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A review towards Friction Stir Welding technique: working principle and process parameters

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Abstract
Friction Stir Welding (FSW) is a solid-state bonding process that employes tools that are not used up and can function to connect two opposite workpieces without melting the workpiece material. The friction force has been micro-structurally tested to reformat or transform the inner state of the structure properties (atomic formation) form in metal since the kinetic energy of friction has been utilised in one of the welding techniques. Right afterwards, the studies reported that the mechanical properties also underwent a significant deformation. The aim is to determine the effect of Welding Procedure Specification (WPS) product quality. As it develops through research and applied experiments, the branch of friction-based welding discipline can be classified depending on how the friction mechanism can produce the finest solid-state joint, which is suitable to the typical property of metal and can be maximised by joint configuration. Friction Stir Welding is a friction-based welding technique that uses the stirring tool to generate friction while the workpieces are stuck on the line of the FSW joint configuration. The relevant correlations amongst process parameters and inside its respective adjustable variables are constructed to the finest principles that produced top-grades empirical reports of the weld properties. In this review, the explanation of the working principle and clarification of process parameters are presented. The cited references are selected from creditable and verifiable articles and books in the last ten years. Expectedly, it will be able to pioneer a new face of simple and understandable review articles.

Keywords:
Friction Stir Welding;
FSW joint configuration;
Positive and negative limitations;
Process parameters;
Tool design;

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INTRODUCTION

The history of Friction Stir Welding (FSW) was initially identified in 1991, located in the UK Cambridge. A group of researchers from The Welding Institute (TWI) chaired by Wayne Thomas invented a novel welding technique that is strongly unique because they revealed that the welding process itself does not melt the workpieces and is able to produce a fine joint with less than 10% of residual defects caused by welding process [1], the welding technique then initially named as Friction Stir Welding as generally abbreviated with FSW.

FSW is one of the Solid-State Welding (SSW) welding methods, namely welding that takes place under the melting point of the workpiece. Rubbing two workpieces continuously will produce heat. This is a basic principle of creating a friction welding process. In the FSW process, a spinning device is emphasised on the material to be joined.

The FSW technique was initially applied to weld aluminum alloys due to its ability that be able to avoid crucial problems of fusion welding technique can make such as hot cracking, porosity, element loss, etc. Since then, FSW has become a trending discussion that leads an increasing number of its developments and research parallel with its associated novel technologies in many manufacturing companies, especially in automobile, aeronautics, aerospace, ship-building sectors, research organisations and universities investing heavily and vigorously in the process and many international conference series dedicated and attributed to its study.

FSW characteristically has unique process parameters that affect the quality of the weld. The main parameters that are critical in FSW are the tool rotation speed, welding speed, and axial force. The tool rotation speed determines the amount of frictional heat generated in the material, and it can significantly affect the quality of the joint. A higher rotation speed generates more heat and results in a softer material, whereas a lower speed results in a harder material. The correct tool rotation speed can help to ensure that the material is adequately softened for the welding process and that the joint quality is satisfactory. The welding speed is another important parameter that affects the quality of the weld. A higher welding speed may result in insufficient mixing, whereas a slower welding speed can result in tunnel defects or voids. The welding speed needs to be adjusted according to the material being welded to ensure that the joint quality is acceptable. The axial force is also a crucial parameter in FSW, as it determines the level of material deformation and the amount of force required to create the weld. A higher axial force can result in a better-quality weld, but it can also increase the risk of distortion or cracking in the material. The axial force needs to be balanced with the other process parameters to ensure optimal results.

In the Friction Stir Weld Technical Handbook, these parameters are further discussed, along with other factors that can impact the quality of the weld. These include the tool design, the material properties, and the clamping system used during welding. The tool design and clamping system must be tailored to the specific material being welded to ensure proper alignment and prevent unwanted vibrations during the welding process. Overall, the process parameters of tool rotation speed, transverse speed, and plunge force are critical to achieving high-quality welds in FSW. The correct adjustment of these parameters can help to ensure that the material is adequately softened, mixed, and bonded to create a solid-state joint. Proper selection of the tool design, material properties, and clamping system are also important considerations in FSW to achieve optimal results.

Based on the joint product that FSW can produce, FSW is categorised as a solid-state welding technique and a novel friction-based welding. Moreover, FSW is nominated as a green technology [2] due to its process property that reminds energy efficiency and environmentally friendly. Also, no gases are evolved and there are no toxic fumes or smoke produced. In particular, the most distinguished amongst FSW with other friction-based welding is that the friction mediator of FSW utilises a non-consumable tool that is specifically engineered to be able to create thermal and material flow dynamics.

However, to achieve optimal results, it is essential to understand the working principle of FSW and the impact of process parameters. The FSW process involves a rotating tool that generates frictional heat and plasticises the material in the joint area. The tool then moves along the joint line, mixing the softened material and forming a solid-state bond without melting the material. One of the primary advantages of FSW is that it can be used to join materials that are difficult to weld with conventional fusion welding techniques, such as high-strength alloys and dissimilar metals. However, several issues need to be addressed to ensure a successful FSW process. One critical factor is the selection of the right process parameters, which include the tool rotation speed, welding speed, and axial force. These parameters can majorly affect the quality of the weld and the properties of the final product. For example, too high a welding speed can result in inadequate mixing, whereas too low a speed can lead to defects such as tunnel defects and voids.

Another important consideration is the design of the FSW tool, which must be tailored to the specific material being welded. The tool material, shape, and dimensions can all impact the temperature breed, structure vortex, and joint quality. Additionally, the selection of the proper clamping system and fixture can ensure adequate alignment of the workpiece and prevent unwanted vibrations during the welding process. The selection of the optimal FSW parameters and tool design also depends on the specific application and the required properties of the final product. For example, aerospace applications may require the use of high-strength alloys, which may necessitate higher axial forces and lower welding speeds. In contrast, automotive applications may prioritise speed and cost, requiring higher welding speeds and lower axial forces.

In conclusion, the working principle and process parameters of friction stir welding are essential factors that must be carefully considered to achieve high-quality welds and reliable products. FSW offers many advantages over traditional welding methods, but the proper selection of process parameters, tool design, and clamping system is crucial to achieving optimal results. Future research in this area will continue to improve our understanding of FSW and lead to further advances in this promising technology.

Plenty of creditable paperwork from eligible authors published in the top-ranked journals have studied and reported numerous aspects associated with FSW, among others are the process principle & parameters, the joint performance, techniques, technology novelty, numerical analysis & simulation, etc. In this review, the emphasis pointed on the actual working principle, a complete process parameter, several of the most used types of tools design, common joints configuration with literature method and as the conclusion, the outlook remarks are summarised. The author conducted this research because he wanted to know what effect the welding quality of FSW products had.

THE PROCESS OF FSW

Many eligible authors in the FSW direction have been elaborately revealing the working principle of the FSW joining technique from simple to detailed understandings in their written works. Referring to A. Zens et al. [3] revealed that Mishra is one of the best experts in FSW and his colleagues re-explains that the fundamental idea of the FSW mechanism is simply divided into 3 phases: drilling, traversing and retracting. More detailed, the illustration of the basic setting-up can be schematically drawn in Figure 1. During the process is conducting the workpieces are then oriented onto two sides of perspective, which correspond to the knowledge direction of tool rotation and the travel, where the tool rotation way vertically with the tool travel direction (opposite orientation of atoms flow diffusion) named as advancing side and where the tool rotation is contrary towards the tool travel direction (parallel to the orientation of atoms flow diffusion) named as retreating side.

