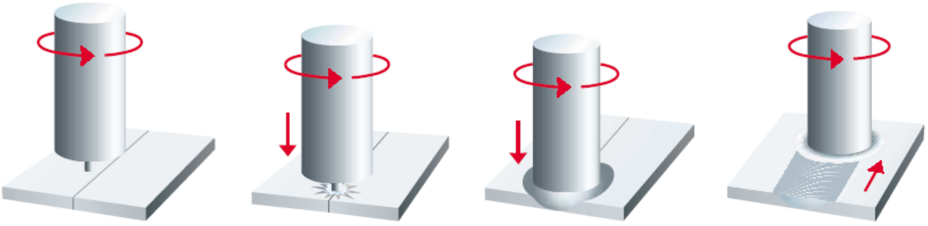


Fig.1: (1 Rotating Tool is Plunged into the Joint Line and Moved Along the Joint. Neither Flux nor Filler Material are Used. (SAPA group, 2003)

Frictional heat, generated mostly under the tool's shoulder, softens the material. During FSW the workpiece is placed on a backup plate and clamped rigidly by an anvil a long the far side to prevent lateral movement. The pin may have a diameter one third of the cylindrical tool and typically has a length slightly less than the thickness of the workpiece. The pin forced into the workpiece until the shoulder contacts the surface of the workpiece while the tool descends further; its shoulder surface touches the top surface of the workpiece and generates heat. The metal is softening and the tool moves along the line of weld. The pin of the rotating tool provides the "stir" action in the material of the workpiece. (Hemanth, 2006).

(Mohanad Okab, 2007) investigate mechanical and microstructural properties of friction stir welding joints for a typical high strength precipitation hardening Aluminum alloys (7020-T6). Effect of welding parameters on mechanical properties of welded joints were investigated using different mechanical tests Based on the stir welding experiment conducted in this study the results show that Aluminum alloy (7020-T6) can be welded using (FSW) process with maximum welding efficiency (87.52%) in terms of ultimate tensile strength using optimum welding parameters (900RPM tool rotational speed, 60 mm/min. welding speed and 0.25mm plunging depth of welding tool). (Hemanth, 2006) in his thesis, developed a three dimensional model to obtain the temperature distribution in the workpiece using ANSYS. A trend line equation which predicts the peak temperature attained during friction stir processing was also developed. The predicted peak temperature is used to obtain the temperature contours through out the workpiece. Friction stir processing was simulated for material Aluminum 5052. Using average values for material properties instead of temperature dependent values affects the final results to a small extent. Using a moving heat source technique is proved to be a reliable method to simulate friction stir processing. (Roy and his group, 2006) developed a dimensionless correlation based on Buckingham's π-theorem to estimate the peak temperature during friction stir welding (FSW)., it can also be used for the selection of welding conditions to prevent melting of the workpiece during FSW. The correlation includes thermal properties of the material and the tool, the area of the tool shoulder and the rotational and translation speeds of the tool. The peak temperatures reported in the literature during FSW of various materials and welding conditions were found to be in fair agreement with the proposed correlation. (Chao, 2003) formulated the heat transfer of the FSW process into two boundary value problems (BVP)-a steady state BVP for the tool and a transient BVP for the workpiece. To quantify the physical values of the process the temperatures in the workpiece and the tool are measured during FSW. Using the measured transient temperatures. Fields finite element numerical analysis were performed to determine the heat flux generated from the friction to the workpiece and the tool. Detailed temperature distributions in the workpiece and the tool are presented. Discussions relative to the FSW process are then given. In particular, the results show that: The majority of the heat generated from the friction, i.e., about 95%, is transferred into the workpiece and only 5% flows into the tool and the fraction of the rate of plastic work dissipated as heat is about 80%.**(** Richardson, 2003)presented a new heat transfer model for predicting heat transfer in friction stir welding (FSW). In this model, Experimental results indicate that the temperature at the tool shoulder contact surface hardly changes with the weld speed and the tool rotational speed. It can be expected that local melting does occur in FSW. So, both the tool rotational speed and the weld speed do not significantly affect the maximum temperature in the weld. The weld speed affects the distribution of temperature in the workpiece. And a perhaeting time is important in FSW; it makes the weld easier. (Chao and Qi, 1999) in this work, a three-dimensional finite element analysis of the FSW process was used. The modeling effort includes a decoupled heat transfer and a subsequent thermomechanical analysis. The temperature fields during the welding, the residual stress distribution and distortion of the workpiece after the FSW process are studied. The results from the modeling are consistent with the available experimental data and trends. The model is then used to study the fabrication process of the FSW for the effect of plate thickness and welding speed.

