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Study of peak temperatures in friction stir spot welding of AA2024-Al/polycarbonate and AA2024-Al/polypropylene systems

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Abstract. Compared to ordinary fusion welding processes, friction stir spot welding (FSSW) have significant advantages for example: joining of conventionally non-weldable alloys, improved mechanical properties and reduced distortion of weldable alloys joints due to the pure solid-state joining of metals. This welding technique gives the online feedback control and opportunity of automation, allowing automatic adaptation to geometrical and environmental variations of the component. However, several fundamentals of the process such as the temperature inside the stirred zone of the weld and its power on mechanical properties, are not yet fully understood. In the present study, FSSW was adopted to weld AA2024 aluminium alloy sheets with both polycarbonate (PC) and polypropylene sheets using two different tools having two different pin configurations. The two tools have conical pin with 2.5 mm height, however, tool (T1) has draft angle of $\approx 16.69^\circ$ and the tool (T2) has a draft angle of $\approx 6^\circ$. The effects of FSSW parameters of the process, typically, the tool rotational speeds and dwell time, on temperature variation in the tool/work piece interface was also recorded, via an infrared camera. The results revealed that, increasing the tool rotational speed and/or the dwell time increase(s) the peak temperature in FSSW of both AA2024Al/polycarbonate and AA2024Al/polypropylene welded joints. For AA2024Al/polycarbonate joints, the peak temperatures recorded for tool T1 are higher than those recorded using tool T2. The peak temperature ranges were found to vary from 54 to 150 °C and from 45 to 136 °C, for joints welded using T1 and T2 tools, respectively. While, for AA2024Al/polypropylene joints, the peak temperatures recorded for tool T2 are higher than those recorded using tool T1. The peak temperature ranges were found to vary from 40 to 115 °C and from 61 to 143 °C, for joints welded using T1 and T2 tools, respectively.

1. Introduction

Metals and plastics are extensively used in the manufacturing industry to produce automobile components, electronic devices, and aircraft. Demands for the utilization of lightweight materials such as thermoplastics and aluminum alloys have increased in recent years to reduce the weight of products without sacrificing its structural strength[1].

Different promising welding techniques for joining dissimilar materials have been developed to solve problems related to convectional joining techniques. Friction stir spot welding (FSSW) is one of these methods. In FSSW, a rotating tool (non-consumable) is plunged into the work pieces to be joined. When the selected plunge depth is reached, the rotating tool is held in that position for a predestined time sometimes referred to as dwell period (t). Afterwards, the rotating tool is retracted from the



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welded joint leaving behind a friction stir spot weld. During FSSW, dwell period and the tool penetration mainly determine the heat generation, weld geometry, material plasticization around the pin and hence the mechanical properties of the welded joint. The shoulder generates bulkiness of the frictional or deformational heat while; the pin assists in material flow between the work pieces [2]. Besides the tool, the other parameters involved in FSSW are, tool plunge depth, the dwell time (t) and the tool rotation speed [3]. During FSSW the low temperatures avoids several of the defects usually observed in fusion welding processes such as cracks and porosities, and so presenting good mechanical properties over arc welding [4]. In addition, the reduced heat input results in lower deformation. In this process, the heat is initially derived from the friction between the welded material and the welding tool (including the shoulder and the probe), which causes the welded material to soften at a temperature less than its melting point. The softened material beneath the shoulder is subjected to extrusion by the tool rotational and transverse movements. It is expected that this process will innately produce a weld with less distortion and residual stress as compared to the fusion welding methods, since no melting of the material occurs during the welding[5].

Joining techniques of lightweight dissimilar materials, mostly metals and polymers, are becoming more and more important in the manufacturing of hybrid structures and components for engineering applications [6-8]. The aim of the present study is to examine the temperature variation during the FSSW of AA2024Al-to-polycarbonate AA2024Al-to-polypropylenesheets at different working conditions via the manipulation of the rotational speeds, the dwell times and the tool design.

