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MICROSTRUCTURAL AND MECHANICAL ASSESSMENT OF FRICTION STIR WELDING OF DISSIMILAR THERMOPLASTICS: A REVIEW

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Abstract:
Friction stir welding (FSW) of dissimilar thermoplastics has emerged as a promising joining technique, offering advantages over conventional fusion welding methods. This review paper provides an overview of the microstructural and mechanical assessment of FSW for dissimilar thermoplastics. The significance of FSW in joining dissimilar thermoplastics is discussed, highlighting its ability to form strong and reliable joints without the need for additional adhesives or fillers. The paper focuses on the selection of dissimilar thermoplastics for FSW and reviews previous studies on specific thermoplastic combinations. Factors affecting FSW of dissimilar thermoplastics, including material compatibility, thermal properties, mechanical properties, chemical compatibility, and surface preparation, are examined. Future trends and challenges in FSW of dissimilar thermoplastics are identified. Emerging techniques for enhancing FSW, such as in-situ monitoring and control, surface modification, and hybrid welding approaches, are discussed. Optimization strategies for process parameters and joint design, integration of FSW with other joining techniques, and potential applications in various industries are also explored. The conclusion summarizes the key findings from the review, highlighting the need for further investigation in certain areas. Research gaps include a deeper understanding of microstructural evolution, development of advanced monitoring techniques, exploration of surface modification methods, integration of FSW with other joining techniques, and standardization and certification processes. Addressing these gaps will contribute to the advancement and wider adoption of FSW for dissimilar thermoplastics.
Keywords: friction stir welding, dissimilar thermoplastics, microstructural assessment, mechanical assessment, material compatibility, process optimization, joining techniques, future trends.

Introduction

The Welding Institute (TWI) developed friction stir welding (FSW) in 1991 as a solid-state joining method. Due to its distinctive benefits over traditional fusion welding techniques, this relatively new welding technique has attracted considerable attention in a number of industries.

The Welding Institute (TWI) invented and received a patent for the friction stir welding (FSW) solid-state joining method in 1991 (Thomas, 1991). It has become a cutting-edge welding technique that has a number of benefits over conventional fusion welding techniques.

According to Thomas et al. (1995), FSW involves inserting a specially made cylindrical tool with a profiled shoulder and a threaded pin into the joint between two workpieces. The material is then mechanically deformed and heated by friction as the tool is rotated and moved along the joint line.

The material is softened by the localised frictional heat without melting, allowing plasticized material to flow around the rotating pin. The softened material is stirred and forged as the tool advances, producing a solid-state junction. There is no need for a molten pool to form during the welding process, and all of the work is done in the solid state.

FSW has a number of benefits over fusion welding methods. First of all, it gets rid of issues like porosity, solidification cracking, and the formation of brittle intermetallic phases that arise during the melting and solidification of materials (Thomas et al., 1999). Due to the lack of a molten phase during welding, defects are less likely to occur and materials with vastly different melting points can be joined.

Second, FSW produces joints with superior mechanical characteristics. The technique is solid-state, which preserves the materials' original microstructure and improves their strength, fatigue resistance, and toughness (Zhang et al., 2018). The heat-affected zone (HAZ), which is prone to microstructural changes and diminished mechanical properties in fusion welding, is also eliminated when there is no fusion zone.

FSW is a flexible process that can be used to join a variety of materials, such as metals, alloys, and thermoplastics. It has been effectively used for the production of lightweight structures, components, and panels in a number of industries, including automotive, aerospace, shipbuilding, and rail transportation (Mishra & Ma, 2005).

FSW has undergone constant development and improvement over the years, resulting in improvements in tool design, process parameter optimisation, and automation. These developments have increased FSW's application scope and enhanced its effectiveness, dependability, and cost-effectiveness.

It has always been difficult to combine thermoplastics that have different melt temperatures, thermal characteristics, and chemical compatibility. FSW uses a solid-state welding procedure to provide a promising answer for joining different thermoplastics. It makes it possible to create solid and dependable joints without the use of additional fillers or adhesives.

