The Effect of Friction Stir Welding Process Parameters on Charpy V-Notch Impact Toughness in HSLA-65

Samuel C. Sanderson
Brigham Young University - Provo

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ABSTRACT

The Effect of Friction Stir Welding Process Parameters on Charpy V-Notch Impact Toughness in HSLA-65

Samuel C Sanderson
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Master of Science

HSLA-65 steel (6.4 mm thick) was friction stir welded at various welding speeds and spindle speeds. Varying weld parameters provided a range of heat inputs. Impact toughness was evaluated as a function of the different weld parameters and corresponding weld heat inputs. Charpy V-Notch (CVN) tests were conducted in parent material and at both the weld nugget centerline and heat-affected zone (HAZ) locations.

The upper shelf CVN impact energy of the weld nugget was above that of the base metal for all weld parameters. The upper shelf impact toughness in the HAZ was largely unaffected by changing weld parameters.

The nil-ductility transition (NDT) temperature in the weld nugget increased with increasing heat input. The toughness, with respect to the ductile-to-brittle transition, was negatively affected by the increase in heat input. The NDT temperature in the HAZ did not correlate with heat input.

The microstructures and microhardness data were examined. Aspects of variation in the impact energy results were identified as the inhomogeneity of the weld microstructure and the placement of the V-notch. Weld nugget microstructures were more inhomogeneous than base metal. Hardness results showed varying values of hardness from the weld crown to the root, transversely across the weld, and longitudinally along the length. Variation due primarily to the inhomogeneity of the weld microstructure is compounded by the location of the V-notch.

Keywords: FSW, CVN, HSLA-65, impact toughness, transition temperature, NDT
ACKNOWLEDGEMENTS

I thank my family for their prayers, love, and support. Thanks to my friends in the Friction Stir Research Lab, past and present. They truly understand and know what it is like. I thank my committee for their essential guidance and evaluation, especially through the long haul. I have learned greater lessons beyond what is presented in this study. Thanks to an elite group of excellent individuals for their treasured assistance and motivation. Lastly, the financial support from Navy contract No. N00014-08-1-0025 and contract program manager Mr. Johnnie Deloach is gratefully acknowledged.
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1 INTRODUCTION

High-strength low-alloy (HSLA) steels achieve improved properties from a refined microstructure with limited amounts of alloying elements [1]. HSLA steels offer good yield strength, fracture toughness, and weight reduction when compared to mild steels [2]. Thermo-mechanical control processing (TMCP) creates a fine grain size that is primarily responsible for the improved strength and toughness in HSLA steels.

Joining HSLA steels with traditional arc welding methods adversely affect the refined microstructure leading to reduced material performance. Conversely, Friction Stir Welding (FSW) is a solid-state joining process, meaning no melting occurs during the process. The mechanical properties following FSW are frequently better than is the parent material.

Post-weld mechanical performance is important because of potential in-service failures at the weld location. Charpy V-notch (CVN) impact testing supplies valuable information about mechanical properties, specifically impact toughness, over a range of possible operating temperatures. The data resulting from CVN testing are used in structural design and acceptance criteria.

This study explores the effects of FSW process parameters on post-weld CVN toughness in HSLA-65 steel.
2 BACKGROUND

HSLA steels have been used more frequently over the last few decades. These steels are replacing the previous generation of steels in numerous industries because of weight and cost savings due to improved strength, toughness, and weldability. The weldability of HSLA steels is improved by the reduced carbon content. Enhanced strength and toughness are derived primarily from a finer grain size.

A fine grain size in HSLA steels is achieved through thermo-mechanically controlled processing (TMCP) and limited alloying additions. TMCP is the deliberate use of controlled rolling and accelerated cooling in the fabrication of HSLA steels. Controlling the extent of deformation and the temperature of deformation during steel processing can produce a desired microstructure with superior characteristics [3]. For example, rolling above the austenite recrystallization temperature reduces the austenite grain size [4]. Subsequent rolling in the inter-critical region increases austenite deformation leading to a reduced ferrite grain size on transformation [5]. Micro-alloying elements limit austenite recrystallization, further refining grains [6, 7, 8].

