The Efficacy of Friction Stir Welding in High Strength Steel Production

Prepared by:
Timothy S. Fountain

Faculty Advisors:
Dr. Michael West
Back to the Future REU Site Director, Department of Materials and Metallurgical Engineering

Dr. Bharat Jasthi
Associate Professor, Department of Materials and Metallurgical Engineering

Dr. Alfred Boysen
Professor, Department of Humanities

Other Advisors:
Cory Anthony
Chief Metallurgist, Nucor Steel, Utah

Program Information:
National Science Foundation
Grant NSF #DMR-1157074
Grant CFSP #ENG-0934383

Research Experience for Undergraduates
Summer 2013

South Dakota School of Mines and Technology
501 E Saint Joseph Street
Rapid City, SD 57701

Table of Contents

Abstract 1
Introduction 1
Background 1
Tool Materials 4
Process Parameters and Other Considerations 7
Objectives 8
Broader Impact 9
Procedure 10
Materials 10
Tool Selection 10
Welding 11
Developmental Bead on Plate Welds 11
Joined Pieces 13
Double Pass Welds 13
Heat Treatment 13
Microstructural Analysis 14
Metallography 14
Microhardness Testing 14
Mechanical Testing 15
Results 15
Microstructural Analysis 15
Metallography 15
Parent Material 16
Weld Nugget 17
HAZ/TMAZ 18
Double Pass Welds 21
Microhardness Testing 23
Mechanical Properties 26
Tensile Testing 26
Parent Material 26
Single Pass Welds 27

Double Pass Welds **28**
Discussion 30
Microstructural Discrepancies 30
Heat Treatment Optimization 31
Martensite Phase Transformation and Sub-Critical Welding 32
Conclusion 32
Summary 32
Recommendations 34
Future Work 35
References 36
Acknowledgments 38

Abstract

Friction stir welding (FSW) of proprietary grade-110 HSLA steel was completed. It was found that FSW can effectively process and join this ultra-high strength material, though questions about its efficiency in a production setting still remain. Material was evaluated in terms of microstructure and tensile properties. All welds underwent phase transformations that resulted in martensite formation in the weld nugget, which embrittled the material and lowered elongation far below customer specifications. Post weld heat treatment restored hardness and ductility to acceptable levels. Welds performed with successful parameters had yield and tensile strengths within 97% or more of parent material values. Elongations were close to meeting customer specifications, but require a different heat treatment to be most effective. Defects occurred in welds with travel speeds of 10 ipm or greater, and also in double pass welds. These defects were severely detrimental to mechanical properties but it is believed that they can be eliminated with further parameter development and altered tool geometry.

Introduction

Background

Friction stir welding (FSW) is a joining practice patented by The Welding Institute of the United Kingdom in 1991. It is unique in that it is a solid state welding technique, meaning that no material actually melts during the process. Instead, a rotating tool is plunged into the weld piece and uses heat generated by friction to plasticize the material to the point where it is soft enough to be stirred together to form a joint. Plastic deformation generates additional heat. A diagram of FSW can be found in Figure 1.

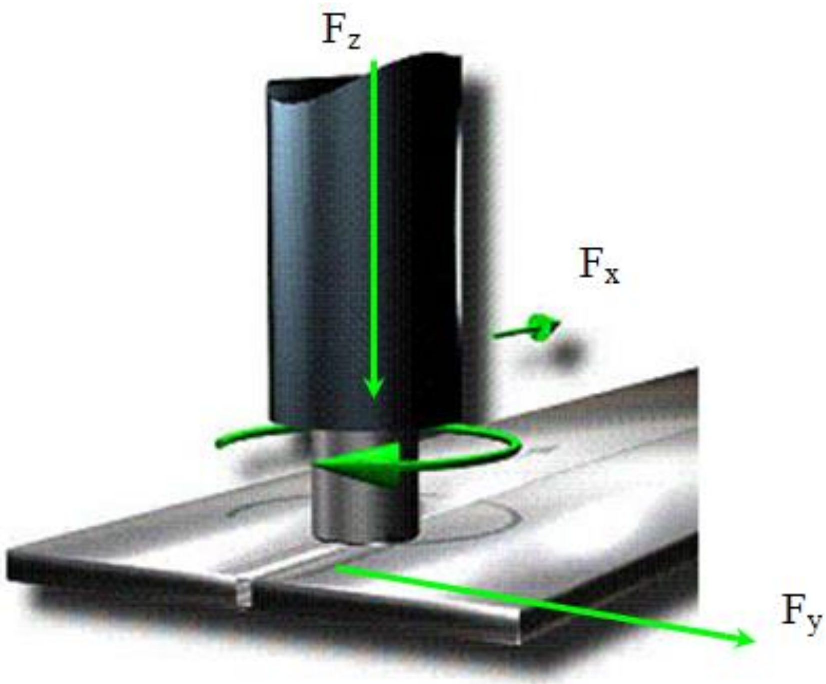

Figure 1: Schematic diagram of friction stir welding and the 3 primary axial loads considered. *Image adapted from http://www.cmfgroupe.com/news/friction-stir-welding/*

Because of the relatively low heat input and its ability to weld material without melting it, FSW holds several advantages over traditional fusion welding techniques. These advantages include the following:

- Weld Quality and Mechanical Properties
    - Smaller heat affected zone (HAZ)
    - Forging, not casting process, that eliminates casting defects such as gas porosity
    - Grain size reduction in the weld nugget
    - Enhanced material properties in weld nugget
    - Warping from high heat input is largely avoided or minimized
    - Parent metal chemistry retained
    - Consistent, defect free welds with correct parameters

- Special abilities
    - Ability to weld materials unweldable by traditional fusion techniques such as 7075 and 2024 aluminum
    - Ability to weld high alloy and specialty materials
    - Ability to join dissimilar materials
    - Ability to avoid brittle phase transformation in steel, eliminating need for post weld heat treatment or tempering process
- Safety
    - Cooler welds performed by machines can help prevent burns
    - No toxic or irritating particulate emissions or fumes
    - No bright UV light emission
    - Quiet
- Cost and Environmental Aspects
    - No filler material
    - Less energy input
    - Less post weld cleanup

FSW has already found a large niche in the aluminum industry because these advantages. However, use in high strength/high temperature (HSHT) materials such as steel has been limited due to concerns with excessive tool wear and slow travel speed. Tools must exhibit high hardness, strength, toughness, chemical inertness, and immiscibility with the weld material and must do so even at very high temperatures. Because of these requirements, the tools capable of welding steel and other HSHT materials are often very expensive. Travel speed is hindered by tool capability and the tendency to form defects when the weld pitch ($\frac{Travel\ Speed}{Rotational\ Speed}$) is too low or too high.

This project was started in conjunction with Nucor Steel, Utah and will examine the production feasibility of FSW in a proprietary microalloyed, high-strength-low-alloy (HSLA) steel for use in a heavy duty structural application. At the time of this writing the specific application and chemistry for this steel are confidential. The goal is to successfully butt weld two angles together to form a channel. Tensile and fatigue properties are critical to its application.

Tool Materials

As noted above, one of the primary difficulties of friction stir welding steel and other HSHT alloys is tool wear. Tools must be tough and both stronger and harder than the materials being welded so that they have the ability to remain intact even in the rigorous service environment they are subjected to. They also must be chemically inert and immiscible to their service environment to prevent chemical wear in the tool and contamination of the weld. It is important to mention that tool failure does not mean that the tool must be worn down to the nub or shattered, it simply means that the tool can no longer create acceptable welds. Tool materials are growing ever more advanced to combat these issues, but a new concern arises with cost. Many of these tools cost between $1000 and $2000 *per inch* of material, making their use prohibitive to industrial use especially if they are subject to failure. Tools can be ceramic, metallic, or can be a composite of both.

Ceramic tools are known for their superior hardness and subsequent resistance to abrasive wear, but are also known for their susceptibility to brittle shattering under high loads or impacts. A common, and probably the best, ceramic tool used in HSHT materials is polycrystalline cubic boron nitride (PCBN). PCBN is second in hardness only to diamond, making it ideal for the abrasive service environment encountered in FSW. Like most ceramics, however, PCBN can experience brittle failure from impact or high stress. Even slight vibrations in the welder can lead to failure of the tool without warning. There have been efforts to toughen this material by adding tungsten rhenium (W-Re) particles to it, and this has been successful in friction stir spot welding (FSSW) trials. Tools with 70% PCBN and 30% W-Re, also called Q-70 tools, have proven to be capable of performing up to 1200 spot welds in high strength dual phase steel with little degradation to weld quality. Q-60 tools, or tools with 60% PCBN and 40% W-Re, tend to wear out and produce unacceptable welds before 1000 spot welds have been completed.

Another ceramic tool that draws considerable interest is silicon nitride (Si_3N_4). Though not as wear resistant as PCBN, it is far less expensive to produce. It has been used effectively in the friction stir spot welding of various advanced high strength steel (AHSS) alloys, though some reports claim them to contaminate welds with Si and N when left uncoated. Reports that mention contamination claim that tools coated in layers of titanium carbide and titanium nitride (TiC and TiN) eliminate contamination, in effect improving weld quality and tool life.

Metallic tools are also used. Though not as hard as ceramics, they are far tougher and hold the extra benefit of being able to be remachined and repaired. For aluminum alloys, tool steel is acceptable, but for HSHT alloys a stronger material is needed. The most effective tools used for HSHT materials are various tungsten-rhenium alloys.

