THEORETICAL AND EXPERIMENTAL INVESTIGATION OF FRICTION STION STIR WELDING FOR COPPER ALLOY

Asst. Prof. Dr. Hani Aziz Ameen

Technical College – Baghdad- Dies and Tools Eng. Dept

Ahmed Hadi Abood

Technical College- AlMusaib- Pumps Eng.

Nabeel Shallal Thamer

Engineering College -Al-Qadisiya University

Abstract

Friction stir welding (FSW) is a relatively new solid-state joining process. This joining technique is energy efficient. In particular, it can be used to join high-strength aerospace aluminum alloys and other metallic alloys that are hard to weld by conventional fusion welding. In this paper the investigation is made on friction stir welding process for joining of copper alloy. Friction stir welding experiments was performed using different pins (pin with straight boundary and pin with curved boundary). Welding joints efficiencies were found for each set. Mechanical and microstructural analysis has been performed experimentally on the welding zone. Non- linear numerical models was built in ANSYS software to simulate the thermal history of a workpiece undergoing friction stir welding by a moving heating source. An accurate prediction of temperature fields is evident. Exclusive result for effect of rotating a friction stir tools with respect to boundary conditions on stress-strain curves is presented. The results shown that the friction stir welding with pin of curved boundary is more efficient than that of straight boundary .

Keywords: Friction Stir welding ,copper alloy, finite element method, ANSYS software, tensile test, microstructure

دراسة نظرية وعملية للحام الاحتكاكي لسبائك النحاس

الخلاصة

تعتبر عملية اللحام الاحتكاكي من اكفأ عمليات اللحام والتي تستعمل لربط المعادن مثل الالمينيوم والمعادن الاخرى والتي من الصعوبة لحامها بالطرق التقليدية . في هذه الدراسة تم تطبيق الحام الاحتكاكي (FSW) لسبائك النحاس من خلال تصميم وتصنيع نوعين من الأدوات (الدبوس بحواف مستقيمة والدبوس بحواف منحنية). وقد وجد ان كفاءة اللحام جيدة لكلا الحالتين وقد تم إجراء تحاليل ميكانيكية ومجهرية على منطقة اللحام . وقد تم انشاء موديل غير خطي ببرنامج الانسز لمحاكاة التأثيرات الحرارية خلال عملية اللحام باستخدام مصدر حراري متنقل . وقد تم الحصول على نتائج الخواص الميكانيكة منحنى (الاجهاد-الانفعال) لكلا الاوادت التي تم تصنيعها. وقد بينت النتائج ان اللحام باستخدام دبوس بحواف منحنية هو اكثر كفاءة من الحواف المستقيمة .

Symbols

k_x, k_y, k_z ……… thermal conductivity in x, y, and z directions

x,y,z …………… coordinates

ρ ………………… density

T ………………… temperature

t ……………… time

Q ………………… rate of heat generation

C_p ……………. … specific heat

δ ……………....... slip factor that compensate for tool/material relative velocity

μ ……………….. friction coefficient

R_s ……………… shoulder radius

R_p ……………… pin radius

L_p ……………… pin length

p ……………….. interfacial pressure

ω ……………….. angular speed

V_t ………………. Tool speed

FSW ……………. Friction stir welding

L_i ……………….. initial position

L_w ………………. Finial position

Introduction

Friction stir welding is one of the new method of welding developed nowadays, many researches in the literature about friction stir welding of aluminum and it's alloys, researches about copper and it's alloys are limited. In this welding process, a rotating welding tool is driven into the material at the interface of, for example, two adjoining plates, and then translated along the interface. Cemal Meran (2006), applied friction stir welding procedures to brass plates with 3 mm in thickness in different rotation and welding speeds. Obtained welded joints subjected about physical virtual, mechanical tests and microstructure investigations and the results had been evaluated. Sun and Fujii (2010), obtained the process window for friction stir welding of commercially pure copper. Hwang et al., (2010), studied the thermal history of a workpiece undergoing Friction Stir Welding (FSW) involving butt joining with pure copper C11000, The appropriate temperatures for a successful FSW process were found to be between 460°C and 530°C. These experimental results and the process control of temperature histories can offer useful knowledge for a FSW based process of copper butt joining. Several investigations (Cao and Qi (1998), Chen and Kovacevic (2003) , Zhu and Chao (2004)) of the thermal stress distribution in friction stir welds were carried out by finite element method (FEM). Lai and Sandstrom(2012), investigated the numerical simulation of residual stresses for friction stir welds in copper canisters and obtained the maximum tensile stress, whether it is predicted by the finite element method.

In this research, it was pointed on friction stir welding capability especially copper alloy plates which are 4 mm in thickness and using two types of pins.

Model Description

The temperature distribution varies in time and space, hence a three dimensional, transient, isotropic with moving heat source model was used to simulate FSW, the general heat transfer equation (Nandan et al, 2006) is:

$$k_x \frac{\partial^2 T}{\partial x^2} + k_y \frac{\partial^2 T}{\partial y^2} + k_z \frac{\partial^2 T}{\partial z^2} + Q = \hat{\lambda} \frac{\partial T}{\partial t} \qquad (1)$$

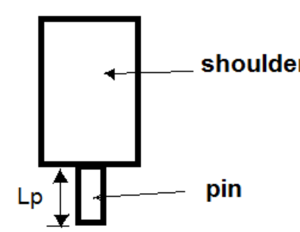
where

$\hat{\lambda}$ ……….. single or combination of material properties = ρC_p

Total frictional heat of shoulder will be [Nandan et al, 2007]

$$Q_s = \int_0^{R_s} dQ_s = \frac{2}{3}\pi(1-\delta) \;\; \omega \;\; \mu \;\; p \;\; R_s^3 \qquad (2)$$

Similar concept, heat generated by lateral surface of the pin is :



$$Q_p = 2\pi(1-\delta)\, \omega \;\, \mu\, p\, L_p\, R_p^2 \qquad (3)$$

The total heat generated from the tool

$$Q_T = 2\,\pi\,(1-\delta)\,\omega\,\mu\,p\,\left(\frac{R_s^3}{3} + L_p R_p^2\right) \qquad (4)$$

During the process the tool travels at a constant speed (V_t). The motion was simulation by changing heat source location as shown below according to the following equation (Ridha, 2009), as shown in Fig.(1).

$$x_{i+1} = x_i + V_t.\Delta t \quad \text{for} \quad L_i \le x \le L_w \qquad (5)$$

where

Δt ………….. time required for the tool to travel from location x_i to x_{i+1}

The three dimensional element SOLID5 was used in the 3-D Coupled-Field Solid analysis, the element has eight nodes with thermal and structural degree of freedom, displacement and temperature at each node. It is applicable to a three dimension steady-state or transient thermal- structure analysis (ANSYS help V.11). According to the above equations and modeling of heat source movement, the following subroutine is made and imported to ANSYS code in order to achieve the moving heat source.

