CHAPTER 2
LITERATURE REVIEW

2.1 INTRODUCTION

The most investigated part in the analysis of FSW is concentrated on the selection of welding parameters. Different materials and joint configurations reportedly demand different parametric combinations. Certain process characteristics determine the accurate thermomechanical bonding of FSW. They can be identified as heat generated, cooling rate, material flow in layers, degree of mixing and filling. Effects of the process parameters on these characteristics are crucial in deciding the strength and quality of the weld. Welding speed, tool rotational speed, axial force, tool geometry, tool tilt angle were identified as the most important parameters in FSW process. Optimized combinations of these parameters have been extensively suggested in various studies [23 - 26]. In most of the analysis of the FSW, the selection of the parameters was limited to rotational speed, transversal speed, tool geometry and axial force.

Weld quality and strength are influenced by the heat input or the highest process temperature and the material flow. In FSW stirred and softened material is subjected to extrusion by the tool pin rotational and traverse movements leading to formation of friction stir processing (FSP) zone. The formation of FSP zone is influenced by the material flow behaviour under the action of rotating tool. However, the material flow behaviour is predominantly influenced by the material properties such as yield strength, ductility and hardness of the base metal, tool design, and FSW process parameters.
The process temperature affects the grain size, dissolution, re-precipitation and distribution of strengthening precipitates which determine the tensile properties of the welds. The material flow in terms of stirring and filling is detrimental in defect formation. FSW joints are prone to defects like pin hole, tunnel defect, piping defect, kissing bond, zig-zag line and cracks, etc., due to improper flow of metal and insufficient consolidation of metal in the FSP (Friction processing zone or weld nugget) region [27]. Therefore, it can be concluded that the process parameters determine the temperature and material flow during the welding process whereby they affect the weld joint formation.

In heat treatable alloys, the static properties of the friction stir welded joints are dependent on the distribution of strengthening precipitates rather than the grain size [28]. The frictional heat and mechanical working of the plasticized material in the weld zone result in coarse and agglomerated precipitates in some areas and the distribution of few needle shaped precipitates in the weld nugget, which leads to considerable softening in contrast to the base metal. This decreases the hardness in FSW joints considerably and yields lower tensile strength than base metal [29].

2.2 HEAT GENERATED IN FSW

The heat generation in FSW is primarily from two sources; Friction between the tool and work piece surfaces and plastic deformation of the work material. The heat generated is conducted to the work piece, tool and support plates. The amount of heat conducted to the work piece determines the success of the metal joining, quality of the weld, weld micro structure and formation of defects. The amount of heat conducted to the tool dictates the tool life. The heat flux during the weld process must ensure a threshold value for the temperature which is enough to soften the material for the tool to process it adequately to achieve the joint. Temperature above this value is undesirable as it may lead to the melting of the base metal. The maximum temperature
required for the FSW process was estimated as 80 – 90% of the melting point of the base metal [30]. The direct and accurate measurement of this heat generation or temperature in FSW was found to be impossible due to the localisation of heat generation and the continuous tool action during FSW. However, experiments were performed to measure the maximum temperature using thermo couples inserted near the weld seam [31]. Reported results of experimental and numerical analyses revealed that 95 % of the heat generated during FSW flows to the work piece, indicating the high process efficiency of the FSW [32].

A set of analytical models were suggested for heat generation based on the tool torque and average power [33, 34]. These models considered only the heat generated through friction. These models were based either on the coloumb’s friction or on the constant shear model.

Localised plastic deformation occurs in the bulk material also contributed to the heat generation during FSW process. The weld power input converted to plastic deformation energy in the bulk material was estimated to have a fraction converted to heat and the remaining stored in the microstructure [35]. The reported results of numerical simulations estimated the fraction of heat generated through plastic deformation as only 2 - 20 % of the total heat generated [35, 36]. Citing this conclusion, many researchers have ignored the heat generation by plastic deformation, in their mathematical models.

Heat generated during FSW is obviously affected by the selection of process parameters for a given material. Heat generation models for FSW have been developed for straight cylindrical [37], tapered cylindrical [38] and pin with eccentricity [39]. The variation of heat generation in terms of energy per unit length with pin eccentricity for the FSW of AA1050 - H12 and AA5754 - H2 are shown in Fig. 2.1.
For the equations developed for heat generation, torque and hence the rotational speed and axial force are the influential parameters for the heat generation. Increased rotational speeds and axial force increase the heat generation. These equations are independent of the welding speed. However it was experimentally proven that at increased welding speeds, heat generated reduces considerably as evident by the temperature values recorded. These observations are logical, as at increased welding speed, the tool has to process more material per unit time and the material ahead of the pin does not get enough time to get preheated. The degree of softening of the base material decreases as the heat input decreases, which in turn increases the power consumption of the process. Fig. 2.2 illustrates the variation of power input and the specific weld energy (weld energy per unit length) with tool traversal speeds [40].

Fig. 2.1: The variation of $Q_{\text{Energy/length}}$ with the tool pin eccentricity for (a) AA1050-H12 and (b) AA5754-H2. [39]

Fig. 2.2: Variation of (a) power consumption and (b) specific weld energy with tool traversal speeds [40]
2.3 MATERIAL FLOW IN FSW

In FSW the material flow under tool action plays an important role in determining the integrity of the weld joint. It may be concluded that the tool shoulder and the pin controls the material flow. The friction between the tool surfaces and the bulk material softens the base material in the immediate vicinity of the tool. The flow of the plasticized material is governed by the tool geometry (size and shape of the shoulder and the pin), rotational and linear speeds of the tool. The tool shoulder diameter and shape is critical, as its grip on the plasticized material organizes the material flow field [41]. The material flow happens in the sticking condition between the tool surfaces and the bulk material surfaces. Hence the heat generation, torque and the welding forces also play a key role in the material transfer.

