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Study of Microstructure & Mechanical Properties on Pure Aluminum & Pure Copper Joint by Friction Stir Welding Process

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Abstract: Friction stir welding (FSW) is a relatively new solid-state joining process. This joining technique is energy efficient, environment friendly, and versatile. In particular, it can be used to join high-strength aerospace aluminum alloys and other metallic alloys that are hard to weld by conventional fusion welding. FSW is considered to be the most significant development in metal joining in a decade. Recently, friction stir processing (FSP) was developed for micro structural modification of metallic materials. The metallic alloys & especially bi-metal joining is difficult by the conventional fusion welding process. Friction Stir Welding has drastically been effective for this scenario. In the present work, the welding of the aluminum plates with copper plates has been focused. The tensile test & optical analysis have been analyzed simultaneously to determine the quality of the welded specimen. While the bulk of the information is related to aluminum alloys, important results are now available for other metals and alloys. At this stage, the technology diffusion has significantly outpaced the fundamental understanding of micro structural evolution and microstructure–property relationships.
Keywords: Friction Stir welding, Fusion welding, Microstructure, Solid State Joining, Optical Analysis.

I. INTRODUCTION

The difficulty of making high-strength, fatigue and fracture resistant welds in aerospace aluminum alloys, such as highly alloyed 2XXX and 7XXX series, has long inhibited the wide use of welding for joining aerospace structures. These aluminum alloys are generally classified as non-weld able because of the poor solidification microstructure and porosity in the fusion zone. Also, the loss in mechanical properties as compared to the base material is very significant. These factors make the joining of these alloys by conventional welding processes unattractive. Some aluminum alloys can be resistance welded, but the surface preparation is expensive, with surface oxide being a major problem.

Friction stir welding (FSW) was invented at The Welding Institute (TWI) of UK in 1991 as a solid-state joining technique, and it was initially applied to aluminum alloys [1] and [2]. The basic concept of FSW is remarkably 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 (Fig. 1). The tool serves two primary functions: (a) heating of workpiece, and (b) movement of material to produce the joint. The heating is accomplished by friction between the tool and the work piece and plastic deformation of workpiece. The localized heating softens the material around the pin and combination of tool rotation and translation leads to movement of material from the front of the pin to the back of the pin. As a result of this process a joint is produced in 'solid state'. Because of various geometrical features of the tool, the material movement around the pin can be quite complex [3]. During FSW process, the material undergoes intense plastic deformation at elevated temperature, resulting in generation of fine and equiaxed recrystallized grains Friction-stir welding (FSW) is a solid state, hot-shear joining process in which a rotating tool with a shoulder & terminating with a tool pin moves along abutting surfaces of two rigidly clamped plates placed on a backing plate. The shoulder makes firm contact with the top surface of the work-piece. Heat is generated by the friction at the shoulder & to a less extent at the pin surface, softens the material being welded. Severe plastic deformation & flow of this plasticized metal occurs as the tool is translated along the welding direction. Material is transported from the front of the tool to the trailing edge where it is forged into a joint. The half-plate where the direction of the rotation is same as that of the welding is called the advancing side, with the other side designated as being the retreating side.

In FSW the test variables include the tool speed (rpm), the weld speed, the normal load or the tool plunge, tool tilt angle & tool geometry. The properties of the weld hugely depend on these welding parameters.

This process is primarily concerned with the joining of aluminum & most often on the extruded aluminum (non-heat treatable alloys), & on the structures that require superior weld strength without a post weld heat treatment FSW is considered to be the most significant development in metal joining in a decade and is a "green" technology due to its energy efficiency, environment friendliness, and versatility. As compared to the conventional welding methods, FSW consumes considerably less energy. No cover gas or flux is used, thereby making the process environmentally friendly. The joining does not involve any use of filler metal and therefore any aluminum alloy can be joined without concern for the compatibility of composition, which is an issue in fusion welding. When desirable, dissimilar aluminum alloys and composites can be joined with equal ease.

