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Analysis of Tool Design parameters for Friction Stir Lap welding of Aluminium and Copper

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Abstract : **Friction stir welding (FSW) has been successfully employed to produce dissimilar Aluminium-Copper lap joint. The present articles provides a comprehensive insight on FSW parameters such as tool materials and tool geometry. The effect of critical aspects of tool geometry such as tool pin, shoulder and the shoulder diameter to pin diameter ratio (SPR) on the mechanical strength of the joint has been discussed. The use of tool shank as a heating or cooling system in FSW is discussed. The main findings with respect to the materials used, tool parameters, mechanical properties, formation of inter-metallic compounds and process parameters accounted in the literature are summarized in thematic table.**

Keywords* — *Al-Cu joint; dissimilar friction stir welding; lap weld; tool design; intermetallic compounds.

I. INTRODUCTION

Aluminium and copper joining finds various applications in electrical, automotive and Heat, ventilation, and Air conditioning (HVAC) /refrigeration industries [1, 2]. The trend in these industries is focused towards replacing the copper parts with aluminium, either wholly or partially, in an attempt to reduce the cost [3, 4]. Aluminium has several advantages over copper namely, a)The material costs are much lower for aluminum, approximately one-third of that of copper, b)Aluminum can carry roughly twice as much electrical current per mass unit., c)Thermal conductivity of pure aluminium is approximately 60 percent of that of copper. Completely replacement of copper with aluminium is not possible in most applications since it will adversely affect the efficiency of the working system. This necessitates the need to join copper to aluminium. The conventional techniques used to join copper to aluminium are ultrasonic welding [5], friction welding [6, 7], and laser welding [8]. During the welding process, due to the application of heat and liquefaction, intermetallic compounds (IMCs) are formed. Esmaeili et. al. [9] welded aluminium and brass using different tool rotational speeds. The Tensile strength quality factor (TSQF) achieved with respect (w.r.t) to aluminium parent material is shown in Table 1. Thick layers of intermetallic layers are reported to consist microcracks which reduce the strength of the joint. Thick layer of IMCs is hard and brittle in nature. A very thin layer of these IMCs in the order of 1.86 um are beneficial to improve the mechanical properties of the joint. A further rise in the thickness of the IMC layer will lead to crack formation and hamper the mechanical properties. It is very difficult to control the thickness of these intermetallic compound layers [9, 10].

Friction Stir Welding (FSW) is one of the newer technique which is found to be feasible to join aluminium and copper. FSW was developed by W.M. Thomas et al. at The Welding Institute (TWI) in Cambridge, UK in 1991 [11]. This process was primarily used for joining aluminium and aluminium alloys [12]. FSW is employed to produce various types of joints, commonly butt joints and lap joints are produced. The quality of joint depends on the tool design and the process parameters.

The tool design is an important aspect which needs to be studied extensively to get good quality welds. The tool design involves components such as pin profile, pin diameter, pin length, shoulder profile, shoulder diameter. The FSW tool is responsible for heating and softening of the materials, pushing material from the front of the tool to the back of the tool and stirring of the materials to achieve mechanical mixing. The tool geometry, material and process parameters with respect to the tool positioning are the important aspects of the FSW process.

Table 1. Summary Of Rotational Speed, Thickness Of Imc's Formed And Tsqf Achieved With Respect To Aluminium Base Metal

Rotational speed (rpm)	IMC thickness (um)	TSQF
200	0	21.65
450	1.86	80.75
750	4.28	64.30
1100	7.32	28.43

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II. TOOL MATERIALS

The tool material is decided according to the mechanical and chemical properties of the base materials to be welded. The melting point of the base materials is an important aspect affecting the selection of the tool materials. In general, the tool materials should possess good strength at elevated temperature, wear resistance, low chemical reactivity and closer dimensional tolerance. In case of FSW of dissimilar Al-Cu welding, the tool geometry is relatively simple, the tool should have good hardness. In literature tool steel is used which achieve a hardness value of approximately 52 HRC. The commonly used tool materials are 1) H13 tool steel [13–16], 2) M2 grade tool steel [17, 18], 3) 2436 steel alloy [19].

