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Friction Stir Welding of AA6082 Aluminium alloy
A state-of-the-art Review

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Abstract — Friction stir welding (FSW) is a relatively new solid state welding process invented by The Welding Institute (TWI), Cambridge, UK in 1991 and has emerged as a new process for welding of aluminium alloys. This process has brought a new revolution in welding of aluminium alloys that were previously not recommended (2000 series & copper containing 7000 series aluminium alloys). Since no melting and re-solidification process occurs in materials subjected to FSW, the resultant weld metal is free of porosity with lower distortion. Welding input parameters play a very significant role in determining the quality of a weld joint. The joint quality can be defined in terms of properties such as mechanical properties and distortion. Generally, all welding processes are used with the aim of obtaining a welded joint with excellent mechanical properties and with minimum distortion. The main objective of the paper is to critically review various papers related to Friction stir welding of AA6082 aluminium alloy. This paper critically examines 8 different papers related to friction stir welding process of AA6082 and reveals the effect of various welding process parameters like tool rotation, transverse speed, tool tilt angle, plunge depth and tool geometry design, on the mechanical and microstructural properties the welded aluminium alloy or various dissimilar alloys. The review helps in selection of most significant process parameters, optimization of process parameters.

Keywords- *Friction stir welding, process parameters, mechanical properties, weld strength.*

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I. INTRODUCTION

Friction stir welding (FSW), a solid state joining technique invented by The Welding Institute (TWI) in 1991, and is one of the most significant developments in joining technology over the last half century. In FSW, the metal joining process occurs without fusion or use of filler materials and is derived from conventional friction welding. AA6082 is a medium strength alloy with excellent corrosion resistance. It has the highest strength of the 6000 series alloys. Alloy 6082 is known as a structural alloy. In plate form, 6082 is the alloy most commonly used for machining. As a relatively new alloy, the higher strength of 6082 has seen it replace 6061 in many applications. The addition of a large amount of manganese controls the grain structure which in turn results in a stronger alloy. It is difficult to produce thin walled, complicated extrusion shapes in alloy 6082. The extruded surface finish is not as smooth as other similar strength alloys in the 6000 series. FSW may produce high tensile stresses elsewhere in the components, FSW results in a much lower distortion and residual stresses owing to the low heat input characteristics of the process.

In FSW process rotating cylindrical tool with a shoulder and a profiled pin is plunged into the abutting plates to be joined and traversed along the line of the joint. The plates are tightly clamped on to the bed of the FSW equipment to prevent them from coming apart during welding. Figure 1 shows the schematic of the friction stir welding process. A cylindrical tool with a shoulder-pin profile rotating at high speed is slowly plunged into the plate material, until the shoulder of the tool touches the upper surface of the material. A downward force is applied to maintain the contact. Frictional heat, generated between the tool and the material, causes the plasticized material to get heated and softened, without reaching the melting point. The tool is then traversed along the joint line, until it reaches the end of the weld.

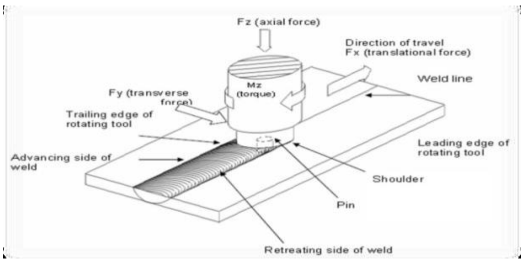

Figure 1. Schematic of Friction Stir Welding

II. CRITICAL AND SYSTEMATIC REVIEW

The different methodologies used for the microstructural and mechanical characterization of the friction stir welded joints are described here separately. This paper reviews the critical results of the influence of FSW process parameters on the microstructural and mechanical properties of friction stir welded AA6082 aluminium alloys as depicted in Table 1. The aim of this paper is to throw light on the used methodologies and the suggested improved methodologies to obtain good quality welds during the FSW process.

A. Scialpi, L.A.C. De Filippis et al (2006), investigated the effect of different shoulder geometries on the mechanical and microstructural properties of a friction stir welded joints. The base material used for the process was 6082 T6 aluminium alloy having thickness of 1.5 mm. The three tools studied differed in their shoulder geometries like scroll and fillet, cavity and fillet, and only fillet. The effect of the three shoulder geometries were analyzed by visual inspection, macrograph, transverse and longitudinal room temperature tensile test. The welding process was carried out rotating the tool at 1810 rpm and at a feed rate of 460 mm/min, with a 2^{o} tilt angle and a 0.1 mm plunge. The tool had a non-threaded pin with a 1.7 mm diameter and 1.2 mm height. The fillet was considered because it can reduce stress concentration due to cutting effect and increase the effective contact surface. Figure 2 shows the TFS, TFC, and TF tools used in the experimentation. Visual inspection of roots and crowns was performed in order to evaluate the shoulder influence on the joint quality. A qualitative analysis of crowns and roots revealed that the roots showed no defects. Figure 3 shows the crowns of the specimens. It was observed that the TFS tool produced a little amount of flash, but the crown is not smooth. The TFC tool produced a smooth surface and very little flash and the TF tool produced smooth crowns and little flashes. [1]

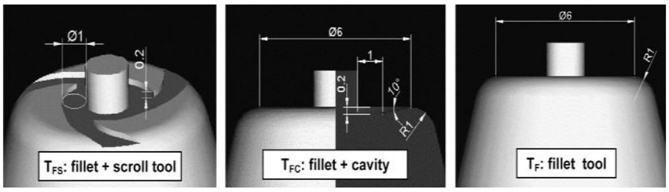

Figure 2. Tools used for the experimentation and their main dimensions in mm

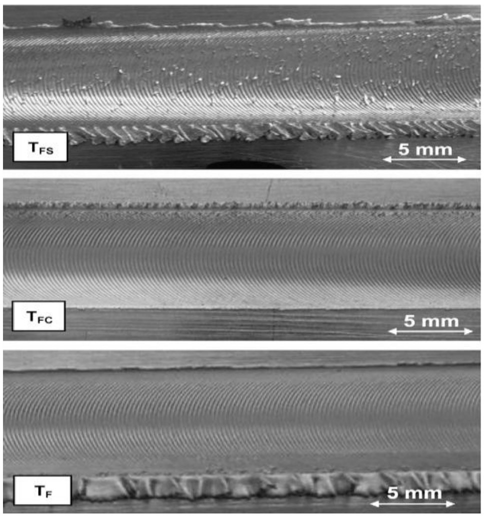

Figure 3. Crown obtained by various tools.