Subroutine of moving heat source

```
!load step 1, initial conditions  25° C
TIME,0.001
DELTIM,0.001,0.001,0.001
TUNIF,25,
solve
 !load step 2..... , apply moving heat flux
j=1
*DO,i,195,85,-5
  TIME,j
  DELTIM,0.11,0.11,0.11,
  SFEDELE,i+5,6,HFLUX
  SFE,i,6,HFLUX, ,qw, , ,
  eplot
  solve
  j=j+1
*ENDDO
```

Experimental Work

The nominal composition of the copper base material used in this work was mention in Table(2). The copper plate dimensions of 200mm (L), 50mm (W), 4mm (T) was used in the present study. The copper plates were clamped rigidly on backup plate to produce butt joint using the FSW technique as shown in Fig. 4.

Tool Geometry

The tool geometry is the most influential aspect of process development. The geometry play a critical role in material flow and in turn governs the traverse rate at which FSW can be conducted. An FSW tool consists of a shoulder and a pin as shown in Fig.(2) (Nandan et al, 2008).

In our research the chemical composition and the hardness of the tool is provided from the Special Institute of the Engineering Industry as shown in Table (1).

Two types of tools pins are designed and manufactured in this work as shown in Fig.(3), which are used to implement the FSW.

Copper alloy

Copper which has much higher thermal diffusivity than steel cannot easily be welded by conventional fusion welding techniques. The base metal used in this work was 4mm thick copper alloy plate, whose chemical composition is provided from the Special Institute of the Engineering Industry as in Table (2)

Welding Process

The samples of 50mm x 200mm were longitudinally fixed using vertical milling machine as shown in Fig.(4) (Muna et al, 2011). The welding tool is composed of shoulder and pin (Fig.(3)).

The welding tool is rotated at high speed into the joint line between two plates to be welded together (Zhili Feng et al,2003). This stirring action of the rotating tool yields a heavily deformed alloy. The frictional heat generated by the welding tool makes the surrounding material softer and allows the tool to move along the joint line. The softened material starts to flow around probe resulting in transferring of material from the leading edge of the tool to the side (Maria Posada et al,2003). In this study, the welding parameters such as tool speed of (1000 rpm) and travel or welding speed of (69 mm/sec) are constants.

Samples Preparation for Microstructure

The samples made from a cross section of the FSW joints and base alloy were ground, polished and etched and observed under optical microscope in sequences steps (Muna et al, 2011). Wet grinding operation with water was done by using emery paper of SiC with the different grits of (220,320,500, and 1000). Polishing process was done to the samples by using diamond paste of size (1µm) with special polishing cloth and lubricant (diamond paste). They were cleaned with water and alcohol and dried with hot air. Etching process was done to the samples by using etching solution which is composed of (99% H_2O+1%HF).Then the samples were washed with water and alcohol and dried. The friction stir welded joint samples were examined by Nikon ME-600 optical microscope provided with a NIKON camera, DXM-1200F.

Mechanical Test

Tensile specimens were machined according to the ASTM E8M-04 , specimen geometry is shown in Fig.(5), it shows standard dimensions to be specified. For plate after welding, all specimens were taken normal to the welding line.

Results and Discussion

Friction stir welding is a fully mechanized process. FSW is a difficult and challenging problem because involves complex interactions between varieties of simultaneous processes. The interactions affect the heating and cooling rates, plastic deformation and flow, dynamic recrystallization phenomena and the mechanical integrity of the joint. Fig.(6) shows the copper welded plate by FSW using pins type A and B.

The result of heating, stirring (in case of FSW) and cooling in the welding process is the strain that occur in the weld metal and base metal regions near the weld. The strain produced is accompanied by plastic upsetting. The stresses resulting from these strains combine and react to produce internal forces (i.e. residual stresses). These forces are reasonable for changing structure properties. To investigate the effect of different pins (A and B) on the tensile strength of friction stir welded plate, a series of tensile tests were conducted for each joint.

The results were compared with tensile properties of base metal and the welding efficiency based on ultimate tensile strength for each friction stir welded plate have been calculated. Fig.(7) shows the stress-strain curve for the copper alloy plate. Fig.(8) shows the stress – strain curve for welded plate using pin type – A- and Fig.(9) shows the stress – strain curve for welded plate using pin type – B- .

Table(3) shows the Mechanical properties of the FSW copper alloy plate using different pins tools type A and type B.
The most important part of modeling welding process is the thermal analysis. Previous researchers have simulate heating load by a heat on all welding line and keep this load for a specific period of time after which the heating load was set to zero and cooling take place. The relative motion between heat source and plate is used in the present work, in this method the movement of heating load takes place by changing location of it, i.e. the tool location was changed according to Eq.(5). Moving heat source using ANSYS requires high programming skills (Subroutine of moving heat source is illustrated in article Model Description). Fig.(10) shows contour of temperature variation through FSW process.

The thermal process and stress evolution process are coupled. Where results of the thermal field will be the cause of the driving force that resulting in thermal stresses while thermal solution will not depend on the stress solution. In this case the temperature distribution, which varies in time and space, is loaded into the stress analysis as a predefined field. Temperature fields affect mechanical fields through thermal expansion and temperature dependent material properties. Thermal expansion or contraction due to transient application of temperature gradient is usually the dominant concern in thermal stress analysis. Fig.(11) shows contour of thermal variation through FSW process.
Fig.(12) shows the microstructures of the FSW for Copper alloy using pins type A and B. According to microstructural observation in this research ,the grain sizes in the weld nugget are significantly smaller than the parent metal and this can be attributed to the mechanical forces operative during welding which cause both refinement and re –alignment of the matrix grains and should be beneficial with respect to various mechanical properties. This is due to the temperature difference between the tool shoulder side and base size and the tool centerline and the edge of the weld nugget which causes the grain size variations. During FSW process only coarser precipitates could nucleate and grow but not finer ones. This aids in the formation of passive film, which remains more intact on surface of the sample.
The microstructure of the copper weld consists of different zones such as TMAZ, HAZ and parent metal. The microstructure of the HAZ has been observed to be finer than the parent metal due to dynamic recrystallization. In the HAZ few coarse grains presence were observed.

Conclusions

The main important conclusions which can be drawn from this work are:

1. The butt joining of copper was successfully carried out using FSW technique via straight boundary pin and curved boundary pin. The results shown that the friction stir welding with pin of curved boundary is more efficient than that of straight boundary and the grain size in the welded zone in case of using curved boundary pin has more refine than that of straight pin, i.e. was developed for microstructural of metallic materials
2. For a given tool rotational and traveling speeds peak temperature increases as tool moves along welding joint because of heat accumulation within the workpiece.
3. Modeling of friction stir welding process using moving heat source is more reasonable than the published model.
4. The present study has demonstrated that normal copper can be successfully joined by FSW.

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Table (1) chemical composition and the hardness of the tool

Grade	C	Cr	P	V	Mo	Co	Hardness H B	Hardness HRC
H.S.S R18 (Russia)	0.7 – 0.8	3.8 – 4.4	17.5 - 19	1 – 1.4	≥ 0.3	----	207 - 255	60 - 62

Table (2) Chemical Composition of the used copper alloy

SAMPLE	Si%	Fe%	Pb%	Mg%	C%	Zn%	S%	AS%	P%	Sn%	Al%	Cu%
METAL SEGMENT	0.001	0.029	0.004	0.001	0.003	28	0.006	0.006	0.013	0.001	0.001	Bal.

