ON THE RELATIONSHIP BETWEEN MICROSTRUCTURE MECHANICAL PROPERTIES AND WELD METAL HYDROGEN ASSISTED COLD CRACKING

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by

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ABSTRACT

Hydrogen introduced during shielded metal arc welding with cellulosic welding consumables can severely degrade the fracture resistance of the deposited weld metal and promote Weld Metal Hydrogen Assisted Cold Cracking (WM HACC), which is a particular type of weld defect with distinctive characteristics. Failure typically occurs after the deposited weld has cooled down to temperatures below 200°C and can initiate within minutes to even days after welding. Due to its time-delayed nature the onset of WM HACC may be undetected and can result in catastrophic failure.

Many important properties of weld metal such as strength, toughness and the resistance to WM HACC are a function of its microstructure, comprised of diverse constituents with characteristic features and different mechanical properties, which co-exist and interact at the smallest microstructural dimensions. Hence, conventional test methods used to determine the bulk material’s properties are not suitable to evaluate the intrinsic properties of its individual microstructural constituents. Because of these experimental limitations, there is a lack of understanding of microstructural aspects that control the mechanical properties and the resistance to HACC at the micro-scale.

Therefore, a major objective of the current work was to address these limitations by employing advanced characterisation and micro-mechanical testing techniques to evaluate the fundamental link between microstructure, mechanical properties and HACC susceptibility for individual weld metal microstructural constituents.

This first part of the work examined the microstructure and mechanical properties of acicular ferrite and upper bainite in weld metal. Two localised microstructural regions, one acicular ferrite and the other one upper bainite, were first selected and then characterised using a high-resolution Scanning Electron Microscope (SEM) and Electron Backscattered Diffraction

(EBSD). Semi-empirical models, based on microstructural aspects and physical principles, were used to determine the theoretical yield strengths of both microstructures. Different micro-mechanical tests were then conducted within each of the initially selected microstructural regions to characterise their intrinsic mechanical properties. Conventional nanoindentation and an advanced characterisation procedure were employed to obtain the yield strength, hardness, elastic modulus and strain hardening exponent. Micro-fracture tests in combination with linear and non-linear approaches of fracture mechanics were used to evaluate the deformation behaviour, fracture behaviour and fracture resistance. This study provided experimental evidence for a direct link between the microstructure and yield strength of acicular ferrite and upper bainite. It was thereby possible to identify the individual contributions of particular microstructural features. Furthermore, the relationship between strength, hardness and toughness was evaluated for both microstructures and the elastic and plastic components of their CTOD's, could be identified. The results also showed that the fracture toughness values measured in microscopic regions of acicular ferrite and upper bainite were at least by an order of magnitude lower than the typical range for the fracture toughness of steels, obtained from conventional fracture tests. This may result from the fact that micro-fracture tests imply small specimen dimensions, which could cause a confinement of plastic deformations that contribute significantly to the fracture resistance. The results may also indicate that not all fracture toughening mechanisms are activated at the micro-scale. Nevertheless, it is worth noting that the fracture toughness values measured in this work, for a relatively ductile material, are higher than those reported for brittle and semi-brittle materials, tested with similar methods at the micro-scale. In the current literature, at such small scales, no empirical data on the fracture toughness of specific microstructural constituents in weld metal is available. Hence, it was not possible to directly verify the results.

The second part of the work examined the microstructure and HACC propagation resistance of acicular ferrite and upper bainite in weld metal. A modified version of the Welding Institute of

Canada (WIC) weldability test was employed to generate WM HACC under controlled conditions. The hydrogen crack propagation through selected microstructural regions of acicular ferrite and upper bainite was then characterised using EBSD. Where The Unit Crack Path (UCP) was utilised as a parameter to evaluate the HACC propagation resistance of both microstructures. Fractographic observations were conducted with a high resolution SEM, to characterise the fracture behaviour in the selected microstructural regions. The investigations showed that HACC propagates along a path of least resistance through the surrounding microstructure, where the UCP was significantly shorter for acicular ferrite than for upper bainite, thereby implying more frequent changes in direction and thus increased dissipation of energy from the crack driving force. The results indicate that acicular ferrite, increases the localised resistance to HACC propagation more than upper bainite, despite its higher strength, hardness and lower fracture toughness, which are all properties usually considered to be detrimental for the HACC resistance of the bulk material. The outcomes of this study suggest that macroscopic observations of the correlation between mechanical properties and HACC susceptibility are not necessarily applicable at the micro-scale. Which also implies that mechanical properties per se are not a good indicator of absolute HACC susceptibility and in fact may be misleading in terms of the intrinsic susceptibility of particular microstructural constituents.

