Chapter

Investigations on Friction Stir Welding to Improve Aluminum Alloys

Bazani Shaik, Gosala Harinath Gowd and Bandaru Durga Prasad

Abstract

Today is an era of metals including Aluminum alloys owing to a fundamental paradigm shift in research objectives. In addition to superior performance and lightweight criteria that are used to define the innovations of yore, scientists today are compelled to take into consideration the environment-friendliness of the new and novel materials being developed due to the concerns of maintaining a sustainable and safe existence. The solid-state Friction stir welding process has immense potential in the areas of automobiles, aerospace and construction industries due to its overwhelming advantages over the conventional fusion welding process of aluminum alloys. The thesis presents an experimental investigation of friction stir welding of dissimilar aluminum alloys AA7075T651 and AA6082T651. Mathematical modeling equations are developed to predict the tensile strength, impact strength, elongation, and micro-hardness of the dissimilar FSW joints AA7075T651 and AA6082T651. The process parameters are optimized for maximum tensile strength and hardness values. Post weld heat treatment is conducted and the metallurgical properties of the FS welded AA7075T651 and AA6082T651 are presented for different combinations of tool rotational speeds. Aluminum and its alloys are widely used in nonferrous alloys for many industrial applications. Aluminum exhibits a combination of an excellent mechanical strength with lightweight and thus it is steadily replacing steel in industrial applications where the strength to weight ratio plays a significant role. In conventional welding, the joining of aluminum is mainly associated with a high coefficient of thermal expansion, solidification shrinkage and dissolution of harmful gases in the molten metal during welding. The weld joints are also associated with segregation of secondary alloys and porosities which are detrimental to the joint qualities. Friction Stir Welding (FSW) and Friction Welding (FW) are the most popular emerging solid welding techniques in aircraft and shipbuilding industries. FSW is mainly used for the joining of metal plates and FW is mainly used for the joining of rods. Both techniques are suitable for high strength material having less weight. These techniques are environmentally friendly and easy to execute. Hence, the study of these techniques can contribute much to the field of green technology. This research work is dealt with the experimental and numerical investigations on FSW and FW of aluminum alloys.

Keywords: Dissimilar Aluminium Alloys, Friction Stir Welding, Process Parameters, Tool

1. Introduction

Some of the previous research works already done by the researchers have been discussed hereafter. **Landry Giraud** et al. [1] Studied the AA7020T651 and AA6060T6 on friction stir welding of dissimilar heat treatable aluminum alloys 7020-T651 and 6060-T6. An experimental analysis is presented based on results obtained from temperatures and efforts measurements in a range of advance speed from 300 mm.min − 1 to 1100 mm.min − 1 and rotational speed from 1000 rev. min − 1 to 2000 rev.min − 1. Dissimilar welding does not seem to induce a hotter side but efforts are very sensitive to process parameters.

Prakash Kumar Sahua et al. [2] investigated dissimilar friction stir welding between aluminum (Al) and copper (Cu) at tool rotation rate of 1200 rev/min, welding speed of 30 mm/min, 0.1 mm plunging depth and 1.5 mm offset towards Al alloy yield highest ultimate tensile strength of 126.0 MPa and yield strength of 119.3 MPa which constitute 95% and 100%, respectively, of the 1050 Al base metal. The highest compressive strength and the bending angle were 7.8 MPa and 65°, respectively, for the specimen with the highest tensile strength. The hardness at the Cu side of the nugget is higher than that at the Al side. In the case of experiment E8 which yield the highest tensile strength, the maximum hardness at the NZ was 176 HV and the average hardness at NZ was 60 HV. Line scanning indicated a mixed flow of Al/Cu materials throughout NUGGET ZONE. **I.A. Kartsonakis** et al. [3] The dissimilar joining of AA6083T3 and AA5083H111 alloys with Tic nanoparticles, multi-wall carbon nanotubes, and cerium molybdate containers reinforcement. AA5083-H111 rich areas in the WN as well as the intergranular corrosion in the AA6082-T6 rich areas in the WN area. Moreover, MoO4 -2 ions that come from the container shell, are adsorbed onto the surface of both resulting in their protection of chloride penetration. Finally, the corrosion process is probably further inhibited due to the formation of cerium oxide films on the cathodic sites of the WN area. **M.-N. Avettand-Fènoël** et al. [4] Studied microstructural and mechanical characterization of an AA2024 – pure Cu linear friction weld. The interface is covered by a discontinuous layer of intermetallic compounds. Al_2Cu, AlCu, Al_2Cu_3 and more particularly Al_4Cu_9 were detected. Two metastable phases, i.e. an Al_3Cu_2 compound and an out-of-equilibrium Al solid solution containing 13 at % Cu, were also identified at the interface and on the Al side, respectively. The weld presents a joint coefficient lower than 0.5 for the yield strength and close to 0.3 for the ultimate tensile strength, and its brittle fracture, initiated by the intermetallic compounds, occurs at the interfacial zone. Due to this drawback, some routes of improvement of the Linear Friction Welding process are finally proposed.

