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REVIEW ARTICLE

A critical review on recent trends in friction stir welding and processing of aluminum metal matrix composite and aluminum

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Abstract

Friction stir welding (FSW) is a solid-state welding technique that has gained considerable attention in recent years as a promising alternative to traditional welding methods for joining aluminium alloys. One of the main advantages of FSW is that it prevents solidification defects that often occur during fusion welding due to the avoidance of high temperatures. This technique involves the use of a rotating tool that is inserted into the material to be welded, generating frictional heat that softens and stirs the material, which is then consolidated under pressure. To optimize the FSW process, it is necessary to understand the microstructural evolution of the material during welding. In recent years, considerable research has been conducted to develop models to predict microstructural evolution during FSW. This research has focused on the analysis of precipitate evolutions and grain recrystallization mechanisms. One of the most important aspects of microstructural evolution during FSW is the precipitation of alloying elements in the material. Models of precipitate size distribution have been developed to follow the precipitation process in multicomponent alloys and multiphase systems. These models have demonstrated their relevance to accurately predict the microstructural evolution of aluminium alloys during FSW.

1. Introduction

FSW has indeed become a technique of choice in the joining of aluminum components since its discovery in 1991. The high mechanical properties and large fatigue performances of the welds produced by this process have been demonstrated in several studies. Fine grains and a restricted heat affected zone are often observed, leading to limited crack development [1]. The tensile and yield strength of the joined materials are typically close to the base material properties, and the process also results in lower levels of residual stresses compared to fusion welding. One of the major advantages of FSW is its ability to produce a homogenous joint, which overcomes the drawbacks of traditional bolting or riveting techniques, such as heterogeneous junctions, mass contribution by added metal, and stress concentration close to the holes, which decreases fatigue resistance [2, 3]. This makes FSW a particularly promising process for light weighting aeronautical structures, reducing manufacturing costs, and increasing the fuel efficiency of aircraft. The use of FSW in industries is a major economic and technical challenge for various sectors, including the aircraft, shipbuilding, and automotive industries, where the first applications have recently emerged. FSW has the potential to revolutionize the manufacturing of various components, leading to weight savings and reduced costs. In conclusion, FSW is a highly promising technique for joining

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aluminum components, and its advantages are particularly attractive for various industrial applications. Its potential to revolutionize manufacturing processes in various sectors makes it a major area of research for the future [4-6].
Furthermore, FSW has been shown to improve the corrosion resistance of Al MMCs compared to traditional fusion welding methods [7]. The improved corrosion resistance is attributed to the fine microstructure and reduced HAZ width achieved by FSW. Additionally, FSW has been used to join dissimilar materials, such as aluminum to magnesium alloys, with successful results [8]. This ability to join dissimilar materials expands the range of possible applications for FSW. However, despite its many advantages, FSW still has some limitations, such as difficulties in welding high-strength aluminum alloys and the need for precise control of process parameters to achieve optimal weld quality [9, 10]. These limitations highlight the need for continued research and development in the field of FSW to improve its performance and expand its applications in industry.

2. Conventional FSW/FSP

Some of the factors that can affect the quality of FSW include the rotational speed and traverse rate of the tooltip, the geometry of the tooltip, the clamping force applied to the workpieces, and the properties of the materials being joined. In addition, the FSW process can lead to residual stresses in the joint, which can affect its long-term durability. To address this, post-weld heat treatment can be used to relieve the residual stresses and improve the mechanical properties of the joint [11, 12]. Overall, FSW is a promising solid-state welding technique for joining AMMCs, but careful control of the process parameters is needed to ensure high-quality joints with optimal mechanical properties. FSW has been widely adopted in various industries, including shipbuilding, railways, automotive, and aerospace. It has been shown to produce stronger and more ductile welds compared to traditional welding methods such as MIG and TIG [13-18]. 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 [19, 20]. 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 [21-24], 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 [25-29]. 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 [30-34]. When joining dissimilar metals and alloys, special attention must be paid to the control and dispersion of intermetallic compounds (IMCs). 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 [35-39]. 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. 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 [40-42]. Further research is needed to fully understand the relationship between processing parameters, microstructure, and properties]. 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].
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 [44]. 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].

