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The premature necking of twinning-induced plasticity steels

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ABSTRACT

An unusual necking behavior was found in twinning-induced plasticity (TWIP) steels during tensile tests, which is quite different from that observed on most ductile metals. A sharp drop of the strain-hardening rate (Θ) arises before necking initiation, rather than after it, leading to the premature necking of TWIP steels. Through carefully examining the evolution of macroscopic defects at various tensile strains using three-dimensional X-ray tomography (3D-XRT), this premature necking behavior was attributed to the multiplication of macroscopic voids during plastic deformation. Combining with the previous theories and present characterizations on the evolution of macroscopic voids, the mechanism of the unusual necking behavior in TWIP steels was quantificationally revealed.

1. Introduction

Twinning-induced plasticity (TWIP) steels get much attention recently because of their outstanding combination of high tensile strength and large uniform elongation [1–3]. Plenty of studies show that the excellent mechanical properties of TWIP steels result from their high strain-hardening capacity [4,5], which can be attributed to the formation of deformation twins during plastic deformation [6–8]. Overall, the previous studies mainly focus on the early stage of plastic deformation, i.e. the stage at which the strain-hardening rate (Θ) recovers [6,9], whereas, rare attention has been paid to the strain-hardening behavior at the late stage of plastic deformation in tensile tests. According to the Considère criterion, necking initiates when the value of true stress reaches that of Θ during tension. So strictly speaking, it is the strain-hardening behavior at the late stage of uniform plastic deformation that directly determines the initiation of necking and then the tensile strength and uniform elongation. Therefore, it is significantly important to study the strain-hardening behavior at the late stage in tensile test for better understanding the deformation and instability mechanisms.

With careful observations on large numbers of tensile stress-strain and strain-hardening curves of TWIP steels in the previous studies [10–16], a consistent tendency of the strain-hardening behavior can be found, that is, the Θ is much larger than the true stress even at the moment just before necking initiation, whereas, it drops sharply and soon reaches the true stress as strain increases, and then necking happens. In other words, if it were not for the sharp decrease of Θ, the strain-hardening capability of TWIP steels should have been high enough to keep the specimen deforms uniformly and the necking should have been postponed to a higher strength and plasticity. This unusual strain-hardening behavior nearby the necking point found in TWIP steels differs from that of most ductile metals. For the metals with plastic deformation governed by dislocations, the Θ decreases slowly before necking and the sharp decrease of Θ only happens after necking [17–20]. Besides, the post necking elongation of these materials is also much larger than that of TWIP steels [21–24]. The slowly decreasing Θ of most ductile metals can be well described by dislocation evolutions, such as dislocation multiplication and annihilation [25–28]. Then, this gives rise to an important question: what is the mechanism controlling the sudden drop of the Θ before necking observed in TWIP steels?

In fact, as claimed above, a similar sharp drop of Θ also exists in other ductile metals, except that it appears after necking [29,30]. The sharp drop of Θ after necking generally results from the

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appearance of macroscopic voids, which are facilitated by the triaxial tensile stress caused by necking [31–33]. On the other hand, the previous studies have shown that, in TWIP steels and double-phase (DP) steels, some voids appear during uniform plastic deformation [34,35]. The initiation of these voids may be related to the inclusions and second phases in these metals. Therefore, whether or not there exist any connections between the sharp drop of the Θ and the macroscopic voids observed in TWIP steels? In order to reveal the mechanism of the unusual necking behavior of TWIP steels and quantify the influence of macroscopic voids on Θ, this study focuses on the strain-hardening behavior and void evolution in Fe-Mn-C TWIP steels.

2. Experimental procedures

2.1. Material fabrication

High-Mn TWIP steels with compositions of Fe-22Mn-xC ($x = 0.6, 0.9, 1.2$) and Fe-22Mn-0.6C-1.5Al produced by induction furnace melting were used in this study. The cast ingots were kept at 1000 °C for 2 h, and then immediately hot forged to square rods with a final dimension of 25×25 mm^2 at 800–1000 °C. After that, the rods were subjected to solution annealing for 1 h at 1050 °C followed by water quenching. The specimens for tensile and compressive tests were sparking cut along the axial direction with gauge sectional dimensions of $15 \times 4 \times 3$ mm^3 and $8 \times 4 \times 4$ mm^3, respectively. Before tensile and compressive tests, all the specimens were electro-polished at 15 °C in a mixed solution of perchloric acid and glacial acetic acid, in order to produce a strain-free and smooth surface. For comparison, some tensile specimens of other materials, including Ni, Ni-Si alloy, Cu, 316LN steels and Al alloys, were also fabricated. The fabrication processes of the counterparts (Ni, Ni-Si, Cu, 316LN steels and Al alloys) were similar to those of the TWIP steel specimens, except for the detailed processing parameters. All the samples used in this study are polycrystals with coarse grains.