U. Donatus et al. [5] Investigated AA6082T6 and Aa5083-O the effectiveness of the anodic oxide layer formed by a novel processing technique (pre-sputter-deposition prior to anodizing) for the corrosion protection of friction stir welds of dissimilar aluminum alloys. It is important to reiterate that the corrosion attack reported in this study are in two categories: (i) the pre-anodizing attacks caused by the anodizing solution at preferentially susceptible regions such as regions of aligned active second phase particles and grain boundaries which were observed in the HAZ of the AA6082-T6 alloy; and (ii) the post anodizing attacks caused by the etching solution which were particularly observed on the AA5083-O alloy regions. The pre-anodizing attack was completely prevented whilst the post-anodizing attack was significantly minimized by prior sputter-deposition of 1 μm thick pure Al before anodizing.

D.G. Hattingh et al. [6] Studied the development of a semi-automated friction stir welding (FSW) technique for joining 38 mm nominal outer diameter (OD) tubes of 6082-T6 aluminum alloy with 3.5 mm nominal wall thickness.

The technique incorporates a retracting tool in order to avoid leaving a substantial hole in the joint line after extracting the tool at the end of the welding process. This is one of the very first applications of FSW to small diameter tubular geometries to be reported in the open literature and the technique is capable of producing small-scale production runs (circa 100) of welded tube specimens with consistent tensile and fatigue properties. The tensile strength of the extruded 6082-T6 tube was 303 MPa while the joint efficiency of the weld was 0.55 both for complete tube specimens and for micro tensile specimens. This compares well with values reported in the literature for 3 mm flat plate specimens of 6082 alloy.

G.K. Padhy et al. [7] Studied recrystallization fractions in the stirred zone of Al 6061-T6 friction stir welds, prepared with and without ultrasonic vibrations, were evaluated using recrystallization fraction maps. Based on the maps, it was suggested that the microstructure evolution can be described as different dislocation manipulation processes. It was observed that the superposition of the static load of FSW on residual ultrasonic softening induces subgrain formation. Subgrain formation was substantial at the center of the stirred zone where the ultrasonic impact was the maximum.

Sivaraman Thapliyal et al. [8] Studied the effect of normal load, sliding velocity, and surface temperature on the dry sliding wear behavior of friction stir processed C95500 nickel aluminum bronze (NAB) alloy. Adhesive wear behavior was studied using the pin on disk tribometer as per ASTM G99-04 standard, using two-level full factorial approaches. The friction stir processed (FSPed) surface under study showed a lower wear rate than as-cast alloy. The wear rate in both conditions, as-cast as well as FSPed, at high temperature was found lower than the one during ambient temperature condition. The wear model and operating wear mechanism were assessed through SEM study of the worn surface and wear debris.

Ho-Sung Lee et al. [9] Studied for the joining of AA2195T0 and T8 FSW butt jointed, it is shown that the temperature in the advancing side is higher than the retreating side which supports the results of micro-hardness profile at nugget zone. For AA2195-T0, The weld zone can exhibit higher micro-hardness than parent material due to grain recrystallization and the hardness profile inside of the nugget depends on the cooling rate. For AA2195-T8, low hardness around the nugget zone is related to the dissolution and coarsening of precipitates at HAZ in the advancing side and/or retreating side. It is shown that the effect of removing oxide is effective on relatively low rotating speed conditions of 300 and 400 rpm, while as little influence to specimens welded higher rotating speed in this study.