The friction mediator has the key role of creating the joint fine and valuable properties is that cylindrical non-consumable tool with a specific engineering design on the shoulder (D) and the probe (d) therewith associated gauge of its geometry and dimension. The FSW tool possesses three significant functions that are

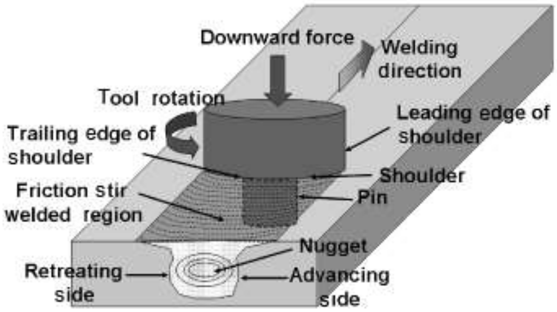

Figure 1. Schematic drawing of the conventional concept of FS processing [3]

creates the frictional heat without any melting transverses sectional inter-surfaces of workpieces, drives the atomic deformations flow and keep manages the heat in the metal beneath the tool shoulder is generated from the workpiece by both the kinetic friction between the rotating tool pin and shoulder and by the intense plastic deformation of the workpiece. The heating softens the material around the pin's cross-sectional area, and when combined with the rotation and movement of the tool, it causes the material structures to move from the front of the pin to the back of it, thus filling the hole in the tool wake as the tool moves along the sectional line. The tool shoulder maintains the atomic deformation flow at a level that is similar to the shoulder position, which is approximately the initial workpiece top side of the surface.

Due to the tool's action and impact on the workpiece, a solid-state joint is formed when executed correctly without any observed melting point. The material structure movement achieved by the pin can be complicated due to various geometric and dimensional features in the tool designs, resulting in gradients in strain load, process temperature, and strain velocity. Consequently, the microstructure in the nugget zone, resulting from this welding process, reflects these distinct thermomechanical distributions and is not uniform across different zones. One of the significant advantages of this solid-state welding technique is the creation of a fully recrystallised, equated, fine-grain microstructure in the nugget due to intense plastic deformation at elevated and calculated temperatures that do not reach the metal's melting point. The microstructure featuring fine-grain texture yields exceptional mechanical properties, fatigue properties, improved formability, and outstanding plasticity.

In addition, Jayaseelan et al. [4] have a characterised knowledge of understandings FSW principles that can be summarily noted i.e. a. The tool pin's length should not exceed the workpiece thickness; b. Ideally, intermittent heat generation mechanisms should occur through friction work and plastic dissipation as a result of transient heat transfer effects and the material's capacity to regain strength as heat is lost to the environment; c. The cyclic heat generation process recurs with each transverse displacement of the tool, resulting in encapsulation that reintroduces the friction work heat generation mechanism before the plastic deformation mechanism; d. The pattern of onion rings on the nugget zone is the typical form caused by the conventional geometrical design of the tool. In conclusion, most of the details of the explanation up to the effort of understanding are self-explanatory.

Singh et al. [5] re-explained the principle operation of FSW. The significant phase during the process is when the tool traversing along the weld line in a plasticised tubular shaft of metal results in severe solid-state deformation involving dynamic recrystallisation of the base metal.

FSW PROCESS PARAMETERS

Technically, the whole process of the FSW joining technique is manufactured by the role of FSW machinery; hence, it is greatly impossible by handcraft of an engineer and can only be conducted on an industrial scale, institute or school. The preferences of the process variables can be changed in accordance with the needs and projects because the machinery is computerised. Based on the FSW fundamental process, there are three main parameters that have an important role: rotational speed, transverse speed and plunge force, so lots of research studies revealed its most appropriate variables or even its associated enhancement methods.

The data of published literature regarding FSW process parameters have been reviewed with the following results of the review below.

O. P. Abolusoro et al. [6] referred the table of the main process parameters in FSW and its effect, respectively. Tool rotation (v, rpm) and transverse speed (n, mm/min) Higher tool rotation rates generate higher temperature while traversing. The softened material from the leading edge migrates towards the trailing edge, and this transferred material consolidates at the tool's trailing edge by the implementation of an axial force. The tool's characteristics are usually defined by the tool tilt and plunge depth, with a small tilt angle (θ) being typical. As the tool is inserted into the sheets, the blank material undergoes a local backward extrusion process up to the tool's shoulder. Additionally, the target depth is important as well to ensure the distance of the shoulder and top surface maintained in a close appropriate distance. In conventional FSW tools, the design division consists of two main parts that are the part of shoulder and pin/probe, both designs are affected the metal flow specifically pin is role of speed distribution and shoulder prevents the plasticised material from escaping from the workpiece. The common tool design for conventional are straight cylindrical, tapered cylindrical, threaded cylindrical, triangular and square pins which depicted in Figure 2.

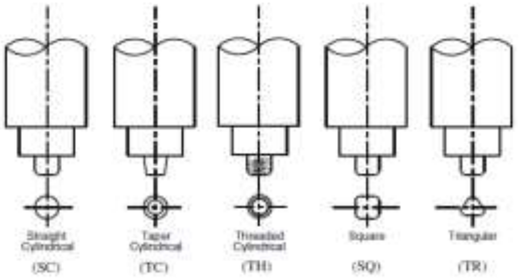

Figure 2. Five common FSW conventional tool designs [6]

Jadhav & Dalu [7] revealed that primary variables that can affect weld properties significantly are tool material including shape and size, tool rotational velocity, welding speed, tool tilt and plunge depth. H13 is the most common material for the tool. In particular, they have been tabulated the process parameters that have been investigated to study every deep effect and its explanation towards FSW process.

V. Msomi et al. [8] exposed an insight from Tiwari et al. re-explained the process parameters of FSW can be divided into two primary segments which classified according to phase of the process viz. tool preparation and during the welding process. Tool geometry design and dimension, an eligible tool have able to give such as performances viz. reducing the welding force, enable easier flow of plasticised material, facilitate the downward auguring effect, and increase the interface between the pin and the plasticised material. the relative dimensional of the pin and shoulder is critical and the most common used of tool's types are cylindrical threaded pin, truncated cone and concave shoulder for conventional FSW.

In A. Heidarzadeh et al. comprehensive review [9] revealed that Threadgill et al. have been detail discussed FSW process which revealed the important notes behind the whole process regarding to FSW technology. The correlation of tool design and flow mechanisms, duly noted that Material deformation generates and redistributes heat, producing the temperature field in the weld however the distribution of heat itself has coming back to metal flow and heat affected area. Computational Fluid dynamics (CFD) is used to study the material flow mechanisms and associated to its tool design, which resulted the two-dimensional flow. The comparative magnitude of swept volume to the pin volume is that quantified the mixing effect. The modeling of three-dimensional flow offers the expansion of affected parameters it is not just the complexity of the tool features which remains future open research. And the second important note is Heat generation during the process and its regimes. The heat from FSW is a complex mutual combination of function of the process variables (traverse and rotation speeds, and down force), as an analytical estimate Figure 3 shows rate of heat input per second and per mm.

The analysis for both like-to-like and AA5083/AA6082 welds assumed that sliding Coulomb friction with a coefficient of friction or sticking friction using an estimate of the limiting shear yield stress was present at the tool/workpiece interface, or contact conditions and/or heat input were inferred from machine torque measurements.

Thermocouple measurements combined with heat flow analysis also offer a way to estimate net power inputs, even though there is no straightforward correlation between temperature and input power or heat. It is noteworthy that there is evidence of a correlation between heat input and the temperature of the backing plate and the tool. The downforce in FSW provides a close thermal contact between the workpiece and the backing plate, but this contact changes with the welding process's position, necessitating complicated calibration. within consideration that by increasing the down force rate pushes the enlargement of process window then can be affected lowering rates of spinning and traveling speeds. CFD modelling has offered a new finding that the responsiveness of heat production, tool downward forces, and the scale of the deformation area with respect to tool configuration and process variables. Figure 4 shows a result of analysis of solidus that corresponds to deformation regime and its key note has unveiled in the origin article.

