Effect of Tool Geometry on Mechanical Properties of Friction Stir Welding of Al Alloys - A Review

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Abstract

Friction stir welding is one of the recent solid-state joining processes that has drawn the attention of the metal joining community. FSW has been employed in several industries such as aerospace, automobile, and marine for joining aluminum, magnesium and copper alloys. The FSW has resulted producing welds which are free from hot cracks, porosity and cast dendritic structure which are quite prevalent in fusion welding process. The various process parameters such as tool rotational speed, weld speed, tool geometry, axial force and tilt angle influence the weld quality in FSW. Several authors investigated the influences of the effect of process parameters like tool rotational speed, weld speed, tool geometry on the mechanical properties and microstructure. It has been observed from the studies that tool geometry affects the mixing and dynamic re-crystallization of the materials being welded. So in the present study an attempt has been made to review of the work which was carried out to investigate the effect of tool pin geometry, shoulder diameter, shoulder length and tool profile on FSW process.

KEYWORDS- Friction Stir Welding, Tool Pin Geometry, Micro Structure, Tensile Strength, Nugget. TMAZ, HAZ.

I. Introduction to FSW

Friction stir welding (FSW) process was invested in 1991 by the Welding Institute, a British Research and Technology Organization. It is a solid-state, hot-shear joining process in which a rotating tool with a shoulder terminating in a threaded pin move along the butting surfaces of two rigidly clamped plates placed on a backing plate. The shoulder makes firm contact with the top surface of the work-piece. Heat generated by friction at the shoulder and to a lesser extent at the pin surface, softens the material being welded. Severe plastic deformation and flow of this plasticized metal occur as the tool translated along the welding direction. The material is transported from the front of the tool to the trailing edge where it is forged into a joint.

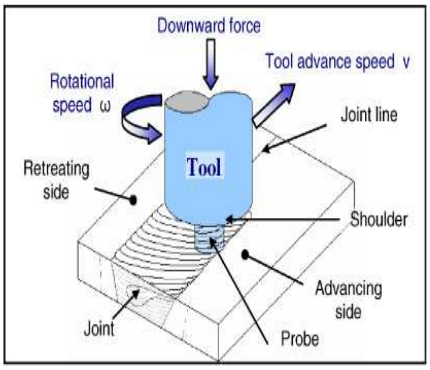

FIG: Friction Stir Welding

FSW involves complex interactions between a variety of simultaneous thermo-mechanical process which affect the heating and cooling rates, plastic deformation and flows dynamic recrystallization phenomena and the mechanical integrity of the joint.

There are many parameters which influence Friction stir Welding process like tool rotational speed, weld speed, tool geometry, axial force, plunge depth, dwell time and tool tilt angle. Tool geometry is one of the most predominant factor affects the microstructure and mechanical properties of the joint. This paper has reviewed the works of various authors who has investigated the effects of tool pin profiles.

M.Ilangovan et al investigated the joining of heat treatable (AA 6061) and non-heat treatable (AA5086) aluminum alloys by friction stir welding (FSW) process using three different tool pin profiles like straight cylindrical ,taper cylindrical and threaded cylindrical. The microstructures of various regions were observed and analyzed by means of optical and scanning electron microscope. The tensile properties and microhardness evaluated for the welded joint. From the investigation, it is found that the use of threaded pin profile of tool contributes to the better flow of materials between two alloys and the generation of defect free stir zone. It also resulted in higher hardness values of 83HV in the stir zone and higher tensile strength of 169MPa compared to other two profiles.

Three pin profiles, namely, straight cylindrical (STC), threaded cylindrical (THC) and tapered cylindrical(TAC), were used to fabricate the joints.

The tensile test results of the joints are given in the following table

Tool pin profile	**0.2%Yield strength /MPa**	**Tensile strength/ MPa**	**Elongation in 50mm gauge length%**	**Notch tensile strength/ MPa**	**Notch strength ratio/NSR**	**JOINT EFFICIENCY**
STC	112	126	11	130	1.03	50.4
THC	151	169	10	178	1.05	67.6
TAC	146	163	13.3	173	1.06	65.2

NSR=Tensile strength of the notched specimen/tensile strength of unnotched specimen.

