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Efficacy of Friction Stir Welded Joints Under Fatigue Loading: A Critical Review

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Abstract:- The current research primarily reviews the efficacy of FSW joints under fatigue loading conditions. The review starts with elaborating the working principle of FSW process along with its advantages and applications in the industry. The impact of the FSW process on the mechanical properties of the materials being joined is discussed. The possible enhancement of mechanical properties by particles inclusion during FSW is also elaborated. It is observed from literature that the inclusion of copper nano particles, Al_2O_3 particles and SiC microparticles proved to be effective in improving the mechanical properties of FSW joints.

The performance of FSW joints under fatigue loading is reviewed in detail. Several researchers investigated the influence of process variables on the fatigue performance of different materials joined using FSW. High-quality FSW steel joints surpassed high-quality arc welds, with fatigue strength increasing with material yield strength. It is observed from literature that fatigue response of FSW joints not only depends on the process parameters but also on external factors like stress ratio, residual stress, defects, weld orientation side etc. It is also worth noting that, inducing compressive stresses in the FSW joints can increase their fatigue life. Post-weld treatments can decrease fatigue crack growth rate and enhance material fatigue life in FSW joints. Laser peening was observed to be effective in reducing growth rates of fatigue cracks and improving the overall fatigue life of FSW joints. FSW joints exhibited a fatigue strength approximately 20% higher than the GMAW joints, and at high stress amplitudes, the FSW joints had a lifespan about three times higher than that of the GMAW joints. There appears to be an opportunity to improve the fatigue response of FSW joints further by suitable nano-particles inclusion during the welding process.

The current review enabled the researchers to identify a research gap in the area of notch fatigue analysis of FSW joints. This needs to be explored further by creating notches of different geometries on the FSW joints and quantifying the impact of notch geometry (depth, width, perimeter length etc. of notch) on their fatigue performance. It is also observed that, literature in the area of evaluating the fatigue performance of FSW joints at different temperatures is scarce. This area can also be further explored.

Keywords*: Friction Stir Welding, mechanical properties, fatigue, particles inclusion, post-weld treatment, residual stress.*

ABBREVIATIONS

FSW	: Friction Stir Welding
HAZ	: Heat Affected Zone
SZ	: Stir Zone
WNZ	: Weld Nugget Zone
TMAZ	: Thermo-mechanically Affected Zone
FEA	: Finite Element Analysis
CCD	: Central Composite Design
RSM	: Response Surface Methodology
LCF	: Low Cycle Fatigue
UTS	: Ultimate Tensile Strength

FSSW	: Friction Stir Spot Welding
ENS	: Effective Notch Stress
IIW	: International Institute of Welding
GMAW	: Gas Metal Arc Welding
DIC	: Digital Image Correlation

1.0. Introduction

FSW was conceived by TWI Ltd of the United Kingdom. It is an innovative method for joining similar/ dissimilar metals or alloys. During FSW operation, a tool which is cylindrical in shape and having a probe is revolved and gradually pushed between two metal plates so that they join. The plates are fastened to avert them from being pushed away while welding. During the operation, large amount of frictional heat is produced between the tool and the plates to be welded. This heat softens (melts) the material of the plates, and permits navigation of the tool through the joint line. The plasticized plate material is moved from one edge of the probe to the other edge and is joined by the adjacent contact of the tool shoulder to yield a weld amid the two metal plates [1].

Friction stir welding is a distinct method among the "deformation-based" solid-state procedures due to the way the material moves and combines to form the joint. When executed correctly, it yields remarkable qualities, which has been the primary driver of its successful application in a multitude of aerospace, automotive, and shipbuilding applications. The schematic layout of the FSW process is presented in Figure 1 [2].

FSW process offers several potential advantages for welding high-strength Aluminium alloys. It does not produce harmful emissions or fumes associated with traditional welding processes, making it environmentally friendly. FSW utilizes localized thermo-mechanical joining, resulting in lower heat input compared to traditional welding methods and this can lead to better mechanical properties in Aluminium alloys. FSW process minimizes defects in welds, which can help maintain or improve the properties of the joining alloys. FSW does not require consumable materials and this makes it cost-efficient and a competent method. These advantages make FSW a promising method for welding high-strength Aluminium alloys, particularly in aerospace industries [3].