Table (3) Mechanical properties

	Young Modules (E) [GPa]	**Yield stress (σ_y) [MPa]**
Copper alloy	130	244
Welded plate with tool type A	102	197
Welded plate with tool type B	135	163

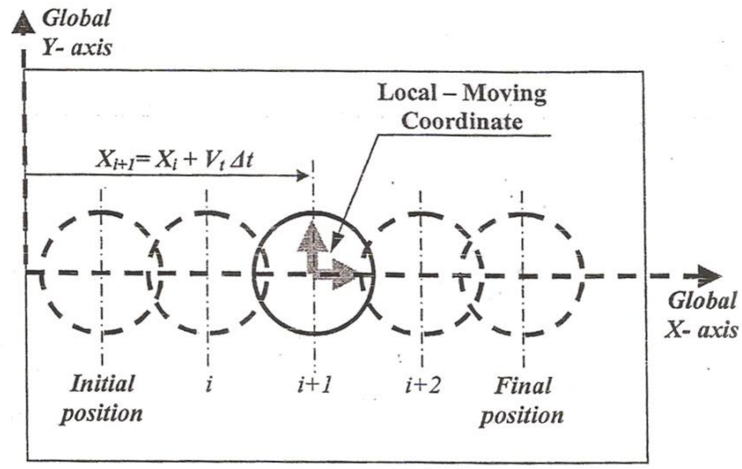


Fig.(1) modeling of heat source movement

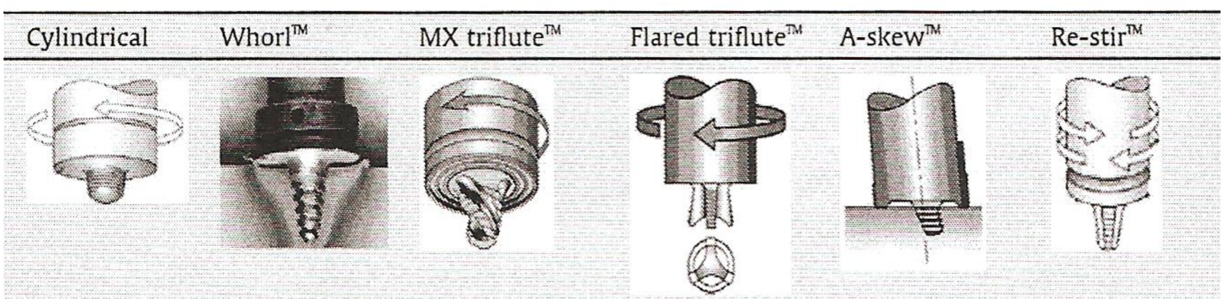
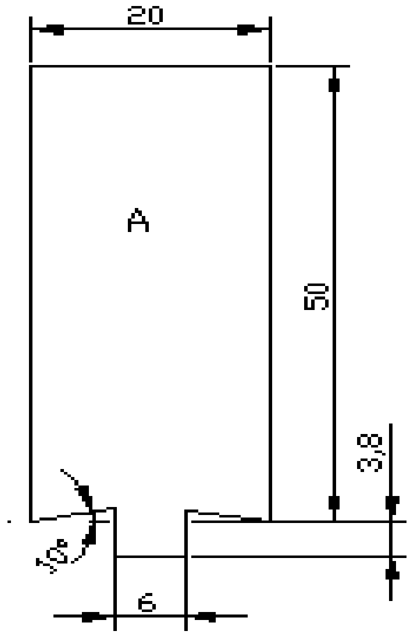
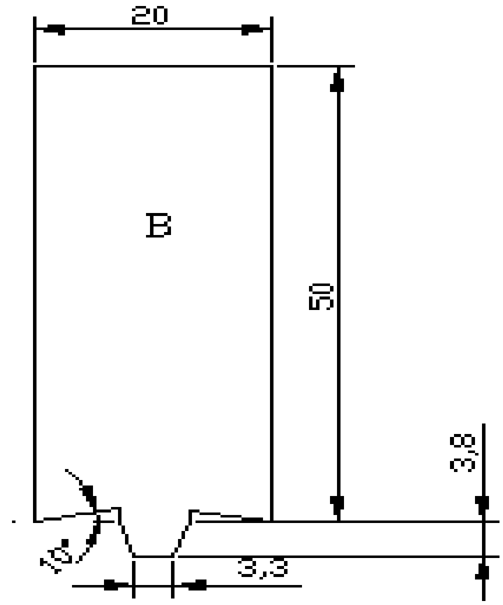


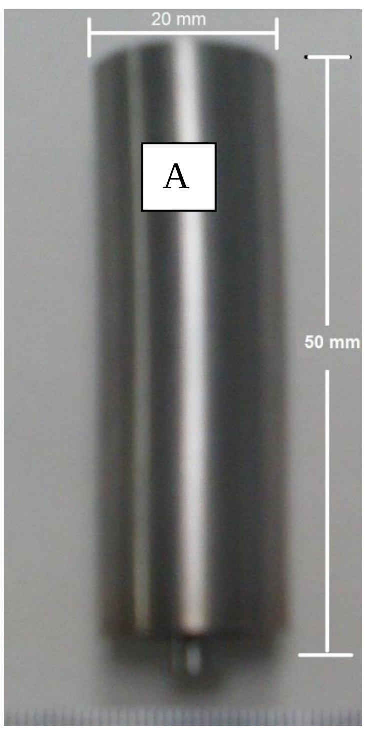
Fig.(2). Tools design (Nandan et al, 2008)



(A) Straight boundary pin



(B) curved boundary pin



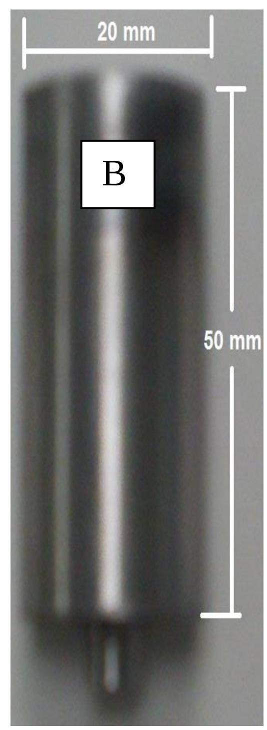


Fig.(3) Tools type A and B, which are designed, manufactured and used in the FSW (all dimensions in mm)