THEORETICAL ANALYSIS

The peak temperature of the workpiece and the effective parameter on it was studied by using Buckingham (pi) theorem to develop a dimensionless correlation.

In physical systems, certain quantities, such as mass, length, and time or (force, length, and time), are considered to be fundamental quantities since they cannot be expressed in simpler terms. All other physical quantities may be expressed in terms of these fundamental quantities.

Velocity is a length divided by time, and density is mass per unit volume (length cubed). (Ranaldv, 1992)

Prediction of the dimensionless Correlation Formulla :-(Roy, 2006)

The variables that influence the peak temperature "Tp" are identified as:

- The heat input per unit length to the workpiece ($f\sigma_8 A$).
- The rotational velocity of the tool (w).
- The thermal property of the workpiece. (k/cp)
- The translation velocity of the tool. (V) and
- The initial or preheat temperature of the workpiece. (Tin)

In these variables, σ_8 represents the yield stress of the workpiece at a temperature of 0.8Ts where (Ts) is the solidus temperature, A is the cross sectional area of the tool shoulder defined as. $A = \pi\left(R_o{}^2 - R_i{}^2\right)$ (1)

Where R_o and R_i are the shoulder and Pin radius respectively.

The factor (f) represents the ratio in which heat generated at the tool shoulder / workpiece interface that is transported between the tool and workpiece.

Its value can be calculated based on steady-state one dimensional heat transfer from point heat source located at the interface of dissimilar materials.(Roy, 2006).

$$f = {\left[(k\rho CP)_w\right]^{1/2}} \Big/ {\left[(k\rho CP)_T\right]^{1/2}} \qquad (2)$$

Where the subscript W and T indicate the workpiece and tool respectively,

k is the thermal conductivity (W/m°C)

Cp is the specific heat , at constant pressure (kJ/kg°C) and ,σ(kg/m^3)

ρ is the density of the material. Thermal conductivity, k and specific heat, Cp are dependent on temperature. The temperature varied from room temperature to high values so the k and Cp changed to form the temperature variation. The values of k and Cp would brought from. (Hemanth, 2006)

The physical quantities are: f (σ_8A, Tp, W, V, Tin, k/cp) = 0

The fundamental dimensions in (M, L, T and θ units are):-

$\sigma_8 A = ML/T^2$, $Tp = \theta$, $W = 1/T$, $V = L/T$, $k/cp = M/LT$, $Tin = \theta$

According to Bukingham π-theorem there will be (6) physical quantities and (4) fundamental units.

$\therefore$ 6-4 = 2 $\therefore$We have two π-terms

$$\therefore \pi_1 = \frac{\theta}{\theta} = \frac{Tp}{Tin}$$

$$\therefore \pi_1 = T^* \qquad (3)$$

$$\therefore \pi_2 = Q^* \qquad (4)$$

The new relationship, written in terms of π_1 and π_2 is:-

$$f_1(\pi_1, \pi_2) = 0$$

$$f_1(T^*, Q^*) = 0 \quad , f_1\left(T^*, \frac{f\sigma_8 \mathrm{A.w\,cp}}{\mathrm{V}^2\mathrm{k}}\right) = 0$$

$$T^* = f_2\left(\frac{f\sigma_8 \mathrm{A.w\,cp}}{\mathrm{V}^2\mathrm{k}}\right)$$

$$\therefore T^* = f_2 Q^* \qquad (5)$$

From equation (5) it can be obtained an relationship connect the peak temperature and heat input. From the experimental results we can arrive to the final correlation so (equation 5) leads to final empirical equation that can be seen in result.