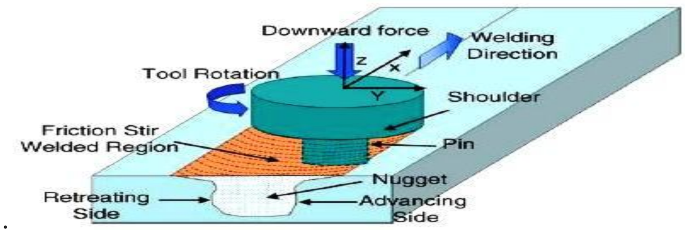

Fig.1: Friction Stir Welding

II. PRINCIPLE OF OPERATION

The welding parameters which are suitable for the selective base metals are taken for the process. The parts have to be clamped rigidly onto the backing bar in a manner that prevents the butt-joint faces from being forced apart. The pin length should be slightly less than the plunge dept. required & both pin length & plunge depth should be slightly less than the plate thickness. The tool shoulder should be in intimate contact with the work surface. The tool is then moved against the work-piece, or vice versa.

Frictional heat is generated by the sliding tool shoulder & pin and the contact face of the work pieces. This heat along with the heat generated by the mechanical mixing process & adiabatic heat within the material causes the stirred material to soften without reaching the melting point, allowing the transverse direction of the tool along the weld line in a plasticized tubular shaft of the metal. The welding of the material is facilitated by the severe plastic deformation in the solid state, involving the dynamic re-crystallization of the base material.

III. EXPERIMENTATION

A. *Material Details*

1) ***Aluminum:*** Aluminum is remarkable for the metal's low density and its ability to resist corrosion through the phenomenon of passivation. Aluminum and its alloys are vital to the aerospace industry and important in automobile industry and structures, such as building facades and window frames.

Table 1: Physical Properties

PROPERTY	VALUE
Density	2.70 g/cm^3
Melting Point	933.47 K (660.32 °C, 1220.58 °F)
Phase	Solid
Thermal expansion	23.1 µm/(m·K) (at 25 °C)
Young's modulus	70 GPa
Thermal conductivity	237 W/(m·K)

Table 2: Mechanical Properties:

PROPERTY	VALUE
Proof Stress	140 MPa
Tensile Stress	150 MPa
Elongation	6 %
Hardness Brinell	43 HB
Hardness Vickers	44 V

a) *Copper:* Copper is found as a pure metal in nature, and this was the first source of the metal to be used by humans. It is used as a conductor of heat and electricity, as a building material and as a constituent of various metal alloys, such as Sterling silver used in jewellery, cupronickel used to make marine hardware and coins and constantan used in strain gauges and thermocouples for temperature measurement.

Table 3: Physical Properties

PROPERTY	VALUE
Density	8.96 g/cm^3
Melting Point	1357.77 K (1084.62 °C, 1984.32 °F)
Phase	Solid
Thermal expansion	16.5 µm/(m·K) (at 25 °C)
Young's modulus	110–128 GPa
Thermal conductivity	401 W/(m·K)

Table 4: Mechanical Properties:

PROPERTIES	VALUE
Proof Stress	340 MPa
Tensile Stress	400 MPa
Elongation	5%
Hardness Brinell	868 MPa
Hardness Vickers	369 a

B. *Tool Specifications*

The tool material used for the welding purpose was a hot worked die steel (HDS-H13) of the following specifications:

Table 5: Material Composition:

ELEMENT	WEIGHT %
Carbon	0.3
Chromium	5.13
Vanadium	1.00
Molybdenum	1.33
Silicon	1.00
Iron	Balance

Table 6: Tool Dimensions

DESCRIPTION	DIMENSION
Shoulder Diameter	25 mm
Tool Pin Diameter	6/4 mm
Tool Pin Length	2 mm
Tool Pin Geometry	Tapered cylinder

C. *The Welding Process*

The Aluminum & Copper sheets of thickness were taken & cut into plates of dimensions using the process of shear cutting. The edges to be welded were then milled using the horizontal milling machine to make the surfaces smooth.

These plates were then clamped on to the 3-Axis Horizontal Friction Stir Welding machine, available at the machining laboratory in the institute (see Fig.5.1 A& Fig 5.1 B). The plates have to be clamped rigidly with proper external supporting plates to avoid excessive vibrations caused during welding process.

Fig. 2: Friction Stir Welding Machine at IISc

Fig. 3: Al & Cu plates clamped to the setup using backing plates.

The tool piece is also fixed to the spindle head of the rotor that rotates the cutting tool piece. The friction stir welding process is initiated via the Computer Numeric Control (CNC) unit that is attached to the rotor unit. The necessary welding parameters are inputted to the system to facilitate the welding process.

