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REVIEW ARTICLE

A critical review on effect of nanoparticles and process parameters on metallurgical properties of friction stir processing of dissimilar aluminum alloys

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Abstract

Friction stir welding (FSW) and friction stir processing (FSP) are unique solid-state joining and surface modification techniques that offer several advantages over conventional fusion welding and surface treatment methods. The ability to modify the microstructure and properties of the weld and surface through the control of processing parameters is a key advantage of FSW/FSP. This has led to a great deal of research on understanding the microstructural evolution during FSW/FSP. One important aspect of microstructural control in FSW/P is the development of grain structures and textures. The high strain rates and temperatures during FSW/P can lead to dynamic recrystallization and the formation of refined and homogeneous grain structures. The degree of grain refinement and texture development can be controlled through the selection of processing parameters such as tool geometry, rotation speed, traverse speed, and applied pressure. Another important aspect of microstructural control in FSW/P is the formation of phases, phase transformations, and precipitation. The ability to control grain structures, phases, and IMCs, as well as the potential for local refinement and the formation of MMCs, makes FSW/P an attractive option for a wide range of applications. Continued research and development will be critical for further advancing the capabilities and potential of FSW/P.

1. Introduction

Friction stir welding (FSW) has gained popularity as it offers several advantages over traditional fusion welding techniques [1-3]. FSW can address issues such as distortions, solidification cracking, micro-segregation, coarse dendritic structures, porosities, surface oxidation, intermetallic formation, wide HAZ, high energy consumption, and environmental pollution [4, 5]. Additionally, FSW allows for better control of microstructure and properties of the weld, making it important to understand the relationship between FSW conditions and microstructure [6-10]. Friction stir processing (FSP) is another technique that can modify the surface microstructure or incorporate a second phase to the material. In FSP, a rotating tool is used to cut a groove or drill holes to insert second-phase particles into the surface of the material, creating a composite structure [11-13]. Both FSW and FSP have a wide range of industrial applications, as shown in Fig. 1. Understanding the relationship between process parameters and microstructure is crucial in tailoring the properties of the weld or surface. During FSW/P of metals and alloys, several important mechanisms drive microstructural

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and textural evolution [14-17]. These mechanisms include dynamic recrystallization, grain refinement, grain growth, and texture development. The exact nature and extent of these mechanisms depend on a variety of processing parameters such as tool geometry, tool material, traverse speed, rotational speed, and axial force, among others [18-22]. Dynamic recrystallization is a common mechanism observed during FSW/P, where new grains nucleate and grow in a dynamically deformed region of the material. This process helps to refine the grain structure of the weld and can also help to eliminate defects such as voids and inclusions. Grain refinement is also commonly observed during FSW/P, particularly in metals with high stacking fault energy such as aluminum alloys [23, 24]. Grain refinement occurs due to severe plastic deformation, and can result in improved mechanical properties such as higher strength and ductility. Grain growth can also occur during FSW/P [25, 26], particularly in the heat-affected zone (HAZ) where temperatures are elevated but below the melting point of the material. The extent of grain growth depends on the peak temperature and the duration of heating. Texture development during FSW/P is also a complex phenomenon, and can be influenced by a variety of factors such as the crystallographic orientation of the starting material, the tool geometry, and the processing parameters [27-32]. The local temperature and strain rate during FSW/P can result in the formation of new phases and the transformation of existing phases. Additionally, precipitation of secondary phases can occur during post-weld heat treatment. Control of these processes is important for achieving the desired microstructure and properties. When joining dissimilar metals and alloys, special attention must be paid to the control and dispersion of intermetallic compounds (IMCs) [33-36]. IMCs can form at the interface between dissimilar materials and can have a negative impact on joint strength and toughness. The selection of processing parameters and tool design can influence the formation and distribution of IMCs. FSP offers additional opportunities for microstructural control and material modification. Local refinement of the microstructure can be achieved through the use of a smaller tool and lower traverse speeds [37, 38]. Additionally, FSP can be used to introduce reinforcement particles into the near-surface region, leading to the formation of metal matrix composites (MMCs). Despite the significant progress that has been made in understanding the microstructural evolution during FSW/P, there are still gaps in our knowledge. Further research is needed to fully understand the relationship between processing parameters, microstructure, and properties [39-42]. Additionally, there is a need for improved tools and techniques for monitoring and characterizing the microstructure and properties of FSW/P joints and surfaces. In conclusion, FSW/P offers a unique opportunity for tailoring the microstructure and properties of welds and surfaces [43, 44].