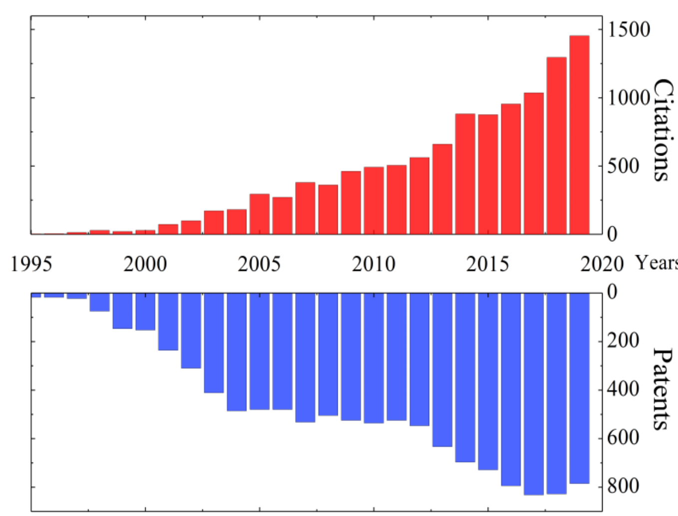

Figure 1: Worldwide patent and article citation related to FSW/FSP

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 [46-49]. The material does not fully melt during FSW, which makes it a solid-state joining process. This leads to several advantages over fusion welding techniques, such as the absence of solidification and cooling stresses, and the ability to join dissimilar materials without the formation of intermetallic compounds at the joint interface. The material flow during FSW also leads to the refinement of the microstructure and the enhancement of mechanical properties in the welded region [50]. It is clear that Friction Stir Welding is a rapidly growing field of interest for both industrial and scientific communities. The significant increase in patent filings and scientific publications over the last decade demonstrates the potential of this technique for joining materials as shown in fig. 1. As further research and development continues, it is likely that even more applications and industries will adopt Friction Stir Welding as a reliable and efficient joining method.

2.1 Material flow during FSW/FSP

The performance of the joint and the material flow depend on the welding conditions and the temperature of the stir zone. The heat dissipation is affected by several factors such as material thickness, welding speed, and ambient temperature. If the heat input is too high, it can lead to slipping conditions, resulting in defects in the joint. The feasibility of welding dissimilar materials of 1 mm-thick sheets using UFSW and CFSW was studied and they analyzed the effect of welding tool rotational speeds and plunging depth on the strength and weld quality of the joint. The study found that less heat inhibited the formation of thick intermetallic compounds. Submerged friction-stir welding (SFSW) has improved the strength and quality of welds, some studies have reported void formation due to material flow [51]. A few investigators have focused on recycled AMMCs. The feasibility of different types of FSW techniques, including traditional in-air SFSW, underwater friction-stir welding (UFSW), and vibrational friction-stir welding (VFSW), is discussed. The effect of these techniques on the thermal distribution and microstructure of welded aluminum alloys is also examined. Gaps in the literature are identified, and recommendations for future work are made. In this review, the focus is primarily on AMMCs.

