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RESEARCH ARTICLE



Assisted cooling approach for FSW of pure copper

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ABSTRACT

This study aims to explore the effect of active cooling with compressed air on microstructure and the mechanical properties of pure copper joint fabricated via friction stir welding (FSW) process. Three-mm-thick copper plates were FSWed at tool rotation speed of 2000 rpm and weld speed of 30 mm/min. Compressed air of 10 psi (68.9 kPa) pressure and 20 psi (137.8 kPa) pressure were aimed at the weld line. Compared to Normal FSW the tensile strength and ductility of joints was increased by 19 MPa (10.79%) and 4 % (30.76%) respectively using 10 psi compressed air pressure. On further cooling using 20 psi compressed air, these values decreased by 32 MPa (18.18%) and 4.65% (35.76%). Active cooling resulted in fine grain structure in the joint nugget zone.

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KEYWORDS

FSW; pure copper; microstructure; mechanical property; compressed air assisted FSW

1. Introduction

Copper (Cu) is extensively used in several fields due to its high electrical and thermal conductivity, good strength and ductility, and excellent corrosion resistance [1,2]; still, there are issues in joining commercial Cu using traditional fusion welding techniques owing to the influence of oxygen (O₂), impurity, and high thermal conductivity [3–5]. During arc welding of Cu and its alloys, at the metal grain boundaries the O₂ segregation take place which may cause weld embrittlement. FSW, an environment friendly solid state joining route invented in 1991 at TWI for joining Al-alloys, is likely to solve these problems [6–10]. In FSW, a joint is produced through frictional heat and severe plastic deformation at temperatures well below the melting point of the weld materials. This way the metal in the welded zone reaches a soft state and a circumferential metal flow is obtained all around the contact surface between the FSW tool and weld joints [11]. Since then, it has been applied to aluminium and studied rigorously.

It is understood that in FSW the fine and equiaxed grains are produced in the stir zone (SZ) which is attributed due to dynamic recrystallization (DRX). FSW process parameters, tool design, workpiece material, vertical force and active cooling has important role on the recrystallized grain size [12–16]. FSW at a higher tool rotational speed (TRS) or higher ratio of TRS/weld speed (WS) resulted in increase in degree of plastic deformation and maximum weld

thermal cycle. This leads to reduced recrystallized grain size which is consistent with the general rules of recrystallization [17]. On the contrary, maximum FSW thermal cycle causes coarse recrystallized grains production [18], and also resulted in significant growth of the grains. For instance, grain refining in stir zone of Cu and its alloys is not sufficient or even some grain coarsening may take place [19–21]. In process cooling reduces the recrystallized grain growth and dissolution of precipitates in and around the SZ [18]. Several attempts have been made to study the effect of the cooling/active cooling workpiece on the grain size of FSWed materials. For example, Çam et al. [22] studied the effect of external cooling on the microstructural evolution in the stir zone of friction stir welded AA6061-T6 al-alloy joint and obtained some grain refining.

Benavides et al. [12] studied the effect of the workpiece temperature on the grain size of FSW of AA 2024 aluminium alloy using steel backing plate. They conducted experiments and compared the results using in normal FSW condition (starting temperature ~30°C) and using liquid nitrogen environment (starting temperature –30°C). It is reported that decreasing the starting temperature of the workpiece using liquid nitrogen cooling leads to grain size reduction of 0.8 µm than 10 µm grain size in normal FSW. Similarly, the maximum SZ temperature was found 0.4× T_m using liquid nitrogen environment than 0.6× T_m using normal