The material flow pattern during FSW was experimentally investigated by many researchers. The material flow regime was established by using marker materials embedded in the work piece, where its movement after deformation was traced [42, 43], or by tracking the material deformation pattern using dissimilar metals for joining [44, 45].

The findings of different studies suggest that there is an unbalance in the material flow between the AS and RS. Material flows more from the advancing side to the retreating side. Material flow from the retreating side to the advancing side occurs in the tool shoulder region. The TMAZ region is under the influence of both the tool shoulder and the pin and the material extrusion is taken place only in the RS of the TMAZ [46]. This observation provides a plausible explanation for the influence of tool speeds on the material flow.
Material on the advancing side of a weld enters into a zone that rotates and advances with the profiled probe. This material was very highly deformed and sloughs off behind the pin to form arc-shaped features when viewed from above (i.e. down the tool axis). The lighter material came from the retreating side in front of the pin and was dragged around to the rear of the tool and filled in the gaps between the arcs of advancing side material. This material did not rotate around the pin and the lower level of deformation resulted in a larger grain size.

FSW is often viewed as an extrusion process. The material is extruded in layers in semi cylindrical patterns by the tool rotation. The periodic deposition of such layers appears as onion ring structure in the nugget zone [47] as shown in Fig. 2.3.

![Onion rings in FSW of AA 6082-T6](image)

**Fig. 2.3.** Onion rings in FSW of AA 6082-T6 [48]

Material flow is remarkably influenced by the tool design and welding process parameters. Arbegast [49] observed a resemblance between the material flow in FSW and extrusion of aluminium alloys. With this approach the metal flow in FSW was explained in terms of five conventional metal working zones: (a) pre heat zone, (b) initial deformation zone, (c) extrusion zone, (d) forging zone, and (e) post heat or cooled down zone as shown in Fig. 2.4.b.
At the commencement of the tool plunging and rotation the area in front of the pin, which is the pre heated zone, temperature rises due to frictional heating and adiabatic heating of material deformation. The extension of pre heat depends on the tool speed and the material thermal properties. As the tool traverses material temperature increases, when it reaches beyond a critical value, and when the stress exceeds the critical flow stress material flow begins. This zone was identified as the initial deformation zone. The material in the deformation zone gets extruded between the pin and the bulk material in the pre heat zone. The material in this zone is directed upwards to the shoulder zone and downwards to the extrusion zone as shown in Fig. 2.4. (a). A small amount of material is trapped beneath the tool tip and follows a vortex flow pattern. In the extrusion zone the material flow follows a direction from the front to the rear with a fixed width. As the tool moves forward, the material flows in layer by layer leaving a cavity periodically. This cavity is continuously filled by the material from the forging zone which follows the extrusion zone, under the prevailing hydrostatic pressure conditions. The consolidation of the material for forging zone is the function of the tool shoulder under the applied axial force. Behind the forging zone the material is cooled under passive or forced cooling conditions, which is identified as the cooled down zone.

The above explained ideal material flow regime, clearly indicates that the material flow in FSW is influenced by the tool geometry, process parameters, and material thermal and mechanical properties. For a good weld condition defined by the non defective nature and adequate strength these parameters are needed to be selected appropriately. Any deviation from this combination of the parameters may result in an incomplete consolidation of the different process zones, which lead to ineffective stirring, material flow and inadequate filling of material. Such a condition will affect
the strength and integrity of the joints. Various reports observing the effect of process parameters on friction stir welding are included in the following sections.

Fig. 2.4 (a) Metal flow pattern and (b) Metallurgical processing zones [49]

### 2.4 EFFECT OF TOOL ROTATIONAL SPEED

Variations in tool rotational speeds do not affect the weld appearance. Semicircular traces are discernable at all rotational speeds while weld surfaces appear smooth as rotational speed increases. However it was reported that if the rotational speed increases beyond a certain limit, material will be subjected to excess heat and this increases the melting and fluidity of material thereby increasing the turbulence. This condition was identified as a possible reason for cavity defect formation [50].

Fig. 2.5. Variation of tensile strength with tool rotational speed [51]
Another observation was about the effect of tool rotational speed in tensile strength of friction stir welds. Many researchers have reported that the tensile strength of the weld increases with tool rotational speed reaches a maximum value and then decreases with further increase in rotational speed as shown in Fig. 2.5 [51]. The tool rotation causes stirring and mixing of material which in turn increases the welding temperature. The temperature influences the grain growth and dissolution of precipitates. The intensity of grain growth and dissolution of second phase particles greatly affect the tensile properties. The heat input is, therefore, to attain an optimum value for the weld to have good tensile properties. At higher heat input, dissolution and grain growth were found to be more, degrading the tensile properties of the weld. On the other hand, at low tool rotational speeds, heat generation is inadequate to plasticize the material which results in the poor stirring and consolidation of the weld metal. At this condition, weld exhibits poor tensile properties [52, 53]. The weld strength increases with the increase in heat input per unit length of the weld up to a certain level. If the heat input is sufficient to assure the homogeneous distribution of the strengthening particles, the possibility of pore formation in the weld is reduced significantly and this enhances the weld strength [54, 55].