For metallographic analysis, all the joints were cross-sectioned perpendicularly along the weld direction. Figure 4 shows the macrostructure of the analyzed specimens. The transverse macro-sections revealed that, the joint region is divided into a thermo-mechanically affected zone (TMAZ) and heat affected zone (HAZ) with noticeable microstructure changes. It was also seen that the part of the TMAZ that experiences high strain and undergoes recrystallization is known as nugget zone (NZ).The optical micrographs revealed that deformation in the TMAZ resulted in severe bending of grain structure. This transition zone corresponded to the edge of welding tool's pin, in which no recrystallization was observed. This was because of the temperature derived from the friction stir processing was not high enough and deformation was not so severe to cause recrystallization. The HAZ zone showed similar grain size as that of the base material. A light influence of shoulder geometry was observed on the nugget grain dimensions, due to the varying heat power generated by the three shoulder profiles.

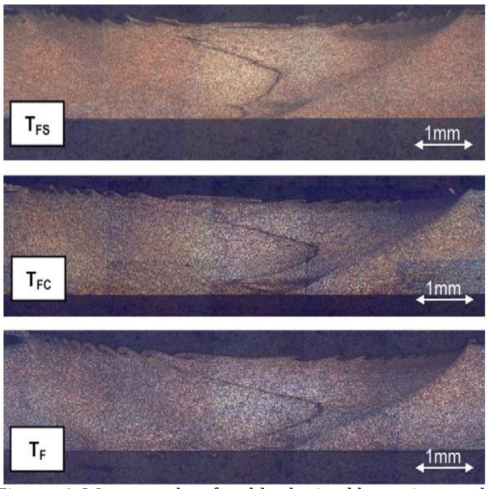

Figure. 4. Macrographs of welds obtained by various tools

In the Mechanical analysis, to evaluate the ultimate tensile strength (UTS) four repeated trials were performed to avoid measurement errors. The analysis revealed that for heat treated aluminium alloys, the weld showed acceptable tensile strength when the UTS of the specimen was higher than 66% tensile strength of the BM. In this analysis, the UTS has been evaluated with reference to a sheet having nominal thickness of 1.5mm. The welds can be considered good in terms of tensile strength. The fracture position in the welds reflected the position of hardness minimum, which means that the strength of the joints were only function of micro-hardness distribution and joints would be considered as defect free. The room temperature tensile behaviour of the material of the NZ and of the BM are showed in Figure 5. It was observed that, the higher tensile strength of the BM was due to the T6 heat treatment, while the higher elongation of the nugget was due to large grain dimension differences.

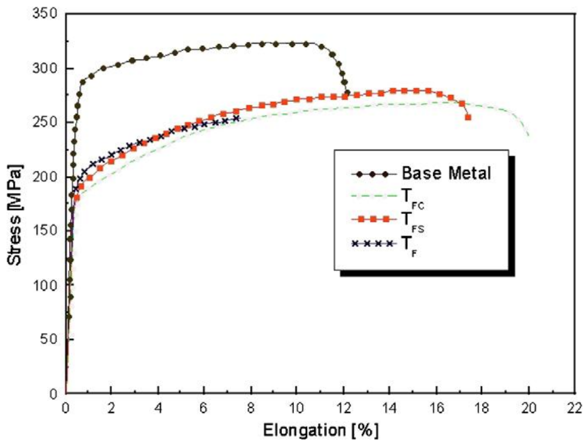

Figure 5. Engineering stress vs. strain curve of the studied joint compared with the base material

Finally the authors concluded that, TFC tool crown is considered to be the best in terms of crown quality. The resulting microstructure was widely investigated by optical microscopy putting out the influence of shoulder geometry on the nugget grain size. In the transverse tensile test the three joints showed good strength and non-considerable differences were observed, while great differences were observed in the longitudinal tensile tests of the stirred zone, because TFS (fillet + scroll) and TFC showed an higher and higher strength and elongation respect to the TF (only fillet). With 460 mm/min and 1810 rpm, TFC can be considered the best tool because the combination of fillet and cavity increases the longitudinal and transverse strength of the joint and provide the best crown surface.

P. Cavaliere, F. Panella et al (2007), investigated the effect of process parameters on mechanical and microstructural properties of AA6082 joints produced by friction stir welding. Various welded specimens were produced by using a fixed rotation speeds of 1600rpm and by varying welding speeds from 40 to 460 mm/min. The mechanical properties of the joints were evaluated by means of tensile tests at room temperature. The microstructural evolution of the material was analyzed corresponding to the welding parameters by optical observations of the jointed cross-sections of the fractured surfaces, to characterize the weld performances. The base metal used for investigation is AA6082-T6 commercial aluminium alloy. 200×80×4mm rectangular plates were welded perpendicularly to the rolling direction. The employed rotating velocities of the cylindrical threaded tool was 1600rpm while the advancing selected speeds were 40, 56, 80, 115, 165, 325 and 460 mm/min. The pin of the tool had a diameter of 6.0mm and was 3.9mm long. A 14mm diameter shoulder was used and the tilt angle was set equal to 3◦. The machine used for the production of the joints was instrumented with a Kistler three-channel load cell in order to record both forces along the tool axis, hereon denoted as FZ, and along the welding direction, hereon denoted as FX, for all the produced welds. Some specimens for the microstructural analysis were prepared by standard metallographic techniques and etched with Keller's reagent to reveal the grain structure. Tensile tests were performed in order to evaluate the mechanical properties of the joints obtained in the different welding conditions. The tensile tests were carried out at room temperature using a MTS 810 testing machine. Specimens were sectioned in the perpendicular direction along the weld line by employing an electrical discharge machine (EDM), the dimensions are shown in Figure 6. [2]

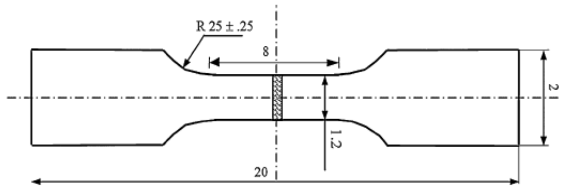

Figure 6. Dimensions of tensile test specimen

The microstructural behaviour of 6082 aluminium alloy joined by friction stir welding was studied by employing optical microscopy in all the conditions of welding speed at the chosen rotating one. In all the welding conditions, the flow of material inside the nugget was evidence for substantial plastic stirring during FSW. The microstructure of the material appeared very fine and equiaxed grains at all the welding conditions were noted by the difference with the starting microstructure revealing the classical elongated grains belonging to the rolling operations. A major difference in grain size and distribution was observed for different ranges of travel speed; up to 115mm/min the microstructure appears recrystallized but nor so uniform because of the different temperature and true strain reached during deformation at lower speeds. With the increase in the travel speed the nugget microstructure appeared more fine and uniform. A strong variation in the mean grain size was observed by increasing the advancing speed from 40 to 165mm/min, no further variations were observed when the speed was increased up to 460mm/min. It was also observed that if the temperature in the nugget zone is decreased then the force acting on the material is not enough to produce a plastic flow proper of a continuous dynamic recrystallization process, while by increasing the temperature of the material for travel speed too low for the used welding speed the material is extremely softened and can be subjected to grain growth after deformation.

