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Experimental investigation on friction stir welding of copper alloys

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Abstract

In this paper, the Friction stir welding successfully applied to join copper alloy and it was found that the defect free weld zone was formed with the condition of 800 rpm and 60 mm/min. The grain structure near weld zone was very different from that of the base metal. Heat affected zone (HAZ) were characterized by grain growth and stir zone had fine and equiaxed grain structure. The Slightly softening region was formed in the weld zone in spite of smaller grain size compare to that of base metal. Hardness of FSW copper weld zone mainly depended on the density of dislocation rather than grain size. Hardness variation also existed in the stir zone from the upper to the lower region with thermal and mechanical conditions and transverse tensile strength of FSW copper joint reached the 87% of tensile strength of base metal.

Keywords: Friction Stir Welding, Copper Alloys, Microstructure Studies, improvement in Mechanical Properties

1. Introduction

The Friction Stir Welding (FSW) technique was invented by The Welding Institute (TWI) in 1991 [1]. Since then, the material flow mechanism during welding and the microstructures of the welds have been discussed vigorously. The FSW process is executed while the materials are in a solid state, thus preventing many of the metallurgical problems that occur with conventional fusion welding, such as distortion, shrinkage, porosity and splatter. Furthermore, improved mechanical properties can also be achieved using this technique. Due to increasing demand for lightweight parts and environmental protection, [2] applied this new welding technology to aluminum products in automotive and aerospace industries. In particular, [3] used the FSW technique to easily weld 2000 and 7000 grade aluminum alloy sheets, which are traditionally difficult to weld with fusion welding.

Few papers on the FSW process discussed the temperature history (such as the temperature range and other forming conditions for a successful FSW process) in a pure copper work piece, where the melting point and material properties of the copper are significantly different from those of aluminum alloys. In this paper, FSW experiments using pure C11000 copper will be discussed, along with the process control required for a successful FSW process. The Welding of copper is usually difficult by conventional fusion welding processes because the copper has the high. Thermal diffusivity, which is about 10 to 100 times higher than in many steels and nickel alloys. The hear input required is much higher than in almost any other material, and weld speeds are quiet low. To overcome these problems, the FSW which is one of the solid state welding techniques is applied to the joining of copper. In this present study we explored the friction stir welding of copper. This study especially characterized and compared the microstructures of the copper base metal with those of the residual FSW zones using optical metallographic (OM) and transmission electron microscopy (TEM). Micro hardness profiles through the weld zone and corresponding tensile strength test data were also correlated with these microstructures. The basic concept of FSW is very simple. A non-consumable rotating tool with a specially designed pin and shoulder is inserted into the abutting edges of sheets or plates to be joined and traversed along the line of joint. The two primary functions of tools are heating of work piece and stirring/intermixing of material to produce the joint.

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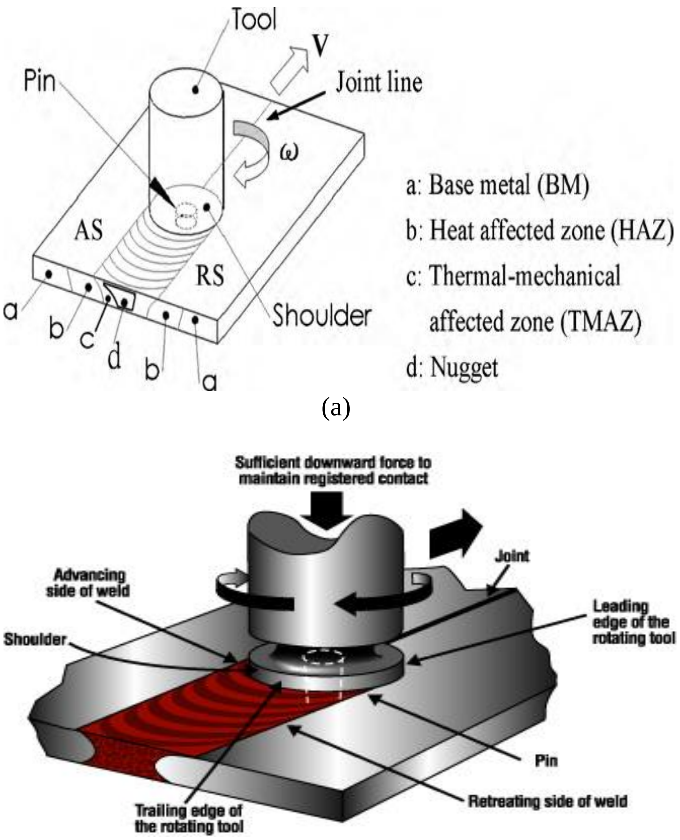


(a)

(b)

Figure 1(a)-(b) - Schematic diagram of FSW [1]

The heating is accomplished by friction between the tool and the work piece. During FSW process, the material undergoes intense plastic deformation at elevated temperature, resulting in the generation of fine and equiaxed recrystallized grains [4]. Heat generated by friction and deformation brings the material into a malleable state that promotes the forward displacement of the tool with the material flowing from the front to the back of the tool where it cools down, The weld is asymmetric since on one side of the weld, called the advancing side, the rotation of the tool is parallel to the advancing direction, while on the other side called the retreating side, the rotation is opposite to the direction of translation of the tool. The stirring of the tool minimizes the risk of having excessive local amounts of inclusions, resulting in a homogenous and void-free weld. Since the amount of heat supplied is smaller than during fusion welding, heat distortions are reduced and thereby the amount of residual stresses [5].

2. Literature Review

The weld quality is very dependent on the welding parameters such as tool rotation rate, the advancing speed and the tool geometry. A FSW joint consists of the various zones involving different microstructures and mechanical properties. The heat affected zone (HAZ) is the most distant from the joint center line. It is not deformed during the process but the microstructure evolves due to the welding thermal cycles, influencing the mechanical properties. The thermo-mechanically affected zone (TMAZ) and the nugget or stir zone (SZ) are highly deformed by the material rotational flow. The grains in the SZ are equiaxed with a much smaller size (several pm) than the base material. Under some welding conditions so-called onion rings are observed in the SZ [6].

2.1 Material flow and mechanism of joining

Recent literature and experimental works have provided significant insight about several features of materials flow during FSW and the joining process. Material flow occurs through the retreating side and the transport of the plasticized material behind the tool forms the welded joint. Three types of flow affect the overall transport of plasticized materials during FSW.

