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An Extensive Review on Effect of Weld line on Various Process Parameter of Friction Stir Welded Sheets

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Abstract: This study aims to review the effect of weld lines movement on the formability and mechanical behavior of Friction Stir Welded (FSW) joints between two different aluminum alloys using the Forming Limit Diagram (FLD) as a key evaluation tool. FSW is a solid-state joining process that provides an excellent mechanical properties compared to other fusion welding process, but the presence of weld lines can significantly influence the material's formability and performance under complex loading conditions. This research paper focused on evaluating the impact of weld line positioning, movement, microstructural variations, and mechanical heterogeneity on the forming limits of the dissimilar aluminum alloy joint. Various weld line positions, including center, offset, and perpendicular orientations relative to the strain. The FLD is generated for both the base materials and the welded joint, providing a comparative analysis of their formability. The study showed that use of optimizing input process parameters such as tool rotation speed, weld speed of tool, pin diameter, shoulder diameter, and tool's pin profile could effectively reduce the negative impact of weld line variation and play a vital role in better welding finished. It also showed that the optimized input parameters improved the microstructure, formability and mechanical properties of the welded blank, resulting in better forming limits and a higher resistance to deformation.

Keywords: *FSW, FLD, Limiting Dome Height (LDH) Test,Weld-Line, Optimization, Mechanical Properties.*

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I. INTRODUCTION

The Welding Institute (TWI) was the very first to implement the friction stir welding (FSW) in 1991. Initially, the solid-state joining process was employed on aluminium alloys. In order to welding of two different sheets to be joined together to establish a bond between them. A non-consumable rotating tool with a tool pin and shoulder diameter is placed into their edges and formed the welded joint line [1, 4]. The procedure is quite straightforward in its basic concept. To ensure proper butting, the work piece is fixed or clamp on a flat backup plate. During FSW, it is held securely by a fixture to prevent unwanted lateral movement.

The positions of the butting side are very critical during FSW, therefore analyzing the direction of travelling speed, tool's rotation, travel directions, and weld axial force is required. The FSW tool travels within sheet in left to right direction and the tool movement in counterclockwise direction. The retreating side is on the left and the advancing side is on the right side, where the rotation of the tool is parallel to the direction of welding direction.

II. FSW PROCESS

A specialized tool featuring an extending pin from the shoulder rotates at several hundred RPM and is methodically inserted into the abutting edges of sheets or plates. The pin's length is slightly shorter compared to the work piece's thickness, and pin diameter is generally taken one-third that of the tool shoulder diameter. The welding is made due to shoulder touches the surface and pin diameter enter the work piece. A pin was inserted and the material beneath the shoulder of tool obtain formed as a result of the friction developed among the tool pin and the sheet. The tool pin is rotated along the weld interface by fixing of the sheet with fixture. During process, heats the work piece, allows easier for the material to mixing to create the joint, and retains the molten metal under the shoulder [2, 3].

As the tool passes during the FSW operation, the weld undergoes a cooling process which effectively fuses the two

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plates together. Upon the extraction of the tool, a hole remains where it was withdrawn from the workpiece at the end of the welding.

Through the effective application of this process, a robust solid-state joint is achieved, and its main characteristic is the absence of melting of metal hence reduce distortion and shrinkage of material on weld-line giving it more overall strength as well as stability. The intricate geometrical features of the tool contribute to a complex material movement around the pin, leading to variations in strain, temperature, and strain rate. This is a result of the intense plastic deformation that occurs at elevated temperatures [25].

III. FSW MICROSTRUCTURES

In Friction Stir Welding (FSW), there is a pressing need for new terminology to accurately describe the microstructures that develop post-welding. The initial effort to classify the microstructures produced through FSW was undertaken by P.L. Threadgill. As illustrated in Figure 1.1, various microstructural zones emerge following FSW, along with a concise explanation of each zone. The weld zone is classified in to various region as follows [24] [26] [27] [30] [33]:

- *Parent Metal:*

This material deformed when situated away from the weld zone. Despite the process of welding may have generated the heat cycle, its mechanical and microstructural characteristics are unaffected.