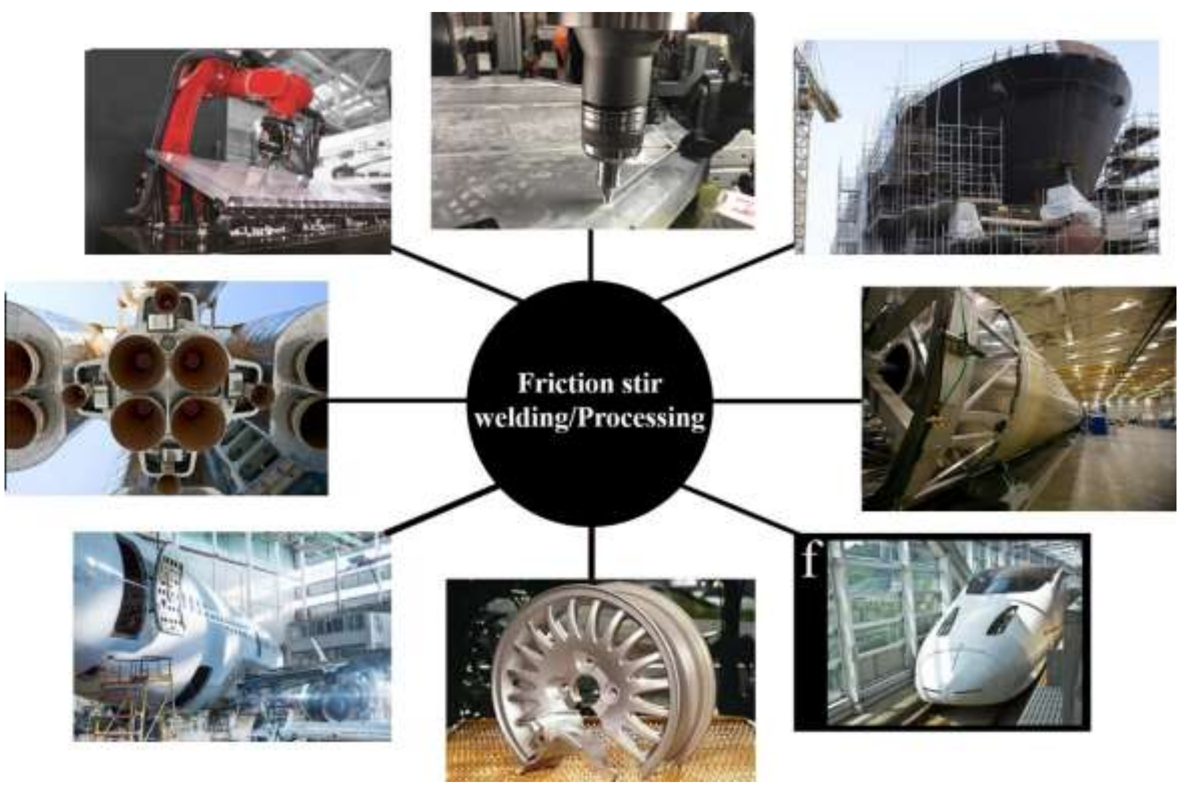

Figure 1: Applications of friction stir welding /processing

Understanding the mechanisms underlying microstructural and textural evolution during FSW/P is crucial for controlling and improving the properties of welded joints and surface treatments. This review provides an updated perspective on the current understanding of microstructural evolution during FSW/P, including a focus on specific metals and alloys, challenges associated with joining dissimilar materials, and microstructural evolution during FSP [45-49]. The review is a valuable resource for both beginners and experienced engineers and scientists seeking to improve their understanding of microstructure development during FSW/P, with the ultimate goal of achieving improved control over weld properties and surface treatments.

2. Grain structure mechanism

The severe thermomechanical excursions experienced by the weld zone material during FSW lead to microstructural changes. The main contributions to heat generation come from friction between the tool and the workpiece and from the large amount of work related to plastic flow that is dissipated as heat. This results in highly non-uniform thermal fields, strains, and strain rates that vary with distance from the rotating pin and shoulder, and with the properties of the processed materials. The weld zone can be divided into four zones based on their distinct thermomechanical characteristics: the stir zone (SZ), thermomechanically affected zone (TMAZ), heat affected zone (HAZ), and base material (BM) [19, 50]. The peak temperature, strain, and strain rate are highest near the surfaces of the pin and shoulder and decrease sharply towards the base material. In the SZ, the peak temperature ranges from 0.9 to 0.75 T (melting temperature) and exhibits a basin-like shape widening towards the upper surface. In the TMAZ, the peak temperature decreases with distance from the weld line from ~0.7 to 0.6 T. The HAZ exhibits a gradual decrease in peak temperature from ~0.55 T to ambient temperature. The strain and strain rate gradients tend to be much steeper than the temperature gradients. In the SZ, the true strain and strain rate can be as high as ≥10 2 and >10 s^{-1}, respectively, decreasing downwards from the shoulder surface and in the transverse direction away from the pin surface. In the TMAZ, the strain and strain rate decrease towards zero at the boundary with the HAZ. The different deformation and thermal histories associated with the SZ, TMAZ, HAZ, and BM result in microstructure evolution that varies sharply with position [51, 52]. This can take place dynamically during processing and statically after processing. The underlying mechanisms of microstructural evolution are complex, and the review will outline these mechanisms to aid in the interpretation of the grain-structure development occurring during FSW.