FSW TOOLS DESIGNS

As the generator of friction in FSW mediates and creates from its tool hence the functions and influences regarding to the design of its geometrical and the adaptation of its dimensional to workpieces are notably considered. Practically, the joint configuration of the workpieces in FSW empirically affects the selection of the geometrical tool design viz. the pin and the shoulder to outcome the finest macroscopy structure on the weld [10] which refers on W. M. Thomas et al. reviews. At Least, it remains for size adjustments to pin dimension in which appropriate to workpieces thickness. The variants of the tool designs have engineered and manufactured to be able to

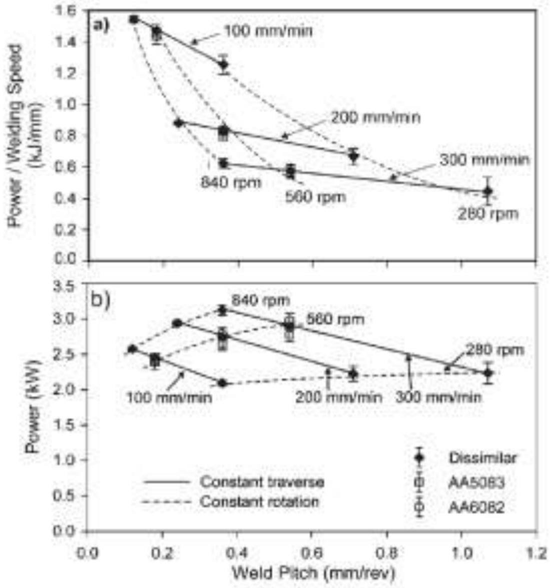

Figure 3. Rate of heat input a per millimeter of weld line and b [9]

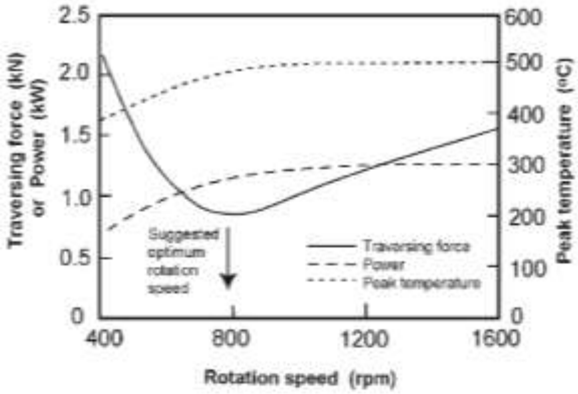

Figure 4. CFD modelling of heat generations affected by the tool [9]

fulfill the demands of the workpiece properties and their typical characteristics. Therefore, it is spread to sustainable designs from conventional to its associated novelty technologies on the top of that not a few designs were not commercially produced for the purpose of research projects or specifically engineered to rare metals properties. Technically, TWI has been clarified the fundamental working mechanisms of how can FSW tool can delivers the weld process without breaking down the melting points of the workpieces and its brief developments [11]. Literature study for FSW tool designs exhibits the recapitulation of used tool designs compilation dedicated to its studies [12]–[38].

In ASM handbook volume 06A: welding fundamentals and Process, C. D. Sorensen [12] has the section of the FSW's tool materials, geometries and performances. In his review the tool materials that frequently used or have been used in various kinds of experiments and applications such as H13, MP-159, WC-Co, Inconel 718, W-1%LaO2 each has the typical match to a welding material individually. The tool geometries that can be derivatively classified into designs and features have key factor to welding characteristics wherein it can be logically presumed with a certain approach method. Conventional designs of shoulder and pin were declared concave/convex, tapered, flat etc. and cylindrical, conical etc. The developed designs such as adjustable pin's length, two side shoulders etc. they were adding another promise that can be considered to the desired characteristics. The performances can be predicted and measured using a numerical modelling mainly based on fluid dynamic models oriented in two and three dimensional. The materials flow mechanisms and the boundary conditions that simulated are the parameters to enable numerical calculations they decoupled the thermal model from the flow model.

El-Moayed et al. [13] through their review have communicated the rational correlations of tool design towards weld properties. As the final morphology of material flow and generated heat fully impacted by the tool design and the ripeness of the weld got impacted by the finest combinations of speed and duration. In details, tool diameters are playing the rule to selecting a correct weld-piece thickness, and the designs themselves are remaining characteristic defect.

The testing against tool design's role of its reacted effects on microstructural behaviors has been demonstrated by Widener et al. that cited by R. Abrahams et al. [39]. The experiment circumstances were throughout microhardness (HV) and electrical conductivity testing. The preparations were two sizes in the same design as well with the material of tool and selected process parameter optimises using DOE approach for each size. The empirical report indicated that smaller shoulder diameter in high speed produced the least degree of variation in hardness and conductivity. However, the development of DOE approach could stable those boundaries' differences.

Burford et al. employed five different tools in their study and those tools were the classic TWI 5651, Tri-flute™, Scrolled shoulder with threaded pin and straight flats, Small (shoulder) Wiper™ with threaded pin and twisted flats, and a Wiper™ (large diameter shoulder) with threaded pin and twisted flats wherein each of tool has its respective developed welding parameters. The main evaluations aimed to establish standards and specifications of basis developing design data towards e-NDE technique feature and wasn't deeply focused on discussing the tools' performances nevertheless they were revealing statistical result of Probability of Detection (POD) versus void size for the Tensile Test analysis results that shows those combinations of parameters potentially possessed low tensile strength [15].

On the experiment carried out by Leon et al. [16], it was reported that the tool profiles used were fabricated in sixteen ratios of dimensions with four geometries identical. Came through the results of thermal analysis, hardness, and tensile tests a comparative analysis of those tools was revealed, it shows all the shapes tend to generate cylindrical volume during rotation as it is called dynamic volume. But each pin has a typical impact on the fusion temperature, the square-shaped pin has the lowest compared with the hexagon-shaped and pentagon-shaped pins as the highest. On the other hand, the triangle-shaped pin possesses the most excess strain rate wherein the elongated grains would take place.

Four variations of cylindrical tool profiles with a 10/3 radius of D/d ratio have been employed in the Gratecap et al. study that reviewed by L. H. Shah et al. [40] i.e., conventional radius conical pin, pinless cylindrical tool, three and four-milled faces pin, besides, the welding travel was in the range of interval 70 to 200 mm/min and the rotational speed was started from 400 up to 850 rpm. The past literature refers to those profiles were revealed similarities in the lobe shape and striation patterns. On the perpendicular line orients the tool, tool 1 produced two stacking lobes formation and residual striations in the base part, on the facing line orients the tool a stacked layers and tunnel were observed. Further, tool 2 produced a successive stacked layer and a zig-zag pattern on the interface wherein then it was being segmented by tools 3 and 4 which were orientating from the facing line.

Sadhu A. et al. [41] briefly reviewed a MX TrifluteTM probe (A023 MK7) that conducted by R. E. Andrews, the probe was installed in a concave-shaped shoulder with a pattern-less surface (the Densimet D176) as resulted the best weld quality. This combination of A023 MK7 and plain concave-shaped operated corresponds to the thickness of the workpieces varying on 213 to 518 rev/min, 15 to 60 mm/min and tilted 2° or 3° successfully created non-oxide particles in the nugget zone, and heat-effected distribution area. Further, the grains sizes deformed varying from 0.1 up to 0.6 mm, and observed that some of the sizes were distributed in a mix. Tool pins made of 3 based-alloys endured from pin length diminishment due to hot shear after a 3.3 m long weld. Tool pin made of forged Ni-based Nimonic 105 alloy has a 20 m long weld without defects. Four types of tools were considered in the trials conducted by Kalmeshwar et al. [19]. The specification of the pin trialed was fixed but the shoulders designs were varied that were machined in the same dimension. Welding and rotation speed were given the same on those types only the plunge depths were slightly different. the generating-force during the housing and traversing serves as a benchmark for performance evaluation wherein referring to the discussion that says the reaction forces have a crucial role to keep density level between the shoulder and welding surface, and it has a correlation with the process temperature might create as long as it doesn't exceed the melting limit of the base material. Graphically, the concave shoulder showed high normal force that occurred because the softened materials during the welding phase were stored in the little space of the concave as if the reservoir causes gapping mechanism that would need more applied forces for the shoulder tights with the workpiece.