The third part of the work examined the microstructure and HACC initiation resistance of acicular ferrite in weld metal. A selected microscopic region of acicular ferrite was characterised using a high resolution SEM in combination with EBSD. Micro-fracture tests were then conducted at different loads on a hydrogen pre-charged specimen, that was fabricated into the selected region with a Focused Ion Beam (FIB). Linear Elastic Fracture Mechanics (LEFM) was applied to determine the range for the threshold stress intensity factor, K_{th}, to initiate HACC. The microstructure, deformation behaviour as well as the fracture behaviour were examined and compared with the data obtained from first part of the work, where a micro-fracture test was conducted on an uncharged specimen, that was fabricated into the same region of acicular ferrite. This study showed that the obtained range for the threshold stress intensity factor of acicular ferrite was well below the threshold values for weld metal as well as low and medium carbon steels with similar yield strengths. This indicates that, at the micro-scale, hydrogen cracks can grow at stress intensity factors well below the threshold values measured with conventional tests at the macro-scale. It seems that also in this case critical fracture toughening mechanisms may not be activated if the specimen dimensions are very small. The crack growth rate in acicular ferrite, also appeared to be significantly lower than typically observed for the bulk material. Besides plastic deformations during fracture and the threshold stress intensity to initiate fracture, the yield strength and the Young's modulus also decreased due to the presence of hydrogen, which correlates well with previous observations and proposed hydrogen embrittlement models.

DECLARATION

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09/01/2017

Walter L. Costin Date

LIST OF PUBLICATIONS

The following journal and conference publications were completed as part of this research.

Journal publications:

Costin, W.L., Lavigne, O., Kotousov, A. 2016, "A study on the relationship between microstructure and mechanical properties of acicular ferrite and upper bainite," Materials Science and Engineering: A 663, pp. 193-203.

Costin, W.L., Lavigne, O., Kotousov, A., Ghomashchi, R., and Linton, V., 2016, "Investigation of hydrogen assisted cracking in acicular ferrite using site-specific micro-fracture tests," Materials Science and Engineering: A, 651, pp. 859-868.

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Lavigne, O, Gamboa, E, Luzin, V, Law, M, Giuliani, M & Costin, W.L. 2014, 'The effect of the crystallographic texture on intergranular stress corrosion crack paths', Materials Science and Engineering: A, vol. 618, pp. 305-309.

Conference publications:

Costin, WL, Lavigne, O & Kotousov, A 2016, 'Characterisation of fracture and HAC resistance of an individual microstructural constituent with micro-cantilever testing', 15th International Conference on Fracture and Damage Mechanics, Key Engineering Materials, Alicante, Spain, vol. 713, pp. 66-69.

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Costin, W.L., Lavigne, O, Linton, V, Brown, I.H., Kotousov, A, Barbaro, F.J. & Ghomashchi, R 2013, 'Micromechanical examination of the relationship between weld metal microstructure and Hydrogen Assisted Cold Cracking', paper presented at 6th Pipeline Technology Conference, Ostend, Belgium, 7–9 October 2013.

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Brown, I.H., Costin, W.L., Barbaro, F & Ghomashchi, R 2012, 'Application of SEM-EBSD for measurement of plastic strain fields associated with weld metal hydrogen assisted cold cracking', 2012 9th International Pipeline Conference, American Society of Mechanical Engineers, pp. 335-341.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

LIST OF ABBREVIATIONS

AIDE	Adsorption Induced Dislocation Emission
B	Bainite
B(GB)	Grain Boundary Bainite
B(I)	Intragranular Bainite
B-AF	Bainitic Acicular Ferrite
bcc	Body Centred Cubic
B-FP(I)	Intragranular Bainite Plates
B-FS(A)	Bainitic Ferrite with Aligned Carbide
B-FS(I)	Intragranular Bainite Sheaves
B-FS(LB)	Lower Bainite
B-FS(NA)	Bainitic Ferrite with Non-Aligned Carbide
B-FS(UB)	Upper Bainite
BSE	Backscattered Electrons
CR	Centre of Rotation
CSL	Coincident Site Lattice
COA	Crack Opening Angle
CTOD	Crack Tip Opening Displacement
EBSD	Electron Backscattered Diffraction
EBSP	Electron Backscatter Diffraction Pattern
ECAD	Equivalent Circular Area Diameter
EPFM	Elastic-Plastic Fracture Mechanics
fcc	Face Centred Cubic

FE	Field Emission
Fe_3C	Cementite
FIB	Focused Ion Beam
GD-OES	Glow Discharge Optical Emission Spectroscopy
H	Hydrogen
HAC	Hydrogen Assisted Cracking
HACC	Hydrogen Assisted Cold Cracking
HAGB	High Angle Grain Boundary
HASCC	Hydrogen Assisted Stress Corrosion Cracking
HAZ	Heat Affected Zone
HE	Hydrogen Embrittlement
HEAC	Hydrogen Environment Assisted Cracking
HEDE	Hydrogen Enhanced Decohesion
HELP	Hydrogen Enhanced Localized Plasticity
HSLA	High Strength Low Alloyed
H	Hardness
HV	Hardness Vickers
IPF	Inverse Pole Figure
IHAC	Internal Hydrogen Assisted Cracking
ISE	Ion-Induced Secondary Electrons
IQ	Image Quality
LAGB	Low Angle Grain Boundary
LEFM	Linear Elastic Fracture Mechanics
LI	Linear Intercept