2.1 Dynamic recrystallization (DRX)

The HAZ is characterized by dynamic recovery (DRV) and recrystallization (DRX). The DRV process involves the annihilation and rearrangement of dislocations, leading to a decrease in dislocation density and an increase in subgrain size. The DRX process involves the nucleation and growth of new grains, leading to a decrease in the average grain size. The recrystallization in the HAZ is less extensive than in the SZ and TMAZ due to lower strain levels and slower heating and cooling rates [53, 54]. In addition, the recrystallization in the HAZ may be incomplete due to the presence of second-phase particles, which act as pinning points and inhibit the nucleation and growth of new grains. The grain structure in the HAZ is complex and may contain a mixture of recrystallized and unrecrystallized regions. The microstructural evolution in the BM is minimal due to the low strain levels and low temperatures experienced during FSW. However, the BM may be affected by the heat input and residual stresses generated during the process, which may lead to distortion, cracking, and reduced mechanical properties [55]. Overall, the microstructural evolution during FSW is highly dependent on the processing parameters and the properties of the processed materials, and it is crucial to understand and control these factors to optimize the properties of the weld. The passage describes two main features of DRX, a process that occurs during deformation of materials [56-59]. The first feature is the continuous deformation of new grains, which results in many lattice dislocations. The second feature is the production of a necklace microstructure consisting of a recrystallized mantle along the initial boundaries with unrecrystallized remnants in the core. CDRX (continuous dynamic recrystallization) is a type of DRX that produces a well-defined subgrain structure in the remnants of unrecrystallized grains, while DRV (discontinuous dynamic recrystallization) produces a network of incidental LAGBs (low angle grain boundaries) having a misorientation of ~1. DRV occurs in grains belonging to transition texture orientations and associated with multiple slips, while CDRX usually occurs in stable orientations where single or double slip is operative. The proportion of recrystallized grains in the necklace structure increases from the periphery to the inner edge of the TMAZ [60, 61]. The DDRX (double dynamic recrystallization) mechanism involves local grain boundary bulging, growth of the DRX nucleus, and stagnant grain growth resulting from DRX grain impingement and a diminished driving force for growth. The principal nucleation mechanism of DDRX is similar to the Bailer-Hirsh mechanism suggested for DSRX (discontinuous dynamic recrystallization). In this mechanism, a network of subgrains readily develops near the grain boundaries leading eventually to boundary corrugations or serrations. The bulged DRX nuclei become separated from the highly dislocated structures by a LAGB or annealing twins, such that the DDRX nucleus is partially bounded by a bulged portion of initial HAGB (high angle grain boundary) and by a LAGB. Both of these boundaries are able to migrate toward the high dislocation density in parent grains. In summary, the driving force for DRX and DDRX is the local dislocation density gradient, which leads to grain boundary migration towards high dislocation density regions and the growth of recrystallized grains. The nucleation of DRX and DDRX involves the bulging of a grain boundary portion, which can be facilitated by DRV and in homogeneities in dislocated structures between neighboring grains of different orientations [62-64]. The critical strain for DDRX decreases with increasing temperature and/or decreasing strain rate. The presence of incoherent particles or coherent dispersions may suppress DDRX if the Zener drag pinning force and the drag force exceed the driving force for boundary bulging due to stored dislocations. Finer DDRX grains may be formed at larger strains due to the larger driving force.

2.2 Post DRX

During metadynamic recrystallization (MDRX), the dislocations in the deformed material migrate to the boundaries between grains and create regions of high dislocation density in the SZ [65]. These high dislocation density regions are then transformed into recrystallized grains during static annealing [66]. The recrystallized grains may have different orientations than the original grains and can form a new microstructure in the SZ. The MDRX process is affected by many factors, such as the material properties, FSW parameters, and the cooling rate of the welded material [67]. The MDRX process can lead to improvements in the mechanical properties of the welded joint by reducing the residual stresses and improving the grain structure. However, excessive MDRX can also lead to the formation of coarse grains and reduced mechanical properties [68]. Therefore, it is important to control the MDRX process during FSW to ensure that the microstructure of the welded joint is optimized for the desired mechanical properties.

2.3 Static DRX

The static recrystallization (SRX) is a process in which new strain-free grains are nucleated and grow to consume the deformed microstructure. There are two main mechanisms of SRX: discontinuous static recrystallization (DSRX) and continuous static recrystallization (CSRX). DSRX occurs in materials with low stacking fault energy (SFE) and involves the migration of pre-existing high-angle grain boundaries (HAGBs) into the deformed matrix, leading to nucleation and subsequent growth of new grains. CSRX, on the other hand, occurs in materials with high SFE and involves sub-grain bounded by low-angle grain boundaries (LAGBs) and HAGBs serving as nuclei. This process is usually accompanied by extensive particle coarsening. The nucleation in CSRX is attributed to subgrain structures produced by preceding strain-induced subgrain formation, which may occur by two distinctly different mechanisms revealed in Fig. 2, migration of LAGBs and coalescence of neighboring subgrains. The driving force for both mechanisms is the reduction of boundary energy. Overall, SRX is an important phenomenon in material processing and can greatly affect the microstructure and properties of materials.

3. Microstructure analysis during FSW/FSP

The extreme processing conditions of FSW, including high temperature, large strain, and high strain rate, make it difficult to investigate the microstructural processes occurring during the process. However, researchers have developed two approaches to investigate these processes: the stop-action technique and the mapping of the transient region. These methods involve either stopping the FSW machine and immediately quenching the material or mapping the region during the welding process to analyze the microstructural changes over time. Despite these challenges, researchers have made significant progress in understanding the microstructural evolution during FSW. It is interesting to note that the microstructural evolution during FSW is not only influenced by the welding parameters, but also by the material properties. For instance, the material's initial grain size has been shown to affect the recrystallization and grain growth during FSW [69]. Furthermore, the presence of second-phase particles or precipitates can alter the deformation behavior and lead to changes in the microstructure [70]. In some cases, the presence of precipitates can even promote dynamic recrystallization [71]. Overall, the microstructural evolution during FSW is a complex process that is influenced by a range of factors, and further research is needed to fully understand the underlying mechanisms.