- First a slug of plasticized material rotates around the tool. This motion is driven by the rotation of the tool and the resulting friction between the tool and the work-piece.
- Another rotational motion of the threaded pin tends to push material downward close to the pin which drives an upward motion of an equivalent amount of material somewhat farther away.
- There is a relative motion between the tool and the work-piece. The overall motion of the plasticized material and the formation of the joint results from the simultaneous interaction of these three effects.

Several plastic flow models have been developed for understanding the material flow phenomena of FSW. These have been used to predict velocities around the tool pin. The velocities have also been estimated from strain rates which, in turn, were obtained from the correlation between grain-size and strain rate [7]. Comparison of the shape of the TMAZ predicted by flow models with microstructural observation has shown satisfactory match. Good agreement between the torque values obtained using dynamometers and the computed values from the flow models for 3ML stainless steel [8], 1 018 Mn steel [9] and Ti-6AI-4V alloy [10] indicates the usefulness of the models to understand the FSW process. Since torque is a measure of the shear stress on the tool and since the shear stress on the work-piece is responsible for both heat generation [11] and plastic flow, validation of the model predictions by experiments indicates that it is appropriate to use the models for the estimation of several important parameters. Though numerical modeling of plastic flow can aid tool design and the optimization of weld quality, there does not appear to have been an application of models towards the prediction of practical processing maps [12]. Arbegast et at. [13] Suggested that resultant microstructure and metal flow features of a friction stir weld closely resemble hot worked microstructure of typical aluminum extrusion and forging. Therefore, the FSW process can be modeled as a metalworking process in terms of five conventional metal working zones:

- Preheat Zone
- Initial deformation,

- Extrusion,
- Forging, and
- Post heat/cool down

The material flow during FSW is quite complicated and the understanding the phenomena of deformation process is difficult. It is important to point out that there are many factors that can influence the material flow during FSW. These factors include tool geometry (pin and shoulder design, relative dimensions of pin and shoulder), welding parameters (tool rotation rate and direction, traverse speed, plunge depth, spindle angle), material types, work piece temperature, etc. the material flow within the nugget during FSW consists of several independent deformation processes also [14].

2.2 Factors Affecting FSW

Friction Stir Welding depends upon various factors that affect the material flow pattern and temperature distribution which in turn affects the microstructural evolution of material.
Few major factors affecting FSW are—

1. Tool Geometry
2. Welding Parameters
3. Joint Design
4. Tool Tilt and Plunge Depth

2.3 Tool Geometry

The tool geometry has the highest impact on FSW. The tool geometry plays a critical role in material flow and hence the welding quality and maximum welding speed of the tool depends upon the design of the tool. As mentioned earlier, the tool has two primary functions [15] such as localized heating And material flow. The friction between the shoulder and workpiece results in the biggest component of heating. From the heating aspect. The relative size of pin and shoulder is important, and the other design features are not critical. The uniformity of microstructure and properties as well as process loads is governed by the tool design. Generally a concave shoulder and threaded cylindrical pins are used. The concave shoulder profile [16] acts as an escape volume for the material displaced by the pin and prevents material from extruding out of the sides of the shoulder. Maintains downwards pressure and hence good forging of the material behind the tool

2.4 Welding Parameters

For FSW, two parameters are very important—

(a) Tool rotation rate (how fast the tool rotates in clockwise or counter clockwise direction).

(b) Tool traverse speed (how quickly it traverses the interface) along the line of joint. The rotation of tool stirs and mixes the material around the rotating pin and the translation of tool moves the stirred material from the front to the back of the pin and finishes welding process. As temperature generated in FSW is due to friction between tool and material, so the higher tool rotation rates generate higher temperature because of higher friction heating and result in more intense stirring and mixing of material. A monotonic increase in heating with increasing tool rotation rate is not expected as the coefficient of friction at interface will change with increasing tool rotation rate. Similarly, the decrease in traverse speed results in generating higher temperatures. These parameters are optimized such that weld will have a sufficiently high heat input to ensure adequate material plasticity but not so high that the weld properties, are excessively deteriorated. In addition to the tool rotation rate and traverse speed, another important process parameter is the angle of spindle or tool tilt with respect to the workpiece surface. A suitable tilt of the spindle towards trailing direction ensures that the shoulder of the tool holds the stirred material by threaded pin and move material efficiently from the front to the back of the pin. Further, the insertion depth of pin into the work pieces (also called target depth) is important for producing sound welds with smooth tool shoulders. The insertion depth of pin is associated with the pin height. When the insertion depth is too shallow, the shoulder of tool does not contact the original workpiece surface. Thus, rotating shoulder cannot move the stirred material efficiently from the front to the back of the pin, resulting in generation of welds with inner channel or surface groove. [17-19].

2.5 Joint Design

The most common joint configurations for FSW are butt and lap joints. In butt Joint, two plates or sheets with same thickness are placed on a backing plate and clamped firmly to prevent the abutting joint faces from being forced apart. In lap joint two lapped plates or sheets are clamped on a backing plate. A rotating tool is vertically plunged through the upper plate and into the lower plate and traversed along desired direction, joining the two plates. In order to produce effective friction stir welded lap joints sufficient metallurgical and mechanical properties must be obtained by a nugget area as wide as possible together with satisfactory nugget integrity [17]. Cylindrical pins allow obtaining large nugget areas because of the large area they present at the sheet-sheet interface. Apart from butt and lap joint configurations, other types of joint designs, such as fillet joints, are also possible as needed for some engineering applications. Preheating or cooling can also be important for some specific FSW processes. For materials with high melting point such as steel and titanium or high conductivity such as copper, the heat produced by friction and stirring may be not sufficient to soften and plasticize the material around the rotating tool. Thus, it is difficult to produce continuous defect-free weld. In these cases, preheating or additional external heating source can help the material flow and increase the process window. On the other hand, materials with lower melting point such as aluminum and magnesium [18].

2.6 Tool Tilt and Plunge Depth

A suitable tilt of the spindle towards trailing direction ensures that the shoulder of the tool holds the stirred material by threaded pin and move material efficiently from the front to the back of the pin. Tilting the tool by 2-4 degrees, such that the rear of the tool is lower than the front, has been found to assist this forging process.

