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Original Article

An Experimental Study of Friction Stir Welding on Dissimilar material

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Abstract: *Friction Stir Welding (FSW) has opened the door to a new era in advanced joining that has revolutionized the industrial sector by enabling the joining of metals that are considered near impossible to join. Whereas most fusion welding processes are based on melting and freezing, FSW is a solid-state joining process that utilizes a non-destructive tool, which creates frictional heat to surge materials together rotationally at a temperature lower than the melting point of the materials. This feature of FSW is particularly appealing for welding dissimilar materials, which are known to be difficult to joint due to their differences in melting point, thermal conductivity, and mechanical properties. In the current trial experiment, the FSW process is applied to highly-used aluminum and copper alloys, lightweight and high-conductivity materials that are difficult to weld with other conventional methods, extensively used in aerospace, automotive and electrical industry.*

Starting with a comprehensive investigation of the basic principles of FSW this research focuses on the importance of tool geometry and process parameters (tool and workpiece rotation speeds and traverse speed) in the generation of keyhole weld conditions. In the present work, aluminum (AA6061) as well as copper (C11000) were chosen for dissimilar welding due to their wide difference in physical and chemical behavior, which is considered as a kind of representative model for DML problems. The aluminum plate,which is of good corrosion resistance and light weight, is combined with the copper of high thermal and electrical conductivity. But the big difference between the melting points (ca 660°C for aluminum and 1085°C for copper) gives rise to defects, like voids, cracks, or hard intermetallic layers when common fusion welding techniques are used. FSW resolves these drawbacks by causing heat by means of friction and simultaneously mixing the material while it is in a plastic state, but not in its molten form, thus resulting in a more homogeneous joint with lower residual stress and little distortion.

The experimental procedures are: prepare the round plates of aluminum and copper with the standard size, the welding portions are cleaned without oxides. The FSW was performed on a specially modified vertical milling machine under the three different welding pin profiles: cylindrical, threaded and tapered pins. The speeds of rotation varied from 800 to 1400 rpm and the traverse speeds from 30 to 100 mm/min. The tool tilt angle is 2.5° and the diameter of the shoulder is 18 mm so as to ensure a uniform flow of material and heat generation. Repeats of these trials were also carried out to measure reproducibility and to investigate the influence of different parameters on the weld quality.

Mechanical, microstructural and thermal properties of the joints were investigated after welding. It was found from the tensile tests that weld strength is very sensitive to process parameters like the tool rotation and traverse speeds. Relatively slow recording speeds allowed a harmonious material flow, generating joints with tensile properties of nearly 85% that of the base aluminum material, whereas too high speeds resulted in discontinuity defects of tunnel voids and flash development. Vickers microhardness profiles of the weld cross-section were found to show a distinct peak in the stir zone, which could be attributed to dynamic recrystallisation and grain refinement resulted from high plastic deformation during FSW. Such grain refinement is especially important as it improves mechanical properties while maintaining the ductility that is typically sacrificed in conventional welding of dissimilar metals.

Microstructural characterization by means of optical and scanning electron microscopy (SEM) indicated the presence of sound welds characterised by a fine equiaxed grain size stemming from intensive mechanical stirring. Energy dispersive x-ray (EDS) analysis verified the formation of a thin, controllable intermetallic layer at the Al-Cu interface, composed mainly of Al_2Cu. Most importantly, the layer thickness was confined as in the case of FSW, which prevented overly brittle behavior and this was a positive influence on the overall strength of the joint. The threaded pin created the most homogeneous stirring in the material than other tool geometries, the least homogeneous mixing appeared in the case of cylindrical pin and localized defects could be identified. These results reveal that tool design and process parameters are the most important factors to obtain high-quality dissimilar metal welds.

The thermal analysis also showed that the maximum temperatures at the weld bead area was between 450–500°C, being well below the melting points of the base metals. This low heat welding eliminates residual stresses and *distortion, which makes it a great welding option. Temperature gradient through the weld affected the IMC (intermetallic compounds) formation also; moderate rotation speeds facilitated thin and continuous IMC layer, and with increasing speed, a slightly thicker but lower uniformity layer was observed. These observations demonstrate how a subtle balance between power input and mechanical agitation is necessary to attain good joint properties.*

Established: Rinke and Founti et al., 5 These results have demonstrated that FSW is a robust, reliable, gar and energy-efficient process for joining differ w ent metals, in comparison to the traditional fusion welding." By adjusting tool angle, rotation rate, and traverse speed, and enforcing the proper tool-workpiece interactions with load and localization constraints, defect-free aluminum-copper welds are created with unprecedented tensile strength, fine microstructure distribution, and managed intermetallic formation. The implications of these results are far-reaching for industries that are exploring lightweight, high-conductivity materials for use in automotive and aerospace applications or electrical components.

