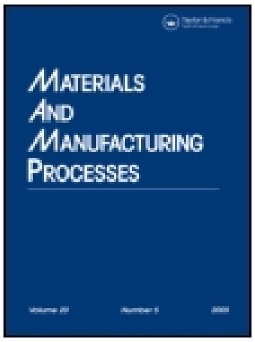

Materials and Manufacturing Processes

ISSN: 1042-6914 (Print) 1532-2475 (Online) Journal homepage: www.tandfonline.com/journals/lmmp20

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To cite this article: A. Kumar & L. Suvarna Raju (2012) Influence of Tool Pin Profiles on Friction Stir Welding of Copper, Materials and Manufacturing Processes, 27:12, 1414-1418, DOI: 10.1080/10426914.2012.689455

To link to this article: https://doi.org/10.1080/10426914.2012.689455

Materials and Manufacturing Processes, 27: 1414–1418, 2012

ISSN: 1042-6914 print/1532-2475 online
DOI: 10.1080/10426914.2012.689455

Influence of Tool Pin Profiles on Friction Stir Welding of Copper

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The influence of tool pin profiles on microstructure and mechanical properties of friction stir welded copper was studied. The different tool pin profiles such as taper cylindrical, taper cylindrical with threaded, triangular, square, pentagonal, and hexagonal having constant shoulder diameters were used to fabricate the joints. Tool rotational speed and traverse speeds were fixed at 900 rpm and 40 mm/min, respectively. The experimental results revealed that the sound defect free joints could be obtained by using six different tool pin profiles and the fracture locations were outside the weld zone on the retreating side. From the investigation it was found that the joints made by using square tool pin profile resulted in better mechanical properties compared to other tool pin profiles which is due to more pulsating actions and with 1.56 dynamic to static volume ratio. The tensile properties of all weld joints showed a relative correspondence to the variation of the hardness in the weld zone. The joint efficiency of square pin profile is more (85%) of the base metal compared to other pin profiles. The observed results were correlated with the microstructure and fracture features.

Keywords Cu-based; Fracture; Friction; Microhardness; Microstructure; Stir; Tensile; Weldability.

Introduction

Copper and its alloys are most important engineering materials due to their good ductility, corrosion resistance, electrical, and thermal conductivity [1]. Welding of copper is usually difficult by conventional fusion welding processes because of copper has high thermal diffusivity (401 w/m.K). Friction stir welding (FSW) is a one of the solid state welding processes in which a non-consumable rotating welding tool pin is plunged into the joint line between the two plates that are to be welded together. The shoulder makes firm contact with the top surface of the workpiece, so that the frictional heat is generated by the tool shoulder. Due to this frictional heat, the surrounding material softens and allows the tool to be involved along the joint line [2]. The material is plasticized and translated along the welding direction, and this plasticized material is transported from the leading edge to the trailing edge of the tool where it is forged into a joint and leaving a solid phase bond between the two plates [3]. FSW is energy efficient, environmentally friendly, with less distortion, faster welding speeds than traditional fusion welding techniques and able to join materials that are difficult to fusion weld [4]. The copper is used in containment canisters for nuclear waste has been manufactured via a FSW process [5]. Fabrication of backing plates of copper alloys were used for the sputtering equipments [6]. The shape of the tool pin profiles influences the flow of plasticized material and affects weld properties [7, 8]. A triangular tool pin profile increases the material flow compared with a cylindrical tool pin profile [9]. The axial force on the work piece material and the flow of material near the tool were affected by the orientation of threads on the pin surface [10]. Tri-flute type pin tool with conical threaded geometry was used to produce good welds in case of AA2024-T4 and AA7075-T6 aluminium alloys [11]. The material flow behaviour is predominantly influenced by the FSW tool pin profiles, tool dimensions, and process parameters [12]. From the reported literature, it was observed that no work has been carried out on FSW of copper using different tool pin profiles such as triangular (TR), square (SQ), pentagonal (PT), and hexagonal (HX) on mechanical and microstructure properties of copper weldments. Hence the present study aimed at investigating the effect of different tool pin profiles such as TR, SQ, PT, and HX. For comparison, the copper welds are made with taper cylindrical (TC) and taper cylindrical with threaded (TT).