Sergey Malopheyev et al. [10] Studied a simple but effective approach for improvement of strength of friction-stir welded 6061-T6 aluminum alloys was elaborated. It involves friction-stir welding (FSW) at relatively high tool rotational speed and welding speed followed by standard post-weld aging. The selected combination of FSW parameters provides high welding temperature as well as the rapid cooling rate. This leads to the complete dissolution of strengthening precipitates in the stir zone but hinders their coarsening in the heat-affected zone.

2. Microstructural investigations on aluminum alloys of AA7075T651 and AA6082T651 on FSW by using three different tools

The microstructural investigations on aluminum alloys AA7075T651 and AA6082T651 are done on the De-Wintor Inverted Trinocular Metallurgical Microscope shown in **Figure 1** and specifications of metallurgical microscope shown in **Table 1** and typical macrostructure of dissimilar of Al Alloys FSW joints showing at different zones shown in below **Figure 2**.

Figure 1.
De-Wintor inverted Trinocular metallurgical microscope.

SNo	Name	Specifications
1	Magnification	50X to 1000X
2	Eye Piece	Paired 15 X and 10 X
3	Objective	5 X, 10 X, 20 X, 25 X, 45 X, 50 X,100X
4	Power	12 Volt, 50 watts halogen lamp
5	Shaft	X-Y direction with 360^0 rotation
6	Polarization	With Polarizer prism
7	Microscale	Attached with 0.01 mm ocular scale

Table 1.
Specifications of metallurgical microscope.

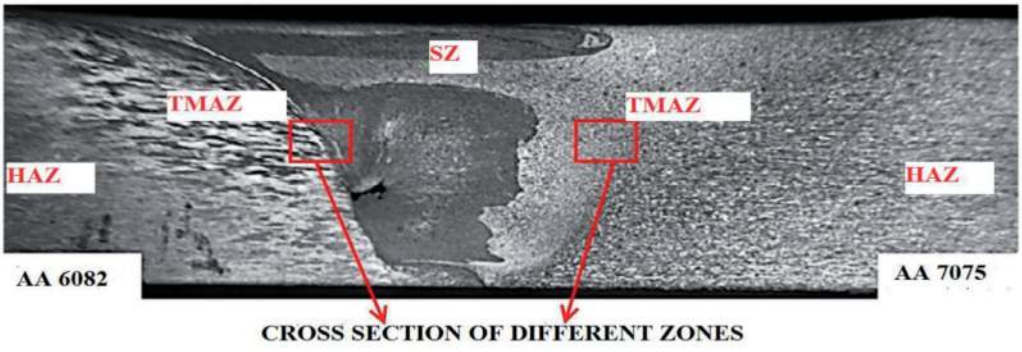

Figure 2.
Typical macrostructure of dissimilar Al alloys FSW joint showing different zones.

2.1 Microstructural investigations of AA7075T651 and AA6082T651 on FSW by using a square tool for samples

Figure 3 shows AA7075 of parent metal has magnification 100 x and etchant hydrofluoric solution are used its shows microstructure of AA7075 parent metal on the advancing side of the FSW process. The parent metal has an inrolled temper condition. The sheet has been cold worked by a rolling process, and primary grains of alpha aluminum is elongated along with direction forming. Eutectic constituents like Cu-Al$_2$, Mg$_2$Si, Zn-Al$_{2,}$and Mg-Al$_2$ precipitated with the direction of rolling.