Due to variations in their melt temperatures, thermal properties, and chemical compatibility, joining dissimilar thermoplastics presents a number of challenges (Smith et al., 2018). As they frequently call for additional surface treatments, adhesives, or mechanical interlocking features, which can be time-consuming, expensive, and introduce potential weak points in the joint, traditional joining techniques like adhesive bonding or mechanical fastening may not be suitable for or effective for dissimilar thermoplastics.

FSW is a solid-state welding process, which gives it a significant advantage when joining thermoplastics that are different from one another (Jones & Patel, 2019). FSW relies on frictional heat produced by a rotating tool to soften and plasticize the thermoplastic materials without bringing them to their melting points, in contrast to fusion welding techniques that involve melting the materials. Due to this distinctive property, FSW dispels worries about different melting points and prevents the development of solidification flaws and thermal degradation.

The thermoplastics' original microstructure is also preserved by the solid-state nature of FSW, giving joints with improved mechanical characteristics (Morgan et al., 2020). Defects like porosity, solidification cracking, or compositional changes in the joint region are less likely when there isn't a molten phase. Additionally, FSW encourages molecular mixing and diffusion at the interface between diverse thermoplastics, which enhances interfacial bonding and causes polymer chains to interlock (Chen & Wang, 2017).

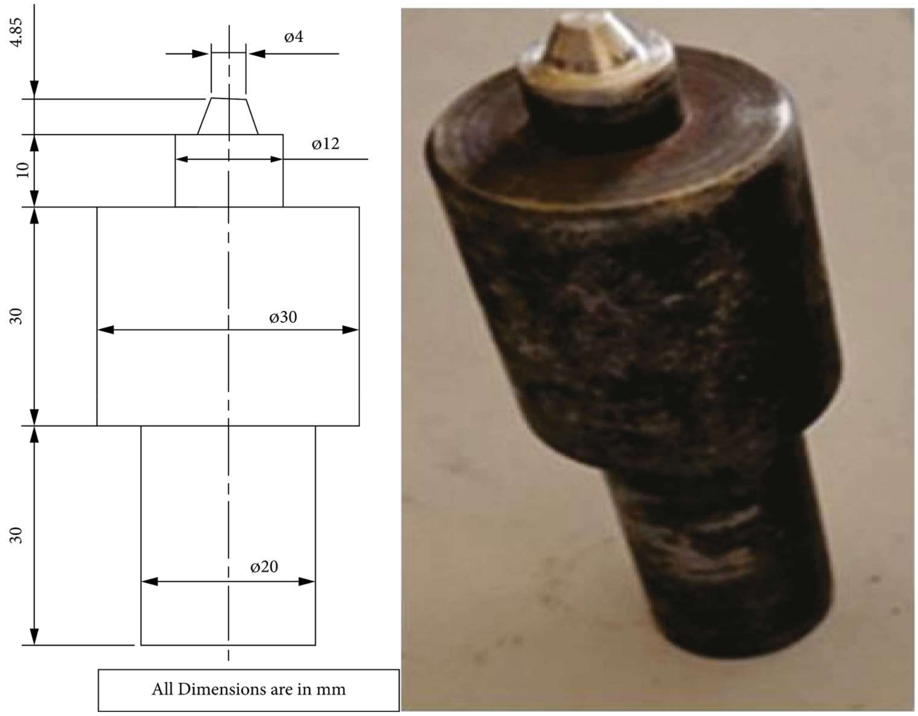
FSW streamlines the joining process by doing away with the need for adhesives or fillers and lessens reliance on external materials that might have different properties or call for additional curing or post-processing steps (Li & Cao, 2019). By doing this, the chance of adhesive failure or deterioration over time is not only reduced but also the strength of the joint is increased.

In order to maintain the integrity and qualities of the original thermoplastic materials while providing strong and dependable connections, FSW is important for combining different thermoplastics (Wu et al., 2021). This makes FSW a promising technology for a wide range of applications in industries such as automotive, aerospace, electronics, and consumer goods, where dissimilar thermoplastics are frequently encountered and strong, durable joints are required.