3.1 Effect of reinforcement particles

It is worth noting that the addition of nanoparticle reinforcements in FSW/FSP processes may also have some challenges. For instance, nanoparticles may agglomerate during the welding process, leading to an uneven distribution of the reinforcement in the weld nugget. This can negatively impact the joint's mechanical properties. Therefore, it is crucial to optimize the welding parameters to maintain a consistent distribution of the nanoparticles. Additionally, the use of nanoparticles may increase the overall cost of the welding process due to the higher cost of the reinforcement material. Despite these challenges, nanoparticle reinforcement has shown promising results in improving the properties of MMC welded joints, and further research in this area can lead to the development of advanced welding techniques with superior joint characteristics. It is important to note that the size and distribution of the nanoparticles also affect their behavior during the FSW process. For instance, an uneven distribution of the nanoparticles can result in the formation of agglomerates, leading to poor joint properties. Therefore, researchers have been investigating various methods to achieve a uniform distribution of nanoparticles, including mechanical mixing, ultrasonic mixing, and magnetic stirring [72, 73]. Additionally, the use of surfactants has also been reported to enhance the distribution of nanoparticles. These methods have shown promising results in achieving a uniform dispersion of nanoparticles, thereby improving the joint properties.

In addition to SiC, other types of reinforcement particles have also been investigated for FSW applications. For example, the effect of Al2O3 nanoparticle reinforcement on the mechanical properties of FSW joints was studied shown in Fig. 3, who found that the addition of Al2O3 nanoparticles improved the tensile strength and ductility of the joints. Similarly, he effects of B4C nanoparticles on the microstructure and mechanical properties of FSW joints in AA2024-T3, and reported that the addition of B4C nanoparticles led to an improvement in hardness and tensile strength. Besides nanoparticle reinforcements, other types of reinforcements such as fibers have also been studied for FSW MMCs. The effects of reinforcing carbon fibers on the microstructure and mechanical properties of FSW joints in Al-Cu-Mg alloy plates. They reported that the carbon fibers contributed to improved tensile strength and elongation, as well as better ductility and toughness. Overall, the use of reinforcement particles or fibers in FSW of MMCs has shown promising results in terms of improving mechanical properties such as strength, hardness, and ductility. However, the optimal type and size of reinforcement depend on the specific MMC being used and the welding parameters employed, and thus more research is still needed to fully understand the underlying mechanisms and to optimize the FSW process for different MMCs.

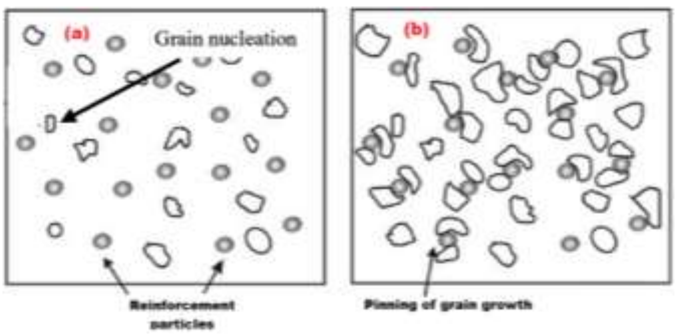

Figure 2: The pinning of grain growth by reinforcing particles [77].

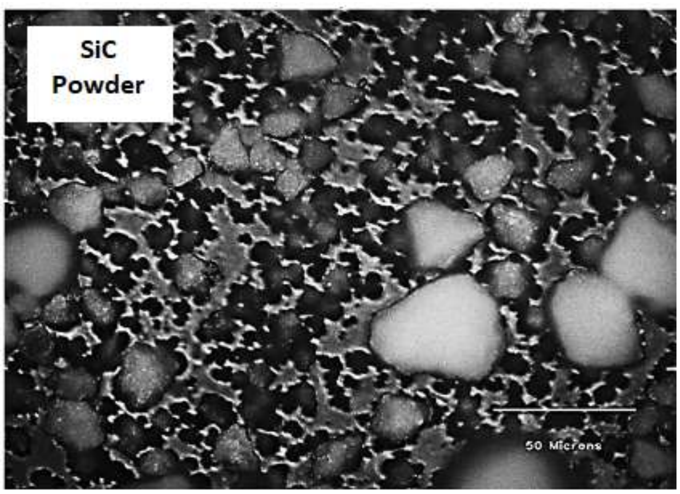

Figure 3: SiC Powder (its SEM Image) [40]

In addition to pinning of grain boundaries, reinforcement particles can also increase dislocation density, which results in improved mechanical properties such as strength and hardness [74]. The distribution of reinforcing particles in the matrix also plays a significant role in the mechanical properties of the MMC. In FSW, the use of a rotational tool with a specially designed probe can facilitate the distribution of reinforcing particles uniformly in the matrix. The tool's rotational speed, traverse speed, and tool geometry also affect the distribution of reinforcing particles in the matrix [75]. Moreover, the distribution of reinforcing particles can be influenced by the tool pin profile, which includes features such as pin length, pin diameter, pin taper, pin offset, and pin thread. The pin profile can be customized to optimize the distribution of reinforcing particles in the matrix, which can ultimately improve the mechanical properties of the MMC [76]. Overall, the use of reinforcing particles in FSW can significantly improve the mechanical properties of the resulting MMC, such as strength, hardness, and ductility, by pinning grain boundaries, increasing dislocation density, and improving the distribution of reinforcing particles in the matrix.