Tungsten is known for its high strength and high melting temperature. However, it has a high ductile to brittle transition temperature and is further embrittled when its recrystallization temperature is exceeded. As a remedy, pure tungsten is alloyed with other materials that both improve these properties and remain stable in the high temperature applications that tungsten is often used in. Three primary alloys are considered when dealing with tungsten tools, and each have different benefits. They include the following:

- Tungsten-Lanthanum Oxide (W-LaO): LaO is added to W in amounts of about 1 weight percent to raise recrystallization temperature and increase creep strength.
- Tungsten-Rhenium (W-Re): Re is added to W generally in amounts of 25% to drastically reduce the ductile to brittle transition temperature (DBTT) and increase the recrystallization temperature. The effect is a much tougher material. This improvement in properties is known as the rhenium effect.
- Tungsten-Rhenium-Hafnium Carbide (W-Re25-HfC): To further improve upon the properties of W-Re, HfC can be added in amounts generally between 2-10%. HfC precipitates along grain boundaries and reduces grain size, thus increasing strength in addition to the toughness obtained through the rhenium effect.

W-LaO is generally the least effective tool material of those listed above due to its tendency to experience plastic deformation after time or in extremely rigorous service environments. Pure W-Re25 is a much more effective tool material than W-LaO, but still can experience significant deformation due to twinning. W-Re-HfC are the best tools of those listed and experience very little wear even over time and in rigorous service environments. When they fail, small particles break off intergranularly and are stirred into the weld material. Previous studies have noticed this loss and contamination as minimal and have reported no degradation to weld quality. Based on the author’s observations in research and literature, W-Re25-HfC is the most effective metallic tool used in the FSW of steel to date.

Process Parameters and Other Considerations

In FSW three parameters are generally considered. They are forge force, spindle speed, and weld travel speed. Forge force is the Z-force (downward force, see Figure 1) applied by the tool on the weld piece and is measured in units such as Newtons or pounds. Forge force helps keep the hot, plasticized material consolidated during the welding process. It also generates frictional heat from the rubbing of the shoulder on the surface of the weld material. Spindle speed is the speed at which the tool rotates and is generally measured in revolutions per minute. The faster the tool rotates, the more heat from friction and plastic deformation is generated. Travel speed is the speed at which the tool moves along the weld path and can be measured in units such as inches per minute, millimeters per minute, etc. Travel speed is very important in production because it determines how quickly a product can be produced. However, care must be taken to balance travel speed with proper spindle speed because a weld with too low or too high of a weld pitch ($\frac{Travel\ Speed}{Rotational\ Speed}$) will result in defects. The goal is to balance these parameters and find a so called "process envelope" for the material. A graphical diagram of this idea can be below in Figure 2.

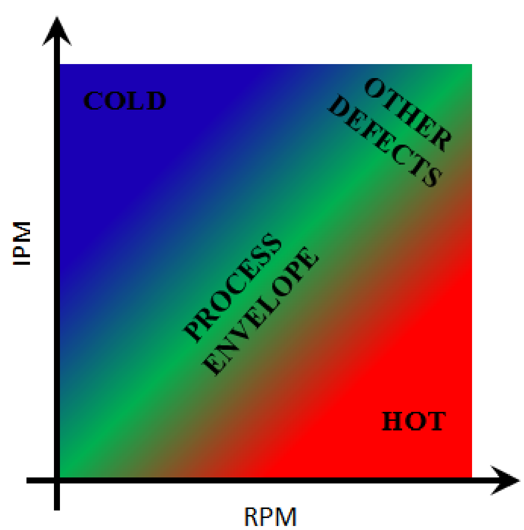

Figure 2. Graphical representation of the balancing of weld parameters in FSW.

A weld with a high travel speed (ipm) and a low rotational speed (rpm) will generate little heat per unit of weld distance. The rotation of the tool is primarily what generates heat from friction and plastic deformation, and if the weld is travelling too fast for the given spindle speed then too little heat is generated. A weld with too little heat is termed “cold” and can form defects. Likewise, too high of a rotational speed will also create defects known as “hot” defects. These parameters must be balanced so that just enough heat is generated for the given travel speed. The goal of industry is to find the top edge of the process envelope, maximizing the travel speed that can be obtained while still maintaining sound, defect free welds. However, this balancing cannot continue ad infinitum. When these parameters are pushed too high other defects happen, and it is also likely that the welding machine and tool will have limitations that prevent further development.

The procedure for developing this process envelope is essentially a trial and error process. Welds are attempted at a certain set of parameters, and then those parameters are evaluated based on the presence of any defects, microstructure, and mechanical properties. The goal is to push the boundaries and find at which points weld qualities to break down. When those boundaries are found it is then possible to say that if welds are made within those boundaries, a quality joint will be created.

Objectives

The first portion of this project will examine the joining of proprietary grade-110 HSLA steel with FSW. Determining production feasibility of FSW for this application will involve examination for defects, characterization of the microstructural changes that take place during welding, and an evaluation of mechanical properties to ensure that customer specifications can be met. Another important consideration will be a quantitative tool wear study, but that is beyond the scope of this paper. In the future these results will be compared to two competing welding styles, tandem MIG and hybrid laser arc welding. Customer specifications include the following:

- 120 ksi Yield Strength
- 130 ksi Tensile Strength
- 12% Elongation

The goal of this project is to develop sound, defect free welds using FSW and to see if those parameters can be optimized to become a worthwhile production practice in the steel industry.

Broader Impact

With engineering safety requirements growing more stringent while consumers hunt for lower prices and lighter weight materials, a new breed of steels is being developed. These include various HSLA alloys and advanced high strength steels (AHSS) that require less material to be used for a given application because of higher strengths. Our particular low alloy material is designed to replace much more expensive high alloy steel while still being able to meet the same customer specifications. Joining of these materials is critical in many industrial applications, but traditional fusion welding techniques have proved problematic. Because of the advanced chemistries and microstructures, defects can occur and much of the mechanical properties of the parent material can be lost as a result of fusion welding. Friction stir welding has proven in the past that it is able to effectively join these materials, but questions still remain if it is a cost effective and efficient method for industrial use. If proven viable, FSW could be a more effective technique than traditional welding methods in terms of mechanical properties, energy input, cost, and safety. The development of welding steel with no brittle phase transformation could eliminate the need for post weld heat treatment or tempering processes, further saving time, energy, and money.

Procedure

Materials

The material provided by Nucor is a grade-110 microalloyed HSLA steel of proprietary chemistry. It is a developmental product and the author has been asked to keep specific details about its chemistry and exact purpose confidential for the time being.

Two thickness of the same material were used. Thinner plates with a thickness of 0.235” in the welded section, and thicker plates with a thickness of 0.40” in the welded section are being developed by Nucor. Though the actual product geometry involves two angles being welded together to form a channel, Nucor produced flat plates to be used in development because of scheduling conflicts in their rolling mill at the height of their product development.

It was later found that the flats have a different microstructure than the angled material. This finding will be discussed in the results under the section titled “Microstructural Analysis.”

Tool Selection

Given the high strength of the weld material, advanced tool material is required. Since one of the primary goals of the project involves finding a process envelope, the tools selected will be subjected to a wide variety of weld parameters that will place large axial loads and torque on them. Therefore, choosing a tough tool is of utmost importance. W-Re-HfC was chosen as the tool material for its high toughness and re-machinability. Rhenium content was 25 weight %, and hafnium carbide content was between 4 and 6%.

Welding

All welds were performed at SDSM&T using an MTS ISTIR 10 Multi-Axis Friction Stir Welding System. Prior to welding the weld edges were machine to be flush, the pieces were sandblasted using garnet, and were then wiped clean using isopropyl alcohol.

There were three different types of weld completed.

1. Developmental bead on plate welds
2. Joined pieces
3. Double pass welds

Developmental Bead on Plate Welds

Developmental bead on plate welds were completed to mimic the effects of welding while saving material. Since the only real difference in the weld pieces of a bead on plate weld and an actual joint is a small space between the two pieces, the comparison is an accurate representation of how a real weld would appear and behave. These welds were performed prior to any actual joining to ensure that good parameters were found before a great amount of material was used. Initially, the welds were performed on the thick angles.

Development in the thick angles involved 7 different weld parameters. They are included in Table 1.

Weld	Rotational speed (rpm)	X-Travel Speed (ipm)	Z-Forge Force (lb)
1	200	2.00	5,000
2	400	2.00	6,000
3	400	3.00	8,000
4	400	3.00	8,000
5	400	3.00	9,000
6	200	3.00	9,000
7	400	4.00	9,000

Table 1: Weld parameters developed in 0.40” thick angles

Samples were evaluated using metallographic techniques and microhardness testing. Specifics on the procedures for these tests will be included in the section titled "Microstructural Analysis."

Development in the thin plates included only two weld parameters, which are included below in Table 2.

Weld	Rotational speed (rpm)	X-Travel Speed (ipm)	Z-Forge Force (lb)
1	400	4.00	9,000
2	400	4.00	6,000

Table 2: Weld parameters developed in 0.235" thick angles

In addition to metallography and microhardness testing, tensile testing was also performed on these welds. The procedures of tensile testing will be discussed in the section titled "Mechanical Testing."

More development was completed using the 0.40" flat material. The goal was to maximize weld travel speed. The parameters are shown below in Table 3.

Weld	Rotational speed (rpm)	X-Travel Speed (ipm)	Z-Forge Force (lb)
1	400	5.00	10,000
2	400	7.00	10,000
3	400	10.00	10,000
4	400	12.00	11,000

Table 3: Weld parameters developed in 0.4" flats

These welds were evaluated using metallography and microhardness traverses.

One developmental bead on plate double pass weld was also performed before actual joining took place. Both passes were performed at 400 rpm, 5 ipm, and 10,000 lb forge force. It was evaluated using metallography and microhardness traverses.

Joined Pieces

Pieces were joined in both the 0.235” and 0.4” thick flat plates.

In the 0.235” plates, material was welded at 4 ipm, 400 rpm and 6000 lb forge force. This weld was saved as a demonstration piece as materials ran low.

In the 0.40” thick plates, double pass welds were completed and will be discussed in the next section.

Double Pass Welds

Double pass welds were completed to achieve full penetration welds in plates that were too thick for single penetration given the author’s available tools. The first weld pass was completed using 400 rpm, 5 ipm and 10,000 lbs and penetrated 0.235” into the weld. After the first pass was completed the weld piece was flipped over and the tool was lined up to run over the exact path that the first weld traveled over. The 2nd pass weld was run at the same parameters as the first pass.

