Friction Stir Welding of Steels: A Review Paper

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ABSTRACT: In the last two decades, significant progress has been made in friction stir welding (FSW) of steels in every aspect of tool fabrication, microstructure control, and property evaluation. FSW of steels has reached a new level of technical maturity thanks to the development of reliable welding tools and precise control systems. Many engineering steels can create high-quality, lengthy welds. FSW has distinct benefits over conventional fusion welding, resulting in joints with superior characteristics. FSW is able to fabricate steel joints with excellent toughness and strength thanks to active control of the welding temperature and/or cooling rate. For example, unfavorable phase transformations in advanced steels can be avoided, and favorable phase fractions in the weld zone can be maintained, avoiding the typical property degradations associated with fusion welding. If phase changes do occur during the FSW of thick steels, microstructure and characteristics can be optimized by adjusting the heat input and post-weld cooling rate. This paper elaborates the applicability of the FSW tools and its applicability in various manufacturing process to solve the existing problems.

KEYWORDS: **Carbon Steels**, ***FSW***, ***High Strength Low Alloy Steels***, ***Oxide dispersion strengthened (ODS) steels, Stainless Steels***

1. INTRODUCTION

Friction stir welding (FSW) is a method of connecting solid-phase materials with a non-consumable tool. Welded materials undergo plastic deformation at high temperatures, resulting in a wrought microstructure rather than the solidification microstructure generated by fusion welding techniques. When compared to fusion welds in the same material, FSW joints generally have better mechanical characteristics in terms of strength and toughness[1]. World-class universities, research institutions, and industrial businesses are all interested in this potential method. Aluminum alloys with FSW have been successfully used in aircraft, offshore, railroads, and automotive sectors. Steel FSW has not yet reached the same degree of commercial applicability as aluminum alloy FSW. The reasons for this are that I FSW of steel is more complex than FSW of aluminum due to tooling needs, and (ii) as a result, FSW steels' potential benefits have not been completely exploited. Friction stir welded steels typically turn red hot locally.

Even at this high temperature, the hot steel maintains a significant flow stress that opposes the flow of a welding tool passing through it, resulting in high contact stresses and tooling abrasion. For FSW of steels, special tools that can withstand high temperatures, stress, and abrasion must be utilized. Tools available are still very costly as compared to FSW tools for usage in aluminum alloys due to limited purchasing volume[2]. To create more cheap and reliable tool materials, additional research funding is required. FSW of steel will become increasingly commercially appealing to a wide range of sectors as research into enhancing tool materials and discovering new applications continues[3]. Investigations on the FSW of steels have grown rapidly in recent decades. There have been a lot of encouraging findings reported. Steel FSW, for example, may be performed at temperatures ranging from 600 to 1200 degrees Celsius. As a result, FSW creates a desirable microstructure in the weld zone, which may be destroyed by fusion welding, resulting in enhanced characteristics of advanced steels. It is timely to highlight recent important achievements and discoveries in FSW of steels, given the many new developments[4].

This paper also intends to illustrate the bright future of FSW techniques applied to steels and to give more insight into where future research may lead. For FSW of high softening temperature alloys, tool materials must have outstanding characteristics at temperatures over 900 degrees. Tool materials must be resistant to both mechanical and chemical wear, in addition to the requirements for strength, fatigue, and some fracture toughness at extreme temperatures. Polycrystalline cubic boron nitride (PCBN) and refractory metals are the two main groups of materials that have had the most success in the last decade[5]. A novel family of PCBN tool materials has just been created. The catalyst/binder phase in this new class is WRe. In comparison to ordinary PCBN tools, the PCBN family of tool materials offers considerably enhanced fracture toughness at the price of wear resistance. Tool wear and fracture are also factors that influence tool performance. Tool wear is caused by both physical and chemical wear[6].

Fig. 1: Illustrates the various machine tools used to complete the process of milling operation on various kind of work pieces[6]**.**

Many early tools for FSW of steels employed refractory metals like tungsten and molybdenum. Despite the fact that these materials were found to be sufficient for welding, they deformed and fractured during the plunge stage due to the high stresses associated with this step of the process and the tool material's high ductile-to-brittle transition temperatures, respectively. Fig.1, Illustrates the various machine tools used to complete the process of milling operation on various kind of work pieces. The ductile-to-brittle-transition temperature of this tool material is significantly lower, which reduces the risk of fracture. Additionally, the inclusion of Rhenium enhanced the material's hot strength, reducing deformation of the probe during the dive and increasing wear resistance. However, the wear rate is still high enough that any features added to the probe or shoulder would rapidly deteriorate.