2.5 EFFECT OF TOOL TRAVERSAL SPEED
The reported analyses deal with low tool linear speeds to ensure adequate material joining [56, 57]. However these reports indicate that tool rotational speeds have significant effect on heat generation and material flow. As the speed increases, temperature decreases. The tensile strength exhibited significant variation at lower and higher welding speeds. At lower welding speeds, heat input increases due to increased tool action and friction. Higher heat input enhances grain growth and grain coarsening. Welds performed at lower welding speeds were reported to exhibit grains which contain many sub boundaries. The sub grain size increases with heat input. The
FSW is associated with severe mechanical deformation and complex thermal cycle. As the tool moves forward, the dynamically recrystallized grains statically grow during the cooling phase of the thermal cycle.

Larger the heat input, greater will be the cooling time which resulted in larger grains with a lower density of dislocations and sub boundaries [58]. For higher welding speed, the exposure of the material to elevated temperature gets shortened. This resulted in rapid cooling of the processed material producing finer grains at the FSP zone. Finer grains generally provide better tensile properties for the welds.

Generally it was observed that as welding speed increases the tensile strength of the weld increases reaching a maximum value and then decreases as shown in Fig. 2.6.

![Graph showing variation of tensile strength with welding speed](image)

**Fig. 2.6.** Variation of tensile strength with welding speed [59]

### 2.6 EFFECT OF AXIAL FORCE

Axial force or down force affects the frictional force and hence the heat in put at the commencement of the welding process. Axial force keeps the shoulder in contact with the material. The axial force aggravates friction and keeps the softened and transferred material in the weld line. Increase in the downward force activates the plastic metal
flow [60]. Axial force at optimum temperature fills the weld cavity, pin driven and shoulder driven material and base material coalesced with each other. If the force is increased above a critical value the sub surface material flow is seemed to be increased. This resulted in the formation of flashes [61]. There is a limiting value for the axial force beyond which the tensile strength of the weld decreases as shown in Fig. 2.7 [62].

![Image](image.png)

Fig. 2.7. Variation of tensile strength with axial force [62]

### 2.7 EFFECT OF TOOL GEOMETRY

A FSW tool has two basic functions: localized heating and material flow. The friction between the shoulder and the material provides the major part of heating. Shoulder is responsible for the trapping of material which is extruded upwards by the tool pin and pushing the softened material downwards, assuring the proper mixing of the softened material and the soundness of the joint. Material softening and mixing to form a sound joint are achieved by the action of shoulder and pin [63].

Studies revealed that the relative size (diameter) of the shoulder and the pin is critical. If the diameter of the shoulder is more than a critical value, heat generated will be more and the material flow from the pin part may not be appropriate [64].
Pin geometry influences the material flow [65]. Moreover the pin geometry affects the grain size of the joint. It also influences the strain rate and dynamic recrystallisation of the stir zone. From the available literature, it is found that a cylindrical threaded pin, truncated cone and concave shoulder were widely used welding tool features. Non circular pin profiles with flat faces were reported to produce better results in terms of mechanical properties [58]. It was observed that the non circular pins allowed the plasticized material to pass around the probe. The relationship between the static volume and swept volume is a deciding factor for the flow of material from the leading edge to the trailing edge of the tool during welding, which in turn decides the weld quality. Moreover the pin with flat faces produces a pulsating stirring action which enhances the material consolidation at lower welding speeds [59].

2.8 EFFECT OF TOOL TILT ANGLE

Various studies reveal that a tilt in the tool towards trailing direction favors the weld joint. Tool tilt increases shoulder action, material stirring and mixing. But higher values of tilt angle retard the tool action. However, effect of tool tilt angle on the quality and strength of weld formation have not been studied in detail. Many researchers apparently used a tool tilt angle for best performance based on trial and error method. The effect of process parameters on the weld quality and strength is largely depends on the weld defect formation.
2.9 WELD DEFECTS

The metal joints formed by the FSW offer better surface quality and appearance than the conventional fusion welded joints. With appropriately selected process parameters, friction stir welded joints provides defect free joints with least distortion and smaller residual stresses [66]. However, the complexity in material flow and thermal cycle, associated with FSW results in the formation of defects such as kissing bond, tunnel defect, voids formation which affect the homogeneity and hence the weld strength.

Heat input necessary for plasticizing the material depends on the friction and degree of plastic deformation. If the heat input is not sufficient it affects the stirring and transportation of metal during welding. On the other hand excess heat input causes turbulence in material flow. In both the cases the tool action becomes ineffective to consolidate the softened material periodically. FSW requires softened material to pass around the pin and get consolidated periodically by the hydrostatic pressure. If the hydrostatic pressure is not adequate, or ineffective, defects are formed [67].

Insufficient heat input and metal transfer causes cavities in the welds known as wormhole defect. Wormhole defects occur for butt joint configuration. Insufficient pressure by the tool shoulder is the triggering factor for worm hole or tunnel defect. It is appeared as a cavity which runs along the weld under the weld surface [68]. Fig. 2.9 captures the macrostructure of a weld nugget with a worm hole defect [69].

![Fig.2.9. Worm hole or tunnel defect [69]](image-url)
Increased heat input as in the case of higher rotational speed and low welding speed, causes poor plasticization of material which leads to tunnel defects. The tunnel defect specifies locations in the weld, which are unfilled by the softened material [70]. Worm hole defects are caused by the excessive welding speed with lower rotational speed. At higher welding speed the tool shoulder becomes incapable to direct or push the plasticized material towards bottom of the stir zone and to maintain the constant depth of tool penetration. This condition leads to the formation of worm hole defect. Lack of consolidation of material may not form tunnel defects always, but they may appear as intermittent cavities known as voids (Fig. 2.10).