Heat Treatment

The material used in this research requires a stress relief step in the as rolled condition in order to meet elongation requirements, and also requires a tempering step to soften martensite after welding. It was decided to perform both of these steps post weld in order to save time and energy. *Every* heat treatment mentioned in this paper involves placing the piece in the furnace at 1150°F, holding for two hours, and then allowing to air cool.

Microstructural Analysis

Microstructural analysis is performed by a combination of metallography and microhardness testing.

Metallography

Metallography involves the polishing, etching, and observation of samples under an optical microscope. All metallograhpic samples were polished to 1 μm and etched with 2% nital. Samples were prepared for all weld conditions.

Microhardness Testing

Microhardness testing was performed to confirm results found through metallography, as different phases of steel exhibit unique hardnesses. Also, weld traverses are completed to examine how far the HAZ/TMAZ extends into the parent material. This information is important because the HAZ/TMAZ is the region of a weld most likely to fail first. Hardness testing also reveals whether or not post weld heat treatment will be a requirement because a very hard weld is likely to be brittle and in need of tempering and stress relief.

Microhardness tests were performed on a Vickers microhardness tester. All microhardness samples were polished to 1 μm. Traverses were completed starting in the parent material on one side of the weld, travelling inwards towards the HAZ/TMAZ region, through the weld nugget, and then out the other side. For double sided welds, traverses were also completed starting in the 2^{nd} pass weld and going downwards through the region of overlap between the weld passes and into the 1^{st} pass until the bottom of the plate was reached. Distance between indents and number of indents varied for each sample.

Mechanical Testing

Mechanical testing involved only tensile testing. Samples were cut out using a water jet cutter and testing was performed according to ASTM standard E8. Bead on plate welds performed in the 0.40” thick material were machined to mimic a full penetration weld. Special attention was given to the zones in which material failed in.

At the time of this writing, samples for fatigue testing were sent out but no data has been received yet.

Results

Microstructural Analysis

The results of microstructural analysis are included below and include data for parent material, the weld nugget, the HAZ/TMAZ, and for double sided welds. Emphasis was placed on comparing the starting microstructures and the microstructural evolutions of the angled material and flat plates.

Metallography

A reference image is provided below in Figure 3 for comparison. It shows a macro image of the different regions of weld material that will be discussed in this section.

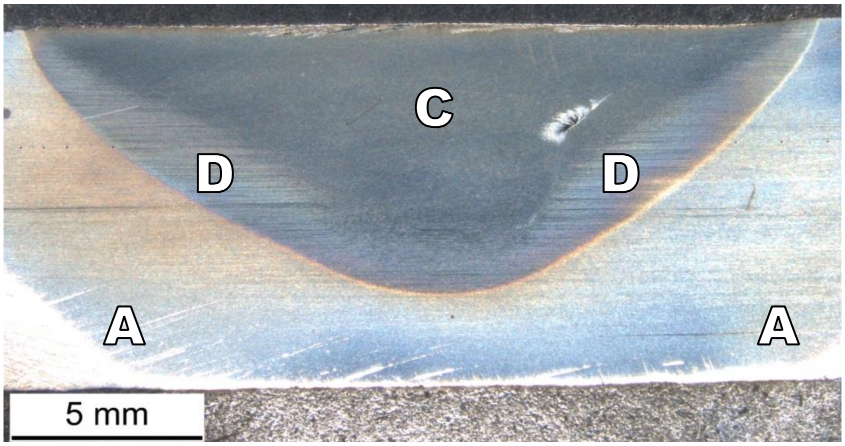

Figure 3: Bead on plate weld with different weld zones labeled.

Zone A: Unaffected parent material

Zone B: HAZ/TMAZ

Zone C: Weld nugget/stir zone

Parent Material

The microstructure of the angled material to be used in production is a mix of ferrite and pearlite. Large non-metallic inclusions are very prevalent in the steel's microstructure. However, the developmental flat plates rolled show a microstructure comprised completely of acicular ferrite. This discrepancy can be attributed to faster post hot rolling cooling rates experienced by the flats to the angles as a result of the difference in geometry. The difference can be seen below in Figures 4 and 5.

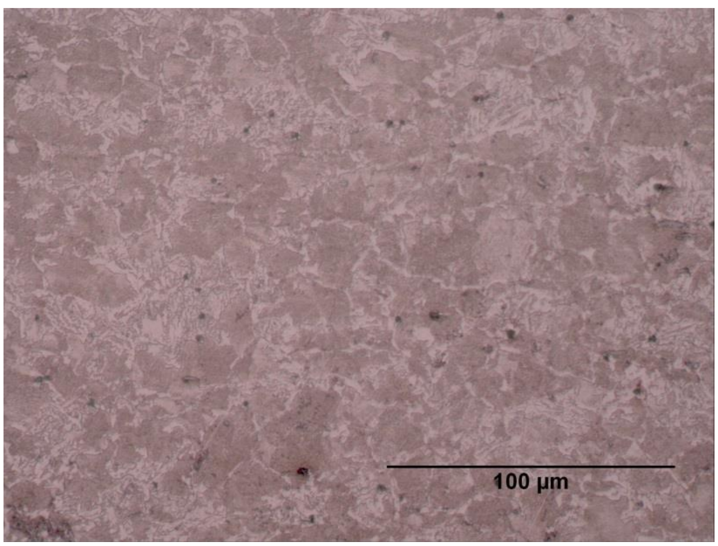

Figure 4: Microstructure of the angled material to be used in production. White areas are colonies of ferrite, darker areas are pearlite. Dark inclusions can be seen.

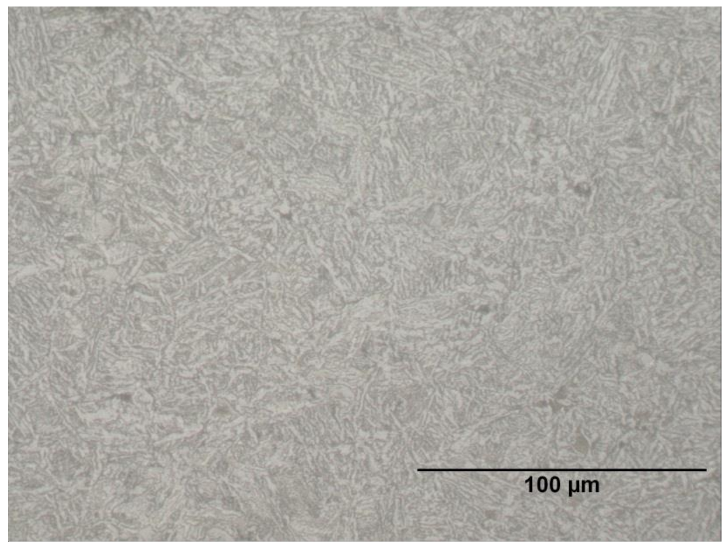

Figure 5: Microstructure of flats rolled to mimic welded portion of the angle material. The structure is completely acicular ferrite.

The ferrite formed in the angled material is also acicular in appearance as opposed to granular. The acicular shape is the result of the numerous non-metallic inclusions present in the metal. Instead of bainite forming in and along the austenite grain boundaries, lenticular shaped ferrite grains branch off of these inclusions as temperatures fall below the austenite transformation temperature, forming the acicular pattern seen in the images above.

Average grain size measurements in the angles were found to be close to ASTM grain size 8.1. In the flats, it was simply noted that the acicular grains are very fine.

Weld Nugget

It is important to compare the microstructure of welded material to parent material to determine if the difference in starting microstructure will have an effect on the performance of the developmental product. Weld nugget microstructure is the same in both the angled and flat plates. Both consist of an acicular pattern consistent with martensite. Because there is no observable difference in images taken of the weld nuggets, only one image of a weld nugget is included below in Figure 6.

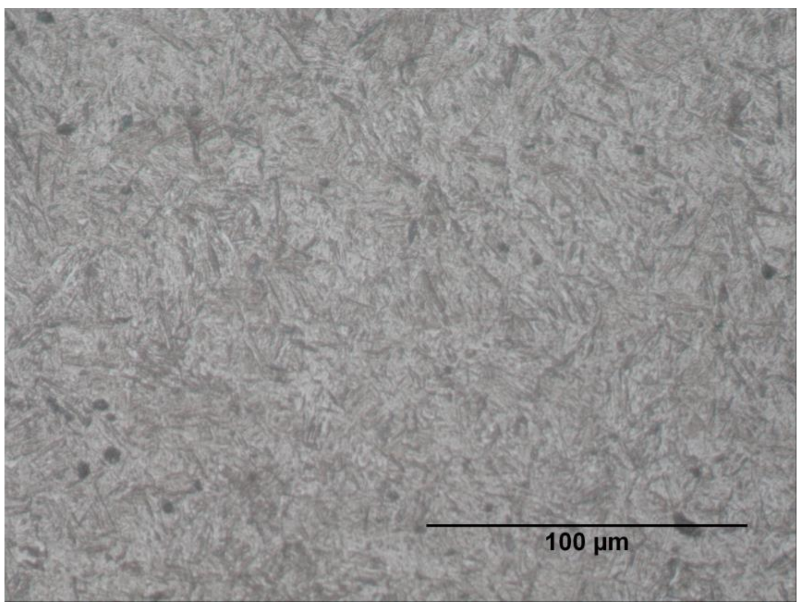

Figure 6: Weld nugget microstructure comprised of martensite. Sample was welded at 10 ipm in the flat plates. Dark inclusions are still present.

Martensite formation in the weld nugget indicates that temperatures exceed austenitizing range and have the rapid cooling rates required for martensite formation. Temperature data obtained by thermocouple readings on the weld piece confirm that material along the joint is in excess of 800°C, sufficient for the austenite formation that allows for martensitic transformation. The large steel anvil on the MTS ISTIR 10 was not heated and acted as a heat sink for the weld pieces, causing the rapid quenching conditions necessary for martensitic transformation to occur.