FSW. Su et al. [23] prepared bulk nano-structured AA7075 aluminium alloy with 100 nm average grain size via friction stir processing (FSP) process in single pass, by rapidly cooling the plate behind the tool using a mixture of water, methanol and dry ice. It was concluded that using FSW multiple passes, process parameter optimization and controlling the cooling rate are the key mechanisms to obtain any nanostructure metal and alloys. Kwon et al. [24–26] used a conical profiled tool pin with a sharpened tip to reduce heat generation during FSP of AA 1050 aluminium alloy. The maximum temperature of 190°C was noticed with a grain size of 0.5 μm . It is reported that with increase of TRS, the heating rate of the SZ was saturated however, the cooling rate linearly increased from 341 to 1473°C/min which prevents fine recrystallized grains in the SZ from coarsening. The average SZ hardness decreases with the increase of the TRS. Similarly, Charit and Mishra [27] obtained a grain size of 0.68 μm in FSP of cast Al–Zn–Mg–Sc alloy using a small diameter tool with threaded pin profile. These results are in agreement with the general rules of recrystallization [16] where the size of recrystallized grains decreases with decrease in annealing temperature. Rhodes et al. [28] found recrystallized grains of 25–100 nm in FSP AA 7050-T76 aluminium alloy using the ‘plunge and extract’ method and fast cooling (dry ice and isopropyl alcohol). These grains were much smaller, high angled and relatively dislocation-free than the pre-existing sub-grains in the parent alloy.

Normally, the strength and hardness of the FSW joints could be improved by lowering the heat input, e.g. reducing the TRS and improving the WS [29–31]. Conversely, defects produce easily at low TRS and/or high WS [29,30]. Hwang et al. [32] performed FSW experiments of pure Cu using following process parameters with temperature measured on both sides of the welds (i) TRS = 800 rpm, WS = 30 mm/min and (ii) TRS = 900 rpm, WS = 50 mm/min. It is found that the temperatures advancing side is higher than retreating side. The hardness obtained at TMAZ was 55% and 70% of pure Cu at considered conditions. Similarly, the tensile strengths were 60% and 70% of pure Cu at considered conditions.

Literatures are scarce to focus on the microstructure and mechanical properties of copper FSW under active cooling with air. In order to reduce cycle temperature and provide active cooling during the FSW process, a 3 mm Cu sheet was FSWed using compressed air aimed at the weld line in the present study. Air was considered for cooling due to

Table 1. Chemical composition and mechanical properties of the pure copper.

Material	Cu	Al	UTS (MPa)	%El
Copper (ETP)	>99.9%	97.15 %	227	23

its ease of availability and it does not interfere with the rotating tool. Under the constant TRS and WS, the aim of this work is to study the effect of compressed air cooling on the microstructure and mechanical properties of pure Cu FSW joints.

2. Experimental procedure

The parent metal used in this work was a 3 mm thick pure Cu sheet. The chemical composition and mechanical properties of the pure Cu is shown in Table 1. The sheet was sectioned into samples of 100 mm $\times$ 50 mm dimension. The FSW of pure Cu was done on the modified vertical milling machine. A conical profiled tool made up of tool steel M2 grade was employed in this study with a shoulder diameter of 18.3 mm, root diameter of 6.2 mm, tip diameter of 3.3 mm and pin length of 2.8 mm. The workpiece is held securely with a rigid SS304 grade stainless steel fixture. The TRS of 2000 rpm, WS of 30 mm/min and tool tilt angle (TA) of 2° kept constant throughout the welding procedure based on the preliminary experiments. Axial plunge load was measured using load cell arrangement which is located below the fixture.

After the preheating phase, a compressed air at pressure 10 psi and 20 psi was introduced in the leading edge of the tool at an angle of 45° with a pipe of radius of 4.7 mm. Temperature was recorded using k-type thermocouple which was attached at the mid-length of the weld coupon and 20 mm away from the joint line on the advancing side. The arrangement for the cooling is shown in Figure 1.

The specimens for micro structural evaluation were sectioned from the FSW joints traverse to the welding directions, polished and then etched with solution of 15 ml hydrochloric acid, 100 ml distilled water and 2.5 g iron chloride, and were studied using optical microscopy. Vickers microhardness was then conducted at the mid thickness of welded samples with a load of 500 g for 10 s. Three sub-size tensile test coupons were prepared and were carried out at a 3 mm/min strain rate.

