Review on Tools for Friction Stir Welding/Processing of Copper

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ABSTRACT
Friction stir processing (FSP), a derived form of Friction Stir Welding (FSW), is widely used to manufacture and develop various composites, to refine microstructure and improve the associated mechanical and physical properties including formability, strength, ductility, fatigue, creep, and corrosion resistance. It also results in elimination of defects. However, tool design, basic geometric configuration and tool material play major role in the use of FSW/P for manufacturing applications, particularly for high melting temperature or high strength alloys. In this review, the FSW/P tools are briefly summarised in terms of the tool types, shapes, and materials. The shoulder applies a downward force to the workpiece surface, which constrains the plasticised material around the probe, generates heat through the friction and causes Severe Plastic Deformation under the bottom surface of the shoulder.

Keywords***: FSP, Metal Matrix composite, Tool geometry, Severe Plastic Deformation***

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1. INTRODUCTION

Friction stir processing (FSP), which is a derived from FSW, was developed for microstructural modification of metallic materials to alter the properties of the material. Welding/processing parameters, tool geometry, and joint design have a significant effect on the material flow pattern and temperature distribution, influencing the microstructural changes of material. These changes in microstructure lead to changes in the basic properties of the material which is processed. The main roles of the FSW/P toolsare to heat the workpiece, induce material flow (plastic flow) and constrain the heated metal to go back into the workpiece beneath the tool shoulder. Heating is created by the friction of the rotating tool shoulder and probe of the tool with the workpiece, which cause severe plastic in the workpiece. The localized heating softens the material which is being processed around the probe. The simultaneous tool rotation and translation cause the movement of the material from the front to the back of the probe. Because of the various geometrical features and material properties of the tools, the material movement around the probe can be extremely complex and it significantly differs from one tool to the other. In this study, literature review related to the FSW/P tools (shoulders and probes) is discussed briefly.

2. LITERATURE REVIEW

2.1 Design of Tool Shoulder:-

In FSP, the shoulder diameter accounts for maximum heat generation. It has been found that shearing between the shoulder surface and the workpiece results in heat generation by 87%, and rest 13% heat is generated by pin [1].

According to Arora et al. shoulder geometry has influence on thermal cycles, peak temperatures, power requirements and torque [2]. Using three dimensional, heat transfer and material flow analysis, an optimal tool shoulder diameter was found out by Mehta et al. which was 18 mm diameter and having a rotational speed of 1200 rpm for friction stir welding of AA6061. Superior properties were obtained by tool shoulder having diameter of 18 mm.

Dawes and Thomas showed in their study that the use of a scrolled-shoulder tool allows the tool to be worked on workpiece without tilting it or giving it a tilt angle. It significantly improves surface finish, mechanical properties of the welds and permits higher welding speeds [3].

There are three shoulder geometries such as flat, concave, convex. Conical shape (with concave shape) with around 2-10˚ cavity (conical angle) helps to push the material downward through centrifugal force which gives the proper material flow for joint formation. Conical angle depends on the thickness of workpieces and the diameter of the shoulder [4].

The shoulder geometries may be with special profile features like scrolled, ridges, grooves, concentrating circles as shown in fig. 2. The flat shoulder tool required lower weld spindle torque than conical or scrolled shoulder tools for same shoulder diameter for friction stir welding of pure copper thin sheets. The scrolled shoulder tool provided the most suitable material flow during welding and the flat shoulder the worst, producing only defective welds. The scrolled shoulder provided greater grain refinement in the nugget zone of the welds than the tools having conical or flat shoulders. This refinement is responsible for the increased hardness and mechanical strength of the copper welds made with this tool [5].

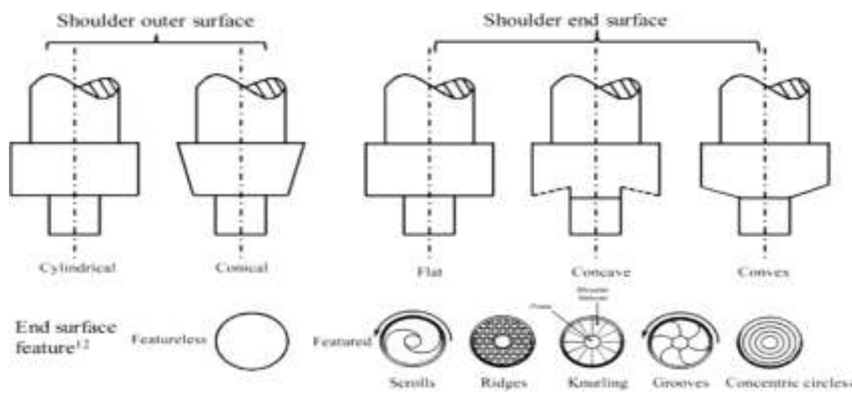

Figure-2:- Various types of tool shoulders with their different designs [5]

For dissimilar metal joining such as Cu-Al FSW system, the tool shoulder geometries and profile affects the material flow, formation of Inter-Metallic Compound (IMCs) and mechanical properties of the joint. Galvao et al. [6] reported that, scrolled shoulder is used to force Cu-Al mixed material downward, which, in turn give good surface morphology. But, large amount of IMCs are formed when scrolled profile is used. These IMCs are responsible to increase hardness and brittleness in the stir zone and this also causes defects. So, scroll surface profile is not recommended in order to achieve defect free dissimilar Cu-Al FSW joint.

