Impact of Static Strain Ageing on the Fracture Toughness Properties of C-Mn Steel Welds in the Secondary Circuit of Pressurized Water Reactors

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Abstract

Pressurized water reactors (PWRs) include a secondary cooling system composed of steel piping elements joined by C-Mn steel welds. Under specific conditions, these weld joints may undergo static strain ageing (SSA), a phenomenon driven by the segregation of interstitial atoms, such as nitrogen, to dislocations at the microstructural scale. Laboratory demonstration of SSA requires a two-step thermomechanical treatment: first, pre-straining to generate a high dislocation density, followed by an ageing heat treatment to enable the migration of interstitial atoms to dislocations via thermal diffusion. Macroscopically, this phenomenon induces changes in mechanical properties. In terms of impact toughness, embrittlement manifests as a shift in the ductile-to-brittle transition curve towards higher temperatures when comparing the strain-aged state with respect to the strained state. However, the influence of SSA on fracture toughness transition curves of C-Mn steel welds has been little studied in the literature.
Therefore, the project is divided into two parts. The first focuses on a detailed description of the microstructural mechanisms involved in SSA. The second, which is discussed here, aims at evaluating its consequences on the fracture properties in the transition domain. Numerical studies are also performed to improve the mechanical modeling of the components while accounting for SSA. The as-welded state is considered in this project to exacerbate the phenomenon.

The mechanical analysis is grounded in an extensive experimental campaign. Blocks are extracted from a full-scale welded pipe mock-up to replicate industrial conditions as closely as possible. These blocks are divided into three groups representing the as-welded, strained, and strain-aged states. From each group, two types of specimens are machined: standard

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Charpy V-notch and four-point single-edge notch bend (SENB) specimens, to study the effects on both impact and fracture toughness properties. Pre-straining is achieved by compressing the blocks to 5% plastic strain in the weld direction, while the strain-aged state is obtained with a subsequent heat treatment at 250∘C for 30 minutes. Afterwards, toughness tests are conducted to determine transition curves for each state. Fracture toughness is analyzed using the Master-Curve approach.

In parallel, finite element simulations using the Beremin model are conducted to compare numerical results with experimental data. These simulations incorporate the Estrin-Kubin-McCormick (EKMC) constitutive law to accurately model the material's behavior under SSA conditions.