特集

溶接プロセス予測モデルの最前線

Frontiers of Friction Stir Welding and Processing*

摩擦攪拌接合・プロセッシングの最前線*

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摩擦攪拌接合（FSW）の開発以降，その技術進展は急速かつ目覚ましいものがある．多くの新技術は，特性上の制約，サイズやコスト的の限界等の困難さに直面することにより，短命のまま消滅してしまうことがあるが，FSWにはそのような問題が見られない．現在でも，研究者および技能者によるFSW技術の発展ならびにFSWの利点を生かす新規かつ最適な方策の模索を繰り返しながら，FSW技術は継続的に拡大している．本稿では，FSWのこれまで進展，ならびに銅および鉄基合金という2つの高融点金属材料に対するFSWの最新状況に焦点を絞り解説する．さらに，FSWの類似技術である摩擦攪拌プロセッシング（FSP）の概略を，選択的な特性変化・改善がどのように可能であるのかを示しながら，述べることをとする．

Summary

Since the inception of Friction Stir Welding (FSW), technical progress has been rapid and significant. Many new technologies “flame out” within a short time as property limitations, scale-up, cost or other such difficulties are realized. This is not the case with FSW. FSW is here to stay and continues to expand as researchers and practitioners advance the technology and learn new and better ways to take advantage of the benefits attributable to FSW. This manuscript highlights progress in FSW including some of the newest advances in FSW to the higher temperature materials such as Cu and Fe base alloys. Further, the concept of “Friction Stir Processing” (FSP), a closely related technology using similar methods as FSW, is presented illustrating how FSP can selectively alter and improve properties for improved structural integrity.

Introduction

To illustrate the frontiers of friction stir welding/processing (FSW/P), this manuscript will focus on two high temperature alloy systems, Cu and Fe alloys. The literature offers a prolific quantity of FSW results on aluminum alloys illustrating improved strength, fatigue life, hardness, and fracture toughness, including all the major aluminum alloy systems of 2XXX, 5XXX, 6XXX, and even the high strength, unweldable 7XXX aluminum alloys¹⁻¹⁹. For a detailed sum-

mary of microstructure and mechanical properties following FSW in aluminum alloys, readers can find an extensive summary in the soon to be published first reference volume on Friction Stir Welding and Processing²⁰. Similarly, most recently, there have been published results on the success of friction stir welding of Magnesium alloys²¹⁻²⁵. Although the data for Mg alloys are not as abundant as compared to aluminum alloys, the welding success is clear. Again, post-weld properties are excellent. However, the intent of this manuscript is to review the frontiers of FSW/P and in the author's estimation, the frontier and future growth is in high temperature alloys. Thus, the emphasis herein will be on FSW, and where applicable FSP, of high temperature Cu and Fe alloys.

For FSW to be commercially acceptable for the high temperature alloys, long tool life is of paramount importance. Both aluminum and magnesium alloys are friction stir welded at temperatures <520°C. At these low welding temperatures, FSW tool life is not a consideration, i.e., common tool steels are sufficient for long life performance. However, the advancement of FSW to high temperature materials is challenged by the ability of the FSW tool to survive in a very severe environment. First, the FSW tool must resist high compression loading at room temperature. During welding or processing, temperatures are very high, for example, 1000°C for copper based alloys and >1100°C for iron based alloys. At these elevated temperatures, the tool must resist high cycle tensile and compressive stresses (rotating and bending), fracture, abrasion, mechanical wear, and chemical reactions with both the atmosphere and the weld metal. To date, considerable research has demonstrated the ability to friction stir weld or stir process Cu and Fe based

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alloys and this manuscript will summarize the potential benefits associated with FSW/P of these high temperature alloys, i.e., microstructure and mechanical properties. However, due to the importance of tool life, comments regarding tool materials and their limitations will be included. First, a brief summary description of FSW and FSP is provided followed by highlights of progress on FSW on Copper and Iron based alloys and ending with a short discussion of high temperature FSW tooling.

