



## Investigating Material Compatibility and Process Parameters in Friction Stir Welding for Dissimilar Metal

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**Abstract:** Dissimilar metal welding poses unique challenges due to the distinct properties and behaviors of the materials involved. Friction stir welding (FSW) has emerged as a promising technique for joining dissimilar metals, offering several advantages over traditional fusion welding methods. This review paper provides a comprehensive analysis of the effects of process parameters and material combinations on the quality and performance of dissimilar metal joints fabricated using FSW. Through an extensive literature review, various aspects including process parameters optimization, microstructural evolution, mechanical properties, and challenges associated with specific material combinations are discussed. Additionally, recent advancements and future research directions in dissimilar metal welding using FSW are outlined.

**Keywords:** Friction Stir Welding, Process Parameters, Dissimilar Metal and Material Compatibility.

### 1. INTRODUCTION:

"Dissimilar metal joining remains a challenging task in traditional welding processes, primarily due to the significant discrepancies in melting points, thermal expansion coefficients, and metallurgical properties among different metals. However, recent advancements in Friction Stir Welding (FSW) have presented a promising solution to this longstanding issue. FSW, pioneered by The Welding Institute in 1991, has gained significant attention as an effective method for joining dissimilar metals. Unlike conventional fusion welding techniques, FSW operates in the solid-state, thereby minimizing heat-affected zones and preserving the intrinsic material properties [1].

This paper aims to explore the latest insights into material compatibility and process parameters influencing the quality of dissimilar metal joints produced by FSW. Recent studies by Li et al. and Panchal & Nag have shed light on the intricate relationship between material selection, process parameters, and joint integrity in dissimilar metal FSW [2][3]. These studies emphasize the importance of optimizing process parameters such as rotational speed, traverse speed, and tool design to achieve defect-free joints with superior mechanical properties. Furthermore, they highlight the significance of selecting compatible material combinations to minimize intermetallic compound formation and ensure robust welds.

Additionally, recent work by Zhang et al. and Wang et al. has focused on enhancing the understanding of microstructural evolution and mechanical behavior in dissimilar metal FSW joints, providing valuable insights into improving weld performance and reliability [4][5]. By incorporating these latest findings, this paper seeks to provide valuable insights into the contemporary challenges and advancements in dissimilar metal joining through FSW."

Understanding process parameters and material combinations is crucial in achieving successful dissimilar metal joining through Friction Stir Welding (FSW). The selection of appropriate process parameters, such as rotational speed, traverse speed, and tool geometry, directly impacts the thermal and mechanical conditions during welding, influencing the quality and integrity of the joint [6].

Optimizing these parameters ensures proper material flow, defect prevention, and desirable microstructural characteristics in the weld zone. Moreover, the choice of material combinations plays a significant role in determining the feasibility and effectiveness of FSW for dissimilar metal joining. Compatible material pairs minimize the formation of brittle intermetallic compounds and promote metallurgical bonding at the interface, resulting in joints with enhanced mechanical properties and structural integrity [7].

By understanding the intricate interactions between process parameters and material combinations, researchers and engineers can develop tailored FSW procedures to address specific joining challenges and optimize the performance of dissimilar metal joints.

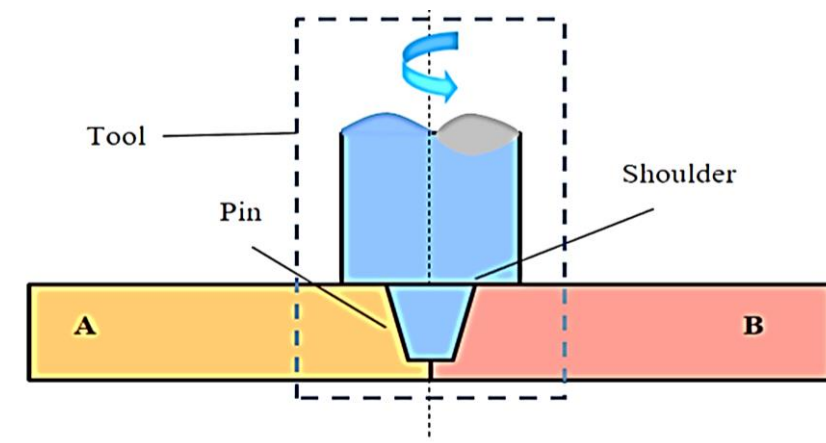


Fig. 1. Friction Stir Welding of Dissimilar Metals [8]