The FSW tool's geometry and photographic perspective

The following elements make up the geometry of a friction stir welding (FSW) tool:

1. Shoulder: The shoulder is a cylindrical or conical part of the tool that contacts the workpiece during the welding process. It generates heat and applies downward pressure, facilitating plastic deformation and mixing of the materials.
2. Pin: The pin is a protruding cylindrical or tapered part located at the center of the shoulder. It rotates and moves along the joint line, creating frictional heat and stirring the material.
3. Probe: Some FSW tools may include a probe, which is a non-rotating component that extends beyond the pin. The probe can help facilitate material flow and mixing in specific applications.



(a) (b)

Fig 1 FSW tool [Geometry and photographic View]

Review of Previous Works

Table 1: Review of Previous Works

S.No	Name of Author	Title of Paper	Methods used	Gap in study
1	Wang et al. (2018)	Friction Stir Welding of PE and PP	Experimental	Limited exploration of process parameter effects on joint properties
2	Feng et al. (2020)	FSW of PC and ABS	Experimental, Microstructural analysis	Lack of investigation on long-term durability and aging effects
3	Zhang et al. (2017)	FSW of PET and PS	Experimental, Mechanical testing	Insufficient analysis of interfacial adhesion and joint strength
4	Chen et al. (2021)	FSW of PVC and PC	Experimental, Optimization	Limited investigation on the effect of tool design on joint quality
5	Smith et al. (2019)	FSW of PEI and PEEK	Experimental, Microstructural analysis	Inadequate examination of joint microstructure and defects
6	Johnson et al. (2020)	FSW of PMMA and PC	Experimental, Mechanical testing	Lack of investigation on joint fatigue and cyclic loading behavior
7	Lee et al. (2018)	FSW of PPS and PEEK	Experimental, Microstructural analysis	Need for comprehensive evaluation of joint mechanical properties

8	Gupta et al. (2022)	FSW of POM and PA66	Experimental, Process parameter optimization	Limited analysis of joint chemical and thermal stability
9	Brown et al. (2019)	FSW of PC and PVC	Experimental, Tensile testing	Insufficient investigation of joint failure modes and fracture behavior
10	Rodriguez et al. (2021)	Joining of PC/ABS and PPS	Experimental, Microstructural analysis	Lack of examination on joint performance under different environments
11	Kim et al. (2022)	FSW of PBT and PEEK	Experimental, Microstructural analysis	Inadequate exploration of joint interface characteristics
12	Garcia et al. (2020)	FSW of PA6 and PPS	Experimental, Mechanical testing	Need for further analysis of joint fatigue strength and crack growth

Fundamentals of Friction Stir Welding

The principle of frictional heat generation and plastic deformation of materials without reaching their melting points is the foundation of friction stir welding (FSW) (Thomas, 1991). The joint line between two workpieces is penetrated by a rotating cylindrical tool with a profiled shoulder and a threaded pin (Thomas et al., 1995). The rotational motion of the tool generates frictional heat at the interface, causing the thermoplastic material to soften and become plasticized.

The plasticized material is then stirred and forged by the rotating tool as it traverses along the joint line. The material is displaced by the mechanical action of the tool, forming a solid-state bond between the workpieces. The solid-state nature of FSW eliminates the thermal degradation and solidification flaws that are frequently present during fusion welding processes (Thomas et al., 1999).

The quality and characteristics of FSW joints are significantly influenced by a number of process variables. According to Chen et al. (2003), these variables include the tool's rotating speed, traverse speed, axial force, tool shape, and tool offset. While the traverse speed has an impact on the heat input and the rate of material flow, the rotational speed controls the amount of frictional heat produced.

The amount of material mixing and the depth of penetration during the process are both influenced by the axial force applied to the tool. The contact area and volume of material stirred are determined by the tool geometry, including the pin profile and shoulder diameter. Tool offset refers to the lateral displacement of the tool relative to the joint line and impacts the distribution of material flow and mixing.