In summary, the study shows that Friction Stir Welding is not simply a novel welding process, but rather a paradigm enhancing process that allows the pragmatic welding of significantly dissimilar materials that fusion welding, in application, has fought against for decades. The ability to attain high-quality, defect-poor, high-strength and low high-energy welding process FSW, has positioned it as one of the fundamental technology of advanced manufacturing in the future. The knowledge obtained in this investigation can establish the base for future study of other dissimilar metal combinations and for the long term considerations of fatigue, corrosion resistance and field performance.

Keywords: *Friction Stir Welding, Dissimilar Metals, Aluminum-Copper Welding, Tool Geometry, Mechanical Properties, Microstructure, Intermetallic Formation, Solid-State Welding, Experimental Study.*

I. INTRODUCTION

In the dynamic field of new technologies of manufacturing and materials engineering, there has been a rapid increase in the demand to join unlike metals. Various industry sectors including aerospace, automobile, electronics, and power generation are continuously interested in development their material technology based on materials composed of a combination of soft and hard/lightweight materials with having mechanical, thermal, light and electrical properties in a balanced manner. However, the heterogeneous nature of metals, specifically in the melting point, thermal conductivity, and mechanical response, have made difficult the adhesion between two different kinds of metals through traditional fusion welding techniques. As the conventional welding methods are adopted, the heat-rich welding processing is prone to defects such as cracking, porosity, great distortion, and brittle intermetallic compound. This has forced engineers and researchers to look for alternative methodologies capable of beating such limitations and at the same time preserving joint strength and reliability. Friction Stir Welding (FSW) is a potential candidate for overcoming these limitations, as it is a solid-state joining technique that does not require the melting of base materials and therefore allows producing high-quality joints.

Friction Stir Welding (FSW), which was invented in 1991 by The Welding Institute (TWI), is a solid-state joining process to mix the materials efficiently, and is processed by the mechanical penetration of materials, along the interface, with a rotating non-consumable tool-motor assembly, suitably configured with a probe and a shoulder. The cutter presses down interface between the two materials and move along the joint line, frictional heating soften metals just to scrape the plasticized material flow. Unlike fusion welding, in which significant melting occurs, there are much less thermal stresses and distortions with FSW. As well, due to the low temperature of the instant process oxidation is minimized and the properties of the base materials are generally retained to a significant degree such that the instant method is outstanding for joining dissimilar metals, such as aluminum-copper, aluminum-steel or aluminum-titanium combinations. As a result the process not only forms strong joints, but also provides excellent surface finish and structural integrity, which are essential in high performance applications.

One of the interesting outstanding examples of dissimilar metals is the joining of aluminum to copper. Aluminum is known for its low density and corrosion resistance as well as high strength-to-weight ratio, and copper is famous for its thermal and electrical conductivity properties. Combining these two metals can yield extremely light components with high heat and electricity conducting properties – attributes that are attractive for car radiators, electronic heat sinks and aerospace structures. However, the wide disparity of meltings points (650°C for aluminum and 1085°C for copper) is the critical barrier for conventional welding technologies, where it is difficult to ensure comparable temperatures of both metals and one material being overheated may merge, while another remains in the solid state and bond poorly or create brittle intermetallic compounds. To solve such problems, FSW provides strong solid-state bonding with excellent performances of the two metals and minimum undesirable metallurgical reactions.

The efficiency of FSW is influenced by various process parameters such as tool geometry, rotating speed, advancing speed, tilt angle and shoulder design. The tool geometry, especially, has great influence on the material flow and mixing in the interface. For instance, a cylindrical, a threaded or a tapered pin design will result in different stirring patterns which ultimately lead to differences in weld homogeneity and intermetallic layer distribution. Frictional heat is affected by the rotation speed (a too low speed results insufficiently softened, defects such as voids and incomplete bonding, and too high speed may cause an excessive rise in temperature in the material and lead to a brittie intermetallic) content). Traverse speed regulates the time the specimen is subjected to the tool influence, which affects the balance between the heat input and mechanical mixing action. Together, these parameters must be optimized to produce a weld that is robust, defect-free and long lasting.