Structures fabricated from HSLA steels are typically arc welded together. Traditional arc welding introduces intense local heating and melting [9]. Thus, following arc welding the “wrought” TMCP microstructure is replaced with a cast microstructure in the weld nugget.
Grain coarsening and brittle regions within the heat-affected zone (HAZ) reduce mechanical properties [9].

The high peak temperature in traditional arc welding of HSLA-65 steel coarsens the refined grain size in the HAZ. Zrilic et al. reported diminished impact toughness in both weld nugget and HAZ metal relative to the base metal following manual metal arc welding of HSLA-100 steel [10]. Following submerged arc welding (SAW), the grain structure in HSLA steel coarsens in both the weld nugget metal and HAZ with increasing heat input [11]. Konkol, Warren, and Herbert reported mixed results in the performance of a variety of multi-pass and single-pass arc welds in HSLA-65 [12]. Most of the arc welds did not meet base metal requirements [12].

Bayley and Mantei also conducted an arc weld study on HSLA-65 [13]. They examined CVN toughness at the weld centerline and in the HAZ 1 mm from the fusion boundary. The weld nugget ductile-to-brittle transition temperature was reported to be nearly the same between welds of low and high heat input. However, between the welds there was a substantial increase in the transition temperature of the HAZ. Transformation products and a coarse-grain microstructure contributed to the increase and negatively affected the HAZ toughness [13].

Friction stir welding is a solid-state joining process. There is no melting in the weld zone. The lack of melting often leads to enhanced weld zone properties compared to arc welding. To complete a friction stir weld, a non-consumable tool is plunged into the weld seam. The tool traverses along the adjoining surfaces to join the materials at temperatures slightly less than the solidus. Utilizing deformation and friction to create heat, FSW produces a consolidated joint without melting. Frequently, the result is a refined microstructure with favorable post-weld properties.
FSW has been demonstrated as a feasible joining process for steels where the post-weld mechanical properties compare well with parent material properties [14]. In a study of FSW of mild steel, Lienert et al. reported no loss in tensile properties [15]. Konkol et al. reported CVN toughness above the specified minimum for the base metal in friction stir welded HSLA-65 [16]. Konkol and Mruczek demonstrated increased toughness in both the weld nugget and the HAZ over the base metal in HSLA-65 steel [17]. The increased toughness was attributed to fine grains in the weld stir zone and an out-of-specification base metal chemistry.

Amid the research in FSW of steels, few studies have looked at the effect of FSW on post-weld toughness. Few studies, if any, have examined the ductile-to-brittle transition and toughness results in HSLA-65 as a function of FSW weld parameters.

The focus of this research is to examine the effect of changing FSW process parameters on post-weld CVN impact toughness in HSLA-65.
3 EXPERIMENTAL APPROACH

3.1 Weld Parameters

FSW parameters for this study were selected to cover a range of heat inputs and follows on work reported by Wei [18]. In Wei’s study, the combination of selected parameters (welding and spindle speed) produced consolidated welds in 9.5 mm (0.375 in.) thick HSLA-65.

Heat input is a measure of energy per length [19]. The combination of relatively high welding speed and relatively low spindle speed produced the lowest heat input. Contrastingly, the combination of low welding speed and high spindle speed produced the highest heat input. The heat input was averaged over the length of the weld for each combination of parameters. The heat input ranged from 1000 J/mm to 4000 J/mm, Table 3-1.

<table>
<thead>
<tr>
<th>Welding Speed [mm/min] (in/min)</th>
<th>Spindle Speed [rpm]</th>
<th>Resultant Heat Input* [J/mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>203 (8)</td>
<td>300</td>
<td>1000</td>
</tr>
<tr>
<td>203 (8)</td>
<td>600</td>
<td>1600</td>
</tr>
<tr>
<td>127 (5)</td>
<td>450</td>
<td>2000</td>
</tr>
<tr>
<td>51 (2)</td>
<td>300</td>
<td>3800</td>
</tr>
<tr>
<td>51 (2)</td>
<td>600</td>
<td>4000</td>
</tr>
</tbody>
</table>

Table 3-1: The selected operating parameters, with resultant heat input, for this study. *The heat input was measured as a result of the process and not specified prior to welding.
3.2 **FSW Procedure**

Bead-on-plate welds in 6.4 mm (0.25 in.) HSLA-65 were performed using a polycrystalline cubic boron nitride (PCBN) tool. The tool had a convex scroll-shoulder step-spiral (CS4) design (Appendix A. CS4 Tool Drawing). The machine head was tilted to 0.5°, and the weld line was parallel to the plate rolling direction. The plates were lightly ground on one side to remove mill scale prior to FSW.