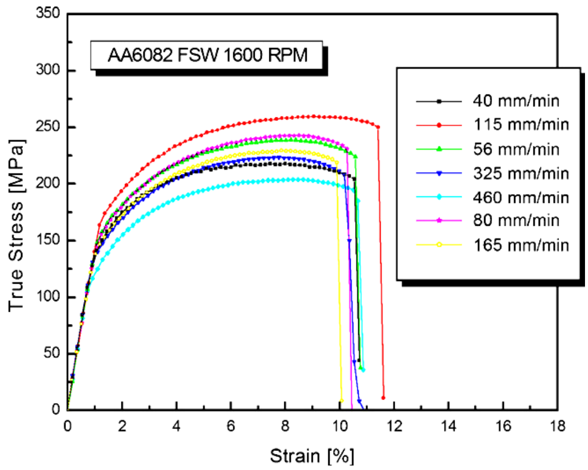

Figure 7. Tensile properties of the studied joints revealing the variation of the welds strength by varying the welding speed.

The base metal tensile properties of heat-treated 6082 aluminium alloy sheets are shown in Figure 7. For the welded joints, strong ductility variations, were calculated as strain to fracture and yield strength variations were measured as a function of the different advancing speeds. The yield strength increased rapidly from the lower speeds up to 115mm/min speed; the maximum yield point value was found to be around 185MPa and then decreased again with highest speeds, revealing strong hardening phenomena. On the other hand, the material ductility seemed to follow the same behaviour and the optimal mechanical properties with elongation equal to 11.6% were achieved around 115mm/min tool speed value, after which a sensible ductility reduction appeared.

Final observations revealed that, the yield strength increased strongly from the lower speeds to 115mm/min and after started to decrease with the increase in the advancing speed, the ductility of the material followed the same behaviour but restarted to increase after 165 mm/min.

P. Cavaliere, A. De. Santis et al (2009), investigated the effect of process parameters on the mechanical and microstructural properties of dissimilar AA6082–AA2024 joints produced by friction stir welding. The welded specimens were produced by varying the advancing speeds of the tool as 80 and 115 mm/min. During the whole experimentation the rotating speed was kept constant at 1600 RPM. The welds were produced perpendicular to the rolling direction for both the alloys. The tool used for the welds was of conical shape made from C40 tool steel with a large diameter of 3.8mm and small diameter of 2.6mm, the shoulder diameter measured 9.5mm. The micro-hardness tests of all the welded zones were measured on a cross-section perpendicular to the welding direction using a Vickers indenter with a 5 N load for 15 s. For evaluating the mechanical properties of the joints, tensile tests were performed at room temperature in a direction transversal to the welding line using a MTS 810 testing machine.

The macroscopic study of the joints revealed that, the cross-section typically featured of the nugget zones of dissimilar aluminium FSW joints, the nugget zones which appeared to be made up of different regions of both the alloys were severely plastically deformed. During FSW, the tool acted as a stirrer extruding the material along the welding direction. Such complex deformation produces the vortex structure composed of alternative lamellae of 2024 and 6082 aluminium alloys. The varying rate of the dynamic recovery or recrystallization strongly depended on the temperature and strain rate reached during deformation which is responsible for the different vortex like structure produced in the center of the welds.

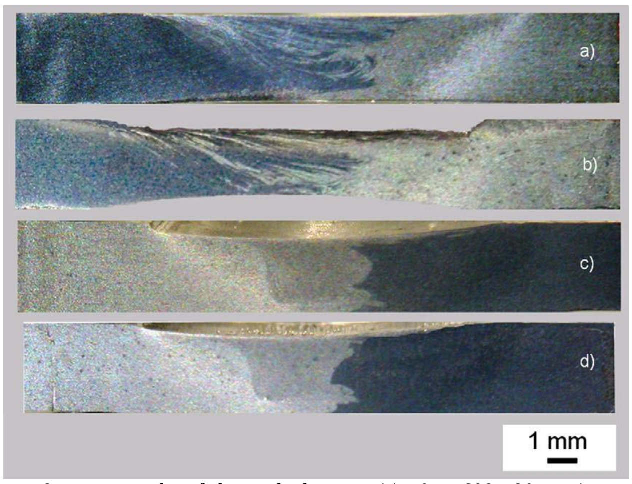

Figure 8. Macrographs of the studied joints, (a) 2024–6082 80 mm/min, (b) 2024–6082 115 mm/min, (c) 6082–2024 80 mm/min, and (d) 6082–2024 115 mm/min.

Figure 8 shows the classical microhardness profiles of dissimilar welds. The highest values of microhardness were reached in the case of dissimilar AA2024–AA6082 when the 2024 alloy was on the advancing side of the tool and the welding speed was 115 mm/min. When 6082 alloy was employed on the advancing side of the tool, the microhardness profile in the weld nugget appeared to be more uniform, indicating a better mixing of the material. In all the cases, the minimum microhardness is reached in the HAZ because of the overaging effect. This is due to the fact that the HAZ has been deformed very slightly, and has different thermo-mechanical behavior with respect to the nugget and the TMAZ

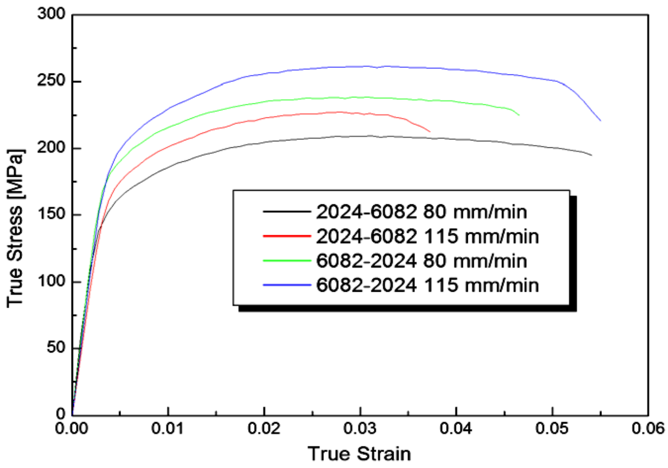

Figure 9. Tensile properties of the studied joints in different configurations

The tensile properties of the dissimilar joints obtained in the various welding conditions are shown in Figure 9. With the same material on the advancing side, the tensile strength increased with the increase in the weld speed of the tool. The value of ductility rises with increasing the weld speed in the case of AA6082 on the advancing side, while it decreases in the case of AA2024 on the advancing side. The best conditions of strength and ductility were reached in the joints welded with AA6082 on the advancing side and with the advancing speed of 115 mm/min. The joints showed lower strength in the dissimilar configuration due to the alternate lamellar structure, but they generally presented higher ductility. [3]

