CHARACTERIZATION AND NUMERICAL SIMULATION OF DUCTILE CRACK INITIATION AND PROPAGATION IN CT SPECIMENS OF DIFFERENT SIZES MACHINED FROM A 316L THICK PLATE

Sihan Cheng[1,2], Jerôme Garnier[1], Bernard Marini[1] , Yazid Madi[2], and Jacques Besson[2]

[1]Université Paris-Saclay, CEA, Service de Recherches Métallurgiques Appliquées, 91191, Gif-sur-Yvette, France
[2]Centre des Matériaux, MINES ParisTech, Paris PSL, CNR UMR 7633
sihan.cheng@cea.fr

Abstract
Measuring fracture toughness for ductile materials requires the specimen size to be large enough for the tests to be valid. The higher the toughness is, the larger the specimen must be. This paper uses experimental and numerical approaches to study the fracture behavior of as-received and aged 316L(N) steel and the effect of the size and thickness of the specimens on the evaluated toughness.

1. Introduction
Crack growth resistance is a key mechanical property to assessing structural integrity. ASTM E1820 and ISO 12135 are two testing standards used to determine $J - \Delta a$ curves. These two standards have minor differences but require the specimens to be large enough to consider the resulting toughness valid. In practice, smaller specimens must often be used because the material is scarce (e.g., irradiated materials) or only available with a specific shape (e.g., plates). Consequently, the question arises of obtaining valid $J - \Delta a$ curves from tests on small or miniaturized specimens. This study investigates the ductile fracture behavior of an austenitic stainless steel 316L(N) in the as-received state and after thermal aging. Its elastoplastic behavior at high strains is determined using various axisymmetric specimens. Homothetic compact tension (CT) specimens and CT specimens with various thicknesses were tested using the elastic unloading compliance method to determine the $J - \Delta a$ curves. Metallographic and fractographic observations were systematically carried out to understand fracture micromechanisms.

2. Results
The 316L(N) material is studied in the as-received and aged (750°C, 2000h) states. Metallographic observations show a variable grain size (90 - 250 µm) and the presence of twins and ferrite, as shown in Fig.1. The principle inclusions contain Al, Mg, Ca, O, and S. After aging, particles containing Mo precipitate inside grains and at grain boundaries. Both material states are characterized by tensile tests on smooth (ST) and notched (NT10, NT4, and NT2) axisymmetric specimens with various notch radii as shown in Fig.2. For both states, the material shows high strain hardening. A decrease in ductility and toughness is observed after aging. The plastic behavior was then modeled assuming von Mises plasticity with a hardening law described by a double Voce model. The law was optimized beyond necking by coupling an optimization software with Finite Element (FE) simulations.

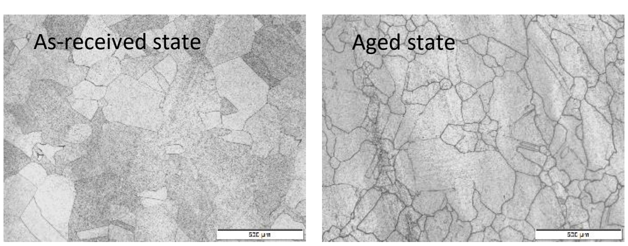

Fig.1 – Metallographie of 316L(N)

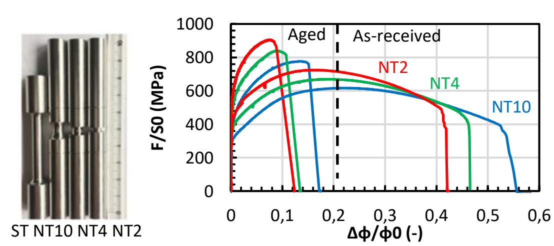

Fig.2 – Tensile specimens and results of notched tensile tests

Experiments on cracked specimens were carried out on CT specimens having a width (W) equal to 25 mm and various thicknesses and specimens with a width of 50 mm. The determination of $J - \Delta a$ curves were carried out according to ASTM E1820. The corresponding curves are shown in Fig.3 and Fig.4. All tests carried out on the as-received state led to invalid values for $J_{0.2}$. On the other hand, all tests on the aged material were valid. For the as-received material, the non-valid $J_{0.2}$ (Fig.5) are increasing when thickness increases. The valid $J_{0.2}$ for the aged state (which is much smaller than for the as-received material) show stable values for different thicknesses. This constant value is in agreement with the ASTM E1820 procedure. Fractographic observations show ductile fracture for both as-received and aged states. Large dimples containing inclusions similar to those observed on polished cross-sections were observed for the as-received state. The aged state showed an intergranular ductile fracture with much smaller dimples.