2. Experimental work

2.1 Materials

In the present investigation, 1.5 mm thick AA2024 aluminium alloy sheets were joined with 3 mm thick polycarbonate (PC) as well as polypropylene (PP) sheets. The AA2024 Al alloy has chemical compositions (weight %) of 3.73% Cu, 1.17% Mg, 0.33% Fe, 0.23% Si, 0.24% Cr, 0.56% Zn and Bal.-% Al. Table 1 lists the mechanical and thermal properties of the AA2024 Al alloy [9]. Table 2 lists the thermal and mechanical characteristics of the polypropylene and polycarbonate sheets [10].

Table1. The mechanical and thermal properties of AA2024 Al alloy [9].

Parameter	Value
Density	2.78 g/cm ³
Melting point	502 - 638 °C
Thermal conductivity (W/m-K)	151 W/m-K
Coefficient of thermal expansion	24.7 µm/m-°C
Tensile strength	Min 427 MPa
Specific Heat Capacity	875 J/kg.°C

Table 2. Thermal characteristics of the polypropylene and polycarbonate sheets [10].

Material	Coeff. of thermal expansion (10 ⁻⁶ /°K)	Specific heat (J /K ⁻¹ kg)	Thermal conductivity (W/m.K)	Melting Temp. (°C)	Tensile strength (MPa)	Density (g/cm ³)
Polycarbonate	66-70	~1200	0.19-0.22	288-316	59	1.15-1.52
Polypropylene	100-180	1700-1900	0.1-0.22	163.8	48	0.97-1.25

2.2.Tool Design

Two tools having different pin configurations were used to perform the FSSW for the AA2024Al-to-polycarbonate and AA2024Al-to-polypropylene sheets. Figure 1 shows a schematic illustration of the FSSW used tools. The tools have conical pins. The pin for the tool (T1) has slope angle of 16.69°,

while the tool (T2) has slope angle of 6° . The pin height and diameter of shoulder are kept constant at 5 mm and 15 mm, respectively, for both tools. The tools are made from H13 tool steel.

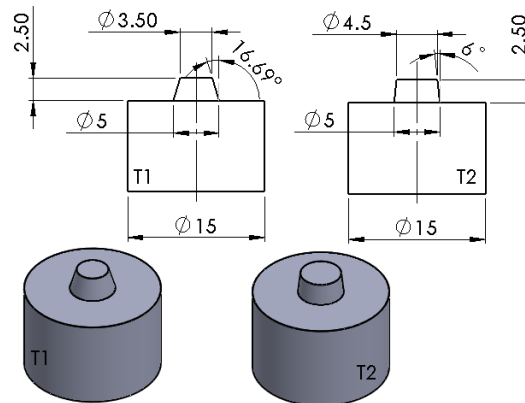


Figure 1. Schematic illustration of the tools used for FSSW (dimensions in mm).

2.3. FSSW Process

The FSSW was carried out using CNC vertical milling machine. Figure 2 shows the experimental setup used for FSSW. The AA2024 Al sheets were located at the top (i.e. facing the tool), while the polycarbonate (PC) or polypropylene (PP) sheets were located at the bottom of the lap-joint configuration shown in figure 3. The FSSW was carried out using three rotational speeds of 500, 1000 and 1500 rpm and three dwell times (t) of 4, 5 and 6 sec.



Figure 2. The FSSW process.

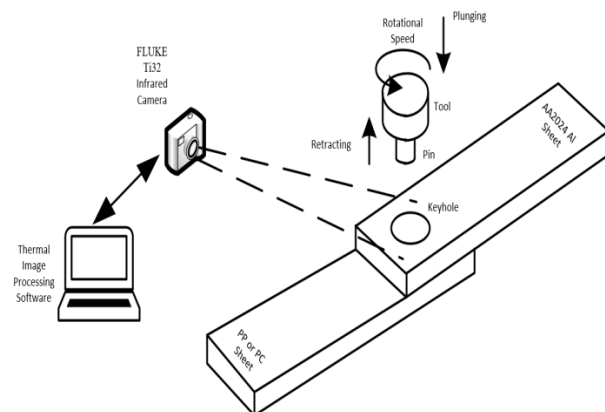


Figure 3. The Lap-joint configurations.

