CHAPTER 6

Friction Stir Welding of Ferrous and Nickel Alloys

Carl D. Sorensen and Tracy W. Nelson
Department of Mechanical Engineering, Brigham Young University

FRICTION STIR WELDING (FSW) is a solid-state joining process invented by The Welding Institute of Cambridge, England (Ref 1). In the FSW process, a rotating tool containing a pin and a shoulder is plunged into the joint between two workpieces, generating heat by friction. Once the heat has built up to the desired level, the tool is translated along the joint. Plasticized base material passes around the tool, where it is consolidated due to force applied by the shoulder of the tool.

Friction stir welding has been applied to metals with moderate melting points. Initially, FSW was applied primarily to aluminum alloys, which could be easily welded due to the relatively low softening temperatures of these alloys. Other relatively soft metals, such as copper, lead, zinc, and magnesium, have also been welded. In contrast, for a number of years it was difficult to weld ferrous alloys and other high-softening-temperature metals due to the lack of suitable tool materials.

Until recently, there were no tool materials that would stand up to the high stresses and temperatures necessary for FSW of materials with higher melting points, such as steels, stainless steels, and nickel-base alloys. In 1998, tungsten alloys and polycrystalline cubic boron nitride (PCBN) were developed to create FSW tools for use in steel, stainless steel, titanium alloys, and nickel-base alloys. Properties of the resultant welds have been shown to be outstanding. Although some issues remain (primarily limited tool life with tungsten-base tools), FSW has been demonstrated as a technically and economically feasible process in high-temperature materials. This chapter summarizes research work performed at a number of different laboratories to make FSW of high-temperature materials a reality. It covers the development of suitable tools, welding equipment, and welding procedures, describes the characteristics of the resulting weldments, and describes the variety of materials that have been tested with the FSW process.

6.1 Tool Materials

The requirements for an FSW tool in high-temperature materials (HTM) are significant. Obviously, the tool must maintain sufficient strength to constrain the weld material at softening temperatures in excess of 1000 °C (1830 °F). Perhaps less apparent, the tool must also be resistant to fatigue, fracture, mechanical wear, and chemical reactions with both the atmosphere and the weld material. To date, two classes of materials have been found that meet these requirements: refractory metal tools and superabrasive tools.

Refractory Metal Tools. The first class of tool materials to be used for FSW of HTM were refractory metal tools. Initially, the tool materials were considered proprietary. Eventually, however, the composition of the tools was revealed.

Tungsten was used as a tool material in many of the early welds performed (Ref 2). Tungsten appeared to have sufficient hot strength to serve

as an FSW tool but suffered problems on the plunge due to its high ductile-to-brittle transition temperature. This necessitated preheating of the tool to temperatures above 300 °C (570 °F) and the drilling of a pilot hole for the tool (Ref 3).

Later tool materials included additions of up to 25% Re to tungsten, which lowered the transition temperature to below room temperature. Tungsten-rhenium tools show increased fracture resistance and improved wear resistance compared to pure tungsten and appear to have become the most widely used refractory metal. Development of production processes continues to improve the tool life of tungsten-rhenium tools. Molybdenum has been used on at least one occasion as a tool material for FSW of steel (Ref 4).

Early tungsten and tungsten-rhenium tools showed a tendency to wear rapidly in the weld, leading to macroscopic inclusions of tool material in the weld zone. Later tools were much more resistant to this problem, but the tool material often continues to dissolve in the weld, leaving a tungsten-enriched stir zone. Furthermore, some researchers report that microstructural changes in the tool indicate ongoing deformation during welding.

Refractory metal tools have been used to weld low-carbon steels, carbon-manganese steels, austenitic stainless steels, and ferritic stainless steels.

Tungsten-rhenium tools show good fracture toughness and can be used for relatively thick welds (up to 13 mm in a single pass). Reported tool life ranges from a quarter meter (tens of inches) up to approximately 4 m (over 10 ft).

Superabrasive Tools. The second class of tool materials used for FSW of HTM is superabrasives. Superabrasives are materials that are formed in presses under extreme temperature and pressure. The two superabrasives that have been used in FSW are polycrystalline diamond (PCD) and PCBN. Both materials consist of small crystals of ultrahard material (diamond or CBN) bonded together in a skeletal matrix with a second-phase material that serves as a catalyst for the formation of the matrix. Reference 5 gives a summary of the characteristics of superabrasive materials.

Polycrystalline diamond has been used for aluminum-matrix composites reinforced with particulate silicon carbide, boron carbide, or alumina. It also shows promise as a tool material for welding titanium, although this work is only in a preliminary stage.

Polycrystalline cubic boron nitride has been used to weld carbon steels, carbon-manganese steels, high-strength, low-alloy (HSLA) steels, high-strength pipeline steels, austenitic stainless steels, duplex stainless steels, dual-phase steels, nickel-base alloys, and other exotic alloys. It has been tested in titanium alloys, with inconsistent results. At times, it performs well; at others, chemical reactions with the workpiece cause rapid wear.

