

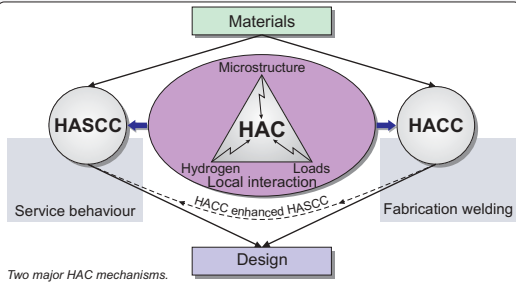
# Numerical Simulation of Hydrogen-Assisted Cracking in Girth Welds of Supermartensitic Stainless Steel Pipelines - Report II

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## INTRODUCTION

A new generation of supermartensitic stainless steel has been developed to replace conventional carbon steel and expensive duplex stainless steel corresponding to the "Fitness for Purpose" concept for flowlines transporting unprocessed oil and gas products in offshore technology. In order to improve the properties of such welded pipelines, matching filler wires have recently been employed particularly for orbital joints. Such welded components require high resistance against hydrogen assisted cracking (HAC) during service and also during fabrication welding. Therefore, quantitative evaluation of reliability of the orbital welds is increasingly needed, which is the purpose of the present work.

## MODELLING



### Boundary conditions

#### Thermal analysis

- Homogeneous temperature distribution just above the melting point in the weld metal during welding.
- Interpass temperature of 40°C.
- Constant volume of the molten metal for each layer.

#### Structural analysis

- Assumption of severe restraint intensity.
- Consideration of thermal effects on stress-strain distribution.

#### Hydrogen diffusion analysis

- Homogeneous hydrogen distribution in the weld metal during welding.
- Reduction of local hydrogen concentration by diffusion and effusion reactions during cooling.
- Consideration of thermal effects on hydrogen diffusion behaviour.

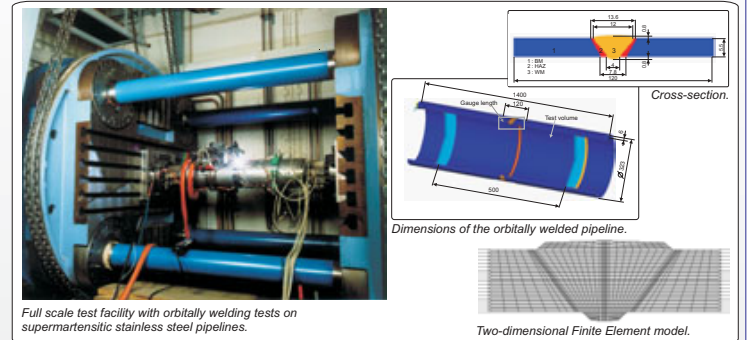
### Numerical simulation

#### FE-model

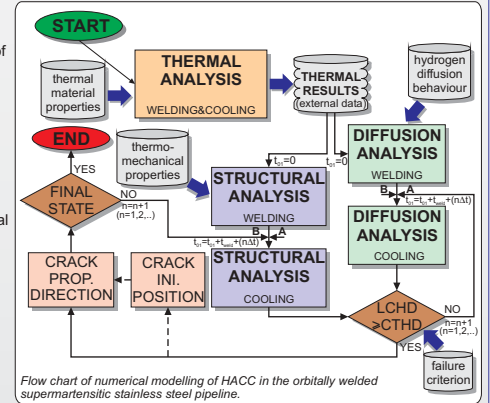
- Two-dimensional finite element model according to the gauge length cross-section of the pipeline orbitally welded by TIG with four layers of matching filler wires.
- Relatively dense finite elements in WM and neighbouring zones.
- Predefined cracking paths in the most susceptible zones to HAC.
- Individual kinds of finite element for respective analysis fields with an additional function of active-deactive finite element.
- Different thermal, structural and diffusion material properties for BM, HAZ and WM.

#### Modelling sequences

- Calculation of temperature distribution with taking into account thermal material properties.
- Saving calculated results of thermal analysis as external data.
- Beginning of parallel calculation of structural analysis and hydrogen diffusion analysis with consideration of previous results as thermal effects.
- Definition of an exact position of crack initiation by using the failure criterion.
- Definition of crack propagation directions.
- Final state.

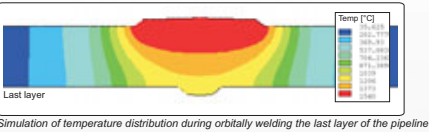


Full scale test facility with orbitally welding tests on supermartensitic stainless steel pipelines.

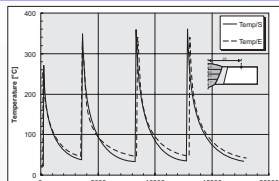


## RESULTS

### Thermal analysis

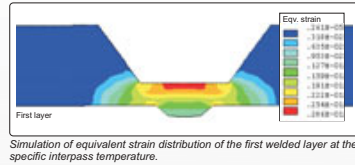


- During welding even the last layer, microstructure of the weld metal and the heat affected zone undergoes phase transformation within the  $\gamma$ -loop.
- Rapid cooling causes complete martensitic transformation.
- Cooling rate at temperature below 100°C is much lower than that at higher temperature and significantly influences hydrogen diffusion coefficients.