The plunge depth is defined as the depth of the lowest point of the shoulder below the surface of the welded plate and has been found to be a critical parameter for ensuring weld quality [19]. The insertion depth of pin is associated with the pin height. When the insertion depth is too shallow, the shoulder of tool does not contact the original workpiece surface. Thus, rotating shoulder cannot move the stirred material efficiently from the front to the back of the pin, resulting in generation of welds with inner channel or surface groove. When the insertion depth is too deep, the shoulder of tool plunges into the workpiece creating excessive flash. In this cases a concave weld is produced, leading to local thinning of the welded plates.

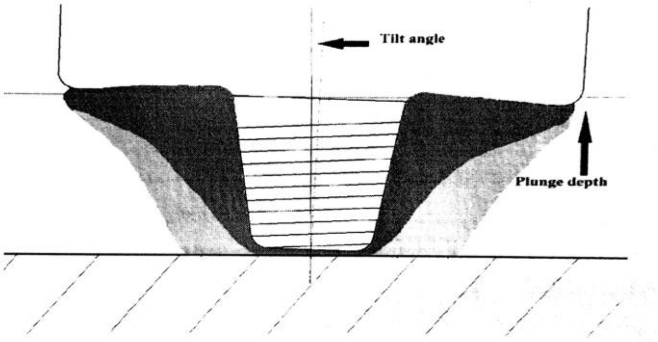


Figure 2: Plunge depth &Tilt angle

A survey of the researches which have been undertaken in this research area is outlined in this chapter. The materials which have been joined, similar or dissimilar, metallic or non-metallic will be discussed in relation to the welding conditions and parameters that gave different results. Here a brief discussion is provided and details will be given in the following sub topics. Traditional copper welding methods are associated with defects like porosity and voids, distortion, hot cracking and liquation cracking. Proper selection of FSW parameters results in a perfect joint which could be stronger than the base materials. Process parameters as well as tool geometry are the key factors that influence the soundness of the joint produced. Bahemmatet. et al recognized the importance of tool geometrical parameters which are height, shape, pin and shoulder that affect both the metal flow and the heat generation due to frictional forces developed.[20-23] Use of the proper tool gives the best results in an FSW weld. Traverse speed and rotational speed are factors that need to be taken into consideration when selecting welding parameters since these parameters determine the strength and overall performance of the joint.

2.7 Copper and its alloys

The similarity in external appearance of the various alloys, along with the different combinations of elements used when making each alloy, can lead to confusion when categorizing the different compositions. There are as many as 400 different copper and copper-alloy compositions loosely grouped into the categories: copper, high copper alloy, brasses, bronzes, copper, copper–nickel–zinc (nickel silver), copper, and special alloys. The table 2 shows the principal alloying element for four of the more common types used in modern industry, along with the name for each type. Historical types, such as those that characterize the, are vaguer as the mixtures were generally variable. Copper alloys are metal that have as their principal component. They have high resistance against. The best known traditional types are, where is a significant addition, and, using instead. Both these are imprecise terms, both having been commonly referred to as in the past. Copper is the oldest metal used by man. Its use dates back to prehistoric times. Copper has been mined for more than 10,000 years with a Copper pendant found in current day Iraq being dated to 8700BC. By 5000BC Copper was being smelted from simple Copper Oxides. Copper is found as native metal and in minerals cuprite, malachite, azurite, chalcopyrite and bornite. It is also often a by-product of silver production. Sulphides, oxides and carbonates are the most important ores. Copper and Copper alloys are some of the most versatile engineering materials available. The combination of physical properties such as strength, conductivity, corrosion resistance, machinability and ductility make Copper suitable for a wide range of applications. These properties can be further enhanced with variations in composition and manufacturing methods.

The largest end use for Copper is in the building industry. Within the building industry the use of copper based materials is broad. Construction industry related applications for Copper include:

- Roofing
- Cladding
- Rainwater systems
- Heating systems
- Water pipes and fittings
- Oil and gas lines
- Electrical wiring

2.8 Copper Application

The building industry is the largest single consumer of Copper alloys. The following list is a breakdown of Copper consumption by industry on an annual basis:

- Building industry – 47%
- Electronic products - 23%
- Transportation - 10%
- Consumer products - 11%
- Industrial machinery - 9%

There are around 370 commercial compositions for Copper alloys. The most common alloy tends to be C106/ CW024A -

the standard water tube grade of Copper. World consumption of Copper and Copper alloys now exceeds 18 million tonnes per annum.

2.9 Copper Designations

The table 1 shows the identifying chemical compositions. Property requirements are covered in EN, ASTM, government and military standards for each composition. The alloy designation system used in the UK and across Europe uses a 6 character alpha-numeric series. The 1st letter is C for Copper-based material the second letter indicates the product form
B = Ingot for re-melting to produce cast products
C = Cast products
F = Filler materials for brazing and welding
M = Master Alloys
R = Refined unwrought Copper
S = Scrap
W = Wrought products
X = Non-standard materials.

There is then a 3 digit number between 001 and 999 with the numbers being in groups as shown in the table below there is then a letter indicating the Copper or alloy grouping, also shown in the table-1.

Table- 1: Copper Designation

Number Series	Letters	Materials
001 – 099	A or B	Copper
100 – 199	C or D	Copper Alloys, Min. 95% Cu
200 – 299	E or F	Copper Alloys, <95% Cu
300 – 349	G	Copper-Aluminium Alloys
350 - 399	H	Copper-Nickel Alloys
400 - 449	J	Copper-Nickel-Zinc Alloys
450 - 499	L or M	Copper-Tin Alloys

Table 2 - Classification of copper and its alloys

Family	Principal alloying element	UNS numbers
Copper alloys, brass	Zinc (Zn)	C1xxxx–C4xxxx, C66400–C69800
Phosphor bronze	Tin (Sn)	C5xxxx
Al-bronzes	Aluminum (Al)	C60600–C64200
Silicon bronzes	Silicon (Si)	C64700–C66100
Copper nickel, nickel silvers	Nickel (Ni)	C7xxxx

3. Properties of copper alloys

Key Properties of Copper Alloys Copper is a tough, ductile and malleable material. These properties make copper extremely suitable for tube forming, wire drawing, spinning and deep drawing. The other key properties exhibited by Copper and its alloys include:

- Excellent heat conductivity
- Excellent electrical conductivity
- Good corrosion resistance
- Good bio fouling resistance
- Good machinability
- Retention of mechanical and electrical properties at cryogenic temperatures
- Non-magnetic Other Properties
- Copper and Copper alloys have a peculiar smell and disagreeable taste.
- These may be transferred by contact and therefore should be kept clear of foodstuffs, although some cooking pans.