Superabrasive materials can be made only in relatively small pieces, due to the high pressure required for manufacturing. Furthermore, these materials are very difficult or impossible to braze. Therefore, superabrasives are used in a composite tool design, as described by Ref 5.

Early trials of PCBN tools in 316L stainless steel showed tool life of 1 to 4 m (3 to 13 ft), with life limited by fracture. Continued efforts at improving the design of the composite tools, together with improvements in the grade of the PCBN, have greatly reduced the tendency of the tool to fracture and have increased its life significantly (Ref 6). The most recent tool life test on PCBN tools showed a tool life of 80 m (260 ft) in 1018 steel.

Polycrystalline cubic boron nitride tools produce an exceptionally smooth surface on the weld. This is thought to be due to the low coefficient of friction between PCBN and the weld metal.

The major limitation in PCBN tools is the maximum depth of the weld. Although a pin 13 mm (0.5 in.) in length has been tested, for practical purposes, the maximum depth of welding at the present time is 10 mm (0.4 in.). Ongoing efforts in the design of PCBN tools should lead to increases in pin length. MegaStir Technologies, the provider of PCBN tools, has plans to achieve a 13 mm weld depth within a year.

Over the past several years, significant efforts were expended on developing tougher, more wear-resistant grades of PCBN (Ref 6). Efforts to understand the effects of different binder phases, ratio of CBN to binder phase, and grain size distributions of CBN on performance were investigated. Performance was evaluated via a turning test on 304L stainless steel. Those grades exhibiting greater wear resistance in the turning tests were subsequently evaluated via FSW in 304L to compare wear results and evaluate toughness.

The PCBN grade-development program was quite successful in that tougher, more wear-resistant grades of PCBN were developed. In addition to improved wear resistance, the improved toughness of the new grades has

enabled both deeper weld penetration (up to 12 mm, or 0.47 in.) and threaded-type features to be incorporated into the tool design. These features are illustrated in Fig. 6.1.

6.2 FSW Equipment

The FSW equipment for high-temperature materials requires improved cooling, higher-precision spindles, and increased machine stiffness compared to that required for aluminum.

Tool Cooling. The welding zone temperatures frequently reach 900 to 1200 °C (1650 to 2190 °F). Further, the materials used for the tool (either tungsten alloys or tungsten carbide shanks) have high thermal conductivity relative to the tool steel commonly used for aluminum. To prevent damage to the spindle bearings and to establish a consistent thermal environment for the tool, cooling of the tool shank is required.

Two different methods for cooling the tool have been used. In the first, a hollow drawbar is used to conduct coolant directly onto the back end of the tool shank. This method provides the highest cooling rate but sometimes provides a machine-specific thermal environment that can make it difficult to transfer operating parameters between machines. There can also be difficulties in establishing a consistent seal between the tool holder and the shank.

The second method used for cooling the tool is to mount a cooled tool holder in the machine spindle. The holder can be designed for any spindle configuration, and the cooling is consistent from machine to machine. The major disadvantage of this cooling method is that the cooled tool holder is generally less stiff than the machine spindle.

Precision Spindles. Strengths of metallic tools at process temperatures are substantially higher than the aluminum alloys being welded. In contrast, for high-temperature materials, the tool strengths are only marginally higher than the alloys being welded. Thus, tool deformation for metallic tools and fracture for PCBN tools are common.

Spindle runout has been demonstrated to be a significant factor limiting the life of PCBN tools. Many FSW machines built for aluminum alloys have relatively high spindle runout, because they were designed primarily to accommodate high process loads. Producers of PCBN tools have recognized the importance of precise spindles and specify a maximum spindle runout of 0.01 mm (0.0004 in.) (Ref 7). Failure to meet this spindle runout requirement has led to premature tool fracture.

Stiff Machines. Cyclic process loads in FSW tend to be higher in many high-melting-temperature alloys than in aluminum. Deflections under load can lead to problems with fatigue failure, particularly with PCBN tools. To minimize these problems, the stiffness for the machine is specified. A deflection of 0.75 mm (0.030 in.) under a load of 45 kN (10 kip) is suggested by Ref 7.

6.3 Weld Metal Properties

A few studies have carefully examined the metallurgy of welds produced in a variety of HTM by FSW. This section summarizes the detailed property and structure results.

6.3.1 Ferritic Steels

Reference 3 reported on welds in low-carbon and Fe-12%Cr steels, using a tool that was later reported to be tungsten-base. The weld zone

(a) (b) (c)

Fig. 6.1 Pin features produced on polycrystalline cubic boron nitride friction stir processing tools, including (a) flats, (b) helical threads, and (c) a combination of convex scrolled shoulder and helical threaded pin

was shown to contain a range of martensite, bainite, and ferrite structures, along with tool debris. A unique feature of this study is a preliminary look at the typical costs of welding, showing that FSW could easily be superior to a variety of other welding processes.

