Characterization of Friction Stir Weldments in 500 Brinell Hardness Quenched and Tempered Steel

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ABSTRACT

Friction stir welding (FSW) was successful in joining 6.4-mm and 12.7-mm (0.25 and 0.5-inch) plates of nominal 0.29C-Mn-Si-Mo-B 500 Brinell hardness steel using a polycrystalline cubic boron nitride (PCBN) tool material. The weldments were made without preheat and exhibited no apparent hydrogen-assisted cracking or distortion, and there was little evidence of tool wear in limited trials. Weldments were also made using gas-metal-arc welding (GMAW) for comparison. The transverse tensile strengths of the FS weldments were greater than those of conventional gas-metal-arc weldments, which were made using a lower carbon electrode. Charpy V-notch toughness of the FSW stir zone and heat-affected zone (HAZ) was similar to that of the plate material; the toughness of the GMA weld metal and heat-affected zone was generally higher. Microhardness varied across the weld region, and was lowest in the overtempered region of the HAZ in the FS welds and lowest in the weld metal in the GMA welds. Previous trials on high-strength low-alloy steels and the present trials on a high strength steel indicate that FSW technology is feasible for joining a variety of steels for structural applications.

INTRODUCTION

FSW has been successfully applied to the joining of aluminum and other relatively low melting temperature metals; however, the application of FSW to joining high melting temperature metals such as steel is more challenging due to the higher operating temperatures involved. Trials were previously conducted on HSLA-65 (ASTM A 945) high-strength low-alloy steel, in which single-pass welds in 6.4-mm (0.25 inch)-thick plates and two-pass welds in 12.7-mm (0.5 inch)-thick plates were successfully made [1].

HSLA-65 is a low-carbon ferritic steel with a specified 538 MPa (78 ksi) minimum tensile strength, which is equivalent to 157 Brinell hardness. The present work was conducted to extend the technology of FSW to a much harder medium-carbon Mn-Mo-B quenched-and-tempered martensitic steel of 500 Brinell hardness (500 BHN). The specified hardness of 500 BHN is equivalent to about 1860 MPa (270 ksi) tensile strength. Because of its high carbon and alloy content, arc or fusion welding must be performed using low-hydrogen procedures to prevent hydrogen-induced cracking in the weld heat-affected zone (HAZ) or weld metal. There are no welding electrodes capable of achieving matching strength in the weld metal; consequently, austenitic stainless steel electrodes or ferritic electrodes with specified minimum tensile strengths up to 689 MPa (100 ksi) are typically used. FSW would be advantageous for replacing arc welding in joining 500 BHN steel due to

its potential to reduce hydrogen-assisted cracking, increase weldment strength, and minimize weld-induced distortion.

MATERIALS

Several 6.4-mm and 12.7-mm thick BHN plates were obtained from a supplier. Both gages were nominally 0.29C-Mn-Mo-B-Ti composition that were austenitized, water-quenched, and tempered at the relatively low temperature of 190ºC (375ºF). Thus, the microstructures consisted of lightly tempered carbon martensite, which resulted in the high hardness.

TOOLS AND EQUIPMENT

Relatively low melting temperature metals such as aluminum alloys are easily FS welded using conventional tool steels. However, these tool materials are not suitable for FSW of steel due to the higher operating temperatures generated during FSW of steels, typically 1000 - 1200ºC (1830 - 2190ºF), which are above the softening temperature of the tool steels. Thus, refractory metals or ceramics are being evaluated for use as tool materials for FSW of steels.

The initial work on FSW of HSLA-65 steel [1] was conducted using a tungsten tool, which is a refractory metal. However, severe tool wear was encountered, which is considered a major impediment to FSW of steels in a production environment. To overcome such an impediment, a FSW tool made from polycrystalline cubic boron nitride (PCBN) has been developed for joining steel [2]. PCBN is a superabrasive, wear resistant material primarily used in machining of superalloys and high-strength steels. The tool material is made by hot isostatic pressing CBN powder and a binder material at ultra-high temperature and pressure, followed by electro-discharge machining or grinding to the desired shape. Because PCBN is difficult to make in large sizes, only the pin and shoulder of the welding tool are made from PCBN. The high temperatures generated and differences in thermal expansion among the various materials in the welding tool required a special tool design for fastening the PCBN tool to the tungsten-carbide shank by a superalloy locking collar. The welding tool is shown in Figure 1. A fluid-cooled tool holder is used to limit the temperature rise in the shank of the tool, thereby solving problems that were encountered with over-heating of the shank during welding. Although the initial welds were made without external gas shielding, it was found that weld appearance was improved and tool life extended by use of an argon gas shroud to protect the weld region during welding. A schematic of the tool holder, gas shroud, and tool are shown in Figure 2. The assembly can also be equipped with a thermocouple in contact with the PCBN tool for transmitting temperatures by radio telemetry during welding.

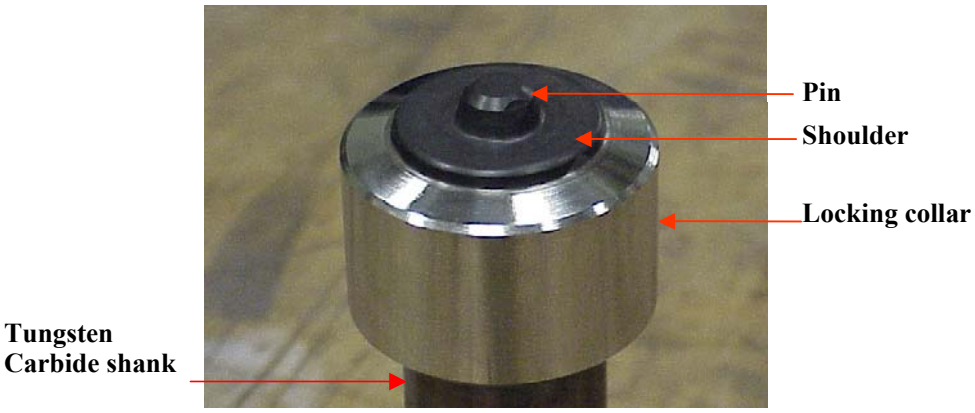


Figure 1. Details of PCBN tool used in FSW.