2.2 Design Tool Pin Profiles:

The shape of the tool pin profiles influences the flow of material that is plasticized and affects weld properties [7-8]. A tool pin profile with straight edges 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].

Khodaverdizadeh et.al [13] have investigated the effect of tool pin profile on FSWed pure copper joints. The results revealed that square pin profile produced finer recrystallized grain structure, higher degree of plastic deformation at the stir zone. In their investigation, S. Cartigueyen et al.[14] has made an attempt to study the effect of tool pin profiles on the formation of stir zone in pure copper at low heat input condition. FSP of copper is carried out with a constant rotational speed (350rpm) and traverse speed (50m/min) and shoulder diameter of 18 mm with six different FSP tool pin profiles. Following Fig. 3 and table 1 shows the characteristics and results produced of all the six types of tools. Fig .4 shows the macrostructure the FSRed samples with various pin profiles.

Figure-3:- Geometric shapes of FSP/W tool: a) Cylindrical b) Threaded c) Triflute d) Triangular e) Square f) Hexagon [14]

Table-1:- Effect of tool pin profiles on Copper used as Base Metal [14]

Tool pin profiles	Comments
Plain cylinder (PC)	Due to low rotation speed, there was no stirring action producing insufficient heat for plain pin.
Threaded cylinder (TC)	Surface having a reasonably good finish and compression, producing flash for the given plunge.
Triflute (TF)	Better surface produced at low-heat input condition and resulted in less flash.
Triangular(TR)	Insufficient movement and compression of material at low-heat input condition.
Square pin (SQ)	Surface having reasonably good finish and compression and produced more heat and flash.
Hexagonal (HE)	Good surface finish and compression, producing thin flash for the given plunge.

Plain cylindrical pin (PC)

Threaded cylindrical pin (TC)

Triflute pin (TF)

Triangular pin (TR)

Square pin (SQ)

Hexagonal pin (HE)

Figure-4:- Defects produced during the process [14].

Ch. Venkata Rao et al. [15] carried out their research in analyzing the role of tool pin profile with respect to changes in the microstructure and corrosion behaviour of AA2219 Al-Cu alloy friction stir weld nuggets. In his research he found that pit density of nugget zone of hexagon tool profile is relatively very low compared to those of other tool profiles. Therefore, it can be concluded that the improvement in pitting corrosion resistance can be achieved in the nugget zone of friction stir welds of AA2219-Cu alloy made with hexagonal tool. Also, EBSD analysis indicated that a continuous dynamic recrystallization process led to the formation of equiaxed grain structure in the weld nugget zone. Relatively more fine grain structure was obtained in hexagon tool profiled welds which lead to formation more low angle grain boundaries in the weld region.

A. Kumar et al. [16] in his study investigated that the mechanical properties of the copper weldments were affected by the tool pin profiles. Among the six different tool pin profiles that were used, the Square pin profile tool resulted in better mechanical properties than other tool pin profiles due to more number of pulsating actions and having Dynamic Volume to Static Volume of 1.56. The weld joint obtained using a Square pin profiled tool possesses 85% joint efficiency compared to the joints made by various tool pin profiles.

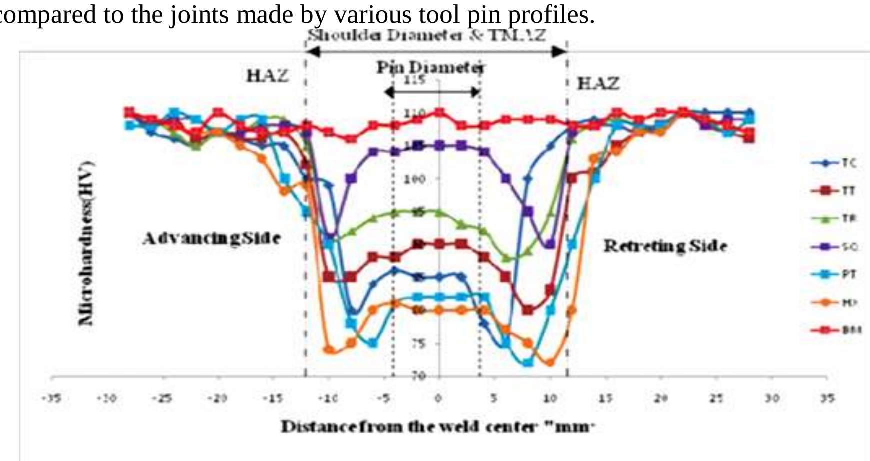

Figure-5:-Microhardness distribution of FSW joints for different pin profiles and the BM [16].

