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Numerical and Experimental Investigations of Heat Generation during Friction Stir Processing of Copper

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Abstract

In this paper, numerical and experimental investigations of heat generation during friction stir processing (FSP) of pure copper were performed. FSP experiments with two different combinations of processing parameters were conducted. Temperature distributions were measured using two K-type thermocouples. Optical microscope (OM) micrographs revealed grain refinement depends strongly on the heat input during FSP. A three dimensional (3D), transient, non-linear thermal model was developed using ANSYS 11.0 software+ to simulate the thermal history during FSP of copper. The simulated temperature distributions (profile and peak temperature) were compared with experimental values. The results of the simulation are in good concurrence with that of experimental results. The results showed that the heat generation during FSP strongly depends on both rotational and transverse speed where the peak temperature was observed to be strong function of the rotational speed while the rate of heating was a strong function of the transverse speed. The peak temperature obtained was about 65% of the melting point of base metal.

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*Keywords:*Friction stir processing; Heat generation; Temperature distribution; Thermal modeling; Finite element simulation; Pure copper

1. Introduction

Friction stir processing (FSP) is a variation of friction stir welding (FSW). FSP is a novel grain refinement method, developed for micro structural modification of various metals and alloys [1-3]. FSP is a one-step thermo-mechanical metal working process which results in friction between FSP tool and workpiece and intense plastic

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deformation around the rotating tool pin. Both these factor contributes major role in heat generation during FSP. The amount of heat generation during FSP has a vital role in resulting microstructure and properties of the material. The dominating heat generating mechanism is influenced by the process parameters, tool pin profile, tool geometry and thermal conductivities of the tool, workpiece and backing plate. Hence, understanding the heat generations and temperature distributions is extremely noteworthy in understanding the process of FSW/P. The prime function of tool pin is to mix the material beneath the tool shoulder, which can be enhanced by threaded pin tool [4-7].

Among lightweight metallic materials, copper and its alloys have found extensive applications because of its high thermal and electrical conductivity, plasticity, softness and formability. However, pure copper is unsuitable for various high end applications due to its poor strength, wear and fatigue resistance. Heat input required for FSP of copper is much higher than FSP of other materials because of the greater heat dissipation through the workpiece. On the other hand, copper is basically a soft metal and can therefore be relatively processed by friction stir processing. Several heat generation models were developed in FSW describing the main heat source as friction between FSP tool and workpiece and intense plastic deformation around the rotating tool pin. As a result of that, optimizing the rotational and transverse speeds of FSP can help to localize heat input and improve stirring which yields effective grain refinement in the stir zone (SZ). The various remarkable contributions in this regard are given below:

Chen et al. [8] proposed a 3D finite element model to study the thermal impact and evaluation of stresses in weld by considering mechanical effect of tool shoulder. Chao et al. [9] have formulated the heat transfer of the FSW process and observed that about 95% of heat generated from the friction was transferred into the workpiece and only 5% flows into the tool as well as about 80% of plastic deformation work was dissipated as heat. Song and Kovacevic[10] have introduced a moving co-ordinate system in a 3D heat transfer model using finite difference method to reduce the difficulty of modeling the moving tool during FSW. Nandan et al.[11] modeled a 3D visco-plastic flow of metals and the temperature fields in FSW and agreed well with experimental values. Qasim M Doos et al.[12] developed two mathematical models for FSW and observed that transient-thermal model was more accurate than fluid -thermal model. Rajamanickam et al. [13] developed a thermo-mechanical finite element model for FSW of aluminium alloy and observed that thermal modeling is useful to predict temperature near tool shoulder. Hani et al. [14] performed FSW for copper alloy using different tool pin profiles experimentally and developed a numerical model to simulate the thermal history and found more reasonable than other models. Hamed Pashazadeh et.al. [15] developed a numerical model for FSW of copper plates and observed that the temperature distributions are not symmetric around welding line and maximum temperature occurs at the behind the tool pin. Many commercial as well as some user-defined codes have been utilized to simulate FSW/P process. Several works on numerical modeling of heat transfer during FSW/P with moving heat source technique have been performed [6,7,16-19] and observed that the use of a moving heat source technique is proved to be a reliable method to simulate FSP [19]. The advantage of using ANSYS software is that the temperature outputs can be obtained at every desired time steps during FSP [19].Boundary conditions, heating and cooling rates with the peak temperature attained by the workpiece establish the thermal history during FSW/P [20, 21]. One of the most important issues that hold back the wide spread use of FSP is the lack of predictive models than FSW. As compared to Al and Mg alloys, copper based materials have received fairly less attention in the numerical modeling domain. Few papers on the FSW process discussed the temperature history in a pure copper and its alloys [14, 15, 22]. Very limited work has been done in the field of FSP modeling and so far no simulation was performed for FSP of pure copper.