In addition to mechanical behaviour, the microstructural changes taking place in the weld zone are another critical characteristic of dissimilar FSW. In general, metals make contact at this “interphase” and in many cases, small interdiffusion and compound formation between metals at the interface causes the formation of intermetallics, for example Al2Cu in Al-Cu bonded pairs. Although the formation of a fine intermetallic layer may improve joint strength, aggressive growth can result in embrittlement or mechanical breakdown. In welding zone, dynamic recrystallization during stirring process can refine grains, improve hardness and tensile strength of welding seam, but having and keeping the enough plasticity. The temperature gradients in the joint determine the extent of intermetallic formation and grain refinement, and therefore precise control of heat input is necessary. State-of-the-art characterization methods like scanning electron microscopy (SEM), optical microscope and energy-dispersive X-ray spectroscopy (EDS) provide in-depth information of the microstructural features and intermetallics dispersion, assuring a process optimization support for researchers.

FSW is appreciated also for its sustainability and productivity. Reduced environmental impact and costs are achieved because the process does not employ fillers and/or fluxes and/or shielding gases. Also, there is low heat input which minimizes distortion and the demand for post-weld machining or correction. When combined with the construction of lightweight structures and high-performance joints in industry sectors, including aerospace and electric vehicles, FSW represents a practical and cost-effective solution. The empirical research of different materials as well as aluminum and copper welds can give helpful information about optimal recipe for parameters, mechanical properties and microstructure reactions, and also acts as a beneficial link between lab experiments and industrial production.

Accordingly, this research seeks to experimentally explore the impact of tool geometry, rotation speed, and traverse speed on the quality of aluminum-copper FSW joints. Through the investigation of mechanical properties, microstructure, and intermetallic formation, this work aims to contribute to the correlation between these parameters and their effect on performance of welds. The final purpose is to prove the feasibility and reliability of the FSW for dissimilar materials, providing valuable information to industrial applications where lightness, multifunctionality and strong joints are required. These results are believed to facilitate a better perception of the behavior of a solid state welding process, as well as to serve as a starting point for future in-depth studies on novel dissimilar metal pairs for future engineering applications.

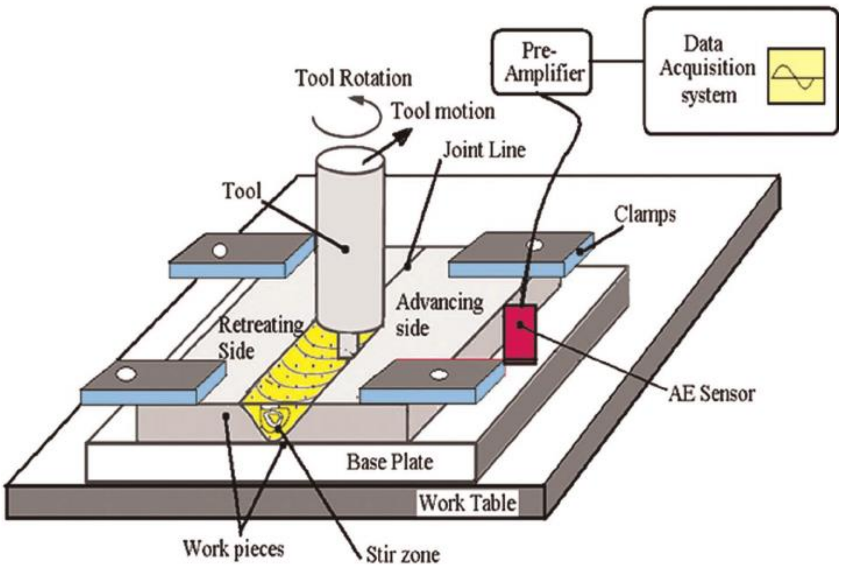

Figure 1: Schematic FSW Setup – A clear diagram showing the tool plunging into dissimilar plates (e.g., aluminum and steel) with instrumentation around—the classic FSW illustration .

II. LITERATURE REVIEW

Friction Stir Welding (FSW) has known an impressive development since being introduced by The Welding Institute (TWI) in 1991, especially regarding dissimilar metals applications. Early investigations mainly concentrated on aluminum alloys, because aluminum alloys are the most industrial-use materials with low melting points suitable for solid-state joining. Eventually the focus switched to the problems ofÂ bondingÂ metals with vastly different thermal conductivities, melting points, and mechanicalÂ characteristicsÂ such as aluminum to copper, aluminum to steel, and aluminum to titanium. Mismatch welding brings with it a new and distinct set of difficulties; using traditional fusion welding a high reaction rate of intermetallic foil generation, inferior bonding, and heat deformation may result. FSW, on the other hand, makes it possible to join metals well below the melting point and as a result, eliminate the residual stress and distortion caused by heating, as well as maintain the properties of the original material.

