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A Review Analysis of Geometries, Welding Parameters, and Materials Used in Friction Stir Welding

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Abstract: A method of connecting dissimilar and similar materials together without melting them is called friction stir welding. It is extensively utilized in sectors including aerospace, automotive, marine, & railroads. This process involves combining different alloys like copper, zinc, magnesium, and aluminum. To achieve successful welds, factors like geometry and tool material, weld angle, axial force, Rotational speed and traverse speed are vital. Researchers have studied effects of these variables on welding results. This literature review aims to analyse welding variables, tool shapes, and materials in friction stir welding. It will be an important tool for research in the future that aims to increase the effectiveness of this welding process.

Keywords: *Process parameters, FSW Tools, Weld angle, Axial force.*

1. Introduction:

The United Kingdom's Welding Institute (TWI) pioneered friction stir welding back in 1991 to join solid state aluminum alloys [1]. Adjacent sheets or plates that to be connected are firmly mounted on specially designed fixture, rotating tool with specifically developed pin and shoulder both are moving along welding Joint line. It is necessary to properly fasten the Parts onto a backing bar so as to avoid forcing apart the joint faces that are next to each other. The pin's length is in a way shorter than necessary weld depth. When tool's shoulder touches the surface of work, plunging is stopped. Tool's purpose is to heat the work piece and displace material to create weld joint. work piece is atedecause of friction and plastic deformation in between tool and work piece. Material softens with localized heating surrounding the pin, and material moves from pin's front to back as a result tool rotation and translation. Material moves around the pin might get fairly complex due to the tool's different geometrical aspects. In this instance, tool consolidates Friction combined with plastic work create heat as soon as the welding tool starts moving over the joint, keeping the work piece sufficiently soft to allow material to move plasticized metal behind it by applying a significant forging force intense solid-state plastic deformation with dynamic recrystallization of parent material permits material's welding. The desired joint is formed as tool is advanced along the weld seam. **Figure 1** displays an operational schematic

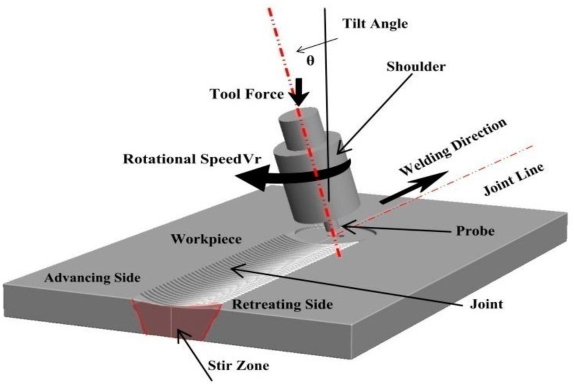

Fig 1: Diagrammatic depiction of friction stir welding.[2]

in a circular motion about the pin. The heat generated during the welding process transfers into work piece, preheating the material in front of welding tool. As a result, work hardening recovers and becomes softer and averaging in materials like aluminum[3]. This metallurgical change could be little, like in the case of welds produced at extremely fast travel speeds, or it could cause the work piece to become significantly softer. In order to avoid voids forming, material is positioned behind the welding tool and pulled around it at the same time. When the joint's welding tool reaches its end, it usually stops moving forward and is removed leaving a keyhole in the work piece where the weld ends. Generally speaking, the weld's end cannot be used and needs to be cut off.

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1.1 FSW Process Parameter

There are various factors that might impact output response, even though the broad principles of how process variables impact the friction stir welding procedure are similar to those of other welding processes. Essential factors in the FSW technique are given below:

1. Material for the Tool (Shoulder and pin)
2. Rotational speed of tool
3. Work piece material
4. Pin Profile
5. Pin diameter
6. Angle of tilt
7. Welding speed
8. The axial force
9. Diameter of the shoulder

Each of these factors could have a substantial impact on the weld joint's properties. The frictional heat generation can be directly correlated with tool's rotational speed, which is friction stir **welding tool's rotation speed** [4]. Transverse speed, or the pace at which a tool travels along a joint line, is not preferred above speed of welding. If sufficient heat input is being given to the weld which favourably affect weld properties is determined by **Tool's rotational speed** and **speed of welding**

2. Microstructure of the FSW joints:

Figs. 2 shows FSW weld regions and 3 depict microstructure zones with forward and backward stoke to understand heat generation and material flow in FSW process. Dynamically recrystallized zone of base material characterize weld nugget microscopic structure due to combined effects of significant plastic deformation and locally high temperature [5][6]. It is reported that a constant, dynamic recrystallization occurs in FSW weld nuggets. Plastic deformation occurs at local level in TMAZ and the temperature rise is smaller than in the weld nugget. Region where material is effected by heat of process is known as Heat-affected zone (HAZ) [7][6]. Conversely, behaviour of material flow is mostly determined by the dimensions, process variables and FSW tool's profiles [6].