Experimental procedure

The base metal (BM) sheets of 3 mm thick copper were welded by butting two plates and stirring them together with a rotating tool assembly by using vertical milling machine (Make HMT FM-2, 10 hp, 3,000 rpm). Mechanical properties of the BM are presented in Table 1. H13 tool steel is chosen as tool material because of its high strength at elevated temperature, thermal fatigue resistance, and low wear resistance. The trial experiments were conducted with TC tool pin profile on FSW of copper by varying tool rotation speed and welding speed, and the optimum rotational speed and welding speeds are found to be 900 rpm and 40 mm/min, respectively; which resulted in better mechanical properties [13]. Keeping the welding conditions such as tool rotation speed at 900 rpm and welding speed 40 mm/min constant and varying the tool pin profiles such as TC, TT, TR, SQ, PT, and HX, the joints were fabricated and

Received February 2, 2012; Accepted April 17, 2012

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TABLE 1.—Mechanical properties of base material.

Material	UTS (MPa)	YS (MPa)	% El	Microhardness (HV)	Impact strength (J)
Pure copper	260	231	31	110	18

are shown in Fig. 1. The welding parameters and tool dimensions used to fabricate in FSW process are presented in Table 2. The FSW joints were fabricated with different tool pin profiles and found to be defect-free, and the surface morphologies of the FSW joints are shown in Fig. 2. From the surface morphology, it is observed that the amount of flash is low in the joints fabricated by SQ tool pin profile compared to other tool pin profiles.

Metallography

The specimens for metallographic examination were sectioned to the required size from the FSW joints in transverse to the welding direction, polished with different grades of papers, and then etched with a solution of 100 ml distilled water, 15 ml HCl, and 2.5 g ferric chloride, the microstructure of the weld zone (WZ) and the unaffected BM were examined with optical microscopy (Model: Nikon; Make: Epiphot 200), and changes in the microstructure of the WZ were found. The fractured surfaces of the tensile tested specimens have been studied with the help of scanning electron microscopy (SEM).

Mechanical Testing

Specimens for tensile testing were taken in transverse to the weld direction and should be taken at the middle of all the joints and machined as per ASTM E8 standards. Tensile test was conducted on computer controlled universal testing machine (Model: Autograph; Make: Shimatzu) with a crosshead speed of 0.5 mm/min.

Specimen for impact testing is taken in transverse to the weld direction and machined as per ASTM A370 standards. The Charpy V notch impact test is conducted at the room temperature. Specimens were cut at the middle of the joints in transverse direction for conducting microhardness survey. Microhardness was carried out using Vickers digital microhardness tester (Model: Autograph, Make: Shimatzu) with a 10 g load and 10 s duration. The microhardness was measured at the interval of 0.15 mm across the WZ, thermo-mechanical affected zone (TMAZ), heat affected zone (HAZ), and base.

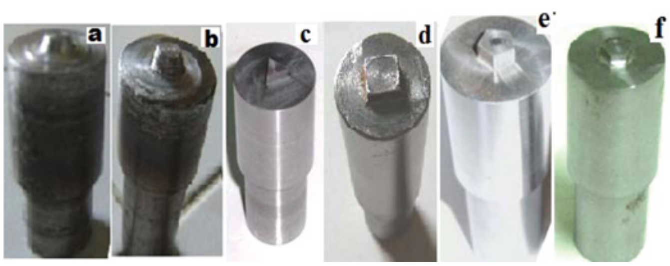

FIGURE 1.—Typical photographs of manufactured tools: (a) TC, (b) TT, (c) TR, (d) SQ, (e) PT, and (f) HX (color figure available online).

TABLE 2.—Welding parameters and tool dimensions.

Process parameter	Value
Rotational speed (RPM)	900
Welding speed (mm/min)	40
Axial force (KN)	5
Tool shoulder diameter, D (mm)	24
Pin diameter, d (mm)	8
D/d ratio of tool	3
Pin length, L (mm)	2.8
Tool tilt angle, θ (degrees)	3