2.4. Temperature Measurements

The temperature measurements during FSSW were recorded using FLUKE Ti32 infrared camera. Since it is very difficult to measure the temperature at the metal/polymer interface region using the infrared camera, the camera was aimed, to capture the temperature images, only at the top surface of the AA2024 Al sheet of the welded joint. The thermal images were immediately captured, after the retracting of the tool, after finishing the FSSW process. It has a powerful 320×240 resolution and it has a thermal sensitivity of 0.045°C . The temperature range of the camera varies from -20 to 600°C . Figure 4 shows a typical output from the infrared camera during FSSW specimen. The figure shows the temperature distribution at the contact between the tool and the workpiece. Fluke Thermography imaging software was used to calculate the temperature distribution on the surfaces of the welded joints.

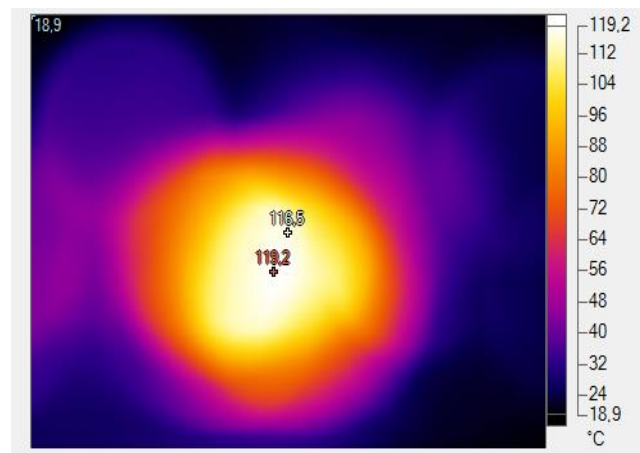


Figure 4. Typical photograph showing the temperature distribution during FSSW obtained using FLUKE Ti32 infrared camera.

3. Results and discussion

3.1. Macrostructure of the Joints

Typical cross-section of the AA2024Al/polymer system joint welded using FSSW is shown in figure 5. The figure shows the interface between the AA2024 Al sheet and the polypropylene sheet after FSSW. A nub or protrusion is also noticed due to the penetration of the pin during FSSW. Figure 6 shows macrographs of AA2024-Al/polycarbonate joint welded using tool T1 and 500 rpm and 4 sec. (see figure 6a); and 1500 rpm and 6 sec. (see figure 6b). It is clear from figure 6 (c) that the black color in the interface is the blending that happened between the AA2024-Al and the polycarbonate at the mentioned conditions. The Al particles that appeared in figure 6 (d) was due to the heat transfer that happened from the aluminum to the polycarbonate sheets due to the high temperature resulted from the high rotational speed (1500 rpm) and high dwell time (6 sec), since the high dense of aluminum rather than the polycarbonate. Therefore, these particles fall and immerse (indulge) in the mushy zone of the polycarbonate. In figure 7 it is also clear the blending regions that happened in the polypropylene and aluminum sides after tensile shear test under the mentioned conditions.



Figure 5. Typical cross-section of FSSW joint illustrating the interface between the AA2024 Al sheet and the polypropylene sheet.

At higher tool rotational speed and prolonged dwell time (t), an intensive stirring of the welded region can take place which increases the heat generated due to friction that occurs between the tool's shoulder and the Al sheet [7,8]. The heat is then transferred, from the upper layer of the Al sheet to the lower layer at which the metal/polymer interface is located. This increasing the temperature at the interface region and leads to the welding of the metal/polymer sheets. It has been observed that the interface regions are not clearly seen using optical microscopy for joints friction stir spot welded at high rotational speeds and high dwell times (t).