- *Heat Affected Zone (Haz):*

HAZ welded area is formed near to the weld line, has undergone a thermal changes. This zones has effected the microstructure and mechanical properties of weld line and this HAZ has not exhibit plastic deformation.

- *Thermal Mechanical Affected Zone (Tmaz):*

In this zone, the tool pin used has caused plastic deformation of the welded area. In this zone, high plastic strain can be obtained without recrystallization, particularly in aluminum. The recrystallized zone (weld nugget zone) and the TMAZ region are usually separate from each other.

- *Weld Nugget:*

This zone is completely recrystallized region that replicates the area that the tool pin used. When the high amount of materials are processed through FSP, the stir zone is widely used. [3, 4].

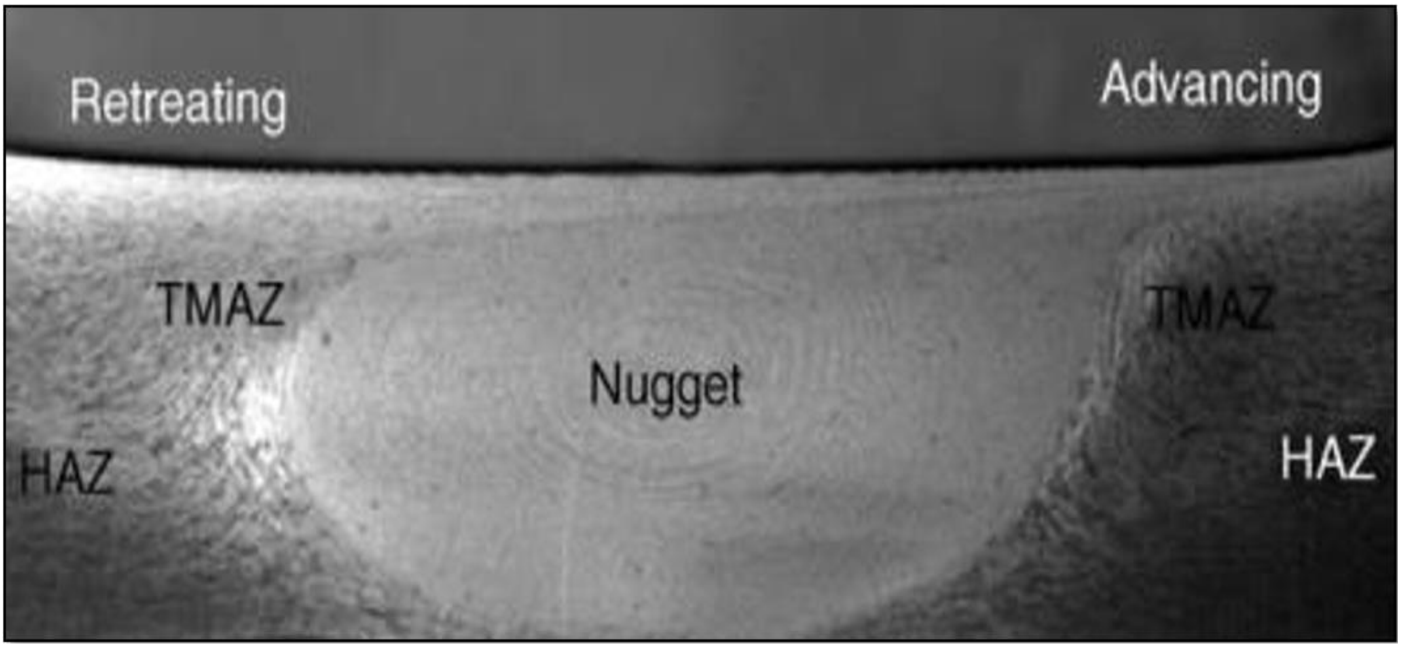

Fig 1 Microstructural Regions in the Cross Section of a Friction Stir Welded Joint [25]

IV. TOOL PARAMETERS

The welded region quality of joints is mostly affected by the input parameters of welding and machine [21]. This paper is attempted to define the different type of tool parameters used to manufacturing of welded joint.