The welding performance from three pins shape designs such as cylindrical, triangle, and square machined on the same dimension were compared using the same process variables, fixed feeding rate of 30 mm/min, and three variations of applied tool speeds from 500, 750, and 1000 rpm. Empirical results show a degradation in tensile properties compared with the base material and the square-shaped resulting in the highest score on bending force. The graphs show the variance values over the applied tool speeds, all the graph's lines that referred to tensile strength, UTS, and bending break-load were inversed as the speeds increased except for elongation. The analysis revealed the stirrer mechanism, the mixing ratio, and the rate for square and triangle pins of feeding the bead based on the variables i.e., the angle and radius calculated under the law of sines in a circular motion that moved in a straight line, the square pin capable to come near to circular outer edge while its rotating that more character than the triangle one although limited by its geometrical disintegration [20].

Sharma et al. [21] reviewed the FSW processing influencers from design variables that hold the key factor to transform the structure and mechanical evolution of the installing-tools that have been used in previous experiments. They took note the tool pin profile plays an essential role in determining the quality of the Friction Stir Processing (FSP) and FSW. Several studies highlight the impact of pin geometry on the flow of plasticised material, resulting in different mechanical properties. Researchers prefer threaded pin profiles for adequately refined grains, homogeneous distribution of particulates, and improved mechanical properties. Triangular pin profile specimens have been observed to produce clusters and improper distribution of particulates, while four-flute cylindrical specimens have severe accumulation of reinforcement particulates. Straight and tapered cylindrical pin profiles result in the development of defect-free joints. The pin profile is considered as the primary source of deformation and secondary source of heat generation in the stir zone, and it is a principal and deciding factor for the quality of the processing, its geometry, impact on localised heating and stirring action, and the resulting homogeneous mixing.

G. H. Li et al. [42] referred a novel invention by Y. X. Huang et al. that introduces a new self-support friction stir welding tool designed to join aluminum hollow extrusions. The tool has an adjustable dip angle and two shoulders that can adapt to changes in plate thickness without requiring pre-drilled pilot holes. The SSFSW technique represents an efficient solution for joining hollow extrusions. The tensile properties of a 5mm 6005A aluminum alloy joint were tested, with results showing an average tensile strength of 190 MPa and an elongation of 6-86%. Fracture surfaces of the samples showed ductile failure. Tensile properties and fracture locations depended on microhardness distributions and weld defects, with microhardness falling dramatically in the region passed over by the shoulder, reaching its lowest value in the softening region. The minimum hardness was located at the interface between the thermo-mechanically affected zone (TMAZ) and the heat affected zone (HAZ).

Zain-ul-abdein et al. [23] employed straight-shoulder smooth-pin (SSSP) tool, the design was optimised to resolve issues with the initial design. The first version had a smooth pin and straight shoulder, but polymer sticking to the pin's surface caused a defective weld joint. Adding a concavity in the shoulder helped contain the material above the weld joint but did not prevent sticking. The utilisation of an optimised design featuring two grooves, namely the concave-shoulder grooved-pin (CSGP) tool, was observed to enhance friction at the interface between the tool and material, leading to a decrease in pileup and sticking of the polymer to the tool pin. Additionally, the hardness profile across the weld nugget for polymers was analysed wheerin tends to decrease in contrast to metals where it increases. The hardness of polymers decreases because of the semicrystalline structure of the polymers. During FSW, the area that is stirred undergoes intense plastic deformation and fusion that results in the randomisation of the crystalline regions, and the quick cooling process does not provide enough time for complete orientation of the molecular chains. As the hardness is proportional to the degree of crystallinity, it reduces in the welded structure compared to the unwelded material, which in turn decreases joint efficiency. Figure 5 displays the variation of hardness across the weld nugget in different composite joints, wherein the hardness within the stir zone of plain welded HDPE and graphite and silica-reinforced composite joints reduced while it remained almost constant in the alumina and SiC-reinforced weld joints. This implies an improvement in the properties of the composite created.

Mishra et al. [24] made an analysis of contemporary tools used in FSW process, The Skew Stir FSW Tool has an oblique shoulder face and asymmetrical probe that improve material flow, leading to reduced void formation in the weld. The Triflute tool has a higher The Whorl tool has a higher ratio of dynamic to static volume compared to a standard tool, resulting in a 100% increase in traversal speed and a 20% decrease in axial force. Its shoulder has a scoop-like shape and its probe is frustum-shaped with a tapered helical ridge and side flats. These features allow for the welding of thick sections of alloys in a single pass, as they promote better frictional heating and material flow.

According to Farzad K. and Adrian P. G. [43] literature observation, Nandan et al. reveals the FSW tools that have been used by TWI, the design of tools plays a critical role in friction stir welding (FSW). It affects heat generation, plastic flow, power required, and uniformity of the welded joint. The shoulder generates most of the heat and prevents the plasticised material from escaping from the workpiece, while the tool-pin affects material flow.

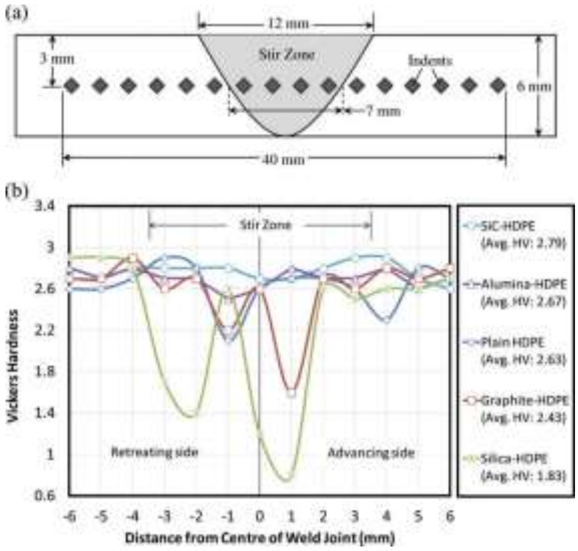

Figure 5. (a) Schematic of weld cross section and indents location and (b) hardness profiles across weld nugget for different composite joints [23]

New tool designs, such as the Whorl and MX-Triflute, have been introduced to facilitate plastic flow and increase heat generation rates. The Flared-Triflute and A-skew tools were developed to ensure a wider weld for lap joints. Material flow is asymmetric about the joint interface, and understanding this asymmetry is crucial for optimal tool design. The choice of pin angle is also an important parameter that influences the FSW process. Tool wear is a concern, particularly for high-temperature, harder alloys. Techniques such as introducing heat sources in front of the tool can reduce tool wear.

