Effects of FSW on Mechanical properties and Microstructure of copper at Weld Joint

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***Abstract*- Special features of copper such as high electrical and thermal conductivities, favorable combinations of strength and ductility, and excellent resistance to corrosion have made it an acceptable material for use in many industrial areas. Due to unique performances characteristic Joining of Copper materials find applications in many sectors including Nuclear, Electrical, and Electronics industries. The copper and copper alloys can be joined by most of the commonly used methods such as gas welding, arc welding, resistance welding, brazing and soldering, but fusion welding of copper is difficult because of its high thermal diffusivity and high oxidation rate at melting temperature, one of the ways to overcome these problems is friction stir welding (FSW). FSW is a solid state welding process in which a non-consumable welding tool is used to generate the frictional heat between the tool and the work piece in order to make a solid state joint. Mechanical property of friction stir welding join of copper is good as compare to the other conventional welding process. Conventional welding process is also decrease the thermal and electrical conductivity of copper at weld joint this difficulty is also overcome by FSW, because of the many advantages of FSW process is prove that the FSW is suitable for the copper and its alloy. In this paper we try to explain the effect of friction stir welding on mechanical property and microstructure at weld joint.**

***Key Words* - FSW, Copper, alloys**

I. INTRODUCTION

Many welding processes are used in manufacturing and other industries for joining the different metals. Mainly the welding processes are divided into two main group (1) fusion welding (2) solid-state welding. Fusion welding processes use intense localized heat source to melt the base metal. Solid-state welding is completed under pressure alone or a combination of heat and pressure. Temperature is generated in solid state welding is below the melting temperature of the joining metal.

Friction stir welding was invented and experimentally proven by Wayne Thomas and a team of his colleagues at The Welding Institute (TWI) UK in December 1991. TWI holds a number of patents on this process. [1]

Friction-stir welding (FSW) is a solid-state joining process (meaning the metal is not melted during the process) and is used for applications where the original metal characteristics must remain unchanged as far as possible. This process primarily used on aluminum and low melting temperature like aluminum, magnesium alloys. The basic principle of FSW involves plunging a spinning tool that has a specially designed pin and shoulder into the work pieces that are intended for welding. [1]

Since melting of materials is avoided, FSW avoids problems such as distortion and metallurgical reactions which typically appear in conventional fusion welding processes. It is reported that the strength of the FSW weld is 30% to 50% greater than those produced by arc welding and resistance spot welding. [1]

Pure Copper is very useful material it's have wild industrial application but the welding of copper by fusion welding process is very difficult because copper have high thermal conductivity, higher expansion coefficient and generate the oxide at melting temperature. FSW is the solid state process so all problem regarding the fusion welding process is overcome by the friction stir welding process. The mechanical property and strength of FSW of copper joint is very good.

II.LITERATURE REVIEW

2.1 WELDING METALLURGY OF COPPER AND COPPER ALLOYS [13]

2.1.1 DIFFICULTIES OF CONVENTIONAL WELDING METHODS FOR COPPER MATERIAL [13]

Pure copper (electrolytic tough-pitch) is very useful material it's have wild industrial application but the welding of copper by fusion welding process is very difficult because copper have high thermal conductivity, higher expansion coefficient and generate the oxide at melting temperature.

Pure Copper (electrolytic tough-pitch) has somewhat better weldability compare to the other copper alloys but must be welded with caution. Although preheat and high heat input are necessary to counteract the high thermal conductivity of these materials. High heat inputs degrade weld properties. Therefore inert-gases shielded arc processes are recommended. Solid state processes can be effective for these materials. The AWS recommended different fusion welding method for Pure Copper (electrolytic tough-pitch) which are mention in Table: 2.1 and the difficulty of different welding method is given in Table: 2.2.and [13]

Table: 2.1 Applicable joining processes for Copper and Copper alloy [13]

Alloy	ETP Copper
UNS No.	C11000-C11900
Oxyfuel gas	Not Recommended
SMAW	Not Recommended
GMAW	Fair
GTAW	Fair
Resistance Welding	Not Recommended
Solid-State Welding	Good
Brazing	Excellent
Soldering	Good
Electron Beam Welding	Not Recommended

Table: 2.2 Difficulties of different welding processes for Copper material [13]

Method	**GTAW**	**GMAW**	**SMAW**	**Oxy-Fuel Gas welding**	**Brazing**	**Laser and Electro Beam Welding**	**Friction Welding**
Problems	Low welding speed	Result weld has a lower conductive	Weld quality is poor	Low welding speed	Low Corrosion resistance at welded region	Copper are difficult to melt with lasers due to high reflectivity and high thermal conductivity	lack versatility (Geometrical Limitations)
	Low penetration	Oxide entrapment	porosity	Oxide entrapment	Excessive oxidation	High hardness in fusion zone	Machining is required after welding
	Preheating required	-	Oxide entrapment	Preheating required	-	High residual stresses	-

2.1.2 Physical Metallurgy of Copper and Copper Alloys for FSW [2]

Cu has an F.C.C. crystal structure, a very good corrosion performance and a high thermal conductivity. But its strength is unacceptably low for load bearing applications. However, pure Cu is mainly used in applications where high corrosion resistance and electrical conductivity is required. Its strength can be increased by alloying. Most commercial Cu-alloys are a solid solution hardened (single-phase alloys). Cu-alloys exhibit no allotropic or crystallographic changes in heating and cooling, but several have limited solubility with two phases stable at room temperature, i.e. α+β -brass. Two phase Cu-alloys harden rapidly during cold working, but they usually have better hot working and welding characteristics than those of solid solutions of the same system, particularly than those with a higher alloy content.

