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High strength butt welds in API 5L X52 line pipe can be rapidly produced by homopolar pulse welding

ABSTRACT

Homopolar pulse welding is a welding process that is being developed to rapidly join API line pipe. This process has particular potential for application in offshore pipeline construction utilizing the J-lay method. The weld joint produced has high strength and a narrow heat affected zone. There is a thin brittle zone at the weld interface, resulting in low impact toughness. The weld line is characterized by a very thin "light band", believed to be a ferrite rich zone produced by a combination of localized melting and mechanical upset. Current developmental research is progressing to eliminate this brittle zone and improve weld geometry.

INTRODUCTION

Homopolar pulse welding (HPW) is being investigated for it's potential as a rapid and reliable one-shot welding process for joining steel line pipe. This process would be especially beneficial in applications where time is critical. One specific application this process holds great potential for is the construction of J-lay seabed pipeline. The J-lay method is required for laying pipe in deep water, but vertical space limitations permit only one joining station. A fast and reliable joining process is required for this method to be economically practical (Ref. 1,2).

Homopolar pulse welding has been the subject of various investigations at the Center for Electromechanics at The University of Texas at Austin (CEM-UT) over the past 15 years. These investigations have typically been short term projects supported by clients for specific applications, resulting in discontinuity in research and limiting process development, but demonstrating the HPW process is applicable to a broad range of ferrous and nonferrous alloys (Ref. 3).

The HPW process fundamentals have been described in several publications (Ref. 4-7), so a very brief description will be presented here. Homopolar pulse welding utilizes the high current, low-voltage pulse produced by a homopolar generator to resistively heat the interface between abutting pipe ends. A mechanical upset force is then quickly applied to forge weld the joint. Typical time required from start of pulse to completion of weld is 3 s. Heat is concentrated at the interface because the interfacial resistance is much higher than the bulk resistance of the pipe in the short distance between the electrodes. The homopolar generator produces the current pulse by conversion of inertial energy stored in the rotating iron-core rotor, requiring no external high peak power sources.

PIPE DIMENSIONS, COMPOSITION, AND MECHANICAL PROPERTIES

The pipe welded was API 5L grade X52, 3 in. nominal diameter schedule 160-line pipe. The actual dimensions were 3.5 in. (89 mm) outside diameter with a wall thickness of 0.438 in. (11.13 mm). The line pipe X52 was selected to be welded and evaluated, due to it's wide use in industry. One disadvantage in this is that there may be considerable variation in chemical composition and mechanical properties of X52-line pipe, dependent on the source from which it is obtained. Table 1 lists the alloy composition of the X52 nonexpanded seamless pipe supplied to us, along with the API 5L standard chemical requirements for this grade pipe. Chemical composition indicates that the X52 pipe welded in this study has a higher weldability than would be the case if the pipe were supplied with a composition nearer the maximum allowable limits for the specification.

Yield and tensile strengths of the supplied pipe were also much higher than the minimum allowable values required by the API specification. The vendor supplied mill-test report indicated a 66 ksi (455 MPa) yield strength, 94.4 ksi (651 MPa) ultimate tensile strength, and 30% elongation in a 2 in. gage length by 0.75 in. width specimen. Minimum allowable values for X52 pipe are 52 ksi (359 MPa) yield, 66 ksi (455 MPa) tensile, and 23% minimum elongation for the same gage dimensions.

This combination of chemical composition, particularly the 0.07% vanadium, and mechanical properties leads to speculation that this was actually a controlled rolled, high-strength, low-alloy (HSLA) steel originally produced to meet the requirements of a higher grade, possibly X65.

WELD FEATURES AND PROPERTIES

Welding conditions

Three separate pipe butt welds were made using X52 pipe and identical welding parameters, as listed in table 2. These parameters were selected based on previous welding experience with AISI 1035 steel pipe of the same dimensions.