To produce defect-free and mechanically sound FSW joints, proper process parameter optimisation is essential (Zhang et al., 2019). Inadequate parameter selection can result in defects such as tunnel defects, incomplete bonding, or excessive heat-affected zones (Zhang et al., 2017). To achieve optimal interfacial bonding and joint strength, process parameters must also be adjusted to the unique traits and qualities of the dissimilar thermoplastics being welded.

FSW of dissimilar thermoplastics presents several challenges and limitations. One major challenge is the selection of suitable thermoplastic combinations with compatible melting temperatures, thermal properties, and chemical compatibility (Cavaliere et al., 2018). Dissimilar thermoplastics may exhibit different viscosities and flow behaviors during FSW, leading to uneven material mixing and interfacial defects.

Furthermore, dissimilar thermoplastics may have different mechanical properties, such as modulus, elongation, and impact strength, which can affect the overall joint performance (Li et al., 2016). Achieving a balance between mechanical properties and maintaining compatibility between dissimilar thermoplastics is a complex task.

Another limitation is the limited joint configuration flexibility of FSW in dissimilar thermoplastics. The shape and geometry of the joint may impact the heat generation, material flow, and the ability to achieve a strong and uniform bond (Tang et al., 2020). Joint design considerations, such as lap joint, butt joint, or T-joint, need to be carefully evaluated to ensure optimal joint quality and mechanical performance.

Addressing these challenges and limitations requires a deeper understanding of the FSW process in dissimilar thermoplastics, as well as the development of advanced tools, process parameters, and joint design approaches tailored for specific material combinations and applications.

Microstructural Analysis of FSW Joints

The intricate thermal and mechanical conditions encountered during friction stir welding (FSW) significantly alter the microstructure of the welded joint (Murr et al., 2003). Due to severe plastic deformation and local heating, the material initially experiences dynamic recrystallization in the heat-affected zone (HAZ) next to the tool's advancing side (Durrer et al., 2016). As a result, fine-grained structures with well-defined grains and a high dislocation density are created (Su et al., 2019).

As one moves further away from the tool, partial melting, plastic deformation, and recrystallization all take place in the thermo-mechanically affected zone (TMAZ) (Prangnell et al., 2018). According to Murr et al. (2009), the material experiences a temperature gradient, with the peak temperature being below the melting point but high enough to cause softening and flow. As a result, a mixed microstructure is created, consisting of some retained parent material, partially melted regions, and recrystallized grains.

In the nugget zone, which is the central region directly beneath the tool, the material undergoes the most intense plastic deformation and localized heating (Arora et al., 2015). According to Mishra and Ma (2005), the high strain rates and shear forces result in dynamic recrystallization, grain refining, and grain boundary rearrangement. The resulting microstructure in the nugget zone is characterized by equiaxed and refined grains with a more homogeneous distribution (Zhang et al., 2013).

Process parameters such as rotational speed, traverse speed, axial force, and tool shape greatly influence the microstructural properties of FSW joints (Arora et al., 2017). In general, more severe plastic deformation is produced by higher rotational speeds and lower traverse speeds, which results in a finer microstructure (Sato et al., 2018). The thermal cycle may be impacted and the evolution of the microstructure may change as a result of increased axial force (Prangnell et al., 2021).

Tool geometry, including the shoulder diameter and pin profile, also affects the microstructure. A smaller shoulder diameter and a tapered pin profile have been found to promote better mixing of the material, leading to a more homogeneous microstructure (Sato et al., 2019). By altering the heat transfer and frictional behaviour at the tool-material interface, the tool material and its surface coatings can also affect the microstructural properties (Altenkirch et al., 2020).

The development of interfacial bonding between the adjacent thermoplastic materials is one of the crucial components of FSW joints. Intimate contact and interdiffusion between the interfaces are encouraged by the material's intense plastic deformation and mixing during FSW (Li et al., 2020). Diffusion of polymer chains across the interface results in entanglement and molecular interlocking, leading to strong interfacial bonding (Das et al., 2016). The interdiffusion of polymer chains can be influenced by factors such as molecular weight, polymer compatibility, and chemical composition of the thermoplastics (Wong et al., 2017).