Through C. S. Wu et al. [44] a review of friction stir welding tools has been exposed by Rai et al. that pointed out some FSW tools insights how it plays role in making bonding among others are shoulder diameter and the face, more important, The shape of the tool pin used in friction stir welding (FSW) has a significant impact on material flow and weld properties. Various shapes, such as cylindrical, triangular, tapered, and columnar with or without threads, have been tested for different alloys and thicknesses of plates. Threaded and fluted pins are believed to increase heat generation rate and improve material flow, while the restir tool, which changes its rotation direction periodically, can resolve issues of inadequate material flow and resulting defects. Tapered tools are preferable for welding thick sheets as they enhance material flow and yield more uniform properties throughout the workpiece thickness. The tools utilised for friction stir spot welding (FSSW) are subjected only to torsion from rotational motion, and cylindrical pin tools are observed to lead to upward material flow near the pin periphery, while the material beneath the shoulder is pushed downwards due to the axial force exerted by the shoulder. The nature of hook formation in the material flow affects the mechanical properties of lap joints, and the pin and shoulder geometries influence the formation of hooks. Various parameters, such as shoulder plunge and scroll design, can also affect the stirring action in FSSW. Ultimately, the choice of tool pin shape and design depends on the specific application and material being welded. In addition, the material of tool made by that tool material properties can affect heat generation, dissipation, and the weld microstructure. High tool wear increases processing costs if the tool material has low yield strength at high temperatures. Factors such as hardness, ductility, and reactivity with the workpiece material are important for tool material selection. Tungsten, molybdenum, and iridium are good choices for their high temperature strength, low reactivity with oxygen, and high hardness. Tool erosion can be caused by reactions between the tool and workpiece or oxygen in the atmosphere. The appropriate tool material should have high temperature strength, be wear-resistant, have a suitable thermal conductivity, and have low reactivity with the workpiece material. Tool properties can be improved by adding alloying elements or coating with a hard, wear-resistant material.

Three tools were tested to investigate the characteristic effects on each design, the shoulder, pin root, and pin bottom diameters remained unchanged at 26 mm, 9 mm, and 6 mm, respectively, the shoulder diameter was reduced to enhance joint integrity, the tool shoulder was flat with no distinctive features. Macrostructure examinations observed that A defect-free weld was obtained only for the CTFL profile. The flow of material during stirring and the impact of temperature and flow stress gradients on the weld zones are described. The superimposed left- and right-hand threads in the CLR profile reduced the size of the weld zones and formed a small tunnel at the interface of the stirred zones. The triflute in the CTFL profile induced a higher strain rate and eliminated the material imperfection in the welds. The microstructure of AS-TMAZ-A and RS-TMAZ-A showed differences in grain size, with AS-TMAZ-A exhibiting greater grain coarsening than RS-TMAZ-A. Onion ring formation was detected, with two zones identified in the upper and lower regions, and this was observed to depend on the tool pin profile. In the HAZ, the grain size was similar for both CL and CTFL pin profiles. The middle of the weld had the largest average grain size, while the cooling in the top and bottom portions of the weld resulted in smaller grains in those areas. joint efficiencies for AA6082 thick plate joints are limited, with one case reporting joint efficiencies ranging from 57% to 61% depending on the location of the measurement along the thickness. The present work discusses the transverse tensile test results of CLR and CTFL profile welds on three locations: top, middle, and bottom. The CLR-Top sample failed from the SZ/TMAZ interface with a joint efficiency of 52%, while the CTFL-Top fractured in the SASZ with a joint efficiency of 54%, which is acceptable for age-hardened material like AA6082. The text suggests that the lower strength in the SZ/TMAZ interface was due to high temperature and turbulent action of the shoulder on soft materials. The specimens CLR-Middle, CLR-Bottom, CTFL-Middle, and CTFL-Bottom all experienced fractures in the HAZ, indicating a reliable weld for both CLR and CTFL pin profiles in the middle and bottom regions. The CLR profile minimised the occurrence of tunnel defects, while the CTFL profile was able to eliminate them completely. The overall average hardness in the SZ was higher for welds made with the CLR profile compared to those made with CTFL profiles. The joint made with the CTFL tool was free of defects, and the average joint strength was slightly greater than that of the CLR profile. However, the joint efficiency of the middle and bottom sections of the weld made with CLR was higher than the corresponding joint efficiencies of CTFL profiles, likely due to the presence of a small tunnel in the CLR profile, which reduced the overall joint efficiency [27].

FSW has been successfully applicated for joining polypropylene, three variations of pins have been set up for the experiment of the effect regarding the pin designs that were machined in the same dimension, The results show that the cylindrical tapered tool shape with 1500 rpm, 45 mm/min, and 1° tilt angle produced the highest tensile strength, with a value of 8.95 MPa for cylindrical samples and a welding efficiency of 35%. The hexagon and triangle tool shapes had lower tensile strengths, with values of 5.62 MPa and 5.78 MPa, respectively, and lower welding efficiencies of 23% and 24%. The analysis of the fractured location shows that the back side of the welded specimen had lower strength, and the breakage was initiated from that point. The ultimate tensile strength for polypropylene was found to be 23 MPa, which is lower than the tensile strength of the welded samples. The text suggests that the composition of polypropylene using the cylindrical tapered tool shape is more concentrated, which may cause inclusion defects in the weld cross-section, but this tool shape still produced the highest welding efficiency [28].

The importance points of FSW tool have been reviewed by Meilinger & Török, the results are the concave and convex shoulder designs are used in FSW, with the concave shoulder producing high-quality welds by creating a reservoir for the shoulder's forging action using material displaced by the pin. The convex shoulder was initially unsuccessful, but became possible for thicker materials with the addition of scrolls that move material from the outside toward the pin. Both designs offer flexibility, improve joint tolerance, and enable easier joining of different thickness workpieces and complex curvatures. Shoulder features like scrolls, ridges, knurling, grooves, and concentric circles can be machined onto any tool shoulder profile to increase material deformation and produce better welds. A round-bottom cylindrical pin improves the quality of the weld root and reduces tool wear, while a flat-bottom cylindrical pin is tilted at a small angle to increase velocity. Truncated cone pins are used for thicker plates and have lower transverse loads.

MX triflute and A-skew pins increase travel speed, while Trivex pins reduce forces. Threadless pins are used in aggressive environments, and retractable pins allow pin length adjustment. Bobbin tools consist of two shoulders and a pin fully contained within the workpiece for ease of fixturing and increased tool travel speeds [29].

Based on S. Tera and J. Luis [45] literature, Mandal et al. conducted an experiment of welding AA7039 to find out the effects of tool design, The pin diameter was found to be the most significant factor affecting the weld tensile strength and cross-sectional area, with a 7-mm-diameter threaded pin being the most effective. Larger pin diameters did not improve the weld tensile properties, potentially due to improper bonding and material mixing. The tool shoulder diameter was also found to have a considerable effect on tensile strength and elongation, with a 19-mm shoulder diameter providing the maximum weld tensile strength. The shoulder surface levels 2 and 3 achieved better weld tensile strength than level 1 or a fully flat surface. The study used response surface regression equations to predict the effects of tool geometries and generated 3D surface response plots for tensile strength, elongation, and weld cross-sectional area. The regression equations were found to be sufficiently accurate, with a maximum error of 5%, and were tested on test case tools with different geometries, with a maximum % error of 8.6% for weld cross-sectional area.

The impact of tool geometry on tensile strength is explored, with stress concentration found to be significantly greater for conical pin tools than for inverse conical pin tools, which leads to greater eccentric loading and joint rotation. The study also found that unthreaded inverse conical pin tools provide better tensile strength, as do cylindrical unthreaded and cylindrical threaded tools with respect to aluminum base metals. Tensile strength is optimised with a pin penetration of 19.05% with respect to the lower base metal sheet thickness, and larger diameter pins provide better tensile strength. However, too large a diameter can lead to excessive heat and weak welds with cavity defects. Scrolled shoulder tools offer better surface morphology but also produce unwanted intermetallic compounds, whereas concave shoulder tools trap less material and produce less flash. An SPR ratio of 3 provides the highest tensile strength, and appropriate heating methods, such as an induction coil or hot air gun, can be used to ensure sufficient heat for the process, while excessive heat can be reduced by using tools with fins or collars with circulating coolant [32].