![Fig. 2.10. Weld macrostructure showing voids.](image)

In some cases the pin length may not be sufficient for a set of selected welding parameters. In such a situation a part of the joint layer may be left without adequate material consolidation. The imperfection, hence caused by the insufficient penetration of the tool is considered as lack of penetration defect (Fig. 2.11). Misalignment of the work piece in the butt joint configuration also leads to lack of penetration.

![Fig. 2.11. Incomplete penetration](image)
If the heat input is in excess, the vertical movement of the metal is retarded by the turbulence in material flow, resulting in smaller size cavities. These defects are known as pin hole defects. Excess heating associated with high plunge pressure causes the softened material to move up to form flashes. Flashes not only affect the appearance, but also reduce the weld strength [71]. It is well established that the tool geometry and welding parameters affect the material flow pattern.

![Flashes shown in weld macrostructure.](image1)

Fig. 2.12. Flashes shown in weld macrostructure.

Another possible defect observed is the kissing bond. Kissing bond is formed at lower heat input during FSW. Lower heat input may not be sufficient to break up the oxide layer present in the parent metal, especially when the faying surfaces are not properly machined. In that case there is high possibility for the oxide layers on the initial butt surfaces to make bonds with oxide free surfaces in the root part of the weld. This flaw appears as a zig-zag line pattern in the weld zone [72]. Heterogeneity in the material flow leads to the formation of weld defects.

![Kissing bond](image2)

Fig. 2.13. Kissing bond
Various reports suggested that tool geometry and welding parameters significantly affect the material flow and hence the defect formation. Scialpi [73] examined the effect of different shoulder geometries in the FSW of thin sheets of 6082 T6 alloys. He observed that defect free welds are generated for shoulders with fillet and cavity. Ramulu et al. [72] analysed the effect of tool speed, welding speed, plunge depth and shoulder diameter on internal defect formation during FSW of AA 6061 sheets. The study has suggested the range of parameters for defective and non defective welds as shown in Figs. 2.14 and 2.15.

![Fig. 2.14. Range of Tool speed, torque and axial force in defect formation [72]](image1)

![Fig. 2.15. Range of welding speed, torque and axial force in defect formation [72]](image2)

### 2.10 OPTIMIZATION OF PROCESS PARAMETERS.

FSW has been extended to a large variety of materials with varied joint configurations and thicknesses. But productivity is still a matter of concern due to the lower welding speed. Efforts to identify an optimum combination of parameters which offers
welding at higher linear speeds with acceptable quality are not yet concluded. Reported efforts for the process optimization of FSW of aluminium alloys were done at lower welding speeds [58, 70]. Optimization techniques at higher speeds were found to be restricted by practical limitations as excessive welding speeds increase the risk of void creation [74]. Reghubabu et al. [75] examined the effect of tool rotational speed and welding speeds on mechanical and microstructural properties of friction stir welded 6082-T6 alloy. In the experiments the highest welding speed tested was 585mm/min and the welding speed corresponding to the optimum condition was 170mm/min. Patil et al. [76] investigated the effect of welding speed and tool pin profile on the weld quality of AA6082 - O aluminium alloy. The study used taper screw thread and tri- flute for pin profiles. They proposed a condition for high strength weld in terms of these parameters; however the maximum value of the welding speed was limited to 80 mm/min. Adamowski et al. [77] analysed the effect of welding speed and rotational speed on the FSW of 6082 - T6 alloy with a highest speed of 585mm/min and with a threaded pin tool.

In most of the analysis of the FSW, the selection of the parameters was limited to rotational speed, transversal speed, tool geometry and axial force. The role and effect of tool tilt angle were not clearly established. It was reported that as the tool tilt angle increases tensile strength and microhardness of the weld joint increases for dissimilar joint of aluminium and copper [78]. Researches on the FSW of dissimilar joints of aluminium and steel indicated that increase in tool tilt angle affects the tensile strength of welded joint [79]. Tool tilt angle of 1.5° or 2° was found to provide good results for aluminium welded joints [80, 11]. Certain studies stipulated that the surface defects can be eliminated with effective filling by tilting the tool for the FSW of aluminium alloys [81]. These reported results concluding the effect of tool tilt angle were also pertaining to lower welding speeds. Ana et al. [82] suggested an optimum condition
for FSW of 6082 - T6 alloy with good strength with a speed of 360mm/min. They have considered welding speed, tool rotating speed, axial force and tool tilt angle as the process parameters; nevertheless the effect of tool tilt on the weld strength was not established. Rodrigues et al. [83] proposed that friction stir welding at higher traverse speeds were strongly dependent on the base material characteristics and plate thickness. They have achieved good welds up to a speed of 350 mm/min for 6mm thick base metal. The process parameters included tool tilt angle; however its effect was not mentioned.

Arora et al. [84] carried out an extensive analysis of the process parameters on the tensile strength of the friction stir welded AA2219 - T87 alloy. The study focused on the effect of tool shoulder diameter, welding speed and axial force. They suggested that welding speed and shoulder diameter influence significantly the tensile strength. Coarsening and or dissolution of strengthening particles were revealed at the weld nugget. They achieved a reasonably good weld efficiency of 75% in terms of the tensile strength, but the welding speed was limited to 180mm/ min as the maximum value. But the effects of axial force on the weld strength have not been elaborated. Even though the micro structural changes have been elaborated using TEM and SEM studies, the micro structural changes and the weld quality were not correlated by incorporating the effect of process parameters.