III. TOOL PIN

A. Tool basics

The FSW tool has three elements namely i) Pin, ii) Shoulder and the iii) Shank. The size and profile of the pin and shoulder is crucial in deciding the tool geometry. The tool geometry impacts peak temperature, impressed force and the material movement during FSW.

The tool pin is responsible for material movement due to the stirring action. Pin shape, length, diameter, surface profile are important aspects of the tool pin. Various tool shapes are used for Al-Cu welding. In literature, the following tool shapes have been used : i) Conical and threaded [16, 20], ii)Inverse conical and unthreaded [14], iii) Cylindrical and unthreaded [1, 19, 21–25], iv) Cylindrical and threaded [26]. The various tool pin shapes are shown in Fig.1.

Fig. 1. FSW tools with a) Cylindrical Unthreaded, b) Cylindrical threaded and c) Conical Threaded profile [27]

B. Tool pin shape

Lap welding is comparatively difficult than butt welding because the oxide at the sheet interface could not be easily disrupted due to the orientation of the weld interface with FSW tool [28]. A tool pin with a conical shape would produce high stress concentrations. The stress concentration reduces considerably when an inverse conical pin is used. The oxide layer cannot be easily disrupted because the tool shoulder rests on the work surface. Forces applied at the end the sheets results in eccentric loading [28]. Fig. 2. shows stress flow lines under the effect of different pin profiles and the corresponding effect on weld sample under loading conditions. Fig. 2(a) and 2(b) shows effect of tool pin geometry on stress concentration when tension shear load is applied. Fig. 2(c) and (d) shows effect of tool pin geometry on stress concentration when load is applied to the ends of unrestrained lap joints. It is observed that the stress concentration in weld for conical pin tool is considerably more as compared to that of inverse conical pin tool. When forces are applied at the end of the lap welds, eccentric loading is observed in the connecting region, which further causes the joint rotation as shown in Fig. 3. Both side lap joining, where the position of the two welded plates is reversed after welding and welding operation is performed again, can eliminate these effects [29].

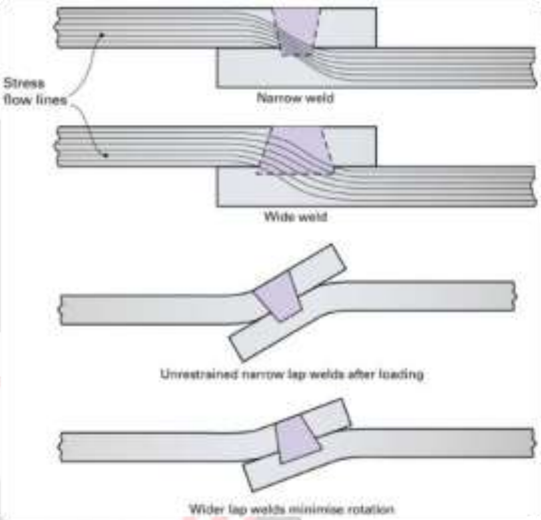

Fig. 2. Comparative stress flow lines :a)Narrow weld, b)Wide weld, c)Unrestrained narrow lap welds after loading, d)Wider lap welds minimize rotation [28]

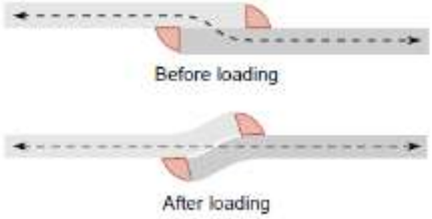

Fig. 3. Joint rotation before and after loading under the effect of forces applied to the ends of lap joints [29]

Akbari et al. [3] produced joints between 7070 Al and commercially pure copper and observed that when aluminium is placed on top of copper plate, a better weld is observed compared with that obtained when copper is placed on top of aluminium plate. This occurs because when the tool shoulder rubs against the top surface plate and generates heat, the comparatively lower thermal conductivity of aluminium results in less heat loss.