3.3 **HSLA-65 Steel Chemistry and Microstructure**

Both the chemical composition of the HSLA-65 used in the experiments and the specification for HSLA-65 according to ASTM A945 are shown in Table 3-2. For the material used in this study, the chemical composition met the ASTM A945 requirements [20].

<table>
<thead>
<tr>
<th>Element (Wt. %)</th>
<th>ASTM A945 Specification</th>
<th>Measured HSLA-65</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.10 (max)</td>
<td>0.077</td>
</tr>
<tr>
<td>Mn</td>
<td>1.10–1.65</td>
<td>1.39</td>
</tr>
<tr>
<td>S</td>
<td>0.010 (max)</td>
<td>0.006</td>
</tr>
<tr>
<td>Ni</td>
<td>0.40 (max)</td>
<td>0.33</td>
</tr>
<tr>
<td>Cr</td>
<td>0.20 (max)</td>
<td>0.147</td>
</tr>
<tr>
<td>Mo</td>
<td>0.08 (max)</td>
<td>0.064</td>
</tr>
<tr>
<td>V</td>
<td>0.10 (max)</td>
<td>0.058</td>
</tr>
<tr>
<td>Nb</td>
<td>0.05 (max)</td>
<td>0.02</td>
</tr>
<tr>
<td>Ti</td>
<td>0.007–0.020</td>
<td>0.012</td>
</tr>
<tr>
<td>Si</td>
<td>0.10–0.50</td>
<td>0.011</td>
</tr>
<tr>
<td>Al</td>
<td>0.08 (max)</td>
<td>0.016</td>
</tr>
</tbody>
</table>
Base metal, weld nugget metal, and HAZ microstructures were measured using Scanning Electron Microscopy. An XL30 S-Feg microscope, with TSL 5.2 Orientation Imaging Microscopy™ (OIM) data collector/analyzer software, was set at 25 kV for electron backscatter diffraction (EBSD) analysis. Measurements were made in a scan area 200 μm x 200 μm with a step size of 0.2 μm. From the weld nugget scans, 10 measurements of separate microstructural constituents were averaged. Figure 3-1 shows a typical Inverse Pole Figure with an Image Quality overlay from scans in the HAZ (Figure 3-1a) and weld nugget metal (Figure 3-1b). The differences in the microstructures are apparent.

![Figure 3-1: Typical Inverse Pole Figure with Image Quality overlay using OIM™ software for the HAZ (a) and weld nugget material (b). The difference in microstructures is visible.](image)

The prior austenite grain (PAG) size was measured following the PAG reconstruction method developed by Abbasi et al [21]. Bainite lath width and packet size were measured using the method developed by Wei [18]. Bainite lath length measurements were based on >15° crystallographic misorientation using an approach similar to the lath width and packet size measurement method.
3.4 **Microhardness Maps and Charpy V-notch Locations**

Microhardness contour maps were generated from a grid of Vickers hardness indents on a transverse cross-section on specimens from the start and end of each weld. These hardness maps were used to locate the CVN notch locations for both the weld nugget centerline and the HAZ. An example of a typical map with CVN notch locations is shown in Figure 3-2.

It was impossible to isolate the notch completely within the HAZ because of the shape and limited HAZ volume resulting from FSW. With regard to the HAZ V-notch location, the V-notch is in contact primarily with HAZ metal and some fractions of weld nugget metal and parent metal. Similarly, the weld center V-notch is in contact with inhomogeneous weld nugget metal, i.e. a composite of varying microstructures from the weld crown to the weld root. In this work, as shown in Figure 3-2, the V-notch in both the HAZ (on the retreating side of the weld) and weld nugget encounters heterogeneous material with various hardness values.