In this paper, therefore, numerical and experimental investigations of heat generation during FSP of pure copper were performed. FSP experiments with two different combinations of process parameters were conducted to understand the sound effects of process parameters on temperature distribution. A 3D, transient, non-linear thermal model with moving heat source was developed using ANSYS 11.0 software to simulate the thermal history during FSP of copper. The results obtained by numerical simulation are compared with experimental data in order to confirm the accuracy of the developed simulation. In addition, an attempt is made to relate the thermo-mechanical aspects with the evaluation of microstructure in the FSPed copper.

2. Experimental Investigation

In this study, commercial pure copper sheets with the size of 150 mm x 100 mm x 3 mm were used.FSP was carried out in a conventional vertical milling machine (3 HP and 2000 rpm). Figure 1(a) depicts the experimental set up showing the arrangement of copper sheet and the selected FSP tool. A high carbon high chromium (HCHCr) tool with a flat shoulder of 18mm diameter (D) and a straight cylindrical threaded pin of 6 mm diameter (d), 2.85 mm long (L) was made followed by hardening and tempering process to increase the hardness to 55-58 HRC. Figure 1(b) shows the FSP tool used in this study with its geometry. Table 1 shows the selected combinations of process parameters to study the thermal histories during single pass FSP on copper. In all the experiments the FSP tool was vertically plunged to 0.1mm depth beneath the sheet surface to attain effective contact for frictional heating with axial downward force of 15 KN. Figure 2(a) shows the schematic representation of friction stir processing scheme on pure copper.

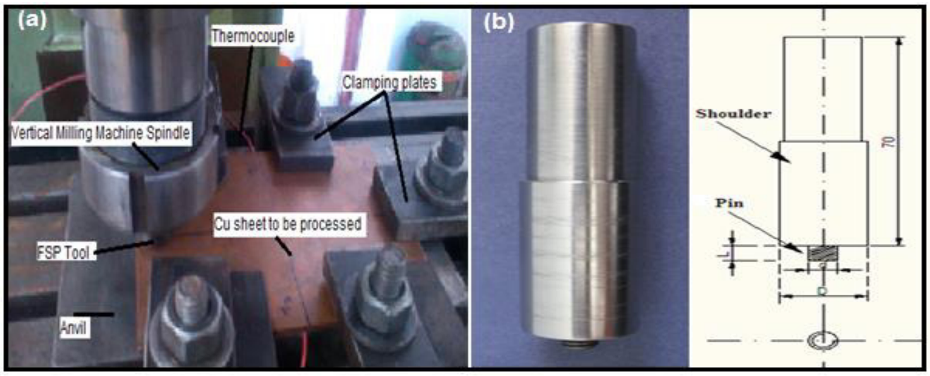

Fig.1.(a) Experimental set up for FSP; (b) Manufactured tool with its geometry

Table 1 Combinations of FSP parameters

Set – 1		Set – 2	
30 mm/min (Transverse speed)	500 rpm	700 rpm (Rotational speed)	20 mm/min
	700 rpm		30 mm/min
	1000 rpm		50 mm/min