EXPERIMENTAL WORK

Due to the lack of specialized stir welding machine, a vertical milling machine was used with variable turning and linear feed. Because the milling machine is not prepared directly to the (FSW), it should be equipped with fixture system. The fixture used was a steel plate with the dimension (350mm x 250mm x 15mm) prepared to be suitable with the table of the Milling Machine. The purpose of this plate was used to fix the plates to be welded on it by using two special steel strips, fig.2 shows the machine with fixture, tool, and plates. The plates were also prevent from sliding during welding by clamping along the long edges of the plates. A low alloy steel welding tool was manufactured to perform the welding of the aluminum plates.

Tool consists of two parts: (part no. 1) adopted to the machine spindle. (part no. 2) consists of two geometries, one of them called the shoulder and the other called the probe. The plates used in this study was AL-alloy (7008H) prepared with the dimensions (200mm x 80mm x 4mm). Each two plates were joining together with the friction stir welding. k-type thermocouples have been used for measuring the temperature distribution.

To read various temperatures with time and save them automatically, a device was manufactured by Integrated Engineering Services (IES) to be compatible with working conditions. This device was used to record the temperatures at the points prepared on aluminum plates. The reader was capable to link with a computer for saving the data that obtained. This device and thermocouples were calibrated in (C.O.S.A.C). Five points were pointed out on one face of the plates to be welded as shown in Fig. 3.

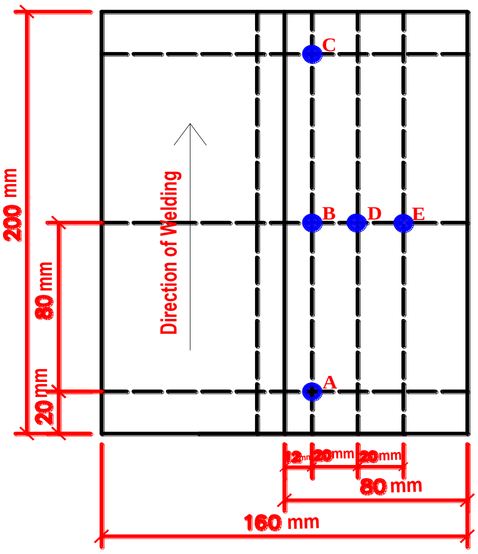


Fig. 2:All items used during FSW. **Fig. 3:Locations of tested points**

Three points (A, B, and C) were shown along the line of welding (12 mm) far away from this line, which was chosen because of shoulder dimensions. Points (A and C) were (20 mm) from the edge of the plate, while point B was in the center of the plate. Points (E and D) were chosen at right angel to the welding line at point B, with (20 mm) between each of them.Special epoxy mixed with some powder from the same Al-alloy was used to improve heat transfer between the plate and thermocouple**.** Type k thermocouple was fixed on each hole at the points A, B, C, D, and E by using some epoxy.In order to investigate mechanical properties of the welded joints and to evaluate the effect of different welding parameters on these properties, tensile test have been conducted.

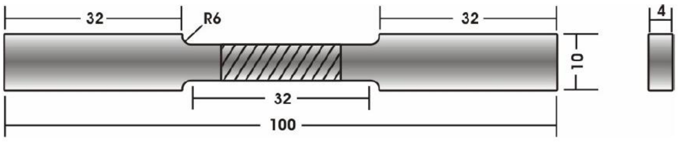


Fig.4: ASTM sub-size sample for tensile test (ASTM, 2003)

The tests had been fulfilled in the laboratories of Specialized Institute for Engineering Industries (SIEI).Fig. 4 shows the sub size sample for tensile test.