As a result, these instruments usually consist of a smooth truncated cone probe and a featureless shoulder. FSW steels were also made with Ni-based or Co-based super alloys as tool materials. Welding ultrahigh carbon steel using an FSW tool constructed of Co-based super alloy yielded good wear resistance after a weld length of 150 mm. A featureless shoulder and a basic smooth truncated cone probe are used in all of these instruments. When features were put on the probe or shoulder, the tool wear rate would be useful to know. Despite the fact that each of these super alloys has been claimed to have some capability welding different steels, each tool material has yet to prove economically viable for various reasons. The PCBN tool material family is brittle. During plunging and welding, a lack of rigidity in the frame on which the spindle is attached, or the ways and rails on which the weld table is mounted, might cause the tool to "surf." Surfing can result in extremely high dynamic loads on the tool, which can result in unnecessary damage and premature failure of very hard tooling such as PCBN, but can also be a disadvantage for other tooling. In addition, a lack of stiffness can cause misalignment between the tool and the desired weld joint. Understanding the formation of weld flaws, post-weld microstructures, and characteristics requires a thorough understanding of material flow and microstructural evolution during FSW.

Despite the fact that several studies have been carried out to elucidate material flow behaviour during FSW, the existing theories are sometimes conflicting. Some research has been done to better understand material flow during FSW of aluminum alloys, but little research has been done on material flow during FSW of steels. When the probe length is sufficient to extend past the top material flow layer, i.e., flow dominated by the shoulder, the material flow during FSW can be divided into three horizontal layers: I an upper layer whose flow is primarily controlled by the shoulder; (ii) an intermediate layer whose flow is primarily driven by the probe surface; and (iii) a bottom layer whose flow is primarily driven by the probe surface. During FSW, these layers may interact with one another, complicating material flow. The material movement in the intermediate layer is the subject of this manuscript. The microstructural examination of a "frozen" keyhole can reveal important information about material movement. The “freezing” FSW technique may be used to create a “frozen” keyhole by halting the tool and quickly quenching the workpiece. The rotating tool, on the other hand, cannot be halted quickly.

Because of the FSW system's inertia the inertial tool rotation and probe movement produced by FSW system relaxation messed up the material distribution around the probe. Despite the fact that the tool spinning was halted within 0.1 second of initiating the emergency stop, a shift in the probe was visible owing to system relaxation. As a result, the material flow around the "frozen" keyhole differs from that surrounding the probe during steady-state FSW. A systematic investigation using various techniques such as emergency weld termination, weld force monitoring, tracer technique, and EBSD examination was used to understand the relaxation of the FSW system and what actually happened during the period from activation of weld termination to cessation of probe rotation. During FSW, the probe deflects away from its "home" location, toward the advancing side of the weld and in the opposite direction of travel, due to contact forces between the welding tool and the workpiece material. Prior to tool extraction, system relaxation permitted the probe to return to its "home" location along an arc route after weld termination was initiated.

The in-situ material distribution produced during FSW was changed as a result of this. A solid circle indicated the probe's end point. The material around the keyhole was clearly disrupted, and the probe location shifted throughout the weld termination. There has been much debate in the literature and FSW community regarding whether or not material in the weld nugget rotates around the probe more than once during FSW. Actually, this may depend on the welding conditions. Material may rotate around the probe more than once during FSW under the following conditions: (1) the material flow is controlled by the shoulder, (2) FSW is conducted using high heat input parameters, or (3) the difference in elevated temperature strength of the material flow zone (MFZ) and heat-affected zone (HAZ) are small. In most situations, material pushed by the probe spins around the probe less than once. At high temperatures, material in the MFZ softens substantially during FSW. In most technical aluminum alloys, Martials in the HAZ preserved substantial strength. The stronger HAZ produce a "die" on both sides of the tool probe when this happens. When engineering alloys, such as age-hardening Al alloys or stainless steel, are exposed to FSW, the weld area is just slightly larger than the diameter of the probe[7].

After the material was placed behind the probe, it was still subjected to plastic deformation at high temperatures, but at a slower pace. Grain coarsening began to take control of the process, resulting in bigger grain sizes and more evenly distributed grains. Through grain boundary migration, some of the twin boundaries developed into conventional HAGBs. The tool shoulder's plastic deformation allowed some LAGB segments to develop within the coarse grains, but not enough to cause recrystallization. In the deposition zone close behind the probe, low fractions of twin boundaries and a comparatively high proportion of LAGBs were detected. The material is still exposed to high temperatures after the tool shoulder has passed, although plastic distortion is minimal. The density of LAGBs reduced owing to recovery under this static annealing environment. In addition to healing, new annealing twins emerged.