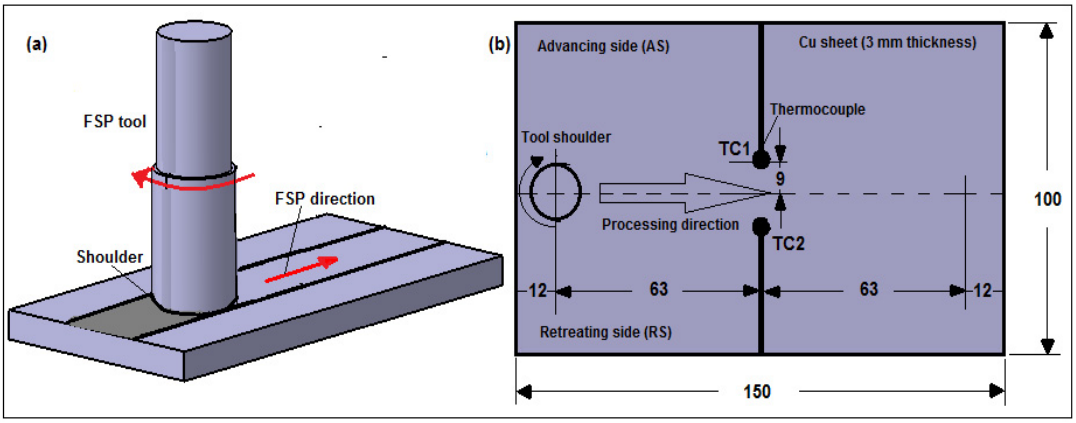

Fig. 2. Schematic representation of (a) FSP; (b) Thermocouple locations

The temperature measurement during FSP can be made by different measurement techniques. Infra-red technique is quite expensive and not possible to measure the temperature below the FSP tool shoulder instantaneously [23, 24]. Therefore, in this work, two K –type thermocouples (1.6 mm diameter) were used to measure temperature profiles. Thermocouples were inserted in blind holes drilled from the bottom of the sheet near the tool shoulder perimeter as shown in figure 2(b) prior to FSP runs. It should be noted that the thermocouples were inserted close to the surface of the sheet i.e. 0.15mm from the top taking into account of tool plunge depth (0.1mm). A four channel temperature data logger was used to record the temperature readings. For microstructural observations, the base metal and FSPed surfaces were cut, prepared and polished and etched as per ASTM standards. The base metal and the FSP zones formed by different process parameter combinations were examined by optical microscope (OM).

3. Numerical investigation

3.1. Heat transfer model

The following heat transfer model is used to calculate the transient temperature fields developed in the workpiece during friction stir processing on pure copper. In the heat transfer analysis, the transient temperature (T) which is a function of time (t) and the spatial coordinates (x, y, z), is estimated by the three dimensional nonlinear heat transfer equation (1) based on Fourier's law of heat conduction

$$k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)+\ Q_{int}=c\rho\ \frac{\partial T}{\partial t} \tag{1}$$

where k is the thermal conductivity, Q_{int} is the internal heat source rate, c is the heat capacity, and ρ is the material density [20,24].

The following assumptions are made in developing the model;

- Workpiece material is homogeneous and isotropic.
- Boundary conditions are symmetrical across the process line.
- Perfect (100%) sticking condition at the interface between the tool pin and the workpiece material.
- Heat generation by the tool pin is only 2% of total heat [25] and hence negligible.
- Heat transfer from the workpiece to the clamp is negligible [26].

The heat transfer coefficients on various surfaces of the workpiece play a significant role in the determination of the thermal history of the workpiece in friction stir processing. Convective and radiative heat loss to the ambient on all workpiece surfaces (except for the bottom), the heat loss (q_s) is obtained by equation (2) [7,11,24,26].

$$q_s=\ \beta(T-T_0)+\ \varepsilon\,\sigma\,(T^4-T_0^4) \tag{2}$$

where T is absolute temperature of the workpiece in K, T_0 is the ambient temperature (300 K), β is the convection coefficient (17 W/m^2 K), ϵ is the emissivity of the plate surfaces (0.65 for pure copper), and σ is the Stefan-Boltzmann constant (5.67 x 10^{-8} W/m^2 K^4).Based on the previous studies [9, 24, 26],a high overall heat transfer coefficient has been assumed in order to account for the conductive heat loss through the bottom surface of FSPed sheets. The heat loss through bottom surface was modeled approximately by using heat flux loss by convection q_b given by equation (3).

$$q_b=\ \beta_b(T-T_0) \tag{3}$$

where β_b is a equivalent fictitious convection coefficient. In this study, the optimized value of β_b was found to be 170 W/m^2 K by reverse analysis approach. Figure 3(a) shows the schematic representation of boundary conditions used in this model based on the actual conditions exhibited in experiments.