Deeper characterization of the martensite was largely unsuccessful. The appearance of martensite found indicates the presence of lath martensite as opposed to plate martensite, which is to be expected from steel with this carbon content. Further characterization proved difficult, as defining packet size is difficult for steels of this carbon content. Attempts to measure prior austenite grain size was thwarted by difficulty in obtaining picric acid for picral etchant.

HAZ/TMAZ

The HAZ and thermomechanically affected zones (TMAZ) are of critical importance because they are the primary zones of failure in welded components. This region shows the largest differences in the welded joints when comparing the microstructures of the angles and flats. As shown in Figures 7 and 8, the angled material shows a granular HAZ/TMAZ while the welded flats show a banded region.

Figure 7: Angle welded at 400 rpm 3 ipm, and 9000 lb forge force showing granular HAZ in the middle. Top right shows parent material, bottom left shows weld nugget.

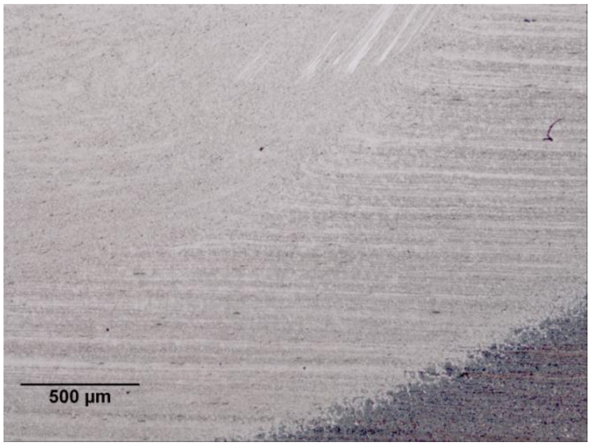

Figure 8: Flat welded at 400 rpm, 7 ipm, and 10,000 lb forge force showing banded HAZ in the middle. Top left shows weld nugget, bottom right shows parent material.

In the angles, grain size is only slightly larger in the HAZ/TMAZ in comparison with the parent material. As shown below in Figures 9 and 10, one sample welded at 400 rpm, 2 ipm travel speed and 6000 lb forge force saw a decrease in grain size number from 8.1 to 7.8.

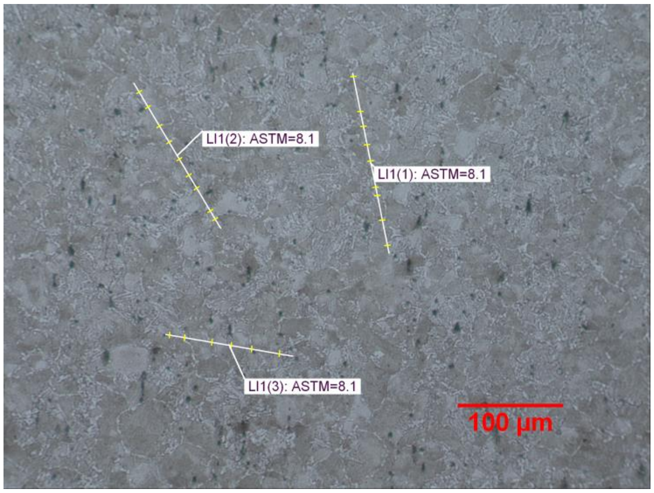

Figure 9: Grain size measurements in unaffected parent material of welded sample.

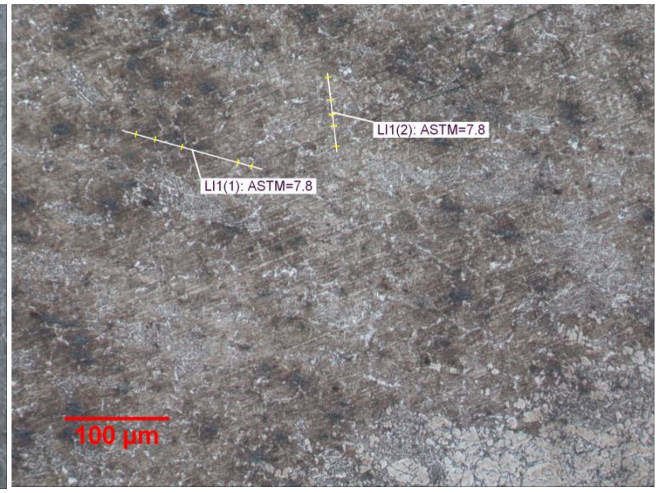

Figure 10: Grain size measurements in HAZ of welded sample.

Since HAZ size directly impacts the performance of the weld, the size of the HAZ as a function of heat input was examined. As expected, welds produced with colder parameters have a narrower HAZ and hotter welds have a broader HAZ. Figure 10 on the next page shows relative HAZ size changing as a result of higher heat input. Rotational speed was held constant at 400 rpm, but travel speeds and forge force was varied. HAZ size generally decreased as travel speed was increased, except in the case of the sample welded at 12 ipm. The 12 ipm sample had a higher forge force and because of the high normal force applied by the tool, frictional heat generated by the rubbing of the shoulder of the tool on the surface of the plates was higher and therefore left a larger HAZ.

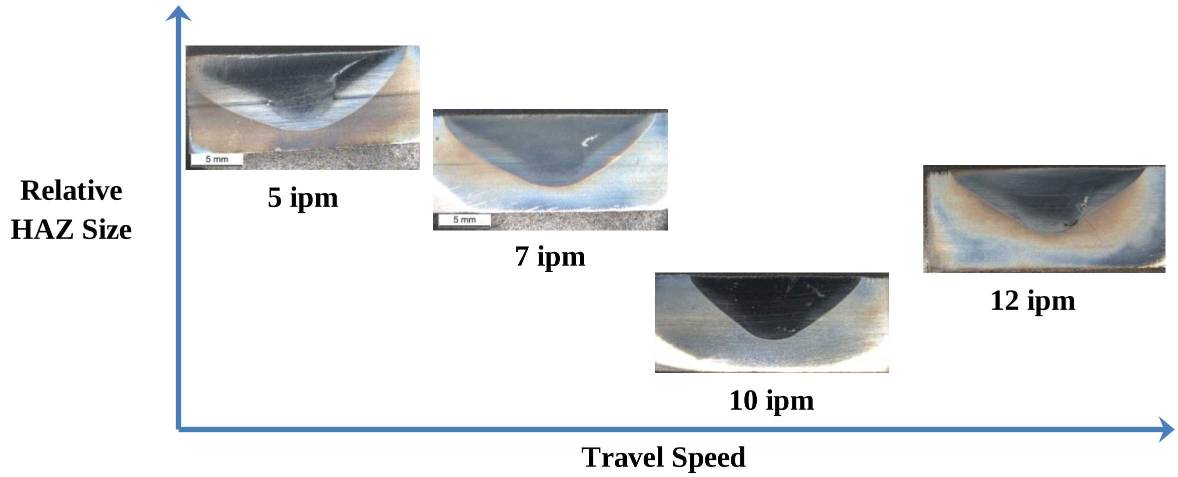

Figure 10: Decreasing HAZ size as a result of lower heat input in faster welds.

Because of the larger HAZ obtained from hotter welds, colder welds are preferred in the FSW of steel so long as they do not produce defects. However, the trials performed at the highest travel speeds of 10 and 12 ipm produced defects typically observed in cold welds. The primary defect observed was scalloping, or periodic void formation. These voids were found on the advancing side of the welds and can be seen below in Figures 11 and 12 in both from the front and side of the weld.

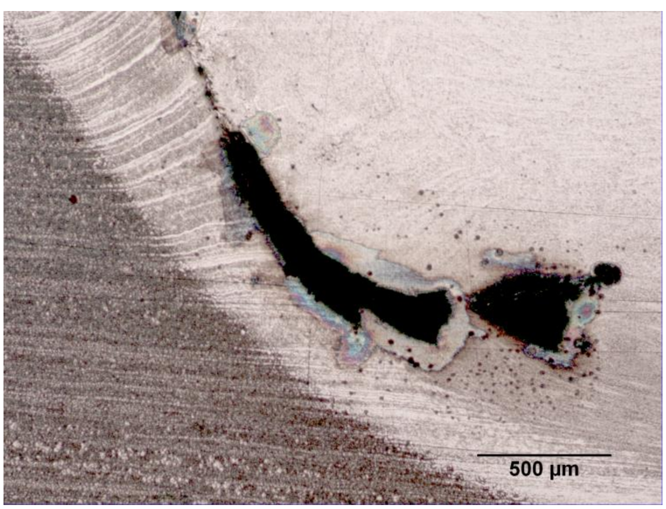

Figure 11: Void in sample welded at 12 ipm seen from the front of the weld.

Figure 12: Perioidic voids in sample welded at 12 ipm seen from the side of the weld.

Double Pass Welds

At the time of this writing, the author did not have a tool capable of completing full penetration welds in the 0.40" thick plates in a single pass, so it was elected to first attempt a double pass weld. A cross sectional image of this type of weld is shown below in Figure 13.

The first pass weld was in effect heat treated by the second pass weld. The martensitic structure of the 1st pass weld was tempered and became a tempered martensite. The 2nd pass weld appeared identical to a regular bead on plate weld except in the areas of overlap with the 1st pass.