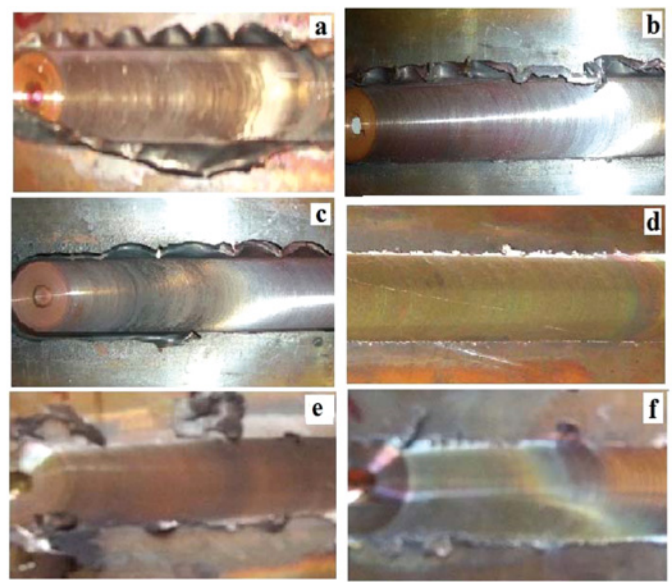

FIGURE 2.—Surface morphologies of the of FSW joints made by (a) TC, (b) TT, (c) TR, (d) SQ, (e) PT, and (e) HX tool pin profiles (color figure available online).

RESULTS AND DISCUSSIONS

Microstructural Studies

FSW is a well-known severe plastic deformation process. The stirring action was observed at the weld center and produces finer grains. The discrepancy reflected significantly different microstructure in the WZ produced by various tool pin profiles as shown in Fig. 3(a–g). It is observed that, the joints made by SQ pin profile tool (Fig. 3d) resulted in very much smaller equiaxed grains compared to other pin profiles. During stirring action of the tool which induces high amount of plastic deformation and frictional heat generation between tool and BM. This is due to the mechanism of constant dynamic recrystalization (DRX). The DRX usually occurs in WZ, and thus the microstructure can be refined [14]. Between WZ and BM, small portions of TMAZ and

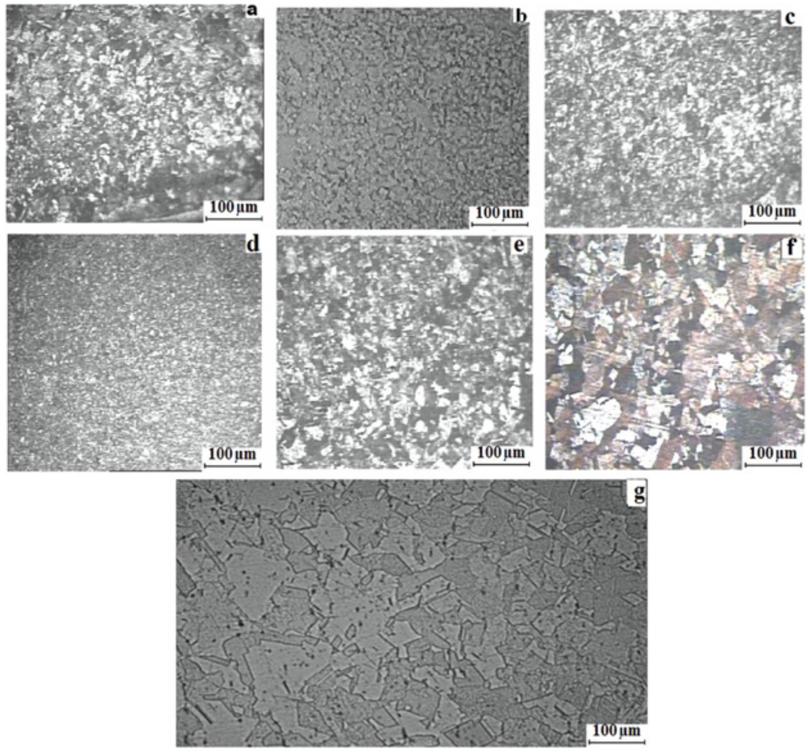

FIGURE 3.—Microstructure of weld zones of processed samples by various pin profiles (a) TC, (b) TT, (c) TR, (d) SQ, (e) PT, (f) HX, and (g) BM (color figure available online).

HAZ were observed. The TMAZ consists of a slightly elongated grain structure due to the annealing affect of heat and severe plastic deformation of material around the pin edge [14]; outside of the TMAZ there is a zone (HAZ) affected only by the heat generation during the welding process [15] in which slightly coarse grains were observed when compared with that of the BM. DRX is of great industrial interest due to the new grains being smaller than the initial grains which improves mechanical properties at room temperature.