- *Shoulder diameter and its shape's design:*

The size of the shoulder main feature of the tool pin which is affecting the welded region. The creation of a strong weld is extremely dependent on the tool pin size because the heat producing by the shoulder radius [6] [31]. Moreover, the movement of shoulder is under the Z-axis [17] [24].

- *Tool Pin size and shape:*

The diameter of pin diameter is same to the thickness of material when the thickness varies 1~8 mm. Generally the pin diameter is 3 mm. Reynolds et al. [10] investigated the effect pin diameter on the welded joint and its strength. Tool rotational speed produced the heat in the welded area, and produced very fine grains structure with great strength. High tool rotational speed with higher heat produced the slow cooling rate. It produced the metallurgical transformation in the weld line Due to less tool rotational speed, the lower frictional heat generated and higher cooling rate resulted in thicker grain formations.

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➢ *Welding speed Effect:*

Increased welding speed produced the fine grain welded joint because of sufficient plastic flow [7]. When the speed exceed the optimum, then bonding between joint is very less. Due to this the welded joint strength is low [10].

➢ *Advantages of FSW Joint*

- Less heat distortion and maximum mechanical properties
- Easily clamped and conventional milling machines is required
- operating in all positions
- Less impact on environment and tool cost
- No consumables is required.

➢ *Limitations and Disadvantages of FSW Joint*

- Exit hole left at exit of tool pin
- High axial forces is required and the piece must be hold and clamp properly during process.
- Very difficulties with thickness variations of the sheets
- Setup cost is very high than others
- High mounted fixture for Clamping is required and backing support is required during welding
- Difficult to hard aluminium such as weld 7 series, 8 series, 9 series.

V. FORMING LIMIT DIAGRAM

Determining the forming behavior of sheet required the Forming Limit Diagram, commonly referred to as the Forming Limit Curve (FLC). In this process, the blanks have been marked with circular grids (circular form) in order to execute an experiment with a Forming Limit Diagram [3]. The sheet is then formed used a press using a draw tool or forming tool. A blank holder holds the blank properly before the punch entry into the die opening, then forming process begins, which is required for attaining a proper deep draw. The punch pushes the blank, developing deformation, after the blank has been securely an appropriate pressure [13] [15] [29].

When the blank with grid marking is stretched, the circular markings converts into the elliptical form, representing the extent of material deformation. Using the microscope, check the strain value in length. The values were taken and FLD is plotted using the points taken from the formed sheet. Using this process, identified the formability of the blank that how much the capacity of the sheet to stretch [34] [35].

In industries, this process is widely used to find out the formability of any materials sheet [1].

Table 1 Key Benefits of using Friction Stir Welding (FSW)

Key Benefits of Friction Stir Welding (FSW)	
Metallurgical Benefits	i.solid phase phenomenon ii.Less distortion iii.Good repeatability and dimensional accuracy iv.During welding, loss of alloying elements is less. v.Great mechanical strength and microstructural joint [20] vi.Weld all type of aluminium material vii.Formability may be done after Joint
Environmental Benefits	viii.No gas and fumes produced ix.No chip formation, waste and solvent x.No Consumable materials required xi.No harmful gases produced
Energy Benefits	xii.Weight Reduction xiii.2.5% energy used when comparison with a laser weld

VI. LIMITING DOME HEIGHT TEST

The LDH test involves clamping a sheet metal specimen between two flat dies and stretching it over a hemispherical punch. The punch is pressed against the material at a controlled speed until the sheet fractures [8-9]. During this process, the material experiences biaxial stretching, which is a common condition in forming operations. The height of the dome at the point of failure is recorded as the limiting dome height. This measurement reflects the material's ability to stretch before necking or cracking occurs [1-3].