LME	Liquid Metal Embrittlement
M	Martensite
M(L)	Lath Martensite
M(T)	Twin Martensite
M-A-C	Martensite-Austenite-Carbide
MVC	Microvoid Coalescence
NMI	Non Metallic Inclusion
OM	Optical Microscopy
P	Pearlite
PF	Primary Ferrite
PF(GB), PF(G)	Grain Boundary Primary Ferrite
PF(I)	Idiomorphic Ferrite
PF(NA)	Primary Ferrite Non Aligned
P-FC	Ferrite/Carbide Aggregate
P-FC(P)	Fine Colony Pearlite
RA	Retained Austenite
ROI	Region of Interest
SE	Secondary Electrons
SEM	Scanning Electron Microscope
SENB	Single-Edge Notched Beam
SMAW	Shielded Metal Arc Welding
SRIM	Stopping and Range of Ions into Matter
TEM	Transmission Electron Microscope
TRIM	Transport and Range of Ions into Matter

UCP	Unit Crack Path
W-AF	Widmanstätten Acicular Ferrite
WF	Widmanstätten Ferrite
WF(GB)	Grain Boundary Widmanstätten Ferrite
WF(I)	Intragranular Widmanstätten Ferrite
W-FP(I)	Intragranular Widmanstätten Ferrite Plates
W-FS(A)	Widmanstätten Ferrite with Aligned Microphase
W-FS(I)	Intragranular Widmanstätten Ferrite Sideplates
W-FS(NA)	Widmanstätten Ferrite with Non-Aligned Microphase
WIC	Welding Institute of Canada
WM	Weld Metal
WTIA	Welding Technology Institute of Australia

LIST OF SYMBOLS

A	projected area of indentation contact
a	notch depth of micro-beam
a_n	crack mouth opening
b	height of micro-beam
C	curvature of the indentation loading curve
C_H	hydrogen concentration for charging procedure
d	diameter
d_{hkl}	spacing of diffracting planes
d_p	size of the plastic zone
E	Young's modulus
E^*	reduced Young’s modulus
E_P	ion energy
F	Faraday constant
F	dimensionless shape factor
G	crack extension force LEFM
H	WIC test plate thickness
h	indentation depth
h_W	height of weld metal throat
h_m	maximum indentation depth
I	moment of inertia
l	restraint length for WIC test
I(t)	oxidation current

$I_H(t)$	oxidation current for hydrogen charged specimen
$I_{ref}(t)$	oxidation current for uncharged specimen
J	crack extension force EPFM
K_c	fracture toughness
K_I	stress intensity factor
K_D	function for strengthening due to dislocations
K_L {L}	function for strengthening due to grain size
K_Q	conditional fracture toughness
K_{th}	threshold stress intensity factor
k_Y	Hall–Petch slope
M_1	mass of incident ion
M_2	mass of target atom
n	strain hardening exponent
P_m	maximum load
P_Q	applied load at a critical point
P_C	critical load at failure
P_{H_2}	hydrogen pressure
P	load
P_u	unloading force during indentation test
Q_H^{abs}	quantity of absorbed hydrogen
R	strength coefficient
$R_{p0.2}$	offset yield point
R_F	restrained intensity
R_p	projected range of implanted ions

R_l	lateral range of implanted ions
r_e	rotation factor
S_n	nuclear stopping power
U_S	surface binding energy
v	effective specimen volume
w	width of micro-beam
Y	sputter yield
z	number of electrons
α	ferrite
γ	austenite
γ_p	fracture energy
Δa	increase of crack length
$\Delta\theta$	allowable angular deviation
$\Delta\delta$	Increase in Crack Opening
δ_p	plastic component of CTOD
δ_e	elastic component of CTOD
ε	strain
θ_{hkl}	angle of incidence on the diffracting planes
λ	wavelength of electrons
ν	Poisson's ratio
ρ_D	dislocation density
Σ	degree of fit between the structures of the two grains
σ_0	lattice friction stress
σ_C	strengthening due to carbon

σ_D	strengthening contributions due to dislocation density
σ_{Fe}	strength of pure annealed iron
σ_{GS}	strengthening contributions due to grain size
σ_{LS}	strengthening contributions due to lath size
σ_P	strengthening contributions due to cementite
σ_R	restraint stress for WIC test
σ_{SS_i}	substitutional solute strengthening
σ_Y	yield strength