RESULTS AND DISCUSSION

Figures from 5 to 10 represent the results of experimental work. In general, the figures represent the relationship between the temperature and time, from Fig.5 it is concluded that the revolution speed and linear velocity had a strong effect on the temperature distribution along the welded plates.

Also, it was noticed that in each curve the peak temperature in(A, B, and C) was affected by the location of welding tool which turning in its limited speed.

The temperature at point (A) began between (30-60)°C then increased highly when the welding tool being at the points of testing, after that the temperatures began to decrease gradually while the welding tool leave the testing point.

From the increase and decrease of temperature at the testing points

This is coincide with point (B) where it's temperature increased as the temperature of point (A) decreased because welding tool passing through point (B) while it leaves point (A).

The highest temperature at point (B) was recorded as the welding tool reaches the point, while it began to reduce when the welding tool leave it. The process of increasing and decreasing the temperature is also true for point (C). The heat building process at point (B) and (C) was very effective factor on the welding process which give more homogenous, smooth and clean welding.

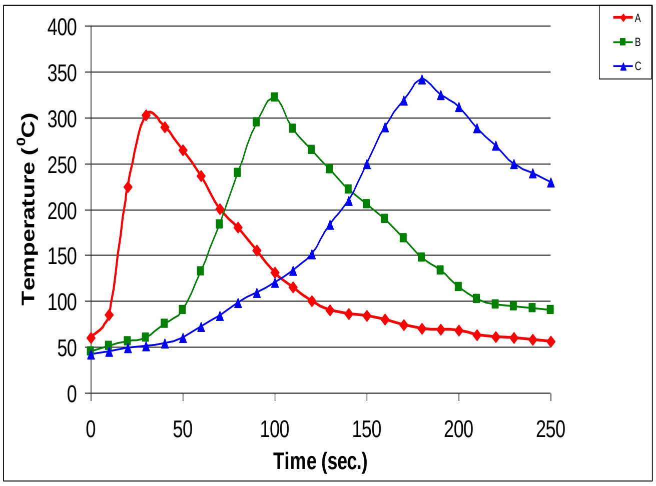


Fig.5:Temperature distribution at points (A, B and C).1430 RPM, 1mm/sec.

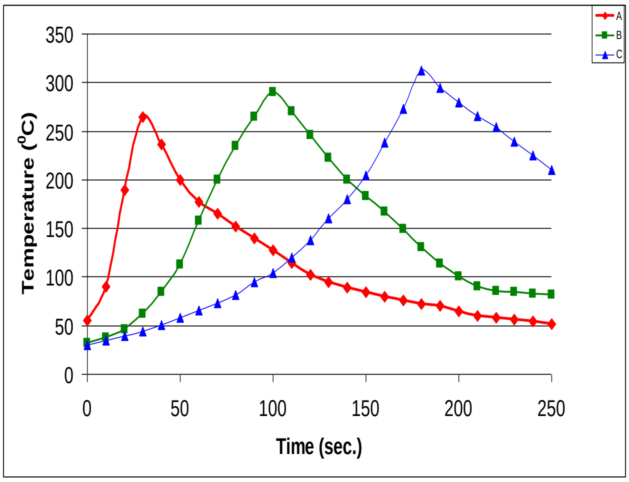
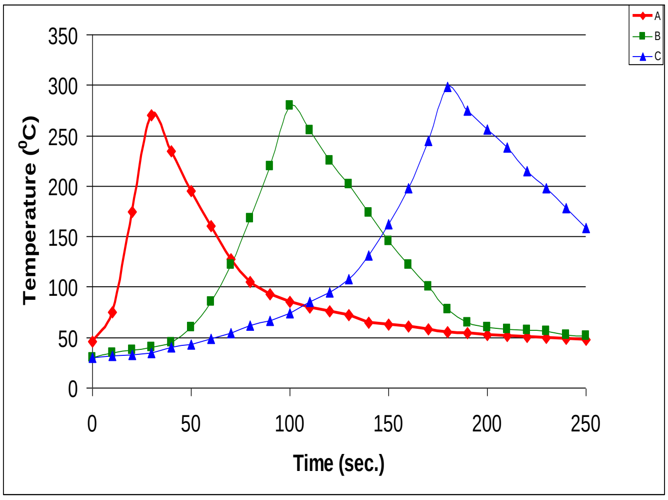


Fig.6: Temperature distribution at points (A, B and C). 1140 RPM, 1mm/sec.