![Figure 3-2: A typical example of a microhardness contour map of a weld transverse cross-section. The black line on the left indicates the location of the HAZ V-notch and the black line centered in the weld nugget indicates the location of the weld centerline V-notch.](image)

Sub-size standard, 5 mm x 10 mm x 55 mm (0.2 in x 0.4 in x 2.2 in), CVN test specimens were cut from centerline and HAZ. The weld length was approximately 1 m (40 in.). The weld length limited the number of specimens from each weld.
3.5 Impact Energy Test Procedure

Charpy tests were conducted on an Instron SI Series impact tester with a 30.2 kg (66.7 lb.) hammer. Weld centerline test specimens were tested at temperatures ranging from -80° C to 0° C in 20° C intervals, while HAZ test specimens were tested between temperatures of -120° C and -20° C in 20° C intervals. Base metal was also tested in 20° C intervals from -140° C to 40° C. The moderately low test temperatures were achieved by using an agitated bath of liquid nitrogen and Ethanol. Much lower temperatures were achieved with a solution of liquid nitrogen and isopentane. The number of specimens used in the testing is shown in Table 3-3.

<table>
<thead>
<tr>
<th>Charpy Specimens</th>
<th>Number of Specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Metal</td>
<td>30</td>
</tr>
<tr>
<td>Weld Centerline</td>
<td>96</td>
</tr>
<tr>
<td>HAZ</td>
<td>101</td>
</tr>
<tr>
<td>Total</td>
<td>227</td>
</tr>
</tbody>
</table>

The absorbed energy from CVN impact tests of base metal, weld nugget metal, and HAZ was plotted as a function of temperature. Results (a minimum of three specimens at each test temperature) were fitted with a hyperbolic tangent (tanh) function, as outlined by Oldfield [22]. Oldfield indicates the nil-ductility transition (NDT) temperature can be estimated from coefficients in the curve-fit [22]. The NDT temperature is the temperature at which a particular steel is likely to fracture in brittle fashion by cleavage and is associated with negligible ductility [23, 24].
4 RESULTS AND DISCUSSION

4.1 Weld Nugget and HAZ Impact Toughness

Figure 4-1 presents the results of the weld nugget and base metal CVN testing. The data are curve-fit (tanh curve-fit parameters in Table 4-1) to delineate the ductile-to-brittle transition and to show both the lower and upper shelf impact energy values.

Table 4-1: Weld nugget hyperbolic tangent (tanh) curve-fit parameters.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>203 (8), 300</td>
<td>1000</td>
<td>52</td>
<td>52</td>
<td>35</td>
<td>-84</td>
</tr>
<tr>
<td>203 (8), 600</td>
<td>1600</td>
<td>46</td>
<td>46</td>
<td>30</td>
<td>-44</td>
</tr>
<tr>
<td>127 (5), 450</td>
<td>2000</td>
<td>47</td>
<td>47</td>
<td>21</td>
<td>-59</td>
</tr>
<tr>
<td>51 (2), 300</td>
<td>3800</td>
<td>53</td>
<td>49</td>
<td>14</td>
<td>-50</td>
</tr>
<tr>
<td>51 (2), 600</td>
<td>4000</td>
<td>42</td>
<td>35</td>
<td>27</td>
<td>-23</td>
</tr>
<tr>
<td>Base Metal</td>
<td>n/a</td>
<td>31</td>
<td>25</td>
<td>25</td>
<td>-66</td>
</tr>
</tbody>
</table>

In the upper shelf, the impact energy of the weld nugget is greater than the base metal at all heat inputs. The impact energy in the base metal upper shelf ranges from 48 J to 61 J. For the low heat input weld (1000 J/mm), the upper shelf CVN results range from 98 J to 114 J. For the high heat input weld (4000 J/mm), the upper shelf CVN results range from 55 J to 76 J.
Figure 4-1: Weld nugget metal and base metal results from sub-size standard CVN testing. The heat input for each weld is listed in order of decreasing heat input. Each weld and base metal is fitted with a hyperbolic tangent curve.