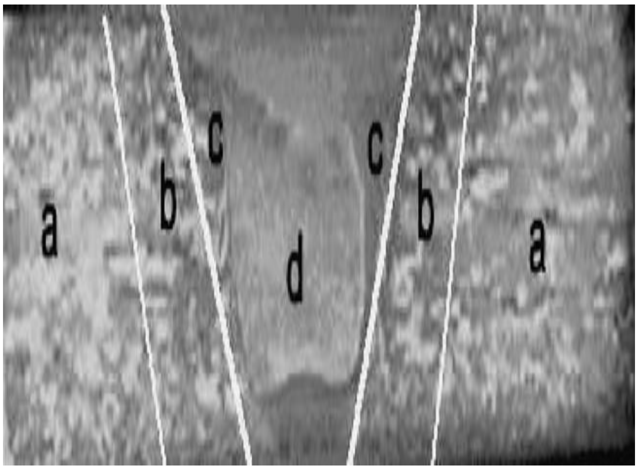

Fig.2–Various Weld regions: (a) Parent material unaffected, (b) HAZ, (c) TMAZ and (d) FSP zone[8]

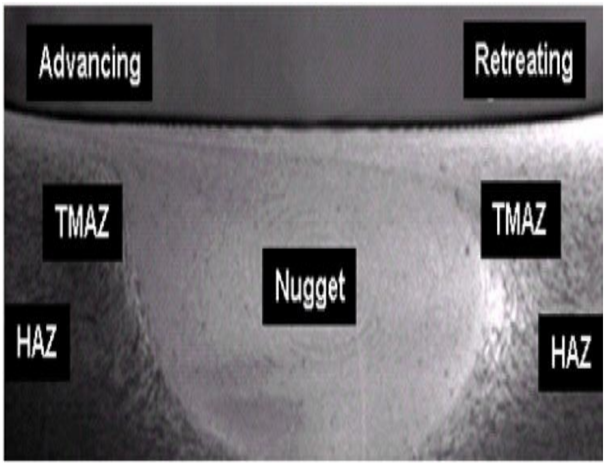

Fig.3 Micrograph displaying several zones of microstructure[6]

Parent metal, also known as **unaffected material**, is the material that is not welded to and has no effect on its mechanical or microstructural properties due to heat.

HAZ: This zone occurs in every welding process it is quiet common. HAZ area has a heat cycle during welding, as the name implies, yet it does not distort. If microstructure is thermally unstable, the lower temperatures than in TMAZ could still having a major effect. Indeed, in Age hardened aluminum alloys, HAZ Area usually shows lowest mechanical characteristics.

TMAZ: Both sides of the stir zone experience this phenomenon. Welding has less effect on the microstructure in this region due to lower temperature and strain. Parent material's microstructure is clearly visible, despite being greatly distorted and rotated, in contrast to the stir zone. Although The entire area that is distorted is technically referred to as the **"TMAZ"** this term is commonly employed to explain any area which is already not addressed by terms flow arm zone and stir zone.

Weld Nugget zone (Stir Zone and Dynamically Recrystallized Zone): Weld Nugget is an area which is severely deformed material that when welding, approximately matches the pin's placement. Compared to the grains in parent material, the grains in the stir zone are frequently an order of magnitude smaller and roughly equiaxed.

3. Process Parameters in FSW:

Numerous experts have carried out different optimization studies for FSW process variables (parameters). The preferred tool pin profile for friction stir welding significantly affects process parameters. Figure 5 illustrates various tool types commonly employed in the process, such as straight cylindrical, conical, hexagonal, threaded, triangular, square, whorl, MX triflute, flared triflute, skew, and others.