Elrefaey et al. [30] used a cylindrical and threaded tool pin to achieve fracture load of 502 N, which is approximately 78% strength of the copper base metal. Xue et al. [1] also used a cylindrical and unthreaded tool pin with 33.3% pin penetration in bottom plate to achieve fracture load of 2680 N which is approximately 82.2% strength of aluminium base metal and 36.2% strength of aluminium base metal. Firouzdor and Kou [26] joined 1.6

mm plates of aluminium alloy AA 6061 and commercially pure copper by FSW using a 4 mm diameter threaded tool pin with 0% pin penetration in bottom plate to achieve fracture load of 2200 N which is approximately 34% strength of aluminium base metal and 38.1% strength of copper base metal. The low tensile strength was achieved due to of 0% pin penetration in the bottom plate which in turn resulted in insufficient amount of heat generated during FSW. Abdollah-Zadeh et al. [20] used a cylindrical and threaded tool pin with 83.3% pin penetration in bottom plate to achieve fracture load of 2680 N which is 70.4% strength of aluminium base metal and 31% strength of copper base metal. However, for lap welding, a conventional cylindrical threaded probe resulted in excessive thinning of the top sheet, causing significantly reduced bend properties [31]. Therefore, cylindrical unthreaded pin profiles are preferred for plate thicknesses up to 12 mm [32]. A tapered threaded pin creates high hydrostatic pressure as well as high temperature [33]. This may lead to formation of intermetallic compounds. Bisadi et al. [14] used an inverse and slightly conical tool pin with 56.7% pin penetration in bottom plate to achieve 74% strength as compared to aluminium base metal and 78% strength as compared to copper base metal. The graph of tensile strength quality factor with respect to aluminium and copper base materials is plotted for the different tool pin profiles, as shown in Fig. 4. It is observed that the inverse conical unthreaded pin gives a high TSQF with respect to both the parent metals [14]. In case of cylindrical threaded and cylindrical unthreaded pins, high TSQF is achieved with respect to aluminium parent metal which is considerably softer as compared to the copper parent metal, thereby resulting in a low TSQF with respect to the copper parent metal [1, 20]. Literature summary of different tool pin shapes for dissimilar Al-Cu FSW is shown in Table 2.

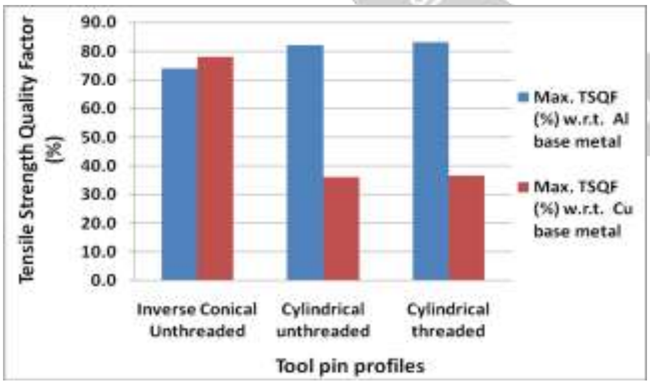

Figure 4. Graph of tensile strength quality factor achieved with respect to aluminium and copper parent metals for various tool pin profiles [1, 14, 20]

C. Tool pin length

B.Kuang et al. [13] used a pinless tool to join aluminium and copper plates, each of 2 mm thickness. A tool with pin will penetrate the surface of the material and leaves behind a hole known as keyhole which is a peculiar feature of the FSW process. Further, the pin is subjected to wear as it is constantly stirring the softened material. A pinless tool will avoid tool wear and prevent the formation of keyholes.

Elrefaey et al. [15, 30] used tools with three different pin lengths to join 2 mm thick A1100H24 alloy to 1 mm thick ETP copper sheet. Additionally, a zinc foil of 50 um was used as a filler between the aluminium and copper sheets while using pin length of 2.2 mm. They used tools with pin length of 2.0 mm, 2.1 mm and 2.2 mm corresponding to pin penetration (with respect to bottom sheet) of 0%, 9.52% and 19.05% respectively. It was observed that for 0% pin penetration, most of the samples failed during the test sample preparation. At 9.52% pin penetration, the samples failed at an average fracture load of 188.03 N, which is significantly higher as compared to that obtained those welded with 0% pin penetration. At 19.05% pin penetration, the samples failed at 498.33 N. The average fracture load of weld with 19.05% pin penetration, with a Zn intermediate layer was almost three fold compared to that of the weld without an intermediate layer. Although the zinc intermediate layer has contributed to reduction in IMCs formed and thereby improving the tensile strength of the weld, the contribution of 19.05% pin penetration also seems to have improved the tensile strength significantly. The pin must penetrate in the copper sheet placed at the bottom by at approximately 25% to minimize the risk of being damaged by the hard copper surface [34]. The graph of tensile shear failure load vs. pin penetration is shown in Fig. 5.