The most known Cu-alloy is brass, which is a Cu–Zn alloy. The alloying with Zn increases the strength of Cu by solid solution strengthening. Zn has a high solubility in the α phase, formed by Cu atoms, up to 36 at-%. Thus, the microstructure of alloys containing up to 36% Zn consists of a single phase α and known as α -brass, while the microstructure of alloys with more than 36%Zn comprises α+β phases. Brass offers very useful properties, such as high strength, conductivity, formability, wear resistance and corrosion performance. The best combination of ductility and strength is obtained by 30 at- % Zn and, therefore, Cu–30% Zn alloys (i.e. 70:30 brass) possesses excellent deep drawability. As mentioned above, α+β brass exhibits better weldability than single-phase α-brass and, moreover, the weldability of single-phase a-brass diminishes as the Zn content of the α-brass increases. Ni–Al–bronze alloys are important naval alloys which are used extensively in propulsion and sea water handling systems. These alloys are usually cast and have very complex metallurgy. They typically contain 9–12%Al with additions of up to 6% each of Fe and Ni.

Although Cu-alloys can be welded with conventional fusion welding processes, i.e. Arc welding, they require a fast heat delivery due to their high heat conductivity, which is 10–100 times higher than that of steels and Ni alloys. Therefore, the heat input required for joining these alloys is much higher, causing quite low welding speeds.

Furthermore, several other difficulties are encountered in fusion welding of Cu-alloys with conventional joining processes, which are:

- Insufficient penetration due to the high conductivity
- High distortion
- Change of color due to oxidation
- Loss of strength in fusion zone (FZ) due to the evaporation of Zn, particularly in high Zn content alloys
- Loss of strength at the weld surface due to the formation of ZnO
- Formation of weld surface irregularities.

High power density welding processes, such as a laser or electron beam welding, can be employed to avoid some of these problems, such as distortion and insufficient penetration. However, the loss of strength in the FZ due to the evaporation of Zn cannot be overcome. On the other hand, almost all of these problems are not expected to be experienced in FSW. However, the higher heat input requirement for FSW of Cu means that the FSW must be conducted at lower welding speeds

and/or higher rotational speeds. This is particularly valid for pure Cu and not for Cu-alloys, which have lower heat conductivity than pure Cu.

2.1.3 Weld Microstructure and Hardness of Copper and Copper Alloys for FSW [2]

The heat input required for FSW of Cu-alloys is much higher than those required for other materials because of the higher dissipation of heat through the workpiece, particularly for pure Cu, this is not expected to hinder FSW of these alloys. This shortcoming can be overcome by conducting the FSW at lower welding speeds and/or higher rotation rates.

The complete dynamic recrystallization was generally observed in the Stir zone (SZ) of friction stir welded single phase and quasi-single phase pure Cu and Cu-alloys, producing fine and uniform equiaxed grains. However, this might not be the case for dual- or multiple-phase Cu-alloys. The existence of multiple-phases in these materials would complicate the plastic flow and recrystallization process during FSW.

Some variations in the grain sizes of the SZ and the tensile performance of the friction stir welded pure Cu and Cu-alloys joints were reported in the literature. The heat input plays an important role in the determination of grain size within the SZ as well as the prior thermo-mechanical state of the material, thus the microstructural aspects, such as the dislocation density and mechanical twinning.

For instance, grain sizes in the SZ can exceed the parent grain size if the peak temperatures experienced within the SZ is sufficiently high and the heat flow is not managed properly even though the weld may still be sound. But several workers reported that reduced the size of the recrystallized grains by decreasing the heat input. They also reported that the hardness increased slightly in the SZ with decreasing the grain size.

2.2 Literature Review on Friction Stir Welding of Copper Material

Pure Copper is very useful material, it has wild industrial application but the welding of copper by fusion welding process is very difficult because copper have high thermal conductivity, higher expansion coefficient and generate the oxide at melting temperature. FSW is the solid state process so all problems regarding the fusion welding process is overcome by the friction stir welding process. The mechanical property and strength of FSW of copper joint is very good. The mechanical property and microstructure of copper joint after FSW is mention in the following research paper. [13, 14, 15, 16]

2.2.1 Tool Design

Tool Material:

Tool material is very important parameter for friction stir welding. With increasing welding temperature the requirements for the tool material become more challenging. Melting point of copper material is 1083°C and Temperature during FSW of copper varies between 790-910 °C so the tool material has the higher elevated strength for the FSW of copper material. Required properties of tool materials for FSW of copper include sufficient strength at welding temperature, wear and creep resistance, fracture toughness at ambient and welding temperatures, inertness to the material to be welded, thermal stability, and good friction compatibility with the base material. [9]

Recently, several attempts have been made to join pure Cu and Cu-alloys by FSW/ FSP. It is well demonstrated that the tool material and geometry exert a significant role in the feasibility of FSW of thick copper plates. A stirring tool made of regular tool steel (i.e. H13) normally used for FSW Al-alloys cannot be used in FSW of Cu-alloys due to the fact that the filling of finely machined threads with Cu and the softening of the tool steel above 540°C, which can only be used for pure Cu up to a thickness of 3 mm. For thicker pure Cu or Cu alloys, special tools made of even higher temperature resistant alloys, are needed. They also proposed that the probe shape is an important variable for FSW thicker Cu plates and the most suitable probe shape is reported to be the MX Triflute, which is considered to be a breakthrough in welding thick Cu plates. They also investigated the effect of tool shoulder design and material on FSW of thick Cu plates and reported that the most suitable material for tool shoulder was sintered W-alloy Densimet with a plain concave contact face.

Savolainen et al. investigated double sided friction stir butt-welding of oxygen-free pure Cu and two Cu-alloys with a thickness of 10–11 mm using tools made of various materials such as H13-type tool steel, Ni-based super alloys, sintered TiC/Ni/W (2 : 1 : 1), hipped TiC/Ni/Mo (3 : 2 : 1), pure tungsten and pcBN. They reported that tools made of Ni-based super alloys are suitable for only 10–11 mm thick pure Cu and Cu-alloy, i.e. Aluminum bronze (Cu–Al–5Zn–5Sn) and not for Cu–Ni alloy (CuNi25) in double-sided butt-welding. They also pointed out that pcBN tools can be used in welding Cu–Ni alloys. However, tools made of this ceramic are very brittle and should be used with special arrangements. They also pointed out that the oxygen content of pure Cu increases during FSW, which may lead to hydrogen sickness, and machining of the joint surfaces before welding, as well as the use of shielding gas, may prove to be beneficial in preventing hydrogen sickness. More recently, tools with convex scroll shoulders made of Ni-based super alloys have, however, been proven to be most suitable for FSW of thicker Cu-alloy sections. There is evidently a potential for the convex scroll shoulder to be used in applications with other materials and thicknesses. [2]