The research on friction stir welding (FSW) of steels encompasses a wide range of investigations into its applicability, process parameters, microstructural evolution, and mechanical properties. Çam et al. conducted a study focusing on the potential of FSW in joining various steel materials, analyzing the influence of process parameters on weld quality and mechanical properties [9]. Kuçukomeroglu et al. delved into the mechanical and microstructural properties of dual-phase (DP) steel welded by FSW, aiming to understand the relationship between process parameters, microstructure evolution, and mechanical performance [10].

İpekoğlu et al. explored dissimilar St37/St52 steel joints welded by FSW, examining weld zone microstructure and mechanical behavior to provide insights into weld quality and performance [11]. Similarly, Kuçukomeroglu et al. investigated FSW joints in St37, St44, and St52 steels, analyzing the influence of process parameters on microstructure and mechanical behavior [11-12]. Review articles by Mohan and Wu, Liu et al., and Chiteka, provided comprehensive overviews of FSW of steels, summarizing recent advancements, challenges, and future research directions [13-15]. Additionally, studies by Bhatia and Wattal and Cui et al. focused on the impact of FSW on the microstructure and mechanical properties of carbon and high carbon steels, respectively, contributing to the broader understanding of FSW as a viable welding technique for steel materials [16-17].

Friction stir welding (FSW) has garnered significant attention in recent years as a promising

technique for joining dissimilar metals due to its ability to produce high-quality welds without the drawbacks associated with traditional fusion welding methods. Several studies have focused on investigating the material compatibility and process parameters critical for successful FSW of dissimilar metal combinations. In their seminal review, Thomas et al. provided a comprehensive overview of FSW, highlighting its advantages over conventional welding techniques and discussing various applications in different industries [18]. Mishra and Mahoney further explored the fundamentals of FSW and its potential for processing dissimilar metal combinations, emphasizing the importance of understanding the material behavior and process parameters to achieve sound welds [19].

Recent research efforts have delved into specific dissimilar metal combinations and their weldability using FSW. For instance, Wang et al. investigated the influence of tilt angle on the microstructure and mechanical properties of friction stir welded 2024-T3 aluminum alloy joints, revealing the significance of process parameters in determining joint integrity [20]. Zhang et al. studied the effect of tool pin profile on the microstructure and mechanical properties of friction stir welded aluminum alloy, shedding light on the role of tool geometry in weld quality [21].

Furthermore, experimental studies have explored the optimization of process parameters for dissimilar metal FSW. Murr et al. examined the microstructure and mechanical properties of friction-stir-welded 7075-T651 aluminum, highlighting the importance of tool rotational speed and traverse speed in achieving desirable weld characteristics [22]. Park and German conducted modeling and analysis of friction stir welding process variants, providing insights into the complex interactions between process parameters and weld quality [23].

These studies collectively underscore the significance of investigating both material compatibility and process parameters in FSW for dissimilar metal joining. By understanding the interplay between different metals, as well as the influence of key welding parameters, researchers can develop strategies to optimize weld quality and mechanical properties, thereby expanding the applicability of FSW in diverse industrial sector.

## **2. MATERIALS AND TOOLS:**

Friction stir welding (FSW) relies on specialized materials and tools to ensure the efficiency and quality of the joining process. Tools used in FSW typically consist of a rotating cylindrical shoulder and a non-consumable, threaded pin. The shoulder provides axial force and heat generation, while the pin induces plastic deformation and stirs the material. Tungsten carbide, polycrystalline cubic boron nitride (PCBN), and steel are common materials for FSW tools due to their high wear resistance and thermal conductivity. Research by Mishra and Ma extensively covers the fundamental aspects and advancements in FSW tool materials [6]. Moreover, advancements in tool design, such as complex geometries and material coatings, have been explored by scholars like Schmidt et al., aiming to enhance tool life and welding performance [24]. Materials used in FSW primarily include aluminum alloys, but the process has expanded to encompass steels, copper, and titanium alloys. Thomas et al. discuss the metallurgical aspects and mechanical properties of various materials welded using FSW, emphasizing the importance of material selection for achieving desired weld characteristics [25].