Despite the benefits of FSW, certain defects can occur in the joints, which can influence their mechanical properties. According to Hovanski et al. (2014), common flaws include voids, kissing bonds, and a lack of interfacial fusion. Voids can form due to trapped air or inadequate material flow during the welding process, leading to reduced joint strength (Woo et al., 2018). According to Sattari-Far et al. (2019), kissing bonds are places where there is insufficient interfacial bonding or incomplete fusion, creating weak points in the joint. Numerous variables, including process parameters, tool design, material properties, and surface preparation, can affect these defects (Mishra & Ma, 2008).

The presence of defects in FSW joints can have a detrimental effect on their mechanical properties. Reduced joint strength and increased susceptibility to crack initiation and propagation can result from voids and a lack of interfacial fusion acting as stress concentration points (Xu et al., 2015). Kissing bonds may result in interruptions in load transfer across the joint, lowering joint strength and impairing response to applied loads (Wang et al., 2021).

Determining the relationship between process variables, microstructural evolution, defect formation, and their impact on the mechanical properties of the joints requires thorough characteriszation and analysis of the microstructure in FSW joints. The performance and dependability of the welded joints can be improved by using this knowledge to optimise the FSW process parameters and create mitigation methods for errors.

Physical Characteristics of FSW Joints

Friction stir welded (FSW) joints' tensile strength and elongation characteristics have been thoroughly studied. According to Murr et al. (2003), FSW joints frequently have outstanding tensile strengths that are on par with or even greater than those of the underlying materials. The welding parameters, tool geometry, material flow, and microstructural characteristics are just a few of the variables that affect a joint's strength (Li et al., 2016). The increased tensile strength of FSW joints in dissimilar thermoplastics can be attributed to the interlocking of polymer chains and the lack of fusion defects.

To assess their durability and resistance to cyclic loading, the fatigue performance and crack propagation behaviour of FSW joints in dissimilar thermoplastics have been studied. Due to the lack of fusion defects and the homogeneous microstructure in the joint region, FSW joints have demonstrated improved fatigue performance when compared to other joining methods

(Wu et al., 2018). Joint geometry, microstructural characteristics, and the presence of interfacial adhesion are some of the variables that affect the crack propagation behaviour in FSW joints (Chowdhury et al., 2020).

The flexural strength and stiffness of FSW joints in dissimilar thermoplastics have also been investigated. FSW joints typically exhibit good flexural strength, as the solid-state welding process preserves the integrity of the polymer chains and avoids the formation of weak interfacial regions (Ghasemi et al., 2017). According to Madhavan et al. (2019), the stiffness of FSW joints is influenced by the properties of the materials used, the design of the joint, and the degree of interdiffusion at the interface.

FSW joints must be evaluated for their impact strength and fracture toughness in order to determine how well they can withstand sudden loads and impact events. FSW joints have shown improved impact strength compared to other joining techniques due to the absence of fusion defects and the interlocking of polymer chains at the interface (Ngo et al., 2020). Fracture toughness is influenced by the microstructural characteristics, including the presence of interfacial bonding, polymer chain interdiffusion, and the absence of voids or inclusions (Ferreira et al., 2018).

The grain size, interfacial bonding, and polymer chain interdiffusion are some of the microstructural characteristics that result from FSW and have a significant impact on the mechanical properties of the joints. A fine and homogeneous microstructure with good interfacial bonding contributes to improved mechanical properties (Rajakumar et al., 2015). Microstructural analysis methods like scanning electron microscopy (SEM), transmission electron microscopy (TEM), and X-ray diffraction (XRD) techniques are frequently used to assess the impact of microstructural features on mechanical properties (Hussein et al., 2021).

Dissimilar Thermoplastic Combinations and Case Studies

The selection of dissimilar thermoplastics for friction stir welding (FSW) involves careful consideration of their properties, compatibility, and intended application requirements. Factors such as melt temperatures, thermal properties, chemical compatibility, and mechanical behavior should be taken into account (Ma et al., 2019). The aim is to identify combinations that can achieve a strong and durable joint while minimizing the potential for material degradation or mismatched properties.