3.1 Corrosion resistance

All Copper alloys resist corrosion by fresh water and steam. In most rural, marine and industrial atmospheres Copper alloys are also resistant to corrosion. Copper is resistant to saline solutions, soils, non-oxidising minerals, organic acids and caustic solutions. Moist ammonia, halogens, sulphides, solutions containing ammonia ions and oxidising acids, like nitric acid, will attack Copper. Copper alloys also have poor resistance to inorganic acids. The corrosion resistance of Copper alloys comes from the formation of adherent films on the material surface. These films are relatively impervious to corrosion therefore protecting the base metal from further attack. Copper Nickel alloys, Aluminium Brass, and Aluminium Bronzes demonstrate superior resistance to saltwater corrosion.

3.2 Electrical conductivity

The electrical conductivity of copper is second only to silver. The conductivity of Copper is 97% of the conductivity of Silver. Due to its much lower cost and greater abundance, Copper has traditionally been the standard material used for electricity transmission applications. However, weight considerations mean that a large proportion of overhead high voltage power lines now use Aluminium rather than Copper. By weight, the conductivity of Aluminium is around twice that of Copper. The Aluminium alloys used do have a low strength and need to be reinforced with a galvanised or Aluminium coated high tensile steel wire in each strand. Although additions of other elements will improve properties like strength, there will be some loss in electrical conductivity. As an example a 1% addition of Cadmium can increase strength by 50%. However, this will result in a corresponding decrease in electrical conductivity of 15%.

3.3 Surface oxidation

Most Copper alloys will develop a blue-green patina when exposed to the elements outdoors. Typical of this is the colour of the Copper Statue of Liberty in New York. Some Copper alloys will darken after prolonged exposure to the elements and take on a brown to black colour. Lacquer coatings can be used to protect the surface and retain the original alloy colour. An acrylic coating with benzotriazole as an additive will last several years under most outdoor, abrasion-free conditions.

3.4 Yield strength

The yield point for Copper alloys is not sharply defined. As a result it tends to be reported as either a 0.5% extension under load or as 0.2% offset. Most commonly the 0.5% extension yield strength of annealed material registers as approximately one-third the tensile strength. Hardening by cold working means the material becomes less ductile, and yield strength approaches the tensile strength.

3.5 Joining

Commonly employed processes such as brazing, welding and soldering can be used to join most Copper alloys. Soldering is often used for electrical connections. High Lead content alloys are unsuitable for welding. Copper and Copper alloys can also be joined using mechanical means such as rivets and screws.

4. Welding of Copper Alloys using Friction Stir Welding

Friction stir welding tool consists of a tool shoulder and a pin. Shoulder produces a majority of the deformational and frictional heat to the surface and subsurface regions and applies a forging pressure to welds, while the pin produces a majority of the heat in the thick work pieces and transports the material around it. Different tool designs will modify their effects on weld properties.

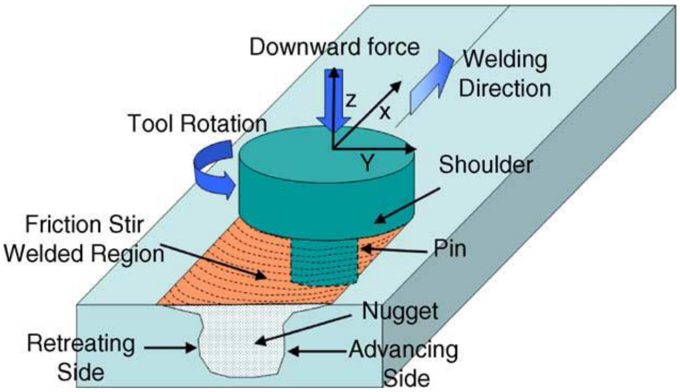


Figure 3 - Schematic diagram of FSW [5]

Tool geometry is the most influential aspect of process development. The tool geometry plays a critical role in material flow and in turn governs the traverse rate at which FSW can be conducted. An FSW tool consists of a shoulder and a pin as shown schematically in Fig. 2. As mentioned earlier, the tool has two primary functions: (a) localized heating, and (b) material flow. In the initial stage of tool plunge, the heating results primarily from the friction between pin and work piece. Some additional heating results from deformation of material. The tool is plunged till the shoulder touches the work piece. The friction between the shoulder and work piece results in the biggest component of heating. From the heating aspect, the relative size of pin and shoulder is important, and the other design features are not critical. The shoulder also provides confinement for the heated volume of material. The second function of the tool is to 'stir' and 'move' the material. The uniformity of microstructure and properties as well as process loads are governed by the tool design. Generally a concave shoulder and threaded cylindrical pins are used.

5. Mechanical Properties of Friction Stir Welding

The most commonly used testing methods to determine the properties of spot welds are lap-shear tension test, cross-tension test, fatigue test and micro hardness. Lap-shear test is a fast, convenient and practical method for evaluating weld property. This test was used in almost all current literature when considering the mechanical properties.
FSW/FSP results in significant micro structural evolution within and around the stirred zone, i.e., nugget zone, TMAZ, and HAZ. This leads to substantial change in post weld mechanical properties. In the following sections, typical mechanical properties, such as strength, ductility, fatigue, and fracture.

5.1 Strength and ductility

Mahoney investigated the effect of FSW on room-temperature tensile properties of C51000
.Tensile specimens were machined from the nugget zone in two directions, parallel (longitudinal) and normal (transverse) to the weld. Longitudinal tensile specimens contained only fully recrystallized grains from the nugget zone, whereas transverse tensile specimens contained microstructures from all four zones, i.e., parent material, HAZ, TMAZ, and nugget zone. Summarizes the longitudinal tensile properties of nugget zone. As-welded samples show a reduction in yield and ultimate strengths in the weld nugget, while elongation was unaffected. Mahoney attributed the reduced strength to the reduction in pre-existing dislocations and the elimination of the very fine hardening precipitates. In order to recover the lost tensile strength of the nugget zone, conducted a post weld aging treatment (121 8C/24 h) on the FSW sample, the aging treatment resulted in recovery of a large portion of the yield strength in the nugget, but at the expense of ultimate strength and in particularly ductility. The increase in the yield strength of post weld samples was attributed to the increase in the volume fraction of fine hardening precipitates, whereas the reduction in the ductility was accounted for by both the increase in the hardening precipitates and the development of precipitate-free zones (PFZs) at grain boundaries. The tensile properties in transverse orientation of FSW C51000 are summarized in. Compared to unwedded parent metal, samples tested in transverse direction show a significant reduction in both strength and ductility. Furthermore, the strength and ductility observed in transverse orientation are also substantially less than those in longitudinal orientation. The post weld aging treatment did not restore any of the strength to the as-welded condition and further reduced ductility. In