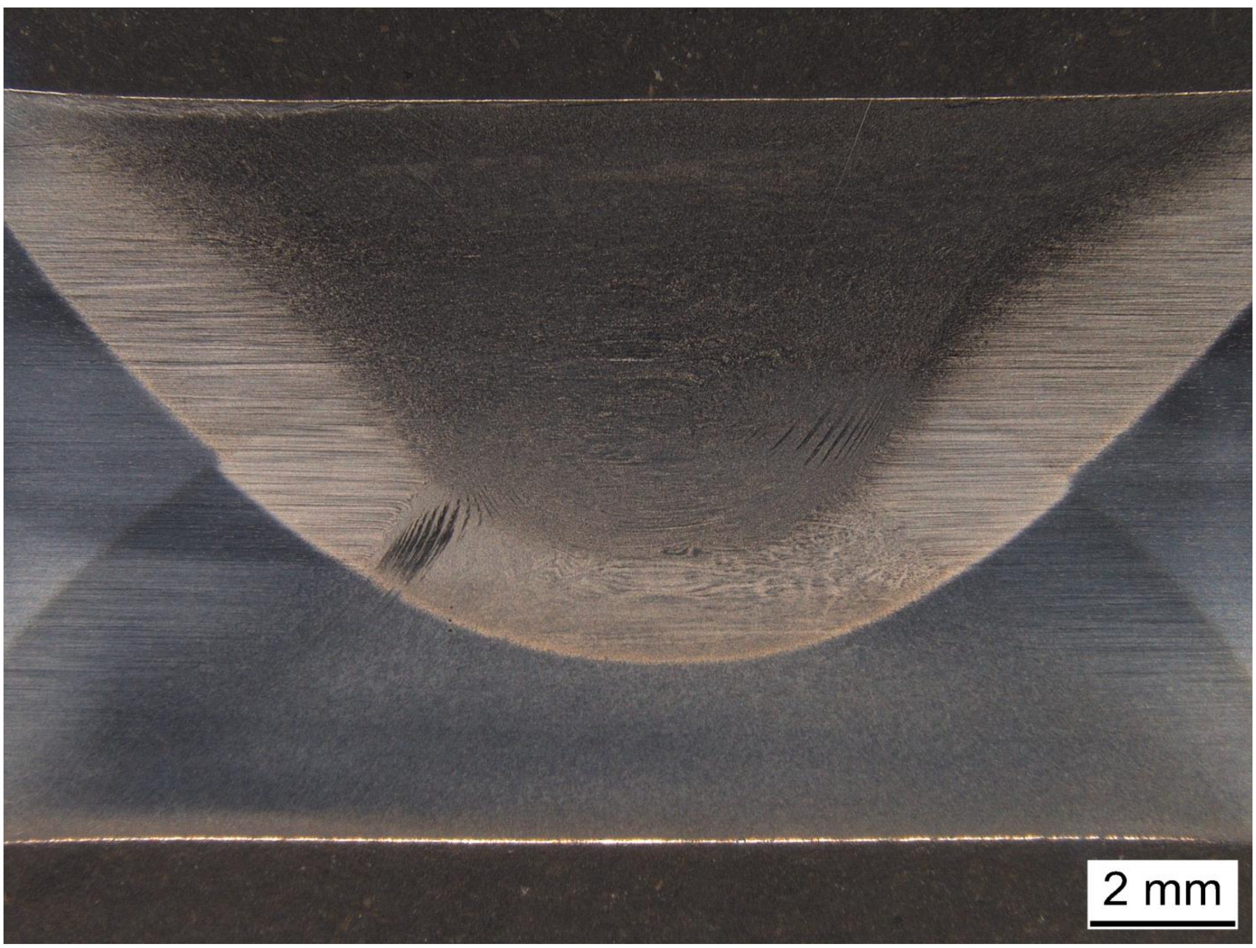

Figure 13: Cross sectional view of a double pass bead on plate weld. The 1st pass weld is the darker bowl shape at the bottom of the image, and the 2nd pass is the more colorful bowl shape on the top of the image.

A unique stir pattern was found here but, as will be explained later, it was not found to play any significant role in the behavior of the material.

Void defects, such as the one below in Figure 15, were found in the latter portions of the welds where the heat input was highest. As the weld travels closer to the end of a plate, heat has less room to disperse and "bottles up" in the material, creating a hotter weld condition and larger HAZ. It is not generally expected to see void defects in hot welds, as they are more prevalent in colder welds where the material is not as plastic. In this case, however, a great amount of material was lost to flashing and it is thought that enough material was removed from the weld so that the process did not have enough material to fully consolidate. More data is needed to confirm this hypothesis, though.

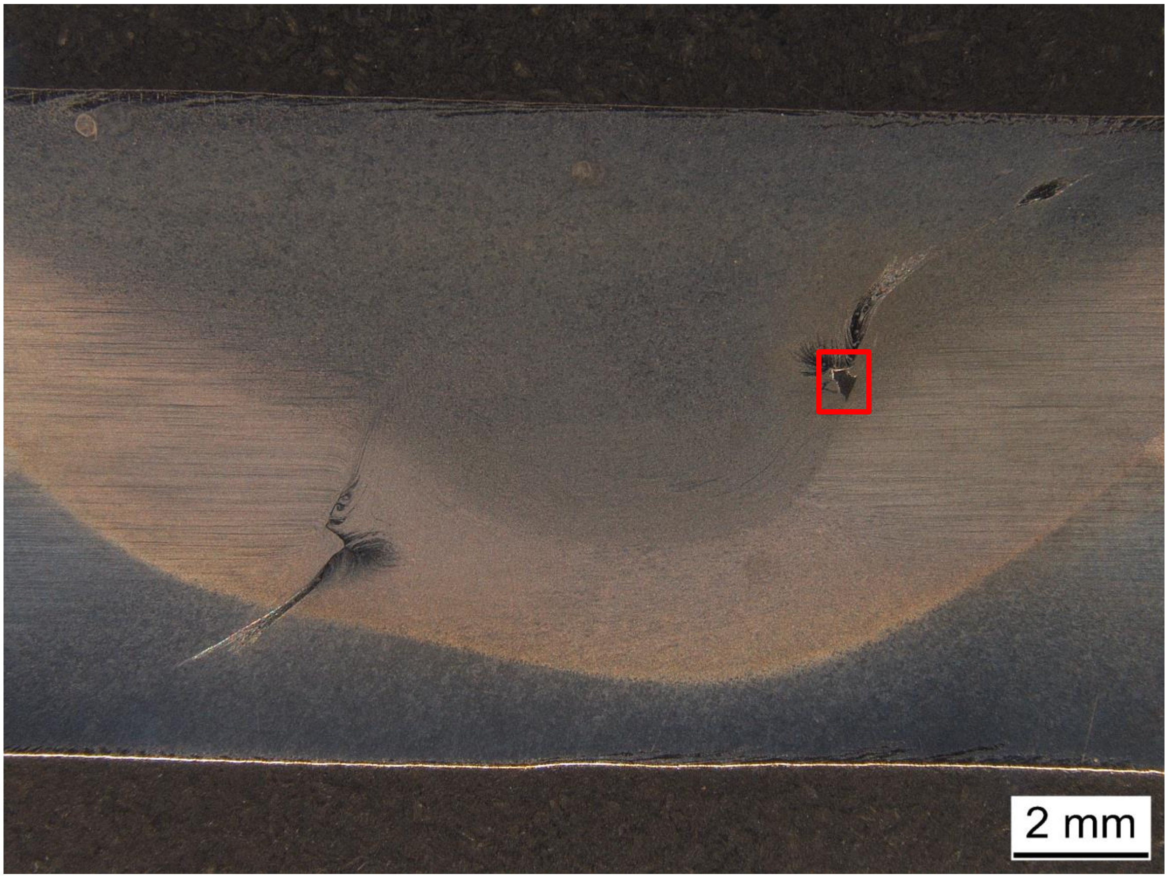

Figure 15: Defect, boxed in red, found near the end of a double pass weld. Note the large HAZ when compared to Figure 13.

Microhardness Testing

Hardness values increase in regions affected by the FSW process. Parent material was evaluated in both the angles and the flats. On average, the angled material consisting of ferrite and pearlite is 33.7 HV higher than the flats that are comprised of acicular ferrite. Data for each of these materials can be found below in Table 4.

Angled Material		0.40" Flats	
Average	342.9	**Average**	309.2
Max	366.8	**Max**	362.7
Min	277.4	**Min**	234.9
Std Dev	27.6	**Std Dev**	25.5

Table 4: Hardness data for both angled and flat material. All values are given in HV.

Hardness in the welded material show the same pattern in all but a single sample. The pattern is that hardness increases from parent material values in the HAZ region and peaks in the weld nugget. Material immediately outside the HAZ visible in the "Metallography" section is consistent with parent material values. Performing a post weld heat treatment returns hardness values in the weld to parent material levels. The hardness in the weld nugget is attributable to the martensitic transformation. A demonstration of this pattern can be seen below in Figure 16.

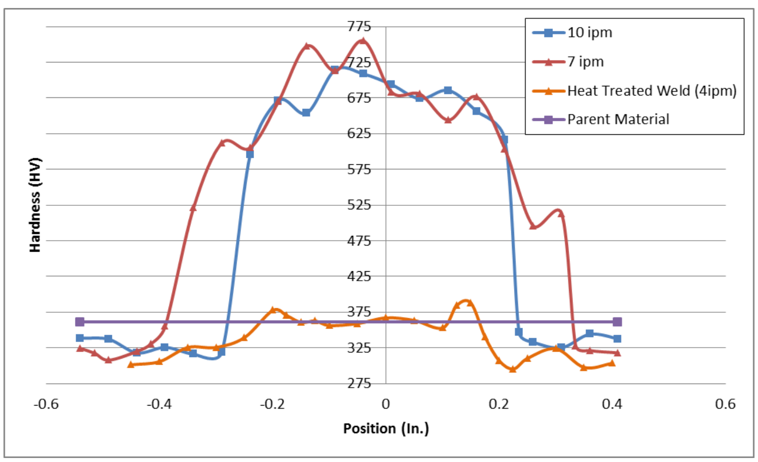

Figure 16: Hardness data for hot weld parameters, cold weld parameters, and weld subjected to post weld heat treatment compared with parent material hardness.