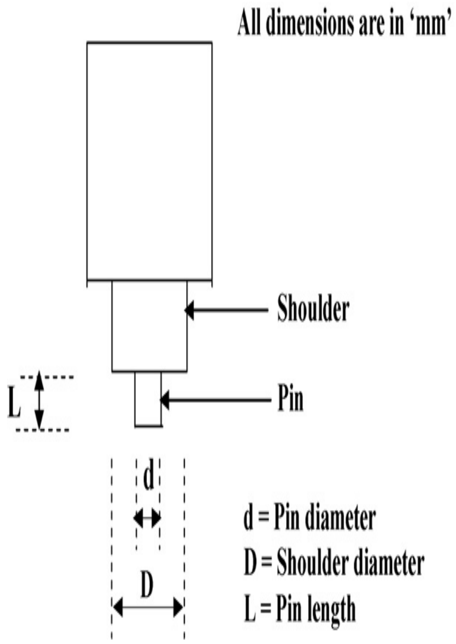

Fig.4 – FSW Geometries[9]

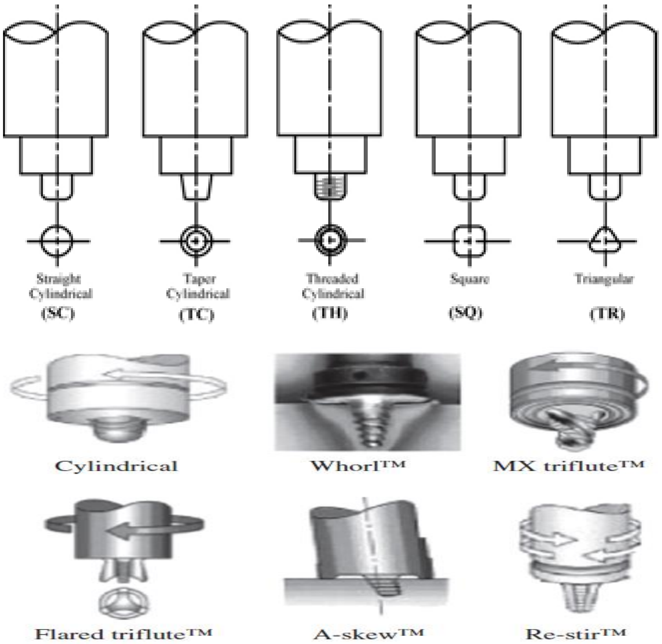

Fig. 5- Different Profiles for Tool Pins[10]

Diameter of the shoulder is determined using a trial error approach, is a crucial geometric parameter needed in design of FSW tool. The characterisation approach could be utilized for optimize FSW process due of the intricate effects of peak temperatures, torque in the process and shoulder diameter on thermal cycles, Heat-treated mild steel or high-strength steel are the materials utilized to prepare the tool pin profile for nonferrous metals. The advancement of design and material selection for specific applications is made possible by tool material breakthroughs in this field.

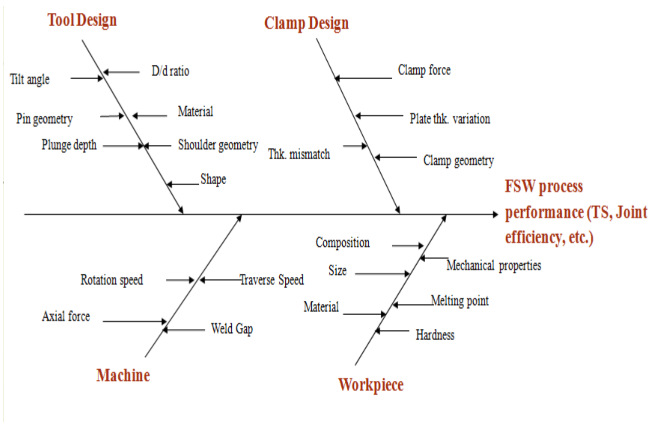

Fig 6. Factors affecting qualities of friction stir welded joint[11]