3. Results and discussion

3.1. Microstructural characterization

3 mm pure Cu sheets were successfully joined in the close square butt joint using FSW. Sound joints



Figure 1. Cooling arrangement with a pipe at 45°.

were obtained at TRS of 2000 rpm and WS of 30 mm/min. The surface morphologies of the joints fabricated using normal FSW, with 10 psi and 20 psi compressed air pressures are depicted in Figure 2(a–c). Figure 3(a–c) shows the SZ microstructure of normal FSW, FSW assisted by compressed air pressures of 10 psi and 20 psi respectively. This is in line with reported literature [33]. It is found that the fine grain size obtained using compressed air FSW. The grain size of the recrystallized SZ is determined by two dominant aspects, degree of plastic deformation and peak

temperature attained during FSW [18]. At the same TRS and WS, although the degree of plastic deformation may remain the same but compressed air directed at the weld line reduces the peak temperature which resulted in finer grain structure [16]. Hence, it is agreed that the peak temperature is the key aspect in determining the grain size. Similar results were reported by Xie et al. [34] in FSW of Cu alloys at constant WS by reducing the TRS. Hence, the grain size reduction in this work is characterized by lower peak temperatures due to the compressed air cooling effect. The peak

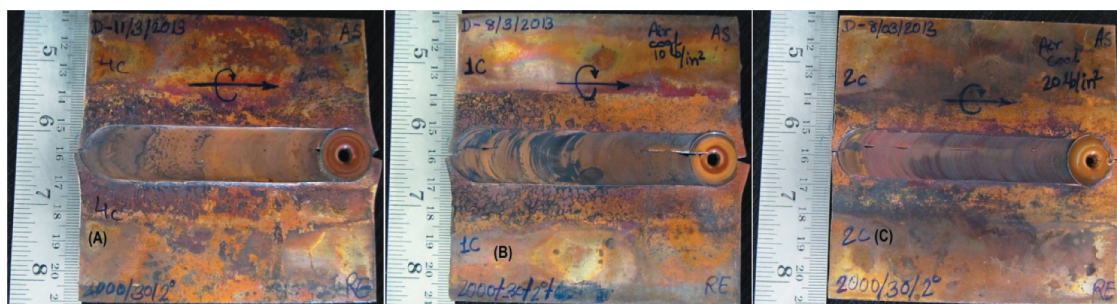


Figure 2. Surface morphologies of the joints using (a) normal FSW, (b) FSW with 10 psi compressed air at weld line at 45° and (c) FSW with 20 psi compressed air at weld line at 45°.

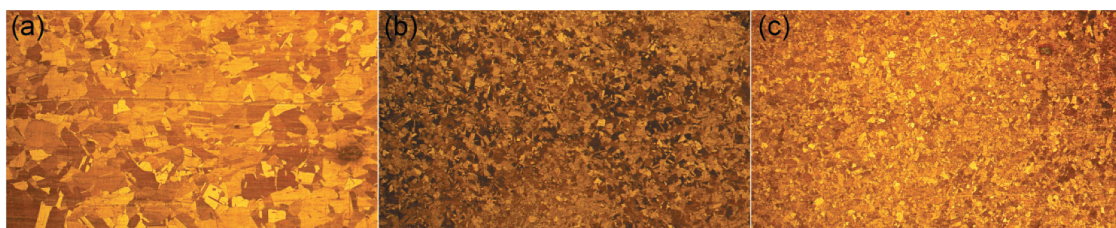


Figure 3. Microstructure of weld nugget at 50 × magnification (a) normal FSW (b) FSW with 10 psi compressed air at weld line at 45° (c) FSW with 20 psi compressed air at weld line.

temperatures after the plunging stage was observed to be 155°C at 10 psi compressed air and 115°C with 20 psi compressed air whereas in normal FSW it was 175°C. Some defects were observed in both cases of compressed air-assisted cooling FSW as depicted in Figure 4. These defects were observed due to the lower vertical force. It is also attributed due to the higher rate of energy extraction from weld line thus leaving a smaller amount of energy for recrystallization than required.