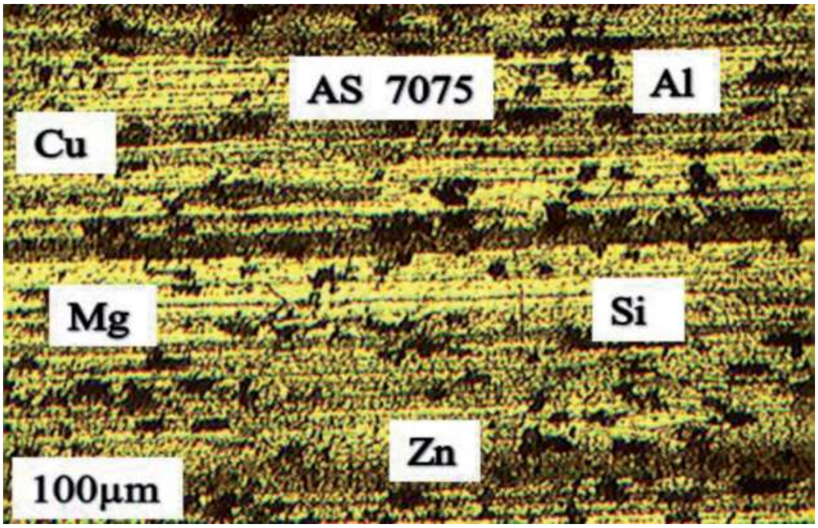

Figure 3.
AA7075 parent metal on advancing side on FSW by using a square tool for samples.

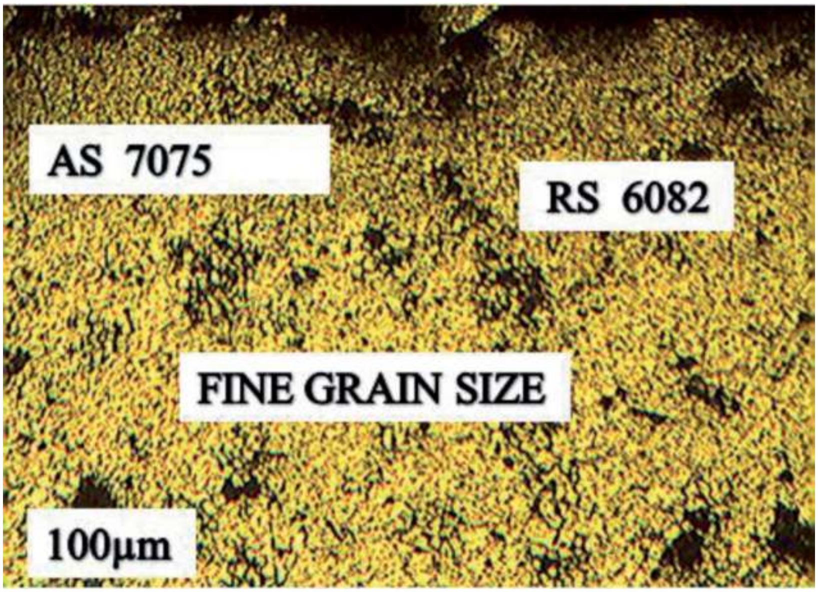

Figure 4.
Eutectic constituents of both AA7075 and AA6082 on FSW by using the square tool for samples.

Figure 4 shows the microstructures of advancing side AA7075 and retreating side AA6082 at shoulder zone of FSW process and the metal matrix underwent fragmentation facilitated the process dissolution of the eutectic constituents for both AA7075 and AA6082 due to frictional heat and stirring. The grains are finer and dynamic re-crystallization has formed as it is revealed by the fine size of the grains of primary aluminum.

Figure 5 shows AA7075 has a thermomechanical transformation zone where the heat process increases with the plasticity of the parent metal and metal has undergone plastic deformation in the direction of the tool.

Figure 6 shows the bottom zone of nugget with two distinct microstructures. The left side is parent metal AA7075 and the right side is nugget zone with fragmented constituents of both AA7075 and AA6082.