2.2. Mechanical testing

Tensile and compressive tests were carried out at a strain rate of 10^{-3} s^{-1} with an INSTRON 5982 testing machine at room temperature and the strain was measured with an extensometer. For each case three samples were tested to ensure the repeatability and credibility of the results. In order to study the evolution of macroscopic defects, interrupted tensile tests at true strains of 0.25, 0.45 and 0.7 were carried out. The compressive test consisted of two steps: the initial specimen was compressed with a strain of 0.4 and the subsequent compressive test was conducted on the specimen with a dimension of $4 \times 2 \times 2$ mm^3 cut from the strained one in order to avoid the effect of compressive bulging.

2.3. Microstructure characterizations

Longitudinal sections of the TWIP steel specimens after tensile tests were grinded and mechanical polished and then a laser scanning confocal microscope (LSCM) was used to characterize the morphology of these specimens. The characterization methods of the counterparts (Ni, Ni-Si alloy, Cu, and 316LN steels) are the same as that of the TWIP steel specimens described above. The fracture surfaces of the TWIP steel specimens after tensile tests were observed by a LEO Supra 35 field emission scanning electron microscopy (SEM). The failed and interrupted tensile (with true strains of 0.2, 0.45 and 0.7) specimens were inspected by a Versa XRM-500 three-dimensional X-ray tomography (3D-XRT) with a resolution of 1.07 μm per pixel. The number and area of the voids detected by XRT were counted by a metallographical analysis software "IPWIN6". The voids (yellow region in Fig. 7) were picked manually and the number and area of the voids were counted automatically by the software.

3. Experimental results

3.1. Tensile/compressive properties of TWIP steels and the counterparts

Fig. 1 shows the results of the tensile tests with Fe-22Mn-xC ($x = 0.6, 0.9, 1.2$) and Fe-22Mn-0.6C-1.5Al specimens, including the tensile stress-strain curves and Θ curves. The necking points, i.e. the intersection of the tensile stress-strain curve and the Θ curve under the true stress-strain coordinates, were marked out. The results show that the Θ of all the TWIP steels recover during the uniform plastic deformation, which can be attributed to the formation of deformation twins [10]. This recovery effect may lead to a great improvement in the Θ of TWIP steels, so that the Θ is much higher than the true tensile stress in most stage of uniform deformation. Even at the moment just before necking, the Θ is about 300–500 MPa higher than the true stress for the four TWIP steels, as shown in Fig. 1. Whereas, the Θ drops sharply without expectations for these TWIP steels with further increasing the strain and it soon approaches the true tensile stress-strain curves and then necking happens. In fact, this phenomenon can be frequently observed in the previous studies on the mechanical properties of the TWIP steels as mentioned above, but there are no remarks or explanations on this phenomenon [10–15].

The above strain-hardening and necking behaviors observed in the TWIP steels are quite different from that in other ductile metals. Fig. 2 shows the tensile stress-strain curves and the Θ curves of Al alloy, Ni, Cu and 316LN steel, in which the necking points were also marked out. It is obvious that the Θ of these metals decreases slowly during uniform plastic deformation as the strain increases, and the sudden drop of Θ only arises after necking, which obviously differs from the strain-hardening behavior of TWIP steels. For these metals, the slow decrease of Θ before necking can be well described by the classical dislocation theories [26,36] and the sudden drop of Θ after necking may be attributed to the appearance of macroscopic voids because of the triaxial tensile stress caused by necking [37]. Therefore, relative to these counterparts, the necking behavior of TWIP steels seems to be unusual. However, despite of the differences, we suppose that the microscopic mechanism of the suddenly dropping Θ of the two kinds of metals should be the same, i.e. the appearance of macroscopic voids.

To clarify the difference in the strain-hardening behaviors between the two kinds of metals and verify the above conjecture, tensile and compressive tests were further carried out with the TWIP steels and their counterparts. Fig. 3 shows the tensile and compressive stress-strain curves and the corresponding Θ curves of a Ni-Si alloy and a TWIP steel. As shown in Fig. 3(a), for the Ni-Si alloy, its tensile and compressive stress-strain curves, as well as the corresponding Θ curves, nearly overlap with each other, indicating that the tensile and compressive flow stresses and strains are symmetric. Thus, the necking point predicted by both the tensile and compressive stress-strain curves almost coincides with each other. For TWIP steels, as shown in Fig. 3(b), the stress-strain curves and Θ curves of tensile and compressive tests also nearly overlap with each other at the early stage of plastic deformation. However, they separate with each other at the late stage of uniform plastic deformation. Under tension, the Θ curve of the TWIP steel behaves in a similar trend as discussed above, i.e. the Θ is about 300 MPa higher than the true stress at the moment just before necking, which then drops sharply in seconds. Whereas, under compression, the Θ curve decreases smoothly without any sharp drop during the