Figure 4-2 shows the HAZ and base metal CVN results as a function of temperature. The data are also curve-fit (tanh curve-fit parameters in Table 4-2). There is observable overlap between base metal impact energy and the impact energy of the HAZ at all heat inputs. The impact energy in the base metal upper shelf ranges from 48 J to 61 J. The upper shelf CVN results for the low heat input weld range from 56 J to 60 J. The upper shelf CVN results from the high heat input weld range from 51 J to 57 J.
The HAZ toughness appears largely unaffected by FSW. The near-equivalence of the FSW HAZ with base metal is a vast improvement over the typical arc welding HAZ. The typical arc weld HAZ frequently contains coarse grains and brittle regions, leading to a loss in toughness.

In this study, isolating the HAZ metal for CVN testing was prevented by the shape of the weld nugget and the diffuse boundaries on both sides of the HAZ (Figure 3-2). Following arc welding, the HAZ is relatively large and coarse-grained. Depending on weld groove geometry, CVN notches in arc-welded material can be positioned in nearly all-HAZ material. However, the
FSW HAZ in HSLA-65 steel is small and biased. As a result, the HAZ results represent a composite of microstructures from regions including weld nugget, HAZ, and parent metal.

<table>
<thead>
<tr>
<th>Parameters [mm/min (in/min), RPM]</th>
<th>Average Heat Input [J/mm]</th>
<th>Tanh Curve-fit Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>203 (8), 300</td>
<td>1000</td>
<td>37</td>
</tr>
<tr>
<td>203 (8), 600</td>
<td>1600</td>
<td>34</td>
</tr>
<tr>
<td>127 (5), 450</td>
<td>2000</td>
<td>34</td>
</tr>
<tr>
<td>51 (2), 300</td>
<td>3800</td>
<td>35</td>
</tr>
<tr>
<td>51 (2), 600</td>
<td>4000</td>
<td>31</td>
</tr>
<tr>
<td>Base Metal</td>
<td>n/a</td>
<td>31</td>
</tr>
</tbody>
</table>

A summary of the upper shelf impact energy for the weld nugget, HAZ, and base metal are presented in Table 4-3. The tabulated data are derived from the tanh curve-fit for the upper shelf, i.e. A+B.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>203 (8), 300</td>
<td>1000</td>
<td>104</td>
<td>59</td>
</tr>
<tr>
<td>203 (8), 600</td>
<td>1600</td>
<td>92</td>
<td>55</td>
</tr>
<tr>
<td>127 (5), 450</td>
<td>2000</td>
<td>94</td>
<td>56</td>
</tr>
<tr>
<td>51 (2), 300</td>
<td>3800</td>
<td>102</td>
<td>61</td>
</tr>
<tr>
<td>51 (2), 600</td>
<td>4000</td>
<td>77</td>
<td>53</td>
</tr>
<tr>
<td>Base Metal</td>
<td>n/a</td>
<td>56</td>
<td>56</td>
</tr>
</tbody>
</table>
4.2 **Ductile-to-Brittle Transition**

The NDT temperature can be derived from the tanh fit, as outlined by Oldfield [22]. The NDT temperature is determined from the combination of two parameters in the curve-fit, \( T_0 \) and \( C \), illustrated in Figure 4-3. The central temperature in the transition region is \( T_0 \), and \( C \) is the distance from \( T_0 \) to the NDT temperature.

Other approaches to transition temperature simply determine the transition temperature by the central temperature \( (T_0) \) in the transition region. This is seen in energy transition temperature (ETT) and in the fracture appearance transition temperature (FATT). The ETT is the temperature at which the impact energy is the average between the upper shelf and lower shelf. The FATT is the temperature at which the fracture surface is 50% fibrous.

![Figure 4-3: Schematic illustrating the hyperbolic tangent curve-fit on two sets of theoretical Charpy impact data [22]. The NDT temperature, derived from the tanh fit, is more descriptive of the ductile-to-brittle transition. It accounts for the steepness of the transition.](image-url)
The NDT temperature more accurately characterizes the ductile-to-brittle transition. It accounts for the steepness of the transition. For example (Figure 4-3), in the schematic two separate theoretical Charpy test results are fitted with a curve (e.g. Curve-fit #1 and Curve-fit #2) and $T_0$ is shared between the curves. Other approaches, relying solely on $T_0$, indicate the transition temperature for both is the same. Clearly, the transition behavior of each is not adequately represented simply by $T_0$. On the other hand, the NDT temperature, for Curve-fit #1 is distinctly different from Curve-fit #2. The different NDT temperatures, rather than a shared central temperature more accurately represent the unique transition behavior of each curve.