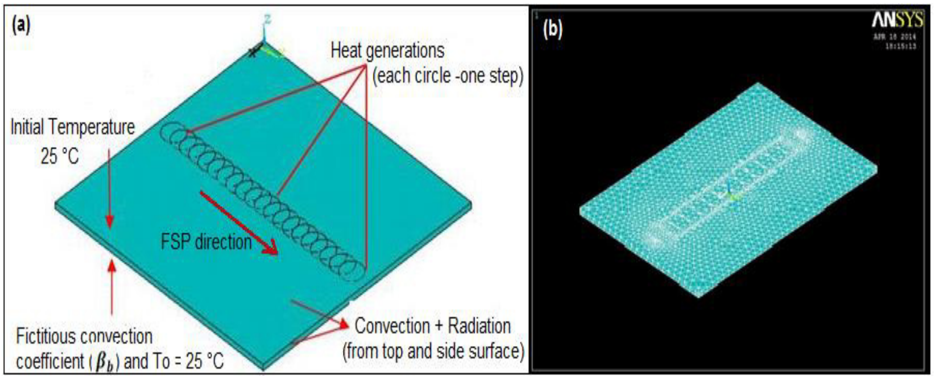

Fig. 3.(a) Schematic representation of boundary conditions; (b) Modeled 3D mesh for copper in ANSYS program

Heat generation during FSP is mainly due to the friction between tool and workpiece and intense plastic deformation around the rotating tool pin. The heat generated by the plastic deformation of FSPed sample near the pin was neglected in this study because of negligible magnitude and is difficult to appraise [9, 26]. Therefore in this model, the heat generated by friction between tool and workpiece is the only source of heat generation. The rate of heat generation (q_r) for this model is obtained using Chao et al.[9] equation (4).

$$q_r = \frac{3\,Q_r}{2\pi(r_0^3 - r_i^3)} \tag{4}$$

$$Q_r = \frac{\pi\omega\mu F(r_0^2 + r_0 r_i + r_i^2)}{45\,(r_o + r_i)} \tag{5}$$

where, $r_o$and r_i are the radii of the shoulder and pin tool, Q_r is the total heat input during FSP and calculated by equation (5)[9], μ is the frictional coefficient of material (0.36 for pure copper), ω is the tool rotational speed, F is the downward force (15KN).In this simulation, the heat flux q(r) obtained from the equation (4) is applied as surface load using the listed boundary conditions. The movement of FSP tool is implemented by creating a local cylindrical coordinate system and calculating heat load at each node at each instantaneous time step.

3.2. Finite element model

In this work, a transient heat transfer analysis was carried out using commercial general purpose finite element package ANSYS® 11.0 [27]. The workpiece is meshed using basic brick element SOLID70 because it has 3D thermal conduction ability and can be used for transient thermal analysis [27]. Hence in this model, SOLID70 with eight nodes and temperature has single degree of freedom at each node and material properties. Since SOLID70 cannot apply heat flux and convection at the same time, a 3D thermal-surface-effect element SURF152 was used for applying convection on the workpiece by overlaying it onto faces of the base elements made by SOLID70. Figure 3(b) shows the modeled 3D mesh for copper sheet in ANSYS program.