Ceramic nanomaterials such as Al2O3, TiO2, SiC, and TiC are commonly used for FSW reinforcement. Meanwhile, carbonaceous nanomaterials such as carbon nanotubes (CNTs) and graphene are also gaining attention due to their exceptional mechanical, thermal, and electrical properties. These nanomaterials can improve the mechanical and physical properties of the joints, such as strength, hardness, wear resistance, and thermal conductivity. However, the dispersion of nanoparticles in the weld and the choice of appropriate nanoparticles are still some of the challenges faced in FSW.

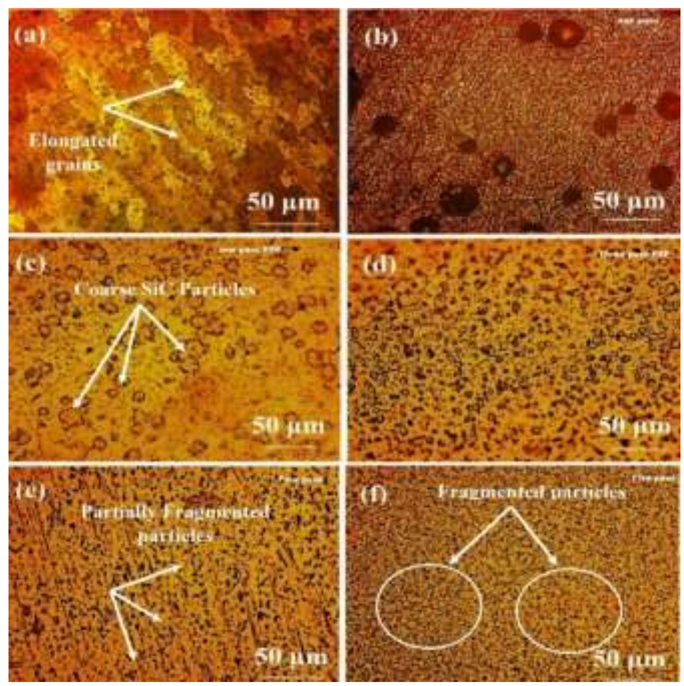

Figure 4: Microstructural variations of AA6082 in different passes [37]

Microstructure analysis across FSP can be done using SEM, an optical microscope, and an X-ray diffraction (XRD) device or machine. Microstructural variations of AA6082 in different passes can be seen in Fig. 4, where elongated and coarse grains of average size 124 micrometres to 128 micrometres were observed. The stirring tool action of one pass FSP due to DRX caused extreme plastic deformation. In the stir zone (SZ) area, AA6082's microstructure underwent significant refinement. Image J programme measured the average grain size, and the observed grain sizes for the first pass, second pass, third pass, fourth pass, and fifth pass were 25.27 µm, 17.43 µm, 12.87 µm, 8.53 µm, and 5.17 µm, respectively [37].

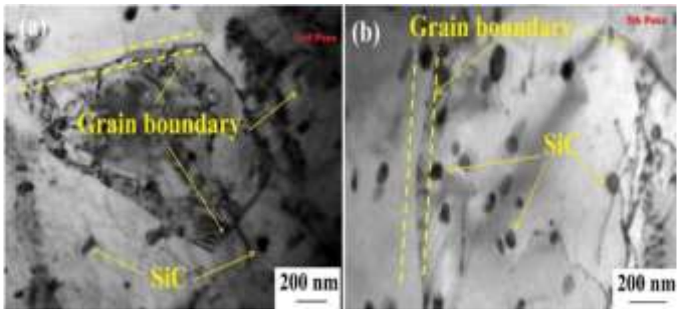

Figure 5: Image depicts refined grains and DRX with several grain boundaries and dislocations [37]

Microstructural analysis is an essential part of understanding the properties and characteristics of materials. In the case of FSP, SEM (Scanning Electron Microscope), optical microscope, and X-ray diffraction (XRD) can be used for microstructure analysis. The microstructural variations of AA6082 in different passes of FSP, where elongated and coarse grains with an average size of 124 micrometres to 128 micrometres were observed. However, in the stir zone (SZ) area, the microstructure of AA6082 underwent significant refinement due to DRX caused by the stirring tool action of one pass FSP. The average grain size for the first pass, second pass, third pass, fourth pass, and fifth pass were 25.27 µm, 17.43 µm, 12.87 µm, 8.53 µm, and 5.17 µm, respectively, as measured by the Image J programme. Fig. 5 depicts the refined grains and DRX with several grain boundaries and dislocations. Such microstructural refinement through FSP can improve the properties of the material, such as increased strength and ductility.