Friction Stir Welding

Friction stir welding (FSW) was invented at The Welding Institute (TWI) of UK in 1991 as a solid-state joining technique, and was initially applied to aluminum alloys²⁶⁾. The basic concept of FSW is remarkably simple. A non-consumable rotating tool with a specially designed pin and shoulder is inserted into the abutting edges of sheets or plates to be joined and subsequently traversed along the joint line, Figure 1. Figure 1 illustrates process definitions for the tool and workpiece. Most definitions are self-explanatory but advancing and retreating side definitions require a brief explanation and knowledge of the tool rotation and travel directions. In the illustration below, the FSW tool rotates in the counterclockwise direction and travels into the page. In this illustration, the advancing side is on the right where the tool rotation direction is the same as the tool travel direction (opposite the direction of metal flow) and the retreating side is on the left where the tool rotation is opposite the tool travel direction (parallel to the direction of metal flow).

The FSW tool serves three primary functions, i.e., (a) heating of the workpiece, (b) movement of material to produce the joint, and (c) containment of the hot metal beneath the tool shoulder. Heating is created within the workpiece by friction between both the rotating tool pin and shoulder and by severe plastic deformation of the workpiece. The localized heating softens material around the pin, and combined with the tool rotation and translation leads to movement of material from the front to the back of the pin thus filling the hole in the tool's wake as the tool moves forward. The tool shoulder restricts metal flow to a level equivalent to the shoulder position, i.e., approximately to the initial workpiece top surface. As a result of the tool

action and influence on the workpiece, when performed properly, a 'solid state' joint is produced, i.e., there is no melting.

Because of various geometrical features on the tool pin, e.g., steps, threads, flats, flutes, etc., material movement around the pin can be complex with gradients in strain, temperature, and strain rate. Accordingly, the resulting nugget zone microstructure reflects these different thermo-mechanical histories and is not homogeneous. In spite of the local microstructural inhomogeneity, one of the significant benefits of this 'solid state' welding technique is the fully recrystallized, equiaxed, fine grain microstructure created in the nugget by the intense plastic deformation at elevated temperature. The fine grain recrystallized microstructure results in excellent strength, ductility, and fatigue properties within the weld nugget. Compared to weld nugget properties following fusion welding, where a cast microstructure is created, resultant mechanical properties following FSW are usually far superior.

Friction Stir Processing

Friction-stir processing (FSP), a close cousin to FSW, is an emerging surface-engineering technology that can locally eliminate casting porosity or other defects and refine microstructures, thereby improving strength and ductility, increase resistance to corrosion and fatigue, enhance formability, and improve other properties²⁷⁾. FSP can also produce fine-grained microstructures through the plate thickness to impart high strain rate superplasticity even in very thick sections (12 mm thick 7050 Al)²⁸⁾. Similar to FSW, FSP involves plunging a rapidly rotating, non-consumable tool, comprising a profiled pin and larger diameter shoulder, into the surface and then traversing the tool across the surface. However, in FSP, no material is joined and the tool designs can be considerably different. In FSP, the goals are to alter the microstructure in the FSP zone and/or to eliminate defects to enhance local properties. Large surface areas can be traversed rapidly by using the appropriate tool design accompanied by rastering, i.e., translating the tool multiple times across the surface in a predetermined pattern. FSP zones can be produced to depths of 0.5 to 50mm in Al, Mg and Cu base alloys, but is more limited in Ti and Fe alloys (<9 mm). Details of the benefits and limitations of FSP, along with examples of current and potential applications in Cu alloys are presented below.

Copper Based Alloys

Two significant and long term research efforts have been ongoing to demonstrate the feasibility to 1) friction stir weld pure copper to seal thick copper canisters for encapsulation of nuclear waste material²⁹⁻³¹⁾ and 2) FSP of a NiAl Bronze (NAB) alloy for efficient fabrication of ship propellers³²⁻³⁷⁾. These two research efforts demonstrate the different benefits of either FSW to reliably weld to create defect free structures in very thick (50 mm) OFHC Cu or use FSP to eliminate casting defects and significantly

Fig. 1 Schematic drawing of friction stir welding.

increase strength in NiAl bronze to depths of 25 mm.