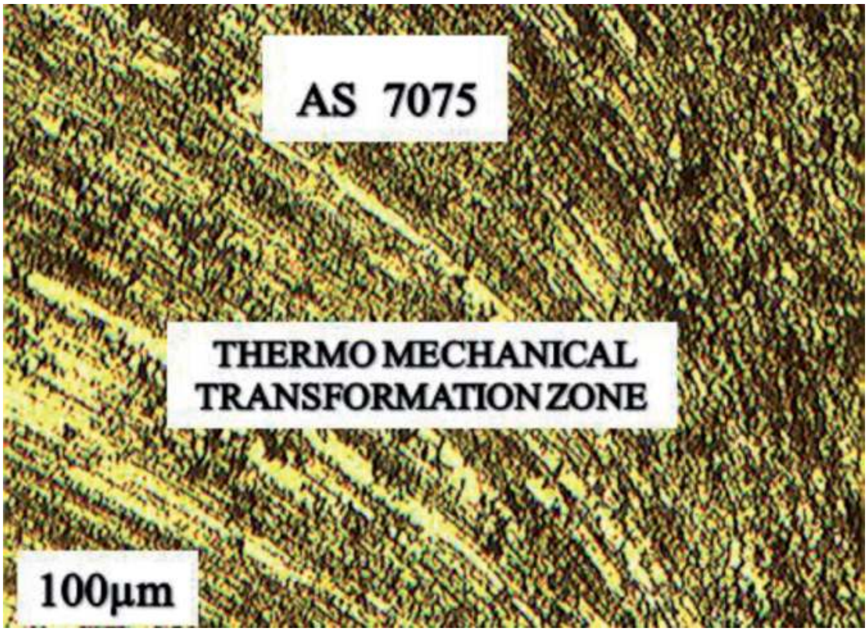

Figure 5.
TMT zone of AA7075 on FSW by using the square tool for samples.

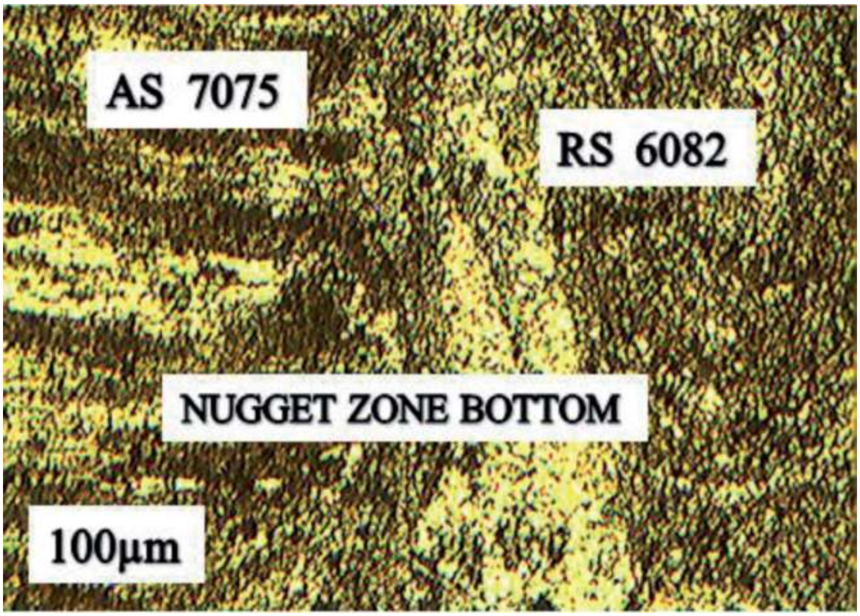

Figure 6.
Bottom zone of the nugget on FSW by using the square tool for samples.

Figure 7 shows microstructures of the upper zone of a nugget. The upper zone showed well re-crystallized grains and effective re-crystallization has taken place due to the conducive temperature existed. The grain size in **Figure 7** is 15 microns and with grain orientation towards the upper direction.

Figure 8 shows from the lower zone of the nugget zone. The grain size in **Figure 8** is mixed varying and elongated.

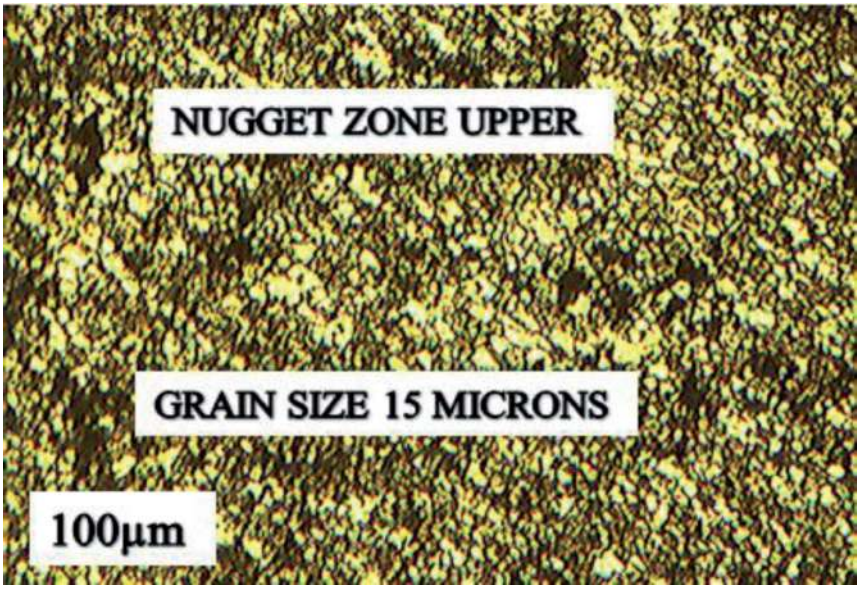

Figure 7.
The upper zone of the nugget on FSW by using the square tool for samples.

