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2009

## Inducing hydrogen assisted cold cracking in high strength steel weld metal

Rian Holdstock  
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**INDUCING HYDROGEN ASSISTED COLD CRACKING IN  
HIGH STRENGTH STEEL WELD METAL**

A THESIS SUBMITTED IN FULFILMENT OF  
THE REQUIREMENTS FOR THE AWARD OF THE DEGREE

DOCTOR OF PHILOSOPHY

FROM

THE UNIVERSITY OF WOLLONGONG

BY

RIAN HOLDSTOCK

*SCHOOL OF MECHANICAL, MATERIALS AND MECHATRONICS ENGINEERING*

*2009*

# **DECLARATION**

This is to certify that the work presented in this thesis has been conducted by the candidate while enrolled as a full-time postgraduate student in the Department of Materials Engineering, University of Wollongong. The results obtained in this study and the conclusions drawn are those of the candidate. The work has not been submitted in total or in partial fulfilment of the requirements of any other university or educational institution.

Rian Holdstock

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To my mother, Bettie, and my brother Louis. I share this achievement with you.

Finally to my patient wife, Lillian, who most likely had to endure more than I had to. You were my foundation during this momentous task. Muito obrigado minha queridinha.

# ABSTRACT

The thesis explores the hydrogen assisted cold cracking in high strength steel weld metal during flux cored arc welding (FCAW) using a technique involving the deliberate introduction of hydrogen into the CO<sub>2</sub> shielding gas. A specific objective was to investigate weld metal cold cracking susceptibility by development of a research tool which permitted control over both the weld metal diffusible hydrogen content and the stress applied during mechanical testing of single bead on plate weld deposits.

The basis for this undertaking is twofold, and stems from the fact that crack mitigating measures traditionally address cracking in the heat affected zone, although it has been shown that weld metal hydrogen assisted cold cracking is more likely when strength matching weld metals are used to join high strength low alloy steels. As a result existing weldability test methods have a limited ability to simulate weld metal hydrogen assisted cold cracking.

The literature relevant to hydrogen assisted cold cracking (HACC) has been reviewed, and the current understanding and assertions relating to HACC have been detailed. The primary findings are that this form of cracking in high strength steel weld metal occurs by localised plastic deformation, which eventually results in fracture through bands of intense shear. The increase in alloying elements and the as-cast nature of the weld metal are also recognised as two key reasons why cracking has migrated from the heat affected zone into the weld metal.

Current welding standards and recognised weldability test methods have also been reviewed to establish the techniques and engineering guidance available. This review indicates that the majority of test methods and all of the welding standards are heat affected zone specific. A further revelation is that weldability test methods typically function as a ranking tool and offer limited scope to serve as a research tool.

The initial experimental investigation of multipass welds in thick plate revealed that the majority of weld metal cold cracking occurred within 48 hours of weld completion. Crack detection was also recorded several days after welding had ceased, indicating that the

diffusion, trapping and stress-strain conditions of solute hydrogen contribute significantly to crack initiation and propagation.

Self restraint multipass weld techniques were then considered as a means of generating weld metal hydrogen assisted cold cracking test data. Subsequent research also evaluated tensile and bend testing to develop cracking in single bead on plate weld deposits. The analysis of the requirements to generate cracking in both single and multipass welds was then used to produce a single bead, applied stress test which preferentially targeted the weld metal. The test methods developed during the experimental phase subsequently allowed manipulation of the diffusible hydrogen content and the magnitude of the applied stress, which in turn facilitated weld metal cold cracking under controlled conditions.

The test specimens were produced by depositing high strength ferritic weld metal onto a strength matched martensitic base material via an automated flux cored arc welding process. In order to increase the susceptibility to cracking, 2% and 5%  $H_2$  was deliberately added to the  $CO_2$  shielding gas.

Both tensile and 4-point bend testing of single pass weld deposits were evaluated, although 4-point bending was ultimately selected as the most suitable test method providing preferential targeting of the weld metal. Standard bead on plate and geometrically modified bead on plate specimen geometries were employed during testing. These were assessed according to their functionality, machinability and reproducibility of the results generated.