Joint Efficiency =Tensile strength of the joint (unnotched)/tensile strength of the lower strength base metal (AA5086).

STC: a joint made by straight cylindrical pin profiled tool.

THA: joint made by threaded cylindrical pin profiled tool.

TAC: joint made by plane taper cylindrical pin profiled tool.

All three pin profiles yielded the surface defect free joints with tool rotational speed of 1100rpm and welding speed of 22mm/min.

The effects of tool pin profile on microstructure and tensile properties of friction stir welded dissimilar AA 6061-AA 5086 aluminum alloy joints were investigated and the following conclusions are derived.

1. Of the three tool pin profile used, the straight cylindrical pin profile tool yielded cross-sectional macro level defects in the stir zone and hence is not suitable for AA6061 and AA 5086 dissimilar joints.
2. Threaded and tapered cylindrical pin profile tools yielded defect free joints (both surface and cross-sectional).The tensile properties of these joints are more or less similar (± 5% variation). However, the threaded cylindrical pin profile tool is preferred over the tapered cylindrical pin profile tool due to the superior performance of the joints.
3. Formation of finer and uniformly distributed precipitates, circular onion rings and smaller grains are the reasons for superior performance of joints fabricated by threaded pin profiled tool compared to tapered pin profiled tool.

Ravi kumar.S et al investigated the dissimilar friction stir weldability of 7075-T651 and 6061-T651 aluminum alloys. The parameters of his study are tool rotational speed, tool speed and tool pin profiles. FSW was carried out using three different tool profiles. They are Taper cylinder threaded(TCT), Taper square threaded (TST) and Simple Square (SS).The tool was machined from H13 tool steel and hardened to 55HRC. Trail experiments are conducted to determine the working and feasible range of process parameters.

Dissimilar friction stirs welding parameter and the selected levels.

S.No	Welding parameter	Unit	Level 1	Level 2	Level 3
1	Tool rotational speed	rpm	800	900	1000
2	Welding speed	mm/min	90	100	110
3	Tool pin profile	-	SS	TCT	TST

The dissimilar joints fabricated using the TCT tool has maximum tensile strength compared to the joints made using SS and TST tools for any welding and rotational speed. The following conclusions are drawn from the investigation of Ravi kumar.S et-al.

- The maximum tensile strength of 205.23MPa occurs for Taper cylindrical threaded profile with the rotational speed of 900rpm and welding speed of 100mm/min whereas, for the parameters 900rpm and 90mm/min, Taper square threaded profile yields lower tensile strength of 178.01MPa. The reason for the lower value can be attributed to the poor fusion of the two plates and this is evident from the macro images which show a larger discontinuity at the butt area.
- It is observed from the Optical and SEM graphs that there is uneven distribution of two materials (7075 and 6061) in the nugget zone for the combinations 900 rpm and 100mm/min(Taper square threaded profile) and 900rpm and 110mm/min (Simple Square Profile) which yields tensile strength of 178.01MPa and 179.12MPa respectively.
- The tapered cylinder threaded tool exhibits good tensile strength of 205.23MPa compared to other tools.

Hamed jamshidi Paper investigated the effect of tool pin profile and post weld heat treatment on the mechanical and microstructural aspects of the friction stir welding dissimilar precipitation-hardenable aluminum alloys. It was found that the tool with a conical probe with three grooves produces a higher temperature than the tool with a square frustum probe. The mixture of materials in the weld nugget of joints welded by the tool with the square frustum probe was more uniform.

The following features adopted for the tools; Tool No. 1 has a 23 mm diameter shoulder with a 2˚ conical cavity and a square frustum probe measuring 3-9 mm in diameter and 7.9 mm in length. Tool No. 2 has a 23 mm diameter shoulder with a 2˚ conical cavity and a square frustum probe measuring 4.5-9 mm in diameter and 7.9 mm in length. Tool No. 3 has a 23 mm diameter shoulder with a 2˚ conical cavity and a conical probe with three grooves measuring 4.5-9 mm in diameter and 7.9 mm in length. The tool inclination angle and axial load were set to 2˚ and 12kN for all experiments.