Reference 8 reported on welds made in DH-36 using a tungsten alloy tool. Radiographic inspection showed full-penetration, sound welds. However, there were indications in the radiograph that tool material was being mixed into the stir zone. Transverse tensile tests showed overmatching of the weld, with failures occurring in the base metal. All-stir-zone tensile tests showed yield strength approximately 50% higher than the base metal, and tensile strength approximately 33% higher than the base metal.

Reference 9 evaluated the feasibility of welding 1018 steel using tungsten- and molybdenum-base alloy tools. Observations of the peak temperature seen during the weld were extrapolated to give a probable maximum weld temperature of 1200 °C. The thermomechanically affected zone was not readily observable in the microstructure of the weld, likely due to the allotropic transformation on cooling. Evidence of microalloying between the tool and the workpiece was found. Stir-zone microstructure was found to consist of ferrite, grain-boundary ferrite, and fine pearlite. In the stir zone, the structure was found to be finer near the shoulder and coarser away from the shoulder. Tensile properties of the resulting welds were found to be acceptable.

Reference 10 reported on the welding of S355 carbon-manganese steel plates, using tungsten-rhenium tools. The welds were made in 12 mm (0.5 in.) thick plate using tools with a pin length of 7.5 mm (0.3 in.). Welds were made from both sides of the plate in order to achieve full penetration. Tool wear was a significant issue. One significant microstructural observation was the tempering of the first pass by the heat from the second pass. Hardness was shown to be higher in the weld zone than in the base material. Longitudinal microtensile specimens were taken from the various regions of the weld, and yield and tensile strengths were consistent with microhardness results. Charpy impact testing revealed that the toughness at –40 °C (–40 °F) was equivalent for the weld material and the base plate. At higher temperatures, toughness for the weld material was significantly lower than the base metal, with the lowest toughness in the heat-affected zone (HAZ). No comparison was made between the toughness of friction stir welds and those produced by fusion welding processes.

Reference 11 reported on FSW of DH-36 steel with W-25%Re tools. No measurable change in tool dimension was found after a welding distance of approximately 1.8 m (5.9 ft). Tensile properties were found to be acceptable, in spite of some defects in the weld zone.

Scientists (Ref 12) welded HSLA-65 using tungsten-base tools. Subjected to bend tests, a 10 mm (0.4 in.) thick weld passed, and a 6 mm (0.24 in.) thick weld failed when bent with the root in tension, due to the formation of surface cracks. Tensile properties of the 10 mm thick welds exceeded the specifications for the base metal. Some 6 mm thick welds exceeded the plate specifications, while others were approximately 10% below the plate specifications. Charpy V-notch (CVN) toughness at both –29 and –40 °C (–20 and –40 °F) were below the base material toughness but exceeded the minimum specification of the plate. The surface of the welded material was found to have small defects due to the roughness caused by the interaction between the shoulder and the surface of the plate. Salt spray corrosion tests indicated no preference for corrosion in the weld zone.

Reference 13 reported on welds in 6.4 and 12.7 mm (0.25 and 0.5 in.) thick HSLA-65 using tungsten-rhenium tools. Radiographic inspection showed traces that may indicate the formation of a wormhole defect at the start of the weld. Postweld distortion of the 12.7 mm plate was measured to be less than that in submerged arc welded (SAW) or gas metal arc welded (GMAW) plates. The welded plates were tested by an underwater explosion test known as shock-holing; the welded specimen met the shock-hole requirements in spite of the radiographic indications and pieces of broken tool material that remained in the weld. Tensile strength of the weld zone was slightly less than the base material. Charpy toughness of the weld zone was significantly less than the base material and showed extreme variability, which was unexplained. Average Charpy values exceeded the specification for HSLA-65 welds.

Reference 2 reported on welds in 0.29C-Mn-Si-Mo-B quenched and tempered steel using a PCBN tool. Weld thicknesses included both 6.4 and 12.7 mm. Microhardness of the stir zone was found to approximately equal that of the base metal. Significant softening was observed in the HAZ. Transverse tensile properties of

friction stir weldments were found to be less than the base metal but greater than comparison GMAW welds. The CVN toughness in the weld zone was found to be at or above the base metal but below the toughness of the GMAW welds, except in the case of the HAZ in the 6.4 mm welds, where the FSW toughness was more than twice the GMAW toughness. In this study, the filler material for the GMAW was carbon steel, so it is expected that the weld material will be both softer and tougher than the weld material with the same composition as the base metal in the friction stir weld.

6.3.2 Austenitic Stainless Steels

Researchers (Ref 14) welded 304L stainless using a tungsten alloy tool. They reported extrapolated peak temperatures in the weld zone of approximately 1200 °C. They reported equiaxed grains in the stir zone, with a grain size slightly reduced from the base metal. They also noticed narrow bands in the stir zone but made no determination as to the origin or detailed structure of the bands. The weld material was found to be stronger than the base metal and to exhibit excellent ductility, with elongation to fracture of more than 50%. Longitudinal residual stresses were found to be close to the base material yield stress.