Most of literatures mention that the tool steel performs well as FSW tool material for up to 3mm thick copper plate. Generally tool steel has good balance of abrasive resistance, strength, and fracture toughness grade. For FSW of thicken copper material (higher than the 4mm) tool material required tougher and stronger than the tool steel. Tungsten carbide and tungsten alloys are suitable as tool material for thick copper material. [14,15]

High-speed tool steel material was used for FSW of pure copper 3mm thick plate [15]. SKH9 high-speed Steel was used for FSW of 3.1mm thick C11000 copper material [14]. Using a general tool steel as the FSW tool material for FSW of 4mm thick pure copper plate [14]. Non-threaded FSW tool made up from high-speed tool steel for 3mm thick pure copper material [16]. WC-based alloy tools used for 2mm thick pure copper plate [17]

Table 2.3 Summary of tool materials and geometries used for FSW Cu and Cu-alloys [2]

Material (Cu/Zn)	Thickness (mm)	Tool material	Pin Geometry
Pure Cu	2.0	Hardened steel	Standard §
Pure Cu	5.0	-	Standard §
Pure Cu	10.0	Ni-based superalloy	MX Triflute
Pure Cu	50.0	Ni-based superalloy (Nimonic 105) (Shoulder: sintered W-alloy Densimet)	MX Triflute (convex scroll shoulder)
NAB (as -cast) UNSC95800*Brass (Cu–9Al–4.5Ni 4Fe)	10.0	Ni-based superalloy	Conical threaded (With a concave shoulder
90 : 10	3.0	Hot-work steelΦ	Slightly conical with threads
70 : 30	3.0	Hot-work steelΦ	Slightly conical with threads
70 : 30	3.0	Hot-work steelΦ	Slightly conical with threads
70 : 30	3.0	Hot-work steel¤	Standard§
63 : 37	3.0	Hot-work steelΦ	Slightly conical with threads
63 : 37	3.0	Hot-work steelΦ	Slightly conical with threads
60 : 40	2.0	-	-

* Friction stir processed plates. Φ X32CrMo3-3. ¤ X32CrMoV12-28. §Cylindrical threaded tool.

TOOL DIMENSIONS:

Tool dimension is very important factor for Friction stir welding. Tool Dimensions are varying with respect to the work piece thickness and materials. No special design was reported in previous literature for Copper to Copper joint.

In FSW tool mainly dimension of two parts is very important. One is shoulder and another is pinned/probe. It's directly affected mechanical property and microstructure of the weld. The FSW tool shoulder was generally reported the concave or flat For Copper joint. Cylindrical and tapered pin was used for copper material in previous Literature and Pin used for copper material was thread less and with thread. Pin length of the tool was generally reported 0.2 mm less than the base material thickness which gives proper plunge force and full penetration in the joint. Shoulder to pin diameter ratio reported in the range of 3 to 4 which is reported slightly higher as compare to shoulder used for aluminum and its alloys. For copper FSW joint, higher shoulder to pin diameter ratio reported because higher heat input is required for copper material because of its has high thermal conductivity and higher melting point. [15, 16, 17]

WC-based alloy tools with concaved shoulder and unthreaded probe, which had a 12 mm-diameter shoulder, 4 mm-diameter probe and 2.0mm probe height, were used for 2mm thick Commercially pure Copper [17]. For 3mm thickness of Copper joint concaved shoulder and standard right-hand threads was reported to produce joint with shoulder diameter 12mm , pin diameter 3mm and pin length 2.85 mm [15]. For 3.1mm thickness C11000 copper plate the length of the pin is designed to be 2.8mm. The diameter of the shoulder, 12mm, is about four times of that of the pin, 3mm, at its root was observed. [16] Non-threaded tool made up of high-speed tool steel whose shoulder diameter is 12 mm and pin diameter and length are 5 and 2.8 mm respectively was used for 3mm thick pure copper. [16] For 5mm thick copper joint produced with a tool which has a 25mm shoulder diameter, 5.5 pin diameter and pin length 4.8mm. [3]

Table 2.4 Summary of tool materials and geometries copper to copper butt joint by FSW

Reference Numbers of Research paper	[16]	[14]	[17]	[18]	[15]	[19]	[3]
Base material grad	Pure copper	C11000 copper	Commercially pure Cu	Commercially pure copper	Pure copper	Commercially pure copper	Copper material
Thickness of plate (mm)	3 mm	3.1mm	2mm	4 mm	3 mm thickness	5 mm	5 mm
Recommended Tool Design							
Tool Material	High-speed tool steel	SKH9 high-speed Steel	WC-based alloy	General tool steel	High-speed tool steel	-	-
Shoulder Diameter (mm)	12 mm	12mm	12 mm	-	12 mm	-	25mm
Pin profile	-	-	Unthreaded probe	-		-	-
Pin Diameter (mm)	5	3mm, at its root	4 mm	-	3	-	5.5mm
Pin length (mm)	2.8 mm	2.8mm	2	-	2.85 mm	-	4.8 mm

2.2.2 MACHINE PARAMETERS

WELDING SPEED (MM/MIN):

Welding speed is also a very important parameter for friction stir welding of copper material. Welding speed directly affect the weld property when the welding speed increases the heat input is decreased and when welding speed is decreased the heat input is increased. Combination of optimum rotational speed and welding speed gives good strength joint. Generally the welding speed was reported in the range of 25 to 400 mm/min in previous literature. [15, 16]

K. Surekha, A. Els-Botes. [16] Authors reported the Friction stir welding of high strength, high conductivity 3mm thick copper with varying travels speed from 50 to 250 mm/min and constant rotation speed 300 rpm. Experiments were conducted at different welding speed 50, 100, 150, 200 and 250 mm/min and at constant 300rpm.

The authors reported that the grain size decreases with increasing the welding speed and micro hardness increases with increasing the welding speed.