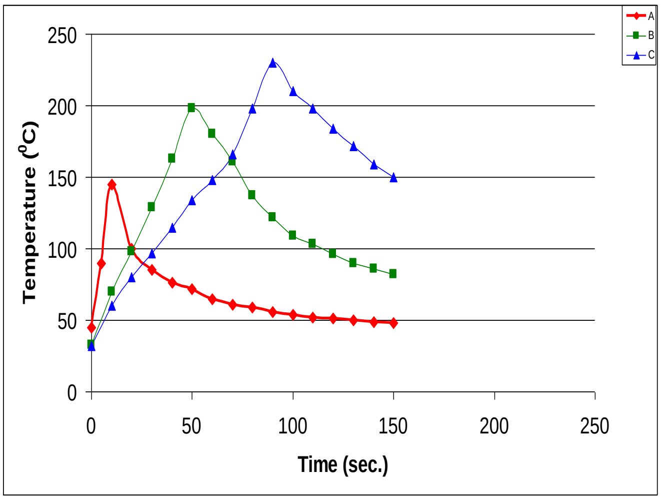
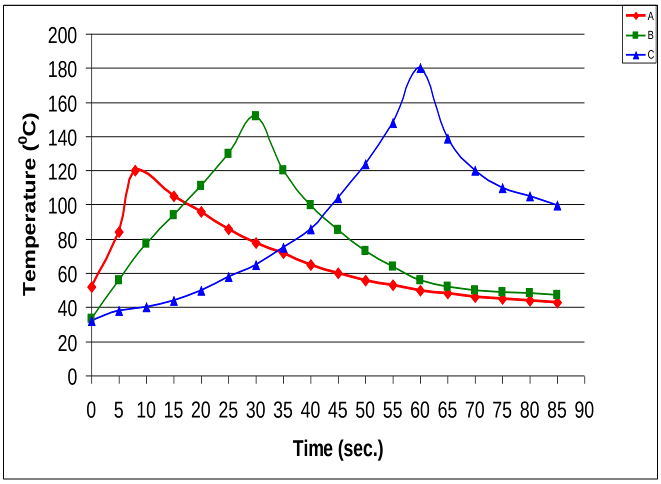


Fig. 7: Temperature distribution at point (A, B and C). 880 RPM, 1mm/sec.

Fig.8: Temperature distribution at point (A, B and C). 1140 RPM, 2mm/sec.



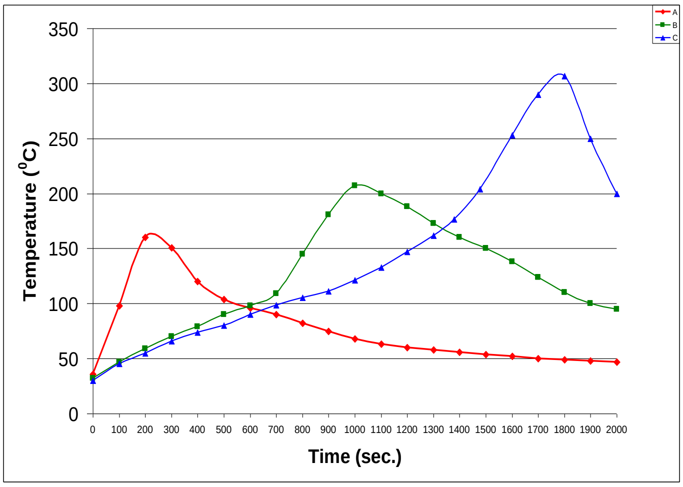


Fig.9: Temperature distribution at point (A, B and C). 1140 RPM, 3mm/sec.