Effect of tool pin geometry and tool speeds were studied in the report of experimental analysis conducted by Biswas et al [85]. It was proposed that tapered pin profile tools produced joints with superior mechanical properties. They have suggested a ratio for the tool rotational speed to the tool traversal speed for the better mechanical properties of commercial grade aluminum. They conducted the experiments with a maximum welding speed of 122 mm/min.
An optimal parameter window was suggested by Doude et al. [86] for the FSW of AA2219 - T87 alloy based on experiments. The defect free welds were produced around 100mm/min welding speed. They have conducted a thorough investigation in the microstructural changes of the FSW joints.

Yan et al. [87] examined the effect of rotational speed, translational speed, and axial force on tensile properties, nugget microstructure and nugget hardness. However, the study was largely focussed on the effect of rotational speed on the welding response variables. It was proposed that increase in rotational speed resulted in increased temperature, less torque and less flow stress, increased yield strength and hardness. The best combination of the strength and ductility corresponds to a rotational speed that does not cause melting. The welding temperature must be near to the solidous temperature for best results. The welding speed values were limited to a maximum of 250 mm/min. They observed that the effect of translational speed on the nugget properties is small. They surmised that at higher translational speeds, the slight increase in hardness is due to the shortening of time period for over ageing.

In the qualitative assessment study of FSW, Liu et al. [88] suggested that ultra sonic vibration enhanced FSW can eliminate tunnel defects. To facilitate the macro analysis, they have divided the nugget zone in to three regions; viz. shoulder affected zone (SAZ), pin affected zone (PAZ), and weld bottom zone (WBZ).

The converging point of these three sub zones act as the epicentre for the tunnel defect (Fig. 2.16). In case of a tunnel defect, a void may form at this point due to the insufficient material flow in the PAZ from the retreating side to the advancing side. In sufficient material transfer in the down ward direction in the SAZ also plays a crucial role in tunnel defect. In their work they supplied additional energy to enhance the material flow rather than identifying proper parametric combination. However, their
results and observations may be extended in the analysis of material flow in order to assure a defect free weld.

![Fig. 2.16 Formation of tunnel defect in FSW [88]](image)

Tunnel defect was reported to be caused by higher welding speed or insufficient axial force [89]. Both these conditions were identified by low heat input and insufficient material flow [90 - 92].

Ramachandran et al. [93] examined the effect of parameters on the FSW of dissimilar joint involving AA 5082 and HAS steel. The study reported the formation of butt joints by varying the tool traversal speed, keeping other parameters as constant. They divulged that tool traversal velocity had significant effect on the weld strength by influencing the intermetallic compound layer formation. They were able to obtain a weld joint efficiency of 91% with a speed of 45 mm/min.
Dude et al. [94] suggested an optimal parameter window for the FSW of AA2219-T87 based on UTS, hardness and volumetric defect formation from their experimental analysis. The force acting was recorded using high speed data acquisition system. The report suggested that for the threaded tool used, voids near the crown is an indication rotational velocity above the optimal range and the voids appeared near the root proclaims the fall in rotational velocity below the optimal value.

Material flow regime determines the extent of bonding in FSW and the evolution of weld defects. As tool rotates and traverses the stirred material is to be deposited continuously without any void in between. Tongne et al. [95] observed the onion ring formation, a characteristic feature of material deposition as the result of periodic deposition of plasticized material in the weld progression. They quantified the extent of onion ring formation and predicted the characteristics of material deposition based on a steady state finite element model. They concluded that the formation of banded structure which appeared as onion rings related to the transient flow conditions which were influenced by the contact conditions between the base material and tool. The tool geometry had a great effect on the contact condition which in turn affects the weld quality. They suggested that the band formation sites depended on the strain rate gradient in the vicinity of the tool and the band formation pattern revealed the occurrence of defects, especially tunnel formation.

Role of tool shoulder geometry and features have been explored in various literatures. Tool shoulder is responsible for the major part of the heat generation, confinement of weld material in the weld seam and the periodic deposition of plasticized material. Majority of the weld defects are the results of poor material flow. Effect of shoulder features on the adequacy of material flow was experimentally studied by Trueba Jr. et al. [96]. They study explored the opportunities of employing additive manufacturing
in tool making by using Ti - 6Al - 4V tools with varying tool shoulder designs. The weld quality in each case was rigorously assessed through destructive and non destructive tests. The analysis was based on the material flow in welding. They claimed that shoulder with a raised spiral profile was capable of producing welds with best quality even in case of non ideal process conditions.

Only a few reports elaborate the parametric studies of FSW at welding speeds higher than 200 mm/min. The obvious reason for the lower or medium welding speed is that at higher speed the weld strength and quality are reduced considerably. The efforts to increase the welding speed without compromising the quality and strength continue to be a challenge. Trimble et al. [97] made a series of FSW to determine the effective combination of parameters to produce good quality welds at higher speeds. They conducted FSW with AA 2024 - T3 alloy and achieved good quality welds at a maximum speed of 355 mm/min. They recommended that tooling with scroll shoulder and triflute pin adequately stirred and transferred material to produce good quality welds at higher welding speeds.

Moshwan et al. [98] investigated the changes in the mechanical properties and microstructural evolution as the rotational speed changes using AA 5052 - O alloy. The weld forces were measured to estimate the variation in weld quality. Five different rotational speeds were used while the welding speed was kept as 120mm/min. It was revealed that dissolution of inter metallic phases during FSW lowered the weld strength. Variation of UTS, welding forces and micro hardness with rotational speeds were recorded to suggest the optimum rotational speed.