both as-welded and aged condition, failures occurred as shear fracture in the HAZ. As reported before, the tensile specimens in the transverse orientation cover four different microstructures, i.e., parent material, HAZ, TMAZ, and nugget zone. The observed ductility is an average strain over the gage length including various zones. The different zones have different resistances to deformation due to differences in grain size and precipitate size and distribution as discussed in Section 4. The HAZ has the lowest strength due to significantly coarsened precipitates and the development of the FPZs. Thus, during tension, strain occurs mainly in the HAZ, the low-strength HAZ locally elongated to high levels of strain (12–14%), eventually resulting in necking and fracture, whereas the nugget zone experiences only 2–5% strain. Therefore, fracture always occurred in the HAZ, resulting in a low strength and ductility along transverse orientation of the weld.

5.2 Fatigue

For many applications, like aerospace structures, transport vehicles, platforms, and bridge constructions, fatigue properties are critical. Therefore, it is important to understand the fatigue characteristics of FSW welds due to potentially wide range of engineering applications of FSW

5.3 Fracture toughness

It is usually accepted that all welded structures go into service with flaws ranging from volume defects like porosity, non-metallic inclusions to different planar defects like cracks induced by hydrogen or hot tearing. There are standards for acceptability of the welds pertaining to different inspection codes. The non-acceptable flaws must be repaired before the weld is put into service. Most existing codes cater toward weld elements made by conventional welding techniques. FSW is generally found to produce defect-free welds. However, no established code exists so far for FSW. Considering potential applications of FSW, there is a critical need for proper evaluation of the fracture behavior of the friction stir welds. 2.8 Work Piece Material

A commercial C51000 ASTM B103 plate which is solution heat treated, stress relieved by stretching then artificially aged is used as specimen for FSW. Chemical composition of work piece material is given in table

Table 3 – Chemical composition of C51000 (ASTM B103)

S.No	Element	Wt.%
1	Tin	4.2-5.8
2	Phosphorus	0.030-0.35
3	Iron, max	0.1
4	Lead, max	0.05
5	Zinc, max	0.3
6	Copper	89.75

5.4 FSW Tool Materials

Tool materials that can be applied during friction stir welding. These materials include tool steel for joining copper, aluminium and magnesium alloys; Polycrystalline cubic boron nitride (PCBN) tools for hard steel and titanium; tungsten based tools for steel and titanium alloys as well.

From the literature reviewed above, it has been shown that HSS, Die/Tool steels and Tungsten Carbide tools are commonly used in FSW of different material types. Straight tool profiles have always yielded best results as outlined by Palanivel and Koshy also carried out tests using HCH Cr steel tool. Five different tool pin profiles, (SS), (TS), (SH), (SO) and (TO) were identified. All the tools, the straight square pin profile yielded the best results at a speed of 60 mm/min in joining C69800.In another research friction stir welding tool pins like straight cylindrical, cylindrical taper, threaded cylindrical, square, and triangular with combinations of 15, 18, and 21mm shoulders were used by Elangovan and Balasubramanian to join copper alloy. In their investigation, square pins provided superior tensile properties with least number of defects.

Table 4 – Chemical composition of HSS M2 Steel

S.No	Element	Wt.%
1	C	0.78-0.88
2	Si	0.20-0.40
3	Mn	0.20-0.40
4	P	0.35
5	S	0.35
6	Cr	3.75-4.50
7	Mo	4.50-5.50
8	V	1.60-2.20
9	W	5.50-6.75

5.5 High speed steel grades

M2 is a high-speed steel in tungsten–molybdenum series. The carbides in it are small and evenly distributed. It has high wear resistance. After heat treatment, its hardness is the same as T1, but its bending strength can reach 4700 MPa, and its toughness and thermo plasticity are higher than T1 by 50%. It is usually used to manufacture a variety of tools, such as drill bits, taps and reamers. Its decarburization sensitivity is a little bit high.

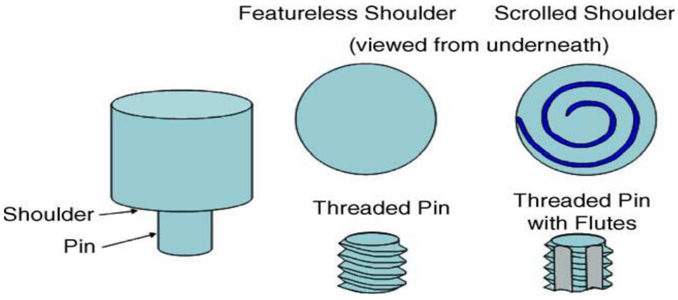


Figure 4 - FSW Tool tip Types

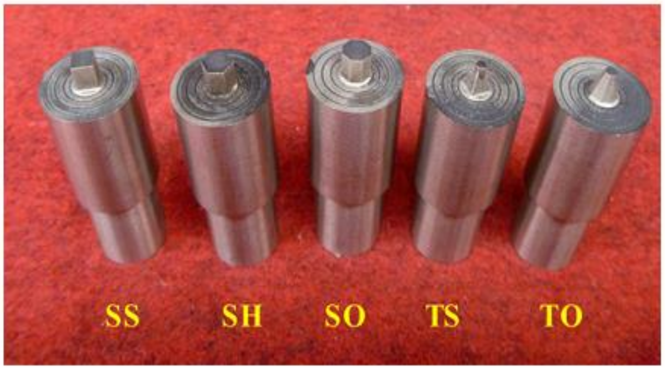


Figure 5 - Tool Pin Profiles

5.6 Microstructure Analysis

Microstructure of the welded joint achieved using the FSW procedure consists of: a) weld nugget, b) thermo mechanically affected zone (TMAZ), c) heat-affected zone (HAZ), and
d) The parent metal. Depending on the microstructure of welded joint, there are three different mechanical properties of the weld. The present research is focused on welding copper and its alloys. Grains of the base material (copper) are elongated in shape and their size is about 30 microns.
Microstructure of the weld nugget is very fine, with a grain size of about 11 microns. This seam zone is characterized by dynamic recrystallization due to the influence of tribological processes (mechanical friction and plastic deformation), which results in higher hardness compared to the base material.