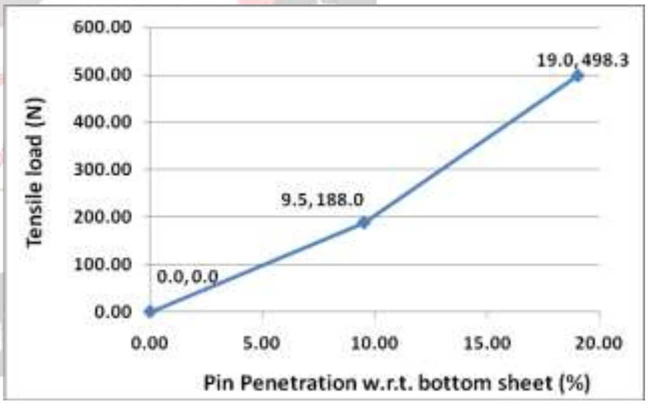

Figure 5. Graph of tensile shear failure load vs. pin penetration [13]

D. Tool pin diameter

P. Xue et al. [1] used a large pin diameter of 8 mm to join aluminium and copper plates of 3 mm thickness each. A larger pin increased the Al-Cu bonding area and produced sufficient heat at lower tool rotational speed of 600 rpm. The tensile strength achieved was 82.2 % as compared to the parent AA 1060 metal. Use of lower rotational speed reduced annealing softening in the heat affected zone (HAZ). The SPR ratio was maintained at 2.5.

The shoulder is responsible for maximum heat generation during the FSW process. For a cylindrical tool,

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it has been found analytically that the shoulder produces around 86% of the total heat produced by the tool by rubbing action between the shoulder surface and the workpiece whereas the pin produces the remaining 14% by the stirring action [35]. B.Kuang et al. [13] used a pinless tool to join aluminium and copper plates, each of 2 mm thickness. The pinless tool produces less heat as compared to tool with pin, thereby leading to partial bonding, and consequently formation of weak welds. Optimization of the process parameters can result in the formation of joints with fair strength, but this will be possible only in case of thin sheets where comparatively lesser heat is required for bonding.

TABLE 2. SUMMARY OF TOOL PIN SHAPES, MATERIALS, MECHANICAL PROPERTIES, IMC'S FORMED AND PROCESS PARAMETERS FOR DISSIMILAR CU–AL FSW SYSTEMS

Tool pin shape	Thickness	Tool parameters	Mechanical properties	IMCs formed	Process parameters	Reference
Cylindrical unthreaded	1(Cu-DHP) + 6(AA6082-T6 and AA5083-H111)	TM: INA SD: 9.5 mm SP : concave 8˚ PD: 3 mm PL :1 mm SPR: 3.17:1	Hardness: 190 HV	Al_2Cu, Al_4Cu_9 Al-Cu	RS: 600 rpm WS: 50 mm/min TTA: 0˚ ATL: 4.5 kN	[23]
	3(Cu) + 3(AA1060)	TM: Heat treated tool steel SD: 20 mm PD: 8 mm PL: 4 mm SPR: 2.5:1	TSFL: 2680 N Hardness: 130 HV	Al_2Cu, Al_4Cu_9	RS: 600 rpm WS: 50 mm/min	[1]
Cylindrical threaded	1.6(Cu) + 1.6(AA6061)	TM : H13 tool steel SD : 10 mm PD: 4 mm PL: 1.6 mm SPR: 2.5:1	TSFL: 2.2 KN	Al_2Cu, Al_4Cu_9	RS: 1400 rpm WS: 75 mm/min TTA: 3˚	[26]
	3(Cu) + 4(AA1060)	TM: Quenched and tempered tool steel SD: 15 mm PD: 5 mm PL: 6.5 mm SPR: 3:1	TSFL: 2709 N Hardness: 90 HV	Al_2Cu, Al_4Cu_9, Al-Cu	RS: 1500 rpm WS: 118 mm/min TTA: 3˚	[20]
	3(Cu) + 4(AA1060)	TM: Quenched tool steel SD: 15 mm PD: 5 mm PL: 6.5 mm SPR: 3:1	TSFL: 2642 N	Al_2Cu, Al_4Cu_9, Al-Cu	RS: 1180 rpm WS: 95 mm/min TTA: 3˚	[16]
	1(Cu) + 2(A1100H24) + (0..05) zinc foil	TM: Tool steel SKD 61 SD: 10 mm PD: 3 mm SPR: 3.33:1 PL: 1.7 mm	Tensile fracture load: 526 N Hardness: 133 HV	CuAl, Al_4Cu_9	RS: 1002 rpm WS: 198 mm/min TTA: 3˚	[30]
Tool pin shape	**Thickness**	**Tool parameters**	**Mechanical properties**	**IMCs formed**	**Process parameters**	**Reference**
Conical Unthreaded	2(Cu) + 8(AA6061-T6)	TM : INA SD: 16 mm	INA	Al_2Cu, Al_4Cu_9	RS: 1000 rpm WS: 30 mm/min	[22]