The final observations revealed that, the vertical force was found to increase with the increase in the travel speed for all the produced joints. The forces acting on the plates in the case of the higher strength material (AA2024) positioned on the advancing side of the tool resulted higher as compared to the corresponding welds with the softer material (AA6082) positioned in the advancing side. Different vortex-like structure resulted in the center of the joints in all the different configurations. The best tensile properties were obtained for the joints with the AA6082 on the advancing side and welded with an advancing speed of 115 mm/min.

T. Minton & D.J. Mynors (2006), investigated whether a conventional milling machine is capable of performing the task of friction stir welding, by producing same thickness welds of 6.3mm and 4.6mm 6082-T6 aluminium sheets using a Parkson Vertical Mill Type A machine. For carrying out the welding process, a single generic tool was designed for the 6.3mm sheet and truncated for the 4.6mm sheet followed by manufacturing from 19mm diameter silver steel. The pieces to be welded were abutted, bolted to a steel backing plate which was bolted directly to the machine's feed table. A FSW capability window with four levels A, B, D and E was designed based on the functional values of spindle speed, feed speed and tool tilt angle (1^{o}). The values for points 1, 2, 4 & 5 were to be determined. Several trials were undertaken to determine the FSW capability windows for two thicknesses, the first set of trials started with maximum speed indicated by point A. The feed speed was reduced in steps, working towards point 'B', until further reductions, based on auditory and visual inspection of the machine and the weld, were inappropriate. The path travelled was parallel to the line 'BD' starting on line 'AB'. The minimum feed speed was determined for the 6.3mm and 4.6mm sheets by setting the spindle speed to the maximum, 1550 rpm, and reducing the feed speed in steps from the maximum of 3.175 mm/s. The minimum spindle speed, for both thicknesses was determined by setting the feed speed to a value of 0.2646 mm/s and reducing the spindle speed from the maximum to minimum up to 620 rpm. With the coordinates of points 1, 2 and 4 determined, 5 was assumed from symmetry. A statistically valid number of welds were produced (and tested: tensile and hardness) using the values at the corners and centre of the capability window. For the two thicknesses three welds were completed for each of the five test conditions with each 86mm in length. Tensile tests were carried out on each welded specimen using an Instron tensile test machine followed by the micro- hardness test using a Future Tech micro-hardness tester with a 1 kg load.

For 6.3mm aluminium plates, all the 12 welds produced under condition 5 failed along the weld line, either within the tool footprint or beyond in the Thermo-Mechanically Affected Zone (TMAZ) or Heat Affected Zone (HAZ) since the HAZ is considered to be the weakest part of the weld and leads to the thermal softening of the material and the lack of compensating deformation. The material structure and weld properties were affected by the identifiable bands produced along the joint, due to the sweeping action of the probe within the TMAZ. It was observed that, almost 8 of the 12 welds failed on the advancing side of the tool while the remaining 4 failed on the retreating side. The dominance of 'advancing tool side failure' matches the observations, and is attributed to the sweeping of the material from the advancing to the retreating side of the tool as it rotates and traverses. The results indicated that even with a less optimal, the milling machine is capable of producing good quality welds. [4]

For welding the 4.6mm aluminium plates, the tool design was truncated by 1.7mm than the design of tool used for welding the 6.3mm aluminium plates. After carrying out the tensile test of each specimen, it was observed that five of the six welds produced under conditions 3 and 5 failed at the centre while 1, 2 and 4 failed within the tool footprint, some at the weld root. Also, the temperature of the plates being welded were much greater than during the 6.3mm trials. Greater amount of heat can be generated with a less optimal tool design and the type of tensile tests are related. The excess heat generated appears to have softened the material excessively at the centre for the conditions 2 and 4 and the large extension seen at the maximum load during the tensile test provides additional evidence for this. It was also observed that with the increase in the temperature, the level of the impurities also increases within the weld, especially at the contact point with the backing plate which enhance failures.

Thus the authors successfully demonstrated that a conventional milling was capable of performing FSW and producing reasonable welds using a relatively stout tool to join 6.3mm thick 6082-T6 aluminium. Lesser quality welds were produced when joining 4.6mm thick 6082-T6 aluminium.

P.M.G.P. Moreira, S.M.O. Tavares et al (2009), carried out mechanical and metallurgical characterization of friction stir welded butt joints of aluminium alloy 6061-T6 with 6082-T6. In view of comparison, all the material joints were made similar from each one of the two alloys used. The work included microstructure examination, microhardness, tensile and bending tests of all joints. The friction stir welds of 3 mm thick AA6082-T6 and AA6061-T6.plates were performed along the rolling direction. The process parameters selected were travel speed of 224 mm/min; tilt angle of 2.5°; rotating speed of 1120 rpm. For all the trials, a tool with smooth shoulder having 17mm diameter and concave angle 7° was used. For evaluation of the mechanical properties, tensile tests of 3 mm thick specimens drawn along transverse direction to weld line were performed according to ASTM E8-M using a 25 mm gage length and 1 mm/min cross-head speed. The reduced section is 60 mm and its width is 12.5 mm; the overall specimen length was 200 mm and the width of the grip section is 20 mm.

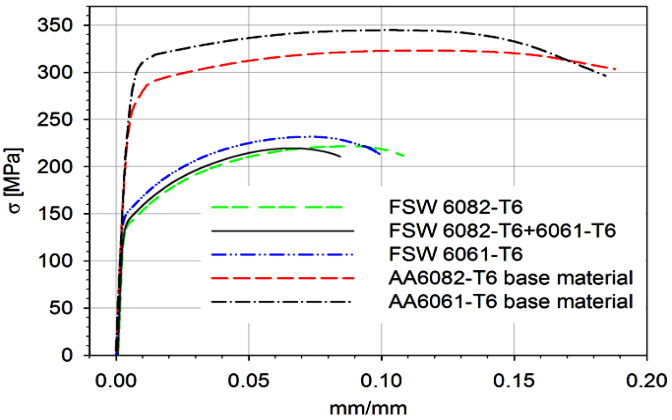

Figure 10. Tensile tests for welded material specimens.