M. Aissani et al. exposed their findings that cited by Somnath C. et al. [46] in their overview elaborates that the FSW tool that has separate shoulder and A tri-flute pin with a conical threaded end was utilised to perform FSW, resulting in severe deformation and equiaxed grain structure in both the nugget and TMAZ due to the effects of thermomechanical stir and dynamic recrystallisation. The shoulder and pin have a significant impact on the stirred zones, including changes in crystalline plane orientation, variations in the shoulder surface at the top and bottom of the weld, and a much narrower HAZ compared to fusion welding methods. The intense plastic deformation and high temperatures during FSW cause changes in grain size in the stirred microstructure zone compared to the base metal, and precipitation can dissolve in and around the stirred zone during welding. The microhardness data revealed an increase in the nugget zone, with values almost identical to those of the parent metal. The HAZ and TMAZ exhibited lower microhardness values, and the nugget zone had a noticeable grain size. Material dragged by the shoulder during welding caused lower microhardness values on the retreating side. The thermal effect of the welding process and the chemical composition of AA7075-T6 caused softening.

The guidelines of basic tool design referring to design parameters revealed by E. Hoyos & M. C. Serna [34], the critical notes were mentioned to some variables such as Aluminum family, Rotational velocity (revolutions per minute), Travel rate (millimeters per minute), Inclination (degrees), Pin size (millimeters), Shoulder size (millimeters), Pin kind, Pin dimension, Shoulder kind, Weld effectiveness. The coefficient of determination (R2) denotes the correlation between variables, and a perfect fit is indicated by an R2 value of 1. It is noteworthy that, in the context of this study, an R2 value greater than 0.9 is regarded as an acceptable threshold. The transportation of the plasticised material along the joint is the responsibility of the pin. In their paper figures 3a-d depict the correlation between the pin diameter and the material thickness. For trials utilising a conical pin, the trend line included the maximum diameter. Notably, the R2 value in the graphs did not fall below 0.93, indicating that they meet the prescribed standards. The pin significantly influences the microstructural changes in the weld, thereby impacting FSW joint strength Pin length is determined based on the plate thickness to achieve complete penetration in tool design. The R2 values are ≥0.99, satisfying the prescribed criteria. Pin length is mainly dependent on the material thickness and should be kept within 5-6% of the difference between the pin length and material thickness, regardless of the aluminum series. The shoulder maintains material position and generates heat during welding, The R2 values ranged from 0.9142 to 0.9457, meeting the acceptable threshold [47] wherein refers to Shude Ji et al. paper.

Bobbin FSW tool with different surface features top and bottom has been developed for applicating FSW in space [36]. the SAA-FSW tool's ability to eliminate the axial force during welding trials on 1/8-inch-thick aluminum 1100. The process parameters chosen were 1500 RPM for the rotation rate and 9 IPM for the traverse speed. The summarised results indicate that the axial force was drastically reduced and averaged 0 N. The study also tested the tool's ability to adapt to changing workpiece positions by placing the workpiece on an inclined surface. The results indicate that the tool successfully adapted to the changing position with no significant impact on the weld quality. Overall, the SAA-FSW tool proved to be effective in reducing the axial force during welding and adapting to changing workpiece positions.

In conclusion, a selected tools should be accurately engineered considering that the desired properties with empirical results have a tight relation in 70% assumption.

Bobbin tool two with fixed-gap H13 tools with varying pin features - a cylinder pin and a cylinder pin with three flats - and flat shoulders with a shoulder diameter of 12mm and a pin diameter of 6mm. using a floating tool holder in a CNC machine. The floating tool holder allows the tool to follow variations in plate thickness and thermal distortion in the vertical axis, which are known to occur in practice. The holder has a vertical tolerance of 4mm, downforce of about 14.5 N, and fitting clearance of about 1mm. The study compares the results of the fixed and floating tool holder for friction stir welding (FSW) of aluminum plates. The use of the commercially available floating tool holder was expected to permit the tool to follow variations in plate thickness or thermal distortion in the vertical axis. The results showed that the use of the floating tool holder resulted in better weld quality, lower forces, and a lower demand for electrical power. The study also found that the fixed tool had less mechanical compliance in its interaction with the substrate, which resulted in off-centered orientation and increased forces and power demand [37].

Figure 6 shows the using tool in the study of the effect of FSW tool profile towards process thermal efficiency, The results show that tools with thermal insulation features had a range of 42.2 ~ 74.4 W of heat flow into the tool, which is a

$$\eta = \frac{Q_1}{Q_1+Q_2} = \frac{Q_1}{Q} \quad (1)$$

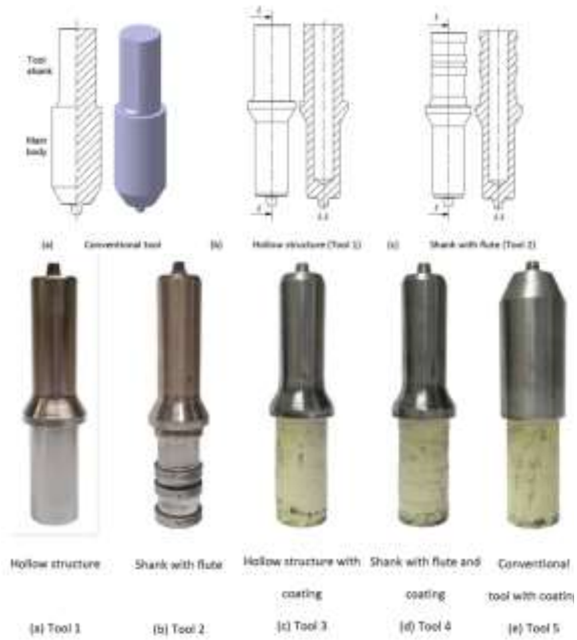

Figure 6. FSW tools used on the study conducted by Hongjun Li et al. [38]

reduction of more than 50% compared to the conventional tool. The FSW tool 4, which incorporated all the structure modification features, exhibited the best performance. The welding thermal efficiency was calculated using the workpiece thermal model (1), and it was found that using tool 4 instead of the conventional tool improved the modification of the tool structure did not have any impact on the surface that came in contact with the workpiece. The heat generated during the FSW process remained constant when it reached a steady state, with almost the same amount of heat produced by the friction and plastic deformation of the workpiece material at the interface between the tool and workpiece. However, the welding thermal efficiency increased from 91.9% to 96.1% [38].

FSW JOINT CONFIGURATIONS

The targeted metals or workpieces ensured to be immobile and firmed on the FSW gantry machine during the welding process is undergoing. Practically, to be able to qualify the motionless settings of the workpieces the adjustable toughest clamps have to be installed on a few certain points on the workpieces. Theoretically, the basic form of joint configuration is classified into two types that are butt and lap configurations. From its basics the idea to expand the workpieces placement settings in FSW has configured [44, 45, 46–53, 54] somehow the developed configurations couldn't be un-referred to its basics. In addition, the comparison between butt and lap has been revealed therewith its typical defects respectively and its summarise [63].

The T-joint [48] one of developed configurations that widely used on aerospace industries, the derivatives are summarised as follows the T-butt joint is a joining process where a tool penetrates the material from the top, creating a twin welding process. The tool pin moves through the skin metal and edges of stinger, resulting in a high-strength joint, The T-fillet joint is a welding process that uses a tool set at a 45-degree angle, with a shoulder profile different from the conventional method. This method is suitable for metal plates with large thickness and provides high strength, The T-lap joint is a fast and simple T-joint production technique that involves tool penetration to the skin metal and contact face of the stinger, without moving along the stinger corners. This method is suitable for metals with a thickness range of 2mm-7mm, with a low surface finish and heat affected zone compared to other methods.