Researchers (Ref 15) reported on welding of 304L and AL-6XN stainless steels. They found a highly refined stir-zone microstructure, with an unidentified dark banded structure in the stir zone. They reported increased microhardness in the weld zone and excellent ductility for both 304L and AL-6XN. They also described the difficulty of achieving sound welds in AL-6XN, because a number of pores were found in the resulting weld. A later report (Ref 16) gave properties of friction stir welds and AL-6XN base metal. Weld metal was higher in yield strength (700 MPa compared to 430, or 102 ksi compared to 62) and ultimate strength (930 MPa compared to 780, or 135 ksi compared to 113) but lower in ductility (50 to 60% reduction in area compared to 75%; 28% elongation compared to 46%). The elongation of the friction stir welds was only slightly below the 30% minimum elongation specified for the base metal.

Scientists (Ref 17) analyzed friction stir welds made in 304 stainless steel. They found a banded structure similar to that identified by Reynolds et al. The dark bands were found to be narrow regions of ultrafine grains. The advancing side of the stir zone was found to contain fine sigma particles as well as even finer carbide precipitates.

Researchers (Ref 18) investigated sigma formation in FSW of various stainless alloys with compositions at various distances from the sigma + austenite region of the Fe-Ni-Cr ternary diagram. They were able to predict the propensity for sigma formation and hypothesized that sigma formation was a marker for recrystallization in 304L. They also demonstrated that welding parameter changes affected the amount and location of sigma.

Later studies (Ref 19) with a convex shoulder, step spiral (CS4) pin tool showed dramatically reduced sigma formation in 304L with the new tool design. No sigma has yet been identified in welds with the new tool.

Because the temperature of the weld zone exceeds 800 °C (1470 °F), the possibility of sensitization exists. A scientist (Ref 20) explored both sensitization and stress-corrosion cracking (SCC) in FSW 304L. The welds analyzed qualified as nonsensitized during an oxalic acid etch test. Double-loop electrochemical potentiokinetic reactivation testing showed regions of increased corrosion susceptibility away from the surface of the specimen. U-bend specimens in boiling 25% NaCl showed no increased SCC susceptibility compared with the base metal.

6.4 Materials Welded with PCBN

As part of the evaluation of PCBN as a tool material for FSW of high-temperature materials, a variety of different alloys have been tested. The materials that have been tested, along with results of preliminary mechanical testing, are given in this section. Table 6.1 summarizes the results of this testing.

6.4.1 Ferritic Steels

A-36. Almost 200 m (over 200 yd) of A-36 have been welded using PCBN tools. A wide range of weld parameters has been found to give fully consolidated welds. Surface quality is excellent. No mechanical property data are available.

Quenched and Tempered Carbon-Manganese Steel. Scientists (Ref 21) welded 6.4 mm (0.25 in.) thick quenched and tempered carbon-manganese steel using PCBN. Tool wear was very low but not measured quantitatively. Greatly refined grain structures in the stir

zone were observed, both in the prior-austenite grains and in the transformation product. The microhardness in the weld zone was approximately the same as that of the base metal. The HAZ showed a hardness reduction from 550 to 350 HV. Transverse tensile specimens exhibited a strength approximately 70% of the base metal, with failure in the HAZ. Elongation as measured in the transverse tensile test was reduced from 9.5% in the base metal to 2.6%. However, because of the reduction in strength in the HAZ, it is likely that this elongation is nonuniform and hence greatly underestimates the ductility of the weldment.

DH-36 steel has been test welded with PCBN tools. It appears to weld at approximately the same parameters as A-36. Fully consolidated welds at travel speeds of up to 250 mm/min (10 in./min) have been achieved. No mechanical properties are presently available.

HSLA-65 steel has been welded at travel speeds of up to 200 mm/min (8 in./min). The resulting welds are of excellent quality. Surface appearance is excellent. The yield and ultimate strengths of all-weld-material specimens are 597 and 788 MPa (86.6 and 114 ksi), respectively, compared with 605 and 673 MPa (87.7 and 97.6 ksi) in the base metal. Elongation and reduction in area are 14.5 and 77% for the weld material, compared with 18.7 and 81% for the base metal. Tool life in HSLA-65 appears to be excellent, although it has not been quantified due to the lack of available metal for carrying out the life test.

X-65. Reference 22 reported postweld mechanical properties in 6 mm (0.25 in.) thick FSW X-65 pipe. Transverse tensile strengths were equivalent to the base metal. All tensile samples fractured in the base metal well removed from the weld or HAZ. Charpy impact results in the weld nugget and HAZ exceeded that of the base metal at –50, 0, and 20 °C (–58, 32, and 68 °F). These results are shown in Fig. 6.2.