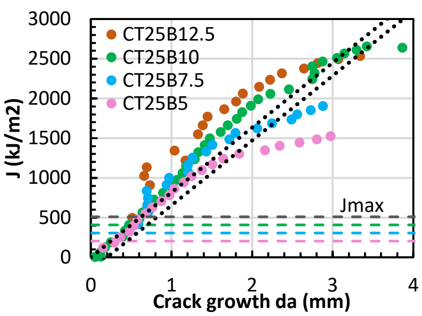

Fig.3 – $J - \Delta a$ curves of the as-received material.

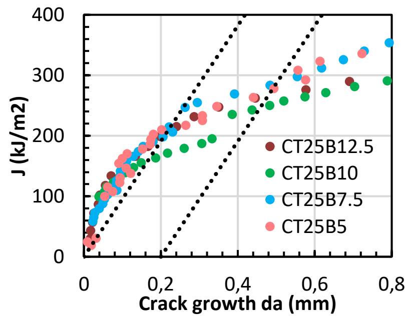

Fig.4 – $J - \Delta a$ curves of aged material.

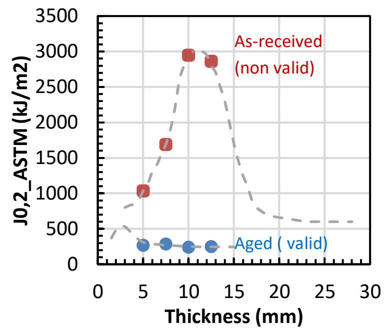

Fig.5 – Evolution of $J_{0.2}$ as a function of thickness.

The effect of specimen width (W) and thickness (B) was studied using Finite element (FE) analyses in the case of the as-received material. The GTN model was used for that purpose. Note that the model was not yet adjusted to the experimental data, so it was only used to simulate observed trends. CT specimens with various widths $W = 8, 25, 50$ mm, and thicknesses were simulated. Results are shown in Fig. 6 and Fig. 7. For a given width, the evolution of $J_{0.2}$ is not monotonous as a function of B. There exists a critical thickness B_c. When $B < B_c$, $J_{0.2}$ increases with B. When $B > B_c$, $J_{0.2}$ decrease when B increases. This result is qualitatively in agreement with the experiments (Fig. 5). $J_{0.2}$ converges to a stable value (J_∞) when B is large enough (Fig. 6). The values of B_c and J_∞ do not depend on the specimen width (Fig. 6). For homothetic CT specimens, fracture toughness increases when specimen sizes decrease (Fig. 7).

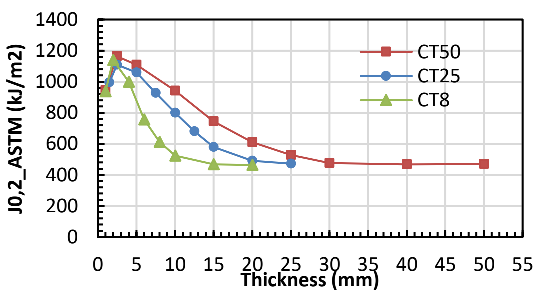

Fig.6 – Evolution of $J_{0.2}$-thickness for CT specimens.

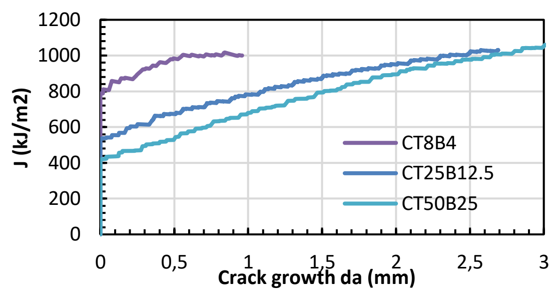

Fig.7 – J-R curves of the as-received material for homothetic CT specimens

3. Conclusions

This study used experimental and numerical approaches to study the effect of specimen width and thickness on the ductile fracture behavior of a 316L(N) steel in as-received and aged states. 316L(N) shows a typical ductile fracture in the as-received state and an intergranular ductile fracture in the aged state. Size effects are observed in the case of the as-received material due to its very high toughness, which does not allow running valid $J - \Delta a$ tests. Finite element simulation could be used to simulate valid tests after adjusting the damage parameters on the experimental database.

Acknowledgments

The financial support of CEA Saclay is gratefully acknowledged. Jean-Luc Flament, Elodie Rouesne, and Amélie Gangloff are acknowledged for their contributing to the experimental work.