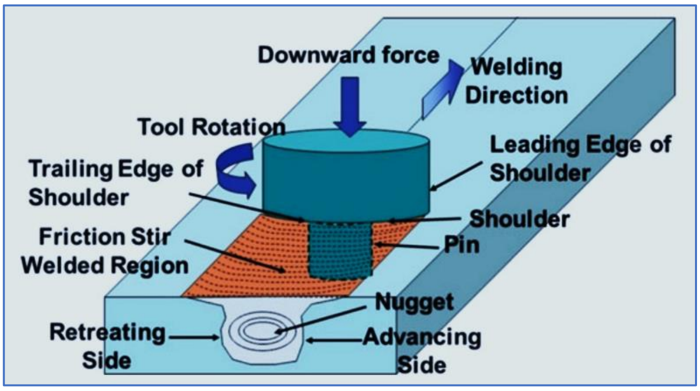

Figure 1: Friction Stir Welding Process

2.0. Impact Of Fsw On Mechanical Properties

R. Ranjan et. al. explored the force control methods in FSW to attain welds of superior quality. The study highlighted the significance of managing "axial force", "travel force", and "torque" throughout the FSW procedure. Researchers have devised feedback control systems to oversee these forces, taking into account factors such as speed of travel, rotational speed of the tool, and tilting angle. It was proved that, by ensuring proper interaction between the tool and workpiece, potential welding defects like "surface voids" and "wormholes" can be mitigated. Experimental verification of these force control strategies had demonstrated promising outcomes in enhancing weld quality and uniformity. Furthermore, the study highlighted the importance of friction-induced heat and its implications on the joining process [4].

Amir Ghiasvand et. al. explored how offsets of tool and pin along with the position of plates impact the heat generated while FSW of AA6061 and AA5086 alloys. CCD and RSM were employed to assess the key variables and their interactions influencing the maximum temperature. Through numerical simulations incorporating diverse input variables and output responses, the study underscored the importance of accurate tool and workpiece modelling, consideration of contact interactions, appropriate mesh size selection, and validation procedures for the numerical model. Furthermore, analysis of variance and regression were undertaken to analyze the effects of plates position and offset of the pin on the maximum temperature in FSW [5].

J. Torzewski et. al. examined the effect of weld parameters on micro-hardness and UTS of AA5083 H111 joined by FSW. The microhardness was measured at various positions on the weld cross-section, and the results showed that there was superior micro-hardness in the SZ than the base material. The micro-hardness values varied marginally in case of the base material and the HAZ, but the SZ exhibited a positive effect of grain refinement on the strength properties of the alloy. Additionally, tensile tests indicated that the failures of specimens occurred outside the joint area in the HAZ, confirming the high strength properties of the FSW joints. The study also evaluated the LCF behaviour of the alloy, and the results indicated cyclic hardening during the LCF process. The findings suggest that weld parameters have a substantial impact on the micro-hardness, tensile, and fatigue properties of FSW AA5083 H111 Aluminium alloy [6].

P. Manikandan et. al. investigated the mechanical properties of FSW joints of AA2219-T87 at different temperatures. The study focused on understanding the tensile and fracture behaviours at room temperature, 77 ºK, and 20 ºK, and how these properties correlate with the microstructures formed during welding. Tensile strength at cryogenic temperatures (77 ºK and 20 ºK) were found to be higher than those at room temperature for the FSW joints. Coupons from the WNZ and TMAZ displayed alike strength properties, but hardness and ductility reduced in TMAZ. The fracture toughness was evaluated at different microstructural regions and higher fracture toughness was observed in WNZ owing to the existence of fine grains. Lower fracture toughness was noted in TMAZ due to combined factors such as strain hardening. The standard full-length tensile specimens failed predominantly in the TMAZ, which had lower hardness and ductility, leading to strain hardening and subsequent failure [7].

Sindhuja et. al. discussed the variations in mechanical and fracture toughness properties of FSW joints of AZ61 magnesium alloy due to changes in heat input. Welding process and its effects on the material's properties were explored, particularly the ultimate tensile strength, grain orientation, and fracture locations. The results showed that the UTS of welds at $\omega/\gamma = 3$ was almost 100% of that of the base material. Here ω is the rotational speed of welding in rpm and γ is the welding speed in mm/min. Fractures cropped up at the points between the advancing side of the TMAZ and the SZ in all cases. The research also discussed the influence of various welding conditions on properties like joint efficiency, UTS, yield strength etc. Additionally, it delves into the microstructural analysis, including the hardness along in the cross-section of the FSW region and the fracture location. The findings contribute to the appreciation of the relation between welding conditions, microstructure, and properties, offering valuable implications for the development of lightweight transportation vehicles and the application of magnesium alloys in structural purposes [8].