Fig. 4: Tool piece fixed to the rotor

D. Vertical milling machine

Milling process removes material by performing many separate, small cuts. This is accomplished by using a cutter with many teeth, spinning the cutter at high speed, or advancing the material through the cutter slowly; most often it is some combination of these three approaches. The speeds and feeds used are varied to suit a combination of variables. The speed at which the piece advances through the cutter is called feed rate, or just feed; it is most often measured in length of material per full revolution of the cutter.

Fig.5: Welded sample

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The welded samples were then marked for cutting out the samples for conducting tensile, fatigue & optical tests. The welded samples were cut out using the abrasive cutting machine for optical examination.

IV. RESULTS

The contribution of intense plastic deformation and high-temperature exposure within the stirred zone during FSW/FSP results in recrystallization and development of texture within the stirred zone and precipitate dissolution and coarsening within and around the stirred zone and. Based on micro structural characterization of grains and precipitates, three distinct zones, stirred (nugget) zone, thermo-mechanically affected zone (TMAZ), and heat-affected zone various zones have significant effect on post weld mechanical properties. Therefore, the micro structural evolution during FSW/FSP has been studied by a number of investigator as follows.

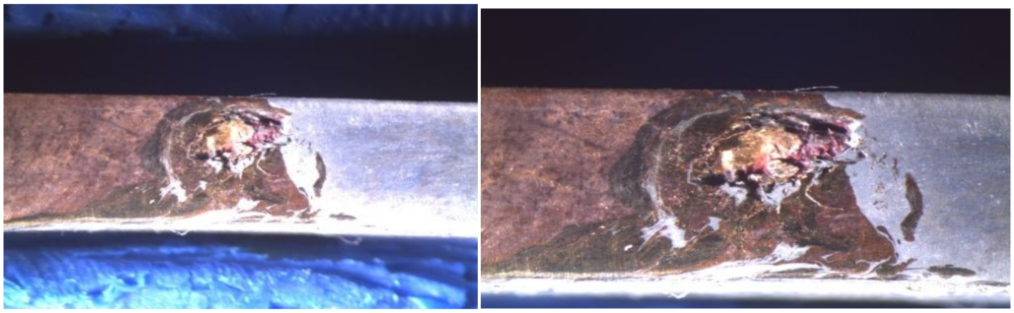

Fig. 6: Friction stir welding when tool running at 500 rpm

Sample 1 at 1.5 and at 1 magnification, it is seen that at lower rpm the weld quality is low and the defects are more as there is low temperature developed at the interface .The weld is weak and at 500 rpm the defects are large. The grain size within the weld zone tends to increase near the top of the weld zone and it decreases with distance on either side of the weld-zone centerline, and this corresponds roughly to temperature variation within the weld zone, the various optical images of other samples friction stir welded at 500 rpm are as follows.

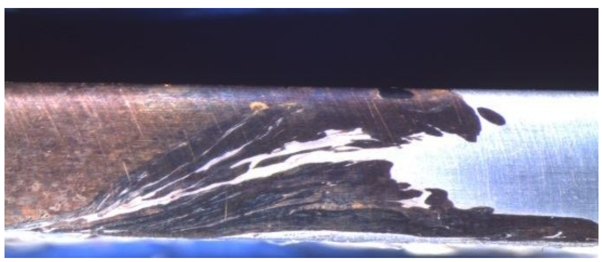

Fig. 7: Sample 2 at 2.5 magnification 1

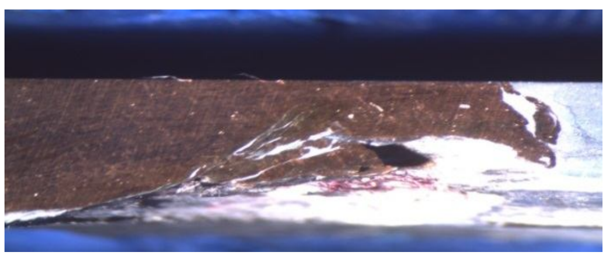

Fig. 8: Sample 3 at 1.5 magnification

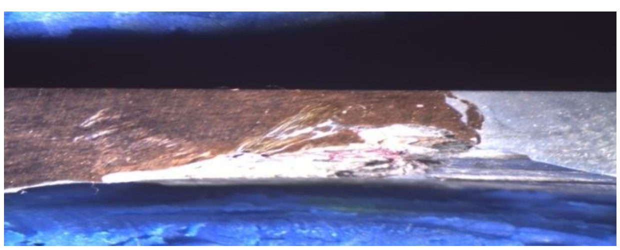

Fig. 9: Sample 3 at 1 magnification 1

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A. Friction stir welding at 800 rpm

The higher tool traverse speed will induce a lower heat input to the weld zone; the rotary speed determines the quality of heat production and degree of plastic

Deformation. The traverse speed determines the heat input per unit length of the weld. At higher rotary speed, the peak temperature is higher and forms lots of plastic metal.