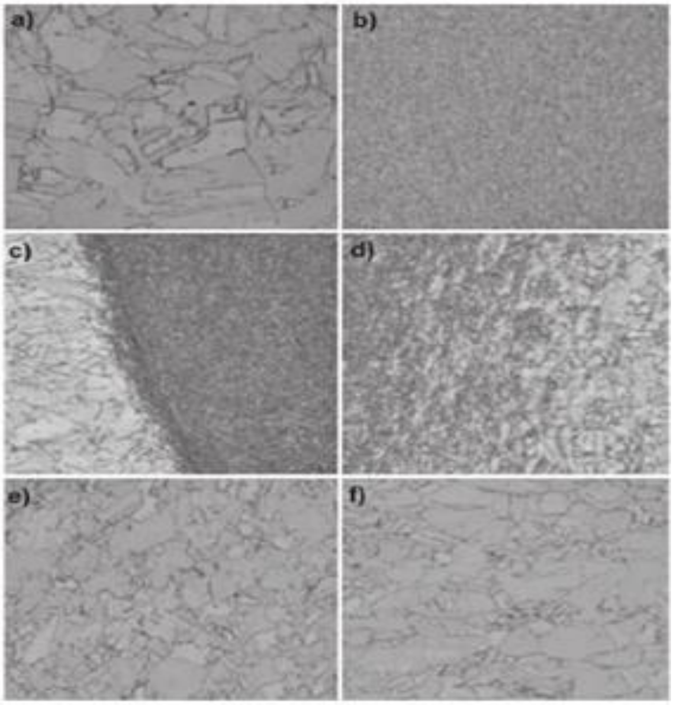


Figure 6: Microstructure of the welded copper joint
(a) base metal, (b) Nugget zone,(c) TMAZ of TMAZ,(d) TMAZ of RS, (e) HAZ of AS, (f) HAZ of RS

6. FSW Experimental Set-Up

A indigenous developed friction stir welding machine (R V machine tools, FSW-4T-HYD) (15 hp; 3000 rpm; 25 kN) as shown in figure 7 is used for welding process. This machine has a vertical spindle to hold the tool and a fixture with four hydraulic actuated clamps and a backing plate with groove (200mm x 80mm) to hold the work piece. Work holding fixture can move in X, Y and Z axis. Groove on backing plate is meant to strongly hold the work piece. Maximum operational speed of spindle is 3000 rpm. Rotational speed, welding speed and tool tilt angle can be altered easily but welding force cannot be changed on this machine.

Figure 7 –Friction stir welding machine (DTU)

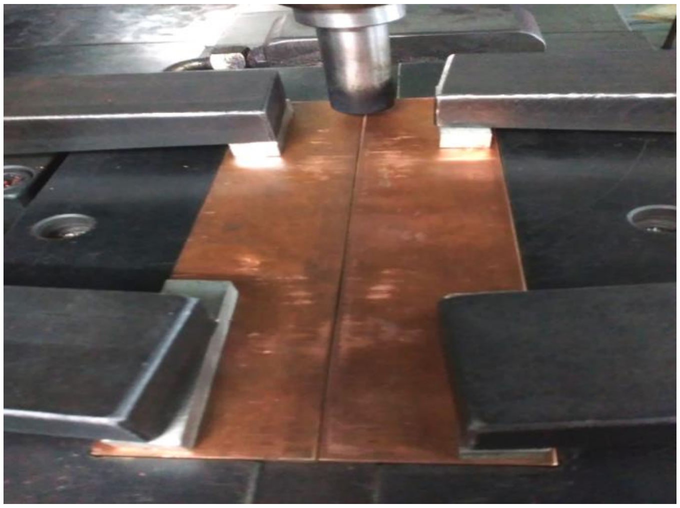


Figure 8 –Tool and work holding device

6.1 Experimental procedure

The 3mm thick plates were cut into the required sizes two plates (200 mm X 40mm) by power hacksaw cutting and milling. Square butt joints were prepared by FSW machine which is mention in section 3.1. The spindle of this selfdesigned FSW apparatus can spin with rotational speeds from (800 rpm – 1200 rpm), and the fixture table, driven by a servomotor, can move with speeds 60 mm/min. Before welding, the work piece is polished and cleaned with acetone on the welding surface and is then placed on a backing plate and clamped rigidly by an anvil along the welding direction to prevent lateral movement (Figure 8). The dimension of the C11000 copper work piece is 200mm×40mm×3mm (L×W×H). The geometry and dimensions of the tool, made of M2 high-speed steel, are shown in Fig. 3. A concave part close to the shoulder is specially designed to prevent massive heat loss from the shoulder to the shank of the tool. Because the thickness of the work piece is only 3mm, the length of the pin is designed to be 2.7mm. The diameter of the shoulder, 19.95mm, is about four times of that of the pin, 4mm, at its root. An inclination angle of 1.5◦, with respect to the welding tool and the normal vector of the work piece, was set before welding to allow the tool to smoothly traverse the work piece.