Fig .10: Temperature distribution at point (A, B and C). 700 RPM, 0.1mm/sec.

According to figs. 5,6&7 it was noticed that the increasing of the revolution speed with constant linear velocity, the temperature of testing points increased. This is because of (At high rotational speed, the relative velocity between the tool and workpiece is high and consequently, the heat generation rate and the temperature are also high).

Fig. 11 represent the curves of temperature distribution at point (B) with various revolution speed and constant linear speed.

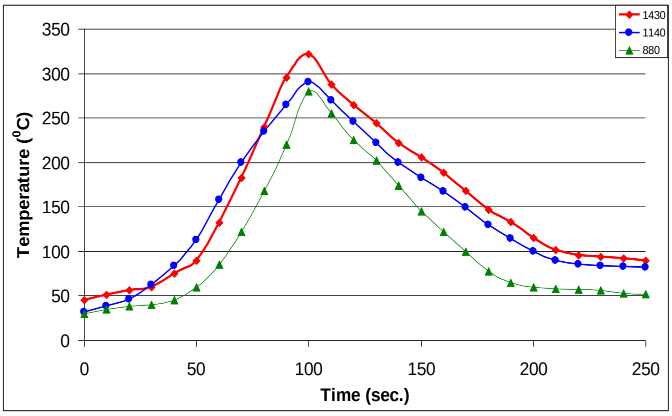


Fig.11: Temperature distribution at point (B) with three variable revolution speeds and constant linear speed (1mm/sec.).

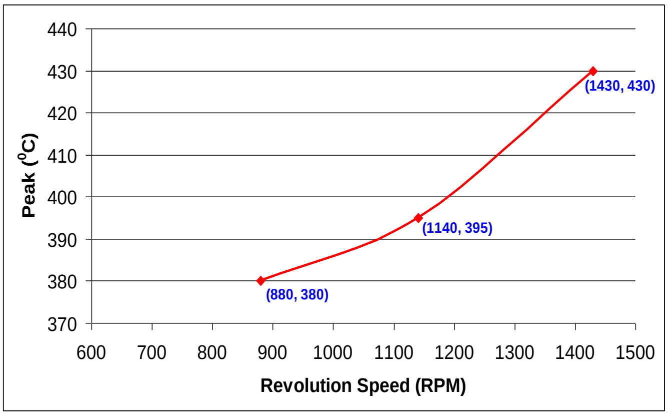


Fig. 12: The effective of rotational speed on the peak temperature.

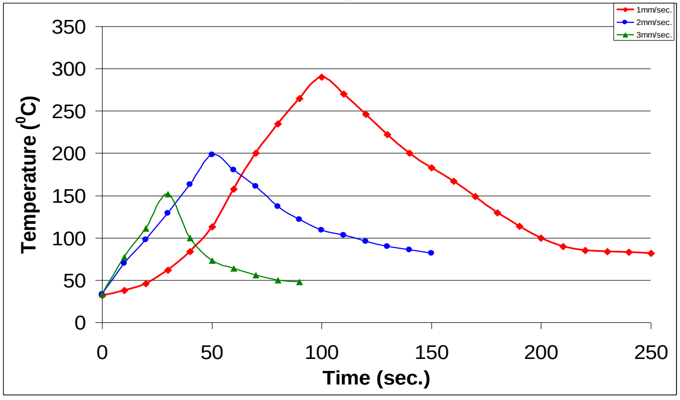


Fig. 13: Temperature distribution at point (B) with variable welding speed and constant revolution speed (1140 rpm).