Rising load and stress controlled test configurations were applied to observe the behaviour of the weld metal mechanical properties. Although the test configurations permitted close control over the test variables (hydrogen, stress, microstructure and time), the results indicated that variations in cold cracking delay times will occur under near identical test conditions. The variations observed are explained in terms of differences in the transport and trapping behaviour of hydrogen in the heterogeneous structure of the weld metal.

The inability to generate closely matching cold cracking delay times under matching conditions suggests that a single time to fracture cannot be realised for the test conditions employed. It is therefore proposed that a maximum delay time after which fracture will not



occur be used as a research outcome, instead of defining specific or closely matching delay times.

Metallographic analysis of the test specimens was also conducted to determine the effect of hydrogen on the evolution of the microstructure and to establish the fracture morphology. Image analysis revealed that a reduction of non-metallic inclusions occurred during welding with hydrogen-rich shielding gas. The introduction of hydrogen into the shielding gas also resulted in a coarsening of the general microstructure, believed to be the product of reduced acicular ferrite nucleation, allowing individual grains to coarsen without being impeded by the growth of nearby nucleated grains.

The morphology of the fractures observed under microscopy and their reliance on the introduction of hydrogen in the shielding gas indicated that the fractures were typical of those produced under weld metal hydrogen assisted cold cracking conditions. Ductile tearing, microvoid coalescence, quasi cleavage and cleavage fracture facets were observed along the fracture path. The cracks were observed to have propagated along both the columnar solidification structure and along the prior austenite grain boundaries. Microcracks were also observed on the fracture faces, which are believed to have contributed to the final fracture by means of crack-linkage. Higher concentrations of impurity elements were also observed on the boundary along which the cracks had propagated. The typical region from which cracking would originate was associated with second phase constituents and low grain boundary ferrite content.

Whilst it was not possible to develop a quantitative test for hydrogen cracking susceptibility; the reasons for the test variability have been explored and show that the interaction of hydrogen with microstructural development may play a significant role in WM HACC susceptibility.

# ABBREVIATIONS

AE	Acoustic Emission Monitoring
AF	Acicular Ferrite
AS/NZS	Australia/New Zealand Standard
AWS	American Welding Society
B	Bainite
CE <sub>IW</sub>	International Institute of Welding Carbon Equivalent
C <sub>EN</sub>	Carbon Equivalent Number
EDS	Energy Dispersive Spectrometer (EDS)
FCAW	Flux Cored Arc Welding
GB	Grain Boundary
GBOP	Gapped Bead on Plate
HACC	Hydrogen Assisted Cold Cracking
H <sub>D</sub>	Diffusible Hydrogen
HEDE	Hydrogen Enhanced Decohesion
HELP	Hydrogen Enhanced Localised Plasticity
HSLA	High Strength Low Alloy
IG	Intergranular
LB-TRC	Longitudinal Bead – Tensile Restraint
MMAW	Manual Metal Arc Welding

Ms	Martensite Start Temperature
MT	Magnetic Particle Testing
MVC	Microvoid Coalescence
NDT	Nondestructive Testing
Pcm	Ito and Bessyo Carbon Equivalent
PM	Parent Metal
QC	Quasi Cleavage
Q&T	Quenched and Tempered
RT	Radiography
SEM	Scanning Electron Microscopy
TEM	Transmission Electron Microscopy
TRC	tensile Restraint Cracking
UT	Ultrasonic Testing
W	Widmanstätten Ferrite
WM	Weld Metal
YS	Yield Strength
Z	Confidence Interval
$\alpha$	Allotriomorphic Ferrite
$\delta$	Delta-Ferrite or Deflection
$\gamma$	Austenite
$\sigma_{\text{eff}}$	Effective Stress

$\sigma_{\max}$	Maximum Stress in Outer Fibre
$\epsilon_{\max}$	Maximum Strain in Outer Fibre

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