With the increase of temperature, thermal activation energy provides lots of energy to the dislocation motion and significant residual stress relaxation is likely to occur. Moreover, there is enough time for the stress relaxation due to long cooling times. At lower traverse speed, i.e., higher heat input per unit length, material further away from the weld line is heated up; this results in an increase in the width of the high temperature zone around the tool and a decrease of thermal gradients, thus reducing the thermal expansion mismatch upon cooling, which has been previously observed in the literature.

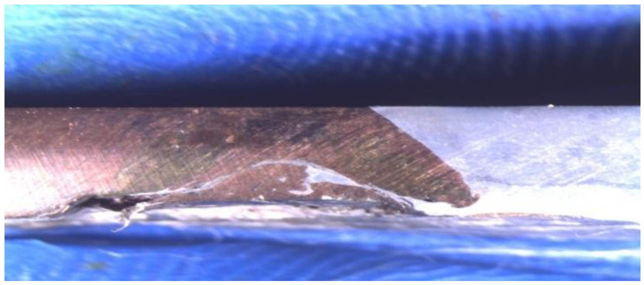

Fig. 10: Sample 1 at 1 magnification

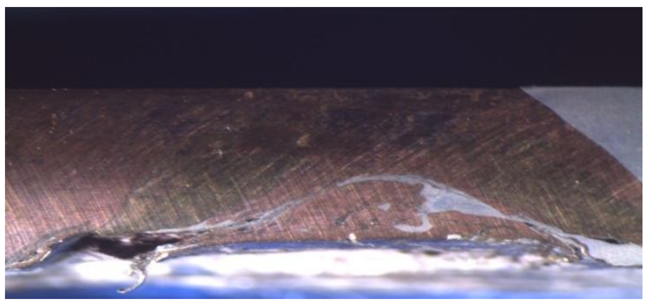

Fig. 11: Sample 1 at 1.5 magnification

Fig. 12: Sample 2 at 1 magnification

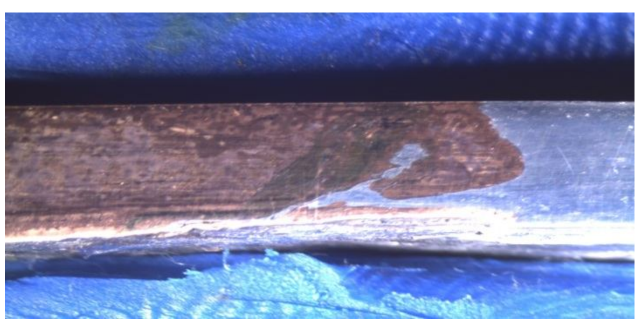

Fig. 13: Sample 3 at 1 magnification

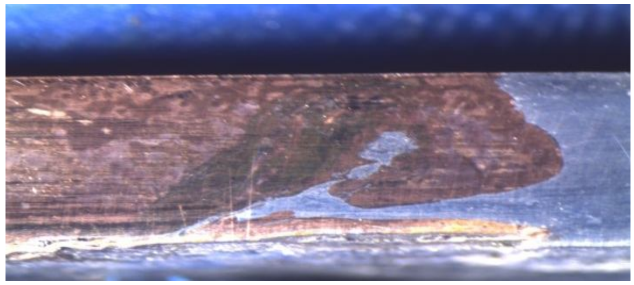

Fig. 14: Sample 3 at 1.5 magnification

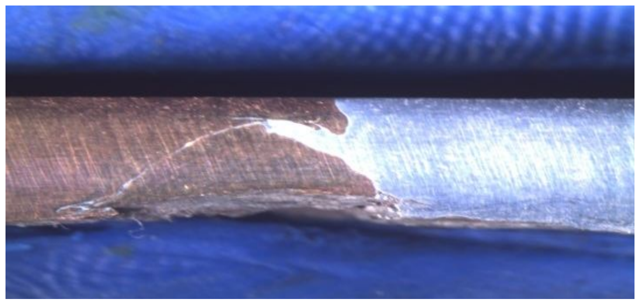

Fig. 15: Sample 4 at 1 magnification

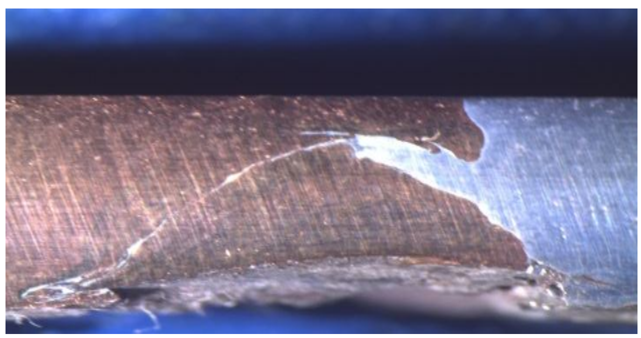

Fig. 16: Sample 4 at 1.5 magnification

B. Plunge depth