The stress/strain records of welded and base material specimens are presented in Figure 1. The tensile test results revealed that friction stir welded and base material (BM) AA6061-T6 specimens presented higher yield and rupture stresses. The dissimilar welded joints showed intermediate behaviour. These joints also possessed the smallest elongation value, and their ultimate stress value was very close to the welded AA6082-T6. It was observed that, fracture occurred near the weld edge line, corresponding to the transition between the thermo- mechanically affected zone (TMAZ) and the heat affected zone (HAZ) and was characterized by the lower hardness.

The Vickers hardness profiles for all welded specimens are presented in Figure 11. A hardness decrease occurs when approaching the TMAZ. The average hardness of the nugget zone (NZ) was found to be significantly lower than the hardness of the base alloy. There is a zone outside the nugget (transition between TMAZ and HAZ) which has the lower hardness value. Hardness in the dissimilar joints presented the lower values of all joints. The lower values occur in the AA6082-T6 alloy plate side. The hardness in the nugget area is similar for all joints and it is always higher than the values in the transition between the TMAZ and the HAZ. The lowest hardness value was observed at the joint retreating side. Fracture in the tensile tests occurred in this softened region, which happened to be the weakest point of the specimen. [5]

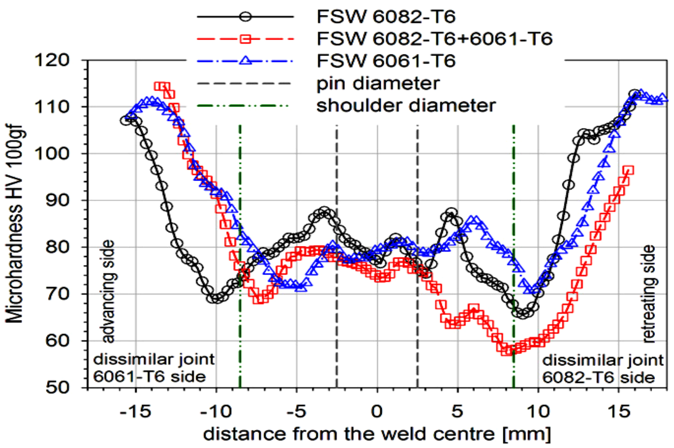

Figure 11. Micro-hardness profile of the FS welded specimens

Figure 12 shows the macrostructure of friction stir welds of each single material, and of dissimilar welds AA6082-T6 + AA6061-T6. In each macrostructure the sites for microstructure examination and different zones (NZ, TMAZ, and HAZ) were identified. At the centre, nugget zone, the mixture of the two different alloys is easily identified. The nugget zone experienced high strain and was prone to recrystallization. Immediately at its side is the TMAZ which ends at the tool shoulder. Outside of the TMAZ there is a zone affected only by the heat generated during the welding process.

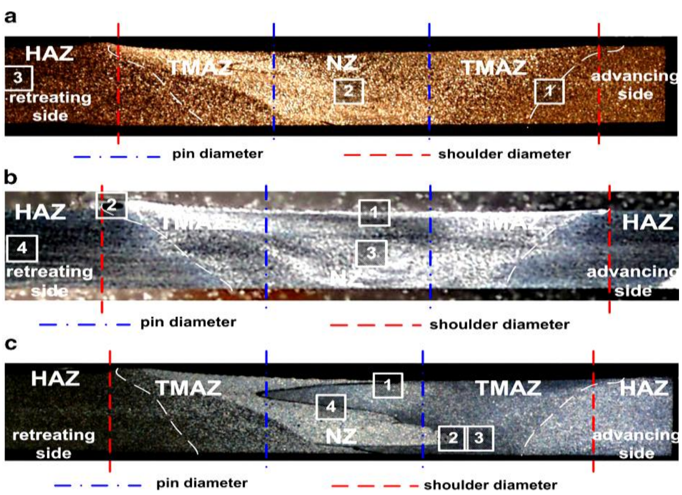

Figure 12. Macrostructure of the dissimilar weld and each base material: (a) macrostructure of the FS AA6082-T6 weld; (b) macrostructure of the FS AA6061-T6 weld; (c)macrostructure of the dissimilar weld.

The bend tests were carried out taking into consideration ASME code and NP EN 910 standard, using specimens with dimensions of 150×20×3 mm. During the test a 1 mm/min cross-head speed was used and two specimens for each type of weld and base materials were tested. No root flaws or other defects were detected in all joints. The load/displacement record was acquired during testing to identify the behaviour of each specimen, as shown in Figure 13. Both base material specimens present a linear behaviour until the load of approximately 420 N is reached. For loads higher than 420 N, for the same displacement the AA6061-T6 presents higher mechanical resistance. The three welded joints present a linear behaviour until a load of approximately 220 N. The friction stir welded AA6061-T6 joint supported higher loads than the friction stir welded AA6082-T6. The dissimilar weld joint shows an intermediate behaviour.

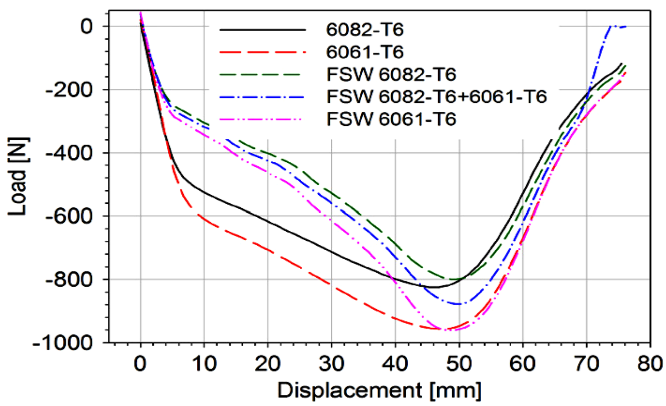

Figure 13. Bending test results.

Final observations revealed that, the friction stir welded AA6082-T6 material showed lower yield and ultimate stresses, and the dissimilar joints displayed intermediate properties. In the tensile tests, failures occurred near the weld edge line where a minimum value of hardness was observed. Microstructural changes induced by the friction stir welding process were clearly identified in this study. In bend tests, no root flaws or other defects were detected in all joints.