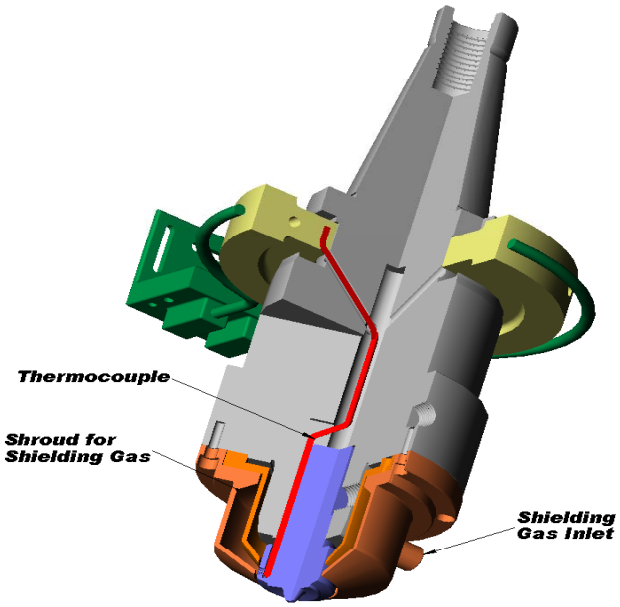


Figure 2. Tool assembly for FSW of steel.
(Courtesy of Advanced Metal Products)

WELDING TRIALS

Several pairs of 6.4-mm and 12.7-mm-thick 500 BHN plates were plasma cut, grit blasted to remove scale, and machined to produce a square edge on adjoining sides. The FS welding was performed at both Brigham Young University and SII Megadiamond, both of Provo, Utah. The GMA welds were made at Concurrent Technologies Corporation (*CTC),* Johnstown, PA. At the time of welding the 6.4-mm plates, the largest PCBN tool available

had a pin depth of 4.3 mm (0.170 inch); thus the plates were joined in two passes, one on each side, at various travel speeds up to 3.28 mm/s (7.75 ipm). The 6.4-mm welds were made without preheat or shielding gas, and exhibited a very smooth surface and exit hole, as shown in Figure 3. There was a slight heat tint adjacent to the stir zone that was caused by the high temperatures generated in the stir zone, estimated to be 1000 - 1200°C. No measurable distortion was observed in the test weldment, and liquid-penetrant inspection revealed no cracking in the stir zone or HAZ.

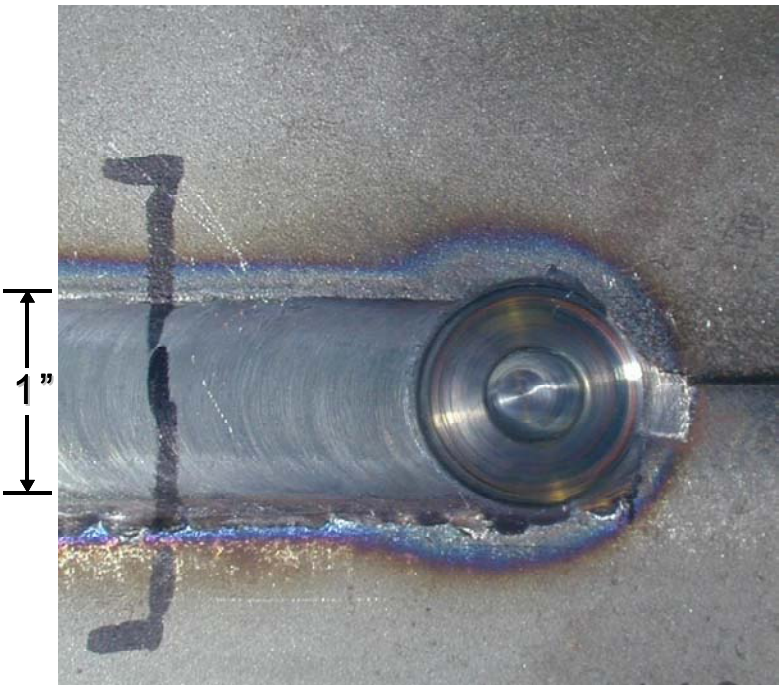


Figure 3. FS weld surface and exit hole in 6.4-mm 500 BHN steel.

Upon availability of tools with longer pins, the 12.7-mm plates were joined with a 5.7-mm (0.225 inch) pin length, one pass on each side, at travel speeds up to 1.9 mm/s (4.5 ipm). Argon gas shielding was used, which resulted in a smoother, oxide-free weld surface than in the 6.4-mm weld, Figure 4. Again, no distortion or cracking were observed. There was little evidence of tool wear after producing approximately 6 m (20 feet) of weld, and it is estimated that PCBN tools should be useful for much greater than 30 m (100 feet) of welding in steels. The limiting factor in PCBN tool life is currently considered to be tool breakage, which can occur if the tool is improperly plunged or extracted, or the spindle has excessive runout.

Figure 4. FS weld surface and exit hole in 12.7-mm 500 BHN steel using argon shielding.

To compare the FS weldments with conventional arc weldments, both 6.4-mm and 12.7-mm plates were joined by the GMAW process using the pulsed-arc mode, argon plus 5-% CO_2 gas shielding, 1.1-mm (0.045-inch) diameter AWS ER-100S electrode, and a 45° single-Vee groove geometry. The 6.4-mm weldment was made in a single pass at 3.81 mms/s (9 ipm) travel speed and the 12.7-mm weldment was made in six passes at 4.57 mm/s (10.8 ipm).

MACHINING OF WELDMENTS

The weldments were sectioned to obtain rectangular transverse-weld tensile specimens per ASTM A370, round longitudinal all-stir-zone or all-weld-metal tensile specimens, 1/2-size or full-size Charpy V-notch (CVN) toughness specimen blanks from the weld region and base metal, and a metallographic specimen. The CVN blanks were etched and notched in the stir zone, the heat-affected zone (HAZ) at 1 mm from the weld interface, 3 mm from the weld interface, and in the unaffected base metal. The CVN specimens were tested at -40°C (-40°F). Vickers microhardness traverses were obtained on the polished transverse section of the weldments at the top and bottom quarter-thickness locations.