Note that because the weld in blue had a faster travel speed, it has a more narrow HAZ region than the 7 ipm sample. HAZ hardness is generally between 450 and 600 HV. Though the peak hardness value appears in the 7 ipm sample, heat input does not appear to affect peak hardness directly. Weld nugget hardness is generally between 650 and 750 HV. Because peak hardness remains fairly constant throughout all weld parameters, and because metallographic analysis shows no evidence to the contrary, it can be concluded that the weld nugget undergoes 100% martensitic transformation.

The one sample that deviated from these results had a much lower heat input than the other samples. It is listed as Weld 1 in Table 1 and its weld parameters were 200 rpm, 2 ipm, and 5,000 lb forge force. Peak hardness in this sample is only 634.9 HV and average weld nugget hardness is 590.8 HV. It can be concluded from this information that this particular weld did *not* undergo complete martensitic transformation, confirming results from previous studies regarding sub-critical temperature welding. More metallographic analysis is required to ascertain other phases present in the weld nugget.

Double pass welds have unique hardness profiles because the second pass weld heat treats the first pass. However, results are still fairly consistent with the findings listed above. The 2^{nd} pass weld has a hardness profile identical to that of a normal weld. The 1^{st} pass weld acts the same as a weld subjected to post weld heat treatment. Hardness profiles are shown below in Figures 17 and 18.

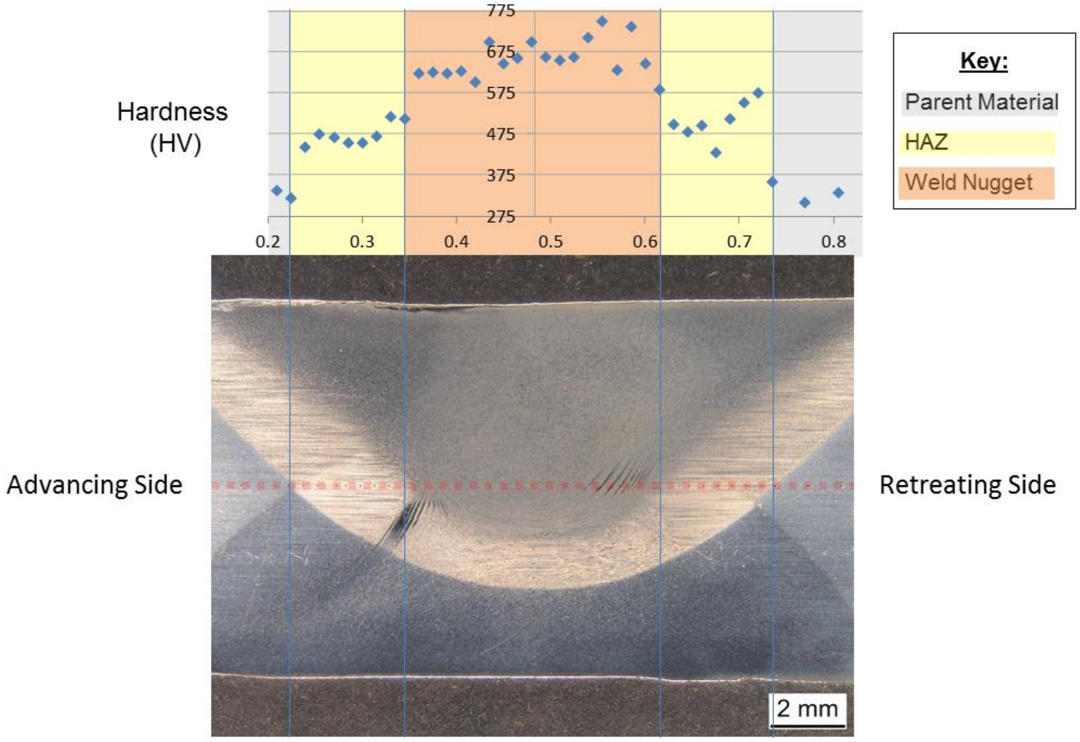

Figure 17: Horizontal hardness profile of a double pass weld.

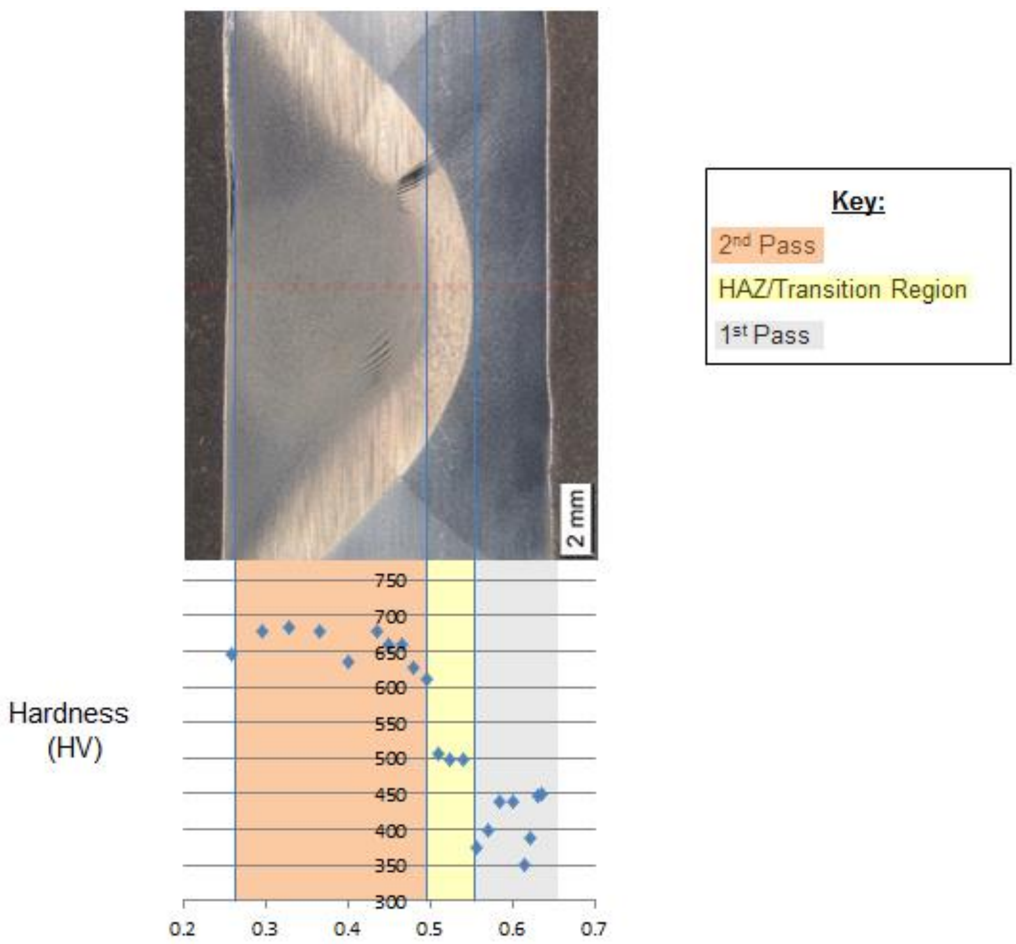

Figure 18: Vertical hardness profile of a double pass weld.

Mechanical Properties

Tensile Testing

Tensile and yield strength values obtained through this testing are generally very close to those of the parent material, but elongation requirements have proven problematic under certain circumstances. Defects were severe enough to cause severe reduction of mechanical properties.

Parent Material

The parent material is designed specifically for a high strength application and therefore must maintain its mechanical properties after welding. Parent material values for each type of material are shown below in Tables 5 and 6.

0.4" Angles			
	YS (ksi)	UTS (ksi)	Elongation (%)
Parent Material, Longitudinal (heat treated)	101 ± 16.1	146 ± 1.1	16.9 ± 0.6
Parent Material, Transverse (heat treated)	121 ± 0.3	148 ± 0.8	11.7 ± 0.8

Table 5: Tensile results of the 0.4" angles in the stress relieved, unwelded condition.

0.40" Flat Parent Material			
	YS (ksi)	UTS (ksi)	% EL
Parent Material Longitudinal	106±0.6	149±0.1	18.6±0.8
PM Longitudinal Stress Relieved	123±2.6	147±2.1	20.3±1.4
PM Transverse	105±4.4	149±1.4	9.9±3.1
PM Transverse Stress Relieved	120±2.2	145±1.5	14.5±0.3

Table 6: Tensile results of 0.4" angles in various unwelded conditions.

The elongations of the 0.4" flats with acicular ferritic microstructures are superior to those found in the ferritic/pearlitic microstructures found in the angles. This is consistent with the microhardness results. YS and UTS values remain relatively unchanged between the two materials.

Single Pass Welded Material

Welded material is weakest in the transverse direction but even in this direction strengths are comparable to parent material values. Elongations drop drastically in the as welded condition but are returned to acceptable levels after post weld heat treatment. Strengths do drop as a result of the stress relief, but previous unpublished work by the author has shown that a different stress relief/tempering practice can improve these properties. Values can be seen below in Table 7.

The longitudinal weld samples are weld metal isolate and show drastic increases in strength but lost any measurable amount of elongation. A few samples had large non-metallic inclusions that drastically reduced strength, but the values were still much higher than in the samples in the transverse directions.

0.4" Angles			
	YS (ksi)	UTS (ksi)	Elongation (%)
Transverse Weld (as welded)	123 ± 1.6	152 ± 10.5	3.2
Transverse Weld (heat treated)	117 ± 0.3	142 ± 1	13.2 ± 2.2
Longitudinal Weld (as welded)	128 ± 0.8	216 ± 10.7	N/A
Longitudinal Weld (heat treated)	145 ± 7.9	155 ± 4.4	10.4 ± 1.2

Table 7: Tensile results of 0.4” angles in various welded conditions.

Similar values are found in the 0.235” flats. Table 8 below contains data for the heat treated weld samples and parent material values for comparison. All samples from the welded material were taken from the transverse direction.

0.235" Flats			
	YS (ksi)	UTS (ksi)	Elongation (%)
Parent Material	123 ± 0.4	143 ± 0.9	12.2 ± 1
Welded Material	121 ± 2.2	145 ± 1.5	9.57 ± 0.7

Table 8: Tensile results of 0.235” angles in the parent material and welded condition. Both sets of data were subjected to the heat treatment practice recommended by Nucor.