L-80, X-80, and X-120. These pipeline steels were welded using PCBN tools. All of these alloys appear to be readily weldable by FSW. An in-depth examination of these alloys is presented by Ref 23. Welding parameters for X-80 were 550 rpm and 100 mm/min (4 in./min) with argon shielding gas. No transverse tensile tests were done on this weld, but the HAZ and stir-zone microhardnesses were higher than the base material. Welds were fully consolidated. A small region on the advancing side of the stir zone appears to have higher hardness than the rest of the weld.

Dual-Phase Steel. Dual Ten 590 dual-phase steel (United States Steel Corporation)

Table 6.1 Results of preliminary friction stir welding testing with polycrystalline cubic boron nitride tools

	Yield strength (weld/base metal)		Ultimate strength (weld/base metal)		rpm/travel		
Material	MPa	ksi	MPa	ksi	mm/min	in./min	Comments
A-36	N/A		N/A		600/150	24/6	80 m (260 ft), 79 plunges tool life, 7
Quenched and tempered C-Mn steel	1040/1400	151/203	1230/1710	178/248	545/130	21/5	. . .
DH-36	N/A		N/A		500/200	20/8	. . .
HSLA-65	597/605	87/88	788/673	114/98	500/200	20/8	. . .
L-80	N/A		N/A		550/100	22/4	. . .
X-80	N/A		N/A		550/100	22/4	. . .
X-120	N/A		N/A		550/100	22/4	. . .
Dual Ten 590 dual phase	496/340	72/49	710/590	103/86	450/240	18/9.5	. . .
304L	51/55	7.4/8.0	95/98	13.8/14	400/75	16/3.0	. . .
316L	434/338	63/49	641/674	93/98	550/80	22/3.2	. . .
AL-6XN	N/A		N/A		350/25	14/1.0	. . .
301L	N/A		N/A		600/300	24/12	Lap weld, small-diameter tool
430	N/A		N/A		550/80	22/3.2	. . .
2507 super duplex	762/705	110/102	845/886	123/128	450/60	18/2.4	. . .
201	193/103	28/15	448/406	65/59	1000/100	39/4.0	16 mm (0.6 in.) tool
600	374/263	54/38	719/631	104/91	450/56	18/2.2	. . .
718	668/1172	97/170	986/1392	143/202	500/50	20/2.0	16 mm (0.6 in.) tool
Narloy-Z	N/A		N/A		450/100	18/4.0	demonstration only
Invar	N/A		N/A		600/150	24/6.0	demonstration only
Ni-Al bronze	420/193	61/28	703/421	102/61	1000/102	39/4.0	. . .

has been welded in a variety of geometries, including automotive sheet. Spindle speeds were 450 to 550 rpm, with travel speeds varying from 150 to 340 mm/min (6 to 13 in./min). Argon was used as a shielding gas. Welds were fully consolidated. Microhardness in the weld zone is higher than the base material. Transverse yield and tensile strengths of 71 and 103 MPa (10 and 15 ksi) are higher than that of the base material (49 and 85 MPa, or 7.1 and 12 ksi). Elongation is only slightly lower than the base metal (22% compared with 25%). Preliminary forming studies have indicated that the weld zone forms about as well as the base metal.

6.4.2 Austenitic Stainless Steels

304L. A 6mm (0.25 in.) thick 304L plate was welded using PCBN tools. Spindle speed was 400 rpm; travel speed was 75 mm/min (3 in./min). A variety of welding parameters were tried. Different parameters were found to lead to widely varying microstructures. Under some conditions, sigma phase was found to be present in the stir zone (Ref 17). Yield strength, tensile strength, and ductility were almost identical in the weld and base metal. Tool life in 304 exceeded 30 m (98 ft). Tool wear in austenitic stainless steels appears to be higher than in ferritic alloys, possibly due to chemical interactions between the tool and weld material.

316L. Reference 24 reported on the welding of 316L using PCBN tools. Welds had full consolidation and good surface appearance. Transverse yield and tensile strength of the weld were essentially the same as the base metal. No significant softening was reported in the HAZ. Ductility of the resulting welds is excellent.

301L. Alloy 301L was welded in a lap weld configuration. Sheet thickness was 1.5 mm (0.06 in.). To avoid wrinkling on the free surface of the lap, a small-diameter tool (10 mm shoulder, 3 mm pin) was used. The small-diameter tool required correspondingly higher rotation speeds to achieve welding temperatures. The joint appeared to be fully consolidated and defect-free under optical inspection. The joint was tested for corrosion in a salt spray environment. Slight corrosion appeared in the HAZ. Significant corrosion appeared in the crevice between the flash and the top surface. Better control of the flash or mechanical removal of the flash following welding are expected to improve the corrosion performance of the lap weld.

AL-6XN has been welded with PCBN tools. Microhardness values look appropriate. It is very difficult to fully consolidate the advancing side of the weld. No mechanical properties data are available. Further weld development on this alloy is dependent on improved PCBN grades.