WELD MACROSTRUCTURES

The transverse sections of the FS and GMA weldments are shown in Figures 5a-d. The FS welds were made in two passes — one from each side. The 6.4-mm GMA weld was made in a single pass, and the 12.7-mm GMA weld was made in multiple passes from one side. Unlike FS welds in aluminum alloys, the FS welds in the steel plates exhibit smaller or no thermomechanically affected zone (TMAZ). The HAZs in the FS welds appear to be wider than in the GMA welds, which could be attributed to the less concentrated heat source compared to a welding arc. Light-etching swirls were observed below the surface towards the outer edges of the stir zones in the FS welds. A considerable amount of grain refinement

was observed in these regions at higher magnification. This may possibly be attributed to additional plastic deformation and grain refinement due to shearing of the metal surface by the tool shoulder. Similar refinement was observed in FS welds in mild steel [3].

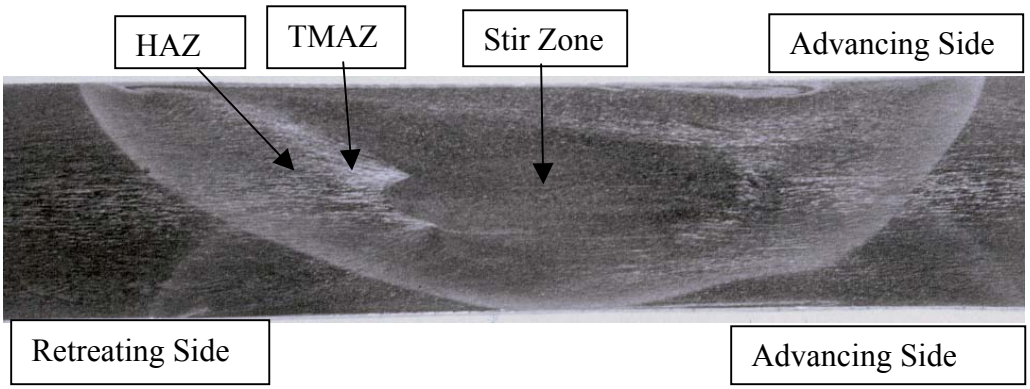


Figure 5a. Transverse section of FS weld in 6.4-mm 500 BHN steel.

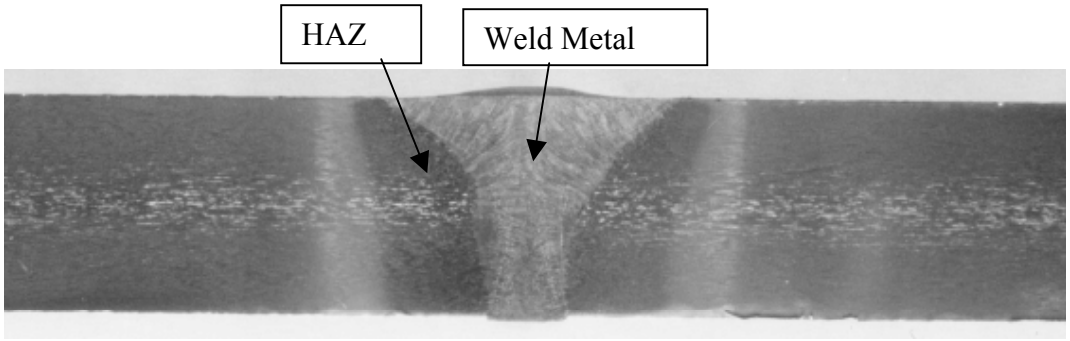


Figure 5b. Transverse section of GMA weld in 6.4-mm 500 BHN steel.

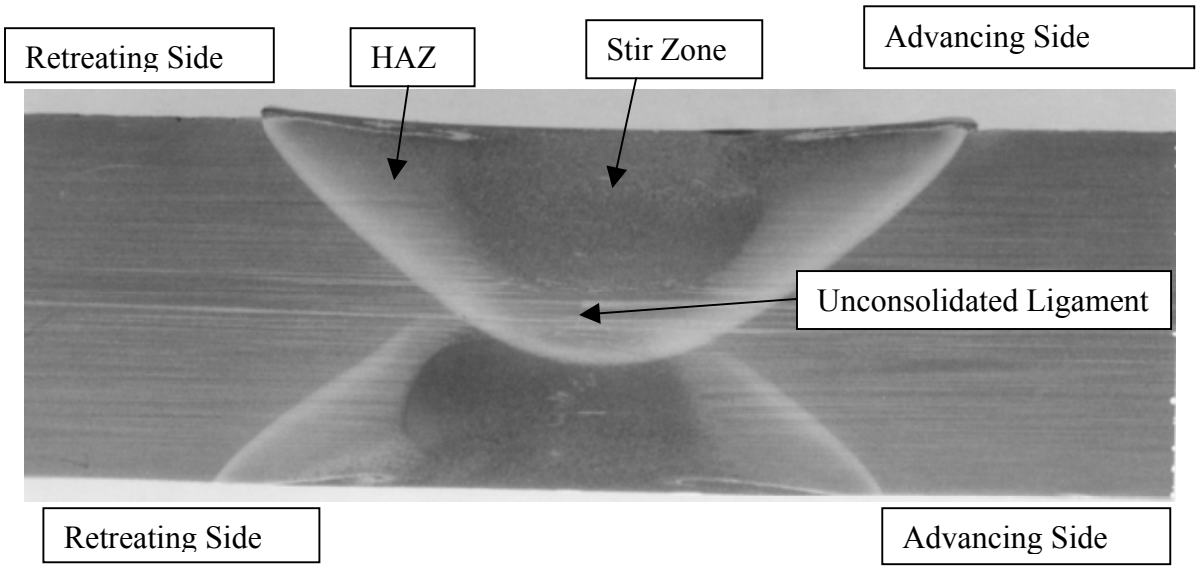


Figure 5c. Transverse section of FS weld in 12.7-mm 500 BHN steel.