Within the HAZ of friction stir welded HSLA-65 there is no significant relationship between the NDT temperature and heat input. The toughness of the HAZ appears unaffected by changes in heat input, which changes result from different FSW process parameters. In the weld nugget of friction stir welded HSLA-65 the NDT temperature correlates with heat input. The NDT temperature increases with increasing heat input. For every 1000 J/mm increase in heat input, the NDT temperature increases approximately 20 °C. The relationship is shown in Figure 4-4. This indicates that changing FSW process parameters toward increasing heat input has a negative effect on the toughness of the weld nugget. The NDT temperatures, summarized in Table 4-4, are from the tanh fit for the weld nugget, HAZ, and base metal CVN data.

The NDT temperatures in the weld nugget are significantly different from the base metal and correlate with heat input. The NDT temperatures in the HAZ are not significantly different from base metal and do not correlate with heat input.
Figure 4-4: The increase in NDT temperature is correlated with the increase in heat input.

Table 4-4: Summary of the NDT temperature (NDTT) in the weld nugget and HAZ.

<table>
<thead>
<tr>
<th>Parameters [mm/min (in/min), RPM]</th>
<th>Average Heat Input [J/mm]</th>
<th>Weld nugget NDTT [°C]</th>
<th>HAZ NDTT [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>203 (8), 300</td>
<td>1000</td>
<td>-120</td>
<td>-81</td>
</tr>
<tr>
<td>203 (8), 600</td>
<td>1600</td>
<td>-74</td>
<td>-84</td>
</tr>
<tr>
<td>127 (5), 450</td>
<td>2000</td>
<td>-80</td>
<td>-88</td>
</tr>
<tr>
<td>51 (2), 300</td>
<td>3800</td>
<td>-64</td>
<td>-101</td>
</tr>
<tr>
<td>51 (2), 600</td>
<td>4000</td>
<td>-51</td>
<td>-85</td>
</tr>
<tr>
<td>Base Metal</td>
<td>n/a</td>
<td>-91</td>
<td>-91</td>
</tr>
</tbody>
</table>
4.3 Aspects of Variation

Aspects of the variation within the weld nugget have been investigated: the weld nugget microstructure and the location of the Charpy V-notch. These are described below. Other potential sources of variation are also discussed.

4.3.1 Microstructure

Optical micrographs in Figure 4-5 show the microstructures of the base metal (Figure 4-5a), low heat input weld metal (Figure 4-5b), and high heat input weld metal (Figure 4-5c).

Figure 4-5: Optical micrographs of base metal (a), low heat input weld metal (b), and high heat input weld metal (c). The base metal is more polygonal and homogeneous than the weld metal.
A comparison of the optical micrographs shows the microstructure changes with increasing heat input. The base metal microstructure is largely polygonal. The distribution of grain sizes in the base metal is approximately uniform. The average ferrite grain size is 9 \( \mu \text{m} \).

The microstructure of the low heat input weld is less polygonal than base metal. The high heat input microstructure contains little to no polygonal features but long, narrow laths. The average lath length increases from about 13 \( \mu \text{m} \) to 26 \( \mu \text{m} \) as the heat input increases from 1000 J/mm to 4000 J/mm. The increasing heat input tends to correspond with an increasingly bainitic appearance in the welds.

The various microstructural constituents in the weld affect toughness. For example, upper bainite has a higher transition temperature than lower bainite [26]. The transition temperature of ferrite is above both lower and upper bainite [26]. Thus, a weld possessing a high fraction of bainite will have less toughness than a polygonal microstructure.

The OIM™ scans in Figure 4-6 clearly display the increasingly bainitic microstructure in the high heat input weld (Figure 4-6b) relative to the low (Figure 4-6a).