Sun et. al. examined the impact of FSW parameters on the strength and microstructure of dissimilar welded Aluminium plates. The research focused on the multi-criteria optimization of FSW for Aluminium composite using a titanium nitride-coated tool. The study examined the effect of “rotational speed of the tool” upon the elongation and the micro-structure of the HAZ. It also delves into the development of mathematical models using Design Expert software and the characterization of the microstructure of the welded samples. The study emphasized the importance of optimizing weld parameters to achieve superior weld joint strength and microstructural characteristics, offering valuable insights for the automotive and aerospace industries [9].

3.0. Mechanical Properties Enhancement By Particles Inclusion During Fsw

The usage of copper nanoparticles in improving the properties of dissimilar FSW alloys (AA5052 and AA6063) was investigated by Barsoum et. al. By employing the Taguchi technique for process optimization, the study identified enhanced tensile strength and microhardness as key outcomes of nanoparticle incorporation. Microstructural analysis demonstrated a homogeneous metal blend and finer grain structure attributed to heightened frictional heat. Additionally, EDX analysis validated the presence of nanoparticles within the SZ, underscoring the potential advantages of nanoparticle deposition in bolstering the mechanical characteristics of FSW dissimilar alloys of Aluminium [10].

The research of Hassanifard et. al. evaluated the tensile and fatigue properties of the joints of Aluminium 7075-T6 with and without the inclusion of Al_2O_3 particles in the WNZ during FSSW. Joint samples with 1wt.% Al_2O_3 particles in the WNZ showed marginally high tensile strength and improved fatigue characteristics when related to the as-welded joints. However, in the case of joint samples with 2.5wt.% alumina particle, there was no improvement in the tensile strength and fatigue characteristics [11, 12].

F Khodabakhshi et. al. conducted a study on evolutions in microstructure and development of textures during dissimilar FSW of an Al hybrid nanocomposite with AA1050. Dissimilar FSW process created mechanical interlocks amid the dissimilar base materials and had a substantial effect on the mechanical characteristics of the welds. The work suggested that the dissimilar FWS process resulted in grain refinement in the SZ with a fine nanoparticles dispersal in the metal matrix. The study concluded that the successful dissimilar FSW process and the resulting microstructural and texture development significantly improved the mechanical characteristics of the dissimilar welds between the hybrid nanocomposite and AA1050 alloy [13].

Sumit Jain et. al. examined the impact of multi-pass FSW of AA6082 and AA5083 with SiC microparticles inclusion upon the joints' mechanical properties. It was demonstrated that the 3-pass FSW joint had better mechanical characteristics due to higher grain refinement. The study also discussed the creation of metal matrix composites with particles reinforcing to augment mechanical characteristics, corrosion, and wear resistance. The grain refinement in the multi-pass FSW joints happened due to the pinning effect of SiCp and dynamic recrystallization, in contrast to the one-pass FSW joint where only dynamic recrystallization was involved. The dispersal of SiCp improved with the increase in number of FSW passes and the 3-passes FSW reinforced joint displayed a uniformly dispersed SiCp and superior tensile strength [14].

4.0. Fatigue Performance Of Fsw Joints

Barsoum et. al. examined the fatigue response of FSW joints, comparing "overlap" and "butt-welded" joints of various thicknesses. The research included fatigue test results, design curves, and FEA to assess the impact of thickness of the plate and nugget-size on fatigue strength. "Butt welded" joints demonstrated higher fatigue strength than "overlap joints" [15].

Hongjun Li et. al. concluded that, in case of FSW Aluminium joints the fatigue performance can be improved by optimizing the process parameters and environmental factors as they play vital role in influencing the fatigue life of the joints. Welding defects, including flash, tunnel defects, kissing bond, and hook-like defects, significantly impact the fatigue properties of materials. Laser peening was suggested as a suitable post-weld treatment to improve fatigue crack growth resistance. It was concluded that the fatigue data for FSW joints are limited, and further test data would be needed for various materials at different stress amplitude and mean stress values [16].

Raj et. al. conducted experimental and numerical investigations on the fatigue response of butt-lap FSW joints used in Aluminium bridge decks. The study assessed the fatigue data by means of the ENS approach and found that the IIW design curve is conservative in evaluating the fatigue behaviour of butt-lap joints of FSW, particularly in the high cycle fatigue. The mode of fatigue failure for the joints was analyzed, and the study emphasized the need for further research to establish a statistically dependable S-N curve built on the ENS method for the estimation of the butt-lap FSW joint's fatigue strength. The challenges associated with the FSW process and the impact of weld orientation on defects was also discussed [17].