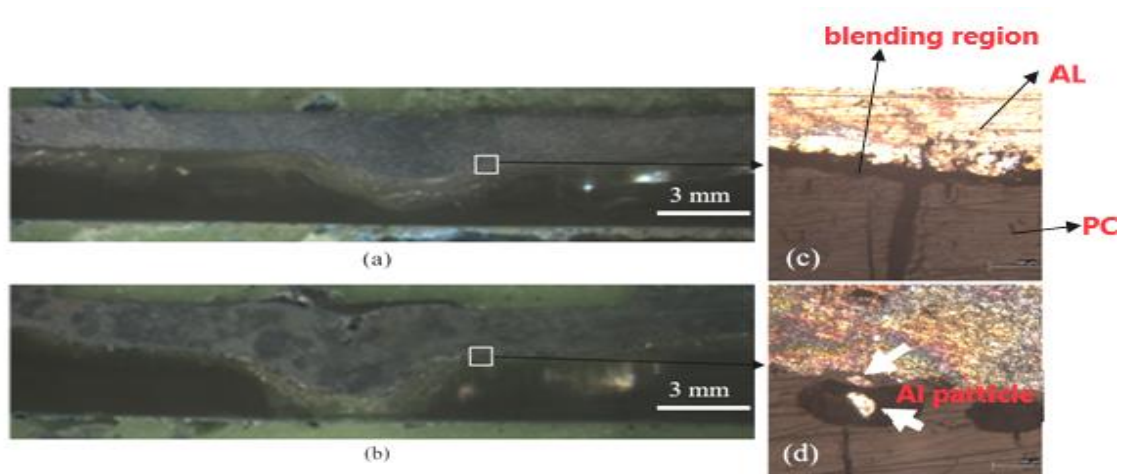


Figure 6. Macrographs of the AA2024-Al/polycarbonate joint welded using tool T1 and (a) 500 rpm and 4 sec.; and (b) 1500 rpm and 6 sec.

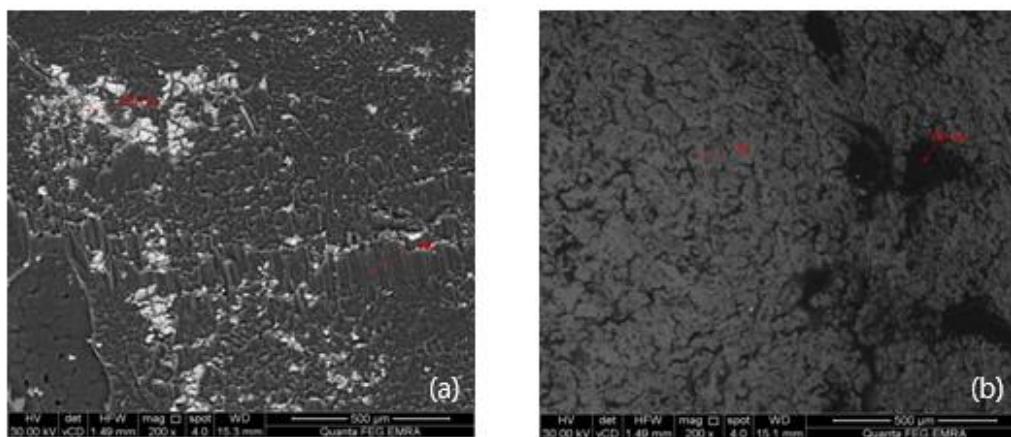


Figure 7. SEM images after tensile shear test at 1500 rpm, 4 sec, T1 (a) polycarbonate side (b) aluminium side

3.2. Peak Temperature Results

Figures 8 and 9 show typical thermographs, taken immediately after retracting the tool, for AA2024Al/polycarbonate and AA2024Al/polypropylene joints, respectively. The joints were welded using the T1 and T2 tools at different tool rotational speeds and constant dwell time (t) of 6 sec. The cross-marks shown in thermographs are located on the surface of the workpieces for tracking the temperature changes during the FSSW process. The points are located in the surrounding area of the tool shoulder boundary. The results revealed that the temperatures near the center of the keyhole are maximum (represented by white and yellow colors). Getting away from the center of the keyhole, the temperatures tend to decrease (represented by red and blue colors).

Figures 10 and 11 show the variation of the peak temperature in FSSW with the tool rotational speed at various dwell times for AA2024Al/polycarbonate and AA2024Al/polypropylene joints, respectively. The results revealed that, in most cases, increasing the dwell time and/or the tool rotational speed increase(s) the peak temperature during FSSW of both AA2024Al/polycarbonate and AA2024Al/polypropylene welded joints. For example, in AA2024Al/polycarbonate joints welded using tool T2 and constant dwell time of 6 sec., increasing the tool rotational speed from 500 rpm to 1500 rpm increases the peak temperature from $\approx 89^{\circ}\text{C}$ to 136°C .