The following properties of pure copper (28) at ambient temperature such as density (8930 Kg/m^3), specific heat capacity (0.385 KJ/KgK), and thermal conductivity (400 W/mK) are used in finite element modeling. Boundary conditions were specified as surface loads through ANSYS® codes. Full Newton-Raphson option was used to solve the transient, non-linear equations. In order to simplify the moving tool on the workpiece sheet in ANSYS program, and to obtain good accurate results, all next steps of shoulder area (circle) was made to formulate it like a moving tool along the processed line in the ANSYS program as shown in figure 3(a). Here each shoulder circle has heat generation and time step, also each circle represents one step. The processing was assumed to start at a spot 12 mm away from the edge of the workpiece and stop after transformation of 138 mm along the processing line in all process simulation as shown in figure 2(b) and 3(b). In this model, the diameter of pin tool was assumed as zero. This assumption was made based on findings from Russell and Sheercliff [25] that the heat generated at the tool pin is in the order of 2% of total heat and hence negligible. This finite element model was parametrically built using ANSYS Parametric Design Language (APDL). The results of this model are then validated by comparing with established experimental results.

4. Results and discussion

4.1. Temperature distribution

In the present study, a numerical and experimental investigations of heat generation during friction stir processing (FSP) of pure copper was performed. FSP experiments with two different combinations of processing parameters were conducted. Figure 4 shows the temperature histories for processed samples at different rotational and transverse speeds. It was observed that the temperatures on the advancing side were slightly higher than those on the retreating side in all process parameter combinations [17]. These results are in consistent with Hwang et al. [29] on pure copper. The following significant information can be derived from these curves: (i) the peak temperature at the advancing side reached during FSP vary between 358°C and 670°C which is 0.33 – 0.62 of the melting point of pure copper (~ 1080°C) when the rotational speed increased from 500 rpm to 1000 rpm. It indicates that no melting has taken place during the process and that the FSP is a solid state process, (ii) the peak temperature, the rate of heating and cooling are crucial to control grain growth and (iii) the time the material is exposed to a temperature higher than the recrystallization temperature, which is also significant because it affects the grain growth during the process. Figure 5(a) and (b) shows the variation of peak temperature during FSP at different rotational and transverse speed combinations. As anticipated the peak temperature increases as the rotational speed increases and the transverse speed decreases [19].These results are used to interpret the microstructure characterization of the process further.

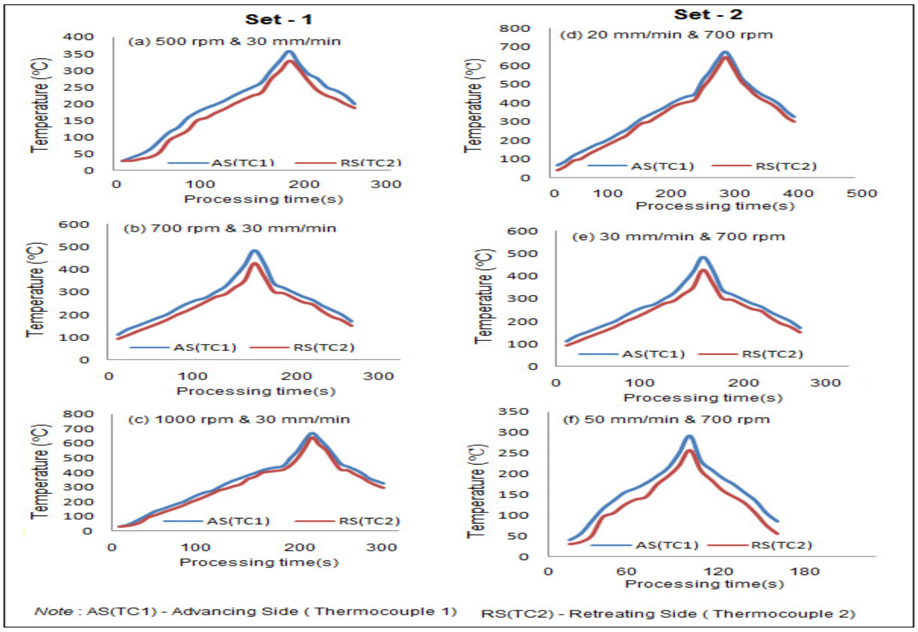

Fig.4 Temperature history during FSP experimentation at various process parameters