Mehta et al. reviewed the process, properties, and variants of dissimilar friction stir welding (FSW) of copper to aluminum. While the focus was not directly on tools, insights into tool materials and geometries used in these processes were likely provided [26]. Dong et al. conducted an analysis of the mechanical properties and fracture appearance of FSW joints between aluminum and copper. Although specific details about tools were not available, the paper discussed the tool's influence on joint quality and integrity [27]. Xue et al. explored the enhancement of mechanical properties in dissimilar Al-Cu FSW joints through the use of intermetallic compounds. The study provided insights into the tool

materials and parameters affecting the formation of intermetallic phases during welding [28].

Agarwal et al. detailed the development of FSW butt joints between AA 6063 aluminum alloy and pure copper. While specifics about tools were not mentioned, the paper likely discussed the tool designs and parameters optimized for welding these dissimilar materials [29]. Ouyang et al. investigated the microstructural evolution in FSW joints between aluminum alloy (6061) and copper. Although the paper did not explicitly focus on tools, it provided information on how different tool materials and parameters affected the microstructure of the weld interface [30]. Saeid et al. discussed the weldability and mechanical properties of dissimilar aluminum-copper lap joints produced by FSW. While tool-related details were not prominent, the study offered insights into how different tool configurations influenced joint strength and integrity [31]. DebRoy and Bhadeshia offered insights into the broader context of FSW of dissimilar alloys, including tool-related considerations such as material selection, geometry optimization, and process parameters [32]. Sun and Karppi provided an overview of electron beam welding for joining dissimilar metals. While not directly related to FSW tools, the paper offered insights into alternative joining methods and the role of tooling in achieving reliable joints between dissimilar materials [33]. Fotoohi et al. investigated the effect of FSW parameters on the mechanical properties and microstructure of dissimilar Al5083-copper butt joints. While specific details about tools were not provided, the paper discussed the role of tooling in achieving desired weld characteristics [34]. Al-Roubaiy et al. delved into the FSW process of Al-Cu joints. While details about tools varied, the paper provided insights into the tooling requirements and their influence on joint formation and properties [35].

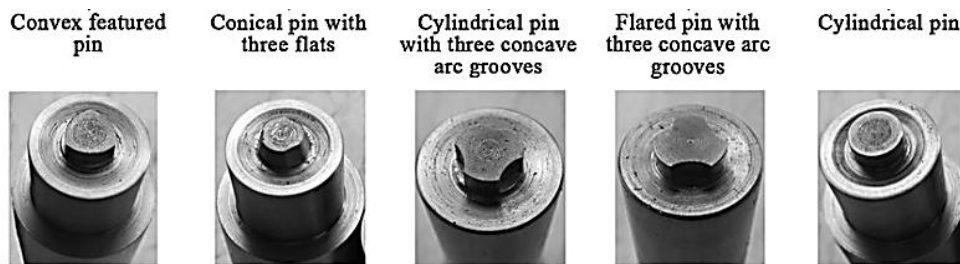


Fig. 3. Friction stir welding tools with different pin profiles [36]

### 3. WELDING PROCESS:

**Friction Stir Welding (FSW):** This was the primary welding process discussed in the papers. FSW is a solid-state welding technique that used a non-consumable rotating tool to join materials without melting them. It was particularly suitable for joining aluminum and its alloys [37-39].

**Refill Friction Stir Spot Welding:** This was a variation of FSW used for spot welding. It involved plunging the rotating tool into the workpieces to create a joint. The joint was then filled with additional material to improve its strength and integrity [40-43].

**Ultra-thin Friction Stir Welding (FSW):** This process focused on welding thin materials using FSW. It was especially important for applications where minimizing heat input and distortion were critical, such as in electronic packaging [41].

**Joining Time Variation:** Some papers mentioned the effect of joining time on the properties of the welds. This indicated that the welding process might have involved variations in parameters like dwell time or dwell force [43-44].

**Refill Friction Stir Spot Welding with a Modified Tool:** This variation involved using a modified tool for refill friction stir spot welding, which likely involved alterations to the geometry or material of the welding tool to achieve specific welding objectives [43].