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		SP : concave PD : TD - 4 mm and BD - 3 mm PL: 4 mm SPR: 4:1			DP: 0.2 mm	
Inverse Conical Unthreaded	3(Cu) + 2.5(AA5083)	TM: Quenched and tempered tool steel SD: 19.1 mm SP : concave 6° PD: TD - 4.5 mm and BD - 5 mm PL: 3.8 mm SPR : 4.24	UTS: 204.51 MPa JE: 78% of Cu and 74% of Al Hardness: 95 HV	Al_2Cu, Al_4Cu_9	RS: 825 rpm WS: 32 mm/min TTA: 3.5° DP: 0.4 mm	[14]

TM: tool material, SD: shoulder diameter, SP: shoulder profile, PD: pin diameter, PL: pin length, DP : Plunge depth, SPR: shoulder diameter to pin diameter ratio, TD : Pin top diameter, BD : Pin bottom diameter, RS: rotational speed, WS: welding speed, TTA: tool tilt angle, ATL : Axial tool load, IMCs: intermetallic compounds, UTS: ultimate tensile strength, JE: joint efficiency, TSFL : Tensile shear fracture load, INA :Information not available.

IV. TOOL SHOULDER

The tool shoulder is mainly responsible for generation of heat during the FSW process. The heat is generated due to the rubbing of the shoulder on the workpiece surface. The frictional heat generated should be sufficient to soften the workpiece material. The softened material can be stirred by the tool pin resulting in proper material mixing, thereby producing sound welds. Shoulder diameter, shape and surface profile are important aspects of the shoulder.

A. Tool Shoulder diameter

The tool shoulder produces around 86% of the total heat produced by the tool as stated earlier. Xue et al. [1] used a large 20 mm shoulder diameter to join 3 mm thick AA1060 and 3 mm thick copper. However, a very large tool shoulder diameter mm can result in excessive heat generation. Excessive heat generation leads to diffusion of aluminum particles to copper. This further results in cavity defect which is accorded to the different contraction coefficients of dissimilar sheets materials.

Galvao et al. [21, 23] used a small 9.5 mm shoulder diameter to successfully join aluminium alloy and copper-DHP plates of 1 mm and 6 mm thickness respectively. Two types of aluminium alloys, namely AA 5083 and AA 6082 were used. They used lower tool rotational speed of 600 rpm and tool travel speed of 50 mm/min was used. The SPR ratio was maintained at 3.17. AA 5083/copper-DHP welds had highly defective Al/Cu interfaces, whereas AA 6082/copper-DHP welds displayed good mixing of base metals in stirred zone in spite of poor surface properties.

B. Tool Shoulder geometry and surface profile

Shoulder geometries, namely, flat, concave and convex can be used. Specific profiles such as scrolls can also be used on the surface of the shoulder. Galvao et al. [21] observed that the scrolled shoulder forces the Al-Cu mixture downwards, which gives a good surface morphology but also leads to formation of large quantity of undesirable IMCs. Flat end shoulder is the simplest type. However, such flat shoulder may not effectively trap the flowing material thereby leading to excessive material flash. Better trapping of material can be done by using a concave shoulder which is effective in restricting material escaping from the sides of the shoulder [36–38]. The action of the centrifugal force created by such concave profile leads to additional pressure and better adherence of the plasticized material on the surface thereby improving the material flow required for joining. The usual degree of concavity used for dissimilar Al-Cu lap joining is 6^o to 8^o [14, 15, 23].