6.4.3 Type 430 Stainless Steel

Reference 24 reported on the welding of type 430 stainless steel using PCBN tools. The weld was performed at 550 rpm, with a travel speed of 80 mm/min (3.15 in./min). The weld was a partial penetration bead-on-plate weld. No mechanical property data were obtained. The weld appeared to be fully consolidated. Surface

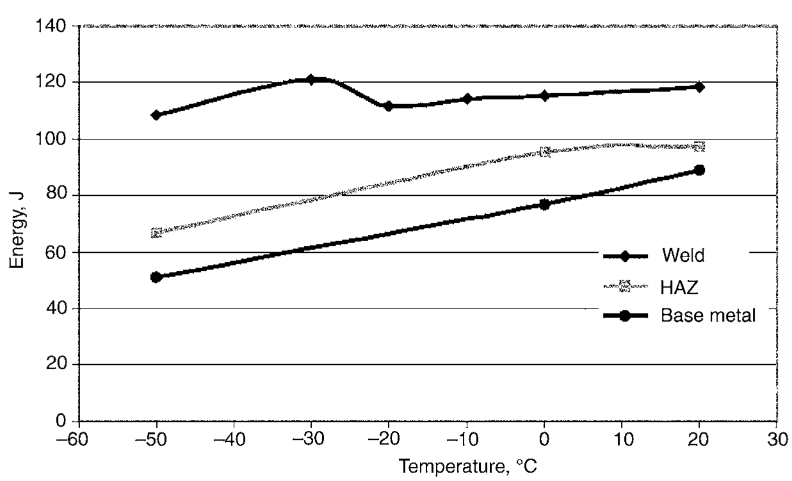

Fig. 6.2 Charpy impact results. HAZ, heat-affected zone. Courtesy of Z. Feng, Oak Ridge National Laboratory

quality was excellent. No HAZ softening was observed. The weld zone had higher microhardness than the base material.

6.4.4 Super Duplex Stainless Steel (2507)

The SAF 2507 (UNS S32750) super duplex stainless steel was welded with a 25 mm (1.0 in.) diameter PCBN tool (Ref 25). Welding parameters of 450 rpm and 60 mm/min (2.4 in./min) produced sound welds with an excellent surface finish. The resulting microstructure was fine-grained (average 4 μm in the stir zone) and equiaxed. Ferrite content varied from 40 to 50% across the weld zone, compared with 45% in the base metal. Corrosion resistance of the weld was determined by ASTM G-48C, which measures the critical pitting temperature (CPT). The CPT for the FSW joints was 65 °C (150 °F compared to 40 to 55 °C (100 to 130 °F) for typical arc welding processes. The yield and ultimate strengths of the welds were 846 and 1045 MPa (122.7 and 151.5 ksi), which were higher than the base metal (705 and 886 MPa, or 102 and 128 ksi). Transverse elongation of the weld was 18%, compared with 30% elongation in the base material.

6.4.5 Nickel-Base Alloys

Alloy 201. A 3.2 mm (0.125 in.) thick alloy 201 sheet was welded in a butt joint configuration using a tool with a 16 mm (0.63 in.) diameter shoulder. The weld was a partial penetration weld, to avoid complications associated with getting the pin close to the backing plate. Yield and tensile strengths of the weld metal were 193 and 448 MPa (28 and 65 ksi), respectively, compared with 103 and 406 MPa (15 and 60 ksi) for the base material. Elongation was 34% for the transverse specimen, compared to 50% for the base material. Very little tool wear was observed in this weld.

Alloy 600 plates (~6 mm thick) were butt welded using a PCBN tool. Spindle speed was 450 rpm, and travel rate was 56 mm/min (2.2 in./min). Substantial grain refinement was observed in the stir zone. Mechanical properties were excellent. Yield strength and ultimate strength were 370 and 720 MPa (54 and 104 ksi), respectively, compared with 265 and 630 MPa (38 and 92 ksi) for the base metal. Elongation was reduced from 50% in the base metal to 27% in the transverse weld specimen. However, it is important to recognize that the nonuniform deformation in transverse weld specimens generally results in reduced elongation measurements.

Alloy 718 sheets (3.2 mm thick) were butt welded using a tool with a 16 mm diameter shoulder. Spindle speed was 500 rpm, and travel speed was 50 mm/min (2.0 in./min). The weld was fully consolidated and exhibited substantial grain refinement as compared with the base material. Yield and ultimate strengths of the transverse weld specimens were 670 and 985 MPa (97 and 143 ksi), respectively. There was not enough material available to make a basemetal measurement. However, for comparison purposes, typical yield and tensile strengths are 460 and 895 MPa (67 and 130 ksi) for alloy 718 in the annealed condition and 1170 and 1390 MPa (170 and 202 ksi) in the precipitation-hardened condition.

6.4.6 Specialty Alloys

Narloy-Z plates (~6 mm thick) were welded at Boeing's Huntington Beach facility using the ESAB SuperStir machine. The weld was made at 450 rpm and 100 mm/min (4.0 in./min). The surface finish of the resulting weld appeared excellent. There was no visible tool wear. Microstructural and tensile data are not available.