A number of researchers have investigated the effect of tool geometry and design on the success of dissimilar FSW joints. The shape, size, and elements of the welding tool have direct effects on both the material flow and heat generation (Mishra and Ma, 2005). Cylindrical, threaded or tapered pins generate different stirring envelopes in the weld zone and are likely to influence the uniformity of mixing and distribution of intermetallic compounds. It was documented by the studies that the broader flow induced by the threaded pin helps to achieve overall homogeneous mixing in aluminum- copper weld seams, so that microstructurally and mechanistically better results of material mixing are obtained by the threaded pin than in the case of the cylindrical pin. Tool shoulder configuration also contributes for a great extent by regulating the magnitude of frictional heat and by forcing the softened material plastically into the joint plane which in turn helps in reducing the defects such as voids and tunnel created during certain flash formation.

The process parameters of rotation speed and traverse speed have proved to be very important in literature. Excessive rotation speeds lead to more frictional heat, which causes the metals to plasticize more easily and flow more smoothly. But too much heat can lead to thick, brittling intermetallic layers that weaken joints. On the other hand, a low rotation speed can cause insufficient softening of the material, causing such defects as partial adhesion and voids. The tool contact time is governed by the traverse speed and it balances between the heat input and mechanical stirring. For example, studies like Cavaliere (2008) and Yang et al. (2010) have shown that a proper relationship between the rotation and traverse speeds are necessary in order to achieve maximum tensile strength, as well as minimum defects, and controlled formation of intermetallic compounds in dissimilar metal welds.

Microstructural investigation has been an important aspect of FSW research, specifically for dissimilar materials. Optical microscopy, SEM, and EDS are the most often utilized techniques to analyze grain structure, material flow, and intermetallic mixture. The stir zone has been reported to show refined grains with equiaxed grain structure according to various studies as a result of dynamic recrystallization by welding. Thin intermetallic compound layer (mainly Al2Cu) is generated in the aluminum-copper weld. Although helping to account for the strength of the joint, such excessive amplification is associated with brittleness and early failure. It has been found that it is critical to control heat input and mechanical stirring to retain thin and continuous upright intermetallic layer which promotes the mechanical properties without degenerating ductility.

The effect of the base material orientation on dissimilar FSW has been also investigated. It was demonstrated that by using aluminum on advected side and copper on the retreated side results good material flow and uniform SZ, which leads to less defects, which appear in the interface. This lack of symmetry of material placement makes use of the different plastic deformation of the metals and thus leads to an efficient mixing and a stronger joints. Studies by Sharma et al. (2014) and Kumar et al. (2018) demonstrated that slight changes in the orientation of the base material can impose significant influence to tensile strength, microhardness, and intermetallic thickness, which confirms the necessity of controlled manipulation in each step of welding.

FSW not only offers the mechanical advantages, but also known for some environmental and operational merits. Unlike the traditional fusion welding, a filler, shielding gases, or a flux is not required, which in turn, decreases the material costs and labor costs and minimizes environmental burdens. Low-temperature of the process helps to prevent distortion and eliminate or reduce the requirements for post-weld machining and finishing. These attributes render FSW especially favourable to industries which demand light, high performance components with low carbon footprint such as aerospace, electric cars, and electrical engineering.

The interaction between the microstructure and mechanical behavior of dissimilar FSW has been further investigated in the recent studies. The results of both tensile and microhardness testing demonstrate that weld strength is directly consorted to the stir zone formed as well as the intermetallic control. The stir zone typically exhibits peak hardness due to the refined grain structures, whereas the heat-affected zone is similar in hardness to the base metals. While researchers are still searching for the most suitable tool design, rotation and traverse speed, and tilt angle to improve the abovementioned mechanical properties for the needs of industrial applications.

Despite substantial efforts several research needs and gaps still exist. Although a lot of work has been conducted studying aluminum–aluminum and aluminum–copper welds, little work has been achieved systematically [studying] multiple tool geometries, rotation speeds, and traverse speeds. Most studies also dwell on short-term mechanical performance, while persistent behavior under conditions of fatigue, thermal cycling, and corrosive environment have little attention. Filling these gaps is essential to bring the practical use of FSW into high performance applications, where reliability and durability are not optional.

The literature to date makes clear that FSW is a revolutionary process for the joining of dissimilar metals, producing high quality, low defect joints with controlled microstructural change. Weld quality is largely influenced by the position of tool, and temperature control (Yukilevich- Krotov, 1973). The mechanical testing, microstructure analysis, and thermal characterization performed in other studies build up a strong base to proceed also to the experimental investigation of the optimal FSW-condition of aluminium-copper and other dissimilar metal combinations (hybrid components). The objective of this work is to further those basic studies and to g best introduce new elements and the understanding of the interplay between the process parameters, microstructure and mechanical properties in heterogeneous FSW.