A few literature reports the effect of certain parameters which are otherwise not common in the investigations. Kumar et al. [99] examined the effect of variation of interposition of the joint with tool axis and the axial force on the tensile strength of
A - Zn - Mg alloy. They have conducted the experiments by continuously changing the axial load by gradually increasing the tool shoulder and base material interface, instead of applying different axial forces. Similarly the interface position of the joint with respect to the tool axis was changed continuously by keeping the tool traversal direction at an angle with the joint line. Material flow changes have been observed in the micrographs to find out a suitable axial force for making defect free weld joint. The variation of UTS with axial force showed a gradual increase, reaching a maximum value and then a decline. The variation in UTS was associated with the defect formation which in turn related to the pin driven and shoulder driven material flow. They suggested a safe range of tool deviation from the weld line for a frustum shaped pin.

The tool shoulder surface geometry is a key feature in the mechanical properties of FSW joints, as they influence the heat generation and the material flow. Scialpi et al. [73] evaluated the influence of shoulder geometry on the microstructural and mechanical properties of thin (1.5 mm) sheets of AA 6082 alloy joints. They used three types of tools with different shoulder features viz. scroll and fillet, cavity and fillet, and only fillet. The performance of these tools were analysed by micrographical examinations, microhardness, room temperature bending and tensile tests. By visual inspection they asserted that the crown and root quality would change with shoulder features. Through micrographical inspection changes in the nugget grain size was established for each tool. They proposed that the tool with fillet and cavity provided best results in terms of tensile strength and hardness for the other selected parameters.

Hariri et al. [100] proposed an optimum combination of tool rotational rate and welding speed focussing on the corrosion behaviour and mechanical properties of friction stir welded AA 5052 alloy. Potentio dynamic polarization, open circuit...
potential monitoring, test of intergranular corrosion, weight loss, tensile test and microhardness tests were used to explore the effect of tool speeds. Welding speed and rotational speed were found to influence grain size by affecting the frictional heat input and degree of deformation. Intergranular corrosion in the form of network attacks was found in NZ at 800 and 2500 rpm. Finer grain sizes were found to repel the corrosion activity. Extra fine grain structure was obtained at 400 rpm and 250 mm/min which were found to lessen the corrosive attack. They suggested optimum values for rotational speed and feed as 400 rpm and 250 mm/min for better mechanical properties and corrosion resistance.

FSW is generally devoid of residual stresses as the joining takes place at lower temperatures. However, for thicker sections and at high temperature process conditions friction stir welded sections show considerable residual stresses. A few reports were found to consider these issues. Gorgil et al. [101] presented their experimental analysis on the effect of tool shoulder features on the mechanical properties and residual stresses of friction stir welded AA 6082-T6 alloy. They have used three types of tools with different shoulder features: a shoulder with scroll, a shoulder with a shallow cavity, and a flat shoulder for the welding of 1.5mm thick base plates. Tensile test with transverse and longitudinal specimen and fatigue tests were conducted to evaluate the mechanical properties and hole drilling method was used to analyse residual stress. Flat shoulder produced higher welding temperature which in turn caused the coarsening of grains in the NZ. Visual observation revealed that shoulder with scroll caused flash formation, whereas flat shoulder and shoulder with cavity produces smooth weld surface with little flash. A key observation in their studies is that the shoulder geometry had little influence in the tensile strength as there was no much difference in the tensile strength for different shoulder geometries. Nevertheless, the fatigue properties were strongly affected by the shoulder geometries.
with shoulder with scroll showed worse fatigue behaviour whereas flat and shoulder with cavity provided better fatigue properties with lower fatigue limit. Residual stress level was low for all joints, perhaps because of the uniqueness in FSW, but residual stress distributions were different for different shoulder geometries. They inferred that shoulder with scroll provided relatively better results when residual stress was concerned.

Ramulu et al. [72] proposed a criterion quantitatively for the formation of defect free welds from their experiments by performing FSW on 2.1 mm thick AA 6061 - T6 alloy. With a focus on the defect free weld formation they analysed effect of welding speed, tool rotational speed, axial force, and plunge depth and shoulder diameter on the FSW process. The study concluded that the shoulder diameters have little effect on the defect formation and higher welding speeds (80 - 120 mm/min) and higher rotational speeds (1300 - 1500 rpm) and increased plunge depth (1.85 – 2 mm) produced defect free welds. As a criterion for defect free weld formation they suggested that the change in axial force and torque with other parameters considered were high for defective welds and less in defect free welds.

Elangovan et al. [62] presented the friction stir processed (FSP)zone of AA 6061 aluminium alloy under various pin profiles and axial forces and the correlation of tensile properties of friction stir welds with FSP zone formation. They fabricated friction stir welds with five different pin profiles: straight cylindrical, tapered cylindrical, threaded cylindrical, triangular and square and three axial force levels: 6 kN, 7 kN and 8 kN. Macro structure of each weld was extensively analysed to understand the defect formation mechanism. They concluded that the square pin profile produced defect free welds with highest tensile strength and the variation in axial force had little effect in that case. On the other hand 7 kN axial force produced
defect free welds with superior tensile properties irrespective of the pin profile used. Interactive effect of axial force and the pin profile was concluded as the square pin profile with an axial force of 7 kN produced FSP region with finest grains which in turn cause high hardness and highest tensile properties. However it may be appropriate to notice that these results were produced with a tool rotational speed of 1200 rpm and a lower welding speed of 1.25 mm/sec.

Jayaraman et al. [102] analysed microstructural evolution of the weld zone of friction stir welded cast A 319 aluminium alloy and the corresponding tensile strength under varying process parameters. The welding was performed with different combinations of tool rotational speed, welding speed and axial force. The macrostructure revealed defect formation and the corresponding microstructure, modes and locations of tensile fracture were compiled to suggest the parametric combination for weld formation with zero defects and superior tensile strength. The precipitation and distribution of eutectic Si particles were found to be one of the decisive factors for the tensile strength. Accordingly, they suggested a combination of parameters at a tool rotational speed of 1200 rpm, welding speed of 40mm/min and 4 kN axial force for the formation of defect free weld with maximum tensile strength.