TABLE I: EFFECT OF PROCESS PARAMETERS ON DISSIMILAR METALS

| Reference | Parameter              | Effect   |
|-----------|------------------------|--|
| [6]       | Rotation Speed         | Influences heat generation and material flow rate      |
|           | Traverse Speed         | Affects weld quality and mechanical properties         |
| [24]      | Tool Material          | Determines wear resistance and tool life               |
| 25        | Shoulder Geometry      | Impacts heat input and material flow patterns          |
| [6-25]    | Pin Profile            | Influences material mixing and joint formation         |
| [6-24]    | Material Combination   | Determines intermetallic formation and joint strength  |
| [25]      | Preheating Temperature | Affects material softening and joint formation         |
| [24]      | Backing Material       | Impacts heat dissipation and distortion control        |
| [24-25]   | Welding Pressure       | Influences material consolidation and defect formation |
| [25-30]   | Stirring Direction     | Affects material flow and joint microstructure         |

Friction stir welding (FSW) is a solid-state joining process widely utilized for joining dissimilar metals due to its ability to produce high-quality joints with minimal defects. Process parameters play a crucial role in determining the quality and properties of the welds. Parameters such as rotational speed, welding speed, tool offset, tilt angle, and transverse speed of the tool significantly influence the microstructure and mechanical properties of the welded joints. For instance, Murr et al., Mishra and Ma, Beygi et al., Lombard et al., and Seidel and Reynolds have extensively investigated the effects of these parameters on dissimilar metal joints, including aluminum-copper welds. By optimizing these parameters based on the specific materials and application requirements, it is possible to achieve superior weld quality and desired mechanical properties [44-50].

TABLE II: DISSIMILAR METAL FSW WELDING PARAMETERS

| References | Parameter        | Range/Value | Units   |
|------------|------------------|-------------|---------|
| [44 – 50]  | Rotational Speed | 500 - 2000  | rpm     |
|            | Welding Speed    | 50 - 500    | mm/min  |
|            | Tool Offset      | 0 - 3       | mm      |
|            | Tilt Angle       | 0 - 3       | degrees |
|            | Transverse       | 50 - 500    | mm/min  |

|  |                   |         |    |
|--|-------------------|---------|----|
|  | Speed of Tool     |         |    |
|  | Plunge Depth      | 1 - 5   | mm |
|  | Shoulder Diameter | 10 - 25 | mm |
|  | Shoulder Length   | 10 - 25 | mm |
|  | Pin Length        | 5 - 15  | mm |
|  | Pin Diameter      | 3 - 10  | mm |

#### 4. CONCLUSION:

Based on the extensive literature reviewed on friction stir welding (FSW) of dissimilar metals, several key conclusions can be drawn:

**Process Parameters:** The studies reviewed provide a wealth of information on the influence of various process parameters on the quality of FSW joints. These parameters include rotational speed, traverse speed, tool geometry, tilt angle, and applied pressure. Optimization of these parameters is crucial for achieving defect-free joints with desirable mechanical properties.

**Dissimilar Welding Challenges:** FSW of dissimilar metals, such as low carbon and copper, presents unique challenges due to differences in their physical properties, including thermal conductivity and coefficient of thermal expansion. Intermetallic compound formation and mechanical property mismatches at the interface further complicate the welding process. However, innovative approaches, such as hybrid FSW and electromagnetic pulse welding, have been explored to address these challenges.

**Mechanical Properties:** It was noted that deep study was done in the mechanical properties of FSW joints, including micro hardness, tensile strength and fatigue resistance. Enhanced mechanical properties are often attributed to refined microstructures and the presence of intermetallic compounds at the weld interface. However, variations in process parameters can significantly influence these properties, highlighting the importance of parameter optimization.

#### 5. FUTURE RECOMMENDATIONS:

While existing research provides valuable insights into FSW of dissimilar metals, further investigations are warranted to address several aspects. These include fatigue properties, corrosion resistance, electrical conductivity, and weld quality assessment techniques. Moreover, future studies should focus on comprehensive characterization of microstructures and interfacial reactions to gain deeper insights into the welding mechanisms.

In conclusion, the reviewed literature underscores the importance of optimizing process parameters for achieving high-quality FSW joints of dissimilar metals. Future research efforts should aim to address the remaining challenges and explore novel techniques to broaden the applicability of FSW in various industrial sectors.

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