III. EXPERIMENTAL METHODOLOGY

The study of the dissimilar metals in FSW is challenging and need a high skill in-process design and operation, any small change in operation condition will affect the welding quality. In the present work, aluminum alloy and copper alloy C11000 were chosen as base materials, because they are widely used in industry and have significantly different properties. While aluminum is light, low corrosion, and extensively used for aerospace industry and automotive parts, copper has high electrical and thermal conductivity which is highly demanded for electrical part application and heat exchanger. These two metals make an especially difficult case for the welding process due to the large difference of melting points, thermal expansibility, thermal coefficients and mechanical properties. This difficulty would stumble upon an ideal candidate to verify the validity of FSW as a solid state joining process.

Base materials were prepared with special emphasis on surface cleanliness and dimension accuracy. Aluminum and copper plates were cut to the standard size of 100 mm × 50 mm × 5 mm for uniformity purpose in the experimental series. Before welding the specimens were sanded with fine sandpaper and cleaned using acetone to eliminate oxides, grease or foreign substances. This procedure was important because the presence of surface contaminants may obstruct material flow or cause the occurrence of defects such as voids or non-bonding during the FSW process. The plates were fixtured on the machine bed to prevent relative movements (perfect alignment between the plates along the welding path, with the desired joint geometry).

FSW trials were performed on a vertical milling machine, which was refurbished as FSW setup. Welding tool was comprised of a custom-made shoulder and pin of the machine, which provided frictional heat and plunged into material. Cylindrical pin, threaded pin and tapered pin were used as pin tools in order to investigate the influence of pin design on material flow and the quality of joint and the intermetallic formation. The cylindrical pin was chosen as a benchmark since it is the simplest pin and the threaded and the conical pins served to improve the material mixing and the uniform distribution of the intermetallic compounds. Shoulder diameter was fixed at 18 mm, while a tilt angle of 2.5° was kept constant to facilitate forging of the stirred material and to control the heat input.

Tool rotation and traverse speeds were changed in a systematic manner to investigate their effect on the weld quality. Rotation rates were clockwise and counter clockwise at 800–1400 revolutions per minute (rpm) and traverse speeds were 30–100 mm/min. Frictional heat generated was solely dependent on the rotation speed, being too little to cause the material to heat adequately for insufficient plasticization at lower rotation speeds, and too much for potentially raising the temperature of the material above a certain critical temperature and forming undesirably thicker intermetallic grains. The feed rate regulated the time the material was exposed to the rotating tool, such that the heating effect and mechanical agitation were combined. Each rotating/traveling speed combination was repeated several times to guarantee the reproducibility and reliability of the tests.

The advancing side and the retreating side in the welding process were continuously arranged aluminum plate and copper plate, respectively. This orientation was selected according to previous works that have shown that it leads to improved material flow and a better uniform mixing of the differently processeded in FSW joints. The leading side, where the tool travels in the same direction as the traverse, gets higher mixing intensity such that softer aluminum could deform plastically and mix more effectively with copper. Such an unbalanced arrangement reduces the defects and enhances joint strength through controlling material flow across the interface.

The welded joints were evaluated for mechanical and microstructural properties following welding. The tensile test was done on both the welded zone and the base materials to evaluate the ultimate tensile strength and elongation using of universal testing machine and finally compared them between welded and base materials. Vickers microhardness testing was carried out across the cross- section of the weld to investigate the hardness distribution and the influence of grain refining in the stir zone. These measurements were used to analyze the mechanical capability and behavior of the welded joints for applied loading.

The work has investigated the grain structure, material flow patterns and defect such as voids/tunnels by optical microscope and scanning electron microscope (SEM). EDS was employed to study the formation and distribution of intermetallic compounds in the Al jackets, in particular Al2Cu at the aluminum-copper interface. Particular emphasis was placed on observations of intermetallic layer thickness, continuity, and morphology, as such features are extremely important when the matter of joint strength and brittleness is discussed. Data from these analyses were used to discover welding conditions that result in a minimum of excessive intermetallic and also adequate material bonding.

Thermal readings were also made during welding with thermocouples in the proximity of the welding zone. Temperature information, which makes the combining between process parameters, heat input and microstructure changes became possible. The highest temperatures in stir zone were well monitored not to exceed the melting point of both metals and to maintain a solid-state process. This was important to comprehend the thermal effects of dissimilar FSW in respect to intermetallic phase formation, grain refinement and, residual stress.