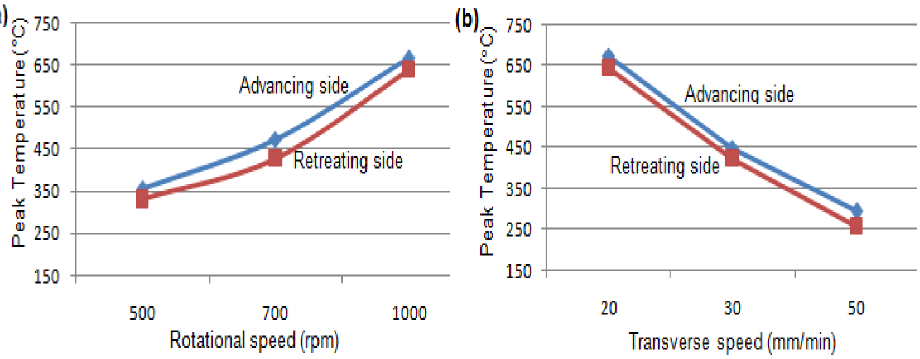

Fig.5. Variation of peak temperature with (a) rotational speed (transverse speed 30 mm/min); (b) transverse speed (rotational speed 700 rpm)

4.2. Simulated thermal history at two different set of process parameters

The simulated temperature history of FSP for pure copper at different process parameter combinations are presented in figure 6(a) and (b). In set 1, at constant transverse speed of 30mm/min, the heat generation and the peak temperature were increased when increasing the rotational speed due to the increased strain rate and plastic dissipation in the stir zone. Increasing speed from 500 rpm to 1000 rpm causes significant changes in the thermal history where the maximum temperature of 683°C is observed at 1000 rpm-30 mm/min in its advancing side as shown in figure 6(a). However in set 2, at constant rotational speed of 700 rpm, it was observed that higher transverse speeds lead to lower temperatures in the stir zone and also increasing the transverse speed from 20 mm/min to 50 mm/min leads to significant variation in the thermal history as shown in figure 6(b) where the maximum temperature of 700°C is observed at 20 mm/min-700 rpm. These observations were consistent with other studies [15]. It was clear that softening degree of the stir zone was affected by the peak temperature and the process duration at high temperature. The exposed duration at three process parameters (20, 30 and 50 mm/min – 700 rpm) were 290.7, 193.8 and 116.3 second respectively. It is clear that the cooling rate in 50 mm/min-700 rpm is higher than other two transverse speeds (20 &30 mm/min). Further, higher transverse speed will reduce the processing time and subsequently the workpiece will stay less time at higher temperatures.

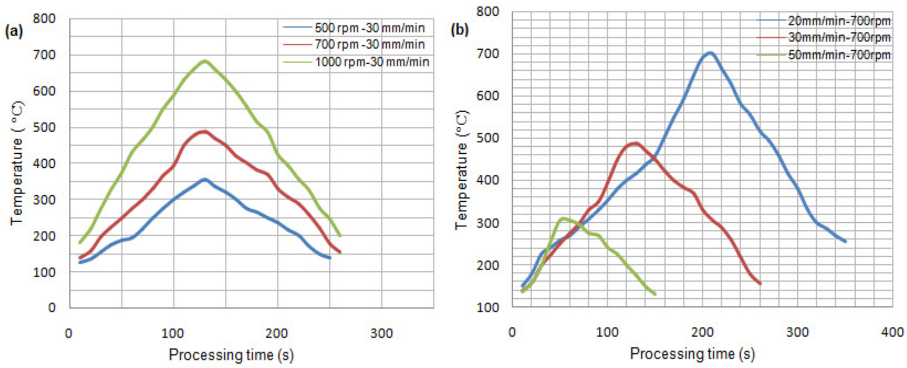

Fig.6. Simulation results of temperature profiles for pure copper at (a) different rotational speeds (constant transverse speed of 30mm/min); (b) different transverse speeds (constant rotational speed of 700rpm)

4.3. Simulated contour of temperature variation for copper

Figure 7(a)-(f) shows the simulated contour of temperature variation during FSP for various process parameters by using ANSYS 11.0. From the analysis, it was observed that along the FSP direction, the temperature values are increased with respect to increase in time duration. Figure 8(a) and (b) shows the trends of simulated peak temperature which are in good agreement with the experimental values for both advancing and retreating side measurements. It can be observed that the peak temperature at the advancing side is considerably higher than retreating side because of the asymmetric material flow around the pin in both experiment and simulation.