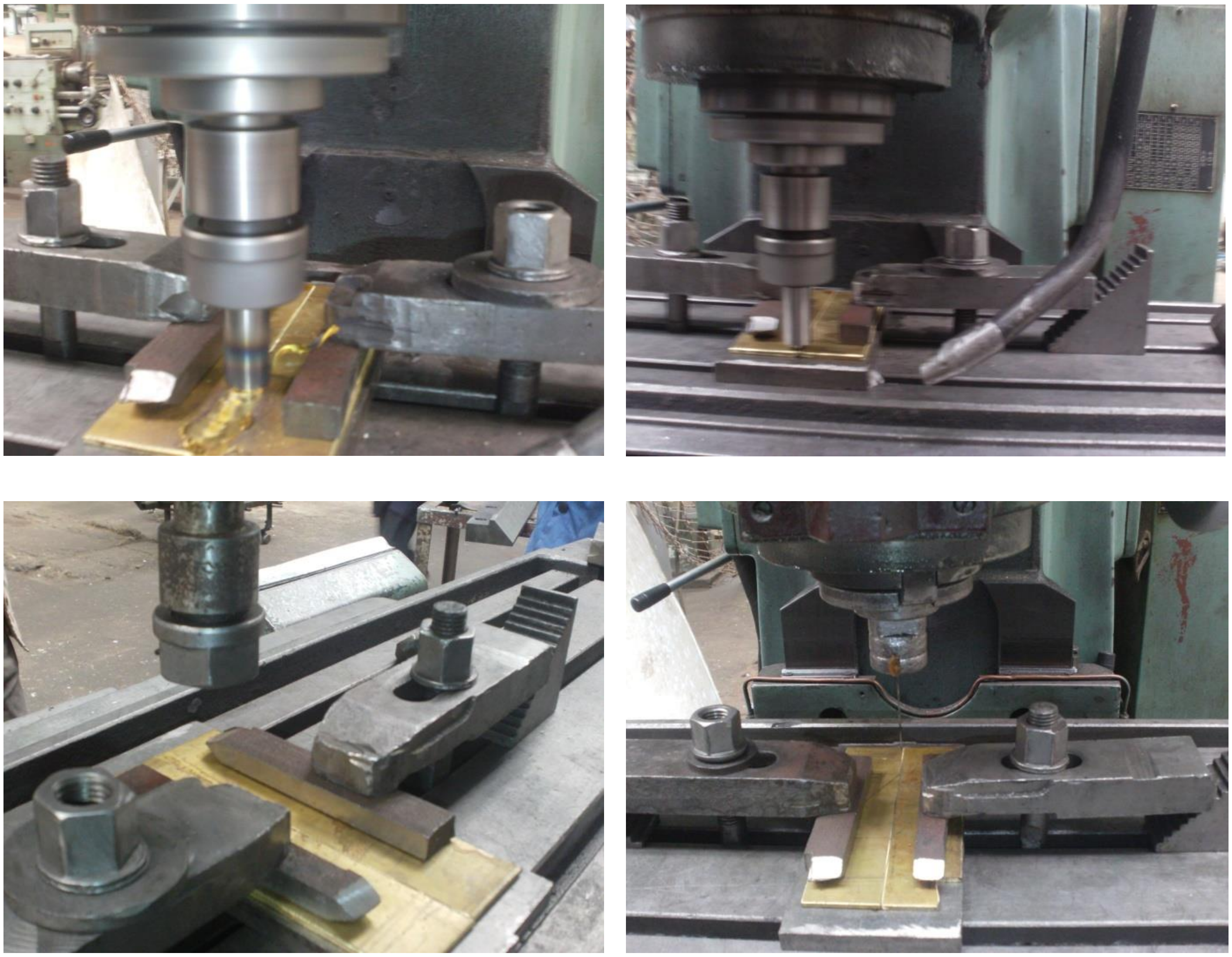


Fig.(4) Vertical milling machine for FSW

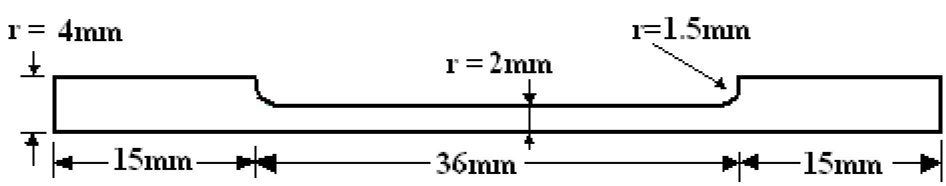


Fig.(5) Tensile test specimen

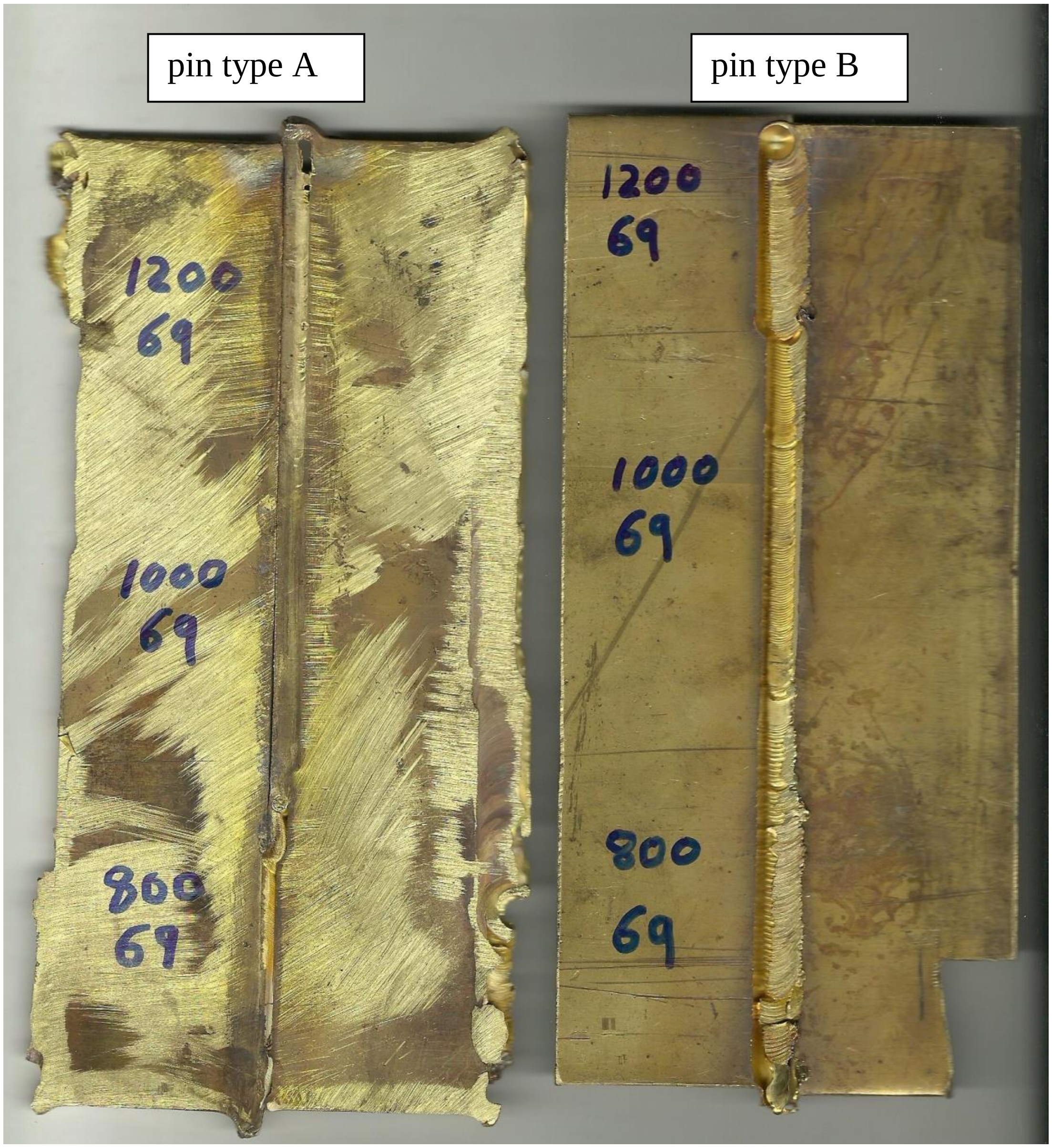


Fig.(6) copper welded plate by FSW using pins type A and B.