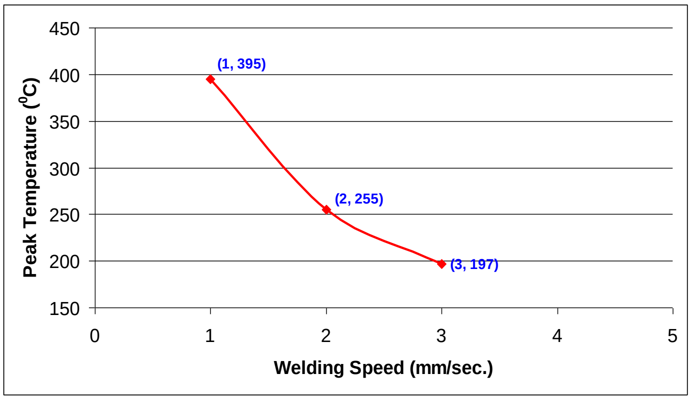


Fig. 14: the effective of linear speed on the peak temperature of welded plate.

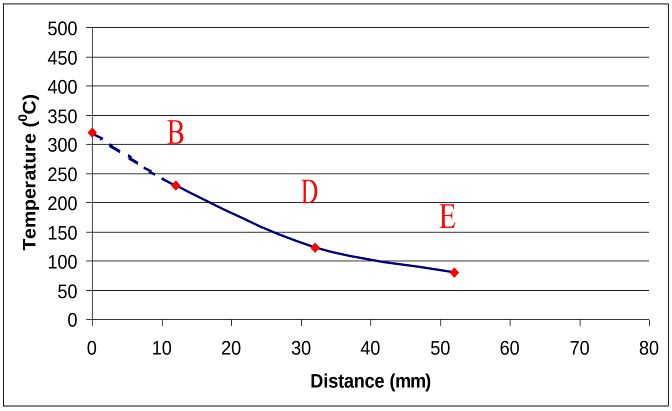


Fig. 15: the Distance from the welding line (700RPM , 0.1 mm/sec.).

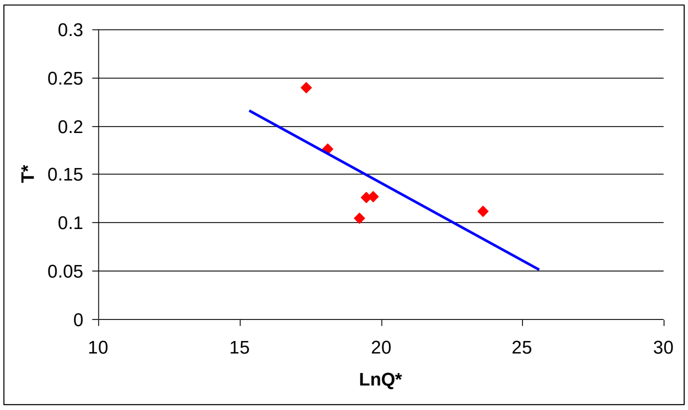


Fig. 16: the relationship between dimensionless peak temperature and dimensionless heat input.

The effect of rotational speed on the peak temperature tested point can be shown in Fig. 12. From figs.7,8&9 it was noticed that the linear speed has a reverse effect on the increasing of temperature, so that with increasing linear speed the temperature become lower and this is because of the fact that at high welding velocity (linear velocity), the heat input per unit length decreased and heat is dissipated over a large volume of the workpiece. So the points that tested had no enough time to increase the temperature.

Fig.13 represents the variation of temperature at point (B) with variable welding velocity. Fig.14 shows the effect of linear speed on the peak temperature of welded plate.

ESTIMATION OF PEAK TEMPERATURE PRACTICALLY.

The highest temperatures recorded at points E, D, and B which lies on a straight line, were drawn against the distance from interface line of welding. This is shown in fig.15. A nonlinear relationship was noticed in the figure because the governor heat balance was conduction and convection. Extrapolating the line joining the points of testing to get the peak temperature at the interface line of welding. The extrapolating procedure was used because it was not easy to measure the peak temperature of the interface line of welding directly with the instruments available. The peak temperatures are listed below.

Table (1): Peak Temperature (experimentally).