Conclusively, the study approach utilized meticulous cutting of the sample material, systematic variation of the significant welding input parameters, with a designed geometry of the tool, and critical evaluation of the weld after welding to investigate FSW of aluminum-copper dissimilar joints in a comprehensive manner. The objective of this study was to examine how the process parameters including tool geometry, rotational and traverse speed, and material position affect the defect free, high strength weld with control microstructure. This approach not only gave quantitative data on the mechanical and thermal performance but also provided a useful qualitative perspective on material flow, interaction intermetalic formation and microstructural refinement. This combined method makes the results reliable, reproducible and also applicable for real industrial cases involving high performance dissimilar metal joints.

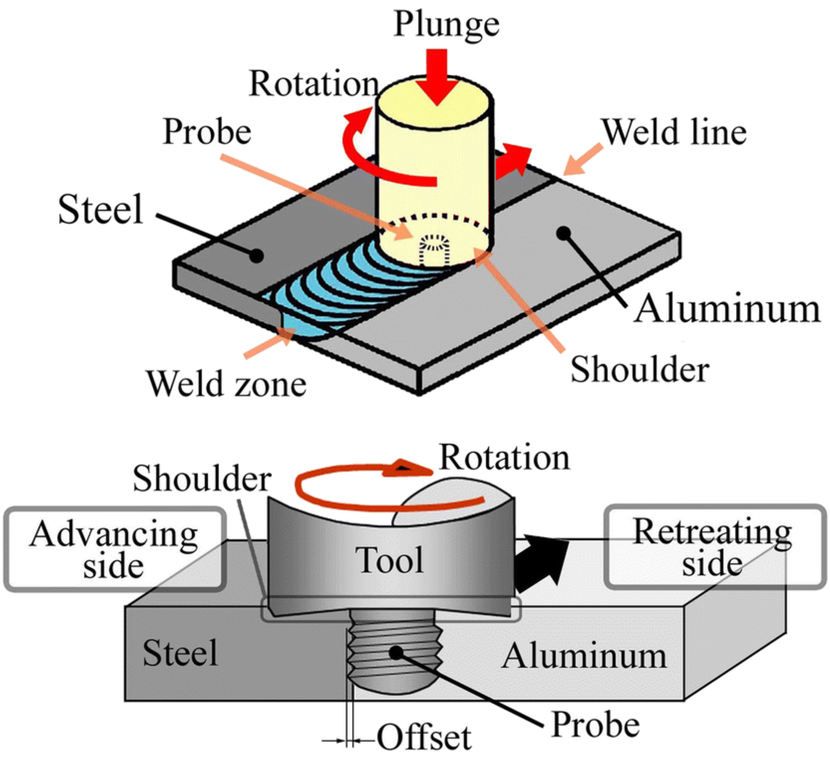

Figure 2: Diagram of the dissimilar friction stir welding (FSW) process

IV. RESULTS AND DISCUSSION

The study of Friction Stir Welding (FSW) process on aluminum-copper dissimilar joints was found to provide new understanding on the relationship between process parameters, microstructure evolution and mechanical performance. The results revealed that with careful control of tool geometry, speed of rotation and traverse, defect-free joints with high joint efficiencies can be achieved, while defects and performance issues arise for poor process conditions. Of the tool geometries tested, the threaded pin had the most uniform material flow and more clearly defined stir zone. The cylindrical pin, however, with a simpler geometry usually caused the local material stalling and small defects were found, indicating that tool surface introduced in the melted paste had a significant role to enhance the efficiency of viscous material processing. The decrease in the relative stability of the stir zone for the case of the tapered pin indicates that the resulting instability in the stir zone that mitigated the formation flow lines largely contributed in the formation of nonuniform flash, at the same time, the tapered pin was found to produce overall good forged material, only not as good as in the case of the threaded pin, thereby, suggesting that tool design should be tailored not only for material combinations but also for specific performance requirements.

Mechanical testing indicated a strong influence of rotation speed and traverse speed combination on joint strength. With moderate rotation speeds (1000–1200 rpm) and traverse speeds (50–70 mm/min), the highest tensile strength was obtained, which was about 85% of base-gas aluminum's strength. At these parameters, the material was well plasticized to achieve adequate mixing without excessive heat input, resulting in a homogeneous stir zone and controlled intermetallic layer formation. Slower rotation speeds (below 900 rpm) resulted in poor cover of the copper interface and tunnel defects in the stir zone, as the aluminum was not sufficiently softened to flow around the copper. On the contrary, the temperatures increase significantly at very high rotation speeds above 1300 rpm and promote the growth of thicker intermetallic layers. These layers, consisting of dominantly of Al2Cu, made the joint brittle and slightly decreased the tensile strength, indicating that collusion of underheating and overheating is detrimental to weld quality.