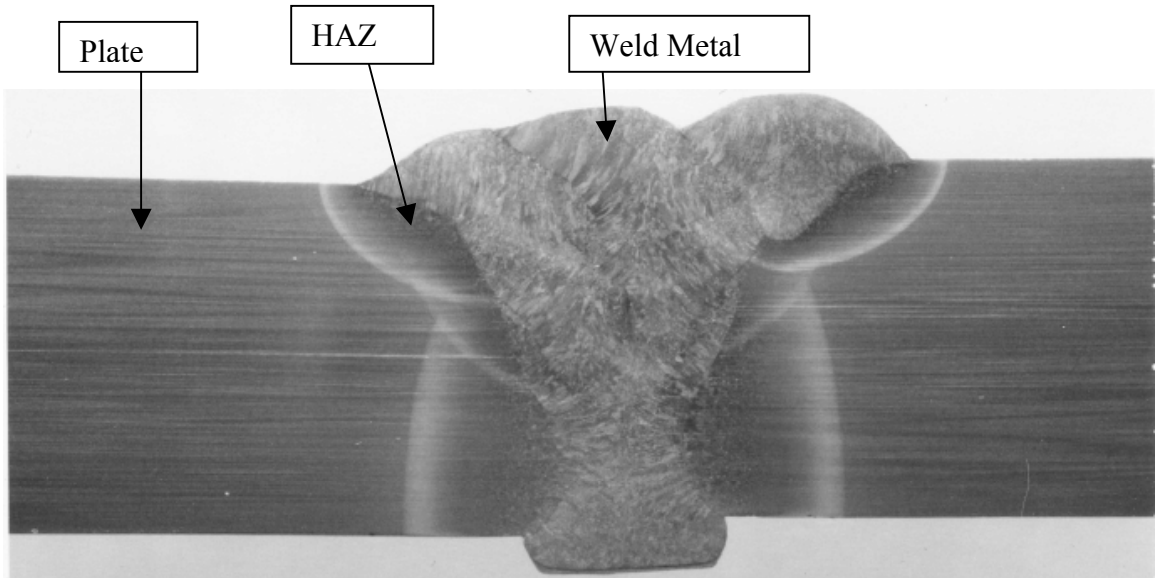


Figure 5d. Transverse section of GMA weld in 12.7-mm 500 BHN steel.

The amount of overlap between the first and second passes in the 12.7-mm FS weld, Figure 5c, was less than in the 6.4-mm FS weld, Figure 5a. This resulted in a small ligament of incomplete consolidation beneath the second pass.

An unusual re-entrant protrusion in the root of the stir zone in the 6.4-mm FS weld is shown in Figure 6. Also shown are the light and dark etching bands in the TMAZ, which are remnants of segregation in the plate. These bands also appear as scallops in the stir zone. As will be discussed, metallographic examination and microhardness testing of the bands indicated that the light bands are martensitic, and the darker bands are a softer bainitic type structure.

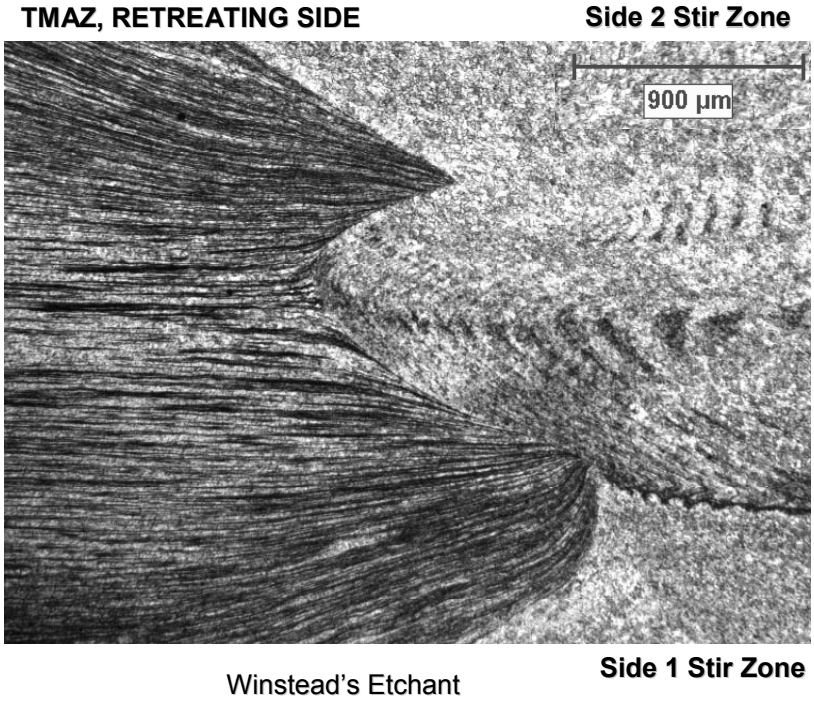


Figure 6. Enlarged view of root region in stir zone of 6.4-mm FS weld.

MICROHARDNESS

The microhardness traverses, obtained along the top and bottom quarter-thickness locations, are shown in Figures 7a-d. The hardness of the base metal, which is quenched-and-tempered martensite tempered at a low temperature of 190ºC (375ºF), is approximately 600 HV, (kg/mm^2.)

The HAZs in both FS and GMA welds are softened to about 300 - 325 HV in the overtempered region (exposed to the subcritical temperature range). The hardness increases in the HAZ are due to re-austenitization and subsequent transformation to bainite or martensite in the regions that are exposed to a much higher temperature. The hardness approaches that of the base metal in the near or coarse-grain HAZ (closest to the stir zone or weld metal).

The hardness in the stir zones in the 6.4-mm FS weld and in the second pass of the 12.7-mm weld approaches that of the base metal. (The 12.7-mm first-pass stir zone was tempered by the second-pass weld.) Scatter in hardness readings was observed in the 6.4-mm stir zone, which is attributed to the presence of the above mentioned martensite/bainite bands. Less banding, and less scatter in hardness, was observed in the 12.7-mm stir zone.

The hardness is about 300 HV in the 6.4-mm GMA weld metal and as low as 252 HV in the 12.7-mm GMA weld metal. This is due to greater admixture from the lower-carbon GMA electrode in the multi-pass 12.7-mm weld.