3.2. Hardness

The two factors that influence the hardness of the stir zone in pure metals are annealing softening and grain refinement. Xie et al. [34] observed that though there was significant grain size reduction,

hardness values of the SZ reduced at a TRS of 600 rpm and 800 rpm due to annealing softening effect. In contrast in this study, although a much high TRS of 2000 rpm was used still FSW assisted with compressed air resulted in higher nugget zone hardness compared to normal FSW. Okamoto et al. [35], Lee and Jung [36] found that the hardness of the SZ was smaller than parent Cu because of the major effect of annealing softening. However, in this study, SZ hardness increases with the application of compressed air. Hence, it is revealed that the grain refinement effect is prominent at the constant TRS and WS of the tool. Rajamanickam and Balusamy [37] reported that high hardness is obtained at smaller heat input in AA2014; this is in line with the current work. The microhardness at different

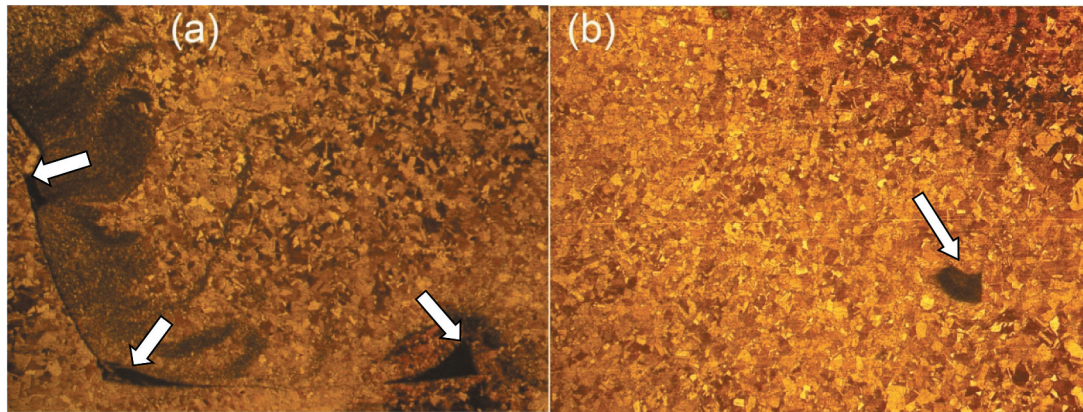


Figure 4. Defects in welds with (a) FSW-assisted cooling at 10 psi compressed air and (b) FSW assisted cooling at 20 psi compressed air.