C. Leitao, D. M. Rodrigues et al (2012), investigated the influence of the plastic behaviour of two aluminium alloys. The two base materials, a non-heat-treatable (AA5083- H111) and a heat-treatable aluminium (AA6082-T6) alloy, were characterized by different strengthening mechanisms and microstructural evolution at increased temperatures. Their plastic behaviour, under different testing conditions, was analyzed and compared. The two base materials were welded under varied friction stir welding (FSW) conditions in order to characterize their weldability. The relation between weldability, material flow during FSW and the plastic behaviour of the base materials, at different temperatures, was analyzed.

In order to analyze the weldability of the AA5083-H111 and AA6082-T6 base materials, 6 mm thickness plates, were welded using different tools and process parameters. Conical shoulder tools, with cone angle of 5° and cylindrical threaded pins, were used. The welding speed (v), rotating speed (w), vertical force (F_z), shoulder and pin diameters (D_s and D_p, respectively) and tool pitch angle (a) were varied accordingly. The testing plan setup by combining the different tool and process parameters, resulted in to welding of total 36 specimens for each base material. After welding, all welds were visually inspected for identifying surface defects like flash and surface flaws. Transverse specimens were also cut from the welds, cold mounted, polished, etched and observed using the Zeiss Stemi 2000-C and Zeiss Axiotech 100HD microscopes, for detecting large and very small internal flaws as well as for analyzing welds morphology. The plastic behaviour of the AA5083 and AA6082 alloys was analyzed by performing tensile tests.

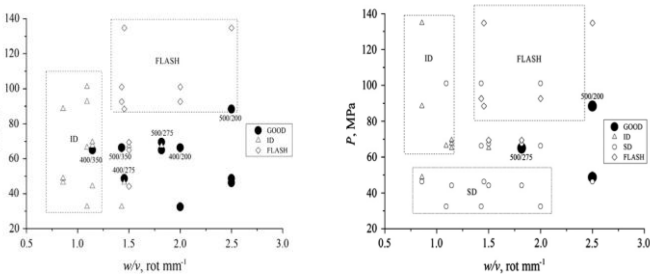

Figure 14. Welding results for the AA6082 and AA5083 alloy.

Visual inspection and metallographic analysis helped in identifying non-defective welds and three main types of defects: internal flaws and flash for both base materials, and surface flaws, for the AA5083 welds. Comparing the results from graphs obtained as shown in Figure 14, relative to the AA6082 and AA5083 alloy, respectively, it was possible to conclude that, for the range of welding parameters tested in this work, the AA6082 base material have higher weldability than the AA5083 base material. For both base materials, flash was mainly formed for the higher values of traverse speed ratio (w/v), corresponding to the higher heat input conditions, and for the higher values of pressure, P, corresponding to the use of the smaller shoulder diameter tool (D_s = 15 mm). For the lower w/v values, internal flaws (ID) were the main type of defect detected for both alloys. [6]

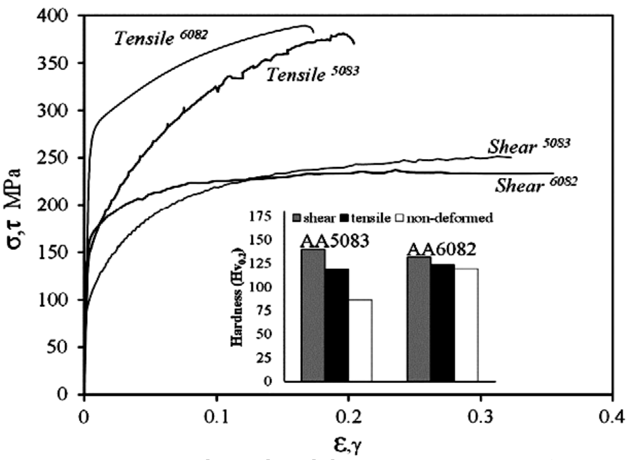

Figure 15. Base materials tensile and shear stress–strain curves (T = 25° C, 5 mm/min).

Figure 15 shows stress–strain curves for both base materials, obtained in tension and shear, at room temperature in quasi-static conditions. Analyzing the curves it is possible to conclude that the AA5083 alloy displays much lower yield strength than the AA6082 alloy, in both shear and tension. However, despite displaying much lower tensile yield strength, the AA5083 alloy exhibits strong Portevin-Le Chatelier effect and pronounced hardening with plastic deformation, attaining tensile strength values very close to that of the AA6082 alloy.

Final observations state that, according to the base materials mechanical characterization results, AA6082 is sensitive to intense flow softening during high temperature plastic deformation, displays good weldability in FSW. For the AA5083 alloy, which according to the base materials mechanical characterization results, displays steady flow behaviour at increasing temperatures, a very poor weldability was registered under the same welding conditions of the AA6082-T6 alloy. This behaviour results from the strong influence of the plastic properties of the base materials, at high temperatures, on material flow during welding, as well as on contact conditions at the tool work-piece interface.

Magdy M. El-Rayes, Ehab A. El-Danaf et al (2012), investigated the influence of multiple passes on the microstructural and mechanical properties of 6082 aluminium alloy. Commercial 6082-T651 AA plates having dimensions 120×100×6 mm were used. A series of Friction stir Process (FSP) runs were conducted perpendicular to the rolling direction at constant tool rotational speed of 850rpm and varying the work piece traverse speed and also the number of FSP passes. FSP was carried out perpendicular to the direction of rolling by applying one, two and three passes in an overlapping fashion as shown in Figure 16. The tool was manufactured from Mo–W tool steel with a flat shoulder of 15mm diameter, and a concentric square pin with an edge length of 6mm, and 5mm long. The FSP runs were conducted in the direction perpendicular to the rolling direction.

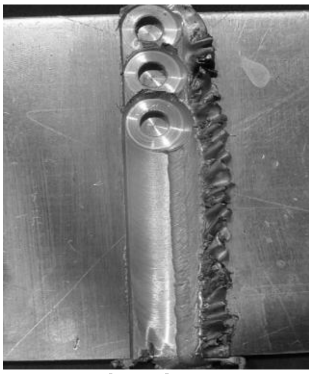

Figure 16. Friction stir processed sample using 3–100% overlapping passes.