Each of these factors could have considerable influence on the qualities of weld joint. **Rotational speed of Friction stir welding tool** is directly correlated with degree of heat produced by friction. [29] The pace at which a tool travels along a joint line is known as transverse speed; **welding speed** is desired. **Tool speed and speed of welding** determine whether weld is receiving enough heat input to positively influence the weld properties. An essential component of friction stir welding technique is forces. The downward forces are placed in parallel with the tool axis (Z-direction), while the transverse forces re used in a direction parallel to welding (X direction). Side force is the force created in Y-direction, which is perpendicular to both the Z and X forces. Defects in the weld are caused by both excessive and insufficient downward force. Using the right tool design determines a weld that is free of defects. The tool has three components, which are shoulder diameter shank and pin A small diameter pin was fully inserted into the work piece's materials from the tool's leading and trailing edges, the pin transfers plasticized material. ensures that the material is properly stirred. Tool's shoulder creates the majority of heat since it rubs on the work piece's surface. Furthermore, producing frictional heat, shoulder keeps preventing the work piece's plasticized material from exiting upper surface. Advancing side of weld refers to the side where velocity vector of tool is parallel to the traverse direction. Conversely, though, the retreating side is where velocity vector of the tool is directed opposite to traverse direction.

4. Summary of the parameters for welding materials, welding parameters and geometry utilized in friction stir welding (FSW):

The following sections contain information on various tools, their sizes and shapes, the materials they are made of, their working settings, and the metals they have successfully connected using FSW. Researchers' diverse efforts and investigations on materials that are either comparable to or dissimilar in order to assess their differences, the FSW tool and its profile individual findings. A more comprehensive understanding of the material and profile FSW tool profile used for joining various metals for a range of applications is provided in **Table 1.**

Table 1: Material of Tool, Geometries and welding Parameters employed in FSW for several Al and Mg alloys

Sr.No	Material of Tool	Geometries	Material Work piece	Welding Parameters	Comments
1.	H13 steel	1.SD: 10 mm; 2.SS: flat with scroll; 3.Shoulder Diameter: 10 mm; 4.Pin Length: 0–1.6 mm [12]	0.9 mm thick 6111-T4 Al alloy,	Dwell time: 2.5/S, plunge rate: 2.5 2000 rev/min; mm/S, FSSW	Better quality using a pin less tool.
2.	-	Pin Shape: Triflute, Trivex[13]	6.35 mm Plate 7075-T7351,	300–540 mm/min 394 and 457 rev/min,	Weld Ultimate Tensile Strength (UTS): 470–488 MPa
3.	Tool steel;	Pin Shape: Threaded[14]	6.35 mm Thick 7075-T7351,	0.3–1.4 mm/rev 190–457 rev/min,	Identified surface scaling and voiding
4.	Tool steel	Pin Shape: SC, SCT, triangular SD: 15 mm, SS: concave, Pin Length: 4.7, 6 mm [15]	5 mm mm Thick Al alloys,	Ranges from 25 to 1000 mm/min Ranges from 600 to 1500 rev/min, 3° tilt	Peak joint Efficiencies ranges from 70 –100%
5.	H13 steel	Pin Shape: SCT, Pin Length: 1.8 mm, Shoulder Diameter: 10 mm, Pin Diameter: 4 mm, 3F with M4 threads[16]	AZ31 Magnesium, 1.5 mm thick material	time: 1, 4/S Ranges from 1000 to 3000 rev/min, dwell Rate of plunge 0–10mm/S FSSW	-
6.	H13 Steel	Pin Diameter: 3–8 mm; Pin Length: 4.2 mm, Shoulder Diameter: 10–20 mm, Flat,	4 mm thick 7020-T6 Al alloy,	80 mm/min 1400 rev/min,	Achieved Peak joint efficiency: 92%

