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PART D

OVERALL CONCLUSIONS

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CONCLUSIONS
7. CONCLUSIONS

The initial phase of the work on welded QT BIS80 and BIS80PV steels involved establishing the need for PWHT in terms of the ductility and compliance of the weldment, and determining the effect of multiple PWHT cycles on properties such as impact, fatigue crack growth resistance, fracture toughness, yield/tensile strength and hardness. The second phase of the work in this project involved determining the need for PWHT in reducing residual stresses and building a model that predicted the impact toughness of the base plate with respect to cumulative PWHT time. Data from these tests and the corresponding analysis led to the following conclusions.

1) The cross-weld properties of 11 mm, 12 mm and 20 mm welded plates exhibited ductility that met Australian Standard specifications with and without PWHT. In addition, the WM impact toughness met Australian Standard specifications with and without PWHT.

2) There was no microstructural change for up to four PWHT cycles at the resolution of optical microscopy in all regions of the weldment (PM, WM and HAZ).

3) The hardness of BIS80PV parent plate decreased significantly with increasing Holloman parameter (extended heat treatment times or higher temperatures). Minor secondary hardening in the PM was also detected for short times at temperatures in the range 540-620°C. Although the WM hardness and PM hardness were suitably matched prior to PWHT, the hardness of the WM decreased below that of the PM after PWHT. The hardness of the WM stabilised with increasing number of PWHT cycles.

4) Impact toughness of the PM decreased as the number of PWHT cycles or holding time was increased and there was a progressive change in the fracture appearance towards a more brittle fracture. SEM fracture analysis of Charpy impact and CTOD samples suggests that the PM undergoes growth and coalescence of second phase carbide particles. The impact toughness of 12 mm BIS80 decreased significantly after 3.2% of plastic strain, but PWHT at 545°C for 30 minutes marginally counteracted the effect of plastic strain.

5) Impact toughness of the WM initially decreased as the number of PWHT cycles reached 2, then gradually increased again with the fracture surface showing an
increase in regions with microvoid coalescence. SEM fracture analysis and literature studies suggest that in the as-welded condition the WM undergoes Charpy fracture predominantly by void coalescence that is initiated by non-metallic inclusions. Upon PWHT, metastable iron-rich carbides form and they promote quasi-cleavage failure, but as the PWHT cycles increase these carbides are replaced by finer more stable alloy carbides, which again promote void coalescence and an increase in impact energy.

(6) The WM impact toughness was higher than the PM and HAZ impact toughness for all plates tested. The impact toughness of the CGHAZ (100% of fracture area) was qualitatively determined to be lower than corresponding PM and HAZ regions. However, the observation that real-life impact failures occur predominantly in the PM region indicates that poor CGHAZ impact toughness is not an issue. It is proposed that the reasons for this observation is that the volume of HAZ is insignificant compared to PM in a transportable pressure vessel and/or a type of brazing effect operates.

(7) There were no significant trends of PM and cross-weld tensile properties with the number of PWHT cycles. However, exposure to some PWHT cycles resulted in stress ratios higher than the specified maximum (0.93) for all QT steels.

(8) Although PWHT caused softening in the sub-zones of the HAZ, it did not result in fracture in the HAZ of cross-weld tensile samples. Fracture occurred in the WM and the tensile properties of the 12 mm BIS80 cross-weld specimens did not comply with Australian Pressure Vessel Standards.

(9) The impact toughness of the PM of 20 mm BIS80PV plate was greater than the impact toughness of the 11 mm BIS80PV plate, because of less detrimental banding and a more favourable chemical composition. The impact toughness of the 12 mm BIS80 plate was higher than that of the 11 mm and 20 mm BIS80PV plate in both the WM and PM, because of a favourable PM chemistry.

(10) The CTOD fracture toughness of 11 mm, 12 mm and 20 mm PM decreased with increasing number of PWHT cycles. In addition, the resistance to fatigue crack growth of the PM was found to be slightly lower after 4 PWHT cycles. Additionally, the 12 mm BIS80 PM showed the highest CTOD values, followed by 11 mm
BIS80PV PM and then the 20 mm BIS80PV PM (which failed by means of unstable crack growth).

(11) PWHT resulted in a substantial decrease in residual stresses through creep strain by thermally activated climb and glide of dislocations.