2.2 Microstructure analysis of FSW/FSP of aluminum alloys

The SZ is characterized by a highly deformed and recrystallized material, which results in a refined and equiaxed grain structure with a unique texture compared to the base material. The material in the SZ experiences high deformation and shear strain rates, which lead to the formation of dynamically recrystallized fine-grained microstructures. The HAZ adjacent to the SZ is a region where the material experiences moderate deformation and temperature rise, and its microstructure is characterized by coarse grains with a high degree of stored energy due to incomplete recrystallization. The TMAZ is the region farthest from the SZ, where the material is minimally affected by the thermomechanical cycles of FSW, and its microstructure is similar to that of the base material. The formation and evolution of these microstructural zones during FSW play a critical role in determining the overall mechanical properties of the joint. For example, the fine-grained microstructure and texture of the SZ contribute to the high joint strength and ductility of FSW joints. On the other hand, the presence of coarse grains and high stored energy in the HAZ can lead to reduced toughness and fatigue life of the joint. Therefore, understanding the thermomechanical cycles and microstructural evolution in each FSW zone is essential for optimizing the process parameters and achieving desirable joint properties. The HAZ adjacent to the NZ experiences temperatures below the melting point, but still high enough to cause significant microstructural changes. The HAZ can be further divided into the TMAZ and the partially transformed zone (PTZ). The TMAZ is characterized by a microstructure that has undergone severe plastic deformation and recrystallization, while the PTZ is characterized by the presence of partially transformed or transformed phases [52]. The width of the HAZ is influenced by the welding parameters and the thermal conductivity of the material. Generally, the higher the thermal conductivity, the narrower the HAZ [53]. The unaffected zone (UZ), also called the base metal, is not directly affected by the welding process and retains its original microstructure and properties. Overall, the FSW process results in a microstructural gradient across the joint, with the NZ having the finest grain size and the highest hardness, and the UZ having the coarsest grain size and the lowest hardness. The HAZ is the region of the material that does not experience significant deformation during FSW, but instead undergoes only a thermal cycle with lower peak temperatures than the NZ and TMAZ. In this region, the microstructure may be altered due to the thermal cycle, leading to changes in the mechanical properties of the material. The microstructural changes in the NZ and TMAZ are mainly due to the dynamic recovery (DRV) and dynamic recrystallization (DRX) phenomena induced by the thermomechanical stirring during FSW. These processes can lead to a refined, equiaxed grain structure in the NZ and TMAZ, which can enhance the strength and ductility of the welded joint. It is worth noting that the microstructural zones and their corresponding properties have a significant impact on the overall mechanical behavior and performance of FSW joints. For instance, the NZ is typically the strongest and most ductile zone due to the refinement of the microstructure, while the TMAZ and HAZ are weaker and more prone to failure due to their coarser microstructures and potential defects introduced during welding. Thus, understanding and controlling the microstructural evolution during FSW is essential for optimizing joint quality and performance.

DRX and DRV are both important thermomechanical deformation mechanisms that occur during FSW, and they have a significant influence on the resulting microstructure of the joint. DRV occurs in high SFE metallic materials like aluminum, where dislocation rearrangement leads to the formation of equiaxed subgrains with low-angle boundaries. On the other hand, DRX occurs in medium to low SFE metallic materials, where new, dislocation-free grains form at various sites in the deformation microstructure. The resulting microstructure is characterized by almost all grain boundaries with an irrelevant presence of tangled dislocations inside, which marks the distinctive difference between the NZ and the adjacent TMAZ. Both DRV and DRX occur as the deformation temperatures exceed 0.3TM, which is typically the case in the TMAZ and NZ of FSW light-alloy joints. It is important to consider the initial metallurgical conditions of the material and the processing and tool parameters when studying and characterizing the different FSW zones. The transients and steep gradients generated by the passage of the pin during FSW should also be taken into account. To optimize both microstructural modifications and mechanical responses of light-alloy welds, two new techniques based on FSW technology are presented in the paper. The first technique is a double-side FSW (DS-FSW) applied to an age-hardened AA6082 alloy, while the second technique involves a slight deviation from the pin transverse welding line during FSW applied to aluminum alloy plates. The role of the material metallurgical status prior to and after FSW is addressed, and the discussion accounts for the improved results from both a microstructural and mechanical viewpoint.

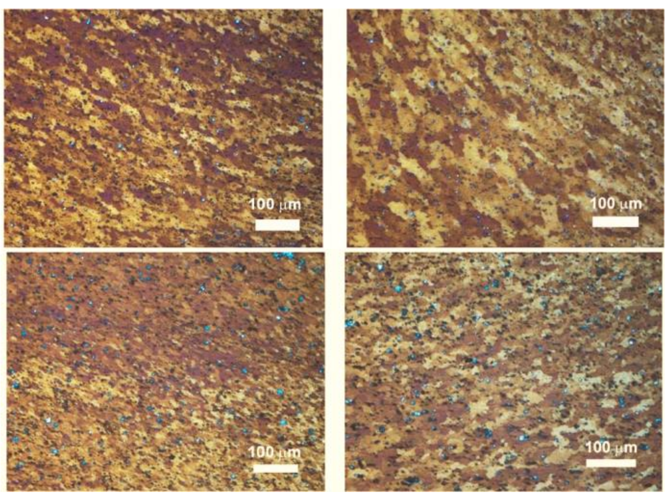

Figure 2: Optical images of friction stir welded joint of AA6082 [54]