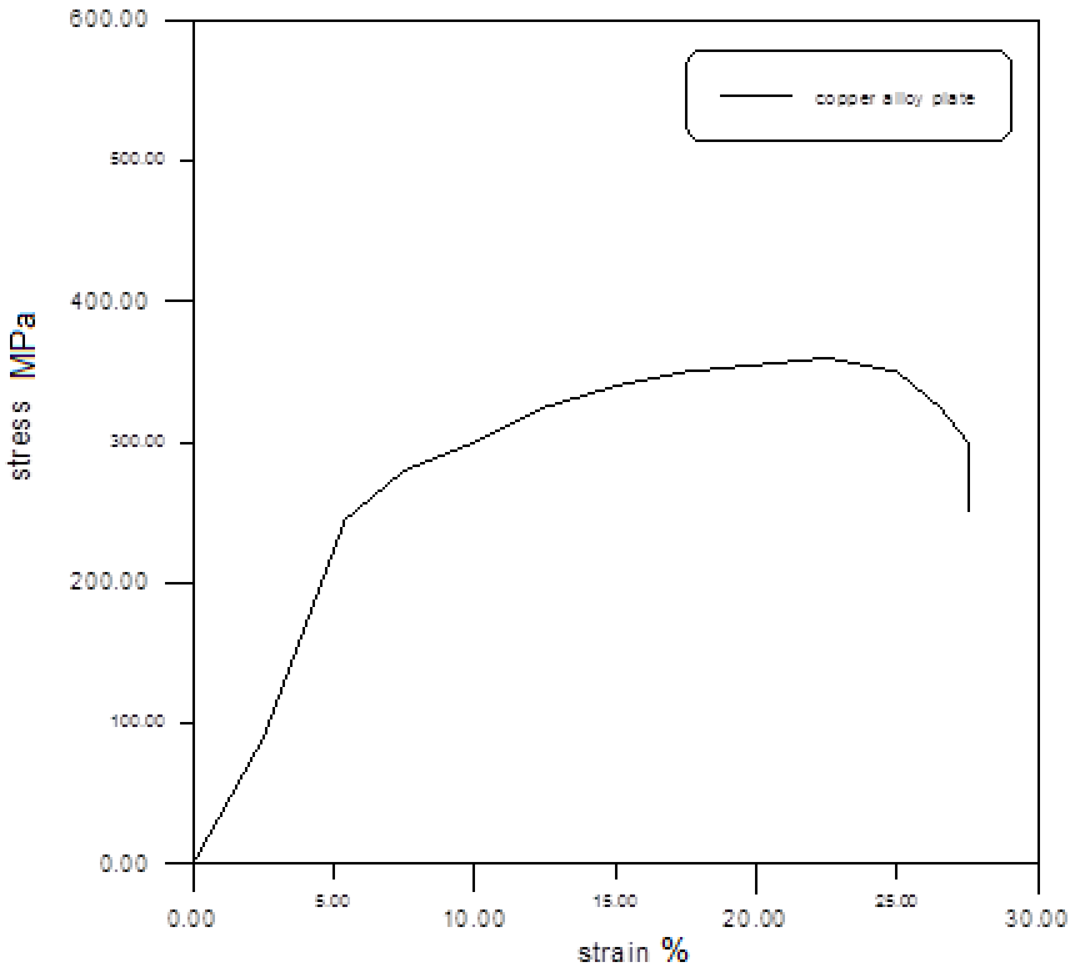


Fig.(7) Stress-strain curve for the copper alloy plate

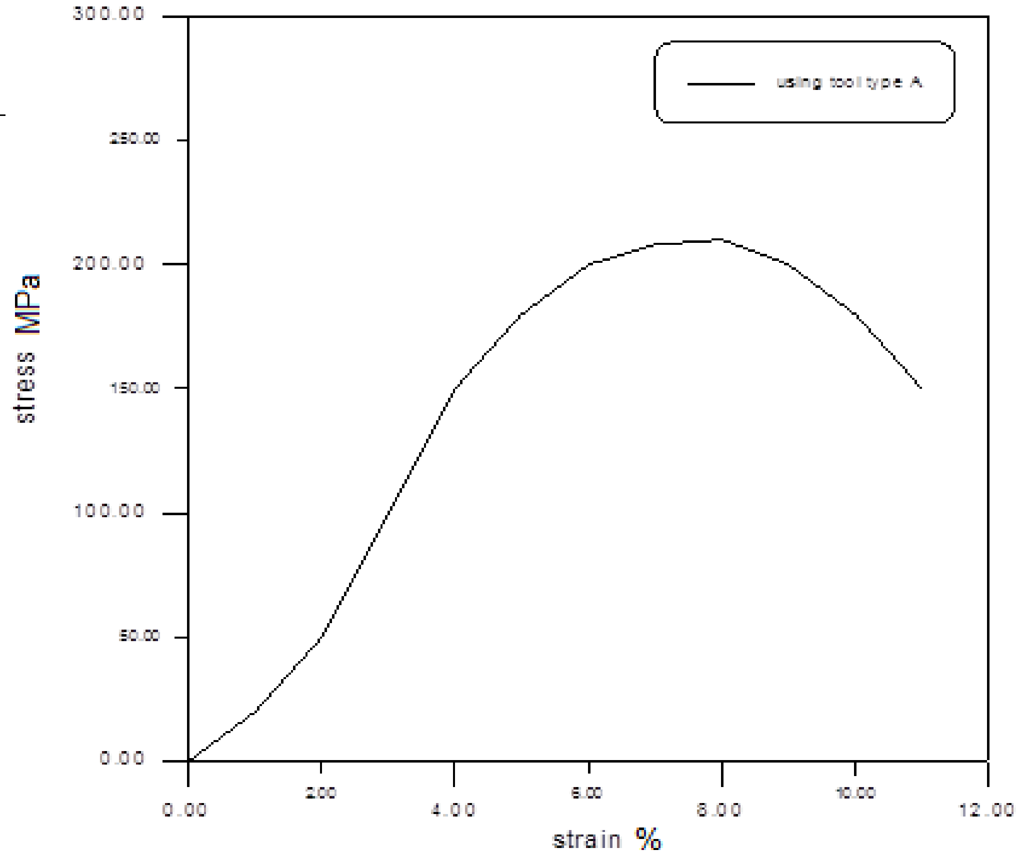