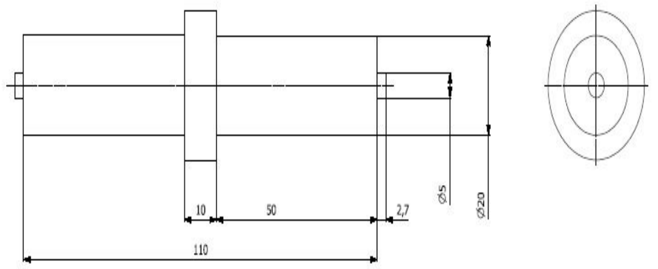


Figure 9 - Dimensions of the tool and pin

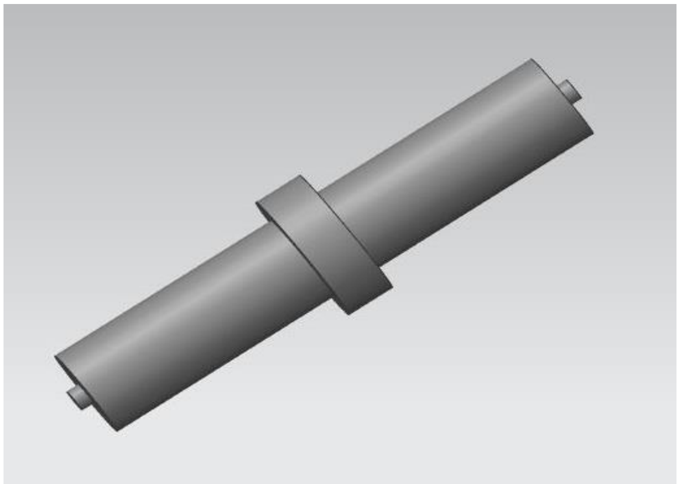


Figure 10- FSW Tool- circular tip

The rotation direction and the direction of motion of the tool are shown in Fig. 4. As further depicted in Fig. 4, two of the four thermocouples (TC1 and TC3) were placed on the advancing side, and the other two (TC2 and TC4) were placed on the retreating side. The distances between the tips of the thermocouples and the joint line are all 6mm. This kind of layout was used to measure the temperature histories on the advancing and retreating sides. Two kinds of welding conditions (a) ω= 800 rpm, *v* = 60mm/min and (b) ω= 1000 rpm, *v* = 60mm/min were selected for the welding experiments. During the FSW process, the pin is first plunged into the work piece with a depth of 2.85mm. At this moment, the downward force is about 5 kN. After the temperature increases to about 400 ◦C, the downward force increases to about 7.5 kN due to the expansion of the heated metal. Because of the capacity limitation of this FSW machine, the downward force has to be kept under 10 kN. The appearance of a welded product with condition (b) is shown in Fig. 5. Circular rings on the surface of the weld could be clearly observed, and a hole was left after the pin retracted from the work piece, just as happens in the standard FSW process.

Figure 11 - Friction Stir Welded for ω= 800rpm and v = 60 mm/min, downward force= 7.5kN

6.2 Tool geometry

Tool geometry is the most influential aspect of process development. The tool geometry plays a critical role in material flow and in turn governs the traverse rate at which FSW can be conducted. An FSW tool consists of a shoulder and a pin as shown schematically in Fig. 2. As mentioned earlier, the tool has two primary functions: (a) localized heating, and (b) material flow. In the initial stage of tool plunge, the heating results primarily from the friction between pin and work piece. Some additional heating results from deformation of material. The tool is plunged till the shoulder touches the work piece. The friction between the shoulder and work piece results in the biggest component of heating. From the heating aspect, the relative size of pin and shoulder is important, and the other design features are not critical. The shoulder also provides confinement for the heated volume of material. The second function of the tool is to ‘stir’ and ‘move’ the material. The uniformity of microstructure and properties as well as process loads are governed by the tool design. Generally a concave shoulder and threaded cylindrical pins are used. With increasing experience and some improvement in understanding of material flow, the tool geometry has evolved significantly. Complex features have been added to alter material flow, mixing and reduce process loads.

Figure 12 -FSW Tool –circular shape pin tool

6.3 Experimental procedure

In this study, commercial pure copper which had 200 mm in length, 40 mm in width and 3 mm in thickness was welded by butting two plates and stirring them together with a rotating tool assembly. The tool rotation speed was 800 rpm with lower welding speed providing optimum welding. A transverse speed of 60 mm/min was also employed. The butted plates were clamped on a steel backing plate. The welding tool titled by a 1.5 degree of angle with welded specimens was rotated in the clockwise direction and specimens, which were tightly fixed at the backing plate, were traveled. Micro structural changes from the weld zone to the unaffected base metal were examined with OM (Optical Microscopy), and TEM (Transmission Electron Microscope). For TEM observation, thin-foil disk specimens, 3 mm in diameter, were cut from the weld zone and the base metal using the electron discharge machine and were prepared by twin-jet electro polishing in nitric acid/methanol solution at 243 K. This thin foils were observed at 300 kv using a JEOL transmission electron microscope. The Vickers hardness profile of the weld zone was measured on a cross section and perpendicular to the welding direction using a Vickers indenter with a 200 gf load for 10 seconds. The tensile test was carried out using an Instron-type testing machine with crosshead speed of 1.67_10_2 mm/s.

Table-5: Tool Parameters

S.No.	Rotational Speed (rpm)	Transverse Speed (mm/min)	Tool Diameter(mm)
1	800	60	4
2	1000	60	5

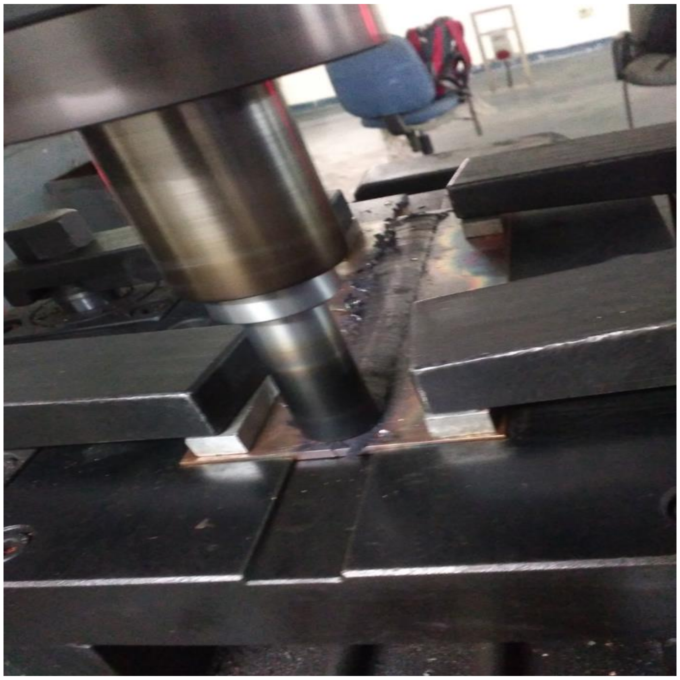


Figure 13 -Tool and work holding device of FSW

Figure 14 -Welded specimens before welding

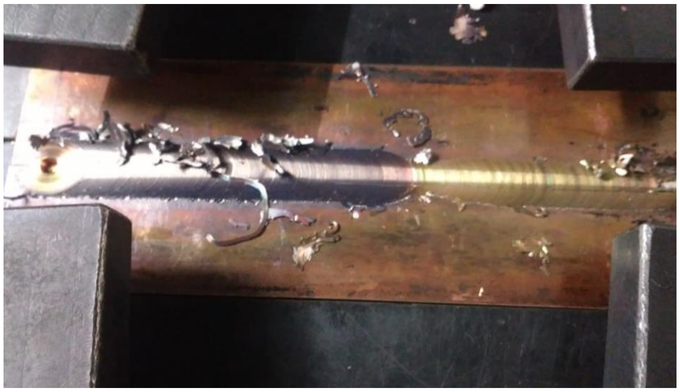


Figure 15 - Welded specimens after FSW

7. Result and discussion

Uniaxial tensile test at room temperature were performed in order to evaluuate the mechanical properties of the joints.To determine the tensile strength of the stir zone ,small tensile test specimens were sectioned in transverse direction of the weld line with an electric discharge machine (EDM). Specimen is cut as per ASTM:B557-06 standard which is shown in figure. Tensile test is performed at a speed of 1mm/min.