Fig. 5 shows the microhardness traverse of friction stir welded samples with various pin profiles and table 2 below shows comparison of various mechanical properties of FSW copper and Dynamic-to-Static volume ratio of different tool pin profiles. It shows that square tool pin profile gives maximum strength along with efficiency and Dynamic to Static ratio.

Table-2:- comparison of various mechanical properties of FSW copper and Dynamic-to-Static volume ratio of different tool pin profiles [16]

Tool pin profiles	TC	TT	TR	SQ	PT	HX
UTS (MPa)	168	187	208	218	207	183
YS (Mpa)	109	129	151	182	178	141
% El	13.5	13.4	14	16	12	03
Microhardness (HV)	85	90	95	105	82	80
Impact strength (J) Joint	13	13	14	16	09	08
efficiency (%)	35	72	80	85	79	70

DV/SV	1.09	1.01	2.3	1.56	1.32	1.21

2.3 Tool Material:

To make a choice for selecting friction stir welding/processing (FSW/P) tool material becomes an important task which determines the quality of the weld produced. Selection of tool material depends on the tool material operational characteristics such as operational temperature, wear resistance and fracture toughness which therefore determines the type of materials that can be joined or processed.

Kudzanayi Chiteka et al.[17] in his study suggested some suitable tool materials for FSP of Copper and it's alloys which include tool steels (HSS, H13), Nickel alloys, Tungsten alloys as well as PCBN.

UgenderSingarapu et al.[18] showed in his study that the rate of machinability H13 tool steels is about 75% of that of the Tungsten (W) group tool steels. H13 chromium hot-work steel is majorly used in hot as well as cold work tooling applications. Having known of its excellent combination of high toughness and fatigue resistance.

H13 is widely used in tooling applications more than any other tool steel. However, according to Y.N.Zhang et al [19], steel tools are not at all suitable for high melting point materials such as Nickel (Ni), Titanium(Ti). For such high strength materials, the welding tools are usually made of hard metals, carbides and metal matrix composites with superior thermal and wear resistance at temperatures higher than 1000^{0}C, such as WC–Co, PCBN and TiC. Y. N. Zhang et al.[19] have mentioned in his paper the suitable materials for FSP of Copper as shown in table 3:

Table-3 Various Tool Materials suitable for Copper with their advantages and disadvantages [19]

Tool material	Advantages	Disadvantages
AISI H13 tool steel	Good elevated temperature strength and excellent machinability.	It undergoes severe tool wear for high strength materials or MMC
Ni/Co based alloys	High strength, ductility, corrosion resistance and creep resistance	Inorder to prevent precipitate over aging and dissolution, temperature must be kept below the precipitation temperature (typically600–800^{o}C).
WC based alloys, WC–Co based alloys	It has Superior tool wear resistance and High temperature strength.	-
Nimonic 90	It has high melting temperature, high creep resistance at high temperatures, good resistance to high-temperature corrosion as well as high temperature dynamic application.	-

K. Nakata et al. [20] in his research study have mentioned the tool materials which are suitable for friction stir welding of various copper and it's alloys. The following table 5 shows the various tool materials used for various materials of copper and its alloys.

Table-4: Compatibility of Tool Material with various forms of Copper [20]

Tool Materials	Copper materials			
	Phosphorus-deoxidised copper	Oxygen-free copper (OFC)	Cupronickel (CuNi25)	Al bronze (CuAl5Zn5Sn)
Tool steel (H13)	Good	Good	Impossible	Poor
Ni-base heat-resisting alloys (IN738LC, IN738LCmod,IN939)	Excellent	Excellent	Impossible	Possible
HIPedTiC–NiMo (TiC/Ni/Mo = 3/2/1)	Impossible	Impossible	Impossible	Impossible
Sintered TiC–NiW (TiC/Ni/W = 2/1/1)	Impossible	Impossible	Impossible	Impossible
Polycrystalline boron nitride (PCBN)	Good	Good	Good	Good
Tungsten(W)	Good	Good	Impossible	Poor

3. CONCLUSION

By reviewing literature based on the Friction Stir Welding/Processing of copper, we get to know the importance of the tool geometry and its material for the Friction Stir Processing tool and its effect on Base material during the operation. It can be seen from the literature review that the most suitable tool material for Friction Stir Processing of Copper would be Tungsten, H13 Tool Steel and PCBN to obtain defect free processed zone. Also, the tool material selected should not be a source of contamination to the final processed Copper. Most favoured tool geometry for processing of copper is square pin tool. Rate of heat generation and plastic flow in the workpiece are greatly affected by the shape and size of the tool shoulder and pin.

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