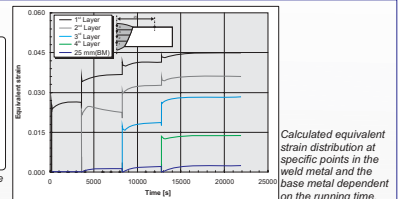


Calculated temperature distribution captured at the specific point in the base metal with a distance of 25 mm from the centre line of the weld metal compared with measured values.

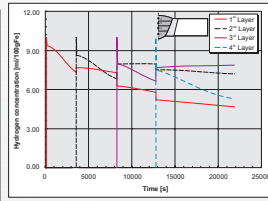
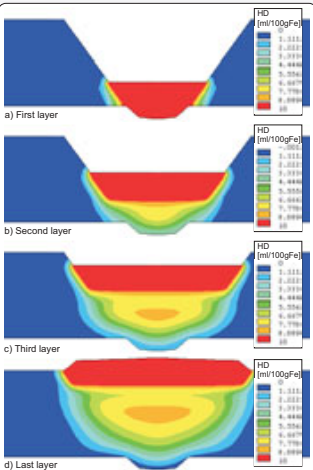
### Structural analysis



- Behaviour of stress-strain distribution in the previously welded layer can be affected by the recently welded layer, strain in the previously welded layer is increased by the recently welded layer.
- Remote zones from the weld metal in the base metal indicate stress-strain distribution in consistency with the flow curve.
- During cooling, local stress and local strain in the welded component increase continuously with time.
- Failure of the orbitally welded pipeline is dominated by strain distribution in the weld metal and the heat affected zone rather than stress distribution.



### Hydrogen diffusion analysis

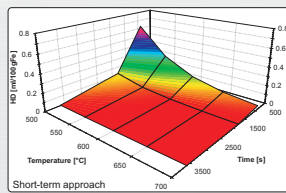
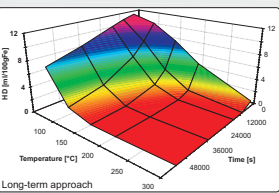


- Due to diffusion and effusion reactions, local hydrogen concentration is rapidly reduced during the early period of cooling.
- Welding of the subsequent layers usually influences significantly the hydrogen distribution in previously welded passes.
- Higher hydrogen concentration in the weld metal than that in the heat affected zone significantly affects HAC of the welded pipeline.
- At room temperature, the maximum hydrogen concentration is still 80% of the initial hydrogen concentration introduced during welding.

Simulation of hydrogen distribution during orbital welding of the supermartensitic stainless steel pipeline with four layers (Assumption: HD = 10 ml/100gFe picked up by the weld metal during welding).

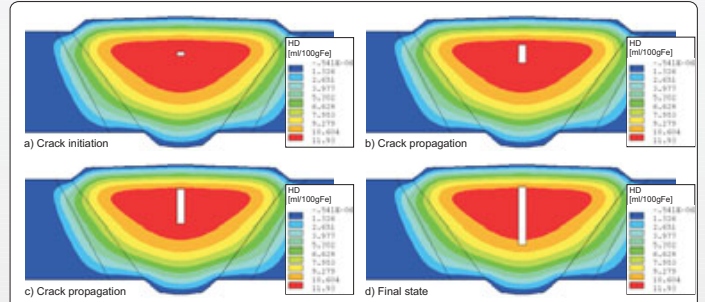
### Effects of PWHT on local hydrogen concentration

- Temperature and tempering duration are defined as significant parameters of PWHT for decreasing hydrogen content.
- With respect to reduction of the hydrogen concentration, the short-term approach is more appropriate than the long-term approach due to a drastical decrease of local hydrogen concentration.



Effects of post weld heat treatment on reduction of local hydrogen concentration in comparison between the long-term approach and the short-term approach (Assumption: HD = 15 ml/100gFe picked up by the weld metal during welding).

### Hydrogen assisted cold cracking (HACC)



- Hydrogen concentration of 15 ml/100gFe picked up during welding, becoming just above 10 ml/100gFe during cooling, is a main reason for HACC.
- Crack initiation is significantly influenced by the local hydrogen concentration rather than local strain, and hence the portion of quasi-cleavage or intergranular cracks may be increased.
- The weld metal is more susceptible to HACC in comparison to the heat affected zone.
- HACC can be avoided if the initial hydrogen concentration is lower than 10 ml/100gFe.
- High hydrogen concentration and local strain distribution with presence of crack in the weld metal will control lifetime of the welded pipeline during exposure to sour service environments.

## CONCLUSIONS

- HACC is preferentially initiating and propagating at the upper of weld pass which means between the third layer and the fourth layer. This is consistent with real failure cases.
- The local interaction between hydrogen concentration, strain distribution and microstructural behaviour dominates HACC, which will not occur if the critical value is not reached by local hydrogen concentration introduced during welding below 10 ml/100gFe.
- However, the crack critical concentration is related to the respective stress-strain distribution and might become considerably lower, if the stresses and strains become higher at local defects like lack of fusion, for instance.
- In order to avoid failure of assembled flowlines during spooling/pipelaying, the short-term approach of PWHT decreases local hydrogen concentration more long-term soaking procedures.