Identification of Ductile to Brittle Transition Temperature by using Plane Strain specimen in Tensile Test and Correlation with Instrumented Charpy Impact Test: Experimental and Numerical study

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Abstract

This study addresses the correlation between the ductile-to-brittle transition (DBT) temperature range of high strength 4140 steel obtained respectively from tensile tests under plane strain (PS) conditions and from conventional Charpy Impact tests. Using notched PS specimens instead of round notched bars aims at applying a stress state close to that experienced in Charpy three-point-bending specimens, in particular in terms of Lode parameter that could influence the development of ductile damage and fracture.

Specimens were taken respectively at 25 mm (P) and at 55 mm (M) from skin of a cylindrical 90-mm-radius hot rolled bar water quenched from 875°C, tempered at 600°C and air cooled. P and M specimens respectively showed a fully martensitic and a martensite-bainite microstructure. Instrumented Charpy Impact Tests (ICITs) were performed from -60°C to +60°C. Two kinds of tensile tests were performed along the longitudinal direction. First, tests at room temperature on cylindrical and plane strain smooth specimens allowed identification of the constitutive behavior of both materials. Then, double-side notched plane strain tensile specimens were tested in a climatic chamber at temperatures from -70° to +60°C to investigate the ductile to brittle transition behavior. Instrumented Charpy Impact Test (*ICIT*) was also performed from -60°C to +60°C.

From impact toughness tests, both P and M microstructures show a linear correlation between fracture energy and crystallinity. Up to 0°C, M specimens have a lower toughness than P specimens. The fracture modes for the two materials are respectively cleavage and quasi-cleavage mode. At higher test temperatures, more tearing ridges are found to connect cleavage facets. For M specimens, the size of cleavage facets corresponds to the packet size of bainite. From 0°C to +60°C, fracture is mainly ductile but there are still isolated cleavage facets; their area fraction decreases when the test temperature and fracture energy increase.

When evaluated with the notched PS tests, the ductile to brittle transition behavior of P specimens and M specimens strongly differ. As classically reported for notched specimens, load vs. notch opening curves of notched PS specimens of the P microstructure show enhancement of flow stress and reduction of notch opening at fracture with decreasing the test temperature. For M specimens, the flow stress, as well as the notch opening at fracture increase with decreasing the test temperature and the transition domain is shifted to higher temperatures (by ~+25°C) compared with ICIT results. Fracture

mechanisms are cleavage, quasi-cleavage and ductile from the lower to upper test temperatures, respectively. Many cleavage facets corresponding to bainite appear on macroscopically ductile fracture surfaces of the M specimens.

Fracture surface observations showed good agreement as for physical fracture mechanisms (cleavage facet size, mixed ductile + brittle fracture in the transition region, ductile fracture at higher temperatures, particular sensitivity of upper bainite to cleavage fracture that reduces fracture energy in the ductile temperature range) between PS and Charpy specimens. While the DBTT of P specimens is similar as in ICIT tests, there is a significant difference in mechanical behavior between P and M specimens for this test on notched PS specimens. The role of cleavage fracture of bainite on the fracture energy in the upper temperature range is to be clarified.

The analysis of load vs. displacement curves allows values of fracture initiation and propagation energy to be compared between ICIT and notched PS tensile tests. More detailed mechanical analysis of tests on notched PS specimens by the finite element method and comparison with numerical simulations of Charpy tests (but under a quasi-static assumption) allows making a comparison of stress and strain states between the two kinds of tests, in particular, at the onset of fracture, both in the ductile and in the brittle fracture cases.

Keywords: Martensite, bainite, ductile fracture, cleavage, ductile-to-brittle transition temperature, mechanical analysis.