		Pin Shape: frustum and SC[17]			
7.	H13 steel	D: 5.2–7.6 mm, Shoulder Diameter: 25.4 mm, PPL: 1.8–7.1 mm[18]	9.5 mm and 12.7 mm Thick 6061-T6 Al,	150 or 200 mm/min, 650 rev/min, 3° tilt	-
8.	H13 steel, 46–48 HRC	PS: SCT, Pin Length: 1.8 mm, Shoulder Diameter: 10 mm, Pin Diameter: 4 mm; threaded and unthreaded 3F[16]	AZ31 Mg, 1.5 mm Thick material	Dwell time: 1/S 1000–3000 rev/min, plunge rate ranges frsom: 2.5 mm/S FSSW	
9.	-	Pin Length: 5.9 mm, Pin Diameter: 5.6 mm, Shoulder Diameter: 26 mm, SS: concave, Pin Shape: SCT[19]	6.3 mm Thick 6061-T6Al,	30–210 mm/min 286–1150 rev/min,	-
10.	H13 steel	SD: 12 mm, SS: concave, convex, flat, Pin Length: 1.6 mm Pin Diameter: 5 mm[20]	1.32 mm Thick 5754 Al,	Dwell time: 2/S; plunge rate: 20 mm/min, 1500 rev/min, FSSW	-
11.	-	Pin Length: 1.65 mm, Pin Diameter: 3.1 mm, Pin Shape: LHT, SC, RHT[21]	2 mm Thick AZ31B-H24 Mg alloy,	300–1800 mm/min 1000–2000 rev/min,	Joint efficiencies ranges from 74–83%
12.	Tool steel	Pin Diameter: 6 mm[22]	6 mm Thick A413 Al and A319 alloy,	120 mm/min 1000 rev/min	No property degradation observed in weld metal
13.	1. HSS 2.SS. 3.MS. 4.HCS 5.Armour steel,	Pin Length: 5.7 mm, Pin Shape: SC, TC, Tri. & Sq. SD: 15, 18, 21 mm, Pin Diameter: 6 mm [23]	6 mm Thick AZ31B Mg alloy,	40 mm/min, 0° tilt 1600 rev/min,	Joint efficiencies ranges from 48.8–96.7%
14.	-	SS: cavity, Fillet Scroll. Pin Shape: SC, Pin Diameter: 1.7 mm; Pin Length: 1.2 mm[24]	1.5 mm Thick 6082-T6 Al,	460 mm/min 2° tilt 1810 rev/min,	Joint efficiencies: 76%
15.	H13 steel	Pin Length: 2–3.5 mm, Shoulder Diameter: 19 mm,	2 mm AZ31B-H24 Mg alloy,	500–2000 rev/min ,1200 mm/min,	Observed Joint efficiencies: up to 62%

		Pin Diameter: 6.35 mm[25]			
16.	High carbon steel	Pin Shape: SC, TC3F, Pin Length: 3.19 mm, Shoulder Diameter: 13 mm, SS: concave, Pin Diameter: 5 mm[26]	4 mm Thick 7020-T6 Al,	100–900 mm/min 2.5° tilt 300–1620 rev/min	-

5. Methodology

The research of literature indicates the major process variables associated with Friction Stir Welding (FSW). The parameters include rotating speed, welding speed, axial force, tool geometry, tool material, tool offset, tilt angle, work piece location, and plunge depth. Controlling these factors is critical to producing high-quality welds. The rotational and welding speeds having a direct impact on heat input throughout the process. Axial force imparted on the tool affects mechanical deformation of the work piece. The selection material of tool is contingent upon the work piece material; for softer materials, tools fabricated from steel are suitable, whereas for harder materials, tools composed of refractory materials are necessary. Tool offset is an essential component for joining dissimilar materials since it prevents the overheating of softer materials. Tool is held on the softer material side as a result. Experiments were carried out by changing some vital variables such as rotating speed and welding speed at different levels, impact of tool offset and work position have been examined.