The axial force during friction stir welding is sensitive to plunge depth of the tool and is one of the prime factors, which exercises control over heat generation during welding. Consequently, the plunge depth for a given tool rotation speed, traverse speed, material and test machine needs to be optimized so as to get a defect-free weld. The aim of this article is study of tool plunge depth (TPD) effects on mechanical properties of friction stir welding of copper and aluminum. The results show that the frictional heat increases and stir zone grain size decreases with increasing TPD at both base metals. At higher TPD, the material press out from shoulder and base metals interface.

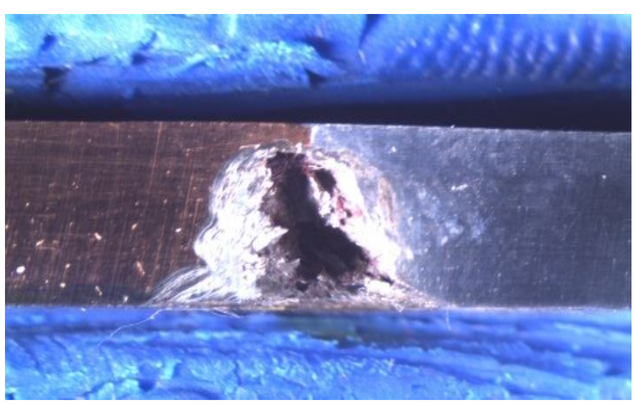

Fig. 17: Sample 1 at 1 magnification

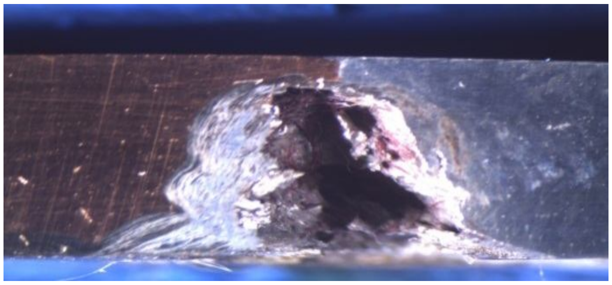

Fig. 18: Sample 1 at 1.5 magnification

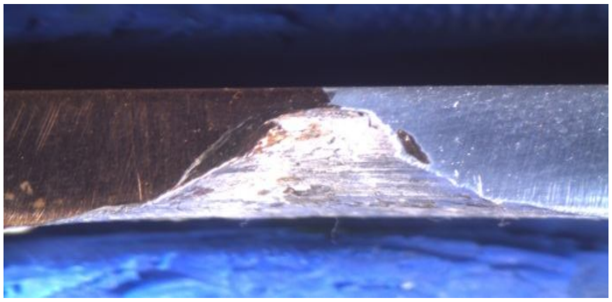

Fig. 19: Sample 2 at 1 magnification

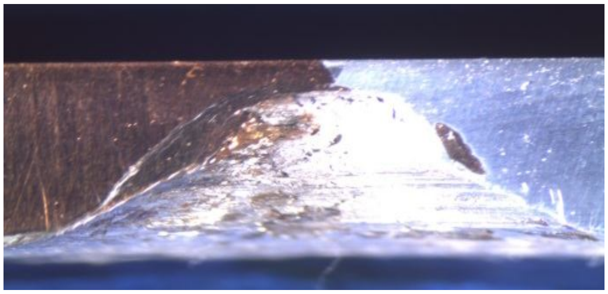

Fig. 20: Sample 2 at 1.5 magnification

C. Varying interface

This section investigates the implications of spindle speed and travel speed on the resulting weld quality. the average temperatures experienced at the tool-shoulder and tool-pin interface when varying the spindle speed and travel speed. It can be seen that the interface temperatures increase for higher spindle speeds due to more heat generation by increased friction and plastic deformation. The temperatures also increase for lower travel speeds, due to more heat being deposited per unit weld length.