Interface geometry and end finish have a large effect on contact resistance, which influences the height and width of the current pulse. Initial contact pressure also affects interfacial resistance and is calculated as the initial contact load divided by the initial contact area at the interface (in this case the cross-sectional area of the pipe). Increasing the interfacial resistance flattens the current pulse, reducing resistive losses and localized heating in other parts of the system, but also reducing the rate of heat input to the weld interface. Interface geometry also influences the upset flow patterns and final weld contour.

Generator revolutions per minute (rpm) is an indication of the inertial energy stored in the rotor and field current determines the strength of the magnetic field applied across the rotor; both of these parameters influence the current pulse shape. Upset pressure is determined by dividing the upset force setting by the preupset cross-sectional area. The upset stop is the maximum allowed displacement in the upset process.

Macrostructure

A macrograph of a typical weld cross section after etching is shown in figure 1. The lips that form on the pipe inner diameter (ID) and outer diameter (OD) are a result of the upset process and pipe end geometry. Elimination or modification of these lips to reduce internal flow restriction and remove a possible site for crevice corrosion is a goal of future research. The light band appearing at the weld line is a common artifact, but was not present in all specimens. The heat affected zone (HAZ) extends approximately 0.25 in. (6 mm) on each side of the weld line. Flow lines formed during the upset process are clearly visible. Discolored areas near the ends of the specimen on the top surface are evidence of localized heating at the electrode edges.

Microstructure

Figure 2 shows the microstructure at a weld line in which the light band is present. This light band is typically present in flash butt welded or high frequency electric resistance welded carbon steel (Ref. 8,9). It has been postulated that this light band is caused by interface melting, with the resultant melt having a higher concentration of carbon and alloying elements, combined with a mechanical upset that forces the liquid phase out of the weld, leaving a ferrite rich weld zone (Ref. 10,11). This light band is approximately 0.25 mm (0.010 in.) wide in the homopolar pulse welded specimens.

The microstructure in the weld zone and immediately adjacent HAZ is a coarse structure with ferritic, pearlitic, and bainitic constituents present. Martensite may be present, but is not readily apparent. Farther from the weld line, the microstructure progresses through a grain refined zone and a partially recrystallized zone at the edge of the HAZ.

Mechanical Properties

Microhardness: Microhardness values as a function of distance from the weld line are plotted in figure 3 for the as-welded and normalized condition. Normalizing was performed by holding at 950°C for 5 min and air cooling. In the as-welded condition, the thin light band at the weld line displays a Knoop hardness comparable to the parent metal, whereas the HAZ immediately adjacent to the light band is significantly harder. The light band region also has a lower hardness than the HAZ and parent metal in the normalized condition, supporting evidence that the light band is a carbon and/or alloy depleted region. Microstructural examination of the normalized weld zone reveals a lower percentage of pearlite in the light band than the adjacent area.

Tensile Strength: A single tensile specimen was prepared from homopolar welded X52 pipe in the as-welded condition. It failed in the parent metal, outside of the HAZ during tensile testing. The specimen gage dimensions were 0.50 in. (12.7 mm) wide by 0.36 in. (9.1 mm) thick in a 2 in. (50.8 mm) gage length. At a strain rate of 2 mm/minute, the specimen exhibited a lower yield point strength of 418.5 MPa (60.7 ksi) and an ultimate tensile strength of 619 MPa (89.8 ksi). TPercent elongation after failure was 23.4%, but failure occurred outside the middle half of the gage length and this value is therefore probably artificially low. Reduction in area of the necked region after failure was 58%. Two possible explanations for the reduced strength values in the as-welded specimen, compared to the mill-test report, are different specimen geometries and localized heating under the electrodes during welding. Table 3 compares tensile test results in the as-welded condition with mill test reports on the parent metal and API 5L specifications.