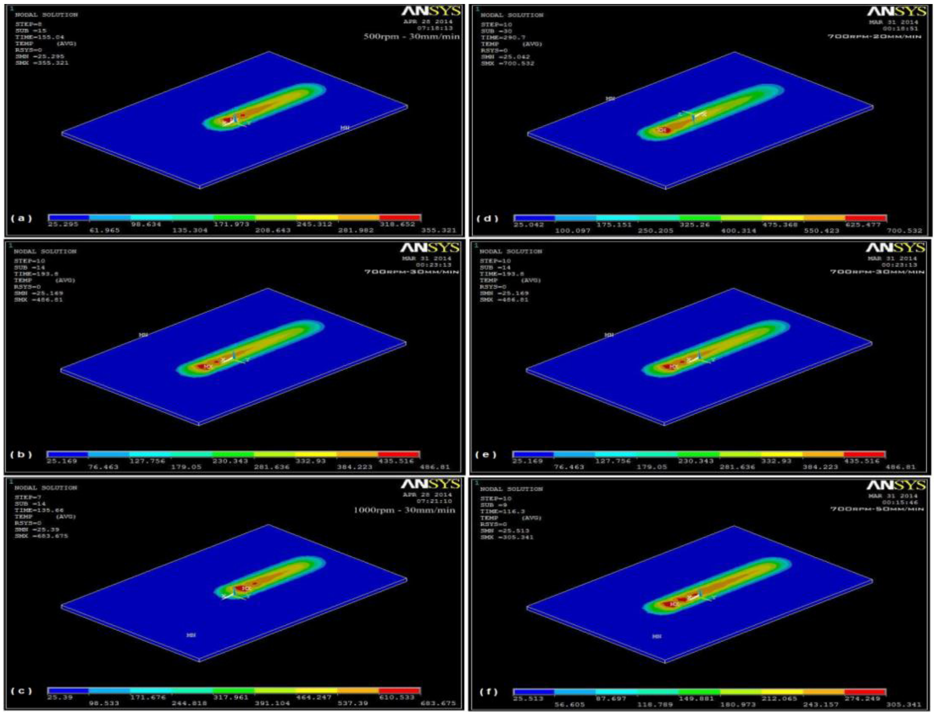

Fig .7. Simulated contour of temperature variation at (a) 500rpm-30mm/min (155.04s) ;(b) 700rpm-30mm/min (193.8s) ; (c) 1000rpm-30mm/min (135.66s) ;(d) 20mm/min-700rpm (290.7s); (e) 30 mm/min-700 rpm (193.8s) and (f) 50mm/min-700rpm (116.3s)

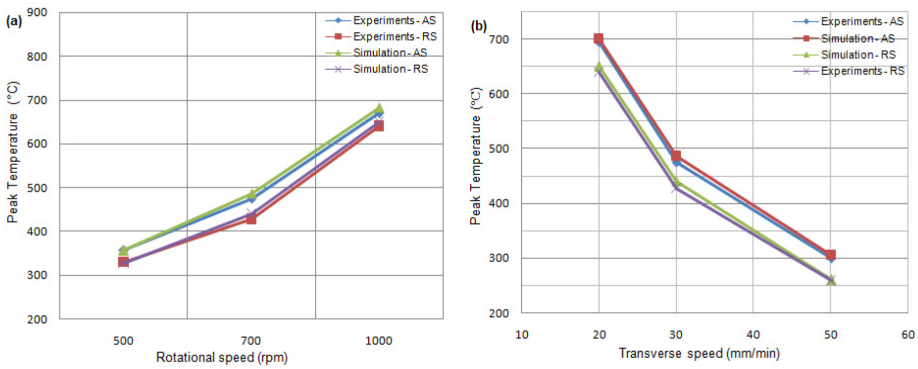

Fig 8 Temperature peaks of simulated and experimented values at (a) different rotational speeds (constant transverse speed of 30 mm/min) (b) different transverse speeds (constant rotational speed of 700 rpm)

