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Damage evolution in TWIP and standard austenitic steel by means of 3D X ray tomography

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The evolution of ductile damage of Fe–22Mn–0.6C austenitic TWIP steel by means of 3D X ray tomography in-situ tensile tests is reported for the first time. The comparison with another fully austenitic steel (316 stainless steel) is also carried out. The damage process of TWIP steel involves intense nucleation of small voids combined with the significant growth of the biggest cavities whereas macroscopical triaxiality remains constant. Due to this high nucleation rate, the average cavity diameter remains constant unlike the 316 stainless steel.

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1. Introduction

The high manganese austenitic steels discovered by Sir Hadfield in 1880 constitute one of the most attractive materials for structural application since they exhibit a unique combination of strength and ductility [1]. However, to widen their application areas, some issues must be tackled. Their fracture behavior is one of them.

Indeed, despite the fact that they have been studying for some time, the mechanisms leading to their fracture are still unclear. Reports often discuss the macroscopical features of the fracture. For example, it has been shown that high manganese steels break in the uniform elongation range before necking at room temperature as shown in TWIP 940 by Chung [2]. Moreover, the fracture surface exhibits a slant surface whatever the stress state was [3]. However the microscopic features that lead to fracture are still under discussion. This subject has been addressed in very few papers and mainly on Hadfield steel (i.e. with a Mn content between 12% and 14%). Bayraktar [4] suggested that the fracture occurs by microvoid coalescence without necking. On the other hand, Abbasi [5] proposed a fracture mechanism based more on the occurrence of intense nucleation. According to that study, nucleation events can take place on inclusions or carbides (but the steel considered in our study does not contain that type of carbides) for large dimples whereas small dimples stem from Mn–C couples and the dynamic strain aging process characteristics of this type of steel [1]. X ray tomography has recently been used [6] on the same steel after fracture of a butterfly specimen. These authors showed the presence of strings of elongated voids aligned in the rolling direction. The authors linked this elongated shape to the plastic anisotropy measured (Lankford coefficients) saying that the deformation of the voids is dictated by the surrounding material when the cavity growth is limited (low triaxiality level). They also showed that the volume fraction of these large elongated voids is not sufficient to explain the fracture of high manganese austenitic steel. They then suggested that a large amount of nucleation events of small voids accompanied by rapid coalescence was responsible for the final fracture. This study gives a lot of information on the damage mechanisms of high manganese TWIP steel but it is restricted to post fracture analysis. Thus an “in situ” experiment for different deformation states is required in order to have access to the evolution of the voids in terms of numbers and size as a function of strain. This will permit to get a better insight on the phenomena responsible for the fracture of TWIP steels.

Thus in situ tensile experiments are reported in this paper. For the sake of comparison, the study is realized on one hand on the TWIP steel and on the other hand on a classic (i.e. containing no Mn) austenitic stainless steel (namely a 316L). The evolution of the

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number of voids, of their size and of their different shape factors is given. Then the experimental results are compared to analytical models describing the evolution of the diameter of the cavities.

2. Experiment

This study compares the damage evolution in two austenitic steels namely 316L and TWIP steel. The first is a stainless steel with a composition of 0.02% C, 16% Cr, 11% Ni, and 2% Mo (balance iron). TWIP steel is high Mn steel where the austenite is stable at room temperature. No other phase such as carbides is observed at room temperature. Its composition is 22% Mn–0.6% C (composition in weight percent, balance iron) with an average grain size diameter of about 2–3 μm, supplied by ArcelorMittal. A sample from both steels was cut from a 1 mm thick sheet obtained by hot rolling and annealing thermal treatment. Micro tensile specimens were machined by electrical discharge machining according to the shape shown in Fig. 1.

X ray microtomography was used to quantify damage during in situ tensile tests. The tomography set-up is located at the ID15 beam line at the European Synchrotron Radiation Facility (ESRF) in Grenoble, France. Tomography acquisition was performed with a voxel size of 1.6 μm^3. Thus the void diameters are calculated with an accuracy of ± 1.6 μm. Initial reconstructed volumes were median filtered and simply thresholded to differentiate the material from the voids by absorption difference. Refer to [7] for more information on the precise experimental procedure.

In order to correlate the distribution of voids with the strain, local values of the strain are obtained by considering the minimum section area S_{min} and using the relationship:

$$\epsilon_{loc} = ln\left(\frac{S_0}{S_{min}}\right) \quad (1)$$

where S_0 is the initial section of the sample. The local strain is then calculated at each step. Using this equation implies that the volume fraction of the voids considered is small enough to keep the total volume unchanged.