Mechanical Properties

Mechanical properties of the joints fabricated by various tool pin profiles of the FSW joints are shown in Table 3. It is observed that the joint fabricated by SQ pin profile experienced superior tensile properties with the joint efficiency of 85% compared to the other joints. This is due to more number of pulsating actions (60 pulses/s) of the tool and having the dynamic volume (DV) to static volume (SV) ratio (1.56) which effects the grain refinement and annealing during the welding process and also the SQ pin profile sweeps large amount of material from the plasticized zone. The joint fabricated by TR pin profile tool shows almost equal to tensile properties to that of PT pin profile tool. This is due to lower number of pulsating action (45 pulses/s) and having high DV to SV ratio (2.3). The friction heat generated by TR pin profile might be smaller than that of SQ pin profile because the contact area of the TR pin profile is lower than the other pin profiles. The joints fabricated by other tool pin profiles such as TC and TT, exhibits lower mechanical properties compared to SQ and TR pin profile tools. This is due to lowest DV to SV ratio and no pulsating action experienced. TT pin profile produces more heat than the without thread pin profile. The more heat input can improve the flow of material and pin exerts an extra downward force that

TABLE 3.—Mechanical properties of FSW copper and Dynamic-to-Static volume ratio of different tool pin profiles.

Tool pin profiles	UTS (MPa)	YS (Mpa)	% El	Microhardness (HV)	Impact strength (J)	Joint efficiency (%)	DV/SV
TC	168	109	13.5	85	13	65	1.09
TT	187	129	13.4	90	13	72	1.01
TR	208	151	14	95	14	80	2.3
SQ	218	182	16	105	16	85	1.56
PT	207	178	12	82	09	79	1.32
HX	183	141	03	80	08	70	1.21

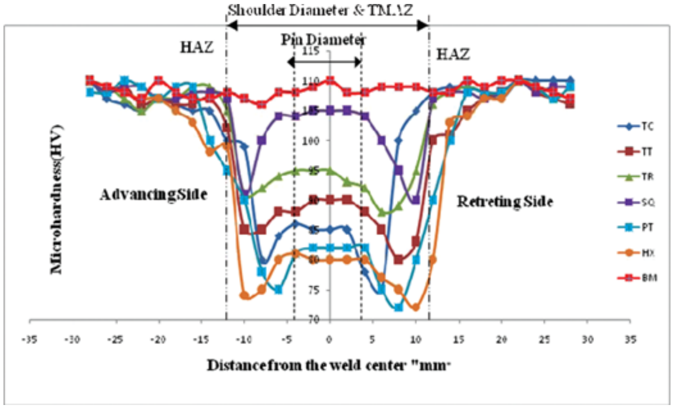

FIGURE 4.—Microhardness distribution of FSW joints for different pin profiles and the BM (color figure available online).

will be beneficial to accelerate the flow of plasticized material. Joints fabricated by HX tool pin profile also exhibits lower mechanical properties compared to SQ, TR, and PT pin profiles tools. This is due to lower DV-to-SV ratio (1.21), even though having high number of pulsating action such as (90 pulses/s) of the tool and produce less sweep plasticized material. Tensile properties of the welded joints which are made by different tool pin profiles such as TC, TT, TR, SQ, PT, and HX exhibits lower values than BM. Impact toughness of the FSW joints were evaluated; the joint made by SQ pin profile tool results higher impact toughness compared to the other joints and the value obtained is almost equal to BM. This is due to fine grain structure resulted in more ductile nature than all other joints.

Microhardness survey was carried out on all the welded joints which are made by different pin profiles. The various hardness profiles of welded joints are presented in Fig. 4. From the hardness survey, both sides of the WZ, TMAZ and HAZ, were presented. The transition between TMAZ and HAZ obtain the lower hardness value due to the difference between the microstructure of TMAZ and HAZ. The hardness of BM has 110 HV; however, at the WZ, the highest hardness value of 105 HV has been observed for the joint fabricated by SQ pin profile tool and lowest hardness value of 80 HV has been recorded in the joint fabricated by HX pin profile tool. This is due to the formation of very fine equiaxed microstructure at the weld region of the joint fabricated by using SQ pin profile tool compared to other joints made by different tool pin profiles which may be accounted for a number of pulsating actions experienced in the WZ of SQ pin profile which resulted in higher strength and hardness. The hardness of the WZ is also influenced by annealing softening and grain refinement in pure metals [16]. Hardness of WZ is lower than the BM after the FSW process, since annealing softening was predominated. For all the joints, the average hardness value of WZ is lower than that of BM due to softening of the material during dynamic recovery and DRX [17].