Submerged cooling media such as water, dry ice, and liquid nitrogen can also affect the distribution of reinforcing particles within the aluminum matrix during FSP. While achieving a completely homogenous distribution of nanoparticles is challenging, cryogenic cooling can improve the dispersion by reducing agglomeration and promoting mixing. The formation of an onion ring pattern in the dispersion of nanoparticles is a common occurrence, with the number and size of the rings affecting the final microstructure and crystallographic texture of the joint. The distribution of nanoparticles in the matrix is an important microstructural aspect that can affect the properties of the final product. In FSP, it is challenging to achieve a completely homogeneous distribution of nanoparticles due to the complex material flow patterns and the tendency of the nanoparticles to agglomerate. The formation of an onion ring pattern is commonly observed in the dispersion of nanoparticles shown in Fig. 6, and the number and size of the rings can influence the overall microstructure and texture of the final product. Therefore, it is important to carefully control the processing parameters to optimize the dispersion of nanoparticles and achieve the desired microstructure and properties.

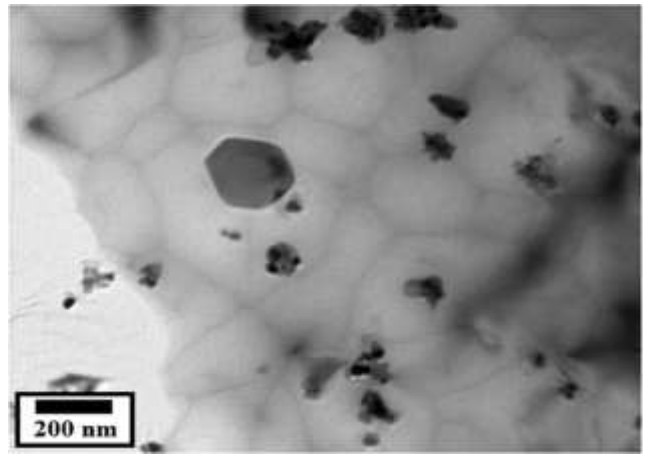

Figure 6: TEM image showing the formation of a nano-scale cellular structure within the aluminum matrix of an Al-Mg/TiO MMC as a result of FSP under cryogenic conditions [78].

In addition to improving mechanical properties, nanoparticle reinforcement can also enhance surface properties such as wear resistance and corrosion resistance. For instance, Singh T et al. [79] reported improved wear resistance in AA6061-T6 joints reinforced with Al2O3 nanoparticles. A reduction in the corrosion rate of AA5083 joints reinforced with TiO2 nanoparticles was observed. It is worth noting that the optimal type and concentration of nanoparticle reinforcement depend on various factors such as the base material, processing parameters, and intended application. Therefore, further research is required to identify the most suitable nanoparticle reinforcements for different materials and applications. Nonetheless, the use of nanoparticle reinforcement in FSW has shown great potential for enhancing the mechanical and surface properties of welded joints.

3.2 Mechanical Properties

The addition of nanoparticles can also have a significant impact on the thermal properties of the weld. For example, the thermal conductivity of AA6082-T6 joints reinforced with SiC nanoparticles was found to be higher than that of joints without reinforcement. Similarly, the inclusion of Al2O3 nanoparticles was shown to enhance the thermal conductivity of the FSW joint in Al-Mg-Si alloys [79]. In summary, the use of nanoparticle reinforcement in FSW can have a significant impact on the microstructure and mechanical properties of the joint. The specific type and dispersion of nanoparticles can influence grain refinement, dislocation density, and subgrain formation. Furthermore, the thermal properties of the joint can also be influenced by nanoparticle reinforcement. While there may be some trade-offs between different mechanical properties, the overall effect of nanoparticle reinforcement is generally positive, leading to improved joint characteristics and surface properties.

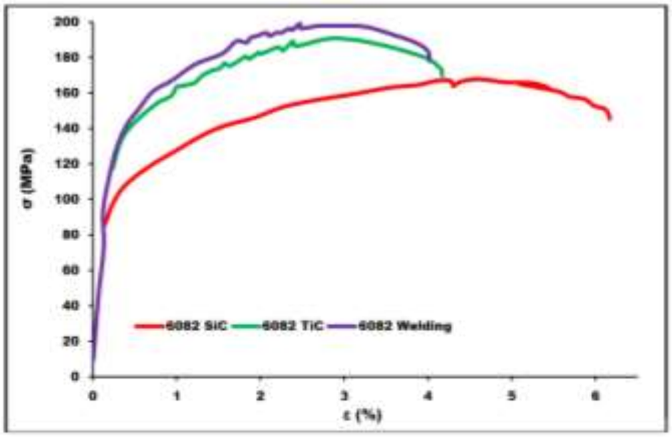

Figure 7: Stress-strain curve for different specimens [80]