The DS-FSW technique has a more uniform microstructure throughout the stirred zone shown in Fig. 2, which is important for achieving better mechanical properties. The coarser recrystallized grains near the top surface of conventional FSW joints may be a result of the temperature gradient across the thickness of the plate during welding, which leads to a difference in grain size between the top and bottom surfaces. The DS-FSW technique overcomes this issue by allowing for a more balanced heat input and better distribution of the recrystallized grains. These results highlight the potential of DS-FSW as a promising technique for improving the mechanical properties of welded joints in light alloys. This indicates that the DS-FSW technique results in a more uniform and consistent microstructure and mechanical properties throughout the joint, while conventional FSW can lead to more localized variations due to the presence of intermetallic particles and different grain structures. The reduced hardness and elastic modulus in the retreating TMAZ in conventional FSW can also negatively impact the overall strength and durability of the joint. Therefore, the DS-FSW technique appears to offer improved performance and reliability for light-alloy welds [54].

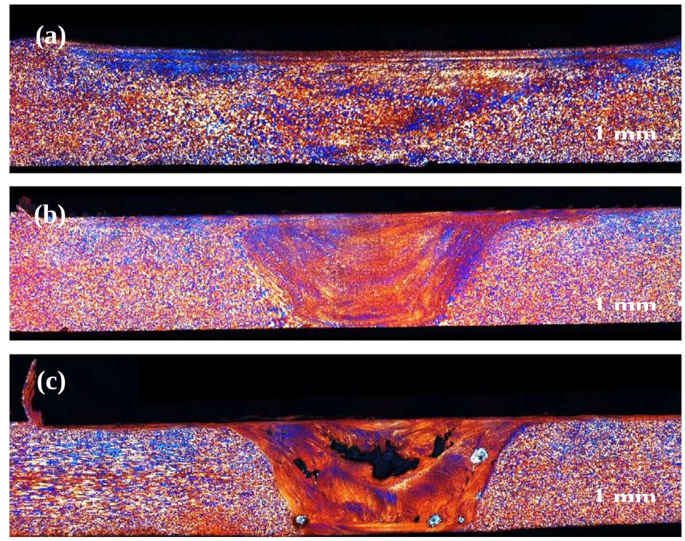

Figure 3: OM image of FSWed joint of AA5754 at (a) R = 0 mm, (b) R = 0.5 mm and (c) R = 1 mm [54].

The microstructure shows a smaller grain size in the NZ with respect to the base material and a more homogeneous distribution of the recrystallized grains (Fig. 3b). On the other hand, for R = 1 mm, a lack of continuity in the stirring zone and the presence of voids and defects are observed (Fig. 3c). The decrease in mechanical properties for R > 0 mm is related to the increased defects and inhomogeneity in the microstructure of the welded joint. However, as the R value increases, the presence of voids and lack of bonding between the tool and material become more evident, resulting in lower UTS and UE values. This can be attributed to the fact that higher R values lead to a decrease in heat input and plastic deformation, resulting in insufficient material flow and inadequate stirring of the SZ. As a result, the microstructure in the SZ is characterized by a more heterogeneous and coarser grain structure, with unrecrystallized regions and lack of deformation, which affects the mechanical properties of the joint (Fig. 3b, c). Therefore, it is important to optimize the R value in order to obtain a sound weld with desirable mechanical properties.

The model predicts the occurrence of dynamic recrystallization when strain and temperature reach critical values simultaneously [55]. The volume fraction of dynamically recrystallized grains increases with increasing strain and temperature due to the chosen process parameters. Fig. 4 shows the computed recrystallized grain size for different tool rotational velocities, and the authors report a good agreement between their simulations and experimental results in the stir zone, where refined equiaxed grains with a size of around 2.5 µm were observed. The authors also show that decreasing the tool rotation speed leads to a reduction in the final recrystallized grain size. The authors report a good agreement between their simulations and experimental measurements in the stir zone. However, they do not provide a detailed description of the measurement procedure used in their study.