Fig.(8) stress – strain curve for welded plate using tool type – A-

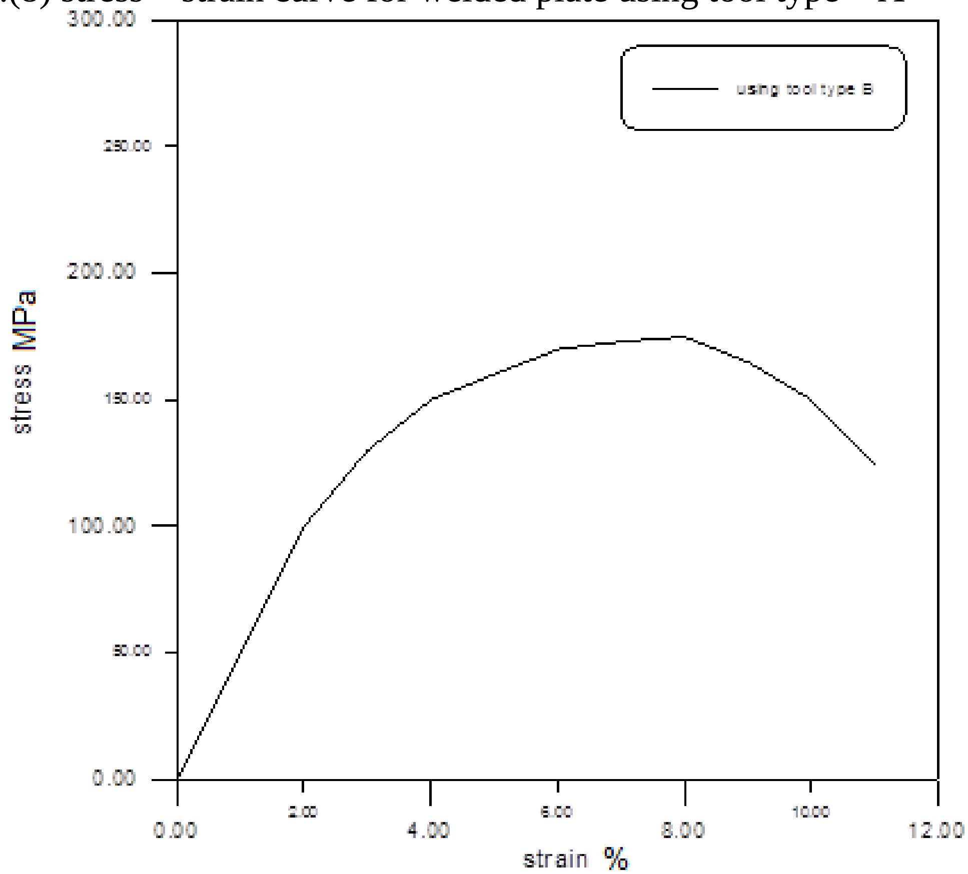
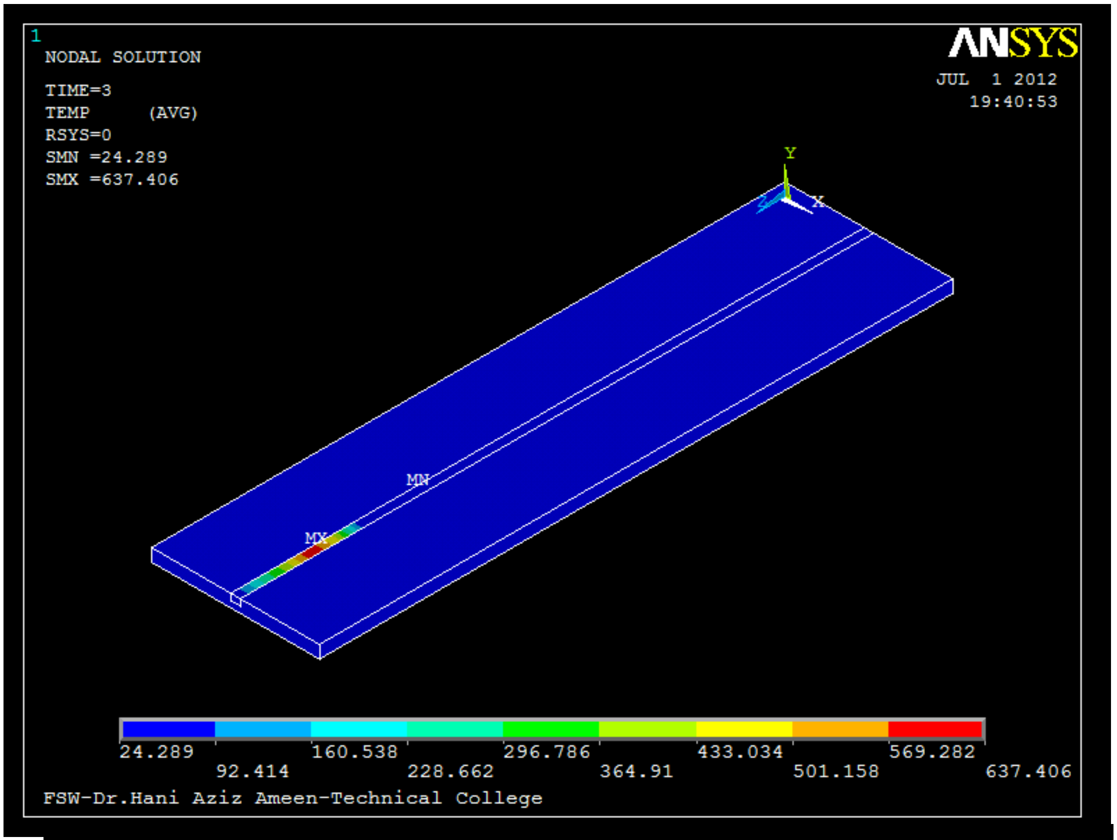