Samples from these welds were defect free and either failed in the HAZ or the parent material. An image of broken tensile samples can be seen below in Figure 19.

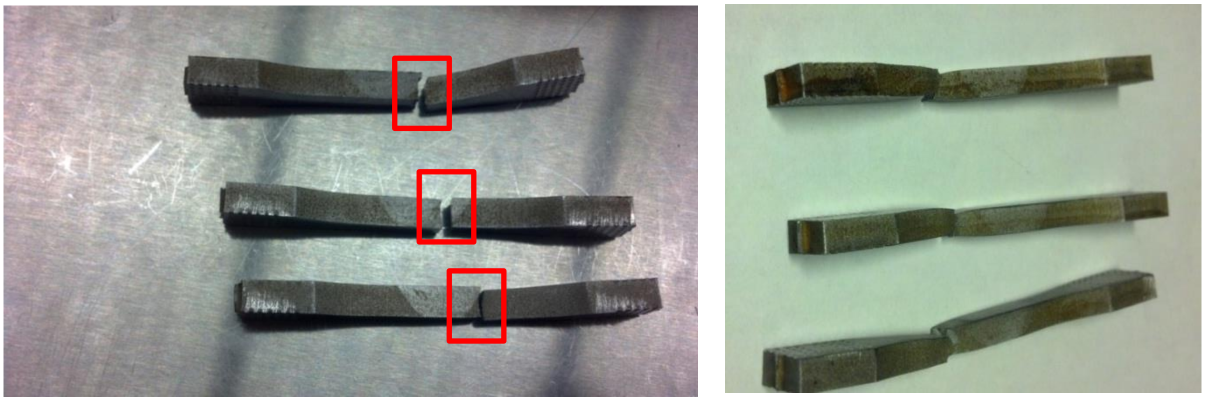

Figure 19: Tensile samples in welded plates that failed outside of the weld.

Double Sided Welds

Double sided welds exhibit high strength and low elongations in all conditions. As discussed earlier, defects were found near the middle and end of the weld and are highly detrimental to tensile properties.

The first developmental weld was performed with no intermediate heat treatment. Its tensile properties are listed below in Table 8. Samples near the end of the weld are defective and fail at a very low tensile strength. It was elected to stop testing these samples to avoid damaging the extensometer since they failed at strains far lower than the offset yield. The results of the defective samples were far below customer specifications and typical results so they are not included below.

Double Pass Bead on Plate Weld			
	YS (ksi)	UTS (ksi)	% EL
As Welded (with defect)	126±2.9	145±17	2.1±1.3
As Welded (without defect)	126±2.9	153±8.6	2.2±1.6
Welded & Tempered	131±3.3	149±3.1	4.9±2.5

Table 8: Tensile results from developmental bead on plate double sided welds.

There is a large standard deviation in elongation results, but one sample was able to obtain an elongation of nearly 7%. Though not up to customer specifications, this result is promising and it is believed that with some parameter development these specifications can be met.

Failure in the as welded condition is of mixed mode. The tempered material in the 1st pass weld exhibits a rough, ductile fracture surface with extensive plastic deformation. The untempered 2nd pass exhibits brittle failure with two separate regions. A picture of the fracture surfaces can be seen below in Figure 20.

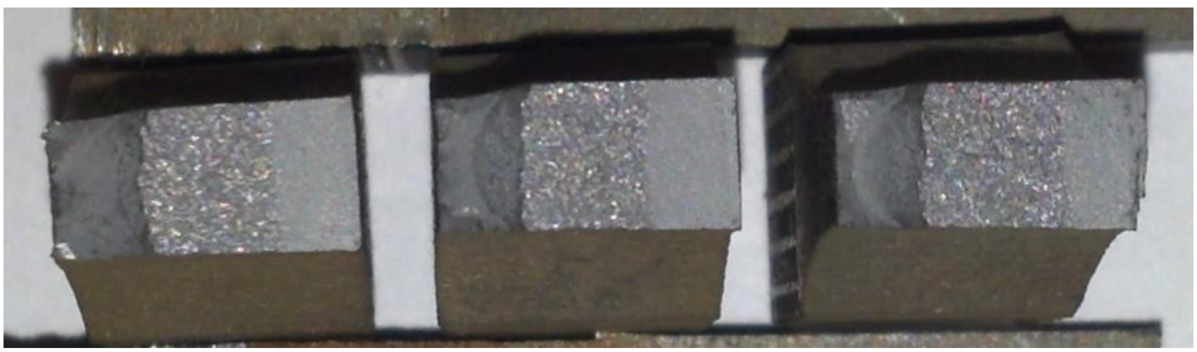

Figure 20: Fracture surface of tensile samples of double pass welds.

Left side: 1st pass weld material with ductile fracture surface

Middle: Region of overlap with brittle fracture surface

Right Side: 2nd pass weld material with brittle fracture surface

Even though elongations do not improve significantly with the post weld heat treating procedures used, the fracture surface was entirely ductile in those samples.

After defects were found in the developmental weld it was elected to perform an intermediate stress relief/tempering step to soften the very hard weld material in the 1st pass. The idea is that the 2nd pass then does not have to stir the very hard martensitic material of the 1st pass and the risk of leaving voids is minimized. These results were not successful and it was found that voids form near the middle of the length of the weld and extend to the end. Excessive flashing occurs in the 2nd pass weld and it is believed that the forge force applied was excessive, especially for the stress relieved condition that the material was already in. As shown below in Table 9, tensile data was quite poor, especially in terms of elongation.

Averages			
	YS (ksi)	UTS (ksi)	% EL
As welded	121±3.5	144±5.0	3.4±0.3
Tempered	119±1.1	135±4.1	3.5±0.5

Table 9: Tensile data from double sided welds

It is possible that the piece lost enough material to flashing that there simply was not enough material left to consolidate the piece and fill in the voids. This evidence is supported by the fact that void formation started in the region where flashing began to become most heavy. However, this is purely speculation at this point and more data would be needed to confirm this explanation.

Discussion

A number of questions and discussion items have been raised by the results of this research. One of those questions is about the microstructural discrepancies between the angled and flat material, another is the possibility of optimizing the heat treatment practice performed in this paper to maximize mechanical properties, and the last is the martensite transformation and the possibility of sub-critical welding.

Microstructural Discrepancies

The first consideration that needs to be made is the difference in starting microstructure of the intended product of angles to the flats produced purely for developmental purposes. The question of whether or not the developmental flats can be an accurate representation of the final product is a concern and adds another variable to an already complex process. It was found that the acicular ferrite structure found in the flats is both softer and more ductile than the ferrite and pearlite microstructure found in the angles. Metallography also reveals an entirely different welded microstructure in the flats than the angles. However, do the properties of the parent material alter how the welds themselves behave? Is it more or less difficult for the tools to stand up to the different microstructures during welding?

Both types of material exceed austenitizing temperature meaning that both also underwent phase transformations. It should also be noted that the portion of the angled material that was not welded was cut off and removed prior to welding for ease of set up, making the thermal conditions experienced during welding essentially identical between the two materials. Weld material and the HAZ had the same hardness values in both the flats and angles. Both UTS and YS values remained relatively constant. Elongations did not vary much, either. Therefore with the current data it is fairly safe to assume that the developmental material produced does provide an accurate representation of the behavior of the intended product.

Heat Treatment Optimization

The heat treatment employed for the parent material stress relief and post weld tempering was used because of cost effectiveness. Based on previous unpublished work by both Nucor and the author, the current procedure of heating material at 1150°F for two hours and air cooling is not the most effective procedure for this product. Better strength and elongation properties can be obtained through cooler holding temperatures. Therefore, even though some of the tensile data provided in this report does not meet customer specifications, there is no concern associated with the process because altering the heat treating practices can significantly improve properties.

Martensite Phase Transformation and Sub-Critical Welding

The martensite transformation that occurs as a result of welding can be detrimental to physical properties because of the brittle behavior and subsequent lack of toughness exhibited by martensite, however it is not unique to the FSW process. Other welding methods have a much greater heat input than FSW and can also form martensite. There are also ways to avoid this transformation entirely. Work by Fuji has shown that welding done with the correct parameters can avoid exceeding austenitizing temperature all together, eliminating the possibility of this phase transformation. The methods developed in his paper are very slow, however, and would be unlikely to be used in a production setting. The materials used were also far thinner and not as strong as the material used in this research, and since plastic deformation provides much of the heat generated in FSW, temperatures were undoubtedly lower in that study than this one. More feasible is reducing the cooling rate to slow enough so that the quenching conditions for martensite cannot occur. This can be accomplished through welding on a hot anvil or by using induction heating. This eliminates the need for any post weld heat treatment to relieve brittle behavior caused by phase transformations in all types of steel.

Conclusion

Summary

With the correct weld parameters, FSW can be an effective joining practice even for ultra-high strength steels such as the one used in this paper. Defect free welds with mechanical properties approaching, and sometimes even improving, those of the parent material have been developed. So far, however, there is still a great deal of development required for it to be an effective production practice. Martensitic transformation is still a large consideration to consider when using FSW on steel, but its effects can be circumvented through proper post weld heat treatment or cooling rate control. The following conclusions can be made:

1. The acicular ferrite found in the flat plates provides an accurate developmental comparison to the ferrite and pearlite microstructure found in the angles actually planned to be used in production.
2. The high temperatures and rapid cooling of the material during welding leads to a martensitic transformation in the weld nugget.
3. Hardness in both the weld nugget and HAZ/TMAZ is very high in the as welded condition, leading to decreased ductility and brittle weld behavior. Post weld heat treatment is required to relieve stresses and temper the martensite if no action is taken to prevent martensite transformation.
4. Post weld heat treatment can restore hardness and ductility to acceptable levels.
5. It is difficult to perform FSW without exceeding austenitizing temperature. Therefore, preventing martensitic transformation is more likely to be accomplished by slowing cooling rates through induction heating or some other method.
6. Material is refined in the weld nugget as a result of forging, drastically improving mechanical properties in the weld metal itself.
7. Tensile properties of the welded material are very close to those of the parent material, though elongation does not always meet minimum customer specifications. A better heat treatment practice can be developed so that the material will meet these specifications.