At lower traverse speed, i.e., higher heat input per unit length, material further away from the weld line is heated up; this results in an increase in the width of the high temperature zone around the tool and a decrease of thermal gradients, thus reducing the thermal expansion mismatch upon cooling, The various optical images observed shows various defects in the interface of the metals. The occurrence of wormhole defects is more difficult to control in materials with high hot strength and low thermal conductivity. Results obtained by varying the interface are shown below.

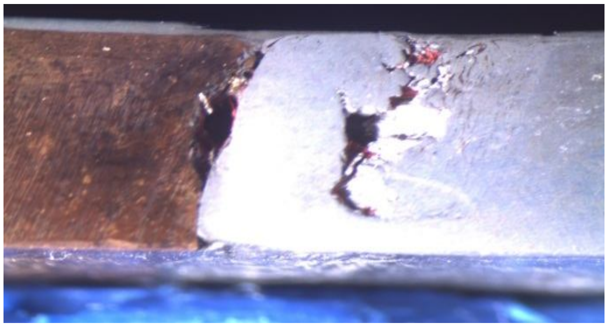

Fig. 21: Sample 1 at 1.5 magnification

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Fig. 22: Sample 1 at 2.5 magnification

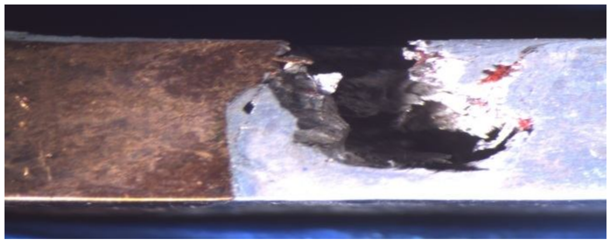

Fig. 23: Sample 2 at 1.5 magnification

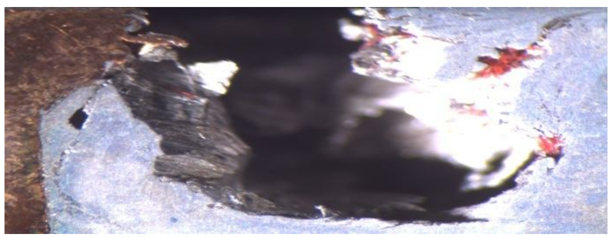

Fig. 24: Sample 2 at 2.5 magnification

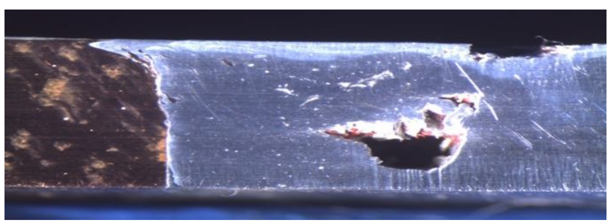

Fig. 25: Sample 3 at 1.5 magnification

Fig. 26: Sample 3 at 2.5 magnification

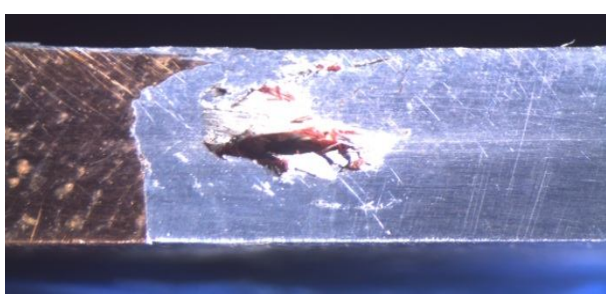

Fig. 27: Sample 4 at 1.5 magnification

Fig. 28: Sample 4 at 2.5 magnification

D. Varying rpm

For FSW, two parameters are very important: tool rotation rate (ω, rpm) in clockwise or counterclockwise direction and tool traverse speed (ν, mm/min) along the line of joint. The rotation of tool results in stirring and mixing of 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. Higher tool rotation rates generate higher temperature because of higher friction heating and result in more intense stirring and mixing of material as will be discussed later. However, it should be noted that frictional coupling of tool surface with workpiece is going to govern the heating. So, 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.