The microstructural results showed that second phase particles existed within the entire base metal microstructure. The thermo-mechanical affected zone (TMAZ), was found in the close vicinity of stir zone (SZ), where the material experienced lesser strains and strain rates as well as lower peak temperatures compared to the SZ. The TMAZ was characterized by a less deformed structure, in which the parent metal-elongated grains are markedly bent due to plastic deformation into the direction inclined to the TMAZ/SZ boundary. The heat affected zone (HAZ) beyond the TMAZ is a zone which experienced a thermal cycle, but did not undergo any plastic deformation and still retained the same grain structure as the parent material. Increasing the number of passes at a given traverse speed, caused an increase in the grain size, this was due to the grain coarsening resulting from the additional/accumulated thermal cycles which the plate has experienced and the simultaneous occurrence of continuous dynamic recrystallization (CDRX) occurring with each FSP pass. [7]

Mechanical characterization of all variants of the process parameters resulted in similar microhardness profile. In general, it can be seen that the SZ became much softer than that of the unaffected base metal. In addition, the TMAZ still experiences more softening than the SZ. The relatively high hardness of the base material in the as-received condition is due to the type of treatment being T651. The TMAZ exhibited significant softening when compared with the SZ. Increasing the number of passes at constant traverse speed is accompanied by SZ softening. This softening is attributed to the larger grain size, accompanying the increase of number of passes. Increasing the traverse speed on the other hand, at a given number of passes, increases the SZ hardness however, this increase is slight with the three passes condition.

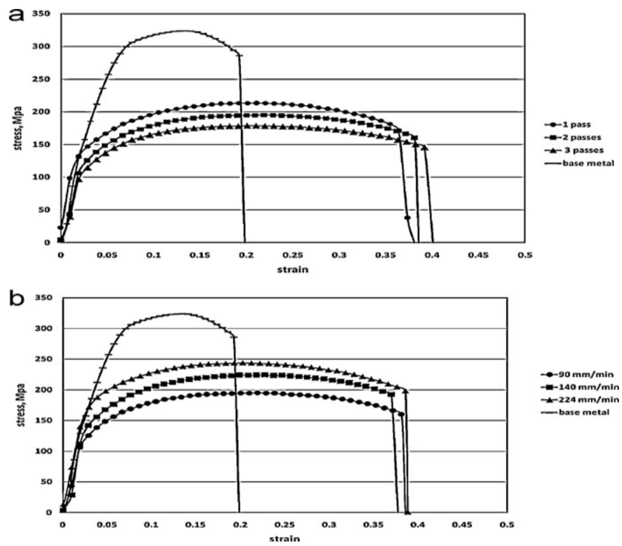

Figure 17. Stress–strain behavior of the SZ showing the: (a) influence of varying the number of passes at 90mm/min traverse speed; (b) influence of varying the traverse speed at 2 passes.

Figure 17 (a) and (b) shows the influence of varying the number of passes and the traverse speeds respectively on the stress–strain curves. In general, the ultimate tensile strength (UTS) and the strain at fracture within all specimens ranged within 178–244MPa and 0.36–0.4 respectively. On the other hand, the base material in the received condition parallel to rolling direction gave higher strength of 323 MPa, and less strain at fracture; 0.2 indicating that FSP reduces strength and enhances ductility. Increasing the number of passes at a given traverse speed decreases the UTS of the SZ. Increasing the traverse speed on the other hand increases the UTS.

Final observations revealed that, FSP caused dynamic recrystallization of the stir zone leading to equiaxed grains with high angle grain boundaries which increased with increasing the number of passes. Increasing the traverse speed on the other hand did not affect the grain size, yet reduced the particles size as well as increased the particle area fraction. Hardness and tensile test results of the stir zone were in good agreement, while increasing the number of passes caused softening and reduction of the ultimate tensile strength, whereas, increasing the traverse speed increased the strength and hardness.

A. Scialpi, L.A.C. De Filippis et al (2008), carried out the mechanical analysis of ultra-thin friction stir welding joined sheets with dissimilar and similar materials .The welded specimens were produced by FSW with 2024 Al alloy sheets in the T3 condition (solution heat-treated, cold worked, and naturally aged) and 6082 Al alloy sheets in the T6 condition. To perform the μFSW (FSW for ultra-thin joints) joints, two 0.8 × 125 × 250 mm aluminium plates were butt welded for a length of 250 mm longitudinally to the rolling direction. The behaviour of the welds was studied in two combinations of the process parameters, defined as μFSW_1 and μFSW_2. The 2024 and 6082 alloys were welded, respectively, in μFSW_1 and μFSW_2 condition, while the dissimilar 2024– 6082 joint was produced only in μFSW_2, which represents the optimized condition for the weaker alloy. The used welding tool was constructed from a 56NiCrMoV7-KU material and it has a cylindrical non-threaded probe with a 1.7 mm diameter, 0.6 mm height and a shoulder with 6 mm diameter. Since the macrostructure and, consequently, the mechanical properties of the Stirred Zone are mainly governed by the retreating side material the dissimilar weld were produced with 2024 Al alloy (higher strength) positioned on the retreating side and 6082 on the advancing side. A visual inspection of roots and crowns of the obtained welds was undertaken in order to evaluate the butt joint quality. All the welds were cross-sectioned perpendicularly to the welding direction for metallographic analysis.

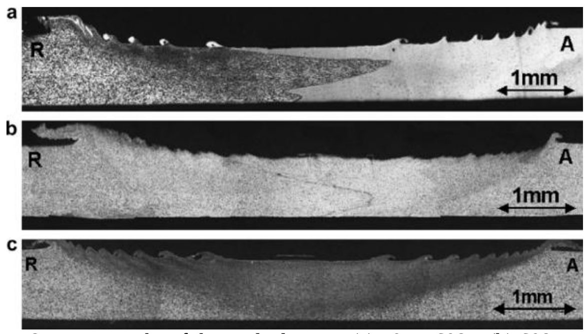

Figure 18. Macrographs of the studied joints: (a) 2024–6082, (b) 6082 to itself and (c) 2024 to itself (R is retreating side, A is advancing side).

The microstructural study of the obtained joints showed no porosity or other defects in both top and root weld surface in the two welding conditions. Figure 18 shows the macrographs of the produced welds. From the different etching response of each material the 2024 Al alloy appeared darker colored than the 6082 one. It was clear that the microstructure of the Stirred Zone is mainly composed of the 2024 alloy fixed on the retreating side. Macrographs of the 6082 and 2024 welded with themselves are shown. unlike FS Welds of similar alloys that exhibit four distinct regions, namely Parent Material, Heat Affected Zone (HAZ), Thermo-Mechanically Affected Zone (TMAZ), and Stirred Zone (also

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called Nugget), the dissimilar welds exhibit eight distinct regions (a) Parent Material, (b) HAZ, (c) TMAZ and (d) Stirred Zone for the2024 Al alloy and (e) Stirred Zone, (f) TMAZ, (g) HAZ and (h) Parent Material for the 6082 Al alloy. The Stirred Zone was the region that experienced the highest strain and had undergone recrystallization. Its microstructure is due to mechanical action of the tool probe that generates a continuous dynamic recrystallization process. The higher temperature and the severe plastic deformation during the welding in the Stirred Zone result in a new equiaxed fine grain structure with an estimated grain dimension < 3 µm both for 2024 and 6082. By moving towards the base metals, adjacent to the Stirred Zone, there was the TMAZ where no recrystallization was observed. It seemed that the temperature, derived from the process, was not high enough and deformation was not so adequate to cause recrystallization. The region adjacent to the TMAZ is the HAZ, where the grain size is similar to the base metal. The HAZ experienced a peak temperature which results in a hardness decrease. Adjacent to the HAZ, there was the base metal.

