

# Mechanical properties of a forged ferritic steel vessel shell containing hydrogen flakes

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## Introduction

During the 2012 outage of the Doel 3 and Tihange 2 nuclear power plants (NPP), in-service inspections revealed the existence of numerous quasi-laminar indications in the reactor pressure vessel (RPV). The indications were quickly identified as being hydrogen flakes formed in ghost lines at the manufacturing stage.

Within the framework of a research project on the evaluation of RPV crack harmfulness (1), IRSN conducted a test program aiming at verifying that the presence of hydrogen flakes is not symptomatic of a weaker material. AREVA NP provided the investigated material, namely two blocks of a steam generator vessel shell in 18MND5 steel, so called VB395. This shell was rejected because of an incident which occurred during the degassing heat treatment. One block was a sound block without flake - the reference block - and the second block included a high density of hydrogen flakes. Those blocks were provided after quenching, tempering and simulated Post Weld heat treatment.

Tensile tests and fracture toughness tests were performed in the ductile-to-brittle transition range as well as in the ductile range of the materials. In the flaked block, different regions were identified and characterized: material without flake nearby the flaked region, material between the hydrogen flakes and material in a large zone within the flaked region. Particular attention was paid to the sampling so that the quenching effect related to the vessel shell thickness is the same for all the specimens. To refine the interpretation of the test results, chemical composition behind the crack front of the specimens was measured after fractographic examinations of the broken surfaces.

## Tensile properties

The ultimate tensile strength of the material from the flaked block - outside the flaked region or between flakes - appeared higher than the one of the reference material. A similar but less marked tendency was observed on the 0.2% offset yield strength (Figure 1). This is correlated with the higher carbon content in the zone where the hydrogen flakes are located, as illustrated on figure 2. This also confirms that the flaws formed within the positive macro-segregated zone. No anisotropy was observed between L-orientation and T-orientation on the tensile properties.

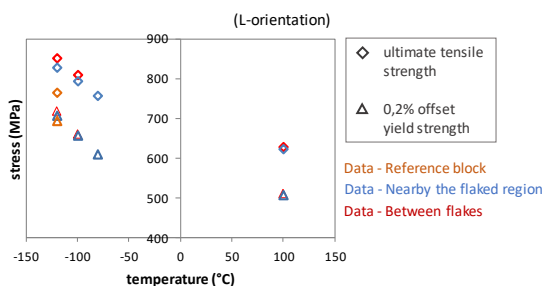


Figure 1: Yield strength (0.2% offset) and ultimate tensile strength evolution with temperature

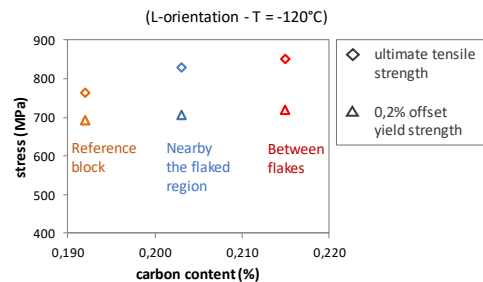


Figure 2: Yield strength (0.2% offset) and ultimate tensile strength evolution with carbon content

## Fracture toughness

The fracture toughness of the two blocks was determined from almost 80 tests on normalized 1/2T-CT specimens. Furthermore, in order to evaluate the harmfulness of a hydrogen flake, specimens with hydrogen flake replacing the usual fatigue precrack were tested.

The reference temperature  $T_0$  of the material between the flakes appears almost 30°C higher than the  $T_0$  of the reference material, as can be seen on figure 3. This difference is mainly related to the variation of the carbon content at the crack tip. Indeed, the mean value of the carbon content between the flakes is 0.22 % (min 0.21% and max 0.22 %) while the mean value of the carbon content in the reference block is 0.19%. Furthermore, as illustrated on figure 4, the material without flake nearby the flaked zone appears slightly tougher than the material between flakes of the flaked region ( $T_0$  around -115 °C vs. -99 °C), which is again correlated with lower carbon content (0.20 % vs. 0.22 %).