Ni-Al Bronze. Cast Ni-Al bronze has been friction stir processed (FSP), as reported by Ref 26. Yield strength of the FSP material (420 MPa, or 61 ksi) was more than double that of the cast alloy (193 MPa, or 28 ksi). Tensile strength also increased substantially due to the processing (700 MPa compared with 420, or 102 ksi compared with 61). However, elongation dropped to 14%, compared with 20% in the as-cast material. Surface finish and tool life were both excellent. In addition to the improvement in as-cast properties, FSP was demonstrated to reduce or eliminate internal porosity due to casting defects.

Invar has been welded in a variety of thicknesses with different welding parameters. Surface finish has been excellent. Weld distortion has been low. Welds are fully consolidated. No mechanical properties are available at this time.

6.5 Additional Benefits

One of the mounting obstacles facing welded fabrication is the mandated restriction of hazardous fumes from arc welding processes. Both

hexavalent chromium and manganese are under heavy scrutiny in the United States and European communities. It is anticipated that the new Occupational Safety and Health Administration (OSHA) restrictions on permissible exposure limits of hexavalent chromium will dramatically increase the cost of welded fabrication in the United States.

Generally, solid-state welding processes are not known for hazardous fume generation. Although it was assumed that FSW would fall into this category, FSW had never been evaluated specifically for hazardous fumes. Reference 27 compared both gas tungsten arc welding (GTAW) and FSW to evaluate the two in a side-by-side evaluation. Both processes were completely enclosed in sealed containers with both inlet and outlet filters. Over the same duration of weld time, the GTAW process generated 1.88 and 0.02 mg/m^3 of manganese and hexavalent chromium, respectively. In contrast, fume generation for FSW was below detectable limits. The results of this investigation are shown in Table 6.2.

6.6 Summary

Friction stir welding of materials with high softening temperatures has been demonstrated to be technically feasible for a wide range of alloys. Pin tool lengths of up to 7.5 mm (0.3 in.) have been reported in the literature, which should allow single-sided welds of up to 8 mm (0.315 in.). Single-sided welds in thicknesses up to 6.4 mm (0.25 in.) have been successfully achieved. Double-sided welds of up to 13 mm (0.5 in.) have been demonstrated.

Two major classes of tool materials have been used for FSW of high-temperature materials. Refractory metal alloys, primarily W-25%Re, have been used to successfully weld carbon steels, austenitic stainless steels, and titanium. Initially, tool wear was severe, but recent improvements in processing of the tool material have led to decreased tool wear and increased tool life. Tool life as long as 4 m (13 ft) per tool has been reported. Initial problems with tool material contamination of the weld appear to have been greatly reduced.

Superabrasive tools, primarily PCBN, have been used to successfully weld ferritic steels, ferritic stainless steels, austenitic stainless steels, nickel-base superalloys, Invar, and Narloy-Z. Attempts to weld titanium with PCBN tools have been inconclusive. Tool life of 80 m (260 ft) has been demonstrated in FSW of 1018 steel, and very low tool wear has been reported on all other alloys. The primary concern in tool life continues to be fracture, and developments in PCBN grades continue to improve the fracture toughness of the FSW tools. The PCBN tools provide an extremely smooth finish when used for FSW or FSP.

Properties of friction stir welds in all of the alloys tested appear to be excellent. In some cases, they exceed the properties of the base metal. In virtually all cases, they exceed the properties of alternative fusion welding processes. Further, FSW has been demonstrated to produce lower distortion than GMAW and SAW in the welding of 13 mm thick HSLA-65 steel.

Table 6.2 Airborne emissions associated with welding 304 stainless steel comparing gas tungsten arc welding to friction stir welding

	Element emission, mg/m^3			
Welding process	Chromium	Copper	Manganese	Hexavalent chromium
Tungsten inert gas welding	0.25	0.11	1.88	0.02
Friction stir welding	<0.03	<0.03	<0.02	<0.01

Courtesy of M.W. Mahoney, Rockwell Scientific

REFERENCES

1. W.M. Thomas, E.D. Nicholas, J.C. Needham, M.G. Murch, P. Templesmith, and C.J. Dawes, International Patent Application PCT/GB92/02203 and GB Patent Application 9125978.8, 1991
2. P. Konkol, Characterization of Friction Stir Weldments in 500 Brinell Hardness Quenched and Tempered Steel, *Proceedings of the Fourth International Symposium on Friction Stir Welding,* May 14–16, 2003 (Park City, UT), TWI, paper on CD
3. W.M. Thomas, P.L. Threadgill, and E.D. Nicholas, Feasibility of Friction Stir Welding Steel, *Sci. Technol. Weld. Join.,* Vol 4 (No. 6), 1999, p 365–372
4. T.J. Lienert, and J.E. Gould, Friction Stir Welding of Mild Steel, *Proceedings of the First International Symposium on Friction Stir Welding,* June 14–16, 1999 (Thousand Oaks, CA), TWI, paper on CD