The major component of the Swedish system for managing and disposing of radioactive waste is the copper canister^{29,31)}. The canisters are to be fabricated from large diameter, thick wall (50 mm) seamless copper tubes. Top and bottom caps are joined to the tube to complete the encapsulation of the waste material. To meet the severe requirements of this application (100,000 year life), oxygen-free copper was selected. However, for long life extrapolation, a defect free weld of extremely high joint integrity and repeatability must be achieved. Following a decade of development, FSW has emerged as the preferred welding process to seal these copper canisters. An illustration of a friction stir weld in 50 mm thick Cu is shown in Figure 2. Numerous tool designs and tool materials, including Nimonic 105 and Densimet, were evaluated and high quality welds were obtained routinely. By tailoring FSW and tool parameters, welds were produced exhibiting uniform, equiaxed grain structures throughout the weld nugget, with a grain size matching that of the base metal and with 100 pct. efficiency in the resulting weld joints, i.e., weld joint properties matched parent metal properties.

Reportedly, welds in OFHC copper approached 900°C for weld durations of ~1 hour and thus a tool material capable of performing in this weld envelope was required³¹⁾. A large number of tool materials were evaluated³¹⁾. Currently, Nimonic 105, a wrought nickel base super alloy, is the selected probe (pin) material and Densimet, a sintered tungsten alloy, the selected shoulder material. Nimonic 105 was capable of producing many meters of weld (up to 20m with no failure or loss of dimensions) and did not twist providing the weld temperature did not exceed 900°C. Increased wear resistance was also achieved using a proprietary carbo-nitriding process²⁹⁾. The majority of tool shoulders used Densimet. Densimet's high temperature capability, good machining characteristics, and high thermal conductivity make it an ideal shoulder material. The rapid rate at which Densimet attains red heat (~700°C in ~3 min), using preferred welding parameters, has not been matched by other materials. This is a good illustration of using a

Fig. 2 Friction stir welding of a 50 mm thick copper canister in one pass.

two-piece FSW tool selecting tool materials to perform best for each tool component. Based on the absence of post-weld tool wear, weld integrity, and process repeatability, it is clear FSW tool materials are available for the intermediate range up to 900°C and that FSW is a reliable joining method for Cu alloys requiring temperatures in the intermediate range of 850°C to 900°C.

The second demonstrated potential commercial application in copper alloys was friction stir processing (FSP) of NiAl bronze, a commonly used material for ship propellers^{32,37)}. A cast NiAl bronze alloy was friction stir processed with the goals of increasing strength and eliminating casting defects. The ability to eliminate casting porosity in NiAl bronze by FSP is illustrated in Figure 3. The thermomechanical processing via FSP “reforged” the material and eliminated all casting porosity in the FSP zone. Three dominant microstructures created by FSP are illustrated in Figures 4b-4d and are in sharp contrast to the coarse as-cast NAB microstructure illustrated in Figure 4a. Details of these FSP microstructures are presented elsewhere including orientation imaging analysis, transmission electron microscopy, and discussions of the microstructural and second phase evolution^{36,37)}.

Yield and tensile strengths for the as-cast NAB are 214 MPa and 445 MPa respectively. In comparison, following FSP, yield strength and tensile strength for the different FSP microstructures are respectively 1) Lamellar: 480 MPa and 756 MPa, 2) Fine grain: 508 MPa and 776 MPa, and 3) Widmannstätten: 572 MPa and 823 MPa and elongations to failure were high. Further, at 10⁶ cycles to failure, the fatigue stress increased from 200 MPa to 440 MPa following FSP. These dramatic property increases reflect the refined multi-phase homogeneous microstructure and the absence of casting porosity following friction stir processing.

FSP of NiAl bronze elevated the tool temperature up to ~1000°C. Further, rastering, whereby the tool is repeatedly traversed across the surface of the NiAl bronze, was necessary to eliminate casting porosity over a large surface area, such as on a ship propeller blade³³⁾. Thus, tool materials and tool designs capable of long operational life in the harsh environment (~1000°C) were required. A number of tool materials were evaluated. Two successful materials were Densimet 176S, a sintered tungsten alloy, and

Fig. 3 Friction stir processing of NiAl bronze illustrating the ability to “heal” casting porosity.