For AA2024Al/polycarbonate, the peak temperatures recorded for tool T1 are higher than those recorded using tool T2. The peak temperature ranges from 54 to 150 °C and from 45 to 136 °C, for joints welded using T1 and T2 tools, respectively. The maximum recorded peak temperature was about 150 °C, for AA2024Al/polycarbonate joints welded using tool T1 and, tool rotational speed and dwell time of 1000 rpm and 6 sec., respectively. While the maximum peak temperature was 136 °C for joints welded using T2 tool and rotational speed and dwell time of 1500 rpm and 6 sec., respectively.

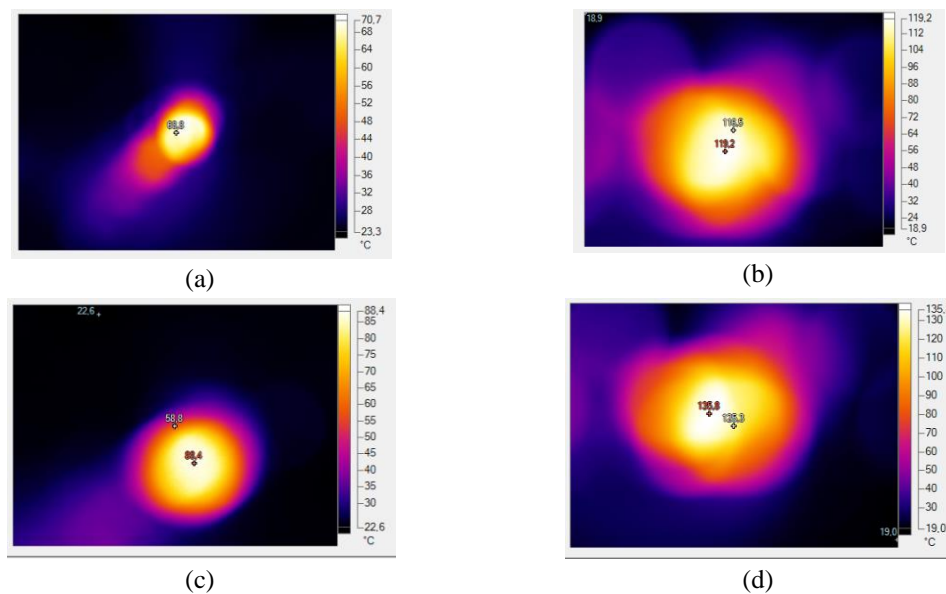


Figure 8. Thermographs of the temperature distributions on the top surfaces of AA2024Al / polycarbonate joints. The joints were welded using dwell time of 6 sec and rotational speed and tools of (a) 500 rpm and T1, (b) 1500 rpm and T1, (c) 500 rpm and T2, (d) 1500 rpm and T2.