Fleury et. al. analyzed the fatigue response in similar FSW joints of AA5086-H32. The study involved welding the Aluminium alloy using different linear speeds and rotating speeds. Tensile tests were conducted to find the joint efficacy of the welded specimens. Hardness, microstructure, UTS, and fatigue responses were examined for the welded specimens that displayed the maximum UTS. Fatigue tests were undertaken at constant stress amplitude, and the broken specimens were analyzed using SEM. The results proved that the fatigue lives of the FSW specimens were less than that of the parent material specimens, which was attributed to changes in mechanical and metallurgical properties caused by the heat induced during the welding process. Further, the residual stresses and plastic strains induced decreased the fatigue life of the welded joints. Weak fatigue responses were seen in the welding zone exposed to the maximum temperatures during the process of welding [18].

Muna K Abbass et. al. studied the fatigue response and fractured sides of dissimilar FSW joints of various Aluminium alloys. The results exhibited that the fatigue performance of the joints was inferior when compared to the base material, with the frailest properties detected in the welding zone. This was attributed to factors such as microstructural changes, stress concentrations, and welding defects introduced during the FSW process. The micro-structure and properties of the welded joints were analyzed and the reasons for formation of welding defects were discussed in detail [19].

Jan Schubnell et. al. discussed the potential for fatigue life enhancement through deep rolling for FSW Aluminium alloys. The researchers highlighted the impact of welding speed on fatigue strength and the benefits of mechanical post-weld treatment. The study concluded that FSW joints exhibit high fatigue strength, especially when deep rolling is applied, and that further post-weld treatment may not be necessary for FSW joints made of EN AW 5083 due to their high fatigue strength. Absence of fusion defects at the root of the weld for dissimilar FSW joints was identified as a critical issue, and deep rolling was projected to have a significant influence on fatigue strength when such defects occur [20].

Li et. al. reviewed the fatigue characteristics of FSW joints in Aluminium alloys, addressing factors like the impact of stress ratios on crack propagation rates, the application of Miner's Rule for cumulative damage assessment, analysis of S-N curves, evaluation of strain cycles, and the dissipation of energy during cyclic deformation. Laser peening was concluded to be efficient in decreasing fatigue crack growth rates and enhancing the fatigue life of materials in these joints [21].

Trimech et. al. undertook experimental and numerical investigation on the fatigue behaviour of butt-lap FSW joints made of Aluminium extrusions and used in bridge decks of highways. The study was intended to characterize the fatigue response of these joints and assess the results using the ENS approach. Specimens were taken from extrusions of bridge decks and verified for real time conditions of fatigue loading. The study also discussed the challenges and complexities associated with assessing and designing fatigue-sensitive details in such structural configurations. Additionally, it highlighted the significance of weld orientation side in influencing fatigue failure modes and the necessity of fatigue tests on real components rather than miniature specimens to represent practical roadway bridge deck conditions in a better way. The limitations of small-scale fatigue tests and the conservative assessment provided by the IIW design curve developed on the ENS approach was also discussed [22].

Infante et. al. discussed the fatigue response of dissimilar FSW Aluminium joints (AA6082 and AA5754) and its usage in the railway structures of less weight. Fatigue tests were conducted on lap joints specimens, and the results revealed lower fatigue life when compared to the base alloys individually. This was attributed to the presence of a “hook” defect inherent to the FSW process. The study also involved finite element modelling and microstructural analysis to characterize the welded seams and evaluate the behaviour of the FSW specimens under constant amplitude loading. Additionally, the research presented S-N curves and discussed the fatigue of FSW joints, suggesting an S-N curve which is shallower for dissimilar welds than for similar welds, indicating an enhancement in fatigue response for smaller stress ranges. The study's conclusions underscored the importance of understanding the fatigue of FSW joints, particularly in dissimilar material joints, and provided valuable insights for the progress and usage of FSW in the railway industry especially for lightweight structures [23].

Jain et. al. explored the microstructural and LCF characteristics of AA5083 H111 FSW joints. LCF tests were performed on both the base material and FSW specimens, with parameters determined using Morrow's Equation and the strain-life approach. The findings revealed a decrease in stress amplitude for FSW joints to achieve the desired plastic strain amplitude [24].