Lanthanated Tungsten ($\text{La}_2\text{O}_3\text{W}$). Other materials, i.e., polycrystalline cubic boron nitride (PCBN) and tungsten rhenium, were also acceptable but the extra cost was not warranted. The Densimet alloy is low cost, easily machinable, retains good strength to 1000°C (tensile strength ~ 210 MPa) and does not require heat treatment. However, it is a powder product and this does lead to erosion of small tungsten particles during FSP. In many structures, this is not an issue. The Lanthanated Tungsten has many of the same benefits as Densimet but retains greater strength at 1000°C (tensile strength ~ 262 MPa) and is more wear resistant showing little wear after 6 hours of FSP in NiAl bronze³³.

With the demonstrated improved properties, elimination of casting porosity, available tool materials, and the established successful processing procedures, FSP of cast NiAl bronze has been demonstrated to be a viable commercial process to enhance fabrication of propellers and potentially other bronze structures.

Iron Based Alloys

Since the initial studies performed by Thomas et al.^{38, 39}, considerable progress has been reported for FSW of steels⁴⁰⁻⁴⁸. Due to the high operating temperature ($>1100^\circ\text{C}$), the tool material is of utmost importance and is the most critical issue for commercial usage of FSW in ferrous alloys. Thus, tool materials will be addressed separately below. Briefly, one of the significant benefits of FSW is the absence of melting, i.e., FSW is solid state. Because there is no melting, there are no harmful gas emissions when welding ferrous alloys containing Cr, Ni, or Mn²⁸. During FSW of an austenitic stainless steel, Mahoney demonstrated harmful gas emissions below the detectability limits, and thus emissions well below industry standards²⁸. This health benefit increases in importance as

monitoring agencies lower harmful emission standards.

Many investigators have illustrated the microstructural and mechanical property benefits associated with friction stir welding (FSW) of ferrous alloys. Depending on the alloy, mechanical strength in the weld nugget generally exceeds that of arc weldments and in many cases, exceeds parent metal strength. Post-weld mechanical property benefits can be attributed to the fully recrystallized, fine grain microstructure. For example, Posada et al. reported on welds made in DH-36 steel using a tungsten alloy tool⁴⁷. Radiographic inspection showed full-penetration, sound welds. However, radiography also illustrated tool material mixed into the stir zone. Even with tool debris, transverse tensile tests showed overmatching of the weld, with failures occurring in the base metal. All-stir-zone tensile tests (longitudinal orientation) showed yield strength $\sim 50\%$ higher than the base metal, and tensile strength $\sim 33\%$ higher than the base metal. Johnson, et al. reported FSW of C-Mn steel plates, using tungsten-rhenium tools⁴⁰. The welds were made in 12 mm thick plate using tools with a 7.5 mm pin length. Welds were made from both sides of the plate to achieve full penetration. Tool wear was a significant issue. Hardness was shown to be higher in the weld zone than in the base material and longitudinal microtensile specimens taken from the weld illustrated yield and tensile strengths consistent with microhardness results, i.e., again improved mechanical properties. Numerous examples such as these, for many ferrous alloys, can be found in the literature all with the same conclusions, i.e., ferrous alloys can be friction stir welded resulting in defect free welds with excellent post-weld mechanical properties. However, when refractory metal tools are used, tool debris is found in the weld and the tool life is limited.

Fig. 4 Microstructural morphologies in NiAl bronze a) as-cast, b) Lamellar, c) Fine grain, and d) Widmannstätten structures after FSP.

Recently, significant success has been achieved in FSW of ferrous alloys using polycrystalline cubic boron nitride PCBN as the tool material⁴⁹⁻⁵⁴. For example, following FSW of a super duplex stainless steel, defect free welds were achieved and the yield and ultimate strengths of the welds were higher than the base material (846 MPa and 1045 MPa following FSW compared to 705 MPa and 886 MPa for the parent metal)⁵². However, when using PCBN for the tooling material, there was no tool wear. PCBN has the unique properties of being an ultra hard material (1500-3500 Vickers) while also possessing chemical and thermal stability up to 1200°C. Thus, PCBN is potentially a prime candidate for use as a friction stir welding tool material to join high temperature metals.