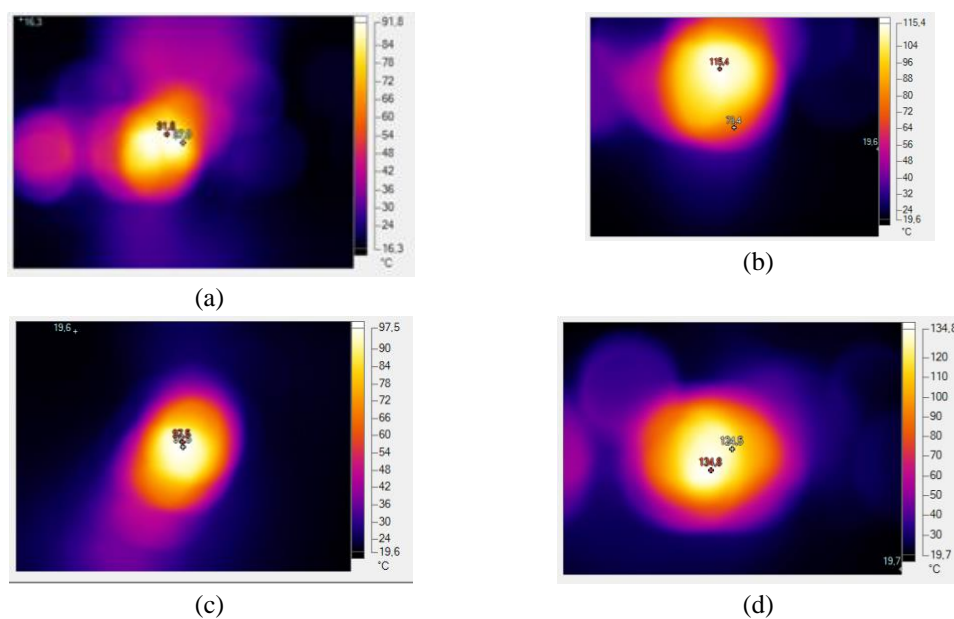


Figure 9. Thermographs of the temperature distributions on the top surfaces of AA2024Al / polypropylene joints. The joints were welded using dwell time of 6 sec and rotational speed and tools of (a) 500 rpm and T1, (b) 1500 rpm and T1, (c) 500 rpm and T2, (d) 1500 rpm and T2.

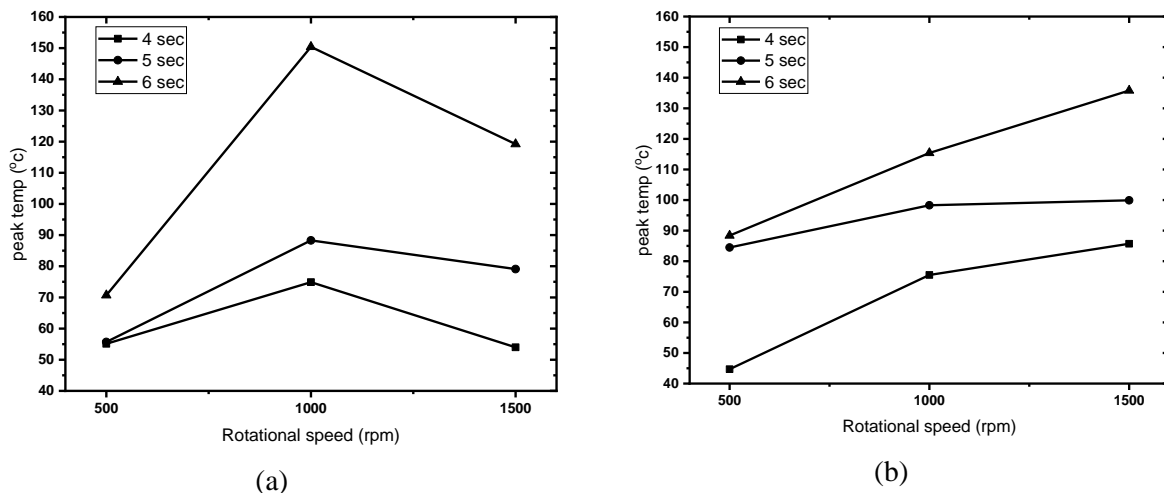


Figure 10. The variation of the peak temperature with the tool rotational speed at several dwell times during FSSW of AA2024Al/polycarbonate joints for (a) tool (T1) and (b) tool (T2).