Pin profiles with the flat faces show greater eccentricity, which is defined as the ratio of the dynamics volume swept by the tool to the static volume of the static volume of the tool. Tool 2 produced a pulsating stirring action in the flowing material because the faces were flat. The influence of friction stir welding parameters on microstructures and mechanical properties of dissimilar friction stir welded AA6082-AA7075 were analyzed using optical microscopy, TEM, microhardness and tensile testing. The following results were obtained:

1. The peak temperature in the welded joints made by the tool with a conical probe with three grooves was higher than for those made by the tools with square frustum probes.
2. In each series of the welds made using different tools, a decrease in the weld pitch resulted in decreased strength of the welds and coarser grain sizes in the weld nugget. Samples welded using a square frustum probe showed finer recrystallized grains and samples welded using a conical probe had larger sized grains.
3. The zinc distribution across the weld shows the atomic diffusion does not occur at the interface of materials that mixing of the materials is mechanical. The mixture of

materials in the welded nugget of samples welded using the tool with a square frustum probe was more uniform than that in the other samples.

M.I.Costa et-al work on dissimilar friction stir lap welding of AA5754-H22/AA6082-T6

Aluminum alloys influence of tool geometry and material properties on weld strength obtained the following conclusions. The hook formation depends on tool geometry and base material positioning. Strongest welds are produced by placing the AA6082 alloy in the top. Conical tools with low shoulder pin diameter ratio hinder hooking

S.M.Bayazid et-al work, the effect of pin profile on defects of FSW 7075 alloy was investigated. Three pins with cylindrical, square and triangle geometry were used for welding. The microstructure of the welding zone showed that the tunnel hole produced by triangle pin has smaller dimensions compared to cylindrical pin. On the other hand, results of optical microscope indicated that the size of grains resulted from the square pin is smaller than the other kinds of tools. Also, the results showed that when the pin is cylindrical, tunnel kissing bond and zigzag line defects are formed. On the other hand, when the pin is triangle original joint line with severe plastic deformation and crack defects are created.

Pin profile plays a critical role in material flow and in turn, regulates the welding speed of the FSW process. Pin profiles with flat faces (square and triangle) are associated with eccentricity. In addition, the triangle and square pin profiles produce a pulsating stirring action in the flowing material due to flat faces. There is no such pulsating stirring action in the case of cylindrical pin profiles. It was reported that two representative defects namely tunnel and kissing bond was easy to form in FSW. In the present study, as mentioned above, these two kinds of defects could also be found in weld zone in cylindrical tool pin profile.

The joints made-up using different tool pin profiles like cylindrical, square and triangle tool with a rotational speed of 1600 rpm, weld speed of 63 mm/min. The following important conclusions were made for the present study. The tunnel, kissing bond and zigzag line defects were observed in weld zone created with cylindrical, also tunnel and crack defects were observed in weld zone created with triangle, but not any defects in samples created with a square pin. Square pin resulted to produce sound welds free from tunnel and kissing body defects.

J.S.Jesus et-al studied the effect of three different tool geometries and two joint geometries on quality of AA5083-H11 T-welds done using the friction stir welding process (FSW). All the tools have concave shoulder with different pin geometries: tapered and threaded, quadrangular pyramidal and progressive pin, part threaded cylindrical and part pyramidal. T-lap and T-butt joints configuration have been studied. Tunnel and kissing-bond type defects have been found in joints produced with a pyramidal pin tool, while welds produced with the tapered pin tool only show presence of oxide lines Sound welds were produced with the progressive tool. No significant change in hardness has been observed in all combinations of tool and joint geometry. The tensile strength efficiency in joints welded with the progressive pin tool has been found to be 100%.

Three different tools were used, with the same shoulder but different pin, respectively pyramidal pin, tapered threaded pin and progressive pi. The tool with tapered and threaded pin was constructed in order to improve the vertical material flow while the tool with progressive pin was designed with the aim of approaching the material flow to the fillet zones. The tool rotational (660-1140 rpm) and traverse (60 mm/min) speeds were chosen based on previous tests. The process were done in a Cincinnati milling machine and in position control, the tool plunge depth was set tentatively. Observe the work piece clamped and prepare to FSW of T-butt joint.