Authors also reported that the yield strength (YS), ductility and ultimate tensile strength (UTS) of the processed zone are higher compared to the base metal and the YS and UTS increased with the increase in traverse speed. At constant rotation speed, with the increase in traverse speed, the heat input and the grain size decreased and hence the mechanical properties improved. [16]

H. Khodaverdizadeh, A. Mahmoudi, A. Heidarzadeh, E. Nazari [19] authors reported FSW of 5mm thick copper at two traverse speeds of 25 and 75 mm/min at a constant rotation rate of 600 rpm (R600T25 and R600T75 samples) for study the effect of welding speed. The authors reported that the mechanical property of 75mm/min welding speed samples are good compared to 25mm/min welding speed because the increase in welding speed the grain size and heat input is reduces so the hardness is increased and tensile strength is also increased. [19]

J.J. Shen, H.J. Liu , F. Cui authors reported FSW of 3-mm-thick copper plates at the different welding speed from 25 to 150 mm/min and constant rotation rate of 600 rpm for study The influence of welding speed on microstructure and mechanical properties of the joints. FSW was conducted at a constant rotation rate of 600 rpm together with different welding speeds of 25, 50, 100, 150 and 200 mm/min [15].

In this paper authors reported that the at low heat input in FSW the hardness and tensile property value are high for copper material. When the welding speed is increases the heat input is decreases so the hardness value is increases. 25mm/min welding speed the hardness value is lower as compare to the 200mm/min welding speed

ROTATIONAL SPEED (R.P.M):

Tool rotation is very important parameter in friction stir welding. Tool rotation is directly related to heat input in weld and directly affect the weld quality. Rotational speed is 41% responsible for getting good quality in FSW. From all previous literature shows 800-1200range is an optimum range reported for Copper FSW joint. Increase in tool rotation speed causes more heat input which, in turn, enlarges the TMAZ and HAZ consequently, results in low tensile strength. But sufficient R.P.M is required to produce friction and heat.[17, 19, 20]

G.M. Xie, Z.Y. Ma and L. Geng [20] authors reported that the FSW of 5mm thick copper plate with three different rotational speed 400,600 and 800 r.p.m. and welding speed was maintain constant. In this paper authors ,investigated welding parameters, no welding defect was detected in the welds and good mechanical property achieved at 800 r.p.m.

Authors also reported Defect-free copper welds were achieved under relatively low heat input conditions with a fine-grained microstructure of 3.5–9 μm was reported at a rotation rate of 400–800 rpm for a traverse speed of 50 mm/min. The Hardness decreases with increase rotation speed and grain size in the nugget zone of the FSW copper decreased with reducing tool rotation rate. With a decreasing grain size of the nugget zone, the micro hardness and yield strength of the nugget zone increased and the ductility decreased. [20]

H. Khodaverdizadeh, A. Mahmoudi, A. Heidarzadeh, E. Nazari [19] authors reported FSW of 5mm thick pure copper material at two different rotation rates of 600 and900 rpm and constant traverse speed of 75 mm/min (R600T75 andR900T75 samples) to study the effect of rotation rate.

The authors reported that in FSW joints, the SZ shows lower hardness relative to HAZ and BM in all rotational speeds. With increasing FSW heat input condition (increasing rotation rate and decreasing traverse speed), the low hardness region widened. The FSW produced two competitive factors influencing the hardness of the SZ. The thermal exposure results in remarkable softening effect, thereby reduces the hardness of the SZ. On the other hand, the significant grain refinement resulting from FSW increases the hardness of the SZ. At higher heat input conditions i.e., Sample R900T75 the softening effect was dominant. Therefore, the hardness values of the SZ were lower than those of the sample R600T75 and a wide low hardness region was observed. Yield strength (YS), ultimate tensile strength (UTS) and hardness of Friction stir welded samples show a decrease compared to BM. It can be due to reduction of dislocation density during recrystallization. Decreasing dislocation density, lower applied stress is required to deform the material. [19]

Y.F. Sun, H. Fujii [17] authors reported FSW of 2mm thick pure copper plate at different rotational speed from 200 to 1200 r.p.m. with welding speed from 200 to 800 mm/min at 1000 to 1500 Kg axial load.

The authors observed groove-like weld defect under 1000kg load, in the stir zone due to the insufficient plastic flow when the rotation speed decreases to 700 rpm.

The authors reported the hardness in the stir zone obtained under 1000 kg is lower than that in the base metal and decreased with the increasing of the rotation speed. However, the hardness increases with higher applied load and when the applied load increases to 1500 kg, the hardness in the stir zone is higher than that in the base metals. In addition, the area of stir zone decreases when the hardness increases,

Authors also reported the yielding point increase with the decrease of the rotation speed and the improved ductility in the stir zone was obtained due to the significant annealing soft during the FSW process. While for the specimen welded under 1500 kg, the tensile specimen shows relatively higher yielding points than the base metals, which finally fractured in the base metals. For the entire specimen welded under 1000 kg, the fracture took place in the HAZ. The tensile specimen welded at1500kg 400 rpm, which fractured in the base metal. It can be found that all the specimens fracture at the locations with lowest hardness value in the samples, which matches well with the hardness measurement. [17]

P. Xue, B.L. Xiao, Q. Zhang and Z.Y. Ma. [21] Authors reported FSW of 3mm thick pure copper plate at a constant traverse speed of 50 mm/ min with different tool rotation rates of 400 and 800 rpm. Authors obtain a very low heat input, the Cu plates were first fixed in water with room temperature and additional rapid cooling with flowing water was used during the FSW process. It was defined as 400-water and 800-water, respectively. For comparison, regular FSW processes were also performed in air at the same welding parameters, and defined as 400- air and 800-air, respectively. [21]

The authors reported under the same FSW parameters, the peak temperatures of the HAZ were significantly reduced when rapid cooling by flowing water was applied during FSW. The peak temperature in the HAZ was as high as 375 °C for the 800-air FSW joint; however, it was reduced to only about 130 °C for the 400-water FSW joint.