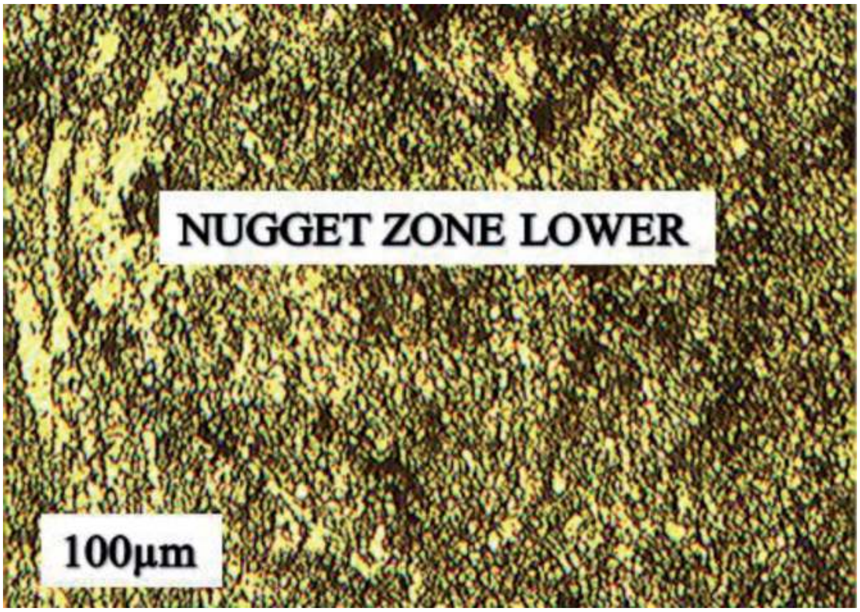

Figure 8.
The lower zone of the nugget zone on FSW by using the square tool for samples.

Figure 9 shows the interface zone of nugget and AA6082 on the right side and nugget on the left side.

Figure 10 shows parent metal AA6082 at the heat-affected zone with more precipitated particles of Mg_2Si in primary aluminum solid solution.

Figure 11 shows the microstructure of AA6082 has the orientation of grain size along the direction at the cold-rolled condition with rolling on eutectic and insoluble constituents.

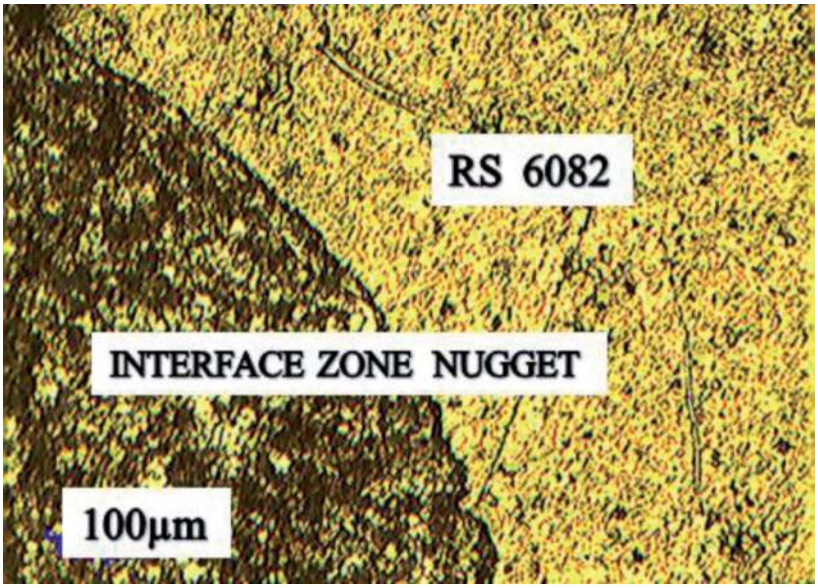

Figure 9.
Interface zone of the nugget on FSW by using the square tool for samples.