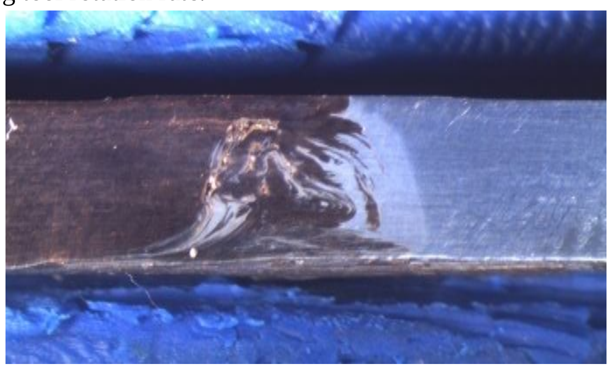

Fig. 29: Sample 1 at 1 magnification

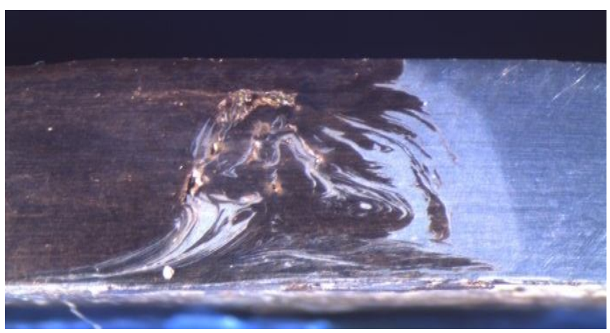

Fig. 30: Sample 1 at 1.5 magnification

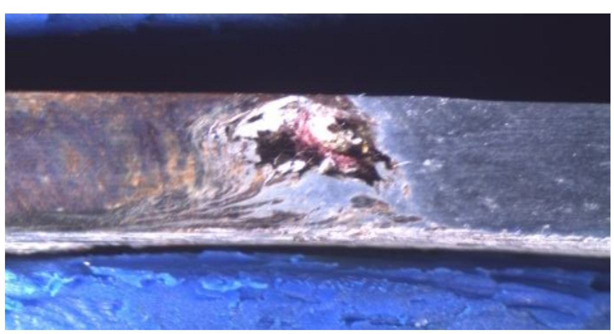

Fig. 31: Sample 2 at 1 magnification

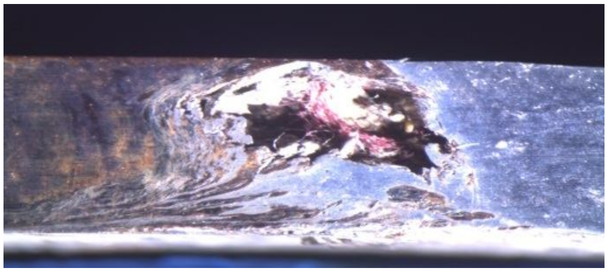

Fig. 32: Sample 2 at 1.5 magnification

Fig. 33: Sample 3 at 1 magnification

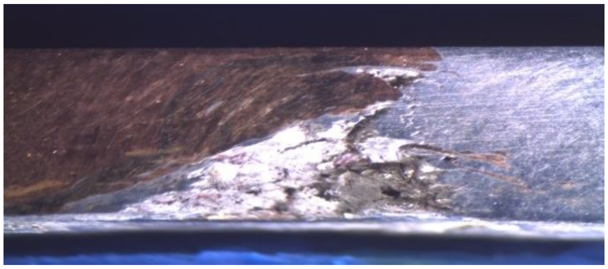

Fig. 34: Sample 3 at 1.5 magnification

V. CONCLUSION

We presented the results of a feasibility study of FSW in order to produce a composite aluminum-copper material. While many investigations have looked into FSW of aluminum to copper.