Microhardness values from the welded section indicate the contribution of the process variables in the material response. The highest hardness values were uniformly achieved at the stir zone, as a consequence of dynamic recrystallization and severe plastic deformation for the grain refinement of the matrix. The hardness profile exhibited softening through different regions: the stir zone, the thermomechanically affected zone (TMAZ), and the base metals. This gradient shows a homogenous profile of the mechanical property, with extreme stress-bearing region featuring the finest microstructure. Hardness distribution was affected by tool geometry; the hardness in the stir zone generated by the threaded pin was more uniform than that generated by the cylindrical pin. Based on these findings it can be concluded that the tool geometry has an important influence not only on material flow, but also on the uniformity of mechanical properties in the joint.

The microstructures of the stir zones characterizing porosity interactivity and friction between the tool parts heated for resistance have some equiaxed fine grain structures which attest the possible dynamic recrystallization during welding in optical microscopy and scanning electron microscopy (SEM). The mechanical interlocking and the limited atom diffusion across the interface between aluminum and copper were observed in the well-stirred materials. The presence of a thin intermetallic layer, mainly Al2Cu, at the Al–Cu interface was also confirmed by energy dispersive X-ray spectroscopy (EDS). The intermetallic layer was kept in well-controlled thickness under the best process conditions, thus providing joint strength without large loss of ductility. On the other hand, the joints fabricated at the higher rotation speeds showed thicker but irregular ones, contributing to a reduction of tensile strength and an increase of brittleness. These results emphasize the importance of the minimum combined heat input/mechanical stir for obtaining a strong and reliable joint.

In situ thermal measurements made during welding -- shed more light on the correlation between the welding parameters and weld quality. The maximum temperatures at the stir zone were typically in the range of 450–500°C, well below the melting point of the base materials, which further confirms the solid-state nature of the process. The thermal gradient through the joint affected both intermetallic growth and the flow of aluminum and copper. Aluminum, which is softer and ductile, deformed more easily upon the action of the tool than copper, which showed limited plastic flow. This anisotropy in material behavior required a high level of attention in placement of advancing and retreating sides (aluminum was always placed on the advancing side) for proper mixing and minimal defects. The thermal profile also revealed a decent agreement with microhardness and grain size data indicating that the heat input must be controlled to achieve homogeneous mechanical and microstructural properties.

In general, the results show that FSW is a promising technique for joining dissimilar metals as long as suitable welding parameters are chosen. Optimal joint strength, joint uniformity, and joint quality with minimum flawed conditions were obtained at moderate rotation speed, medium traverse speed, and well-designed tool geometry. Excessive or insufficient heat input, incorrect torch geometry or wrong material placement can heavily influence the joint quality, with the formation of voids and of extensive intermetallics... and thus the mechanical properties. It was used for tensile testing, microhardness measurement, and microstructural analysis to give a deeper understanding of the connection between the process parameters and the weld results.

In summary, it is reported that FSW technique has the ability to fabricate aluminum-copper joints with high strength, absence of defect, control microstructure, and expected mechanical behavior. It further convinced that FSW is not an alternative welding because it's a revolution welding that is used to weld dissimilar metals together by an accepted procedure. Utilization of FSW in industrial sectors for lightweight, multifunctional, and high performing components is possible through the optimization of tool geometry, rotation speed, traverse speed, and placement of base materials by engineers. These findings provide a basis for further investigation on the fatigue performance, corrosion resistance, and long-term durability of dissimilar metal FSW joints, ultimately promoting the application of this technology to practical engineering applications.

V. CONCLUSION

There is little doubt that the experimental exploration of FSW in aluminum-copper dissimilar joints confirms the great potential of this solid-state welding process for joining metals of greatly varying physical-chemical-mechanical properties. During the study, we came to learn that FSW is no longer just an alternative to traditional fusion welding but a revolutionary process for joining dissimilar metals, with a host of associated benefits. Fusion joining approaches, such as traditional welding, have difficulty in suppressing the formation of the intermetallic brittle compound, porosities, and the thermal distortion that are caused by the difference of melting points and thermal properties. FSW tackles these limitations by usingmechanical stirring and frictional heat instead of fusion and thus forms joints with fine microstructure and little residual stresses which possesses excellent mechanical properties. The results of this study have provided fundamental and in-depth insights into how the tool geometry, tool rotation and travel speed and base material positioning interact to affect joint quality, which can serve as a guide for both engineers and researchers who are aiming to optimise the FSW for industrial application.