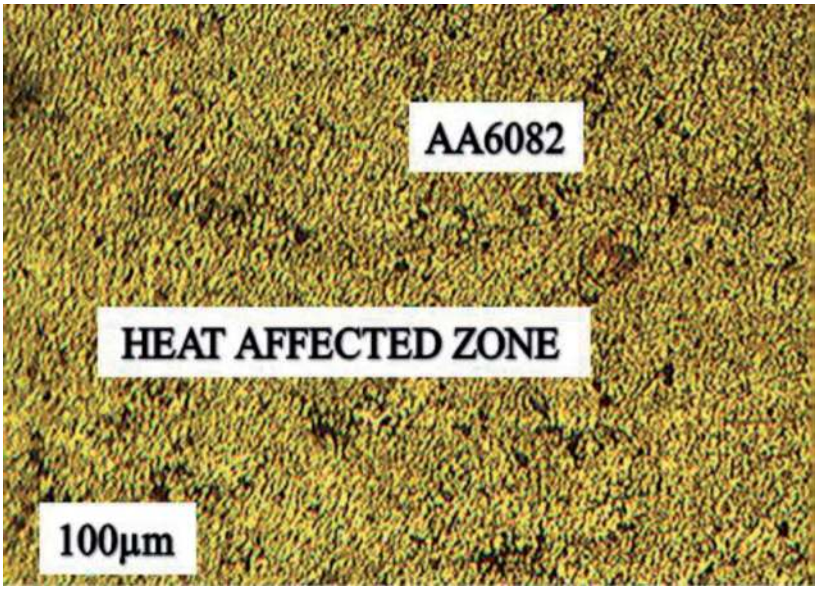

Figure 10.
Parent metal heat-affected zone of AA6082 on FSW by using a square tool for samples.

3. Conclusions

In this work, the important weld strength are analyzed after conducting experiments using the Friction Stir welding setup. The results presented in the work can be used for further analysis. That is using the experimental data empirical models can be developed and then these models can be used for finding the optimal process parameters to get the best output characteristics of welded joints. Then the problem can be solved by using an optimization algorithm after formulating the objective function. Later the entire process can be automated which helps to increase the production rate without increasing the unit cost of the welded joints.

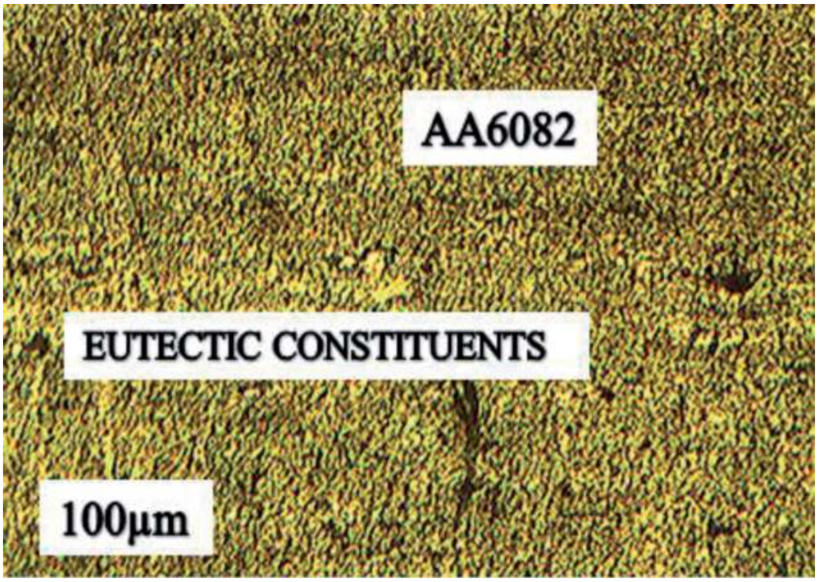

Figure 11.
AA6082 in cold rolled condition on FSW by using a square tool for samples.