8. Double sided welds can be performed but more weld parameter development is required for them to be effective. There are also more efficient possibilities to be used than the procedures used in this paper.
9. No tool wear was observed in any weld trials, but inspection was purely visual and no quantitative results have been obtained.

Recommendations

The author recommends the following solutions to further improve weld properties and production feasibility:

1. Perform post weld heat treatment at a lower temperature. Cooler heat treatments for this material have proven more effective for Nucor in the past and could provide an easy and immediate upgrade to all current weld parameters as well as future ones.
2. Use a tool with a more featured surface than the smooth one currently used. The features will be more suitable for the grabbing and transporting of weld metal during the process, especially in cooler welds. These tools can potentially eliminate the problems with voids experienced in the welds with faster travel speeds and the double sided welds.
3. Perform welds at sub-critical cooling rates to avoid the martensitic phase transformation. This particular material requires a stress relief step even in the as rolled condition, but the ability to weld without brittle phase transformation can be massively useful to this and other steel joining applications.
4. Perform welds in the 0.4” material with lower forge force. The material experienced excessive flashing and a wider HAZ when high forge force was applied. A lower forge force could eliminate post weld clean up, material loss, and can help to narrow the HAZ.

5. Obtain a larger tool for single pass welds in the 0.4" thick material or perform a self-reacting weld in which two tools weld the plates simultaneously. Both properties and efficiency would improve with these methods.

Future Work

Though FSW of steel has come a long way, a great deal of development is still required before it can be an effective production practice. Steps to be taken in the future include the following:

1. Further parameter development that involves pushing the process envelope to maximize production efficiency using different tool materials and geometries.
2. Fatigue testing.
3. Single pass welds in 0.40" thick material using larger tools or performing self-reacting welds.
4. Sub critical welding using induction heating, heated anvils, or even welding in a cooled atmosphere to prevent reaching austenitization temperature so that martensite does not form in the weld.
5. Quantitative tool wear studies to help determine cost effectiveness and capabilities of FSW in steel production.
6. Exploration of cost effective tool materials.

References

1. Ahn, B. W., Choi, D. H., Kim, D. J., & Jung, S. J. (2012). Microstructures and properties of friction stir welded 409l stainless steel using a si3n4 tool. Materials Science and Engineering, 532, 476-479. doi: 10.1016/j.msea.2011.10.109

2. Babu, S. S. (2004). The mechanism of acicular ferrite in weld deposits. Current Opinion in Solid State and Materials Science, 8, 267-278. doi: 10.1016/j.cossms.2004.10.001

3. Baek, S., Choi, D., Lee, C., Ahn, B., Yeon, Y., Song, K., & Jung, S. (2010). Structure-properties relations in friction stir spot welded low carbon steel sheets for light weight automobile body. *Materials Transactions*, *51*(2), 399-403.

4. Barnes, S. J., Bhatti, A. R., Steuwer, A., Johnson, R., Altenkirch, J., & Withers, P. J. (2012). Friction stir welding in hsla-65 steel: Part i. influence of weld speed and tool material on microstructural development. Metallurgical and Materials Transactions, 43A, 2342-2356. doi: 10.1007/s11661-012-1110-z

5. Chao, Y. J. (2002). Failure mode of spot welds: Interfacial versus pullout. Science of Welding and Joining, 8(2), 133-137.

6. Choi, D. H., Ahn, B. W., Yeon, Y. M., Park, S. H., Sato, Y. S., Kokawa, H., & Jung, S. B. (2011). Microstructural characterizations following friction stir welding of dissimilar alloys of low- and high-carbon steels. Materials Transactions, 52(7), 1500-1505. doi: 10.2320/matertrans.M2010438]

7. Chung, Y. D., Fujii, H., Nakata , K., & Nogi, K. (2009). Friction stir welding of high carbon tool steel (sk85) below eutectoid temperature. Transactions of JWRI, 38(1), 37-42.

8. Feng, Z., Santella, M. L., David, S. A., Steel, R. J., Packer, S. M., Pan, T., Kuo, M., &Bhatnagar, R. S. (2005). Friction stir spot welding of advanced high-strength steels - a feasibility study. Retrieved from http://www.ornl.gov/~webworks/cppr/y2001/pres/122418.pdf

9. Fujii, H., Cui, L., Nakata, K., & Nogi, K. (2008). Mechanical properties of friction stir welded carbon steel joints – friction stir welding with and without transformation. Welding in the World, 52(9/10), 75-82.

10. Ghosh, M., Kumar, K., & Mishra, R. S. (2011). Friction stir lap welded advanced high strength steels: Microstructure and mechanical properties. Material Science and Engineering, 528, 8111-8119. doi: 10.1016/j.msea.2011.06.087

11. He, K., & Edmonds, D. V. (2002). Formation of acicular ferrite and influence of vanadium alloying. Materials Science and Technology, 18, 289-297. doi: 10.1179/026708301225000743

12. Hovanski, Y., Santella, M. L., & Grant, G. J. (2007). Friction stir spot welding of hot-stamped boron steel. Scripta Materiala, 57, 873-876. doi: 10.1016/j.scriptamat.2007.06.060

13. Huang, T., Sato, Y. S., Kokawa, H., Miles, M. P., Kohkonen, K., Siemssen, B., Steel, R. J., & Packer, S. (2009). Microstructural evolution of dp980 steel during friction bit joining. Metallurgical and Materials Transactions, 40A, 2994-3001. doi: 10.1007/s11661-009-0016-x

14. Krauss, G. (2005). *Steels: Processing, structure, and performance*. Materials Park: ASM International.

15. Keeler, S. (2009, June). *Advanced high strength steel (AHSS) application guidelines*.

16. Khan, M. I., Kuntz, M. L., Su, P., Gerlich, A., North, T., & Zhou, Y. (2007). Resistance and friction stir spot welding of dp600: a comparative study. Science and Technology of Welding and Joining, 12(2), 175-184. doi: 10.1179/174329307X159801

17. Kren, L. (2011, August 08). *Developments in making gigapascal-strength steels*.

18. Leonhardt, T. (2009). Properties of tungsten-rhenium and tungsten-rhenium with hafnium carbide. JOM, 61(7), 68-72.

19. McPherson, N. A., Galloway, A. M., Cater, S. R., & Hambling, S. J. (2013). Friction stir welding of thin dh36 steel plate. Science and Technology of Welding and Joining, 18(5), 441-451. doi: 10.1179/1362171813Y.0000000122

20. McPherson, N. A., Galloway, A. M., Wood, J., & Carter, S. R. (n.d.). A comparison between single sided friction stir welded and submerged arc welded dh36 thin steel plate.

21. Miles, M. P., Hartman, T., Cunningham, C., Saunders, N., & Hovanski, Y. (n.d.). High speed friction stir spot welding of advanced high strength steel. 299-307.

22. Miles, M. P., Ridges, C. S., Hovanski, Y., Peterson, J., Santella, M. L., & Steel, R. (2011). Impact of tool wear on joint strength in friction stir spot welding of dp 980 steel. Science and Technology of Welding and Joining, 16(7), 642-649. doi: 10.1179/1362171811Y.0000000047

23. Ohashi, R. (2011). Henry granjon prize competition 2010 winner category a: "joining and fabrication technology" study on friction stir spot welding of dual-phase high-strength steel sheets. Welding in the World, 55(9/10)

24. Ohashi, R., Fujimoto, M., Mironov, S., Sato, Y. S., & Kokowa, H. (2009). Friction stir joining of high strength steel sheets for automotive. Welding in the World, 53(5/6), 23-28.

25. Ohashi, R., Fujimoto, M., Mironov, S., Sato, Y. S., & Kokowa, H. (2009). Effect of contamination on microstructure in friction stir spot welded dp590 steel. Effect of contamination on microstructure in friction stir spot welded DP590 steel, 14(3), 221-229. doi: 10.1179/136217108X388642

26. Rodelas, J., Mishra, R. S., Hilmas, G., & Yuan, W. (2009). Mechanical evaluation of friction stir spot welded advanced high strength steels. Friction Stir Welding and Processing, V, 171-180.

27. Santella, M., Hovanski, Y., & Pan, T. Y. (2012). Friction stir spot welding of advanced high strength steel. SAE International, 5(2), 382-390.

28. Santella, M., Hovanski, Y., Frederick, A., Grant, G., & Dahl, M. (2010). Friction stir spot welding of dp780 carbon steel. Science and Technology of Welding and Joining, 15(4), 271-280. doi: 10.1179/136217109X12518083193630

29. Sato, Y. S., Yamanoi, H., Kokawa, H., & Furuhara, T. (2008). Characteristics of microstructure in ultrahigh carbon steel produced during friction stir welding.ISIJ International, 48(1), 71-76.

30. Thompson, B., & Babu, S. S. (2010). Tool degradation characterization in the friction stir welding of hard metals. Welding Journal, 89, 256-262.

Acknowledgments

Funding for this research was provided by the National Science Foundation. Thanks goes to Maddie Kincaid and Jack Moehring for their help in research tasks, and to Dr. Alfred Boysen for the unparalleled time and effort he puts into helping each of his students grow as communicators. Thanks also goes to the staff at the Arbegast Materials Processing Lab at SDSM&T including Todd Curtis, Kristopher Klus, Matthew Carriker, and David Christian. A very special thanks goes to Dr. Michael West and Dr. Bharat Jasthi who were the primary advisors for this project and without whom this project would not have been completed. Finally, a great thanks goes to Cory Anthony of Nucor Steel, Utah, who made this project possible and was a continued support throughout the entirety of the research.