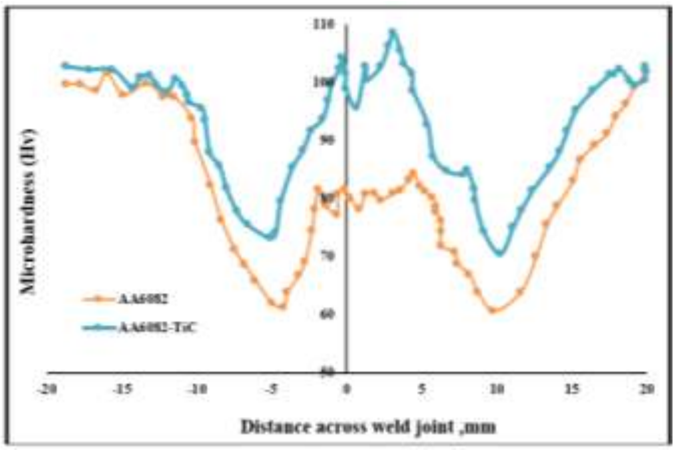

Figure 8: Diagram showing microhardness values of the different specimens [79]

The tool geometry also plays a significant role in FSW joint properties. Several studies have investigated the impact of tool geometry on the microstructure and mechanical properties of joints. The tool pin diameter, shoulder diameter, and pin shape all influence the amount of heat generated during the process and the degree of material mixing in the stir zone [81]. Studies have shown that a smaller pin diameter generates less heat, which leads to finer grain sizes and improved mechanical properties and shown in Fig. 7,8 [81]. A smaller pin diameter also produces a larger shear zone, which leads to increased material mixing and better bonding between the two sides of the joint [82]. The shape of the pin also affects the material flow during the process, with tapered pins providing better mixing than cylindrical pins. The shoulder diameter also plays a role in the joint properties, with larger shoulder diameters resulting in larger heat-affected zones and coarser grain sizes. However, a larger shoulder diameter can provide better support for the workpiece and reduce the likelihood of defects such as tunnel defects revealed in Fig. 9. In conclusion, FSW is a versatile solid-state welding process that can produce high-quality joints in a variety of materials. The process parameters, such as tool geometry, rotational and traverse speeds, and material flow, all influence the microstructure and mechanical properties of the joint. The addition of nanoparticles can further enhance the mechanical properties, but the choice of nanoparticle type can have a significant impact on the final properties.

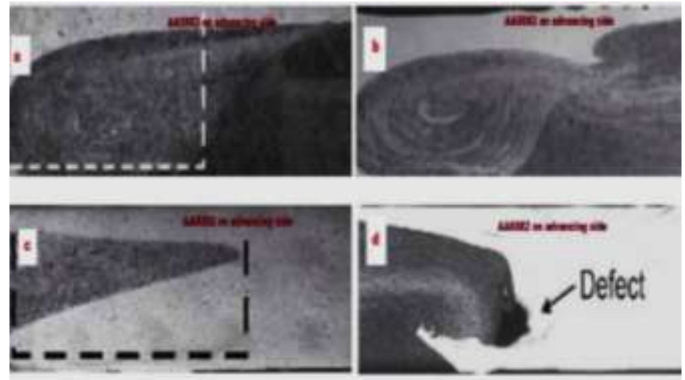

Figure 9: Macroscopic image showing dissimilar welding (AA5083 - AA6082) defects [83]

The inclusion of nanoparticles in dissimilar Al joint FSW processes can lead to agglomeration and defect formations shown in Fig. 10, especially with a single pass and AA5083 on the advancing side. However, with multiple passes and changing the direction of the advancing side, a more uniform weld nugget can be achieved, referred to as possessing an onion-ring structure. The rotational speed and traverse speed also play a role in nanoparticle distribution and agglomeration, as observed in SiC-reinforced dissimilar welding of AA5083 and AA6082. The nanoparticle distribution in the weld nugget can also be affected by the position of the nanoparticles during the welding process. For example, the agglomeration of TiC nanoparticles was found to be more prevalent at the bottom of the stir zone, whereas SiC nanoparticles tended to agglomerate near the top. Overall, careful control of process parameters and nanoparticle distribution is necessary to achieve a high-quality dissimilar Al joint with nanoparticle reinforcement using FSW. On the other hand, the specimen produced at a rotational speed of 1250 RPM had a more homogeneous particle distribution, and the particle agglomeration and porosity were significantly decreased.

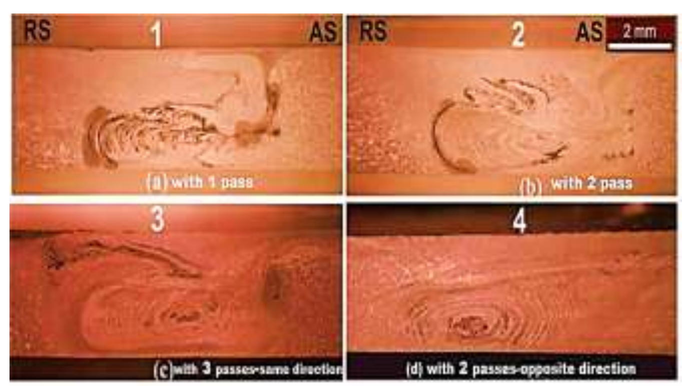

Figure 10: Macroscopic image of weld nuggets with a different number of passes and in different directions [44].