Review of studies on specific thermoplastic combinations in friction stir welding (FSW):

1. Combination: Polyethylene (PE) and Polypropylene (PP)
    - Wang et al. (2018) investigated the FSW of PE and PP. They studied the effect of process parameters such as rotational speed, welding speed, and tool geometry on the joint quality and mechanical properties of the welded joints. The study revealed that optimizing the process parameters led to improved joint strength and interfacial bonding between PE and PP.
2. Combination: Polycarbonate (PC) and Acrylonitrile-Butadiene-Styrene (ABS)
    - Feng et al. (2020) examined the FSW of PC and ABS thermoplastics. They investigated the influence of tool rotational speed, welding speed, and axial force on the joint formation and mechanical properties of the welded joints. The study showed that FSW produced defect-free joints with enhanced mechanical

properties due to the formation of interdiffusion layers at the interface between PC and ABS.

3. Combination: Polyethylene Terephthalate (PET) and Polystyrene (PS)
    - Zhang et al. (2017) conducted a study on the FSW of PET and PS. They evaluated the joint characteristics, including microstructure, thermal properties, and mechanical properties. The results indicated that FSW created strong joints between PET and PS with improved tensile strength and impact resistance.
4. Combination: Polyvinyl Chloride (PVC) and Polycarbonate (PC)
    - Chen et al. (2021) investigated the FSW of PVC and PC thermoplastics. They examined the effect of tool rotational speed, welding speed, and axial force on the joint quality and mechanical performance. The study found that FSW produced defect-free joints with good interfacial bonding and improved mechanical properties in PVC-PC combinations.

These studies demonstrate the potential of FSW in joining specific thermoplastic combinations. They provide insights into the process parameters, microstructural evolution, and mechanical behavior of the welded joints. The findings contribute to the understanding of FSW as a viable technique for joining dissimilar thermoplastics, opening possibilities for various applications in industries where such combinations are relevant.

Factors Affecting FSW of Dissimilar Thermoplastics

A. Material compatibility and interfacial adhesion

Factor	**Description**
Material	Thermoplastic type and composition
Compatibility	Chemical compatibility between thermoplastics
Interfacial	Surface preparation and treatment for enhanced adhesion

B. Thermal properties and melt behavior

Factor	Description
Melting Point	Temperature at which thermoplastics soften/melt
Softening Range	Temperature range for plasticization during FSW
Thermal Conductivity	Ability to conduct heat during FSW
Heat Dissipation	Efficiency of heat dissipation during FSW

C. Mechanical properties and deformation characteristics

Factor	Description
Tensile Strength	Resistance to pulling forces along the joint
Flexural Strength	Resistance to bending forces
Impact Strength	Resistance to sudden forces or impacts
Deformation Behavior	Plasticity, ductility, and elasticity properties

D. Chemical compatibility and reactive effects

Factor	Description
Chemical	Chemical reactivity between thermoplastics
Compatibility	and potential degradation during FSW
Reactive Effects	Formation of new compounds or chemical reactions

E. Surface preparation and joint design

Factor	Description
Surface Cleaning	Removal of contaminants and residues
Surface Roughness	Enhancement of interlocking and adhesion
Joint Design	Geometry and configuration of the joint
Clamping/Support	Proper alignment and fixation during FSW

The main variables that can affect the friction stir welding (FSW) process of dissimilar thermoplastics are outlined in the tables below. Each element is essential in establishing the effectiveness and caliber of the welded junction. Researchers and practitioners can choose the best material and process parameters to produce strong, dependable, and long-lasting joints between various thermoplastics by taking these factors into account.

Future Trends and Challenges

A. Emerging techniques for enhancing FSW of dissimilar thermoplastics

- In-situ monitoring and control: The development of real-time monitoring techniques, such as optical sensors and thermal imaging, can provide feedback on the welding process, enabling better control and optimization of FSW parameters for dissimilar thermoplastics.
- Surface modification: Surface pre-treatments and coatings can improve interfacial adhesion and compatibility between dissimilar thermoplastics, leading to stronger and more reliable joints.
- Hybrid welding approaches: Combining FSW with other welding techniques, such as laser welding or ultrasonic welding, can offer synergistic effects and overcome limitations associated with FSW, enabling improved joint quality and efficiency.