A circular lock bead is employed in this process, while a 100 mm dome tooling is utilized to stretch the sheets. The initial objective is to determine the sheet width that results in the minimum dome height [28]. This test establishes a correlation between the limiting dome height and the material's formability. The dome height is used to indicate the material's ability to accommodate strain distribution [12] [14] [19]. S.M. Chan et al. [29] conducted limiting dome height testing using tailor welded blanks made from commercial-quality cold rolled steel.

VII. FSW WELDLINE

A crucial aspect of evaluating the quality and mechanical properties of FSW joints involves analyzing the weld lines, which are categorized based on their orientation: transverse and longitudinal.

➢ *Transverse Weld Lines:*

Transverse weld lines refer to sections of the welded joint that are perpendicular to the direction of the welding tool's travel. These lines are commonly used for mechanical

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testing, such as tensile and hardness tests, as they provide insight into the overall integrity and uniformity of the weld zone. The transverse section includes SZ, TMAZ, and HAZ. Each of these regions exhibits distinct microstructural characteristics due to variations in temperature and plastic deformation during welding. Studies on transverse weld lines often focus on identifying defects such as voids, incomplete fusion, or material mixing issues, which may arise due to improper welding parameters or tool design. The mechanical performance of the transverse weld line is directly influenced by the quality of these zones and their interaction under loading conditions [30].

➢ *Longitudinal Weld Lines:*

Longitudinal weld lines, on the other hand, are parallel to the direction of the welding tool's movement. They offer valuable insights into the microstructural evolution and residual stress distribution along the weld seam [22-23]. By analyzing longitudinal sections, researchers can study the grain refinement within the stir zone, the extent of material flow, and the presence of any continuous defects like tunnel voids or kissing bonds. Longitudinal evaluations are particularly useful for understanding the behaviors of the weld under cyclic loading or in-service conditions, as they highlight stress concentration zones and potential fatigue failure points. Furthermore, these sections are crucial for validating numerical models of material flow and heat transfer in FSW [32].