Tensile mechanical properties of the achieved FS Welded joints have been evaluated by means of standard tensile tests in the transversal direction; the standard UNI-EN 10002^{-1} was used for reference and five specimens for each jointed materials have been prepared. The tests were performed at room temperature with deformation velocities below 10^{-4} s^{-1}. It can be remarked that the dissimilar welded specimens exhibit a reduction of the mechanical strength with respect to the 6082 base material properties of the same order as the equal material µFSW joints, 30% reduced values for the ultimate tensile stress (UTS); at the same time, ductility properties in terms of maximum elongation to rupture and tensile curve shape are also slightly reduced, as visible in Figure 19.

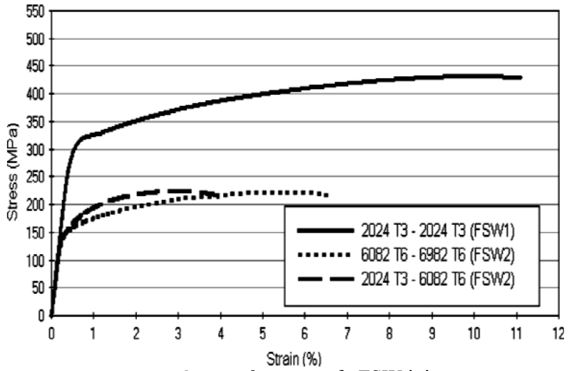

Figure 19. Tensile curve of µFSW joints.

These results were good enough, considering the typical decaying behaviour of welded joint with respect to the base metal. In particular, the 2024 welded specimens showed very high UTS values (about 91% of the base material strength, that is 470 MPa) and elevated yield strength. The 6082– 6082 and the 2024–6082 joints showed similar strength with an UTS about 69% of the 6082-T6 base material (330 MPa). [8] All the studied welds showed very limited data spreads for yield and ultimate stresses and elongations. The results show that these joints show excellent mechanical properties: tensile tests show that the failure occurs in the welded zone and it was by the irregularities in thickness rather than by the presence of defects; the elongation to failure remains good, especially if compared with traditional welding techniques.

TABLE I. SUMMARY OF THE RESEARCH PAPERS

Pp No.	Author	Substrate material	Methods and Parameters used for study.	Conclusions
1.	A. Scialpi, L.A.C. De Filippis	AA 6082 alloy	Mechanical and Microstructure testing, Tool and Shoulder geometry.	-The tool shoulder with combination of fillet and cavity proved to be the best, which increased the longitudinal and transverse strength of the joint and provide the best crown surface.
2.	P. Cavaliere, F. Panella	AA 6082 alloy	Mechanical and Microstructure testing, welding process parameters	-Strong variation in the nugget mean grain size with increase in the advancing speed. -The yield strength tends to increase at lower speeds but starts decreasing with the increase in advancing speeds.
3.	P. Cavaliere, A. De. Santis	AA6082–AA2024 alloy	Dissimilar joints, Mechanical and Microstructure testing, changing the alloy positions.	-The forces acting on the plates in the case of the higher strength material (AA2024) positioned on the advancing side of the tool resulted higher with respect to the corresponding welds with the softer material (AA6082) positioned in the advancing side -The best tensile properties were obtained for the joints with the AA6082 on the advancing side and welded with an advancing speed of 115 mm/min.
4.	T. Minton & D.J. Mynors	AA 6082 alloy	Use of Milling Machine for performing FSW, Mechanical and Microstructure testing.	-Successful demonstration to show that a conventional milling is capable of performing FSW and producing reasonable welds using a relatively stout tool to join 6.3mm thick 6082-T6 aluminium. Lesser quality welds were produced when joining 4.6mm thick 6082-T6 aluminium.

5.	P.M.G.P. Moreira, S.M.O. Tavares	AA6061-AA6082 alloy	Similar and dissimilar welding, Mechanical and Microstructure testing, Bend Testing.	-The friction stir welded AA6082-T6 material showed lower yield and ultimate stresses, than the dissimilar joints with intermediate properties. -In the tensile tests, failure occurred near the weld edge line where a minimum value of hardness was observed. Microstructural changes induced by the friction stir welding process were clearly identified in this study. -In bend tests, no root flaws or other defects were detected in all joints.
6.	C. Leitao, D. M. Rodrigues	AA5083-AA6082 alloy	Welding process parameters, Plastic behavior, weldability.	-AA6082 is sensitive to intense flow softening during high temperature plastic deformation, displays good weldability in FSW. -AA 5083 alloy displays steady flow behaviour at increasing temperatures, and very poor weldability.
7.	Magdy M. El-Rayes, Ehab A. El-Danaf	AA 6082 alloy	Multiple pass FSW, Mechanical and Microstructure testing	-Dynamic recrystallization of the stir zone occurred leading to equiaxed grains with high angle grain boundaries which increased with increasing the number of passes. -Increasing the number of passes caused softening and reduction of the ultimate tensile strength, whereas, increasing the traverse speed increased the strength and hardness.
8.	A. Scialpi, L.A.C. De Filippis	AA2024 - AA6082 alloy	Dissimilar welding, µFSW (FSW for ultra-thin sheets), Mechanical and Microstructure testing	-The 2024 welded specimens showed very high UTS values (about 91% of the base material strength, that is 470 MPa) and elevated yield strength. The 6082– 6082 and the 2024–6082 joints showed similar strength with an UTS that is about 69% of the 6082-T6 base material (330 MPa). -Tensile tests show that the failure occurs in the welded zone and it is by the irregularities in thickness rather than by the presence of defects.

III. CONCLUSION

All the cases studied in the above paper were related to the microstructural and mechanical characterization of friction stir welded joints for AA6082 aluminium alloy. It is found that there is drastic change in the microstructural and mechanical properties of the joints with the changes in the process parameters and the tool geometry. Thus it proves that good quality weld joints can be obtained by proper selection of process parameters and using appropriate tool geometry. Table 1. Shows the summary of the research papers on FSW of AA 6082 aluminium alloy.

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