The compilation of joint configurations has briefly shown and illustrated such as square butt, (b) edge butt, (c) T butt joint, (d) lap joint, (e) multiple lap joint, (f) T lap joint and (g) fillet joint [49]. An old publishment reported that W. Thomas et al. from TWI successfully apply the artificial-lap configuration, ANE joint configuration lap welds performed slightly better than RNE configuration lap welds, the latter had better fatigue performance with longer probe length and/or slower travel speed. The investigation found that, As the lap welds were not likely to fail in shear across the welding area, tensile fatigue failures were expected to initiate from the notch located at either side of the weld, where the secondary bending stress due to the lap offset is tensile. Increasing the width of the weld would not increase its fatigue strength as the notch morphology is critical. The study demonstrated that lap welds produced using a Skew-stir™ method were significantly different from those made with a traditional pin-type probe, as they had a smaller notch at the weld's edge and a path that deviated less from the original sheet interface. The photo-macrographs of typical Skew-stir™ welds that underwent fatigue testing confirmed that fatigue failure primarily occurred in the sheet material rather than through the weld region. The use of 8.25 mm long probes ensured good penetration of the lapped sheet [50].

Joint configuration able to provide comfortable reach for welding line for a specific tool, as example in 2005 Martin from TWI used Stationary Shoulder Friction Stir Welding (SSFSW) for corner joints on T configuration, the first sample showed smooth weld surfaces, small heat affected zones, and no reduction in cross-section, but the sharp internal corner may decrease joint properties, particularly in fatigue susceptibility, the second sample showed the fracture located at the HAZ, the third sample showed the same fracture location as sample 2 [51].

Single lap joint has been introduced by Tiago [52] Hybrid SLJ joints experienced mode II fracture for lower downward shoulder forces and mode I fracture for higher forces. The adhesive failure was mostly cohesive. However, increasing the force did not improve joint performance in hybrid joints. In fact, due to the high peal forces on the adhesive, the joint produced with 450 kgf showed the best performance, as compared to those produced with 500 and 550 kgf.

Amir A. et al. [64] conducted an experiment as the advances of Tour et al. experiment that revealed the typical defect occurred on the application of lap set-up, the hooking defect in friction stir welded lap joints, which is one of the most common defects. This defect is more likely to occur in the advancing side of the weld due to the higher temperature in that area. The amount of hooking defect increases with more heat transfer and turbulent material flow in the weld area. Figure 6 illustrates the hooking defect on the advancing side of the weld area in two different conditions and the failure caused by this defect during a tensile shear test.

M. A. Elnabi et al. [65] exposed A. C. F. Silva et al. works wherein three variations of joint configurations (butt, T and double-pass overlap joints) prepared in order to find out which one was giving the support for seeking UTS optimisation the effects of different parameters on the ultimate tensile strength (UTS) of friction stir welded joints, specifically for butt, T, and lap joints. In butt joints, an improved UTS is achieved with a rotational speed of 1000 rpm and a welding speed of 216 mm/min, but an interaction between welding speed and rotational speed was found to improve UTS at 290 mm/min with 1000 rpm. The shoulder diameter ratio (D/d) was found to be a critical factor in joint strength, with a 15-mm shoulder diameter providing the soundest welds. For T joints, a rotational speed of 1000 rpm and a low welding speed provided good joint mechanical properties, and a high probe penetration was found to lead to improved joints. In lap joints, high rotational speed (1500 rpm) and high welding speed improved the UTS, and double weld runs were applied to avoid hooking defects. The study identified optimal values for achieving high UTS, including 1000 rpm, 290 mm/min, and a shoulder diameter of 12-15 mm for butt joints, 1000 rpm, 76 mm/min, a shoulder diameter of 15 mm (D/d=2.5), and a probe penetration of 3.90 mm (130% of the main plate thickness) for T joints, and 1500 rpm, 290 mm/min, and probe penetration of 3 mm (50% of plate thickness) for lap joints. The study highlights the importance of considering various parameters and their interactions in achieving high joint strength in friction stir welding.

A novel double-butt-lap joint configuration has invented by Uttam et al. [55] and the implication to FSW properties has been studied as well. The crucial point regarding tensile results in the given text is that the joint configuration has a distinct effect on tensile properties, as shown by the variation in UTS, percentage elongation, and joint efficiency for different joint configurations. The study found that the reduction in the height of the lower bond (LB) in the DBL configured joint increases UTS, while almost a similar observation can be seen for percentage elongation. The joint efficiency of the DBL configured joints was found to be higher than that of SSB. Furthermore, the study suggests that as the nugget grain size becomes finer, the tensile properties also increase, as a finer grain size obstructs dislocation movement due to increased grain boundary.

Puzzled-lap joint has been demonstrated on the comparative study conducted by Kumar & Hussain [56], Tensile tests were conducted on base metal, butt weld, and lap weld, and the engineering stress-strain curves were shown in Figure 7. Lap welds demonstrated better tensile properties than butt welds in transverse tension tests, and failure occurred in the thinner upper weld, not at the nugget between plates.

Various options exist for welding T-configurations using FSW, such as butt joints or overlap configurations with extrusions, and T-butt or comer fillet welds without an extrusion. Comer fillet weld is the most promising as it guarantees the integrity of the base panel outer side and has few restrictions in application for thick plates [57].

T-configuration became the fix variable wherein tool geometries, tool traveling speed, and rotational rate were varying, the hardness profile of a T-joint showed a double trough with a maximum point between them indicating highest hardness value, approximately 145 HV. The HAZ region in the aluminum alloy exhibited declined hardness values until it reached approximately 115 HV. The maximum failure load was obtained at a high rotational rate of 1000 rpm and low traversal speed of 50 mm/min. A lower failure load value was obtained at 1000 rpm but at a higher traversal speed of 100 mm/min [58].

On this review the experimental scenario was similar with the above review the noticeable distinction was highlighted on the object. Empirical result obtained by the tensile tests exposes that the fracture behavior of the samples in the experiment was found to be influenced by the welding parameters, as evidenced by the fact that some samples fractured on the retreating side and others on the advancing side. High temperatures generated during the process can weaken mechanical strength and lead to fractures, with higher heat generation occurring at the advancing side. The tensile strength values varied between the samples, with FSW5 achieving the highest ultimate tensile strength due to its compatible welding parameters, resulting in good mechanical properties. The suitable rotational speed was found to be 910 rpm, as shown by the increasing tensile values for FSW3 and FSW4. A rise in rotational speed or a reduction in transverse speed can lead to an increase in grain size in the Nugget Zone, and also an increase in deformation grain size in the thermo-mechanically affected zone. However, it is important to ensure that the rotational speed and transverse speed are compatible. The process parameters are significantly influenced by the amount of heat generated, with higher rotational speeds leading to increased heat generation, while the effect of the transverse speed on heat generation is relatively minor. If the rotational speed is too high and the transverse speed is too low, it can adversely impact the structural and strength properties of the material [59].