The authors reported the higher hardness observed in the 800-water and 400-water joints. That is to say, the low heat input was achieved by enhanced heat transfer from the tool and plate into the surrounding water in this case. [21]

The authors also reported the tensile strength was obtained nearer to base metal at 400 rpm. That is to say, the low heat input in 400rpm joint in flowing water case so the hardness was measured high compare then the other. Tensile strength was high in 400-water joint because of the higher hardness. [21]

Y.M. Hwang, P.L. Fan, C.H. Lin [14] authors reported the thermal history of a workpiece undergoing Friction Stir Welding (FSW) involving butt joining of 3.1mm thick pure copper C11000. The authors conducted FSW experiments with rotational speeds from 400 to 1200 rpm and 20 to 60 mm/min welding speed

The authors reported there is no significant difference in hardness between the advancing and retreating sides. The hardness of the welded part is smaller than that of the base metal, because of dynamic recovery and dynamic recrystallization. The harnesses at the TMAZ, for welding conditions (a) ω= 800 rpm, v = 30mm/min and (b) ω= 900 rpm, v = 50 mm/min, were about 55% and 70% of the base metal before welding, respectively.

After the tensile test the authors reported the necking zone generally occurred at the mid-point of the test piece for the base metal and the weld at condition (a). By contrary, the necking zone occurred at the HAZ for the test piece at condition (b). That is because a lower hardness was obtained at the HAZ on the retreating side. The tensile test results are consistent with the hardness test results

The authors reported that the appropriate temperatures for a successful FSW process were found to be between 460 ◦C and 530 ◦C. The temperatures on the advancing side were slightly higher than those on the retreating side. [14]

TOOL TILT ANGLE (°):

Tilt angle gives higher compressive force which increase axial force. High heat input is required For FSW of copper material because copper have melting point at 1083°C so to built sufficient heat high friction is required and friction force increase with increase the axial force. Using the proper tool tilt angle increase the axial force to get better joint strength in FSW. For copper to copper FSW joint the tool tilt angle used from 1º to 3º for getting the high axial force. In cooper material tool tilt angle with the concave shoulder design gives better result. [14, 18, 20, 3]

2.2.3 MICROSTRUCTURES

Microstructures play an important role in copper to copper joint. The microstructure morphologies different in different zone at different FSW Parameter. The Parameter used in FSW is change the microstructure of stir zone (SZ) heat affect zone (HAZ) and thermo mechanical affected zone is also change. It was reported that the heat input reduces the grain size of microstructure decreases and strength of joint increase.

G.M. Xie, Z.Y. Ma, and L. Geng [20] authors achieved FSW of 5mm thick pure copper under low heat input conditions of 400–800 rpm for a traverse speed of 50 mm/min. The authors reported that the reduction in the grain size with a decreasing rotation rate is attributed to the reduced heat input. At a constant traverse speed, the decrease in the rotation rate reduced the heat input of the FSW, thereby decreasing the size of the recrystallized grains. In stir zone the grain size is increases with increasing rotation rate because heat input is increasing.

K. Surekha, A. Els-Botes [16] authors reported the FSW of 3mm thick pure copper with various traverse speed (50, 100, 150, 200 and 250 mm/min) to study the effect of welding speed.

In this paper author reported that the grain size has become finer in the FSP samples in comparison to the base metal. The grain size of the recrystallized nugget zone is determined by the dominant factor among the two factors, degree of deformation and the peak temperature attained during FSP/FSW. Fig. 2.1 a–f shows the optical images of the base metal and the stir zone of FSP samples. The grain size decreased with an increase in the welding speed because of the reduction in heat input. At 250mm/min welding speed the grain size in nugget zone is very fine compare to the other welding speed and at 50mm/min welding speed the grain size in nugget zone is high compare to other welding speed. [16]

J.J. Shen, H.J. Liu, F. Cui [15] reported FSW of 3mm thick copper plates with different welding speeds of 25, 50, 100, 150 and 200 mm/min and at constant rotational speed 600rpm. In this paper authors reported that the grain size of nugget zone was reduced with increasing the welding speed. [15]

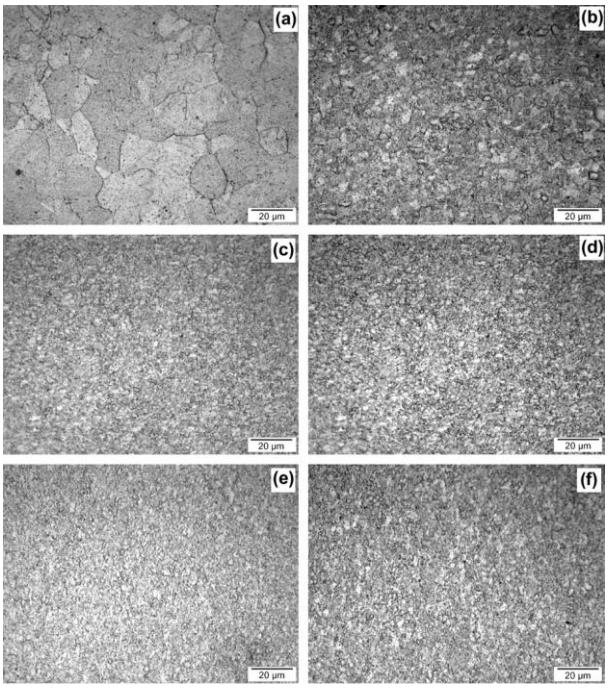

Fig. 2.1 Optical micrographs of (a) BM and (b)–(f) nugget regions of processed samples at (b) 50, (c) 100, (d) 150, (e) 200 and (f) 250 mm/min.[15]

Table 2.5 Summary of copper to copper butt joint by FSW

Research paper name	Development of high strength, high conductivity copper by friction stir processing (16)	Experimental study on Friction Stir Welding of copper metals (14)	Investigation of the welding parameter dependent microstructure and mechanical properties of friction stir welded pure copper (17)	The joint properties of copper by friction stir welding (18)	Effect of welding speed on microstructure and mechanical properties of friction stir welded copper (15)	Effect of friction stir welding (FSW) parameters on strain hardening behavior of pure copper joints (19)	Research on Friction Stir Welding and Tungsten Inert Gas assisted Friction Stir Welding of Copper (3)
Base material grade	Pure copper	C11000 copper	Commercially pure Cu	commercial pure copper	pure copper	Commercial pure copper	copper material
Thickness of plate(mm)	3 mm	3.1mm	2mm	4 mm	3 mm thickness	5 mm	5 mm
Recommended Tool Designs							
Tool Material	high-speed tool steel	SKH9 high-speed Steel	WC-based alloy	general tool steel	high-speed tool steel	-	-
Shoulder Diameter (mm)	12 mm	12mm	12 mm	-	12 mm	-	25mm
Pin profile	-	-	unthreaded probe	-		-	-
Pin Diameter (mm)	5	3mm, at its root	4 mm	-	3	-	5.5mm
Pin length (mm)	2.8 mm	2.8mm	2	-	2.85 mm	-	4.8 mm