(12) BIS80 can only be considered to be suitable as a pressure vessel steel if the stress ratio requirement and mandatory PWHT are omitted from the Australian Standards. If PWHT remains in the Standards, then a weld consumable needs to be used that results in appropriate cross-weld tensile properties following PWHT.

(13) The relevance of a stress ratio requirement (0.93 maximum) is considered to be of uncertain significance in terms of failure under high strain rate conditions (road tanker accident).

(14) The variations in impact energy for the Charpy tests performed are attributed mainly to the amount of splitting or delamination and the number of fracture acceleration sites that result in large voids or cleavage cracks ahead of the crack tip.

(15) A back propagation neural network model was developed that successfully predicts impact energy for variations in PWHT time, PWHT cooling, alloy content, sample thickness, sample orientation and test temperature (over the data range). The error limits of the model are also within the statistical boundaries of the data used to generate it.

(16) The following predictions of the neural network model are confirmed by experience. The impact energy:

- increases dramatically with increases in test temperature and testing longitudinal to the direction of rolling,
- decreases with increasing cumulative PWHT time or number of PWHT cycles,
- decreases with increasing amounts of C, Mn, S, B and Cr,
- decreases most significantly with increasing Mn and S, and
- is only slightly affected by material thickness, PWHT cooling method, and B content.
CHAPTER 8

REFERENCES


Ambrose, S, 1992, ‘Highway Accident with a QT Steel Pressurised Road Tanker’, Not Published.


Treated Welded Steel Construction, pp. 79-90.


Folias, E. S., 2000, ‘Predicting Failures in Cylindrical Pressurized Vessels from Tests carried out on Flat Plates’, *9th International Conference on Pressure Vessel Technology*, pp. 893-903.


Lumb, R. F., 2000, Verbal Communication.


*Neural Computing*, 1996, Neural Ware Inc., Technical Publications Group, Pittsburgh, U.S.A.


Pohl, A., 2000, Verbal Communication.


*Using Neural Works*, 1996, Neural Ware Inc., Technical Publications Group, Pittsburgh, U.S.A.


PUBLICATIONS
‘MULTIPLE PWHT OF SUBMERGED ARC WELDED QUENCHED AND TEMPERED PRESSURE VESSELS STEELS’
Sterjovski Z, Dunne D and Ambrose S
Presented and Published at the International Institute of Welding (IIW) Asian Pacific International Congress, Suntec Centre, Singapore, October 2002.

‘CHARPY PREDICTION USING ARTIFICIAL INTELLIGENCE’
Sterjovski Z, Dunne D and Ambrose S
Oral and Poster Presentation at the 7th International Conference and Exhibition - Operating Pressure Equipment, Carlton Crest Hotel, Sydney, Australia, April 2003.

‘NEURAL NETWORK MODELLING OF TOUGHNESS OF QT STEEL FOR TRANSPORTABLE PRESSURE VESSELS’
Sterjovski Z, Dunne D and Ambrose S

‘EFFECT OF MULTIPLE PWHT CYCLES ON FATIGUE CRACK GROWTH AND TOUGHNESS OF QT STEELS’
Sterjovski Z, Carr D, Dunne D and Ambrose S

‘MODELLING OF REPEATEDLY POSTWELD HEAT TREATED QUENCHED AND TEMPERED STEEL’
Z. Sterjovski, D.P. Dunne and S. Ambrose

‘PERFORMANCE OF SUBMERGED ARC WELDED QT STEEL WITHOUT PWHT’
Sterjovski Z, Dunne D and Ambrose S
‘CREEP TESTING OF REPAIR WELDED PRESSURE VESSEL AND PIPELINE STEELS’
Z. Sterjovski, D. P. Dunne, A. B. L. Croker & M. R. Finlay
4th International Conf. on Operating Pressure Equipment, Brisbane, April 9-11, 1997

‘CREEP IN REPAIR WELDED CR-MO- (V) PRESSURE VESSEL STEELS’
Z. Sterjovski, D. P. Dunne & A. B. L. Croker

‘CHANGES IN COMPOSITION AND MORPHOLOGY OF H TYPE CARBIDES IN HAZ OF ½Cr-½Mo-¼V REPAIR WELDS’
Australasian Welding Journal, Volume 42, Third Quarter, 1997