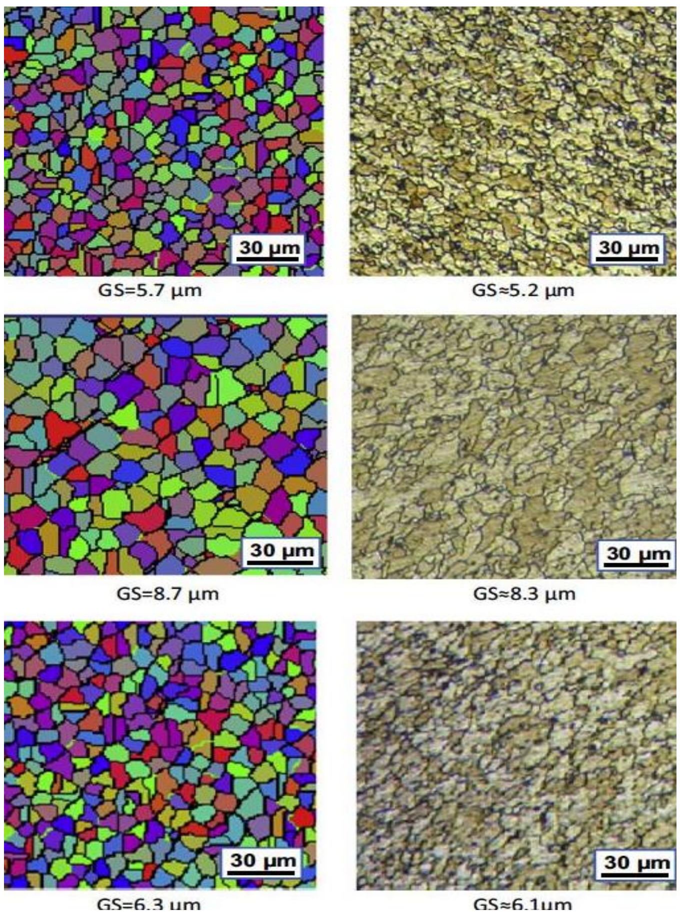

Figure 4: Experimental microstructure of SZ for TRS, TS and shoulder diameter at 900 rpm, 120 mm/min and 16 mm [56]

The increasing the rotational speed and decreasing the travel speed resulted in smaller grain sizes, improved mechanical properties, and reduced defects in the weld [57]. They also observed that UFSW caused a slight reduction in the hardness of the base metal, but this reduction was less than that caused by conventional welding methods. The authors concluded that UFSW was a promising method for welding marine-grade aluminum alloys and could provide improved mechanical properties and reduced defects compared to conventional welding methods shown in fig. 5. Additionally, the microstructure and mechanical properties of 6061 and AA7075 aluminum alloy joints welded by FSW was investigated [58] and found that the FSW joint exhibited a smaller heat-affected zone and finer grains compared to the FSW joint. The UFSW joint also displayed higher ultimate tensile strength and elongation, as well as improved fatigue performance. The effect of tool pin length on the microstructure and mechanical properties of 2219-T6 aluminum alloy welded by FSW. Their results showed that increasing the tool pin length could improve the mechanical properties of the joint, such as ultimate tensile strength and elongation. Moreover, the joint with a longer pin length had a finer and more uniform microstructure compared to the joint with a shorter pin length.

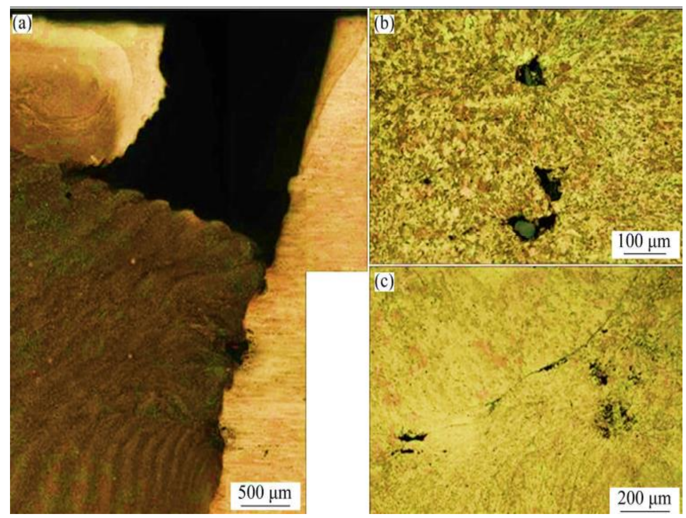

Figure 5: Welding defects formed under different process parameters: (a) 800 r/min, 200 mm/min; (b) 1000 r/min, 300 mm/min; (c) 1400 r/min, 100 mm/min [57]

