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Study on the fracture toughness of friction stir welded API X80

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ABSTRACT

Mixed results regarding fracture toughness in friction stir welded HSLA steels have been reported. The range of welding parameters used in these recent studies has been very limited. With only a few welding parameters tested, the effect of spindle speed, travel speed, and heat input on the fracture toughness of friction stir welded HSLA steel remains unknown. To understand how the friction stir welding process parameters affect fracture toughness, double sided welds in API X80 were performed and analyzed. Results show that at room temperature friction stir welded API X80 exceeded industry minimum fracture toughness requirements in both the API Standard 1104 and DNV-OS-F101 by 143% and 62%, respectively. The process parameters of spindle speed and heat input have been shown to effectively control the fracture toughness of the stir zone. Relationships have been established that show that fracture toughness increased by 85% when spindle speed decreased by 59% and heat input decreased by 46%.

1. Introduction

High strength low alloy (HSLA) steels have been developed to have both high yield strength and high fracture toughness. However, in practical applications steel must be welded. Traditional arc welding degrades the mechanical properties of the base metal (BM), especially in the coarse grained heat affected zone (CGHAZ) [1]. Friction stir welding (FSW) has been proposed as an alternative method of welding HSLA steels. FSW has many benefits over traditional arc welding; chief among them is that no melting is required.

Recent research on the fracture toughness of FSW HSLA steel has shown mixed results. Fairchild et al. found that FSW toughness was significantly below BM toughness [2], while Santos et al. found that weld toughness exceeded that of the BM [3]. In both studies few welding parameters were used, yielding little information on fracture toughness's relationship with FSW parameters. Because fracture toughness has been documented for only a few process operating points, it is not yet

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Nomenclature

FSW	friction stir welding
HSLA	high strength low alloy
API	American petroleum institute
HI	heat input
BM	base metal
RPM	revolutions per minute
TMCP	thermal mechanical controlled processing
HAZ	heat-affected zone
CGHAZ	course grain heat-affected zone
CTOD	crack tip opening displacement
PAG	prior austenite grain
SZ	stir zone
HZ	hard zone
$CTOD_Q$	geometry dependent crack tip opening displacement
J_Q	geometry dependent J-integral
CT	compact tension
EBSD	electron backscatter diffraction
TTHF	through thickness hardness fraction
HV	hardness Vickers

possible to make conclusions on how FSW affects toughness. This study will document and provide understanding on how FSW affects toughness over a wide range of input parameters.

1.1. Background of HSLA steel

API X80, an HSLA steel designed to have high strength and high toughness specifically for pipelines [4], was used in this study. As in all HSLA steels grain size refinement is the primary strengthening and toughening mechanism in API X80 [5]. The fine grain size is achieved by thermomechanically controlled processing (TMCP), a combination of repeated rolling at elevated temperature followed by accelerated cooling [6]. This carefully controlled process has resulted in excellent fracture toughness in API X80, with crack tip opening displacement (CTOD) values of 0.43 mm being reported [3].

In addition to grain size reduction TMCP also results in specific microstructural constituents. Microstructures of bainite, polygonal ferrite, and martensite–austenite constituents have been observed in API X80 [3,7]. API X80's microstructures have each contributed to its high toughness. Lower bainite has proven to increase both strength and toughness, due to its high dislocation density and refined substructure [3,8]. Refinement in bainite packet size has also shown increased toughness and reduced ductile to brittle transition temperature [9]. Refined polygonal ferrite grains are a known ductile phase [10]. The reduction of prior austenite grain (PAG) size through TMCP has been shown to increase toughness [11–13]. Reductions in carbide sizes and distributions have also yielded improvements in toughness [12,14–16].

1.2. Background of arc welded HSLA steel and fracture toughness

HSLA steels require welding in most practical applications. Traditional arc welding causes many deleterious effects to the TMCP microstructure's size and morphology. Changes in microstructure occur when the weld metal resolidifies as a coarse grain cast microstructure. Arc welding employs a filler metal which adds alloying elements to the weld nugget. Filler can mitigate some negative effects in the weld nugget, but it cannot improve the heat-affected zone (HAZ). Therefore, the only way to control HAZ microstructure is by altering the thermal cycle of the weld.

A great deal of research has focused on understanding and improving fracture toughness of the HAZ in arc welds [17,18]. Many authors have reported that reducing the quantity and grain size of martensite–austenite constituent improves fracture toughness [16,19,20]. Shi and Han demonstrated that reducing the PAG size increased toughness [19]. Upper bainite has been established as a brittle phase [11,21], with low toughness [1,20,22], partially due to interlath carbide distribution [23].

Multiple authors have reported that heat input (HI) can be used to control the HAZ microstructure and properties [24–27]. Shimamura et al. showed that HAZ toughness increased by forming lower bainite at low HI [28]. Suarez et al. found that CTOD increased as HI decreased [29].

Despite research efforts, arc welding still results in degradation of the base metal properties.

1.3. Background of FSW and fracture toughness

FSW offers many benefits over traditional arc welding; no filler material is needed, it can be used to weld dissimilar materials, lower peak temperatures are required, and most importantly, FSW doesn't require melting and resolidification.