Twin boundaries occur preferentially to release the low energy contained in the material as compared to other HAGBs (from the low plastic strain caused by tool shoulder). In the weld zone, a low percentage of LAGBs and a large percentage of twin boundaries were found. Because the material deformation during FSW is mostly in the form of simple shear, a shear texture component is predicted to develop. A direct comparison with ideal shear texture components seen in the face centered cubic material can complete the texture identification process. The texture analysis reference frame was rotated to align with the local shear coordination system before the identification. This is in line with one of the shoulder's primary tasks, which is to produce downward force during FSW[8]. The microstructure development gets more complex when allotropic phase transition occurs during FSW of steel because the austenitic phase at increased temperatures is devoured by the room temperature phase during the transformation.

The phase transformation changes the deformation history, texture, and grain structure of the austenitic phase. To understand the microstructural development at increased temperatures during FSW, the preceding austenitic microstructure must be retrieved from the room temperature phase. Deformation of the material causes some extra heating. The tool is sunk until the shoulder of the tool makes contact with the workpiece. The most significant source of heat is friction between the shoulder and the workpiece[9]. The relative size of the pin and shoulder is essential in terms of heating, while the other design aspects are not. The heated volume of material is likewise contained by the shoulder. The tool's second duty is to 'stir' and 'move' the material.

The tool design determines the consistency of microstructure and characteristics, as well as process stresses. Concave shoulders and threaded cylindrical pins are commonly utilized. Carbon steels are by far the most often utilized steels. Carbon steel is a mixture of iron and carbon with no defined or needed minimum content of additional elements to achieve the desired alloying effect. Manganese, silicon, and copper are the only additional elements permitted. Steel may grow harder and stronger by heat treatment as the carbon content increases, with a commensurate loss in ductility. Carbon steels are classified as low-carbon steel, medium-carbon steel, high-carbon steel, and ultra-high-carbon steel based on their carbon percentage content. Fig. 2, Illustrates the mechanism of friction stir welding in which a tool is used to complete parting of a work piece[10].

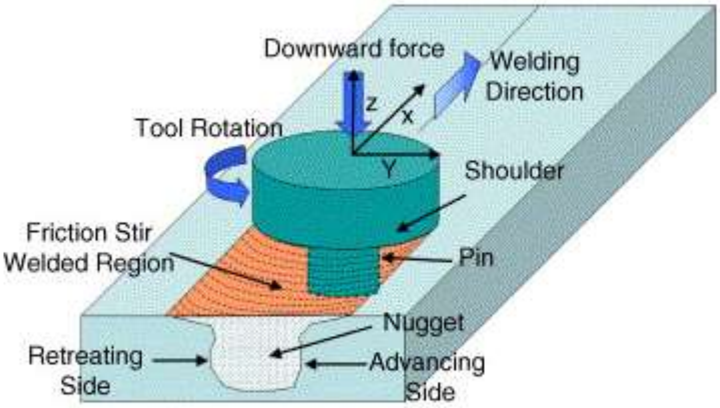

Fig. 2: Illustrates the mechanism of friction stir welding in which a tool is used to complete parting of a work piece[10]**.**

In general, suitable joints may be created utilizing fusion welding procedures in low or medium carbon steels. Increased carbon equivalent, on the other hand, decreases steel's fusion weld ability. According to recent studies, FSW has numerous benefits over fusion welding techniques when it comes to connecting carbon steels. FSW is a "solid state" joining method since it is conducted at lower temperatures than fusion welding, i.e., considerably below the melting point. Solid state welding reduces the residual stress and deformation in steel that would otherwise occur during fusion welding.

2. DISCUSSION

The quantity of chromium in stainless steel differs from that in carbon steel. For corrosion resistance, a minimum of 10.5 percent chromium content by weight is required. On the exposed surface of stainless steel, a protective oxide layer develops spontaneously and swiftly. If this layer is damaged under normal conditions, it repairs quickly, allowing stainless steel to last millions of years under consistent corrosion conditions. According to their crystalline structure, stainless steels are classified as austenitic stainless steel, ferrite stainless steel, duplex stainless steel, and martensitic stainless steel. The most prevalent type of stainless steel is austenitic, which gets its name from the FCC (Face Centered Cubic) crystalline structure. Because of its comparatively high nickel concentration, austenite is stable at room temperature and has better corrosion resistance than martensitic and ferrite grades. Stainless steel FSW began roughly a decade ago. Austenitic stainless steel was utilized as a test bed for studying the microstructural development during FSW and the nature of material flow, in addition to investigations focused on weld characteristics.