Niu et. al. undertook fatigue analysis of the FSW AA6061-T6 Aluminium alloy, covering various aspects. It was observed that the joint comprised of distinct zones such as the SZ, TMAZ, HAZ, and parent metal. Microscopic assessment revealed the absence of welding defects. The S-N diagram indicated potential infinite fatigue life at 62-68% of the yield strength. Fatigue response of the welded material closely matched that of the parent material under low-stress amplitudes but exhibited lower performance at higher amplitudes. Tensile testing results demonstrated reduced yield strength and ultimate tensile strength in FSW specimens compared to the parent material. The welded specimen also displayed decreased ductility. Variations in microstructure were observed across different zones, with the SZ showcasing a fine-grained structure attributed to dynamic recrystallization. Grain size gradient towards the HAZ was noted, with smaller grains at the bottom side due to increased heat generation. The study offered valuable insights into the microstructural and mechanical behaviour of the AA6061-T6 alloy during friction stir welding, underscoring the significance of comprehending these factors for optimizing welding processes and enhancing material performance [25].

Rajneesh et. al. investigated the inter-granular cracking behaviour in FSW joints of AA5086-H321 alloy under cyclic loading. The investigation focused on tests related to fatigue crack growth in different zones of the weld joint, revealing that intergranular cracking was primarily observed in the WNZ due to the presence of high-angle grain boundaries, smaller grain size, and the formation of Mn-rich and Mg-rich precipitates along the grain boundaries. The study also highlighted the inverse parabola-type trend in the area fraction of intergranular facets with respect to increasing stress intensity factor, regardless of the applied load ratio and stress amplitude. The presence of Mn-rich second-phase particles and Mg-rich phases along the grain boundaries in the nugget zone was identified as a significant factor contributing to the intergranular cracking behaviour. The critical role of microstructural attributes like grain size, grain boundaries, and precipitates on the fatigue crack growth behaviour in the weld joints of AA5086-H321 alloy was highlighted [26].

Harish Suthar et. al. found that temperature and strain distribution variations brought about by FSW produce a variety of microstructures in and around the WNZ. This affects the base material's initial strengthening mechanisms, particularly in Aluminium alloys that precipitate-harden. LCF behaviour of the FSW joint and base material of AA6061-T6, indicate reduced fatigue life in different FSW joint zones in comparison to the base material. Process-induced softening brought on by the loss of precipitate hardening in the FSW joint increased the fatigue damage. Due of their borders that are prone to cracking, specimens from the HAZ on the proceeding and receding sides have a shorter fatigue life than those from the nugget/ SZ. Significant cyclic strain hardening is seen in all zone-wise specimens of AA6061 FSW joints when compared to the parent material [27].

Athanasios Toumpis et. al. presented a thorough analysis of the fatigue response of FSW low alloy steel. Experimental procedures involved testing samples at various stress ranges to improve statistical validity. Microstructural characterization unveiled a consistent microstructure with notable refinement of grains in the slow traverse speed weld. Fracture surface analysis indicated a consistent pattern of brittle fracture on the outer retreating side, with cracks originating from lap defects. FSW of DH36 grade steel exhibited reasonable fatigue lives, even at a stress level in the tune of around 90% of yield strength, surpassing the weld detail class of the IIW for single side fusion welded butt joints. The study concluded that welding parameters played a crucial role in influencing the fatigue behaviour of the weldments. Highly refined, homogeneous, and flaw-free micro-structure along with best fatigue response were observed in welds done at slow speed [28].

Extensive testing was carried out by Helena Polezhayeva et. al. to assess the fatigue response of DH36 steel in FSW marine grade DH36 steel. X-ray diffraction measurements and fatigue testing revealed that the intermediate speed weld demonstrated enhanced fatigue strength in comparison to standard recommendations. Analysis of residual stress profiles and crack initiation sites identified key factors influencing fatigue life. The study concluded that utilizing the intermediate welding speed was optimal for achieving superior fatigue performance in friction stir welded DH36 steel [29].