Table 4-5 contains the average measurements of the microstructure constituents in the weld nugget. The measurements of lath length and width, PAG size, and packet size are tabulated as a function of weld parameters. The average lath length steadily increases with increasing heat input. The average PAG size also increases with increasing heat input. However, the increase is not statistically significant, meaning the increase is as likely to be a random event as not.
Figure 4-6: Inverse Pole Figure with Image Quality overlay from OIM™ scans of the low heat input weld microstructure (a) and the high heat input weld microstructure (b). From low to high heat input, the appearance of the microstructures becomes increasingly bainitic.

Table 4-5: Average measurements of the weld nugget microstructure.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>203 (8), 300</td>
<td>1000</td>
<td>12.6</td>
<td>29.7</td>
<td>1.1</td>
<td>6.8</td>
</tr>
<tr>
<td>203 (8), 600</td>
<td>1600</td>
<td>17.1</td>
<td>31.2</td>
<td>1.7</td>
<td>10.8</td>
</tr>
<tr>
<td>127 (5), 450</td>
<td>2000</td>
<td>18.2</td>
<td>33.2</td>
<td>0.9</td>
<td>7.5</td>
</tr>
<tr>
<td>51 (2), 300</td>
<td>3800</td>
<td>20.9</td>
<td>38.4</td>
<td>1.1</td>
<td>7.6</td>
</tr>
<tr>
<td>51 (2), 600</td>
<td>4000</td>
<td>26.0</td>
<td>38.6</td>
<td>1.0</td>
<td>7.5</td>
</tr>
<tr>
<td>Base Metal</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Because the average lath length increases consistently with heat input, there is potentially some effect on toughness. The increase in average lath length is essentially an increase in the effective grain size. Increased effective grain size has a negative effect on toughness [27, 28]. Thus, the general decrease in impact toughness is associated with increases in average lath length, as a function of increasing heat input.
4.3.2 Charpy V-notch Location

The location of the V-notch is another potential source of variation in weld nugget toughness. The variation at the V-notch depends upon the local microstructure. The microstructure in friction stir welded HSLA-65 is heterogeneous. Microhardness contour maps in Table 4-6 show weld transverse cross-sections with varying levels of hardness. The maps also show the hardness variation from the beginning to the end of the weld, from the crown to the root of the weld, and from the advancing side to the retreating side across the weld.

Table 4-6: Transverse cross-section microhardness contour maps show the variation in hardness from weld crown to weld root, as well as changes in hardness from the weld start to end. Weld parameters are listed from top to bottom in order of increasing heat input. The black line in each contour map indicates the location of the HAZ V-notch.

<table>
<thead>
<tr>
<th>Parameters [mm/min (in/min), RPM]</th>
<th>Start of Weld</th>
<th>End of Weld</th>
<th>Vickers Hardness [HV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>203 (8), 300</td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
<td>333-334, 319-333, 305-319</td>
</tr>
<tr>
<td>203 (8), 600</td>
<td><img src="image3" alt="Image" /></td>
<td><img src="image4" alt="Image" /></td>
<td>291-305, 277-291, 263-277</td>
</tr>
<tr>
<td>127 (5), 450</td>
<td><img src="image5" alt="Image" /></td>
<td><img src="image6" alt="Image" /></td>
<td>249-263, 235-249, 221-235</td>
</tr>
<tr>
<td>51 (2), 300</td>
<td><img src="image7" alt="Image" /></td>
<td><img src="image8" alt="Image" /></td>
<td>207-221, 193-207, 179-193</td>
</tr>
<tr>
<td>51 (2), 600</td>
<td><img src="image9" alt="Image" /></td>
<td><img src="image10" alt="Image" /></td>
<td>165-179</td>
</tr>
</tbody>
</table>

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The data in Figure 4-7 are vertical microhardness traces along the V-notch at the centerline of the weld. The two traces are on specimens from the start and end of the 127 mm/min, 450 RPM weld. The dotted line in Figure 4-7 is an arbitrary threshold to facilitate the following discussion. Points above the dotted line are considered “hard”.

Figure 4-7: Differences along vertical microhardness traces in two specimens from the same weld, one from the weld start and one from the end of the weld. The dotted line is an arbitrary threshold. Above the dotted line are points with a larger area fraction of microstructure that transitions at higher temperatures.