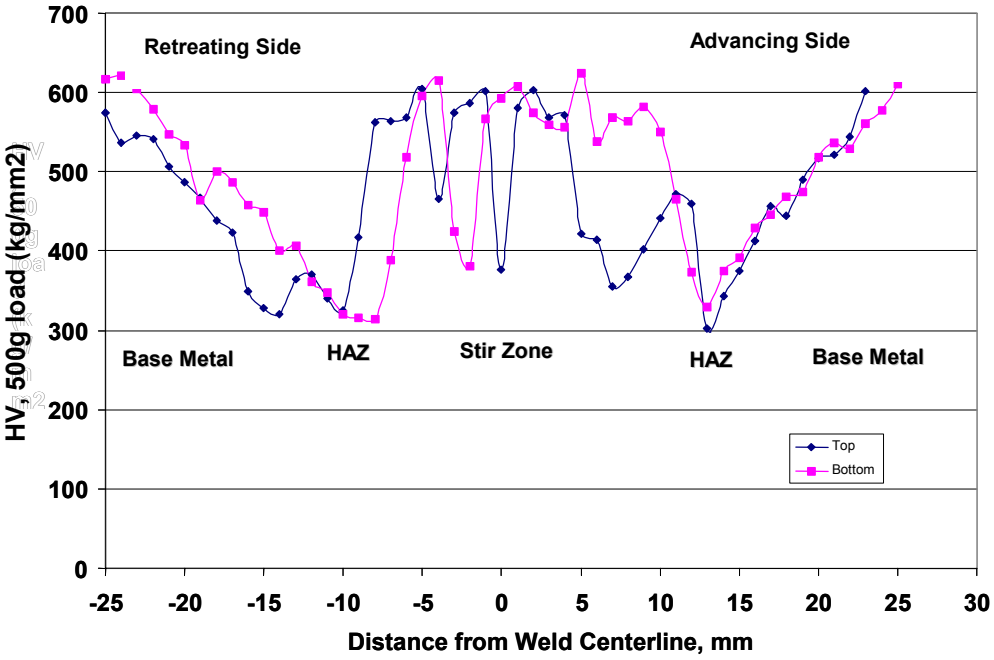


Figure 7a. Microhardness of two-pass FS weld in 6.4-mm 500 BHN steel.

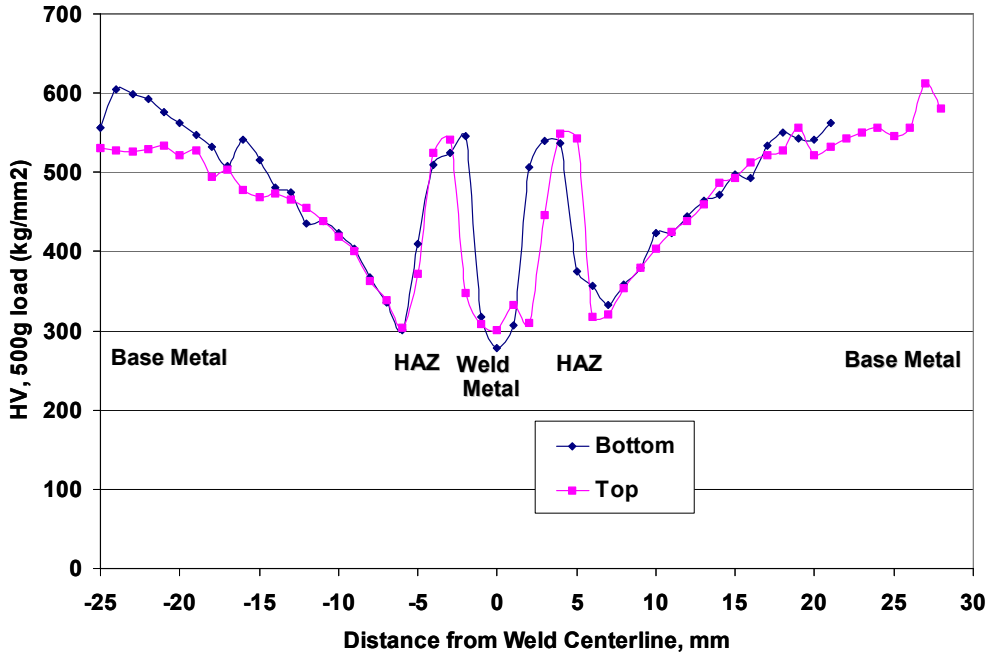


Figure 7b. Microhardness of single-pass GMA weld in 6.4-mm 500 BHN steel.

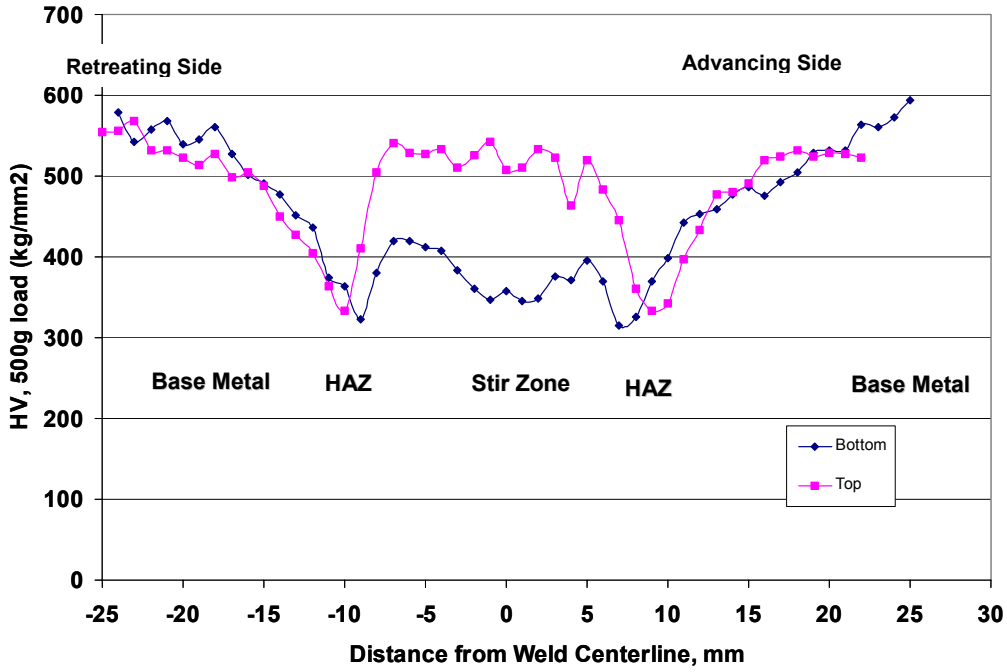


Figure 7c. Microhardness of two-pass FS weld in 12.7-mm 500 BHN steel.