4.4. Microstructural Analysis

Microstructural observations were carried out on as-received and FSPed copper samples at the cross sections perpendicular to the FSP direction by optical microscope (OM).The microstructural results show that FSP produced more homogenous microstructure with significant grain refinement. Figure 9(a) shows the microstructure of the base metal which has a fine microstructure with an average grain size of about 35µm.The observed grain refinement are in good agreement with earlier studies conducted by Hwang et.al [29] and Sun & Fuji [30].

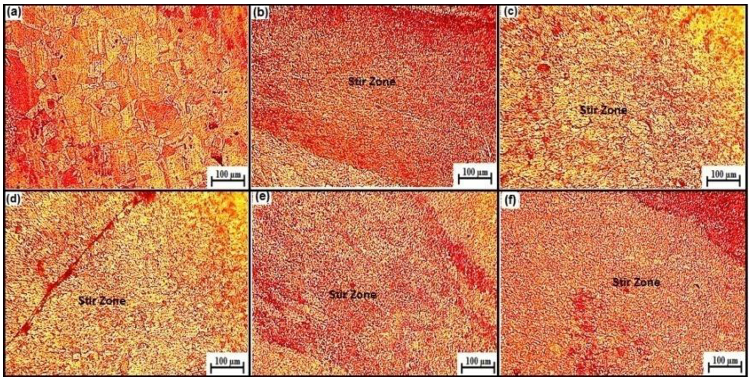

Fig.9 Optical microstructure of (a) base metal and stir zone of processed copper at (b) 500 rpm-30 mm/min; (c) 1000 rpm-30 mm/min ; (d) 20 mm/min-700 rpm ;(e) 30mm/min-700 rpm and (f) 50 mm/min-700rpm

Figure 9(b) – 9(f) compares the evaluation of microstructure with base metal by comparing grain refinement as a function of heat generation in stir zone of FSPed samples at different process parameter combinations. It is observed that the finest grains were experienced on the retreating side of the SZ near the tool pin. In set 1, at constant transverse speed of 30 mm/min, the progressive increase in rotational speed from 500 rpm to 1000 rpm showed an increase in grain size from the base metal as shown in figure 9(b), 9(e) and 9(c). Nevertheless, in set 2, at constant rotational speed of 700 rpm, the progressive increase in transverse speed from 20 mm/min to 50 mm/min showed a considerable reduction in grain size from the base metal grain size. The grain size was reduced from 35µm in the as-received condition into very fine grain size as shown in figure 9(d) -9(f).In both sets, no major defects or voids were noticed in the stir zone of FSPed copper samples.

5. Conclusion

Friction stir processing of commercially available pure copper was studied by investigation through a three dimensional, transient heat transfer modeling and experimentation. The following conclusions were drawn:

- Thermal modeling is found helpful to predict temperature near tool shoulder. The results of the simulation are in good agreement with that of experimental results. The difference between them is less than 15°C.
- The experimentation results show that the temperature achieved during FSP plays a significant role in determining the microstructure. It is observed that the peak temperature near the process zone increases as the rotational speed increased. Temperature decreases as the tool transverse speed increases.Increase in temperature during FSP was found to have a significant effect on grain size of FSPed copper.
- Experimental and simulation results shows that the temperature in advancing side is higher than retreating side .
- The results showed that the heat generation during FSP strongly depends on rotational and transverse speed, where the peak temperature was observed to be strong function of the rotational speed while the rate of heating was a strong function of the transverse speed.
- In the future, further development of this model requires assessment of pin effect, shoulder design, material flow etc during FSP on copper.

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