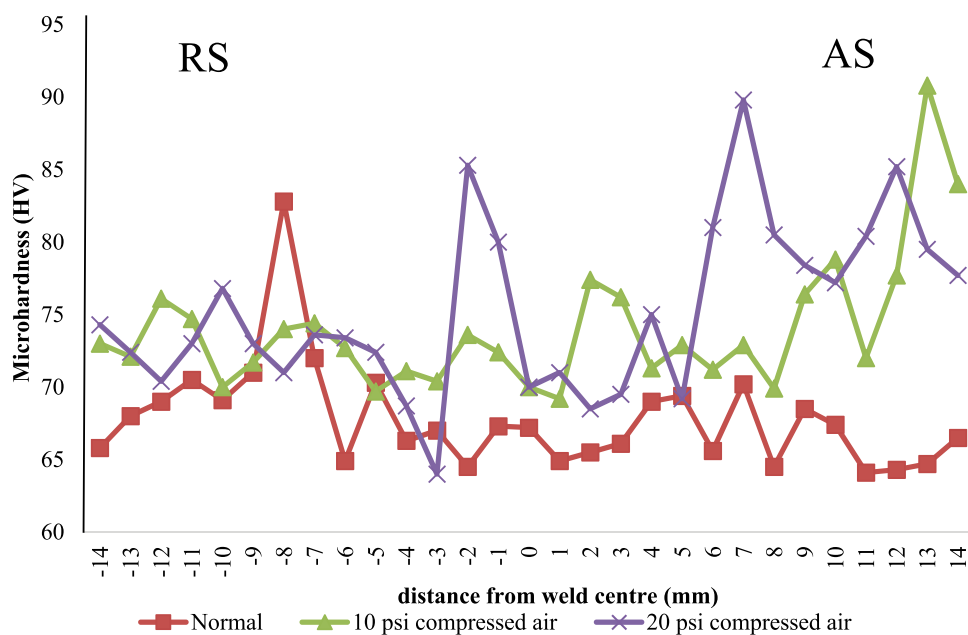


Figure 5. Micro-hardness of FSWed samples at different conditions.

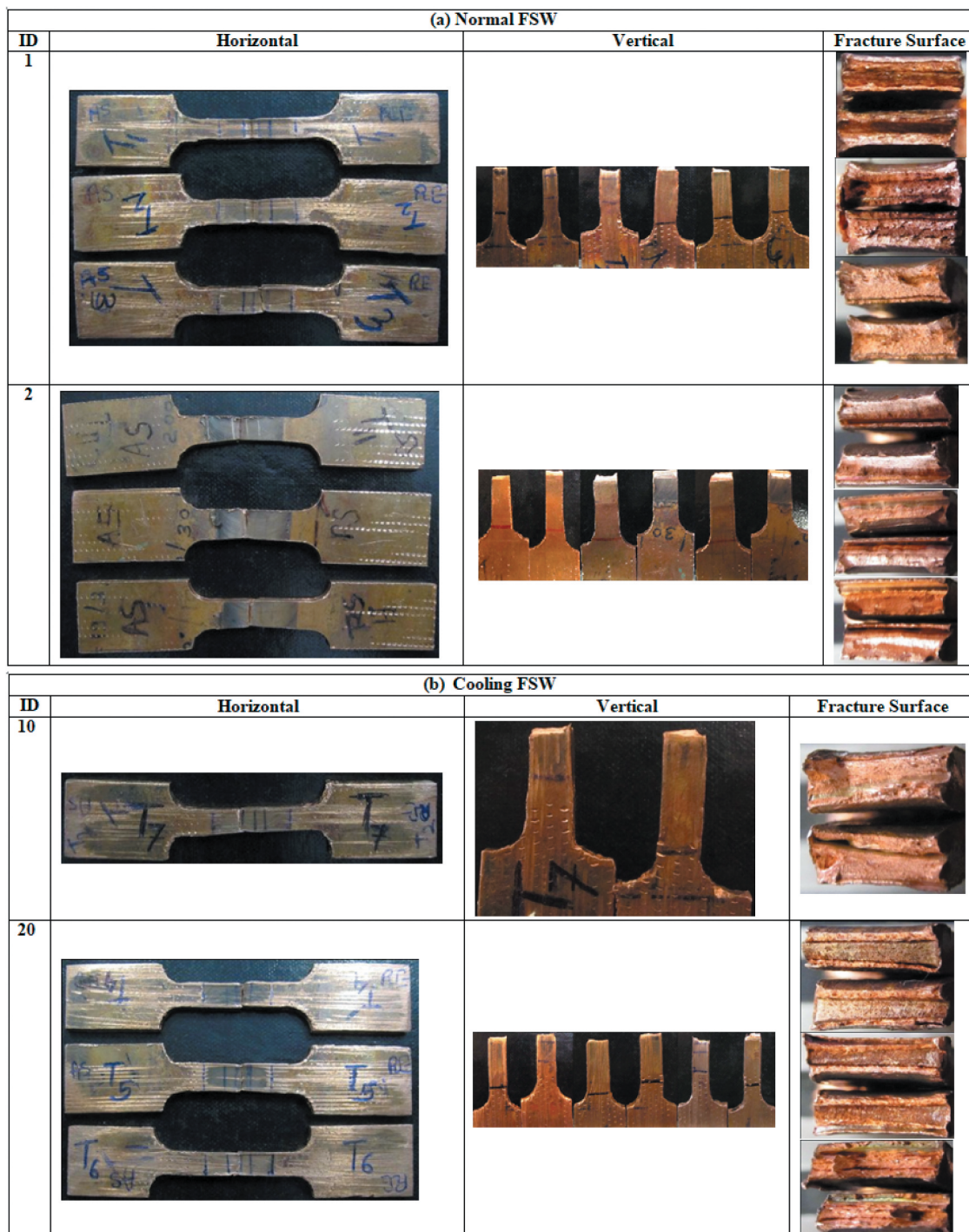
Table 2. Mechanical properties of FSWed pure copper at different condition.