An increase in tool rotation speed led to a decrease in grain size in the stir zone. However, beyond a certain rotation speed, there was a slight increase in grain size due to the decrease in heat input caused by the reduced contact time between the tool and the material. Another study conducted by HUANG et al [59] investigated the effect of rotational and traverse speeds on the microstructure and mechanical properties of FSW joints in 6061-T6 aluminum alloy. The results indicated that a higher traverse speed led to a decrease in grain size, while a higher rotational speed resulted in a larger grain size. Additionally, increasing both the traverse and rotational speeds led to a refined microstructure with high strength and ductility. These studies demonstrate the importance of optimizing tool parameters to control grain size and ensure desirable mechanical properties in FSW joints.

The increase in rotating speed causes more severe plastic deformation and dynamic recrystallization, resulting in a greater degree of grain refinement and a decrease in average grain size. The microstructure evolution during FSW is complex and involves multiple mechanisms, but in general, the combination of plastic deformation, frictional heating, and strain-induced grain refinement leads to the formation of equiaxed grains in the SZ shown in fig. 6 [60].

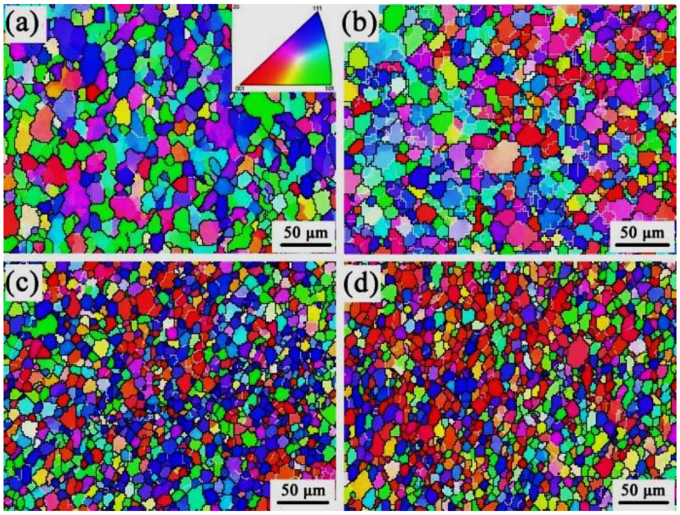

Figure 6: EBSD image at SZ obtained at different TRS (a) 600 rpm, (b) 800 rpm, (c) 1000 rpm and (d) 1200 rpm [60].

2.3 Mechanical properties of FSW/FSP

The effect of reinforcement particles can influence the microstructure and mechanical properties of the joint by promoting grain refinement and subgrain formation, as well as affecting dislocation density. Additionally, nanoparticle reinforcement can also have a positive impact on the thermal properties of the weld, such as enhancing its thermal conductivity. However, it is important to note that the specific type and dispersion of nanoparticles can affect these properties, and there may be some trade-offs between different mechanical properties. Overall, nanoparticle reinforcement has shown promise in improving joint characteristics and surface properties in FSW.

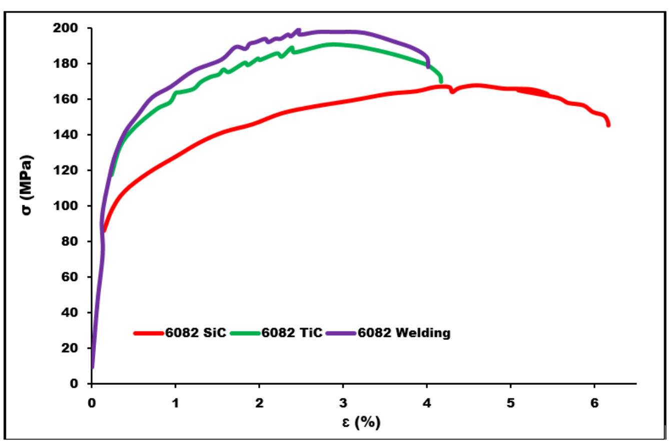

Figure 7: Stress-strain curve for different specimens [61]

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. 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 [61, 62]. 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 [63].