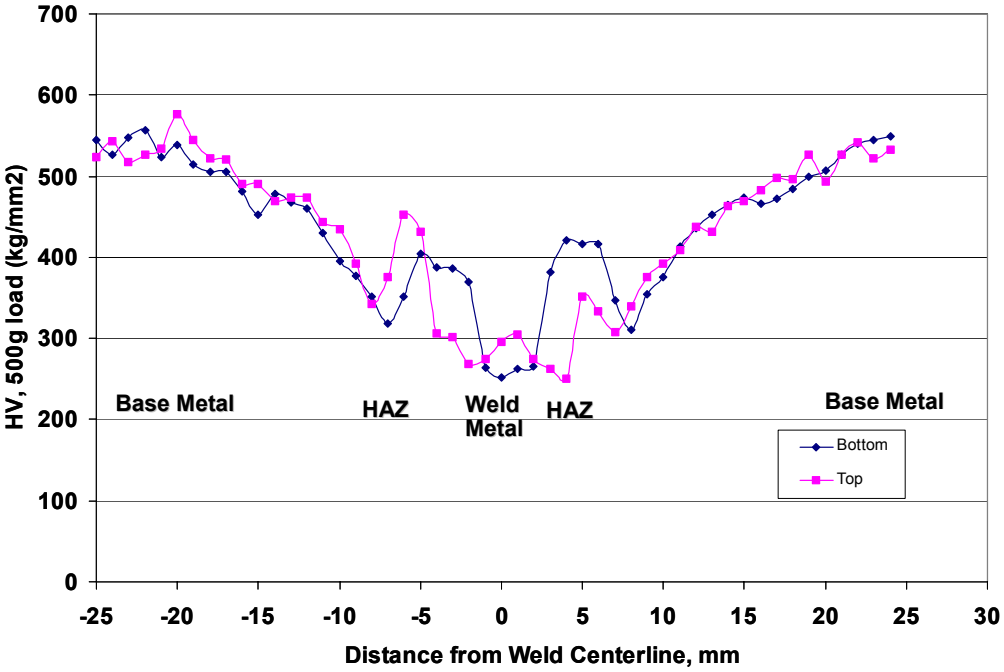


Figure 7d. Microhardness of multi-pass GMA weld in 12.7-mm 500 BHN steel.

TENSILE PROPERTIES

The transverse weld tensile test results on the FS and GMA welds are shown in Table 1, along with the tensile properties of the plates. The transverse tensile strengths were 1233 and 1214 MPa (179 and 176 ksi) for the 6.4- and 12.7-mm FS welds versus 1091 and 937 MPa (158 and 136 ksi), respectively for conventional GMA weldments. The joint efficiencies (based on tensile strength) are 72 % and 70 % for the FS welds and 63 % and 54 % for the GMA welds. As expected from the hardness data, the tensile fractures occurred in the weld metal for the GMA welds, which is the softest region. The fracture in the 6.4-mm FS weld was in the HAZ, also the softest region. However, the 12.7-mm FS weld fractured in the stir zone, which may be attributed to the lack-of-consolidation between the two passes. The transverse elongations in both the FS and GMA weldments were much lower than in the parent plate; however, transverse elongation, along with yield strength values in transverse weld testing are generally not meaningful in ferrous weldments because the fractures may occur in the HAZ or base metal and are thus dependent on weld width and extensometer gage length.

Longitudinal 6.4-mm diameter tensile specimens with a 25-mm gage length were obtained from the 12.7-mm FS and GMA weldments. As shown in Table 2, the all-stir-zone tensile strength of the 12.7-mm FS weldment is 1436 MPa (208 ksi), which is substantially higher than the all-weld-metal tensile strength in the low-carbon, low-alloy ER-100S GMA weld metal, 834 MPa (121) ksi. However, the ductility of the stir zone, as measured by the elongation and reduction of area, is substantially lower than that for the GMA weld metal due to the formation of a higher-carbon martensitic microstructure.

Table 1. Transverse Tensile Properties[1] of FS and GMA Welds in 500 BHN Steel

Plate Thickness, mm	Material	Yield Strength, MPa (ksi)[2]	Tensile Strength, MPa (ksi)	Elongation in 50 mm (2 in.), %	Fracture Location	Joint Efficiency, %
6.4	FS[3]	1040 (151)	1233 (179)	2.6	HAZ	72
6.4	GMA	942 (137)	1091 (158)	4.8	WM	63
6.4	base metal	1428 (207)	1727 (251)	11.3	-	-
12.7	FS	1123 (163)	1214 (176)	2.8	SZ	69
12.7	GMA	867 (126)	937 (136)	5.5	WM	53
12.7	base metal[4]	1486 (216)	1767 (256)	13.0	-	-

1. Mean of two specimens
2. Measured across 50-mm (2-inch) gage length
3. Reported by Brigham Young University, mean of three specimens
4. 6.4-mm round specimens, 25-mm gage length

Table 2. All-Weld-Metal Tensile Properties[1] of FS and GMA Welds in 12.7-mm 500 BHN Steel

Welding Process	Yield Strength, MPa (ksi)	Tensile Strength, MPa (ksi)	Elongation (in 25.4 mm), %	Reduction of Area, %
FS	1092 (159)	1436 (208)	2.0	5.4
GMA	773 (112)[2]	834 (121)	22.0	73.0

1. Mean of two 6.4-mm-diameter specimens
2. Single value.

CHARPY V-NOTCH TOUGHNESS

The CVN toughness values are shown in Table 3. Because of the curved nature of the weld interface and HAZ, it was not possible to locate the notch in a specific region of the HAZ; thus the crack path in the HAZ specimens passed through portions of the stir zone or weld metal and various HAZ regions. Although all of the values for the FS welds are relatively low, they are still higher, in most cases, than the base metal. The toughness of the GMA weld metal and near HAZ (1-mm location) was generally higher, which could be attributed to the inherently higher toughness of the low-carbon weld metal, and for the 12.7-mm GMA weld, the tempering effects of the multipass weld.