In this present work, development in process modeling, microstructure and properties, material specific issues, have been addressed. Tool geometry is very important factor for producing sound welds. However, at the present stage, tool designs are generally proprietary to individual researchers and only limited information is available in open literature. From the open literature, it is known that a cylindrical threaded pin and concave shoulder are widely used welding tool features**.** The Al and cu regions were observed to etch differently and produced sharp contrast features in optical metallographic. This provided vivid images illustrating flow visualization and complex flow patterns which were observed to vary with tool (or headpin) rotation speeds and slight variations in tool axis geometry. In addition, increasing tool rotation speeds, as a consequence of the temperature-induced variations in residual grain size and sub-grain microstructures, the eld strength, as determined by residual micro hardness profiles.

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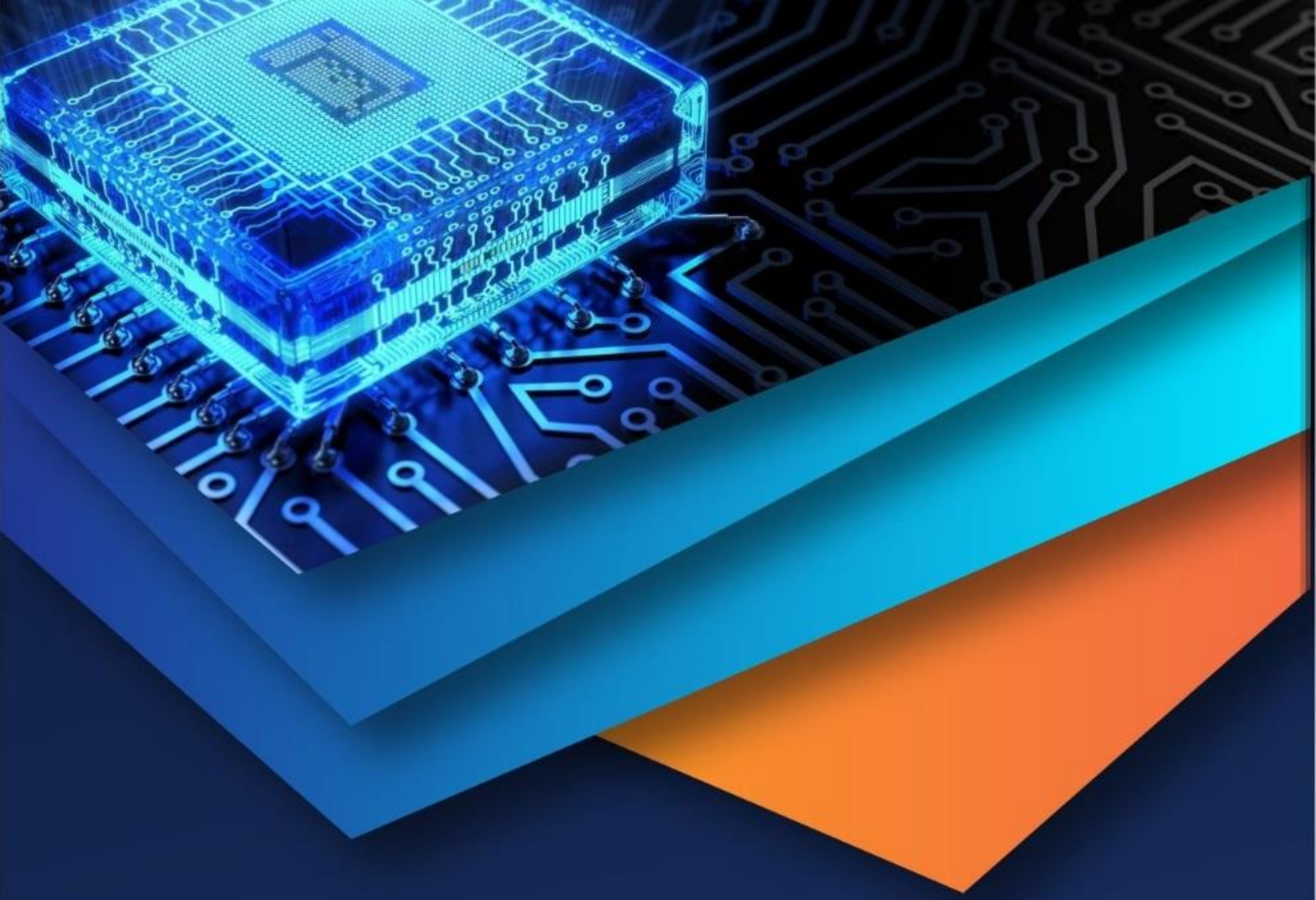

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