Rodrigues et al. [103] examined the effect of tool shoulder features on the microstructural and mechanical properties of 1mm sheets of AA 6016 - T4 alloy welds. Non defective welds were obtained using conical shoulder and scrolled shoulder tool where welding speeds were 180 mm/min and 320 mm/min. Tool rotational speeds 1800 rpm and 1120 rpm. As the welding temperature at higher rotational speed, welds produced were identified as hot and cold welds and they were distinguished by the appearance of the crown as shown in Fig. 2. 17. Conical shoulder tool produced hot welds with larger grain size and few coarsened precipitates. Larger
grain size in the report indicates slower cooling of the weld. Scrolled shoulder tool was reported to produce cold weld. Nuggets in that case were composed of grains smaller in size and many coarsened precipitates. This difference in microstructure was viewed to be the reason of reduction in hardness in case of cold welds. A reduction in elongation of 70% and 30% was observed for cold weld and hot weld respectively. They concluded that the tool shoulder geometry and welding parameters have significant impact on the material flow and mechanical properties of friction stir welds.

Fig. 2.17. Crown view of (a) Cold weld (b) Hot weld

Among the earlier reports, Patil and Soman [76] explained the effect of tool pin profile and welding speed on friction stir welded butt joints. They used triflute and taper cross section with threads pin profiles for butt welding AA 6082 - O alloy at a tool rotational speed of 1200 rpm, and welding speeds of 60 mm/min, 70 mm/min, 75 mm/min and 85 mm/min. It was proclaimed that the pin profile and welding speed significantly affect the tensile properties. They concluded that the taper and screw threaded pin profile produces superior quality weld than that of triflute pin irrespective of the welding speed. The highest ultimate and yield strength were reported for the welds produced by taper and screw threaded pin profile at a speed of 70 mm/min. For the triflute pin joint, UTS attains the maximum value for the welds fabricated at a speed of 60 mm/min. According to the report the authors were able to achieve a higher tensile strength value of 92.3% of the base metal value but at a very
low welding speed. It is significant to note that the shoulder and pin diameters of the tools were different. However the authors have not explored their significance and interactive effect.

Rodrigues et al. [104] reported a rare attempt to examine the feasibility of FSW of aluminium alloys at higher welding speeds. It was reported that the feasibility of FSW depends on the type alloy and thickness of the base metal apart from the general process parameters. They assessed the weldability of AA 6082 - T6 and AA 5083 - 111 alloys based on the defect formation analysis and mechanical strength characterisation. FSW of the alloys were performed for various tool geometry, welding speeds, rotating speeds, axial forces and tool tilt angle. The maximum speed tested was 350 mm/min for 6mm thick plates. By calculating the maximum energy consumed per unit length they suggested that FSW is less dependent on tool parameters and process parameters at high rotational speeds. Attaining the hot weld conditions, according to their analysis, was depending on the base material properties, which was more feasible for harder materials like 6082 alloys. Based on the maximum energy consumption and defect formation they proposed parameter window for good weld formation.

Barlas and Ozsarac [105] studied the effect of tool rotational speed, tool tilt angle and the direction of tool rotation on FSW of Al 5754 alloy using a threaded tool. Higher tool rotational speeds were tested in various trials. Best results were obtained for tool rotation of 1100 rpm, 2° tool tilt and counter clockwise rotation. With the support of the macrographs of the transverse sections of the welds, the authors revealed that the clockwise rotation of the right handed threaded tool in various trials with different parameters caused defects. The trials performed with tool rotation in counter clockwise direction produced non defective welds. They also suggested that shape of
weld nugget zone changes with the tool tilt angle and the direction of tool rotation. For clockwise rotation cavity defects occurred beneath the tool pin irrespective of other process parameters. For vertical tool application the defects were formed on both AS and RS whereas for $2^0$ tool tilt the cavity was formed only in the RS. The authors concluded that insufficient heat input, stirring rate and axial force caused the defect formation in case of trials with clockwise rotation. They also opined that a slight increase in penetration depth with increase in tool rotational speed will favour the elimination of defects. Though it was not elaborated in their study, the macrograph clearly indicated the difference in material flow with the direction of tool rotation, where the location of defect formation was changed from interface to pin bottom as shown in Fig. 2.18. The direction of tool rotation with respect to the direction of thread advance will obviously have an effect on the material flow, the severity of which needs further investigation.

![Fig 2.18 Material flow: (a) Tool rotation clockwise and tool tilt angle $2^0$ (b) Tool rotation clockwise and tool tilt angle 0 (c) Tool rotation counter clockwise and tool tilt angle $2^0$ [105].](image)

Many studies summarized the effect of various parameters to the in-process thermal cycle experienced during FSW. Reynolds et al. [106] studied the relationship between welding parameters, hardness distribution and thermal history in FSW of Al 7050
alloy. Tool rotational speed, welding speed and axial load were selected as the parameters for the experimental trials while temperature-time history was recorded using FEM simulation. A series of welds were made with 7050 - T7451 alloy plates of 6.4 mm thickness and the highest welding speed tested was 5.1 mm/s. Weld power and welding speeds were chosen as the secondary parameters to rationalise the hardness variation in welds prior and after post weld treatment. They suggested that the rate of heating up and rate of cooling was dependent only on the weld speed and the weld temperature attained can reliably be correlated with the weld power rather than the primary process parameters. The study correlated the nugget hardness with peak temperature and the precipitation of M phase particles. Based on the thermal history and hardness distribution they deduced an optimum weld schedule which corresponds to a peak temperature value which is between the solution treatment temperature and the melting temperature and a higher welding speed.