Condition	Tensile strength	% Elongation
Normal FSW	176 MPa	13
FSW-assisted cooling (65 kPa) 10 psi	195 MPa	17
FSW-assisted cooling (130 kPa) 20 psi	144 MPa	8.35

conditions is depicted in Figure 5. It can be seen from Figure 5 that SZ hardness is higher in case of assisted cooling FSW at 20 and 10 psi compressed air pressure than normal FSW. This is attributed due to the cooling effect of compressed air.

3.3. Tensile properties

Table 2 illustrates the tensile testing results of normal FSW and FSW with compressed air pressure at 10 and 20 psi. Table 2 implies that the tensile strength of the joint at 10 psi compressed air pressure was higher than both normal FSW and FSW-assisted cooling at 20 psi compressed air. Tensile strength increases to 195 MPa from 176 MPa for a 10 psi compressed air while, at 20 psi compressed air the tensile strength decreases to 145 MPa. Figure 6(a–b) shows the fractured samples in

**Figure 6.** Fractured tensile samples in (a) normal FSW and (b) assisted cooling FSW.

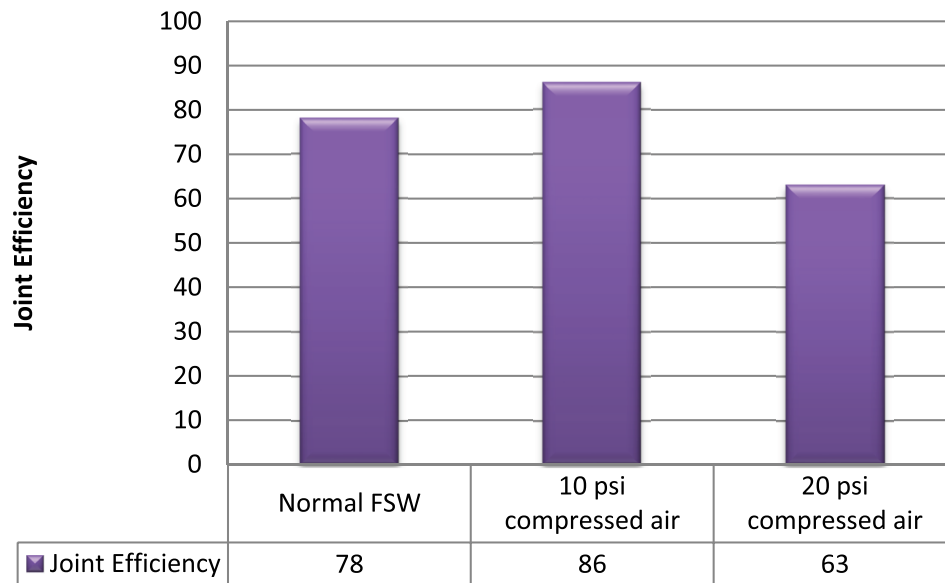


Figure 7. Joint efficiencies in normal FSW, and assisted cooling FSW.

