

Experimental investigation on pipeline steel welds fabricated using formulated SMAW electrode coatings

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Conclusions and Scope for Future Work

This chapter outlines conclusions drawn from the current study. The conclusions are as follows:

6.1 CONCLUSIONS

6.1.1 Ductile fracture modeling

Tensile and SENB tests were performed with X70 steel and weld material. SENB tests were performed with different crack depth with $a_o/W = 0.25$, and $a_o/W = 0.50$. Experimental results from flat tensile and SENB $a_o/W = 0.50$ tests were used to determine the GTN model parameters. The work has utilized 2-D plane strain fine element analysis with GTN material model with a critical element size of 0.2 mm for X70, and 0.1 mm for weld. The GTN parameters were identified using regression analysis. The VVF parameters for BM X70 are $f_o = 0.00114$, $f_N = 0.001$, $f_c = 0.178$, and $f_f = 0.25$; and for WM are $f_o = 0.007$, $f_N = 0.0018$, $f_c = 0.03$, and $f_f = 0.4$. The model parameters were then successfully validated on the experimental measurements of flat notch tensile and $a_o/W = 0.25$ SENB tests. The transferability of the GTN model parameters and critical element size was illustrated by simulating the SENT $a_o/W = 0.35$ specimen and notch round bar tensile tests from literature. The validation of GTN parameters in different stress states and in-plane and out-plane conditions has confirmed the accuracy of the model parameters.

The pop-in observed in the weld SENB cannot be modeled by homogenous single material assignment. A modified fracture process zone was tested with the GTN model, in which a brittle section was assigned in the fracture process zone at a definite interval. The results have shown that this modification is effective for capturing pop-in behavior. To elucidate the role of crack tip sharpness on the fracture behaviour, $J - \Delta a$ curves of X70 SENB were compared using the simulation of the test with EDM cut and sharp crack. The simulation results suggest that SENB with EDM cut shows higher initial fracture toughness, however, with the crack growth, fracture toughness values coincide with SENB sharp crack. Therefore, it is inferred that SENB with EDM cut crack can be used for GTN parameter identification. Further analysis may be extended to other geometric and loading conditions.

6.1.2 Weldment characterization

The average cap-to root microhardness of the weld AF_W was 302.4 ± 19.5 HV and SF_W was 285.8 ± 18.5 HV, which was higher than the microhardness of CE_W (234 ± 19.7 HV). The weld AF_W has resulted in an average impact energy of 22.13 J/mm, the weld SF_W has 19.9 J/mm, and the weld CE_W has 22.99 J/mm. Even with same electrode rod coating composition has shown significant effect. Weld AF_W with 1.259 Ni% has performed better than SF_W (1.38 Ni%) and CE_W (0.6 Ni%). It also shows that the beneficial effect of Ni increase is conditional.

The optical micrograph of the weld has shown AF_W and SF_W with thin GBF, and low polygonal ferrite due to the presence of Ni. The weld CE_W has lower Ni content (0.6%) and has shown thick grain boundaries. The SEM analysis shows that the martensite austenite increases as Ni content increases. The results of the CCT and TTT curves generated by the MUCG83 model for each weld composition are aligned with the present work. Predicted phase fraction microhardness vs. cooling rate results are in good agreement with the experimental microhardness results.

The yield to ultimate tensile strength ratio of X70 was 0.8, whereas for the weldment AF_W it was 0.81. For weldment SF_W and CE_W it was nearly 0.85. lower yield to ultimate tensile

strength ratio is desirable for pipeline safety. Due to thin GBF, fine acicular ferrite morphology and low polygonal ferrite of AF_W and SF_W weld have lower hydrogen embrittlement susceptibility.

6.1.3 Bead-on-plate investigations

An increase in BaO has a strong increasing effect on δNi , a comparatively lower but significant increasing effect on δNi was observed with the increase in Al_2O_3 . An increase in CaF_2 has a positive effect on the δMo , and δMn . The individual increase of Al_2O_3 , CaO , and BaO has shown a reducing effect on manganese transfer. The microhardness increases with the increase in CaF_2 . Optical microscopy of welds has shown acicular ferrite improves with higher BI flux, due to which microhardness values were also improved as compared to lower BI flux. The weld-bead laid with the flux ratio nearly $\text{CaF}_2:\text{CaO}:\text{Al}_2\text{O}_3 = 1.76:0.73:0.51$ shows good slag detachability.

6.1.4 High temperature wettability investigations

The contact angle increases with the increase Al_2O_3 and CaF_2 , whereas it decreases with the increase of CaO and BaO . The reaction between Al_2O_3 and CaF_2 resulted in the formation of complexes $[\text{AlO}_n\text{F}_{4-n}]$ ($n = 0 - 4$). The CaF_2 present in the melt as Ca^{2+} and F^- due to higher CaF_2 concentration ($\sim 35\%$) which has positively affected the contact angle. The higher work of adhesion is associated with a lower contact angle. The work of adhesion increases with the increase of CaO and BaO , whereas it decreases with the increase of Al_2O_3 and CaF_2 . The increase of BaO is more prominent in increasing the work of adhesion as compared to the CaO . The individual increase of Al_2O_3 and CaF_2 increases the floatation coefficient, whereas an increase of CaO and BaO decreases the floatation coefficient.

6.1.5 Thermophysical and physicochemical investigations

Calcite and witherite has positive influence on weight loss. Fluorspar has shown reducing effect on weight loss. The thermal stability of the fluorspar is higher than that of the other mineral, which leads to reduced gaseous infiltration in the molten weld pool. The weight loss mainly occurred due to moisture, crystallization water, calcination, and other volatile compounds that are present in the mineral. An increase in CaO and BaO , that is, calcite and witherite, has a positive effect on the enthalpy change; the weight loss of these minerals happens at the expense of heating enthalpy. An increase in alumina has an increasing effect on thermal diffusivity. An increase in calcite has a decreasing effect on thermal diffusivity. Higher thermal diffusivity and conductivity carry heat more quickly, which is suitable for electrode coating. Water vapor solubility is approximated to be 3.095 to 3.546 for molten slag.

6.2 SCOPE FOR FUTURE WORK

- The ductile crack growth investigation can be extended for finding the J-Q parameters, J-A parameters. The Q and A parameters focuses on the constraint effect, near tip stress field, which are more suitable for more complex fracture scenarios. This frameworks extend classical fracture mechanics by accounting for real-world complexities such as geometry effects, material inhomogeneities, and multi-axial stress states.
- The hydrogen effect on the weld metal can be tested using in-situ hydrogen charged tensile test. Different charging conditions can also be investigated. The effect high triaxiality can be tested under in-situ charging condition using notch round tensile bar.
- Investigation of pipeline steel and weld can be extended using hydrogen informed GTN model simulations.
- Corrosion tests of the developed welds and its HAZ region along with X70 base can be done.

- Long-term field applications and economic feasibility study can be done.
- Moreover, fatigue and corrosion resistance could enhance the comprehensive mechanical and metallurgical analyses.