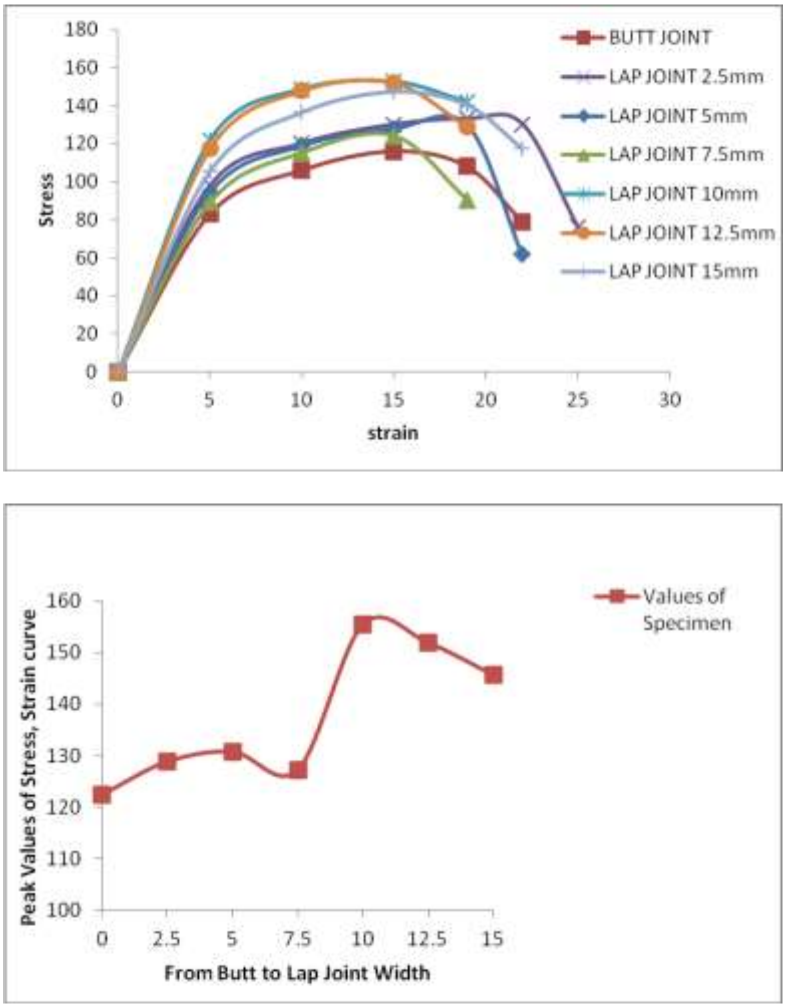

Figure 7. Stress -strain curve for tension test (up) & Optimum values of Stress, Strain Curve (down) [56]

T-joint configuration has been analysed through laboratory experiment and pareto charts observation by Mourad et al. [60], simply, from stress-strain graph indicates that the tensile strength of all T-joints was lower than the base material. The tensile strength was found to be proportional the velocity of revolution remained consistent within the range of experimentation, but a perfect blend of rotational and traverse velocities was essential to achieve a reinforced joint. Certain welds that were prepared at a pace of 10 mm/min were observed to have flash and tunnel defects, which were caused by the exalted plunge forces and swift movement of the rotating tool across the weld line. When a high axial force was applied along with lower travel velocities, the metal pieces were exposed to frictional heating for a prolonged period, resulting in weakened joints. On the other hand, when higher travel velocities were applied, the weld area was exposed to frictional heating for only a short duration, leading to inadequate hotness and inferior metal plasticity, resulting in void formation. The tensile strength of the joints was discovered to be indirectly related to the travel velocity, with 4 mm/min weld-moving speed resulting in the highest strength and 10 mm/min resulting in the lowest.

An innovative overlap-joint configuration (symmetric and asymmetric) has been demonstrated by Wang et al. [61] The creative overlap joint arrangements generate a wavy weld interface imprinted in the steel sheet by using a roller. While welding, the probe manipulates the wave's central and lateral peaks, creating intense plastic deformation and heat that causes interfacial diffusion and atomic bonding. By applying pressure to the valleys of the wave, the probe creates a mechanical locking effect on the AA. After undergoing four analytical steps, it was concluded that the two-pass welds of the inventive overlap joint displayed the best mechanical properties overall, exhibiting stronger mechanical strength properties at lower weld pitch ratios. However, the groundbreaking overlap joint with a single pass produced a larger hook, which reduced the AA sheet's effective thickness, influencing the mechanical resistance of the welds. Voids were identified at the Al-Fe interface, which were minimised with the multi-pass welding. The layered structure and intermetallic compounds were selectively formed at higher weld pitch ratios, and the microhardness profile closely mirrored the initial shape of the innovative overlap joint.

T-pull tests to assess the durability of welded fastenings joining the skin and stringer in aircraft structures. The tests reveal that the fracture happens within the nugget zone, which is linked to the existence of a hooking flaw, and that it transpires in the thermo-mechanical affected area. Inadequate material remixing and stirring lead to the fracture taking place on the retreating side across all specimens. The effectiveness of the welded joints was compared to traditional riveted connections and while found to be lower, this information is valuable for replacing riveting to welding. Process parameters do not affect the T-pull strength, as the failure occurs far away from the weld beam, except for one sample where the failure occurred in the weld bead due to a shorter defect length [66]. Last but not least a comparison of butt and lap configuration is summarised in Figure 8 [63].

FSW LIMITATIONS

FSW offers and expands more abilities to weld metals from lights up to heavies' specifications wherein in other joining techniques it's quite challenging to be conducted. For example, a study from V. Pedro et al. revealed that FSW possibly be able to produce the same joint quality like the fusion welding could offer in light metals confirmed with the other found advantages rewritten by M. Miodrag et al. [67].

The advantages, disadvantages and limitations of FSW can be observed from several points of views such as economic sector, welding process limitations, joint defects, procedurals, apparatuses etc. In detail, based on its studies and experiment reports in the past few years FSW advantages and limitations have reported among others are a book edits by Schwartz that has been reviewed through K. P. Mehta & V. Pedro [68] summarised process and product advantages also limitations, moreover, economic advantages and disadvantages are described.

Figure 8. butt & lap on each variables preparation [63]

In a book of Friction Stir Welding: Dissimilar Aluminum Alloys by the creation of Khan et al. [69] highlighted the FSW process advantages over fusion welding and its conventional process disadvantages, Soron & Kalaykov revealed the process advantages of using FSW robot that briefly rewrite by Fransisco B. F. [70], Fu zhi-hong et al. written the basic of process advantages of FSW and its common process limitations that becomes one of references cited by S. Karuppan et al [71]. Based on the literature review above, it can be identified that the limitations come from process variables gradually reduced concomitants with the developing and sophisticating of FSW technologies and novelties.

Friction Stir Welding (FSW) is a solid-state joining process that presents various benefits over traditional welding techniques, including no need for filler material, resulting in a cleaner and more eco-friendly process, lower heat input, which reduces thermal distortion and residual stresses, and the ability to bond materials that are difficult to weld using traditional fusion welding methods [72][73]. However, FSW also has limitations, such as the requirement of a costly, specially designed tool, which is material and thickness-specific, limiting its versatility. FSW may not be suitable for joining materials of significantly different thickness or strength, and its slower welding speed, which depends on the tool material strength, cooling system, and material being welded, can make it less suitable for high-volume manufacturing applications. Therefore, it is necessary to consider the advantages and disadvantages of FSW before deciding whether it is the most appropriate joining method for a specific application.

SUMMARY OF THE REVIEW

The relevant correlations amongst process parameters and inside its respective adjustable variables are constructed to the finest principles that produced top-grades empirical reports of the weld properties.

Friction Stir Welding (FSW) is a solid-state bonding process that utilises heat and pressure to create a joint between two metal parts. This is achieved using a spinning tool that is immersed into the material being welded, causing friction and heat to be generated, which softens the material and enables it to be formed into a joint.

The working principle of FSW involves the use of a specially designed profile on the rotating tool to generate friction and heat in the material being welded. The resulting heat softens the material, allowing the tool to move along the joint cross-section, mixing and forging the softened material to create a joint.

Several process parameters can be adjusted during FSW, including the rotational speed of the tool, traverse speed, axial force applied to the tool, and tool geometry. These parameters have a significant impact on the amount of heat generated, material flow, and joint quality.

Optimizing the process parameters is crucial to ensure a high-quality joint is produced in FSW. The ideal combination of process parameters is determined by the material being welded, the joint design, and the desired properties of the joint.

In summary, FSW is a solid-state joining process that uses a rotating tool to generate heat and pressure, softening the material being welded and enabling it to be formed into a joint. The process variables, such as the tool rotational speed, weld-moving speed, downward force, and tool design, need to be carefully adjusted to produce high-quality joints.

The literature breakdown for FSW principles and process parameters is re-structured in this review. In conclusion, it is observed that the weld quality of the product of FSW is considerably affected by three headings from the FSW process, viz. tooling associating to pins and shoulders designs, machining referring to the speeds of travel and rotation and outsourcing settings such as workpieces placement and base metal properties, in particular, duly notes that they are in cause-and-effect correlation.

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