C. Shoulder diameter to Pin diameter ratio

The collective action of the tool pin and tool shoulder is required to produce sufficient heat and to efficiently utilize the heat produced. One aspect of selecting a proper combination of pin and shoulder is proper selection of shoulder diameter to pin diameter ratio (SPR) ratio. SPR is responsible for maintaining heat input and its distribution.

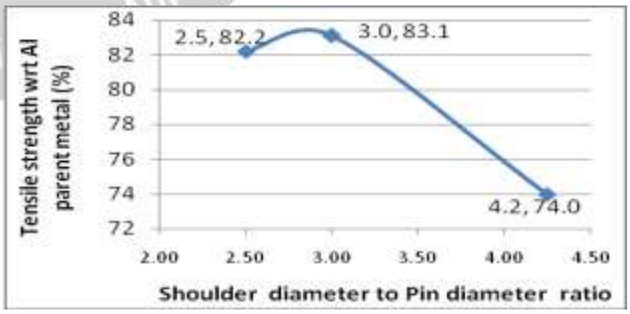

Figure 6. Graph of Tensile strength achieved with respect to aluminium parent metal vs. SPR [1, 14, 20]

For materials with large thickness, the pin should be more responsible for thermal input since the heat generated due to frictional heating by the shoulder may not reach the lower plate in sufficient amount. The general range for SPR is 2:1 to 5:1. Higher heat input would require a higher SPR ratio. The graphs of SPR ratio vs. tensile strength quality factor (TSQF) with respect to aluminium is shown in Fig. 6. The graphs of SPR ratio vs. tensile strength quality factor (TSQF) with respect to copper is shown in Fig. 7. In Fig. 7, the SPR ratio corresponding to TSQF with respect to copper parent metal (i.e. 52.30) is infinity but the SPR ratio is assumed to be 9 for better representation of the variation of TSQF with respect to SPR ratio.

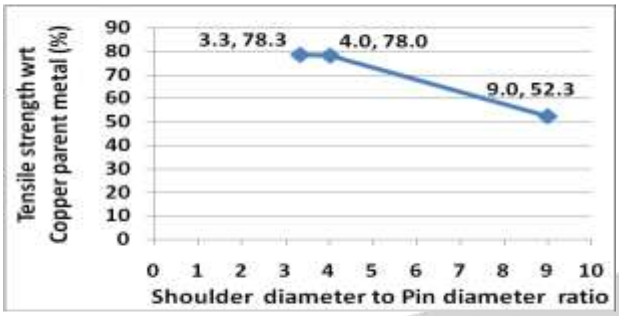

Figure 7. Graph of Tensile strength achieved with respect to copper parent metal vs. SPR [13,14,30]

V. TOOL SHANK

The tool shank is responsible for proper holding of the tool in the machine spindle. The tool shank diameter should be in accordance with the collet size available for the machine, which can be a conventional milling machine, a CNC milling machine or a specialized Friction Stir welding machine. The shank can also perform additional function of providing heating or cooling systems. If sufficient amount of heating necessary to soften the base materials in not produced by the FSW process, then external heating element such as induction coil [39] or hot air gun can be used to heat the tool shank. Alternatively, if there is excessive heating the tool shank contains fins which allow more surface area for cooling. This will allow some of the excessive heat produced during FSW to be lost by conduction. Packer S.M. et al. [40] used a liquid cooled tool holder to achieve better control over the FSW process. Colligan et al. [41] used a cylindrical collar which allows coolant to flow inside the tool body through the open spaces specially created within the tool as shown in Fig. 8. The FSW tool with induction coil and hot air gun are shown in Fig. 9 and Fig.10 respectively. The shank may also consist of a collar of diameter larger than that of the tool to resist failure of the tool due to high shear loads.