Recommended Parameters							
Rotational Speed (rpm)	300 rpm	400 to 1200 rpm	400 to 1200rpm	1250rpm	600 rpm.	600 and 900 rpm	1000 rpm
Feed (mm/min)	50, 100, 150, 200and 250 mm/min	20 to 60 mm/min	200 to 800 mm/min	61 mm/min	25,50 ,100,150, 200mm/min	25 and 75 mm/min	80 mm/min;
Tool Tilt angle (°)	-	1	3	3	-	-	2.5º
Load (KN or kgf)	-	10 kN	1000 to 1500 kg.	-	-	-	25kN
							TIG process parameters welding amperage, I=230A; voltage, U=20V.

Table: 2.6 Summary of mechanical and microstructure testing of copper FSW

Research Paper Name	**(16)**	**(14)**	**(17)**	**(18)**	**(15)**	**(19)**	**(3)**
Base material Grad	Pure copper	C11000 copper	Commercially pure Cu	commercial pure copper	pure copper	Commercial pure copper	copper material
Thickness of Plate(mm)	3 mm	3.1mm	2mm	4 mm	3 mm thickness	5 mm	5 mm
Mechanical and Metallurgical Testing							
Tensile Strength	BS-270Mpa 50mm/min-319Mpa 100mm/min-322Mpa 150mm/min-323Mpa 200mm/min-323Mpa 250mm/min328 Mpa	50mm/min=60 % 30mm/min=70 %	1000kg1000rpm-225Mpa 1000kg900rpm-230Mpa 1000kg800rpm-239Mpa 1200kg600rpm-265Mpa 1500kg400rpm-266Mpa BS-266Mpa	87%	-	BS-234Mpa R600T25-216MPa R600T75-221Mpa R900T75-219Mpa	-
Hardness	BS-84.6HV 50mm/min-101.9 HV 100mm/min-102.5 HV 150mm/min-111.8 200mm/min-112.6 250mm/min-113.6	50mm/min=55 % 30mm/min=70 %	-	60HV to90HV	-	BS-107HV R600T25-82HV R600T75-88HV R900T75-39HV	-
%EL	BS-22 50mm/min-24 100mm/min-23	-	-	-	-	BS-47 R600T25-36 R600T75-43 R900T75-39	-

	150mm/min-23 200mm/min-23 250mm/min-23						
Grain Size	BS-19.0 µm 50mm/min-9.3 µm 100mm/min-6.1 µm 150mm/min-5.9 µm 200mm/min-3.6 µm 250mm/min-3.0 µm	-	1000kg1000rpm-24.1µm 1000kg900rpm-22.2µm 1000kg800rpm-15.4µm 1200kg600rpm-6.2 µm 1500kg400rpm-3.57µm BS-16.2µm	-	-	BS-76 µm R600T25-14 µm R600T75-9 µm R900T75-12 µm	-

III. Welding Defects in Copper FSW Welds [9]

Arbegast (2008) and Zettler et al. (2010) have analyzed and classified the welding defects occurring in aluminum alloy FSW welds, but their results are not directly applicable to copper FSW welds. Figure 2.2 shows a schematic presentation of the appearance and location of welding defects in copper FSW welds. Flash formation and plate thinning due to the effect of the tilted shoulder are not considered as welding defects in this Doctoral Thesis, but as characteristic features of FSW welds. [9]

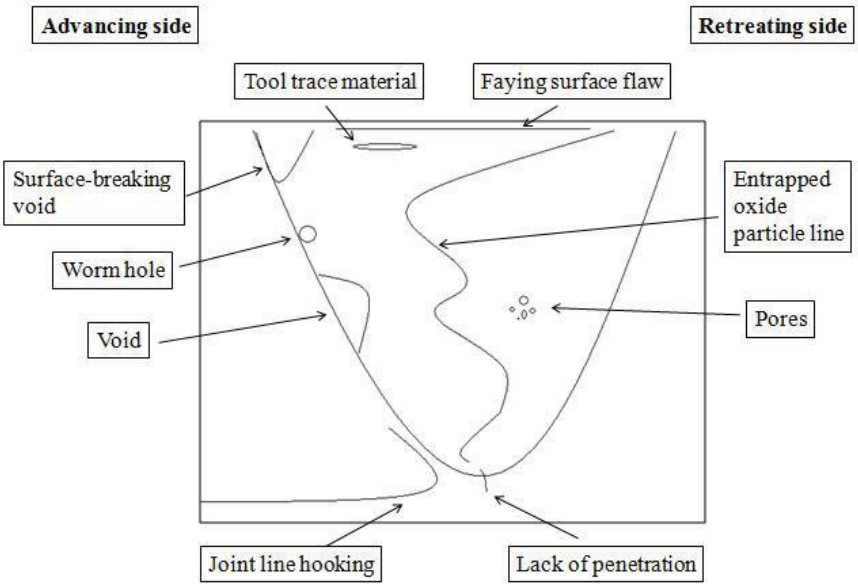

Figure 2.2 A schematic presentation of the location of different welding defects in copper FSW welds. [9]

2.3.1 Voids

Voids are volumetric, contain no material, and are aligned with the welding direction. They are generally continuous throughout the entire weld. Figure 2.3 shows a double-sided weld of Cu-DHP with a void on the advancing sides of the welds. The voids can be located on the advancing side or at the root of the weld depending on the process variables. The size of the voids varies also greatly. Voids indicate that the weld has been too cold. The temperature has not been sufficient to properly plasticize and deform the material. This is due either to a too high traverse speed, too low rotation speed, or too low plunge depth. Plate thickness variations or too wide welding gaps can also cause the formation of voids. In this work the defects known as “worm holes” are considered as voids. Worm holes are small voids which are aligned through the wall thickness direction instead of along the welding direction. [9]