Seerangan et. al. explored the weldability of high-strength steels (HSS) through FSW and compared the fatigue properties of S690 and S355 high strength steel plates to design recommendations and other welding techniques. It highlighted the limitations posed by the weldability of HSS like reduction of strength, toughness, and fatigue properties, which restricted their widespread use. FSW was identified as a promising technology for achieving high weld quality, and the study explored its potential benefits for joining industrial grade steel plates. The research demonstrated that the high-quality FSW steel joints surpassed high-quality arc welds and design recommendations, with fatigue strength increasing with material yield strength. The micro-structure and fatigue response of the FSW joints were thoroughly examined, revealing the presence of dynamically recovered micro-structure in the SZ of ferrous metals, lower peak temperatures, smaller heat-affected zones, and improved mechanical properties compared to base materials. The research established that friction stir welding enhances the weldability and fatigue properties of high-strength steels, offering higher fatigue strength compared to traditional welding techniques and design recommendations [31].

Edwards et. al. looked into the fatigue response of FSW titanium structural joints. Taking inspiration from earlier work on butt weld joints, FSW technique for corner and T-joints was developed. A bending fatigue test was performed on a restricted set of corner joints to evaluate their fatigue life. The application of stress concentration parameters allowed for a comparison of corner joints and butt joint data. Similar fatigue performance was displayed by the welded joints when compared to specimens that were machined from wrought product shapes. Researchers evaluated the microstructural properties of the weld cross-sections and applied a post-weld heat treatment to remove any remaining stresses. It was concluded that, FSW can create structures with similar fatigue performance of wrought materials [32].

In the study undertaken by Ruijie Wang et. al., the fatigue performance and weld-seam cross section characteristics of FSW linear joints made of aluminum alloy AA2024 were investigated experimentally. The results indicated that more plausible results can be obtained using the fictional notch radius approach and the Morrows modified Manson-Coffin damage equation [33].

Texier et. al. presented a comprehensive analysis of the fatigue performance and microstructural characteristics of GMAW and FSW aluminium alloy assemblies, utilizing optical micrographs, in-plane local displacement fields, tomographic and topographic analyses, fractographic examinations, and DIC techniques to assess the influence of welding processes on fatigue behaviour and crack initiation mechanisms. It was found that fatigue response of welded joints was reliant on the process of welding, with the FSW demonstrating superior fatigue resistance compared to GMAW. The FSW joints exhibited a fatigue strength approximately 20% higher than the GMAW joints, and at high stress amplitudes, the FSW joints had a lifespan about three times higher than that of the GMAW joints. Fractographic analyses revealed that cracks initiated from microstructural features and large sub-surface grains, and the study also identified a “structural-contact-fretting” crack initiation mechanism that had not been previously reported in the literature. X-ray tomographic studies showed no defects in FSW specimens, while the GMAW specimens exhibited a substantial volume fraction of pores, which contributed to the inferior performance of the GMAW joints under fatigue loading [34].

Daniel et. al. explored the fatigue response of a hybrid overlap FSW and adhesive bonding method used on an Al-Mg-Cu alloy commonly used in aircraft construction, demonstrating noteworthy increase in strength and ductility by the “hybridization” of the overlap FSW joints. The “hybrid FSW bonded joints” attained higher strength than “FSW overlap joints”, with even the lowermost performing hybrid joint attaining a superior joint efficiency than the topmost performing FSW joint [35].

5.0. Conclusions

- It is observed from literature that the inclusion of copper nano particles, Al_2O_3 particles and SiC microparticles proved to be promising in improving the mechanical properties of FSW joints.
- Several researchers examined the impact of FSW parameters on the fatigue performance of different materials joined using FSW. It is observed from literature that fatigue response of FSW joints not only depends on the process parameters but also on external factors like stress ratio, environment, residual stress, defects, weld orientation side etc.
- High-quality FSW steel joints surpassed high-quality arc welds and design recommendations, with fatigue strength increasing with material yield strength.
- It is worth noting that inducing compressive stresses in the FSW joints can increase their Fatigue Life.
- Post-weld treatments can decrease fatigue crack growth rate and improve material fatigue life in FSW joints. Laser peening was observed to be effective in this context.
- The FSW joints exhibited a fatigue strength approximately 20% higher than the GMAW joints, and at high stress amplitudes, the FSW joints had a lifespan about three times higher than that of the GMAW joints. There appears to be an opportunity to improve the fatigue response of FSW joints further by suitable nano-particles inclusion during the welding process.

- There is a research gap in the area of notch fatigue performance of FSW joints. This needs to be explored further by creating notches of different geometries on the FSW joints and quantifying the impact of notch geometry (depth, width, perimeter length etc. of notch) on their fatigue performance.
- Literature in the area of evaluating the fatigue response of FSW joints at different temperatures is also scarce. This area can also be further explored.

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