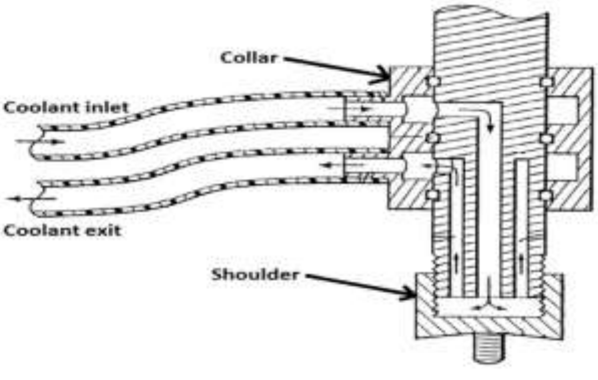

Figure 8. Internally cooled FSW tool [41]

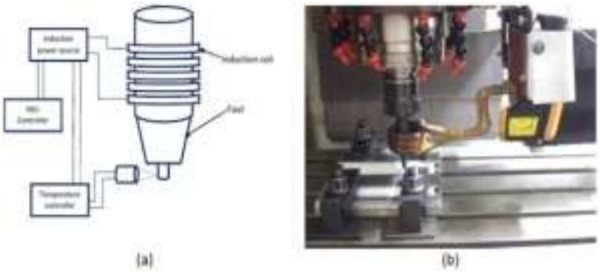

Figure 9. FSW tool with induction coil : a)Schematic, b)Set-up [39]

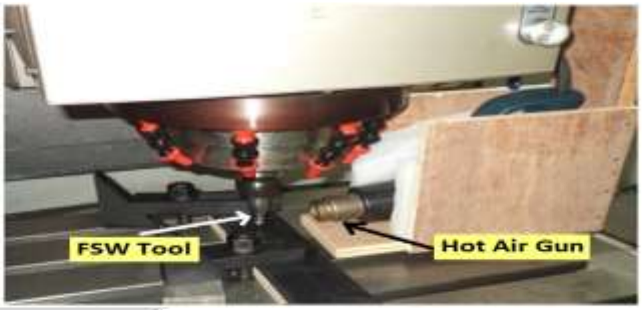

Figure 10. FSW tool with hot air gun [27]

VI. CONCLUSION

The prominent aspects such as tool geometry, materials, mechanical properties, IMC's formed and process parameters for dissimilar Al-Cu welds have been summarized with special emphasis on tool pin profile. The effects of tool geometry on tensile strength of weld with respect to tool pin, tool shoulder and SPR ratio have been discussed. Stress concentration in weld for conical pin tool is considerably more as compared to that of inverse conical pin tool resulting in greater eccentric loading and joint rotation when forces are applied at the ends of the unrestrained lap joints. The tool with pin having an inverse conical and unthreaded profile was also found to give good tensile strength with respect to both the base metals whereas tools with pin having cylindrical unthreaded and cylindrical threaded profiles gave good tensile strength with respect to aluminium base metal. Tensile strength achieved with penetration of 19.05 % with respect to the lower base metal sheet thickness was found to be significantly better than that with tool pin penetration of 9.52 %. At 0 % pin penetration, the samples had negligible strength. Further research needs to be carried out to find the optimum value of pin penetration for Al-Cu dissimilar weld system. A larger diameter pin results in good tensile strengths even at low tool rpm. However , a much larger tool diameter can result in excessive heat generation and result in a weak weld with cavity defects. For joining sheets with thickness 1 mm to 2 mm, tool with a shoulder diameter of approximately 10 mm will generate the required heat whereas for joining thick sheets i.e. 2 mm and above, tool with a larger shoulder in the range of approximately 15 mm to 20 mm would be suitable.

A tool with scrolled shoulder is found to give better surface morphology but produces undesirable IMCs. A tool with concave shoulder is more effective in trapping of material during welding as compared to that of tool with flat shoulder and thereby results in less flash. The tensile strength of joint is highest at SPR ratio of 3. The SPR ratio of 2.5 also resulted in good quality joints. However SPR ratio above 4 resulted in comparatively weaker joints. To provide sufficient heat for the FSW process, suitable heating arrangements such as induction coil or hot air gun can be used. Alternatively, excessive heating in FSW can be overcome by using the tool shank with fins or by using collars with circulating coolant.

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