Figure 16: Tensile Test Machine

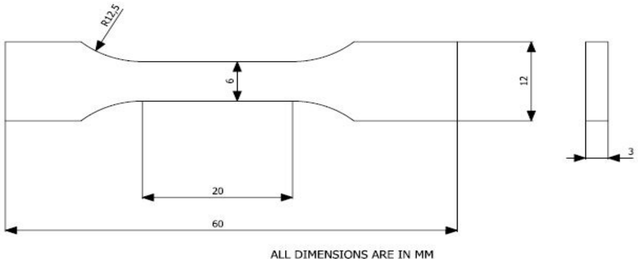


Figure 17 -Tensile Test Specimen

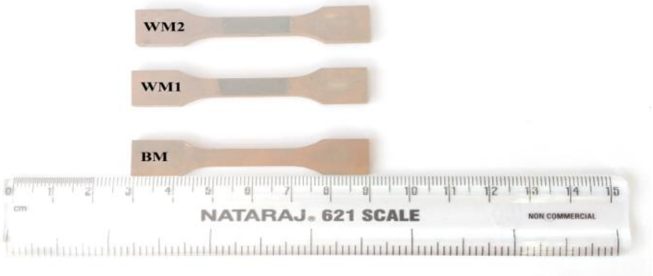
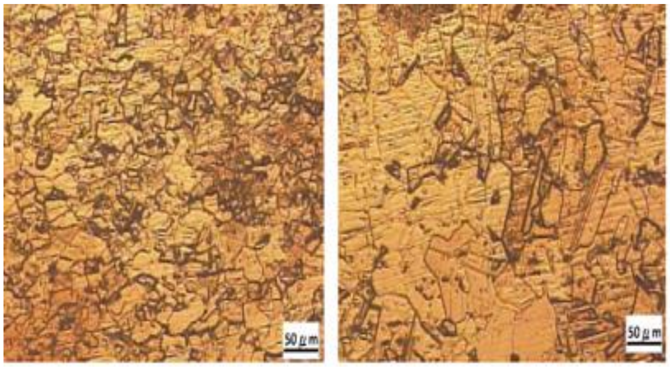


Figure 18 -Tensile Specimen Base Material 2&3. Welded Material

Figure 19 -Welded Plate after cutting Tensile Specimen



Base material Welded specimen

Figure 20-Microstrcture of copper specimen

The Similar joints C51000 ASTM B103 were successfully joined by the Friction Stir Welding process and showed no visible defects from the outside. The parameters for which joining was successful for all combinations

The tensile strength of all the joints were lower than those of the base material, regardless of the rotational speeds and welding speeds as previously noted. Tensile tests were carried out and Figure gives the results of the tests.

The Similar joints were successfully obtained at various speeds and feeds. The joint strongest had a maximum tensile strength of 241 MPa. This strength is 87% of C51000 ASTM B103 base material.

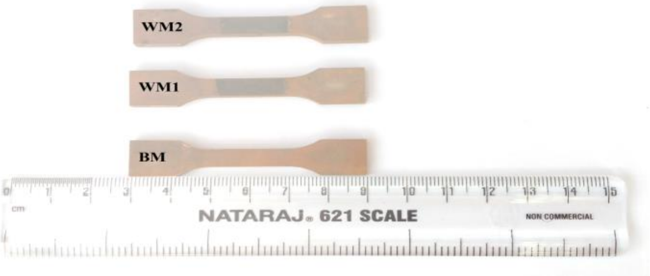


Figure 21: Tensile Test Specimen

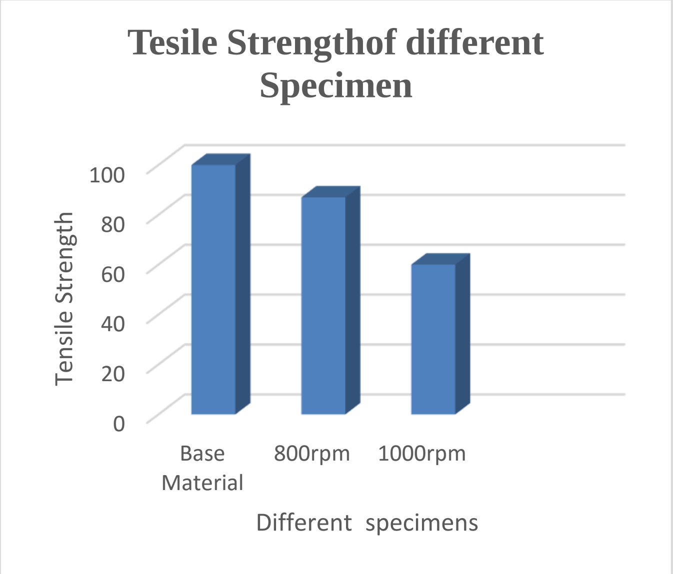


Figure 22 -Tensile strength of different specimen

Study on FSW of C51000 ASTM B103 with parameters ranging from 800 to 1200 rpm and 60mm/min is conducted. Tensile test results shows that, tensile strength of Friction Stir joint decreases with respect to the base material , When welding is done by FSW the best parameter of Friction Stir Welding for copper C51000 ASTM B103 of 3mm plate thickness is 800 rpm and 60mm/min in which 87% of tensile strength of base material.

8. Conclusions and Recommendations

Friction stir welding method can be successfully applied to join copper and acquired results are as follow

1. Defect free weld zone was formed with the condition of 800 rpm and 60 mm/min. The grain structure near weld zone was very different from that of the base metal. Heat affected zone (HAZ) were characterized by grain growth and stir zone had fine and equiaxed grain structure.
2. Slightly softening region was formed in the weld zone in spite of smaller grain size compare to that of base metal. Hardness of FSW copper weld zone mainly depended on the density of dislocation rather than grain size. Hardness variation also existed in the stir zone from the upper to the lower region with thermal and mechanical conditions.
3. Transverse tensile strength of FSW copper joint reached the 87% of tensile strength of base metal.

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