The fractural morphology of the tensile specimens of the fracture surface of the weld joints were studied using the SEM to understand the mode of failure. The fractured surface of tensile specimens made by different pin profiles and BM is presented in Fig. 5(a–g). All joints were failed on the retreating side (RS) during tensile testing. It can be found that all the specimens fractured at the locations with lowest hardness value in the samples, which matches well with the hardness measurement. From the observed fracture surfaces of the tensile specimens welded by SQ tool pin profile are nearly the same

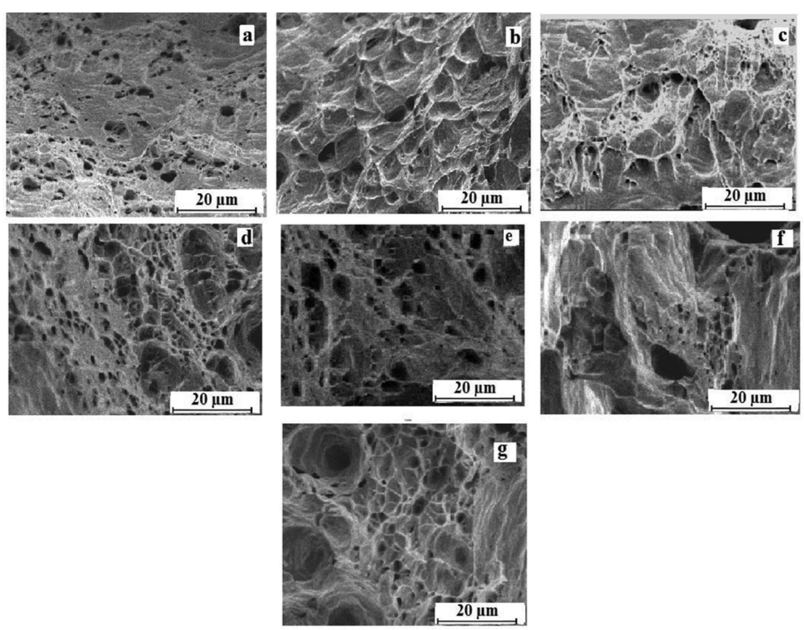

FIGURE 5.—Fracture surface of tensile samples: (a) TC, (b) TT, (c) TR, (d) SQ, (e) PT, (f) HX tool pin profiles, and (g) BM.

as fracture features of the BM, but the size of the dimples is smaller than those of BM, which is due to formation of extremely fine grains at the WZ produced by FSW which enhanced resistance for tensile deformation [18]. But in case of other FSW joints fabricated by other tool pin profiles, it is observed that there is absence of large voids than SQ pin profile and BM. Figure 5f shows flat and smooth fracture surface suggesting low ductility and brittle fracture compared to the joints made by other pin profiles.

Conclusions

The effect of various tool pin profiles on microstructure and mechanical properties of friction stir welds of copper was investigated. The main conclusions were drawn as follows:

1. The mechanical properties of the copper weldments were affected by the tool pin profiles.
2. Among the six different tool pin profiles used, the SQ pin profile tool resulted in better mechanical properties than other tool pin profiles due to more number of pulsating actions and having DV to SV of 1.56.
3. The weld joint obtained using a SQ pin profiled tool possesses 85% joint efficiency compared to the joints made by various tool pin profiles.
4. DV and SV ratio and pulsating action of pin affect the mechanical properties of FSW joints.
5. Defect free welds were obtained for all the six tool pin profiles.
6. The microstructure at the WZ of FSW joint using a SQ pin profiled tool is observed to be finer and with more equiaxed grains than BM due to DRX.

Acknowledgments

The authors would like to thank the authorities of National Institute of Technology (NIT), Warangal, India, for providing the facilities to carry out this work.

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