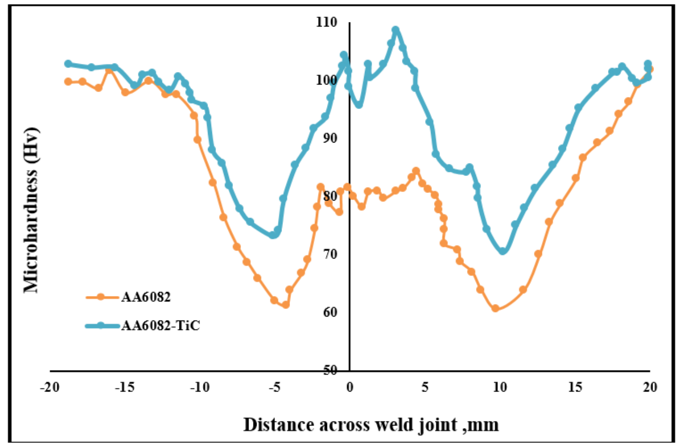

Figure 8: Diagram showing microhardness values of the different specimens [62]

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 [63]. However, a larger shoulder diameter can provide better support for the workpiece and reduce the likelihood of defects such as tunnel defects. So, 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.

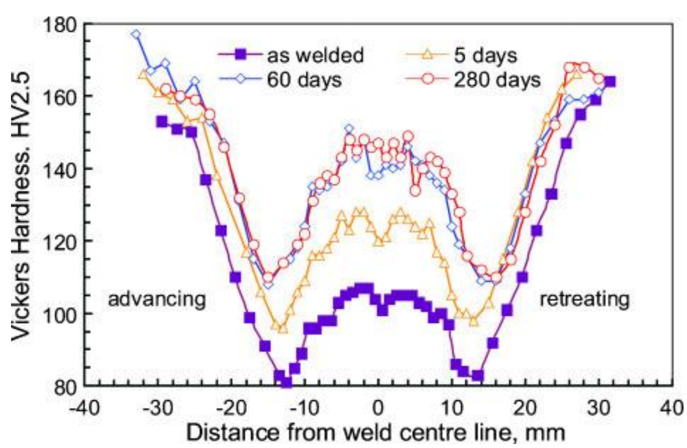

Figure 9: Microhardness variation revealing natural aging in 6 mm 7075–T6 alloy [64]

The effect of post-weld natural aging on a 7075-T6 weld was observed and softening occurs in the HAZ, with a rapid drop in hardness as the TMAZ is approached shown in Fig. 9. The nugget shows the greatest recovery in strength. Precipitate coarsening is found to be dominant in the HAZ, while dissolution is dominant in the nugget, followed by natural aging. The passage also mentions that for naturally aged tempers (T3/T4), coarsening may cause a strength increase in the HAZ. It is important to note that precipitate evolution is not limited to the bulk of the grains and may have implications for ductility, toughness, fatigue, or corrosion resistance [64].