Fig.(9) stress – strain curve for welded plate using tool type – B-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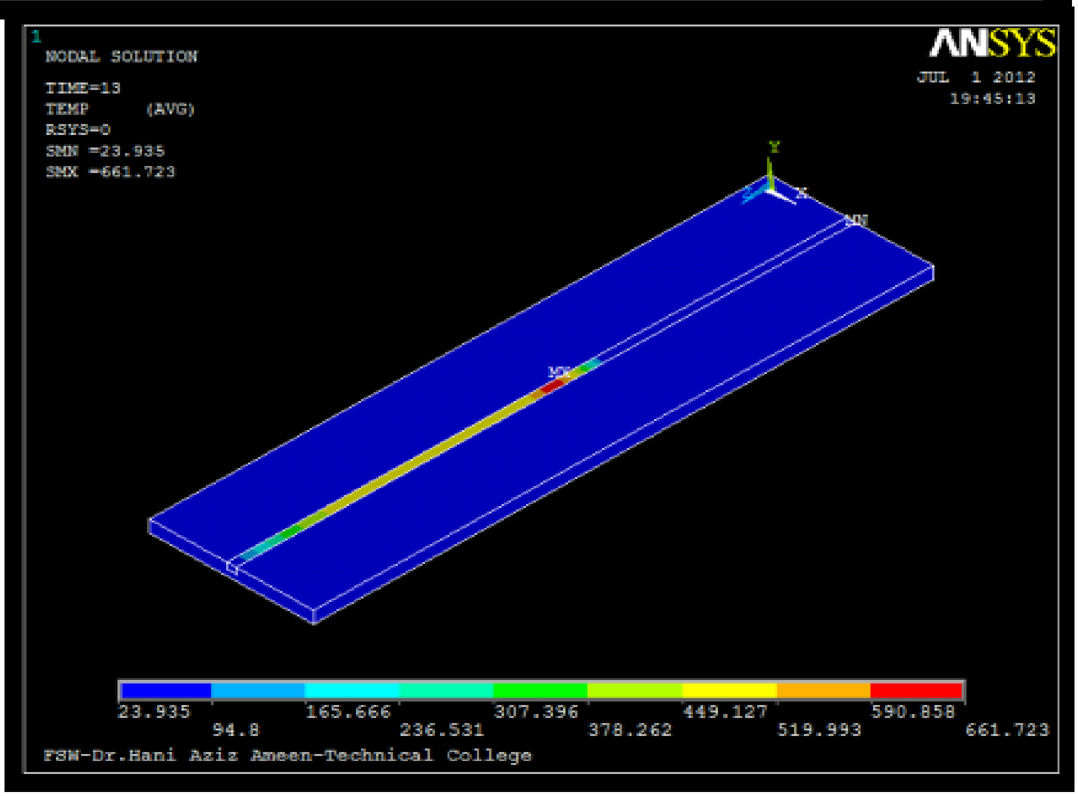
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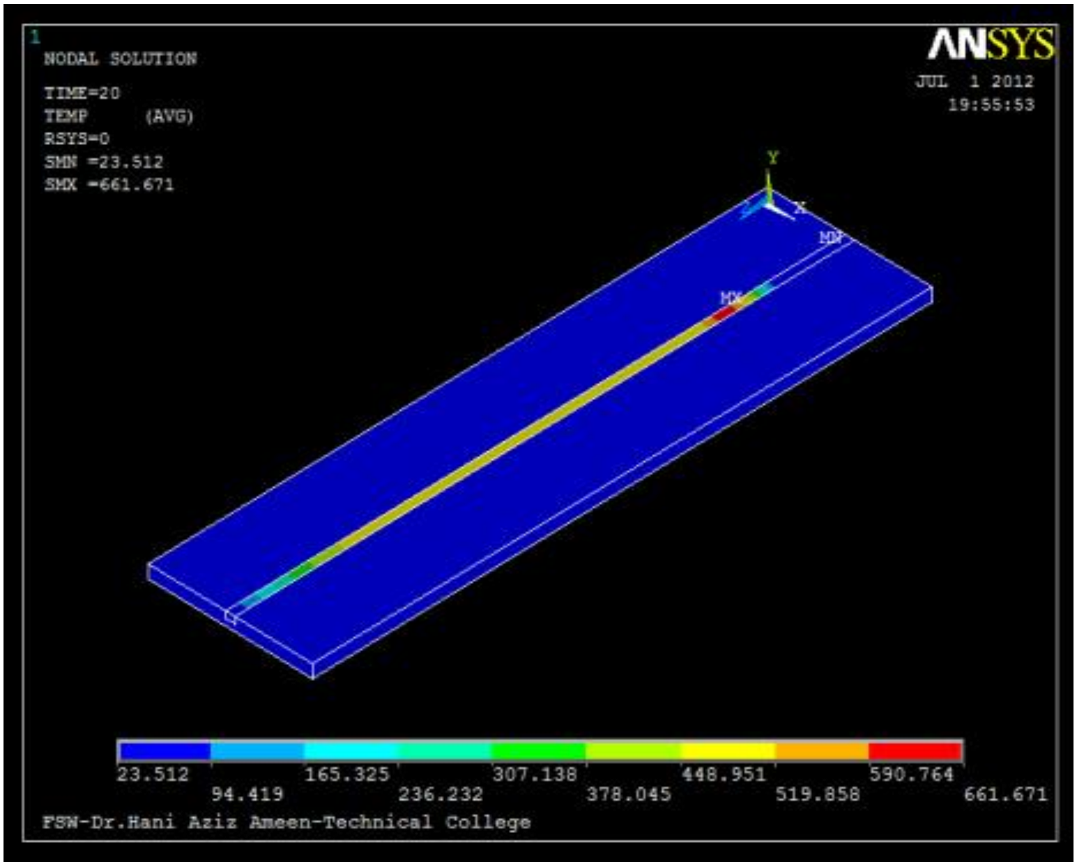
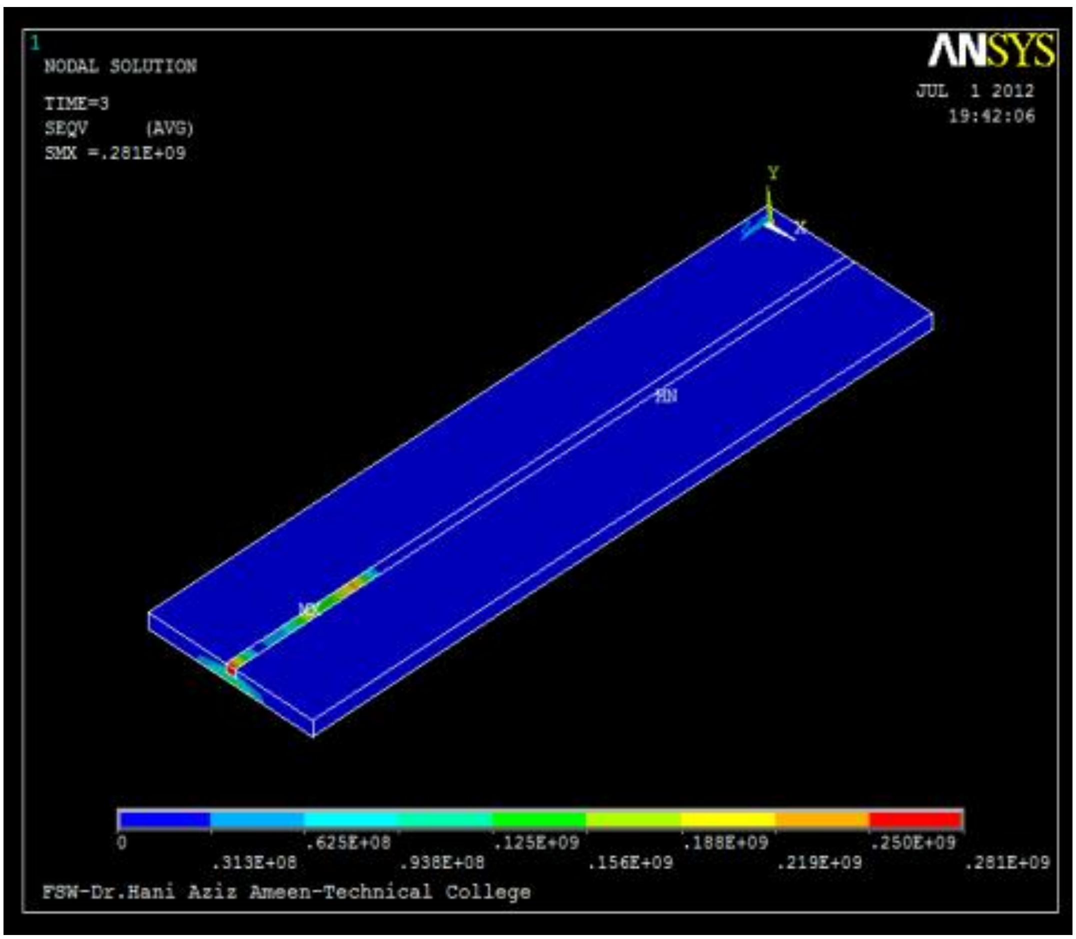
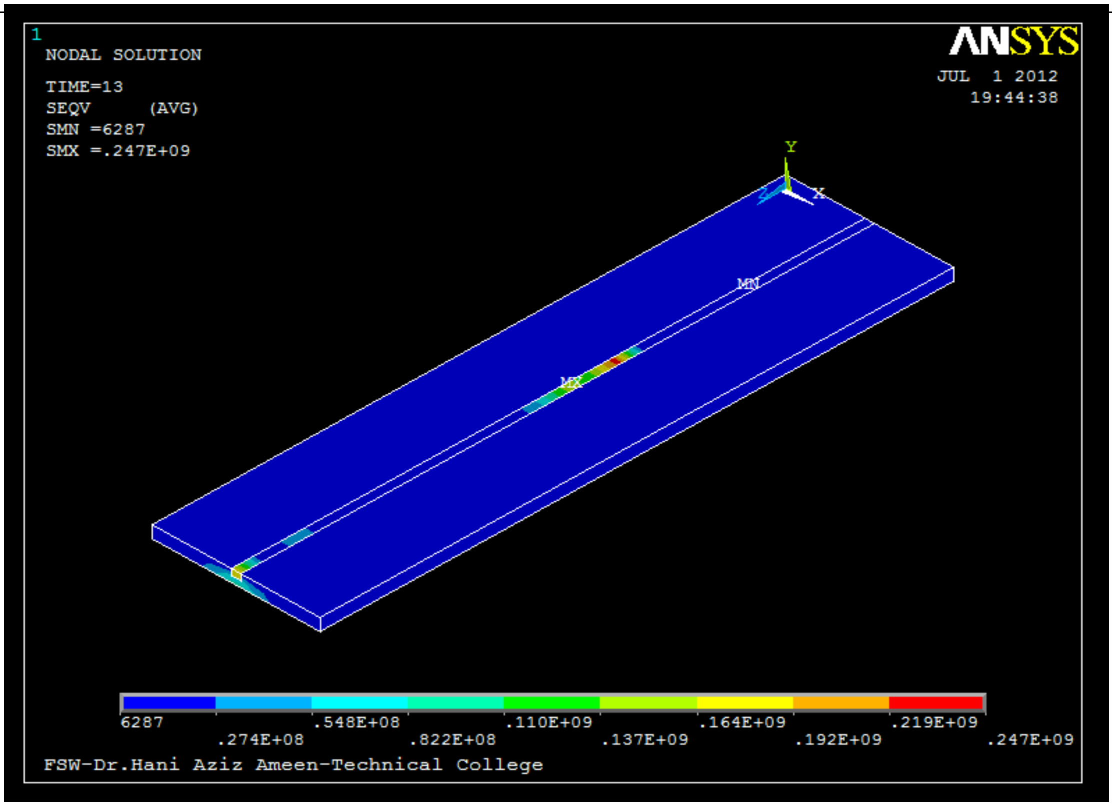