The fraction of points (area) above the threshold at the start of the weld is 56%. The fraction above the threshold at the end of the weld is 78%. The larger fraction of “hard” material is anticipated to have a lower toughness, assuming the microstructure of the “hard” areas transitions at different temperatures.
Both specimens are from the 127 mm/min, 450 RPM weld, yet there is a difference in the fraction of “hard” material along the V-notch. These differences contribute to variations in toughness. The variations are especially pronounced in the transition region because of the transition temperatures of the various microstructure constituents, noted above.

Figure 4-8 shows three traces near the centerline of the specimen from the end of the 127 mm/min, 450 RPM weld. One trace is at the intended V-notch location. The other two deviate from the centerline by ±1 mm. The ASTM E23 standard for Charpy impact testing allows for ±1 mm tolerance on the placement of the V-notch in the Charpy specimen [29].

![Graph showing differences along microhardness traces in three specimens from the same weld, one on the centerline and the other two off-center by 1 mm. The dotted line is an arbitrary threshold. Above the dotted line are points considered “hard” for area fraction calculations.](image)

Figure 4-8: Differences along microhardness traces in three specimens from the same weld, one on the centerline and the other two off-center by 1 mm. The dotted line is an arbitrary threshold. Above the dotted line are points considered “hard” for area fraction calculations.
The fraction of material above the threshold along the trace at the V-notch is 78%. At +1 mm from the V-notch, the fraction of material above the threshold is 67%. The fraction of “hard” material -1 mm from the V-notch is 56%. Differences in the fraction of “hard” material contribute to the variation in toughness.

The variation in microstructure is compounded by the variation associated with V-notch location. The heterogeneity of the microstructure and hardness extends from weld to weld, from the weld crown to the root, and across the transverse section. Thus, the location of the V-notch in friction stir welded HSLA-65 will nearly always exhibit variation.

4.3.3 Other Sources of Variation

The sources of variation already discussed, the post-weld microstructure and the location of the V-notch, are major potential sources of variation. Other potential sources are separated by the perceived magnitude of their contribution, major or minor.

Two additional major potential sources of variation are the machining of Charpy specimens and the non-randomization of welds. As previously noted, variation is present in the location of the V-notch, even within the machining and location tolerances provided by the ASTM E23 standard. The variation is potentially enlarged by errors in machining the specimens if the region of interest, such as the weld nugget, is off target. However, care was taken to minimize this possibility. Additionally, the welds were conducted over an extended period of time and not, for example, all conducted on the same day. This could have introduced a bias. The CVN testing of the individual samples, however, was randomized to eliminate biasing based on the location of the Charpy specimens within a weld.

Minor potential sources of variation are experimental error and FSW tool wear and breakage. Inherently, the temperature control of the cooling bath for the specimens prior to
impact testing and the impact tester used during the testing have relatively minor uncertainty. Likewise, there was possibly some minimal FSW tool wear in the welds conducted. As well as some minor variation introduced by a new FSW tool when the original FSW tool broke after a few welds.
5 CONCLUSIONS

1. The upper shelf impact toughness of friction stir welded HSLA-65 is above base metal at all the weld parameters.

2. The HAZ toughness is unaffected by FSW. This is a significant improvement over traditional arc welding, because the HAZ typically contains brittle zones. The HAZ is a composite of three regions of material; the majority is HAZ material, with minor fractions of both parent material and weld metal.

3. The weld nugget NDT temperatures increase with increasing heat input. For every 1000 J/mm increase in heat input, the NDT temperature increases approximately 20 °C. The weld nugget NDT temperatures are all above the base metal NDT temperature, except at the lowest heat input weld. The minimum weld nugget NDT temperature is -120 °C, and the maximum weld nugget NDT temperature is -51 °C at the lowest and highest heat inputs, respectively. The weld nugget toughness of friction stir welded HSLA-65 is negatively affected by increasing heat input.

4. There is significant scatter in the transition region. Variation is attributed to inhomogeneity of the weld microstructure, location of the V-notch, and experimental error.
REFERENCES


APPENDIX A. CS4 TOOL DRAWING