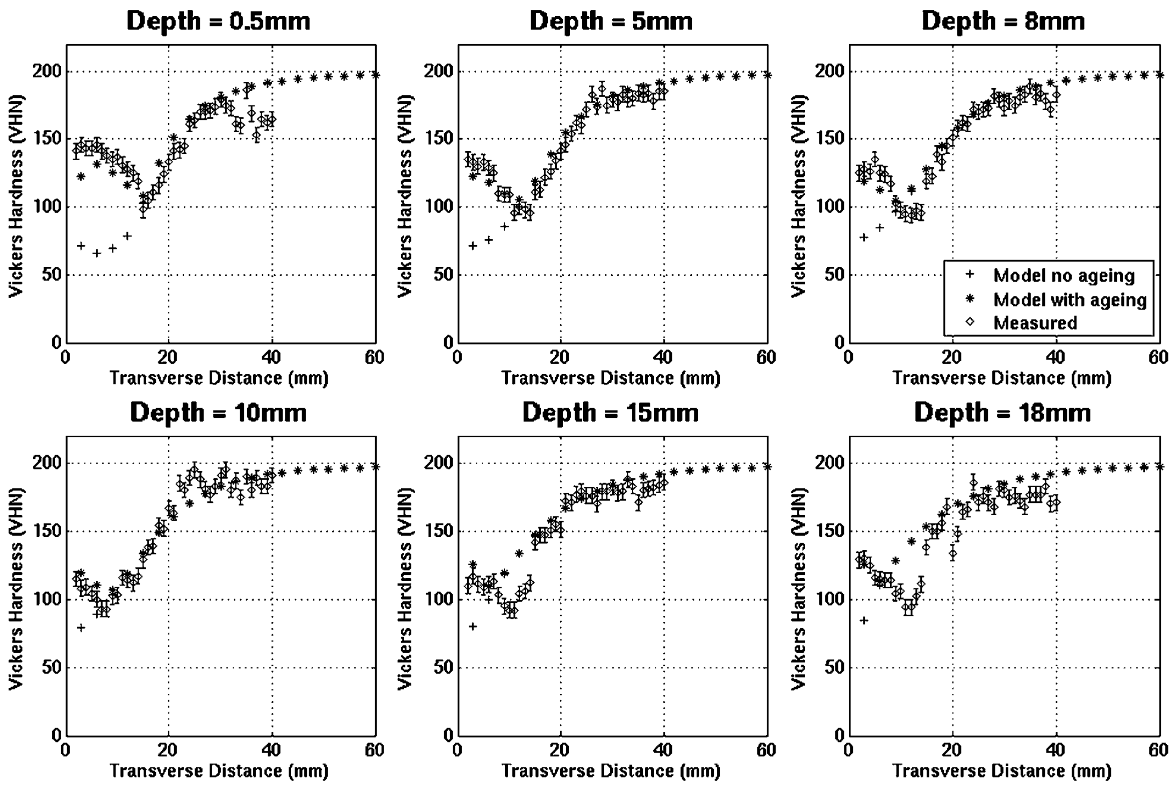

Figure 10: Semi-empirical model predictions and measured hardness profiles in 20 mm thick friction stir weld in 7449–TAF, at six different depths through thickness [65]

Fig. 10 illustrates the predicted and measured hardness profiles for a heat-treatable aluminum alloy, including the predicted curves immediately after welding and after natural aging. The graph shows that the measured hardness profiles match well with the predicted curves, indicating that the model used to predict the precipitation behavior of the alloy is accurate. The predicted curve for the natural aging process shows a significant increase in hardness, demonstrating the effectiveness of natural aging in improving the strength of heat-treatable aluminum alloys. Overall, this Figure emphasizes the importance of understanding the precipitation behavior of heat-treatable aluminum alloys and the impact of post-weld treatments on their properties [65].

3. Conclusions

The study discussed two different improvements to the FSW technique, which were found to significantly enhance the mechanical properties of the welded sheets compared to conventional FSW methods. The first improvement involved double side welding, which was applied to an age-hardenable AA6082 alloy and successfully improved its mechanical response. The second improvement involved a small lateral deviation from the centerline transverse motion of the rotating pin during welding, which was applied to a widely used, non-age-hardenable AA5754 sheet. Both improvements were studied by subjecting the welding sheets to different heat treatments, and the resulting improvements in mechanical response and microstructural modifications across the welded zones were analyzed. Specifically, the TMAZ and HAZ were examined to determine the benefits of using these two new FSW approaches. The friction stir welding (FSW) technique has emerged as an advanced and promising method for joining similar and dissimilar metals and alloys in various engineering and manufacturing fields, such as oil and gas pipelines, automotive and aviation industries. The latest new approaches and methods have widened the potential of FSW to include new metal processing applications, wider light alloy candidates, and new metallurgical production techniques, such as additive manufacturing (AM). The two new FSW approaches presented in this study demonstrated a clear mechanical improvement of FSW joints in aluminum alloy sheets, both age-hardening and non-age-hardening. These new approaches and methods make FSW one of the most prominent and promising welding techniques, promoting new technology frontiers in the making and repairing processing of light metal sheets and plates. Recent metallurgical developments, such as AM, have shown the applicability of FSW to complex parts and components, promoting the adoption of this technique to a manufacturing scale. The combination of friction stir processing (FSP) with other derived friction non-melting strengthening methods can be considered as a direct evolution step of FSW, able to scale up all the possible application fields of this non-fusion metal attrition technique.

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