Fig.(10) contour of temperature variation through FSW process





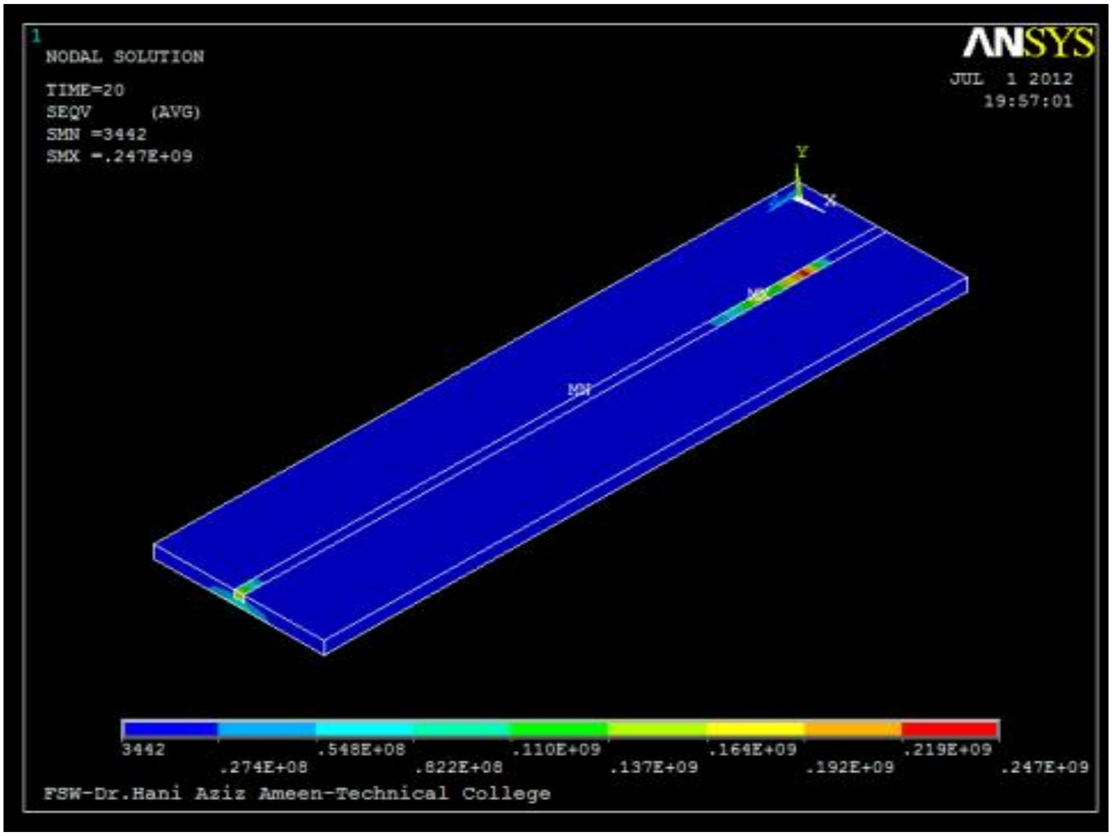
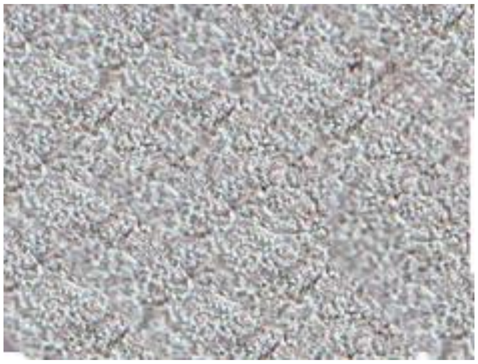


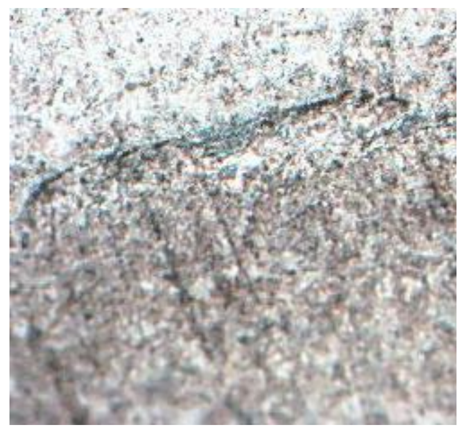
Fig.(11) contour of thermal stress variation through FSW process.



Haz zone (pin type A)

Haz zone (pin type B)

welded zone (pin type A)



welded zone (pin type B)

Fig.(12) microstructures of the FSW for Copper alloy using tools type A and B