Impact Toughness: Room temperature Charpy Impact tests were performed on standard size specimens prepared from as-welded, welded and normalized, and parent-metal material. A bar chart displaying these test results is presented in figure 4. Notch location, with respect to the weld line, has a drastic influence on impact toughness. Charpy impact energy, with the notch located at the weld line was 9.6 J (7.1 ft-lbs),with a calculated 6% shear fracture appearance. Locating the notch 2.1 mm (0.083 in.) resulted in 52% shear fracture and raised the impact energy to 118 J (87 ft-lbs) - as tough as the parent metal outside of the HAZ. At a notch location of 3.5mm (0.14 in.) from the weld line, the impact energy was 137 Joules (100 ft-lbs) with 72% shear fracture. Impact toughness of a welded specimen after normalizing at 950°C for 9 min was 74 J (54 ft-lbs) with the notch located at the weld line.

CONCLUSIONS

Homopolar pulse welding is a promising method for rapidly joining steel pipe. Preliminary research on welding API 5L grade X52 line pipe has resulted in a near full strength weld with a narrow embrittled zone. Process optimization is expected to yield further improvement.

DIRECTIONS FOR FUTURE DEVELOPMENT

There are several areas in which further developmental work needs to be done before homopolar welding of line pipe can become a commercial process. These areas are uniformity, repeatability, impact toughness, weld contour, and quality assurance.

The effect of varying each of the many different weld parameters in the homopolar pipe welding process is currently being experimentally examined. The goal is to differentiate between primary and secondary parameters in the process and concentrate on determining the critical parameter window required for producing uniform, repeatable, and tough welds. The effect of postweld heat treatment (PWHT) on microstructure and impact toughness of homopolar welds is also being investigated, recognizing that high impact toughness may require PWHT, as has been reported for some flash butt welded steels (Ref. 12-14). Homopolar welding has the advantage that PWHT may be performed by homopolar pulse resistance heating without removing the pipe from the fixture, reducing handling time.

Modifying the weld contour to remove or eliminate the lips formed in the upset process is also planned. The effect of pipe end preparation prior to welding will be investigated, along with mechanical methods to shape the contour during welding or remove excess material after welding. Quality assurance or nondestructive testing methods will be examined after progress has been made in the above development areas.

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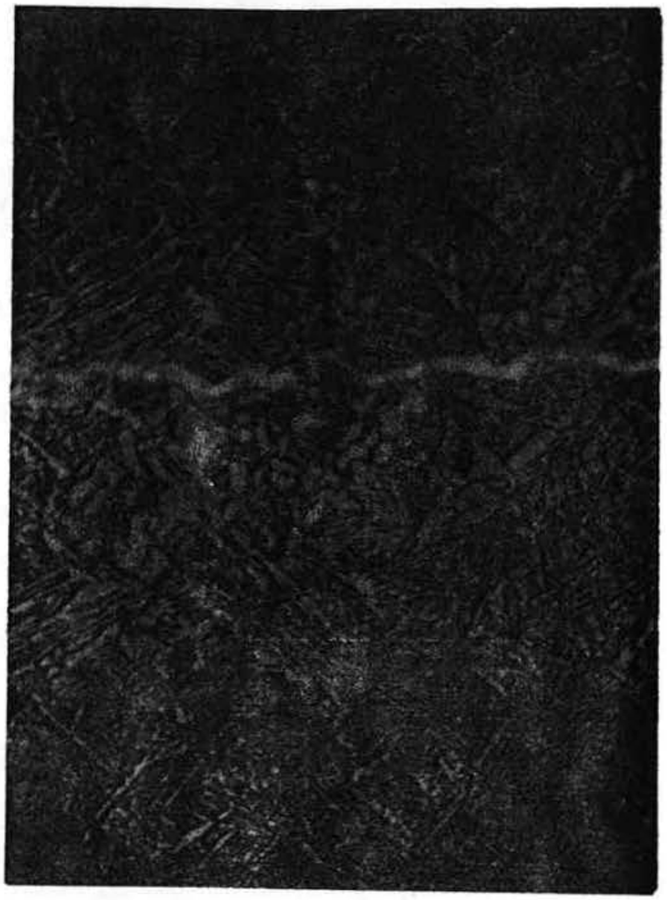

Figure 2. Micrograph of weld line (200x magnification)