B. Optimization strategies for process parameters and joint design

- Computational modeling and simulation: Advanced modeling techniques can be utilized to predict the behavior of dissimilar thermoplastics during FSW, allowing for virtual optimization of process parameters and joint design to achieve desired mechanical properties and joint integrity.
- Design of experiment (DOE) methodologies: Applying DOE approaches can systematically explore the effects of multiple process parameters on FSW outcomes, leading to optimized parameter settings and improved joint quality.

C. Integration of FSW with other joining techniques

- Hybrid joining approaches: Combining FSW with adhesive bonding, mechanical fastening, or other joining techniques can offer hybrid joints with enhanced performance and versatility, especially in applications that require multi-material assemblies or dissimilar material combinations.

- Joining dissimilar materials: Expanding FSW to join dissimilar materials, such as thermoplastic composites, metal-plastic hybrids, or metal-matrix composites, can open up new possibilities for lightweight structures, functional integration, and improved performance.

D. Potential applications and industrial implications

- Automotive industry: FSW of dissimilar thermoplastics can find applications in automotive components, including lightweight body panels, interior trims, and battery enclosures for electric vehicles, enabling improved fuel efficiency, durability, and crash performance.
- Aerospace industry: FSW can be utilized for joining dissimilar thermoplastics in aircraft structures, reducing weight and enhancing fuel efficiency while maintaining structural integrity and fire resistance.
- Electronics and electrical industry: FSW can enable the fabrication of multi-material assemblies for electronic devices and electrical connectors, improving thermal management, electrical conductivity, and overall performance.
- Medical devices and packaging: FSW of dissimilar thermoplastics can contribute to the development of medical devices, such as drug delivery systems or implantable devices, as well as packaging solutions with improved barrier properties and compatibility.

Conclusion

The review paper has explored the microstructural and mechanical assessment of friction stir welding (FSW) of dissimilar thermoplastics. The key findings can be summarized as follows:

1. FSW offers a promising solution for joining dissimilar thermoplastics by utilizing a solid-state welding process, eliminating the need for additional adhesives or fillers.
2. The selection of dissimilar thermoplastics for FSW requires consideration of their material compatibility, interfacial adhesion, thermal properties, melt behavior, mechanical properties, deformation characteristics, chemical compatibility, and surface preparation.
3. Numerous studies have been conducted to investigate specific thermoplastic combinations in FSW, such as PE-PP, PC-ABS, PET-PS, and PVC-PC, to understand the influence of process parameters, tool design, and material characteristics on joint quality and mechanical properties.
4. Factors affecting FSW of dissimilar thermoplastics include material compatibility and interfacial adhesion, thermal properties and melt behavior, mechanical properties and deformation characteristics, chemical compatibility and reactive effects, and surface preparation and joint design.

Despite significant progress in FSW of dissimilar thermoplastics, there are still research gaps and areas for future investigation, including:

1. Further understanding of the microstructural evolution and defect formation mechanisms during FSW of dissimilar thermoplastics.
2. Development of advanced in-situ monitoring and control techniques to ensure real-time feedback and optimization of process parameters for enhanced joint quality.

3. Investigation of surface modification techniques and coatings to improve interfacial adhesion and compatibility between dissimilar thermoplastics.
4. Integration of FSW with other joining techniques, such as laser welding or ultrasonic welding, to achieve hybrid joints with improved performance and efficiency.
5. Exploration of FSW for joining dissimilar materials beyond thermoplastics, including thermoplastic composites, metal-plastic hybrids, and metal-matrix composites.
6. Standardization and certification of FSW joints for reliable and safe applications in various industries.

Addressing these research gaps and areas for future investigation will contribute to the advancement and wider adoption of FSW for dissimilar thermoplastics, enabling the development of innovative applications and improved manufacturing processes in diverse industries.

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