Tool Material for FSW of Ferrous Alloys

Most recently, a new PCBN grade, MS80, was developed specifically to friction stir weld ferrous alloys. The MS80 grade of PCBN offers excellent wear resistance and increased resistance to fracture. The improved toughness of the MS80 grade, compared to MS100, a conventional cutting tool grade, increased design flexibility thus further enhancing FSW performance and providing deeper weld penetration (up to 9mm). An illustration of the latest PCBN tool design is shown in Figure 5a. In early studies, using the commercial MS100 PCBN grade, a conventional tool design was used, Figure 5b. This early tool design was limited to a smooth concave shoulder with a pin length 6 mm containing three small flats. The combination of the MS100 material and the simple featureless design were adequate to demonstrate the feasibility to friction stir weld ferrous alloys and has provided welded material for microstructural studies. However, with MS100, a more aggressive tool design was not possible. Also, this material/design combination was not adequate for commercial welding applications and could not survive FSW of all ferrous alloys.

The MS80 grade offered increased toughness with reduced wear compared to the MS100. Accordingly, it was now possible to add features to the pin, without risking premature fracture. More complex pin features enhance metal flow from the front of the tool to fill the cavity left in the tool's wake. In other studies, pin features have been shown to expand the range of possible weld parameters over

which defect free welds could be made²⁸. A step spiral pattern was added to the MS80 PCBN pin, Figure 5a. Although not as efficient as a thread in moving metal, this step spiral pin design did increase metal flow.

Although a significant improvement in performance was realized, the step spiral pin with a smooth concave shoulder still included a tool tilt of 2-3°. With a tool tilt, FEA analysis illustrated inhomogeneous loading especially on the trailing edge of the tool shoulder and a small increase in load behind the pin possibly due to the advancing load on the pin, Figure 6. These high loads at the trailing edge of the tool produced high cyclic fatigue loading during FSW resulting in premature cracking in the shoulder. It would be beneficial to uniformly load the tool using the entire tool surface area to reduce compressive loads.

A second tool design iteration, again possible with the higher toughness MS-80, enabled features to be added to the tool shoulder and reversed the shoulder slope to convex. This new design, reduced loads normal to the tool by ~40%, distributed the loads more homogeneously over the tool shoulder, and allowed x and y tool movement without tilting the tool. In addition, this design reduced the surface undercut associated with plunging the heel of the shoulder. This latest tool design change further increased tool life and has been shown to make defect free welds in high strength ferrous alloys over an even broader range of weld parameters.

PCBN FSW tools have been successfully used to evaluate the ability to friction stir weld a large number of high temperature alloys including ferritic steels, ferritic stainless steels, austenitic stainless steels, nickel-base superalloys, and Invar. Tool life of 80 meters has been demonstrated in A-36 steel, and very low wear was observed on all other alloys⁵⁴. Wear is a secondary issue for most welding applications using PCBN. Primarily, tool life is limited by fracture. Grade developments, as shown above, have increased fracture toughness and in concert increased tool life and have accommodated design changes for improved metal

Fig. 5 a) Photograph of a friction stir weld tool with an MS80 PCBN insert contained in a metal housing. The PCBN has a step spiral pin with a convex shoulder with features to enhance metal flow. b) The early simple tool design fabricated from MS100 PCBN.

Fig. 6 FEA result illustrating nonuniform loading on the tool shoulder when the tool is tilted during FSW.

flow. Currently, research and development is continuing to further enhance PCBN fracture toughness.

Summary

Friction stir welding and processing of copper alloys has been demonstrated to be commercially viable. Defect free welds have been demonstrated in very thick Cu (50 mm) in one pass. Also, FSP has been used to eliminate casting porosity and significantly increase the mechanical properties of cast NiAl bronze. Further, long life tool materials are available for the temperature range required for FSW/P of copper alloys (900°C to 1000°C).

Friction stir welding of ferrous alloys is a greater challenge due to the increased temperature (>1100°C), but many investigators have demonstrated defect free welds and increased mechanical properties following FSW. Unfortunately, tool life is limited with refractory metals. However, polycrystalline cubic boron nitride (PCBN) tools are showing considerable promise for long-life performance. Because of PCBN grade improvements, e.g., MS80 grade, pin tool lengths up to 9 mm have been successfully demonstrated. In addition, the improved toughness of the MS80 has allowed tool design changes to increase metal flow and potentially expand the weld parameter window including a step spiral feature on the pin and a convex shoulder tool design. This tool design coupled with the MS-80 PCBN grade results in the longest tool life when friction stir welding ferrous alloys.

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