The peak welding temperature in stainless steel can be higher than 1200 °C during FSW when high heat input parameters, such as high rotation rate and low welding speed, are utilized. The phase transition of austenite to ferrite happened when austenitic stainless steel was welded at such high temperatures. The latter weld was performed on a thicker plate (6 mm) at a lower welding speed than the previously described FSW stainless steel, decreasing the cooling rate after FSW. Thinner welding plates (2 mm) and faster welding speeds of the previously stated friction stir welded stainless steel led in a faster cooling rate, perhaps preventing ferrite breakdown to Sigma. The corrosion resistance of the weld would be considerably decreased if sigma phase formed on the advancing side of the stir zone. This is because sigma particles, which develop at grain boundaries, have a high proportion of Cr, reducing the amount of Cr available to build a protective oxide layer locally.

The area in the stir zone that did not include sigma phase demonstrated superior corrosion resistance than the base metal due to grain refinement. Ferritic stainless steels can also be welded using FSW. Due to the quick cooling rate and extreme plastic deformation, the original coarse equated ferrite grains in the BM were converted into fine equiaxed ferrite and fine martensitic lath after FSW. The hardness of the stir zone was double that of the BM as a result of the microstructure alteration. Tensile tests revealed that the welded metal was too close to the base metal. Hourglass and center-crack tension specimens were used to test fatigue life and fatigue crack development characteristics, respectively. When compared to the BM, the FSW joint had a longer fatigue life and was more resistant to fracture development. The microstructure of duplex stainless steels is a combination of ferrite and austenite phases.

When the ferrite and austenite phases are in roughly equal quantities, they have a greater resistance to stress corrosion cracking and a higher strength than austenitic stainless steels. This qualifies them for industrial use in the oil and gas, petrochemical, pulp and paper, offshore, and pollution control sectors. In the weld metal and HAZ, fusion welding of duplex stainless steel creates a microstructure comprising coarse ferrite grains and both inter granular and intra granular austenite phases. One of the primary technical problems in light weighting steel body components has been the trade-off between strength and ductility. This is especially true with dual-phase and other multi-phase steels, which are more difficult to predict in terms of hardening behaviour and spring back than single-phase steels. The lower ductility of high strength alloys has limited their usage in general; as a result, most contemporary effort is focused on achieving better degrees of formability. Joining challenges are just as essential as generating challenges when it comes to AHSS. In AHSS, friction stir joining techniques for both linear and spot welding applications have been studied. In comparison to carbon steel, high strength low alloy (HSLA) steels have a low carbon percentage and a relatively high manganese concentration.

In different combinations, small amounts of chromium, nickel, silicon, molybdenum, copper, nitrogen, niobium, titanium, and aluminum are utilized. HSLA steels are designed to outperform ordinary carbon steel in terms of mechanical characteristics and/or resistance to air corrosion. The majority of HSLA steels are produced using thermal mechanical methods that produce homogeneous refined microstructures, resulting in a superior combination of high strength and excellent toughness. Welding is a critical step in the construction of large-scale pipelines for the high-pressure transmission of crude oil and natural gas over long distances. Significant reductions in strength and toughness occur in the HAZ during fusion welding of 30 pipeline. In addition, hydrogen-assisted cracking can occur in the HAZ of a fusion weld.

The pipeline thickness and HSLA steel consumption can be decreased if a more efficient and reliable alternative joining technique is employed to weld HSLA steels. The basic metal structure of equiaxed ferrite converts to upper binate with some polygonal ferrite when an HSLA-65 steel with a thickness higher than 6 mm is welded by FSW. This means that the welding temperature is higher than the A3 transition temperature. The stir zone frequently has a higher hardness than the underlying metal when the microstructure is polished. According to the Hall-Petch relationship, the yield strength of the weld metal is largely reliant on the grain/lath size.

3. CONCLUSION

Researchers have surmounted numerous challenges and achieved significant progress in both FSW and FSSW steels during the last two decades. The outcomes are extremely promising. Through the regulation of the welding temperature and/or cooling rate, FSW techniques may fabricate steel joints with outstanding toughness and strength. FSW allows for more precise control of phase transitions that occur during fusion welding, allowing for the targeting of certain phase fractions for a given alloy composition. Controlling the post-weld cooling rate can effectively minimize the loss of microstructure and characteristics if phase transformation occurs when FSW is applied to thick steels. Grain refinement in the stir zone typically offers superior mechanical characteristics than fusion welding while also increasing hydrogen embrittlement resistance. In some situations, advancements in tooling materials have made it viable to consider FSW of steel as a manufacturing method. The benefits of FSW that have revolutionized welding in aluminum alloys may not be as rapid in steel, but in the future years, this solid state joining technique will benefit a growing number of applications. Although there has been conducted extensive research in the sector of FSW but this domain is not limited and more research is demanded to explore the full potential of the FSW.

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