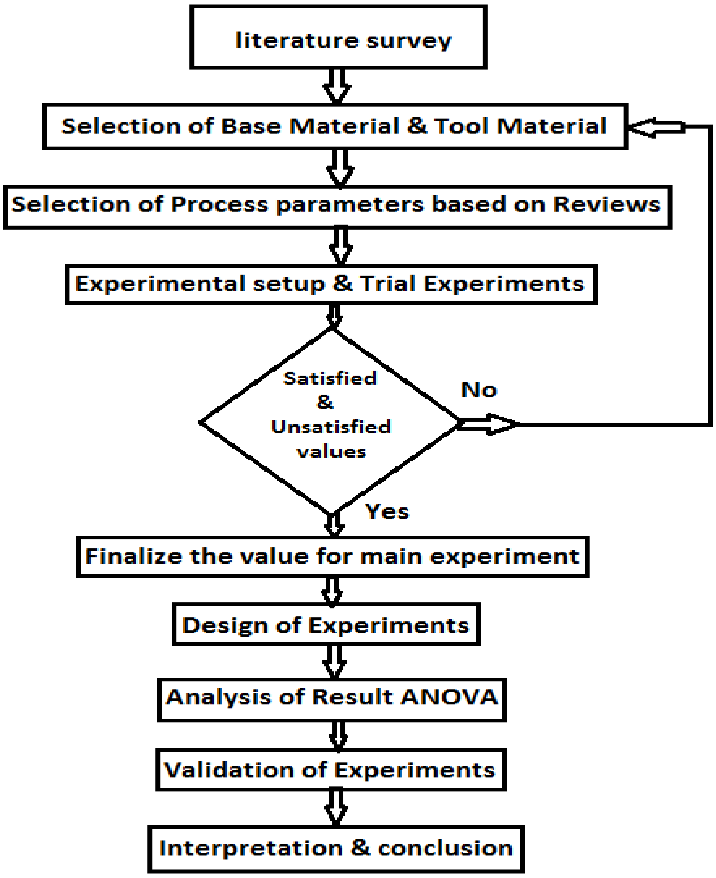

Fig 7. Research Methodology

Critical Welding variables:

The following are some of the welding process variables that are commonly considered in FSW:

5.1 Tool tilt and plunge depth: It is the distance between the welding plate's surface to the shoulder's lowest point. The pressure beneath the tool is increased as the shoulder is plunged below the plate surface, supporting the tool's back in achieving correct material forging by Tilting the tool 2 to 4 degrees, such that the rear face is lower than the front face, will aid in the forging process. It provides necessary downward power, allowing tool to thoroughly penetrate weld and rectify problems such as a significant under match in weld thickness or pin rubbing on the backing plate surface.

5.2 Rotation of Tool and traverse speeds: In order to ensure effective welding cycle, these both factors are more crucial and need to be selected carefully. For optimum weld quality, rotational speed and traverse speed should be adjusted to produce hotter weld. Additionally, material surrounding to the tool should be heated to a level that allows for the extensive plastic flow needed and reduces stresses that could break the tool. Conversely, an overly high heat input could degrade the weld joint's ultimate characteristics. [27]

5.3 Material Flow: Better material forging will come from the extrusion chamber and frozen pin process. FSW is majorly influenced by process parameters previously stated [10]

5.4 Welding forces: The welding cycle must be regulated by identifying the optimal set of welding settings to minimize tool breakage and eliminate excessive wear and strain on the tool and related equipment. During welding, a number of forces will operate on the tool.: torque is required to spin tool, the tool motion is parallel to a traverse force and a downward force keeps the tool in position. [10]

Conclusions:

Several studies have been executed on similar and distinct Aluminium alloys, titanium, Mg, Cu, and steel according to an analysis of various studies on FSW. This research makes it clear how important it is to comprehend material flow in the tool rotating region in order to design tool shape and optimize friction stir welding process parameters. To improve its optimization, it is therefore necessary to develop more reliable FSW models and suitable tool designs. The metallurgical and welding characteristics of the fused metals are significantly affected by form and material makeup of FSW tool. Additionally, selection of the FSW tool's material is crucial factor that calls for comparative analyses between titanium, steel, and their composites for connecting various metals.

Significant study has also been done, according to the analysis, utilizing a variety of FSW tools, including the straight square, straight hexagon, straight octagon, concave, tapered square, and cylindrical, cylindrical taper, and cylindrical threaded. In addition, research has been done on threaded and non-threaded Tapered Octagon variants. Furthermore, examining Trapezoidal, Taper Threaded, and Threaded Conical tools with a variety of independent parameters such as tool rotation speed, feed rate (or welding rate), axial force, and tilt angle. In addition, Dwell Time and Clamping Force are important factors in addition to Plunge depth. A number of dependent parameters, including ultimate tensile strength, % of elongation, and shear tensile, are the goals of these investigations.

The review highlights that tool wear is often overlooked in FSW of Al alloys. For steel, titanium, and metal matrix composites, tool wear in FSW becomes crucial. Surprisingly, only a handful researchers have delved into FSW tool wear. Suggestions indicate that utilizing computational models can optimize FSW tool design for better performance.

Nomenclature:

PL- Pin Length **SS**- Shoulder Surface shape, **PD**-Pin Diameter, **SCT**-Straight Circular Threaded**, TC3F**-Tapered circular with 3 flats, Flats, **SC**-Straight Circular, **UTS**-Ultimate Tensile Strength, **FSSW**-Friction Stir Spot Welding, **FSW**-Friction Stir Welding, **PS**-Pin Shape, **FSP-** Friction stir processed zone, **HAZ-**Heat-Affected Zone, **TMAZ-** Thermo Mechanically Affected Zone,

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