For square tool in this work, the important weld strength. That is using the experimental data empirical models can be developed and then these models can be used for finding the optimal process parameters to get the best output characteristics of welded joints. Then the problem can be solved by using an optimization algorithm after formulating the objective function. Later the entire process can be automated which helps to increase the product rate without increasing the unit cost of the welded joints and microstructural changes of Nugget Zone Top and bottom, TMT zone of the AA 7075 T651 where the heat of the process increases the plasticity of the parent metal and metal has undergone plastic deformation in the direction of tool and eutectic constituents of Cu-Al, Mg-Al, Mg-Si of different grains formation are developed.

Author details

Bazani Shaik[1]*, Gosala Harinath Gowd[2] and Bandaru Durga Prasad[3]

1 Department of Mechanical Engineering, Ramachandra College of Engineering, Eluru, Andhra Pradesh, India

2 Department of Mechanical Engineering, Madanapalle Institute of Technology and Science, Madanapalle, Andhra Pradesh, India

3 Department Mechanical Engineering, Jawaharlal Nehru Technological University College of Engineering, Ananthapuramu, Andhra Pradesh, India

*Address all correspondence to: bazanijntua@gmail.com

References

[1] Landry Giraud, b, Hugo Robea, Christophe Claudina, Christophe Desrayaud, Philippe Bocher, Eric Feulvarcha," Investigation into the dissimilar friction stir welding of AA7020-T651 and AA6060-T6" Journal of Materials Processing Technology 235 (2016) 220-230-May 2016

[2] Prakash Kumar Sahu, Sukhomay Pal, Surjya K. Pal, Rahall Jain," Influence of plate position, tool offsets and tool rotational speed on mechanical properties and microstructures of dissimilar Al/Cu friction stir welding joints" Journal of Materials Processing Technology 235 (2016) 55-67)- April 2016.

[3] I.A. Kartsonakis, D.A. Dragatogiannis, E.P. Koumoulos, A. Karantonis, C.A. Charitidis" Corrosion behavior of dissimilar friction stir welded aluminum alloy reinforced with nano-additives, DOI: doi: 10.1016/j.matdes.2016.04.02, Reference: MADE 167, PII: S0264-1275(16)30492- - April 2016

[4] M.-N. Avettand-Fènoël, G. Racineux, L. Debeugny, R. Taillard "Microstructural characterization and mechanical performance of an AA2024 aluminum alloy — Pure copper joint obtained by linear friction welding, PII: S0264-1275(16)30311-2, DOI: doi: 10.1016/j.matdes.2016.03.02, Reference: JMADE 150- March 2016.

[5] U. Donatus, G.E. Thompson, X. Zhou "Effect of prior sputter deposition of pure aluminum on the corrosion behavior of anodized friction stir weld of dissimilar aluminum alloys" Scripta Materialia 123 (2016) 126-129.

[6] D.G. Hattingh, L.G. von Welligh D. Bernard L Susmel R. Tovo M.N. James "Semiautomatic Friction Stir Welding of 38 mm OD 6082-T6 Aluminium Tubes, Journal of Materials Processing Technology, DOI: http://dx.doi.org/doi:10.1016/j.jmatprotec.2016.07.027, PII: S0924-0136(16) 30253-9, Reference: PROTEC 14896-July 2016.

[7] G.K. Padhy, C.S. Wu and S. Ago, Sub grain formation in ultrasonic enhanced friction stir welding of aluminum alloy, Materials Letters, http://dx.doi.org/10.1016/j.matlet.2016.07.033- July 2016.

[8] Shivraman Thapliyal, Dheerendra Kumar Dwivedi "Study of the effect of friction stir processing of the sliding wear behavior of cast NiAl bronze: A statistical analysis" Teratology International 97 (2016) 124-135-January 2016.

[9] Ho-Sung Lee, Jong-Hoon Yoona, Joon-Tae Yoga and Kookie Nob" Friction Stir Welding Process of Aluminum-Lithium Alloy 2195" Procedia Engineering 149 (2016) 62 –June 2016, Novy Smokovec, Slovakia.

[10] Sergey Malopheyev, Igor Vysotskiy, Vladislav Kulitskiy, Sergey Mironov, Rustam Kaibyshev "Optimization of processing-microstructure-properties relationship in friction-stir welded 6061-T6 aluminum alloy" Materials Science & Engineering A 662 (2016) 136-143- March 2016.