Table 3. CVN Toughness of Welds in 500 BHN Steel

Plate Thickness, mm	Welding Process	Energy Absorbed at -40°C (-40°F), J (ft-lb)			
		Stir zone	HAZ, 1 mm[3]	HAZ, 3 mm[3]	Base metal
6.4[1]	FS	11 (8)	8 (6)	15 (11)	9 (7)
6.4[1]	GMA	19 (14)	11 (8)	6 (5)	9 (7)
12.7[2]	FS	26 (19)	26 (19)	41 (30)	28 (21)
12.7[2]	GMA	74 (55)	122 (90)	55 (41)	28 (21)

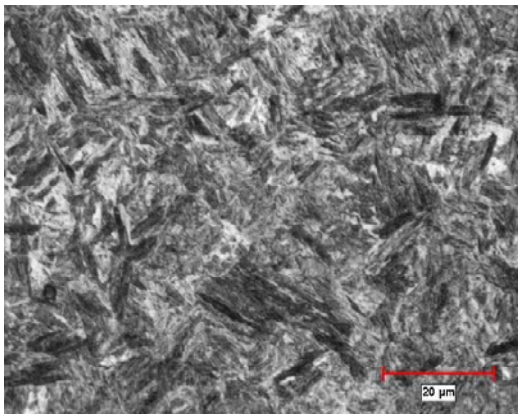
1. Average of five 1/2-size specimens
2. Average of five full-size specimens
3. Distance from weld interface

MICROSTRUCTURES

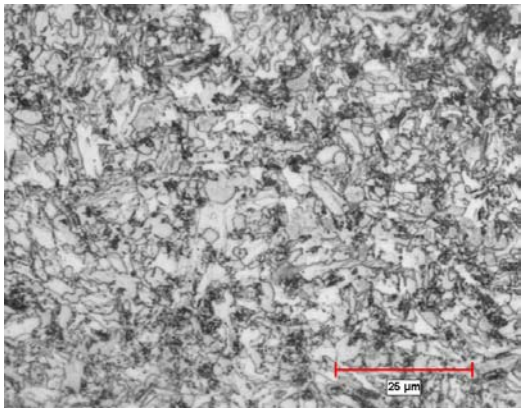
The microstructures of the base metal, HAZ, and stir zone in the FS welds are shown in Figures 8a-e. The microstructures in the base metal, far (fine grain) HAZ, and near (coarse grain) HAZ were similar for both plate thicknesses; thus representative photos of either thickness are shown here. The base metal (Figure 8a) is a lightly tempered carbon martensite as a result of the austenitizing, quenching, and low-temperature tempering treatment. The fine-grain HAZ (Figure 8b) appears to contain fine polygonal ferrite, agglomerated carbides,

granular bainite, and martensite. In this region, the martensite to austenite transformation upon heating was incomplete. The prior martensite transformed to ferrite and undisolved carbides upon heating, and the newly formed fine austenite grains transformed to granular bainite and martensite upon cooling. In the coarse-grain HAZ, Figure 8c, carbide dissolution was complete and grain growth occurred, which increased hardenability. This resulted in a coarse martensite-bainite structure. The stir zone in the 6.4-mm FS weld (Figure 8d) is non-uniform and consists of discontinuous bands of martensite and bainitic-type ferrite-carbide aggregates.

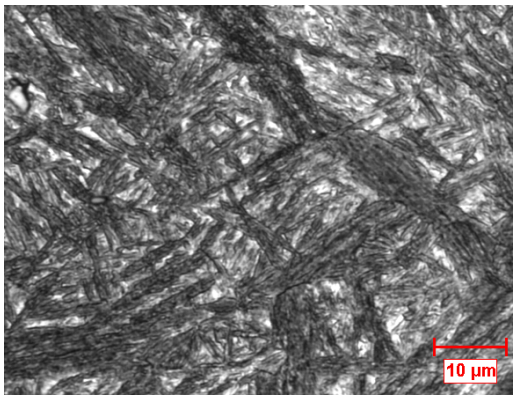
Less banding was evident in the stir zone of the 12.7-mm FS weld, Figure 8e. The bands are associated with the banding that is evident in the HAZ at low magnification, Figure 6. The banding is caused by differences in etching rate as a result of slight differences in chemical composition in the base metal as a result of solidification segregation in the ingot, which is still remnant in the plate after rolling. As shown in Figure 9, microhardness impressions of the banded areas of the stir zone indicate that the light-etching regions are much harder than the dark-etching regions, and are nearly equivalent in hardness to that of the base metal. Thus the alloy-rich bands transformed to martensite and the alloy-lean bands transformed to bainite upon cooling after welding.



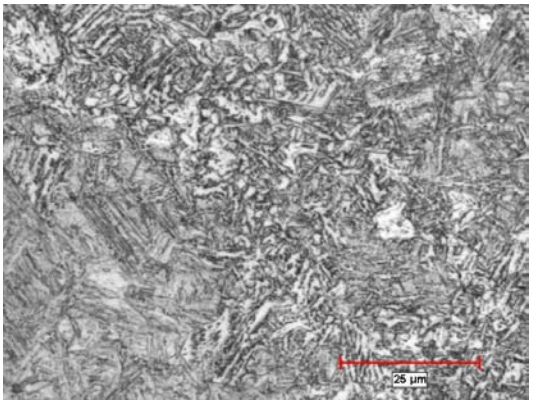
8a. Base metal, 6.4-mm plate.



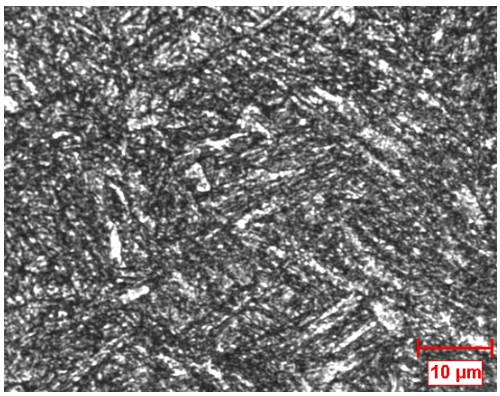
8b. Fine-grain HAZ, 6.4-mm plate.