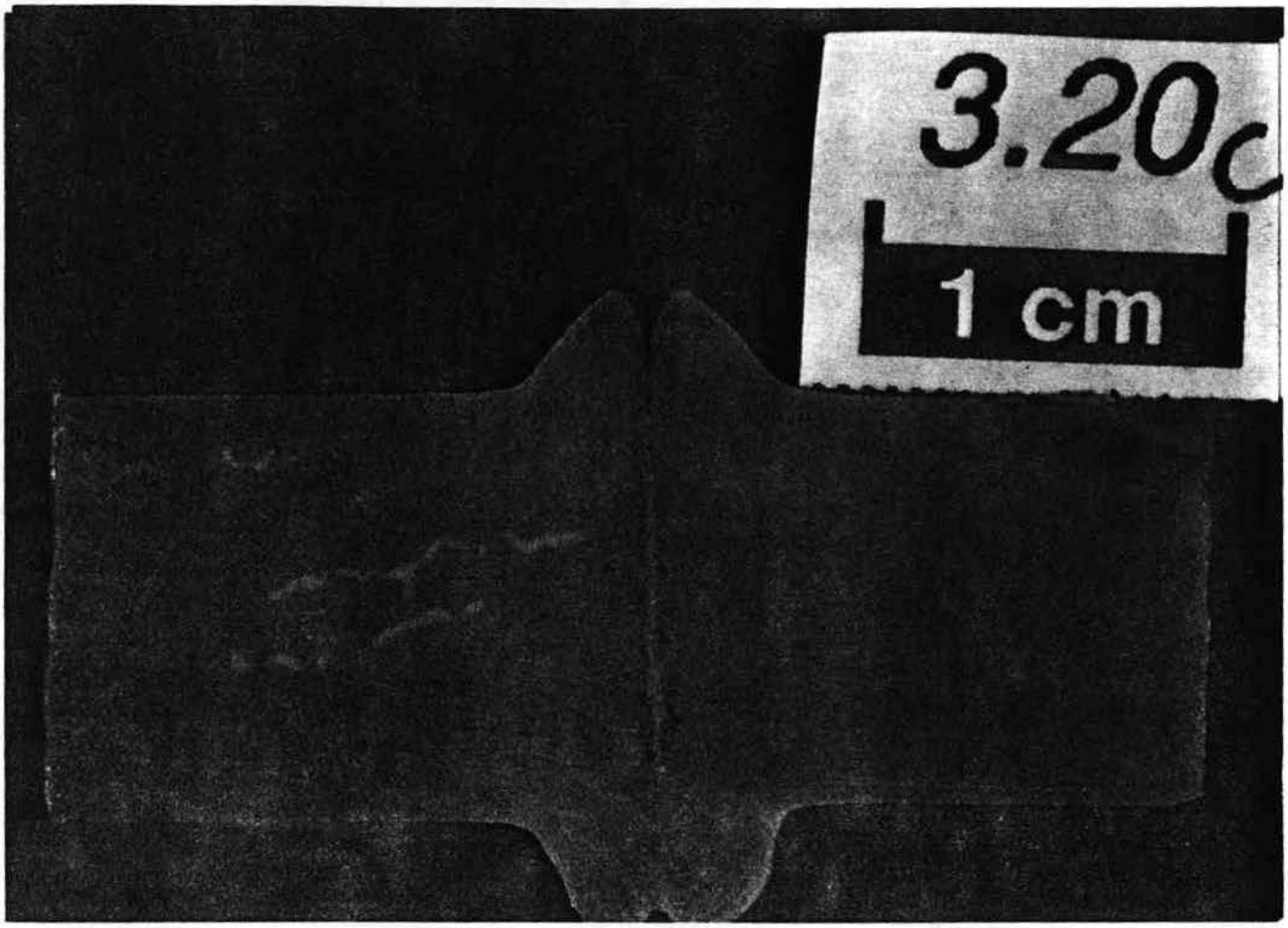

Figure 1. Typical cross section of homopolar welded X-52 steel pipe joint

Table 1. Chemical Composition of Pipe (weight percent)