Therefore, the use of a higher rotational speed in conjunction with a multiple-pass approach in the same direction is recommended to achieve improved mixing and dispersion of TiC nanoparticles within the base metal substrate in dissimilar Al weld joints shown in Fig. 10. The onion ring structure is formed due to the shearing forces generated by the tool during the welding process, causing the particles to move radially and axially shown in Fig. 11. The outermost ring consists of highly deformed material, while the innermost ring consists of less deformed material. The onion ring structure has a significant impact on the mechanical properties of the weld, such as improved hardness, tensile strength, and ductility. The SiC nanoparticles also refine the microstructure of the weld, resulting in a smaller grain size and improved distribution of intermetallic compounds. Furthermore, the SiC-reinforced weld exhibits better corrosion resistance than the unreinforced weld due to the uniform dispersion of SiC nanoparticles, which act as a barrier against corrosion.

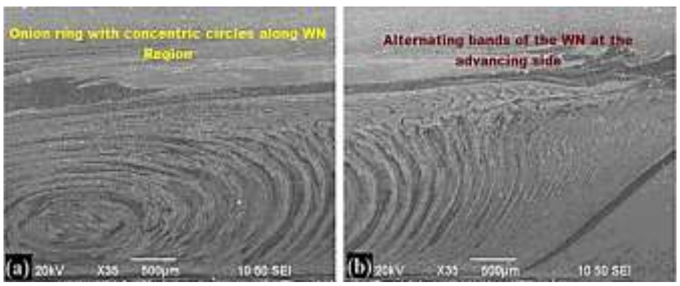

Figure 11: SEM micrographs: (a) concentric circles in the center of WN, (b) alternating bands of the WN at the advancing side [44].

The higher hardness in the weld nugget of SiC-reinforced joints compared to TiC-reinforced joints can be attributed to the strengthening effect of SiC nanoparticles, which act as obstacles to dislocation movement and enhance the overall strength of the material. This increased hardness may also contribute to the reduction in softening along the HAZ of AA6082 shown in Fig. 12, as the harder material may be more resistant to deformation and microstructural changes caused by the heat input during welding. Overall, the type and amount of reinforcement and the processing parameters can have a significant impact on the mechanical properties and microstructural characteristics of dissimilar aluminum welds. It is interesting to note that the addition of magnesium and chromium as filler materials during the welding process led to improved corrosion resistance properties in AA5052 and AA6082. The use of Response Surface Methodology allowed for the optimization of process parameters to achieve minimum corrosion rates. The same RSM technique also resulted in a maximum weld nugget hardness of 93HV, which is quite high. However, it was observed that the refined grains produced during the welding process led to severe permanent deformation in the weld nugget zone. These findings suggest that a trade-off between weld strength and ductility may need to be considered when selecting process parameters for dissimilar aluminum welding.

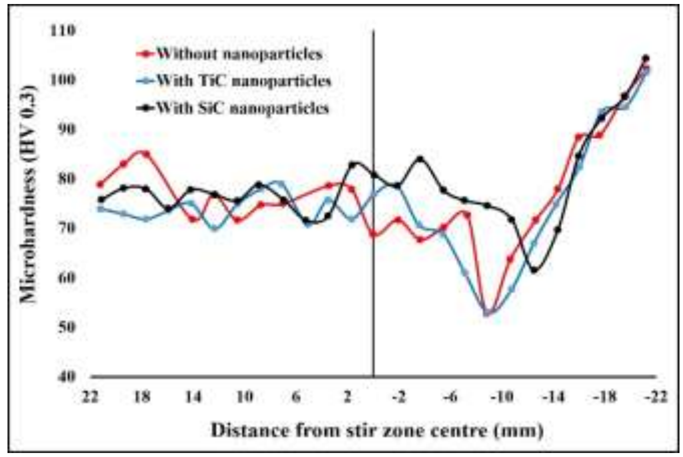

Figure 12: Microhardness distribution of dissimilar Al joint [83]

4. Conclusions

It has been reported that nanoparticles such as SiC, TiC, and Al2O3 can effectively reinforce FSW joints and improve their mechanical properties. The addition of nanoparticles can lead to an increase in hardness, strength, and wear resistance of the joint. However, the degree of improvement is highly dependent on several factors such as the type, size, and distribution of nanoparticles, welding parameters, and the matrix alloy composition. In addition to FSW, the use of nanoparticle reinforcement in FSP has also been explored. FSP is a solid-state joining technique that involves the use of a rotating tool to create frictional heat and plastic deformation in the material. Similar to FSW, the addition of nanoparticles in FSP can lead to an improvement in mechanical properties and microstructural characteristics. Cryogenic cooling has also been found to be effective in further refining the grain structure and improving the properties of the joint. Overall, the research on nanoparticle reinforcement in FSW/FSP is still in its early stages, and more studies are needed to fully understand the potential and limitations of this technique.

For SiC and TiC carbide nanoparticles, uniform distribution is important, while TiO2 nanoparticles require more passes and modest traverse and rotation speeds. Both reinforced and non-reinforced joints showed base metal intermetallic composites, but fresh precipitation and grain size formations were influenced by nanoparticle reinforcement. Both reinforced and non-reinforced joints had the same intermetallic composites, but reinforced joints had smaller grain sizes. Grain size formation was influenced by the amount of nanoparticle reinforcement. Nanoparticle dispersion was affected by the rotational speed of the tool, directional changes, and number of passes.

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