8c. Coarse-grain HAZ, 12.7-mm plate.



8d. Stir zone, 6.4-mm plate.



8e. Stir zone, 12.7-mm plate.

Figure 8. Microstructures in FS welds. Nital etchant

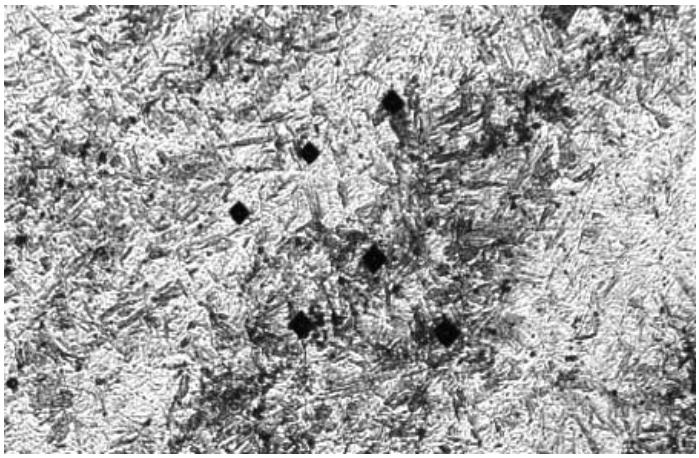
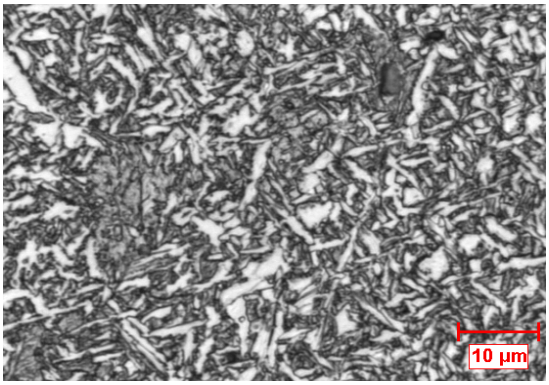
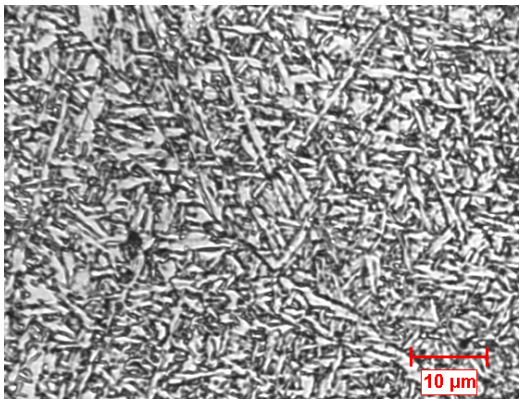


Figure 9. Microstructural banding in stir zone of 6.4-mm FS weldment. Light region: HV = 495, dark region: HV = 340. Winstead's etchant.

The base metal and HAZ microstructures in the GMA welds were similar to those of the FS welds, although the extent of the coarse-grain HAZ region appeared to be greater in the GMA weld. However, the weld metals exhibited significantly different structures, Figure 10. Because the 6.4-mm GMA weld was made in one pass, the weld metal contained a substantial amount of admixture from the base metal in addition to the lower-carbon electrode, and consisted of a mixture of Widmanstatten ferrite, bainite, and martensite, Figure 10a. The weld metal in the 12.7-mm multipass GMA weld had less admixture, thus contained substantially more ferrite, Figure 10b. This would explain the very low hardness in the weld metal as shown in Figure 7d.



10a. Weld metal, 6.4-mm plate.



10b. Weld metal, 12.7-mm plate

Figure 10. Microstructures in GMA welds.

CONCLUSIONS

1. FS welds were successfully made in 6.4-mm- and 12.7-mm-thick plates of nominal 0.29C-Mn-Si-Mo-B 500 Brinell hardness (500 BHN) steel using a polycrystalline cubic boron nitride (PCBN) tool material with and without shielding gas. The weldments were made without preheat and exhibited no apparent hydrogen-assisted cracking or distortion, and there was little evidence of tool wear.
2. The transverse tensile strengths of the 6.4-mm and 12.7-mm weldments were 1233 and 1214 MPa (179 and 176 ksi) for the FS weldments versus 1091 and 937 MPa (158 and 136 ksi), respectively, for conventional GMA weldments.
3. The all-stir-zone tensile strength of the 12.7-mm FS weldment was 1436 MPa (208 ksi), which is substantially higher than the all-weld-metal tensile strength in the GMA weldment, 834 MPa (121) ksi. However, the ductility of the stir zone, as measured by the elongation and reduction of area, was substantially lower than the GMA weld metal.
4. Microhardness varied across the weld region, and was lowest in the overtempered region of the HAZ in the FS welds and lowest in the weld metal in the GMA welds.
5. Charpy V-notch toughness of the FSW stir zone and heat-affected zone were similar to that of the plate material; the toughness of the GMA weld metal and heat-affected zone was generally higher.
6. Previous trials on high-strength low-alloy steels and the present trials on 500 BHN steel indicate that FSW technology is feasible for joining a variety of steels for structural applications.

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ACKNOWLEDGEMENTS

The author is pleased to acknowledge the following for their technical assistance and cooperation: Professors Tracy Nelson and Carl Sorensen of Brigham Young University, Scott Packer of Advanced Metal Products, and Lars Llijeblad and Russell Steel of SII Megadiamond. The author also acknowledges Matthew Marushcok of *CTC* for the metallographic examinations.

This work was conducted for the Tank Automotive Research Development & Engineering Center (TARDEC) by Concurrent Technologies Corporation (CTC) through the National Center for Excellence in Metalworking Technology (NCEMT). CTC operates the NCEMT under Contract No. N00014-00-C-0544 to the U.S. Navy as part of the U.S. Navy Manufacturing Technology Program.