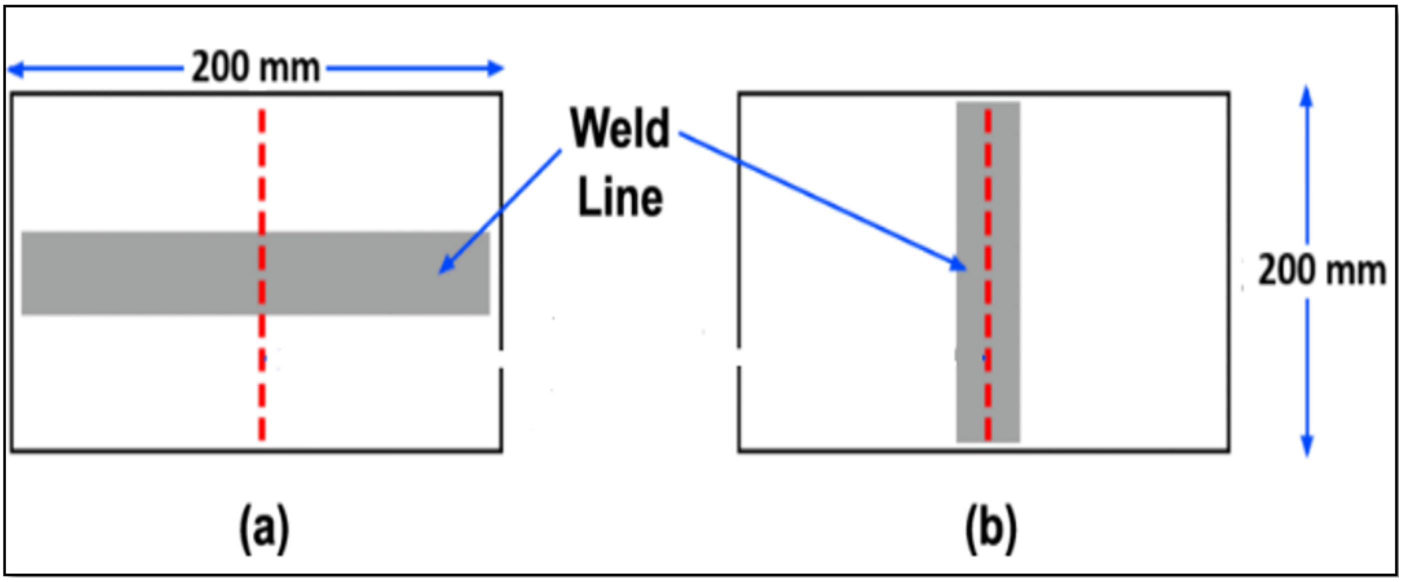

Fig 2 Welded Specimen (a) Perpendicular (b) Parallel [15]

➢ *Research Gap*

The automotive industry continues to advance, striving to offer a balance of luxury, safety, and fuel efficiency to meet the ever-evolving demands of consumers. A significant focus has been placed on materials used in automotive body panels, as these materials must meet critical requirements for formability and crashworthiness, posing unique challenges for design engineers. The weight of a vehicle directly impacts its fuel consumption, emphasizing the need for materials and designs that optimize safety and fuel efficiency. In modern automotive and aerospace applications, steels and aluminum alloys have emerged as leading choices due to their favorable mechanical properties, ease of manufacturing, and design flexibility. Aluminum, in particular, stands out as one of the lightest engineering metals, offering an exceptional strength-to-weight ratio compared to steel. With its advantageous properties—including high strength, low weight, corrosion resistance, recyclability, and formability—aluminum alloys are increasingly being utilized in a wide range of applications. This trend reflects the growing recognition of aluminum as a material that supports both performance and sustainability in engineering designs.

VIII. RESULT AND CONCLUSIONS

The review concluded that the impact of weld line on the friction stir welded (FSW) sheets as follows:

➢ *Weld Line and its Influence:*

The presence and positioning of the weld line significantly impacted the formability limit and the overall mechanical properties of the friction stir welded sheets. The strength of the weld decreased as the weld line shifted away from the optimal path, leading to a reduction in the forming limit of the material.

➢ *Process Parameters Optimization:*

The study showed that use of optimizing process parameters such as tool rotation speed, welding speed, and the tool's pin profile could effectively reduce the negative impact of weld line variation and play a vital role in better welding finished. Optimized parameters improved the microstructure and mechanical properties, resulting in better forming limits and a higher resistance to deformation [11-12].

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➢ *Forming Limit Diagrams (FLD):*

The forming limit diagram demonstrated that the optimized process parameters significantly enhanced the forming limits compared to standard FSW conditions. The weld line, when aligned with the optimal conditions, exhibited higher strain distribution, allowing for more efficient material deformation without failure.

➢ *Mechanical Properties:*

The mechanical testing of the welded joints revealed that the regions close to the weld line exhibited decreased strength and elongation compared to the base metal. However, the optimized process parameters mitigated these reductions, leading to an overall improvement in mechanical performance [20].

In this study findings, the effect of weld line positioning and the optimization of friction stir welding process parameters are crucial factors in determining the forming limit and mechanical properties of welded sheets. The study demonstrates that careful control and optimization of welding parameters can reduce the detrimental effects of weld line variations, resulting in improved forming limit curve and better overall performance of the welded joint. The use of forming limit diagrams provides a valuable tool for assessing the impact of process parameters on TWB blank material behavior during forming, thus offering insights into the design and production of high-performance friction stir welded components. Further research is needed to explore more complex welding conditions and their interactions with different materials to extend the findings to a broader range of applications.

COMPETING INTERESTS

The authors have no competing interests to declare.

AUTHOR CONTRIBUTION

Kamran Ahmad: Conceptualization, Writing – Original Draft, Writing – Review & Editing.

Dr. Praveen Kumar: Conceptualization, Writing – Original Draft, Writing – Review & Editing.

Dr. Vaibhav Chandra: Conceptualization, Writing – Original Draft, Writing – Review & Editing.

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