The heterogeneity in microstructure of friction stir welded precipitation hardened aluminium alloys is crucial in deciding the corrosion properties as FSW influences the behaviour of strengthening precipitates. Rao et al. [107] studied the effect of tool pin profile on the evolution of weld nugget microstructure and pitting corrosion of AA2219 alloy. A series of welds were made using tools with conical, square, triangle, pentagon and hexagon pin profiles. The performance of tools was assessed by measuring the temperature during welding, micro hardness survey, and microstructural changes including distribution of strengthening particles.

The study concluded that the shape of the weld nugget is dependant only on the shape and size of the tool pin, not on the welding parameters. More over the welds formed by the hexagonal pin exhibited equiaxed grain structure finer than other welds presumably by the dynamic recrystallisation. The second phase CuAl$_2$ particles were
more uniform and small in case of hexagonal pin, which was reported to be attributed to the higher degree of deformation owing to more number of flat faces in the hexagonal pin tool. The heat generation was found to be more for hexagonal pin tool which caused the disintegration and uniform distribution of eutectic network. Better dissolution of the precipitates were found in case of hexagonal pin which resulted in better corrosion properties of the weld nuggets better than the base metal due to the reduction in galvanic coupling. Hexagonal shape was the better option for tool pin profile for optimum combination of microstructure, hardness and corrosion properties.

Mishin et al. [108] precisely carried out the microstructural characterization of friction stir welds of 6082 commercial aluminium alloy using transmission electron microscopy (TEM) and scanning electron microscopy (SEM). They revealed that the weld nugget microstructure was characterized by large range of disorientations and resembled to a well recovered structure typical of hot deformed aluminium alloys. They suggested that TEM with suitable tilting can only reveal such characteristics for a particular region. However the process parameters used were not mentioned in the report.

The structural changes occurred during FSW by the heat input is paramount in deciding the weld performance. The metallurgical and structural transformations in weld joints are crucial and hence require close evaluation. Apart from the simulation studies some experimental studies put forward a realistic explanation in this extent. Cao et al. [80] conducted an experimental study to examine whether the maximum temperature reached the melting range and the possibility of occurrence of liquation. They have conducted FSW of AA2219 alloy as it has clear lower bound of melting temperature and as a bench mark to check the occurrence of liquation, gas metal arc welding (GMAW) of alloy was also performed. They spotted liquation from the
reaction of θ (Al2Cu) particles with surrounding aluminium matrix forming distinct composite like eutectic particles indicating outstretch to eutectic temperature. However in case of FSW, they ruled out the possibility of liquation as the nugget contains only θ particles, often larger in size, with no traces of eutectic particles. But they suggested that the θ particles underwent agglomeration and carried away by the stirred and transferred material throughout the weld. However no apparent correlation was evident between the extend of agglomeration of θ particles and the weld parameters.

Kamble et al. [109] studied the effect of pin geometry, tool rotational speed and welding speed on the mechanical and electrical properties of AA 6101 - T6 alloy joints made by FSW. They have used square and hexagonal profiled pin tools for weld joining. The maximum welding speed was limited to 120 mm/min. They concluded that the square pin provided better mechanical properties and microstructure. The welds made by using hexagonal pin tool exhibits traces of oxides and tunnel defects. In all the cases of weld joints the loss of conductivity was found to be negligible.

Singh et al. [110] discussed the effect of post weld heat treatment on the microstructure and mechanical properties of friction stir welded 7039 aluminium alloy. The experimental trials were conducted at a constant rotational speed of 635 rpm and welding speeds of 8 mm/min and 12 mm/min. For the selected parameters, they concluded that the tensile strength of the welds increases with the welding speed and the hardness decreases with increase in welding speed. It was observed that the post weld heat treatment lowered the ultimate tensile strength, yield strength while it improved the percentage elongation. The hardness of the as weld joint was reported to be decreased with welding speed except at the weld centre while the effect of welding speed was reversed for heat treated welds. But they have not discussed the cause of the difference in the properties of as welded and heat treated welds.
Cavaliere [111] studied the effect of process parameters on the tensile, fatigue and crack behaviour of various aluminium alloys from 2xxx, 3xxx, 5xxx, 6xxx and 7xxx series. The experimental campaign used threaded pin tools of different pin length and shoulder diameters. The parameters tested were rotating speed, weld speed, tool tilt, revolutionary pitch and axial force. The experimental data was used to create a database capable of generating a model to predict the weld quality under various parameters.

Prior studies in the FSW regime discussed the benefits of the process, optimum operating conditions based on the selection of process parameters and additionally the effect of the process parameters on the strength and quality of the weld joints. The results of these studies stipulated that process parameters determine the welding process temperature and the material flow during weld formation. However certain parameters, for example, the tool tilt angle have not been contemplated in these studies. Tool tilt angle, apparently has a significant effect on the material stirring during the FSW. The structural characterisation of the friction stir welds, especially for age hardened aluminium alloys is another aspect worth to be studied. Different experimental analyses have examined the structural changes of metal during FSW. However, the effect of tool parameters on structural changes of has not been adequately addressed. Most of the experimental analyses on the effect of process parameters in FSW are confined to lower welding speeds. Even though such studies are significant in understanding the FSW process, process mechanism at higher welding speeds is equally important, as it determines the acceptability of the FSW process as an alternate joining process.

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