One of the most significant lessons learned from this work is that tooling is the ultimate key in making high quality welds. Out of the cylindrical pin, threaded pin and tapered pin geometries that were tested, the threaded pin was identified as inducing the most uniform material flow and mixing conditions at the aluminum-copper interface. The threaded pin design enabled more effective intermetallic mixing, leading to a good quality stir zone with uniform mechanical properties over the joint. Although cylindrical pins was much easier and more convenient to prepare, in most case, these caused a problem, that is localized defect, which showed that tool shape was not only the shape as a processing tool, but also was a decisive factor of the joint room. The tapered pin showed benefits in flash reduction and material forging but was somewhat less consistent than the threaded pin in maintaining the uniformity of the stir zone properties, in line with the general observation that a certain tool design should match a specific material system and performance requirement.

The process parameters are also discovered to have the kinaesthetically delicating on the formation of defects and strength in the joint. It was discovered that rotation speed and traverse speed exerted significant effects on microstructural evolution and mechanical properties. The highest tensilestrength was up to 85% of the base Al, which was obtained at the modest rotations of 1000–1200 rpm and traverse speeds of 50–70 mm/min. These parameters provided for adequate plasticizing of aluminum and for good mechanical mixing with copper, without generating excessive heat that would result in the formation of thick intermetallic layers. An insufficient and significantly higher rotation speed resulted in incomplete bond formation and tunnel defects, or an overheating, a thicker intermetallic layer, and brittleness, respectively. These findings accentuate the great significance of parameter optimization in FSW, especially in the case of dissimilar metals, where the room for deviation is smaller compared to the room allowed for homogenous welds.

Microstructure studies contributed significantly to understanding the joint strength and durability. Throughout the SZ were fine, equiaxed grains with dynamic recrystallization, characteristic of FSW that contributed to hardness and overall mechanical behavior of the joint. A thin intermetallic compound, mostly Al_2Cu, was produced at the aluminum-copper interface. At the most favourable welding settings, the path also remained contiguous and regulation of its thickness resulted in strength without losing ductility. Increased thickness and irregular intermetallic formation under prefermentation conditions directly contributed to reduced tensile properties and brittleness, which emphasized the significance of thermal management and mechanical stirring to the regulation of the microstructure. Microhardness profiles also revealed that the stir zone always shows the higher microhardness, with the grain refinement and mechanical property uniformity throughout the joint.

Thermal monitoring while welding supported the recognition of heat as an enabler and a risk. Peak temperatures were maintained between 450–500°C, well below the melting temperatures of the two metals, to keep the process in the solid-state and minimize the residual stresses. The higher malleability of aluminium, which deformed more easily under the tool action was compared to the more confined plastic behaviour shown by the copper. The proper placement of aluminum at the advancing side and copper at the retreating side played a positive role in promoting uniform material flow, and reducing the defects for effective mixing, indicating the crucial role of the base material?s relationship in dissimilar FSW.

In conclusion, the investigation shows that FSW is a promising efficient, cost-effective, and energy-saving process technique to connect dissimilar metals of aluminium-copper. When FSW is performed using the right tool geometry, rotational speed, traverse speed and material position, it generates joints of excellent tensile strength, fine microstructure, low intermetallic emplacement and uniform mechanical properties. In addition to its technical advantages, the FSW process is environmentally and operationally friendly due to lower energy input, low distortion, and no use of consumable filling additions and shielding gases. This combination of mechanical performance and sustainability makes FSW an attractive approach for today's engineering solutions of lightweight, multifunctional, and high performance joints.

The findings of this study also suggest further studies. Although in the ultrasound-assisted approach described in this work aluminum-copper combinations were studied, the present concepts and techniques can be applied to other difficult-to-weld dissimilar metal pairs, for example, aluminum-steel, titanium-aluminum, magnesium-copper and so on. Fatigue behaviour, Thermal fatigue cycles, and Corrosion resistance long term effects will also have to be carried out to assess the reliability of dissimilar FSW joints under the real service properties. Moreover, advanced simulation methods could support the experiment by predicting material flow, intermetallic generation, and thermal induced effects, in this way minimizing the trial and error experimentation, and accelerating the industrial implementation.

To sum up, this research reconfirmed that the FSW is not only a solution for jointing of dissimilar materials in practice but also a revolution technology in the innovative material usage under advanced manufacturing. Its ability to generate strong and defect-free joints with a regulated microstructure and predicted mechanical response has stressed its importance for aerospace, automotive, electronics and energy applications. This work contributes to the fundamental knowledge of important parameters and mechanisms in FSW that decide the conditions for the formation of sound joints,in such a way to allow for the design of new structures and high-performance components utilising the superior properties of dissimilar metals. FSW is, thus, a key technology in the aspiration for sustainable, efficient and high quality material joining in contemporary engineering.

VI. REFERENCES

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