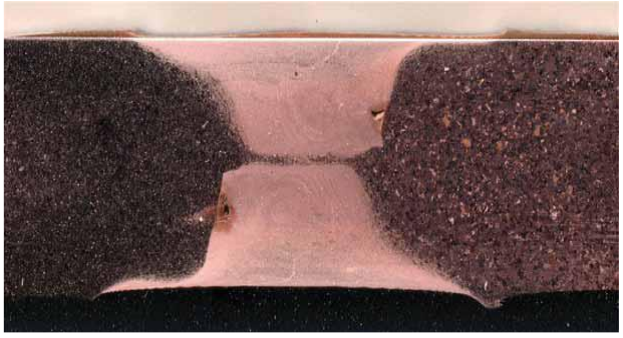

Figure 2.3 An example of a double-sided Cu -DHP FSW weld with voids on the advancing sides of the welds.

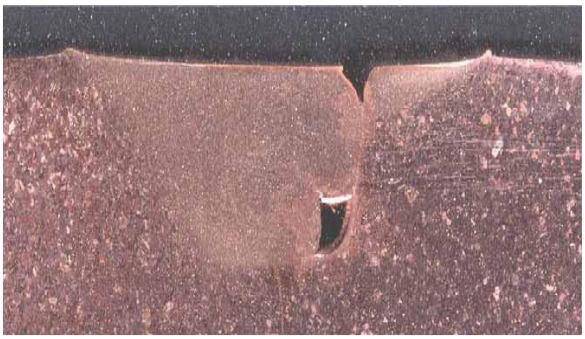

Figure 2.4 Similarity in the formation of surface-breaking and sub-surface voids in a Copper FSW weld.

Figure 2.5 LOP in a Cu-DHP weld.

Figure 2.6 Entrapped oxide particle lines in a double-sided Cu-OF FSW weld.

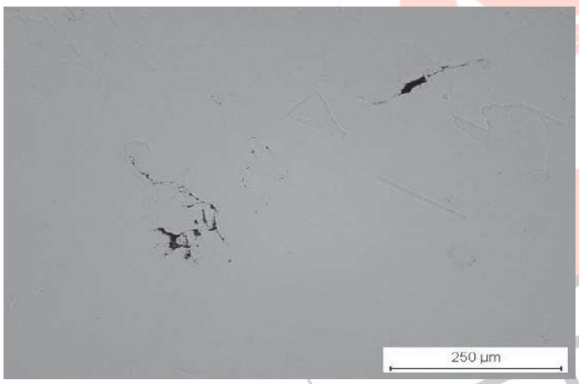

Figure 2.7 Oxide inclusions in the overlap zone of 50 mm thick copper FSW weld.

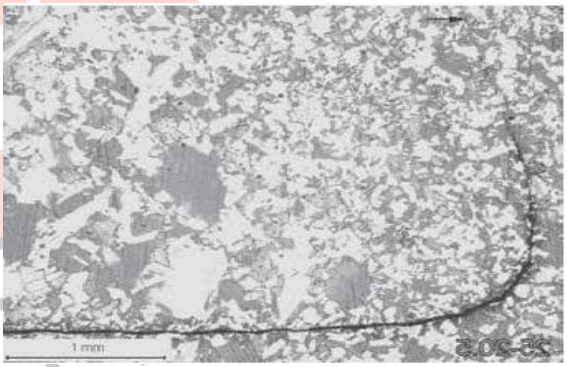

Figure 2.8 Joint line hooking in a 50 mm thick copper FSW weld.

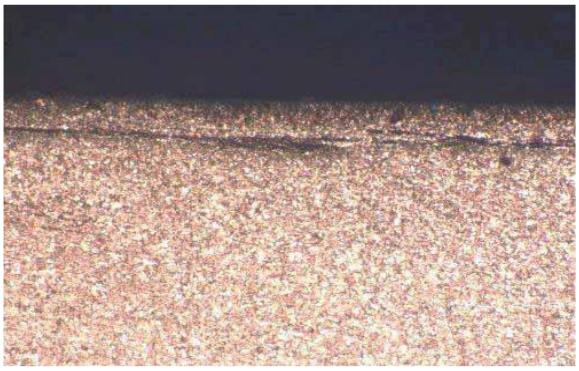

Figure 2.9 Faying surface flaw in a Cu-DHP weld

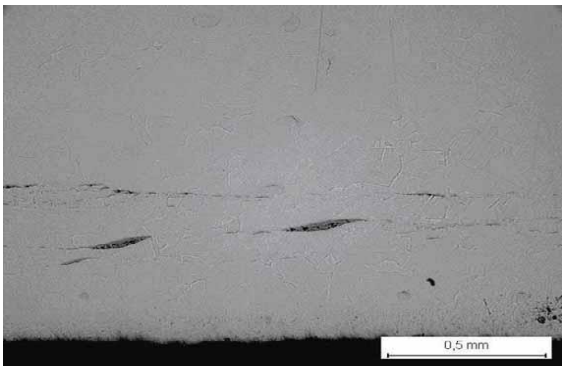

Figure 2.10 Trace material from the nickel-based superalloy Nimonic 105 tool

There are different opinions related to the definition of a void. In this work voids can be surface-breaking or sub-surface as they are closely related to each other. Figure 2.4 shows the similarity in the formation of surface-breaking and sub-surface

voids. Voids form when the amount of heat and pressure has not been adequate to fill the space behind and below the tool. [9]

2.3.2 LACK OF PENETRATION

Lack of penetration (LOP) leaves the plates at the root of the weld unjoined, though they may have some weak bonding. This type of defect is effectively a crack, which causes the structure to fracture easily due to the high stress concentration factor. It causes a reduction in tensile strength and loss of fatigue strength. The severity of the defect depends on its size. The primary reason for LOP is a too short tool probe. It can be caused also by a too low plunge depth, plate thickness variation, improper tool design, or tool misalignment in relation to the butting surfaces. It is possible to detect LOP with radiographic, ultrasonic, eddy current, or dye penetrate testing (in through-thickness welds), but no reliable NDT method is available at the moment. The only definitive method is a bend test with the root in tension. In critical applications, the weld root is recommended to be machined. Figure 2.5 shows a LOP defect in a Cu-DHP weld. [9]

2.3.3 ENTRAPPED OXIDE PARTICLES

Entrapped oxide particle lines are occasionally called “lazy S” or “kissing bond”. They consist of a semi-continuous layer of oxide particles along the joint line. The amount and connectivity of the micron-sized voids is highest at the root of the weld and diminishes towards the top of the weld. Figure 2.6 shows entrapped oxide particle lines in a Cu-OF weld.