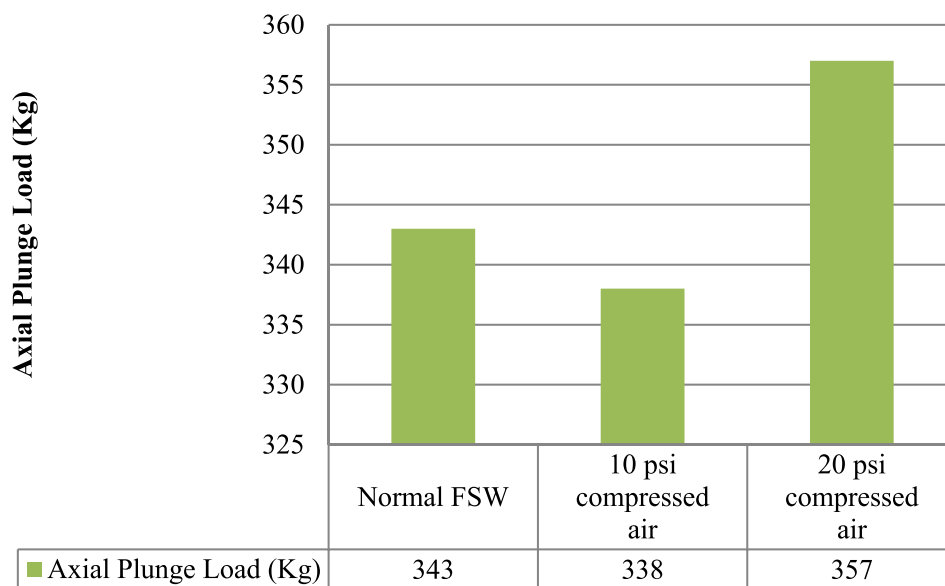


Figure 8. Axial plunge load in normal FSW, and assisted cooling FSW.

normal FSW, and assisted cooling FSW. It can be seen that all the samples are failed in a ductile manner. Similarly, percentage elongation increases by 30.76% for FSW assisted cooling at 10 psi compressed air pressure and decreases by 35.76% for 20 psi compressed air pressure. The joint efficiencies in normal FSW and assisted cooling FSW are shown in Figure 7. The maximum joint efficiency is found at 10 psi compressed air than normal FSW and 20 psi compressed air pressure. Similarly, the axial plunge load is less in 10 psi compressed air than normal FSW and 20 psi compressed air pressure as can be seen in Figure 8. Although, there were defects found in both cases of active cooling still mechanical properties in the case of FSW with 10 psi improved suggesting that if by applying proper

plunging forces defect-free weld were obtained then mechanical properties would improve further.

4. Conclusions

In this work, the microstructure and mechanical properties of FSW of pure copper was studied using compressed air cooling of 10 and 20 psi pressure. The following conclusions are drawn.

Defect-free FSW joints of pure copper were obtained at 2000 rpm in normal FSW.

The hardness in weld nugget with FSW assisted cooling using compressed air was higher than the normal FSW due to fine grains structure and cooling effect. The effect of grain refinement is prominent at the constant tool rotation and weld speed.

Despite defects in weld joints, the tensile strength of joints produced using FSW assisted cooling using compressed air at 10 psi pressure was found to be higher than normal FSW and FSW assisted cooling using compressed air at 20 psi. It occurs due to fine grain structure in a 10 psi compressed air. The tensile strength decreased on increasing the cooling pressure due to larger extraction of heat than required.

The fine-grain structure was observed in both cases where FSW-assisted cooling using compressed air due to a decrease in the peak temperature cycle.

Percentage elongation increases to 17% in FSW-assisted cooling using compressed air at 10 psi compressed air and decreases to 8.35 % in FSW-assisted cooling using compressed air at 20 psi.

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Disclosure statement

No potential conflict of interest was reported by the author.

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