Plate No.	Revolutions Speed (rpm)	Linear Velocity (mm/sec)	Peak Temperature (Exp) (°C)
1	1430	1	430
2	1140	1	395
3	880	1	380
4	1140	1	395
5	1140	2	255
6	1140	3	197
7	700	0.1	320

Results of peak temperature (Tp) calculation during (FSW) :-

According to dimensionless correlations used to calculate the peak temperature of **eq.(5)** with the developed correlation. From the present study we have various parameters, linear velocity and rotational speed, affected on heat input and peak temperature. So, depending on these parameters Fig.16 has been obtained. As can be seen from Fig.16 the data can be fitted by using correlation theory and **eq.(6)** result from the correlation.

$$T^* = 0.468 - 0.0163\ln(Q^*) \qquad (6)$$

By using the equation above the peak temperature has been calculated and listed in table (2).

Table (2):- Peak Temperature theoretically.

Plate No.	Revolutions Speed (rpm)	Linear Velocity (mm/sec)	Peak Temperature (Exp) (°C)
1	1430	1	375
2	1140	1	333
3	880	1	292
4	1140	2	260
5	1140	3	243
6	700	0.1	385

Tensile Test Results:-

To investigate the effect of different welding parameters on tensile strength of welded joint, tensile tests were conducted for each joint using three specimens for each of the welded joints and the results are averaged. The test results compared with the tensile properties of base metal and the welding efficiency for friction stir welding have been calculated for each experiment.

Table (3): Tensile Strength in FSW .

	FSW No.	Revolution Speed (RPM)	Welding Speed (mm/sec)	Tensile Strength (N/mm2)	Joint Efficiency %
1st Set	1	880	1	215.5	81
	2	1140	1	191	72
	3	1430	1	66	26
2nd Set	1	1140	1	191	72
	2	1140	2	119	45
	3	1140	3	fail	fail
3rd Set	1	700	0.1	131	49.6
Base metal	-	-	-	264	-

Note:

- Values of tensile strength are average of (3) specimens.
- Joint Efficiency = test of tensile strength / ultimate tensile strength (Base metal).

According to the results obtained it can be noticed that the mechanical properties affected by temperature distribution for welded plates as is explained below:-

The 1st set of readings in table (3), are the results of tensile test which decreasing with the increasing of revolution speed while the temperature increased with revolution speed increased (see fig. 12) this means that it's important to select a specified value for revolution speed to get a good joint efficiency.

In the 2nd set of readings in table (3), the result of tensile tests decreasing with increase of welding speed, beak temperature decreased too, (see figure (14)), from studying the behavior of the welding surface it was clear that the welding is non homogenous one, with rough surface and with some cracks in welding zone.

In the third part of table (3), due to longer time of welding when compare it with the above sets, the time affect the configuration of welding, the first zone of the welded plate shows poor welding efficiency joint when compare it with the last zone which shows homogenous and high efficiency joint. This was due to the long time which rise the temperature of plate in the last part of the process, and means that the preheating process in the last part of plate gives the homogenous, smooth, and strong section. This phenomena is agreed with(Richardson, 2003).

From the above discussion it is clear that we must select the optimum values of revolution speed and welding speed to get a good joint because it is not necessary to select high revolution speed or low welding speed to get a good joint as shown in the results of tensile tests.

From these results of mechanical test which shows that the revolution speed (880 RPM) with welding speed (1 mm/s) are the best values of experiment in (FSW) that get (81%) welding joint efficiency. This welding joint efficiency could be considered as a good result compared with fusion welding to the Al-Alloy so the (FSW) for Al-Alloy can be considered a more suitable process.

CONCLUSIONS

According to the results of the present study of FSW process on selected Al-Alloy several conclusions can be written as follows:

- Optimum mechanical properties obtained with peak temperature reach to (75%) of melting point of plate metal.
- The maximum weld strength obtained in this study was (215.5N/mm^2) of 81% weld efficiency.
- We must select optimum welding parameters to obtain good weld and there is no necessary to use high values of revolution speed or linear speed. In the present study the optimum values was 880 RPM with 1mm/sec welding speed.
- A correlation for peak temperature has been obtained. $T^* = 0.468 - 0.0163\ln(Q^*)$

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