Entrapped oxide particles are due to insufficient cleaning of the butting surfaces prior to welding or insufficient breaking and mixing of the original oxide layers on the butting faces. The formation of entrapped oxide particle lines can be prevented by decreasing the traverse speed, increasing the rotation speed, or placing the butting faces on the advancing side of the tool where more efficient mixing occurs. Improvements in the tool design can also disrupt the oxidised layers more efficiently. Entrapped oxide particles are undesirable, as they may lead to a loss of mechanical properties or cracking, although they may be tolerated in certain circumstances. Entrapped oxide particles are very difficult to detect using NDT methods. [9]

The origin of entrapped oxide particles in FSW welds of oxygen-free copper with about 40 ppm of phosphorus (Cu-OFP) was studied by Savolainen et al. (2008). It was noticed that oxide removal using nitric acid and the use of shielding gas both reduce the amount of entrapped oxide particles, and that best results are obtained when using both measures simultaneously.

The second form of entrapped oxide particles is large inclusions. The presence of oxide inclusions (smaller than 300 _m) has been noticed in FSW welds of 50 mm thick copper. They are generally found near the surface in the overlap zone of the weld. They are thought to be caused by oxidation due to welding in air and they can be possibly avoided by using shielding gas during welding. The oxide inclusions can only be seen with metallographic studies, not by NDT methods.

2.3.4 JOINT LINE HOOKING

Joint line hooking (JLH) is generally seen in lap joints, but due to the special joint geometry of the spent nuclear fuel canister weld, it is also detected at the root of the 50 mm thick copper FSW weld. An example is shown in Figure 2.8. It forms when the vertical joint line is pulled out in the horizontal direction by the material flow. It may also be due to too long tool probe or too large plunge depth. JLH was most pronounced where the circular welds overlapped. The size of the defect has been reduced from the maximum of 4.5 mm to the minimum of 1 mm by shortening the tool probe and/or by using a mirror-image tool probe. JLH can be easily detected using ultrasound, but not with radiography. [9]

2.3.5 FAYING SURFACE FLAW

According to Bird (2003), faying surface flaw is located at the top surface of the plate and it is a surface-breaking defect. It can contain oxides and it is metallurgically similar to a rolling lap. Figure 2.9 shows a faying surface flaw in a Cu-DHP weld. Colegrove et al. (2003) noticed that near the top of the weld, where the shoulder is dominant, the thin copper strip placed in the joint line (while friction stir welding aluminum) was very little disturbed by the flow. It can be assumed that the faying surface flaw is formed in a similar manner. Instead of the copper strip, it is the oxide layer from the joint line which is not properly dispersed near the tool shoulder and that is what the faying surface flaw consists of. Faying surface flaw may have harmful effects on the corrosion properties of the material. [9]

2.3.6 TOOL TRACE MATERIAL

Traces of nickel (20 ppm) were found in 50 mm thick copper FSW welds when using nickel-based superalloy Nimonic 105 as tool probe material (Cederqvist 2006). The trace material is usually located close to the surface, but it may be found anywhere in the weld. The size of the inclusions is smaller than 300 µm. They originate from tool wear caused by high temperatures and process forces. They can be detected using high-sensitivity radiography or chemical analysis. [9]

2.3.7 PORES

Copper FSW welds have been noticed to contain single pores or pore lines in all areas of the weld. Single pores are 0.1-0.5 mm in diameter, and pore lines may be up to 9 mm in length. They are due to incorrect welding parameters, especially too small tool plunge depth. They can only be detected with metallographic studies, not with NDT methods. [9]

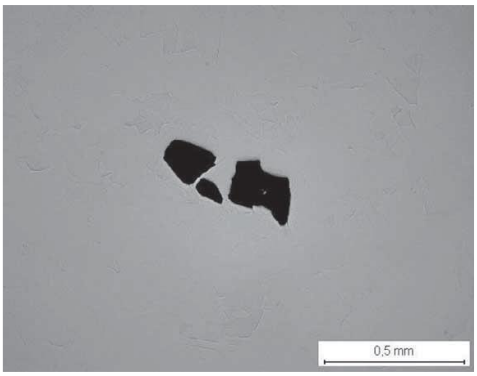

Figure 2.11 Pores in the overlap zone of a 50 mm thick copper FSW weld. [9]

CONCLUSION

In the preset investigation address the comparative study on Friction Stir Welding (FSW) of copper material. As per the literature FSW Provide the some remarkable advantage to join the copper material.

Tensile Strength (TS) values and %Elongation (%EL) values increase with increase the welding speed in FSW. At constant rotation speed, with the increase in traverse speed, the heat input and the grain size decreased and hence the mechanical properties improved. [16].At higher welding speed the tool is contact with the plate for less time so the heat input is less so when welding speed is increase the heat input is decrease and when the welding speed is decrease the heat input is increase. Combination of optimum rotational speed and welding speed gives good Tensile Strength (TS) values and %Elongation (%EL) values for copper material. In friction stir welding of the copper the nugget zone has slightly small equiaxed grain compare to parent metal. Because of the dynamic recrystallization the nugget zone grain size become small and fine. In normal FSW of pure copper small and fine grain size in nugget zone at low heat input condition and coarse grain size at high input conditions.

Generally friction stir welding not too much affect the microstructure of copper material at weld joint so mechanical property of weld joint is all most similar to base metal. This advantage of FSW process make more suitable for Copper and Copper alloy.

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