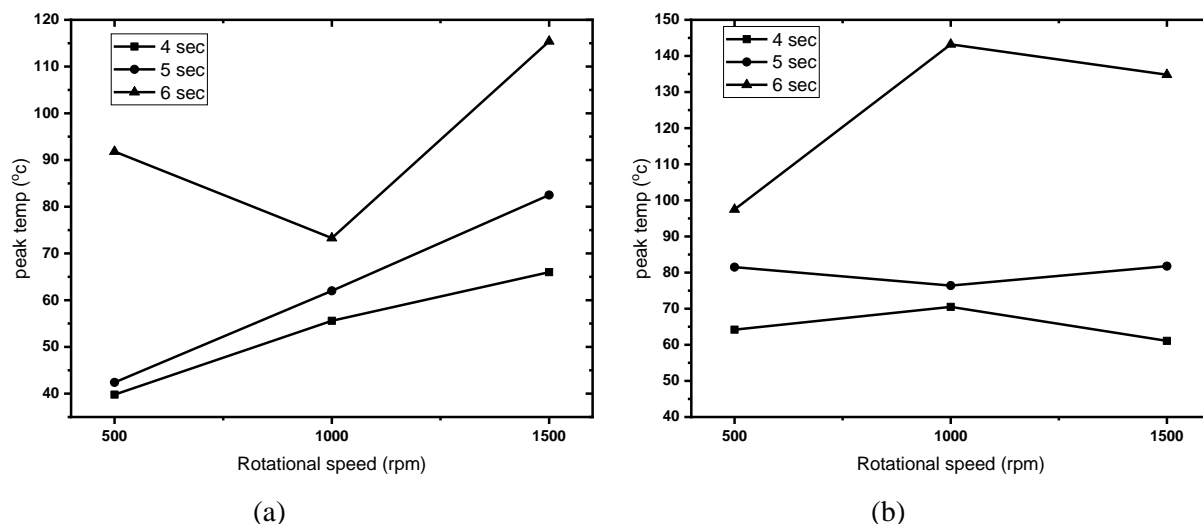


Figure 11. The variation of the peak temperature with the tool rotational speed at several dwell times during FSSW of AA2024Al/polypropylene joints for (a) tool (T1) and (b) tool (T2).

In contrast, for AA2024Al/polypropylene, the peak temperatures recorded for tool T2 are higher than those recorded using tool T1. The peak temperature ranges from 40 to 115 °C and from 61 to 143 °C, for joints welded using T1 and T2 tools, respectively. The maximum peak temperature for tool T1 was 115 °C and recorded for joints welded using rotational speed and dwell time of 1500 rpm and 6 sec., respectively. While for tool T2, the maximum peak temperature was 143 °C and recorded for joints welded using rotational speed and dwell time of 1000 rpm and 6 sec., respectively.

Figures 12 and 13 show the variation of the peak temperatures with the tool rotational speed and the dwell time (t) for AA2024Al/polycarbonate and AA2024Al/polypropylene joints welded using T1 and T2 tools, respectively. The red colored areas indicate the maximum peak temperature regions. While the blue colored areas represent the minimum peak temperature regions. The red areas are shifted toward the higher rotational speeds and dwell times.

There are three possible heat sources generated during FSSW process, i.e., friction work at the tool's shoulder and top workpiece interface, friction work at the interface of top and bottom workpiece,

and plastic deformation of the workpiece material [11]. It is well known that the tool's shoulder has greater influence on the heat generation process than the influence of the tool's pin [12]. So, the tool's shoulder and top workpiece interface contributes the most heat to the FSSW process. In the present work, only the temperatures distribution at the interface between the tool's shoulder and top workpiece are recorded. During FSSW process, the heat transfers from the top surface to the bottom of the joint i.e. to the interface between the metal/polymer interface as well as to the bottom polymer sheet. The heat transfer to the polymer/metal interface depends on the heat transfer coefficient of the AA2024 alloy ($1000 \text{ W/m}^2\cdot\text{k}$) [13].

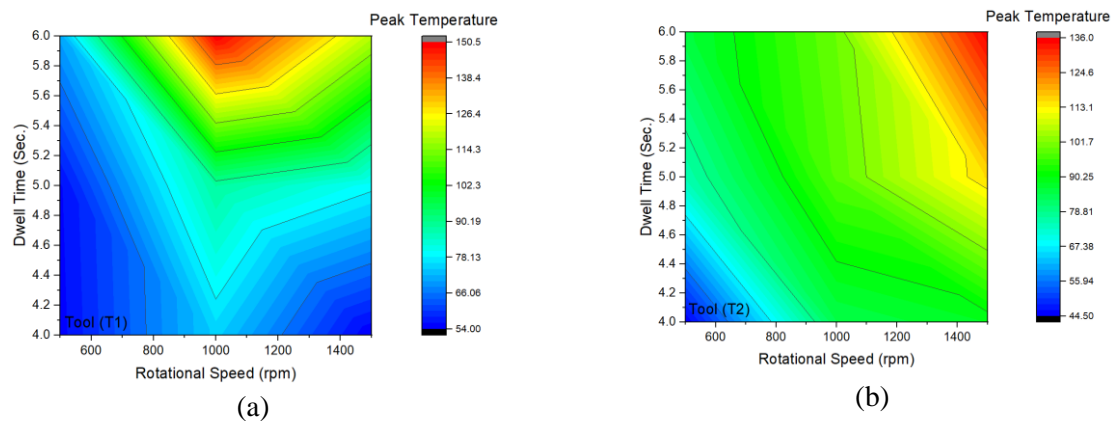


Figure 12. Contour plots showing the variation of the peak temperatures with the tool rotational speed and dwell times during FSSW of AA2024Al/polycarbonate joints for (a) tool (T1) and (b) tool (T2).