5. C.D. Sorensen, T.W. Nelson, and S.M. Packer, Tool Material Testing for FSW of High-Temperature Alloys, *Proceedings of the Third International Symposium on Friction Stir Welding,* Sept 2001 (Kobe, Japan), TWI, paper on CD
6. M. Collier, R. Steel, T. Nelson, C. Sorensen, and S. Packer, Grade Development of Polycrystalline Cubic Boron Nitride for Friction Stir Processing of Ferrous Alloys, *Mater. Sci. Forum,* Vol 426–432 (No. 4), 2003, p 3011–3016
7. S.M. Packer, T.W. Nelson, C.D. Sorensen, R. Steel, and M. Matsunaga, Tool and Equipment Requirements for Friction Stir Welding of Ferrous and Other High Melting Temperature Alloys, *Proceedings of the Fourth International Symposium on Friction Stir Welding,* May 14–16, 2003 (Park City, UT), TWI, paper on CD
8. M. Posada, J. DeLoach, A.P. Reynolds, M. Skinner, and J.P. Halpin, Friction Stir Weld Evaluation of DH-36 and Stainless Steel Weldments, *Friction Stir Welding and Processing,* TMS, 2001, p 159–171
9. T.J. Leinert, W.L. Stellwag, Jr., B.B. Grimmett, and R.W. Warke, Friction Stir Welding Studies on Mild Steel, *Weld. J.,* Jan 2003, p 1-s to 9-s
10. R. Johnson, J. dos Santos, and M. Magnasco, Mechanical Properties of Friction Stir Welded S355 C-Mn Steel Plates, *Proceedings of the Fourth International Symposium on Friction Stir Welding,* May 14–16, 2003 (Park City, UT), TWI, paper on CD
11. T.J. Lienert, W. Tang, J.A. Hogeboom, and L.G. Kvidahl, Friction Stir Welding of DH-36 Steel, *Proceedings of the Fourth International Symposium on Friction Stir Welding,* May 14–16, 2003 (Park City, UT), TWI, paper on CD
12. P.J. Konkol, J.A. Mathers, R. Johnson, and J.R. Pickens, Friction Stir Welding of HSLA-65 Steel for Shipbuilding, *J. Ship Prod.,* Vol 19 (No. 3), Aug 2003, p 159–164
13. M. Posada, J. DeLoach, A.P. Reynolds, R. Fonda, and J. Halpin, Evaluation of Friction Stir Welded HSLA-65, *Proceedings of the Fourth International Symposium on Friction Stir Welding,* May 14–16, 2003 (Park City, UT), TWI, paper on CD
14. A.P. Reynolds, W. Tang, T. Gnaupel-Herold, and H. Prask, Structure, Properties, and Residual Stress of 304L Stainless Steel Friction Stir Welds, *Scr. Mater.,* Vol 48 (No. 9), May 2003, p 1289–1294
15. A.P. Reynolds, M. Posada, J. DeLoach, M.J. Skinner, and T.J. Lienert, FSW of Austenitic Stainless Steels, *Proceedings of the Third International Symposium on Friction Stir Welding,* Sept 2001 (Kobe, Japan), TWI, paper on CD
16. M. Posada, J. DeLoach, A.P. Reynolds, and J.P. Halpin, Mechanical Property and Microstructural Evaluation of Friction Stir Welded AL-6XN, *Trends in Welding Research, Proceedings of the Sixth International Conference,* April 15–19, 2002 (Pine Mountain, GA), ASM International, p 307–311
17. S.H.C. Park, Y.S. Sato, H. Kokawa, K. Okamoto, S. Hirano, and M. Inagaki, Rapid Formation of the Sigma Phase in 304 Stainless Steel during Friction Stir Welding, *Scr. Mater.,* Vol 49 (No. 12), Dec 2003, p 1175–1180
18. C.D. Sorensen and T.W. Nelson, Sigma Phase Formation in Friction Stirring of Iron-Nickel-Chromium Alloys, *Trends in Welding Research, Proceedings of the Seventh International Conference,* ASM International, 2005
19. C.B. Owen, "Two-Dimensional Friction Stir Welding Model with Experimental Validation," M.S. thesis, Brigham Young University, Provo, UT, 2006
20. T.D. Clark, "An Analysis of Microstructure and Corrosion Resistance in Underwater Friction Stir Welded 304L Stainless Steel," M.S. thesis, Brigham Young University, Provo, UT
21. C.J. Sterling, T.W. Nelson, C.D. Sorensen, R.J. Steel, and S.M. Packer, Friction Stir Welding of Quenched and Tempered C-Mn Steel, *Friction Stir Welding and Processing II,* TMS, 2003, p 165–171
22. Z. Feng, "Friction Stir Welding of API Grade X-65 Steel Pipe," Annual AWS Conference (Dallas, TX), American Welding Society, 2005
23. A. Ozekcin, H. Jin, J.Y. Koo, N.V. Bangaru, R. Ayer, and S. Packer, "A