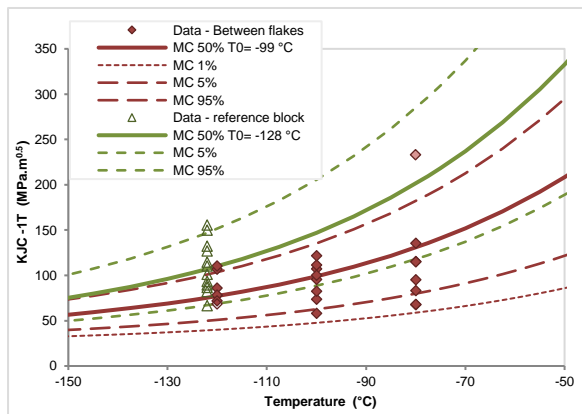


Figure 3: Fracture toughness between the flakes and in the reference blocks

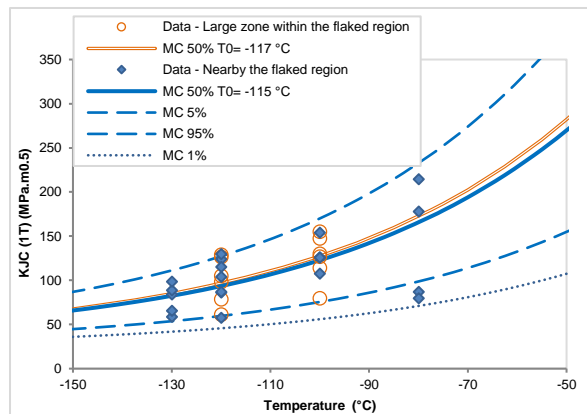


Figure 4: Fracture toughness nearby the flaked zone and in the large zone within the flaked zone

Tests on CT specimens with flake as precrack were analyzed using 3D elastic-plastic X-FEM simulations allowing the modelling of the irregular flake geometry and the calculation of  $K_J$  evolution along the flake front. The reference temperature obtained on specimens with flake is similar to that of the material between flakes (-102°C vs. -99°C). It results that hydrogen flakes behave like fatigue precracks.

Fractographic examinations revealed cleavage fracture although a few intergranular facets were localized on some specimens. Nevertheless, the specimens where the latter fracture aspect was observed did not lead to the lowest toughness values.

Finally, the test results at 100 °C show that  $J_{0.2}$  between flakes is much higher than the values specified by the RCC-M code.

## Conclusion

Hydrogen-induced cracking may occur in ghost lines of macrosegregation zones of large forgings when unfavorable conditions - well known and avoided by steel manufacturers - are met. The test results suggest that the flake occupies the entire ghost line and that the presence of flakes is not symptomatic of a weaker material. The variation on  $T_0$  observed within the flaked material is consistent with the variation of the carbon content.

## Acknowledgment

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## References

- 1) R. Chaouadi et al., "Fracture toughness characterization of vessel forging with hydrogen flaked specimens", *Proceedings of the ASME 2016 Pressure Vessel and Piping Conference*, PVP2016-63632, July 2016, Vancouver, Canada (2016)

## Summary

In the framework of hydrogen flakes issue encountered in Doel 3 and Tihange 2 nuclear power plants, IRSN conducted a testing program aiming at verifying that the presence of hydrogen flakes was not symptomatic of a weaker material. AREVA NP provided two blocks of a steam generator vessel shell in 18MND5 steel, one of them containing a high density of hydrogen flakes.

About 100 tensile tests and fracture toughness tests were performed in the ductile-to-brittle transition range as well as in the ductile range of the materials. In the flaked block, different regions were identified and characterized: material without flake nearby the flaked region, material between the hydrogen flakes and material in a large zone within the flaked region. To refine the interpretation of the test results, chemical composition behind the crack front of the specimens was measured after fractographic examinations of the broken surfaces.