The beginning of the tensile test is carried out with a stress triaxiality of 0.33. After some deformation, triaxiality may evolve if the sample shape changes. This is considered by using the Bridgman formula [8] modified by Wierzbicki [9] considering the curvature radius of the surface of the sample R_S:

$$T = \frac{1}{3} + \sqrt{2} ln\left(1 + \frac{a}{2R_S}\right) \quad (2)$$

a being the width of the minimum section.

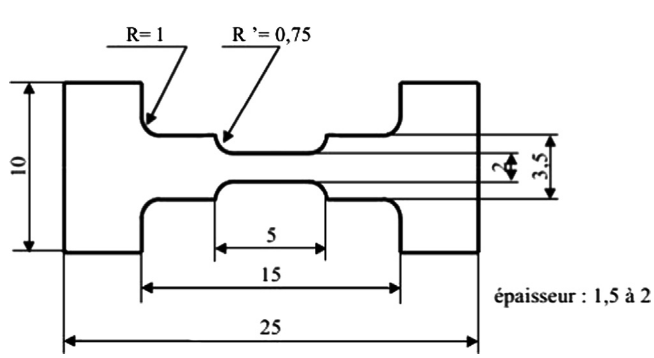

Fig. 1. Specimen geometry for in situ X ray tomography.

3. Results and discussion

3.1. Tensile behavior

Mechanical behavior (stress/strain) was monitored during the 3D X ray tomography experiment. The tensile curves obtained for the two steels are given in Fig. 2. It is worth noticing that these curves were calculated considering the minimum section of the sample, thus the stress and strain values are very high since they constitute local values and not macroscopic ones. These values may be considered as ultimate ones. It is clearly seen that both steels behave completely differently. 316L presents a yield strength of about 400 MPa and then exhibits a large strain hardening up to maximal strength of about 1600 MPa at a strain of 1.6. On the other hand, the mechanical properties of TWIP steel are outstanding with an ultimate tensile strength of about 2600 MPa and a fracture strain of about 0.55. The yield strength seems to be about 800 MPa but this is a rough estimation since no points were recorded at very low strain. Reports state a value of 400 MPa for yield strength at room temperature [10]. The strain hardening is very high compared to other steel grades and thus larger than the strain hardening of the 316L. The values observed here are in accordance with other studies [10] and explain the current interest in these steels and their promising use in safety parts in the automotive industry. It is important to note that the deformation modes of these two steels have been observed to be the same i.e. twinning and dislocation glide [10,11].

Fig. 3 shows the 3D tomography of the two investigated steels just before final fracture. For the sake of comparison, the same state for DP steel from [12] is also shown. In these three images the voids are underlined by an opaque red color surface while the outside surface of the sample is transparent. The differences in fracture behavior between the DP steel with a ferritic matrix, the austenitic steels 316L and TWIP are obvious in this figure. When the first ones exhibit an important necking and a very high void density before fracture, TWIP steel shows no localization of the deformation and only a small void density. It is important to note that in the case of 316L the cavities seem to be aligned in the direction of the tensile stress. This could be due to heterogeneities in the material such as chemical segregation [13].

Figs. 2 and 3 underline that even if the underlying deformation mechanisms are the same in 316L and TWIP (i.e. mechanical twinning and dislocation glide), they lead to different mechanical macroscopic behaviors and that damage behavior must be also

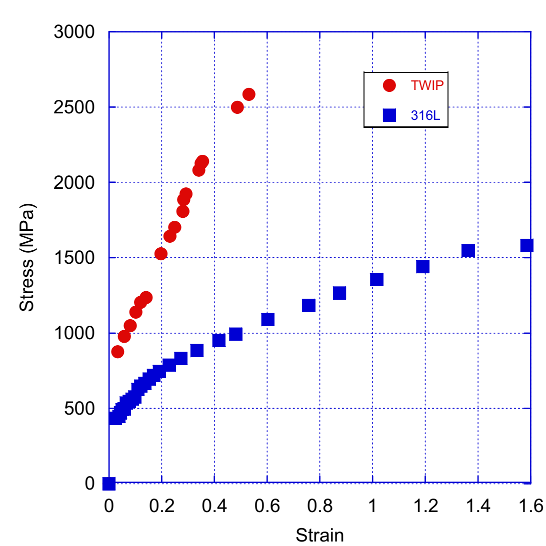

Fig. 2. Stress/strain curve obtained during the in situ tensile test.

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