	C	Mn	P	S	V
Mill Report (Heat Analysis)	0.23	1.04	0.010	0.009	0.08
Independent Lab Test *	0.23	1.05	0.010	0.010	0.07
API 5L X52 seamless nonexpanded (maximum allowable percentages)	0.31	1.35	0.04	0.05	

* also 0.24 Si, 0.07 Cr, 0.02 Mo, 0.03 Cu, and 0.05 Ni

Table 2 - Homopolar Welding Parameters

Interface geometry		flat, butt weld
End finish		lathe turned
	63	μs (1.6 micron)
Generator rpm	3,000	rpm
Field current	450	A
Initial contact pressure	3,200	psi (22 MPa)
Upset pressure	20,000	psi (138 MPa) *
Upset stop	0.0625	in. (1.59 mm)

* upset applied at 0.7 s after start of pulse

Table 3. Tensile Properties

	Yield ksi (MPa)	Tensile ksi (MPa)	% Elong
As Supplied (mill test)	66.0 (455)	94.4 (651)	30.0
As Welded	60.7 (418)	89.8 (619)	23.4
API 5L minimums			
X52	52.0 (358)	66.0 (455)	20.8 *
X65	65.0 (448)	77.0 (530)	18.1 *

*-calculated per API 5L for cross-sectional area of 0.20 in^2 (129 mm^2)

Figure 3 - MICROHARDNESS TRAVERSE

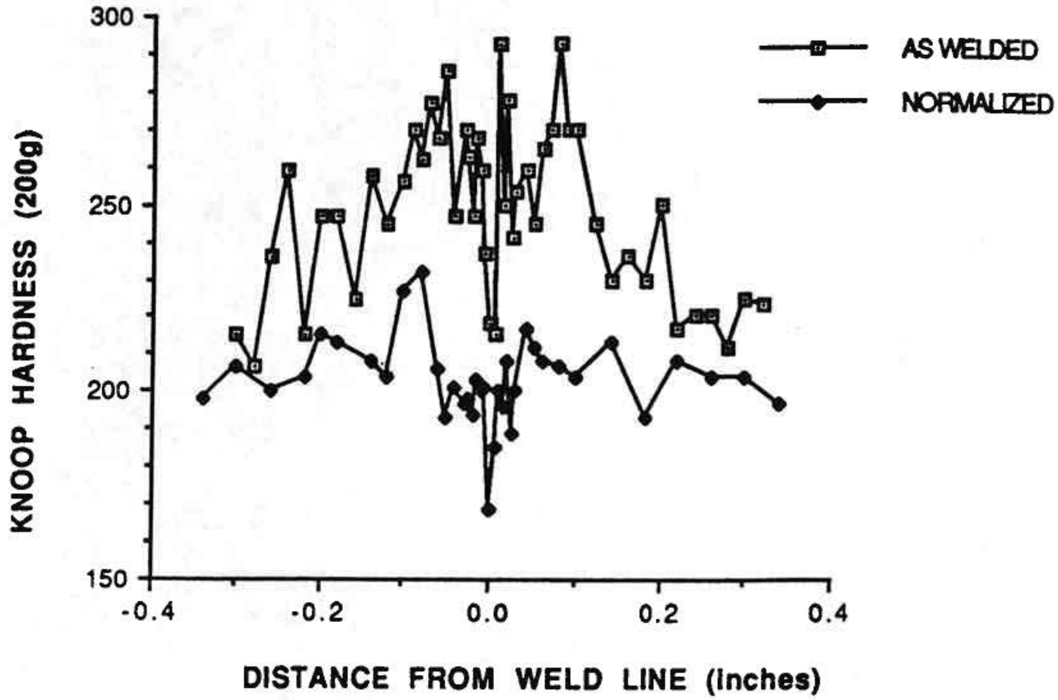

Figure 4 - IMPACT ENERGY OF WELDED X52