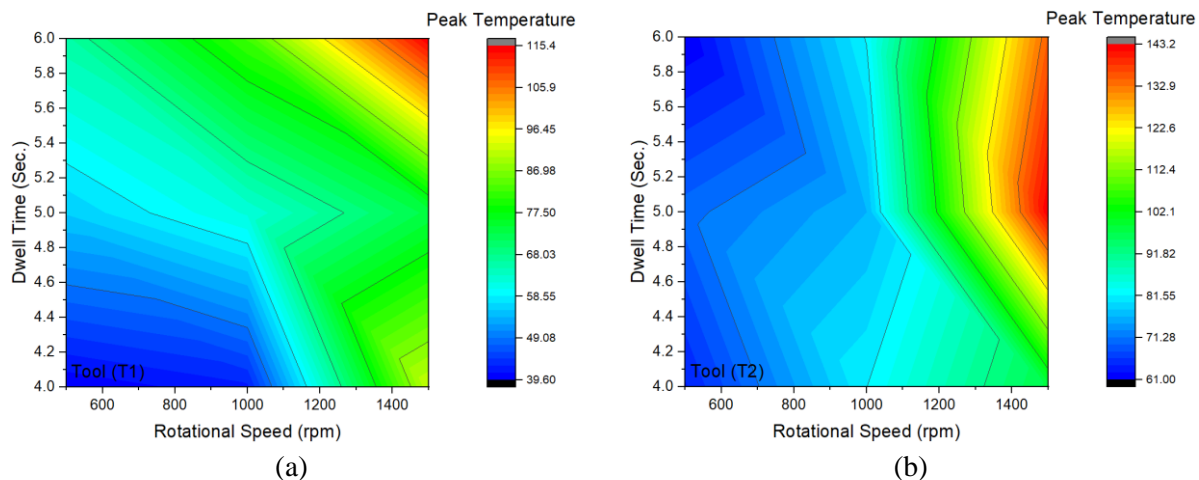


Figure 13. Contour plots showing the variation of the peak temperatures with the tool rotational speed and dwell times during FSSW of AA2024Al/polypropylene joints for (a) tool (T1) and (b) tool (T2).

The heat input during FSSW can be calculated using the following equation [14]:-

$$Q = \frac{13}{12} \mu \frac{N}{K_A} \omega R \quad \dots(1)$$

Where: Q is the heat input in Watt, R is the stir tip radius in mm, N is the vertical compressive force in Newton, ω is the rotational speed in rad/sec and it is equal to $2\pi N$, N is number of revolution per minute (rpm), μ is the coefficient of friction between the workpiece and tool's shoulder, K_A is the tool shoulder profile surface area ratio expressed by the ratio of shoulder profile contact area (A_c) to tool circular cross sectional area, (i.e. $K_A = A_c/A$). According to this equation, and as noticed in the present investigation, increasing the tool rotational speed increases the heat input. This is also reported by many investigators [10-14].

4. Conclusions

The main conclusions are:

- Increasing the dwell time and/or the tool rotational speed increase(s) the peak temperature during FSSW of both AA2024Al/polycarbonate and AA2024Al/polypropylene joints.
- For AA2024Al/polycarbonate joints, the peak temperatures recorded for tool T1 are higher than those recorded using tool T2. The peak temperature ranges vary from 54 to 150 °C and from 45 to 136 °C, for joints welded using T1 and T2 tools, respectively.
- For AA2024Al/polypropylene joints, the peak temperatures recorded for tool T2 are higher than those recorded using tool T1. The peak temperature ranges were found to vary from 40 to 115 °C and from 61 to 143 °C, for joints welded using T1 and T2 tools, respectively.

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