J.S.Jesus et-al concluded that it is to weld T-joints with fillet radius by FSW without thickness reduction of the skin or other defects; All welds showed excellent appearance, except welds performed with pyramidal pin tool, which had cavities; Grain refinement in weld zones (14.9µm-8µm); No significant hardness variation in the weld zone; The oxide lines disappeared using the tool with progressive pin in T-butt joint;

Amit Goyal et-al investigated the effect of different geometries of tool pin on mechanical properties of FSW joints has been studied in the present paper. The process was carried out on AL alloy AA3003 plates of 5mm thickness. The four studied welding tool differed from pin profile with straight cylinder, threaded, triangular and square. The rotational speed of the tools and transverse feed has been kept contact as 1100 rpm and 20 mm/min respectively. The effect of four geometries has been analyzed by micro hardness and tensile test.

A tool of high carbon high chromium steel is employed for four tools having different tool geometry viz. Straight cylinder, threaded, triangular and square has been used to fabricate the joint. The rotational speed of the tools and transverse feed has been kept constant as 1100 rpm and 20 mm/min respectively.

Tool material	**High carbon high chromium steel**
Length of tool	40mm
Tool shoulder diameter	18mm
Pin diameter	6mm
Length of probe (single pass)	4.7 -4.8 mm
Length of probe (double pass)	2.7 – 2.8 mm

The joint fabricated by double passes have shown higher ultimate tensile strength and percentage elongation as compared to single pass joints. The study found that similar trend is followed by all the tool profiles. Micro hardness analysis of the welded specimen shows an increase in hardness in the welded region. Double pass welded joints shows higher value of hardness as compared to single pass weld nugget as well as in HAZs.

Naveen Saini and Sushil Kumar Sharma et-al optimized combination of parameters are typing to be found using welding parameters i.e. rotational speed (1000 – 4000 rpm), travel speed (10-40 mm/min) and tool pin length (4-5 mm). Results show that with higher rpm, lower travel speed and higher pin length gives better results.

Process parameters are selected on the basics of pilot experimentation. From literature it was evident that rotational speed, travel speed, and tool pin length are the major parameters in friction stir welding. These parameters show the large percentage contribution in terms of tensile strength of friction stir welded joints.

Pin length also shown its effect and increasing pin length gives better tensile strength with every rotational speed. Full-length pin gives more surface contact area and produces more frictional heat which provides better tensile strength.

In Ajay S.Gupth's this research rotational speed and welding speed were taken as process parameters. The aim of the research is to evaluate the effects of different welding speeds (50,65&80 mm/min), rotational speeds (1200 &1500 rpm) and tool pin profiles on the weld quality of AA6082-T-6. Straight cylindrical, taper threaded and hexagonal pin is used as tool pin profile in this research. There is no visual effect found, consequently obtained results explain the stress variation as a function of strain. The fabrication of friction stir welded plates of AA6082-T6 using the hexagonal pin profile reaches the ultimate tensile strength of 72 % of the base metal ultimate strength.

II. Configuration of tool geometry

In this research, a tool made of H-13 tool steel heat treated to HRC50-52 with an 18mm shoulder diameter is used. The image of different tool pin profile used in this research in order to carry out joints. Three different tool pins are selected.

These are presented as following

1. Straight Cylindrical Pin (SC)
2. Tapered Threaded Pin(TT)
3. Straight Hexagonal Pin (HT)

The results from experimental investigation are

- The results indicate that the pin profile effect on the mechanical properties of welded joints.
- Among the eighteen joints in this experiment, the joints produced using the straight hexagonal pin profiled tool at a rotational speed 1500 rpm and welding speed 65 mm/min showed the best tensile properties.
- The tensile strength of the straight hexagonal pin at 1500 rpm and 65 mm/min reaches to 71.77% of the base metal ultimate strength, but the UTL reaches 93.61% of the base metal UTL.
- The straight cylindrical and taper threaded tools resulted in ultimate strength goes to 35.38% and 44.61% respectively of the base metal ultimate strength.

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