Scripta Materialia 123 (2016) 122–125

Contents lists available at ScienceDirect

Scripta Materialia

journal homepage: www.elsevier.com/locate/scriptamat

Outstanding mechanical properties of high-pressure torsion processed multiscale TWIP-cored three layer steel sheet

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ARTICLE INFO

Article history:
Received 17 April 2016
Received in revised form 5 June 2016
Accepted 8 June 2016
Available online xxxx

Keywords:
TWIP steel
Layered materials
Severe plastic deformation
High-pressure torsion
Multiscale materials
Strain hardening

ABSTRACT

Three layer steel sheets composed of a twinning-induced plasticity (TWIP) steel core and two interstitial free (IF) steel sheath layers are processed by high-pressure torsion (HPT) up to 1 turn under an applied pressure of 6 GPa. The HPT-processed layered sheets demonstrate extraordinarily enhanced mechanical properties, showing high strength as well as very good ductility. Experimental studies reveal that the improvement of the mechanical properties originates from inhomogeneous strain imposed during HPT process and two distinct hardening mechanisms of each layer: grain boundary hardening of the IF steel and deformation-twinning-induced hardening of the TWIP steel.

The processing of bulk nanostructured materials (BNMs) through severe plastic deformation (SPD) in order to produce grain sizes smaller than several hundred nanometers, has drawn a great deal of attention in materials science and engineering society [1–4]. The formation of ultrafine-grained (UFG) and nanocrystalline (NC) structures [2,3] is made possible by the SPD processing due to its powerful grain refinement effect which imposes an enormous amount of strain without mechanical rupture. Among several SPD methods presented so far [1–4], high-pressure torsion (HPT) is particularly attractive because it provides sufficient torsion revolutions under very high pressure which results in homogeneous and fully recrystallized microstructure. Hence, the mechanical strength of a HPT-processed material is greatly improved on account of considerably refined nanograins and high defect density [1, 5–10].

In spite of the highly improved mechanical strength of BNMs produced by SPD, limited ductility and reduced strain-hardening behavior of the final materials have restricted their practical applications [11, 12]. Several ways to obtain better ductility of BNMs have been propounded thus far [13,14], and most of them are intended to produce heterogeneous microstructures such as bimodal [14,15] and gradient structures [16,17]. However, the production and the control of such heterogeneous microstructures are less well known, and the achievement of ultrahigh strength without a significant loss of ductility is very challenging in a single material because the diminished hardenability after SPD is an intrinsic characteristic of most metallic materials [13].

In this context, we suggest a new approach to surmount the limitations of SPD-processed BNMs by manufacturing multiscale layered materials using HPT. The material used in the study is a layered material composed of a twinning-induced plasticity (TWIP) steel core and two interstitial free (IF) steel sheath layers. The results clearly show that the IF steel layers reached saturation point earlier during HPT than the TWIP steel core, with the grain size rapidly approaching about 100 nm. Throughout the experiments, it is revealed that the difference in the degree of deformation between the components of the layered material under HPT, and the combination of their distinct deformation mechanisms, result in outstanding mechanical properties.

The chemical compositions of the TWIP steel and the IF steel used in the study were 15Mn–0.6C–1.2Al and 0.1Mn–0.002C–0.04Al, respectively. The primary slab of about 40 mm thick was produced by welding of the layers, then subjected to hot rolling at 1100–900 °C to become approximately 2.5 mm thick. Lastly, it was cold rolled to 1.0 mm thickness, and consequently annealed at 830 °C for 30 s. The final thickness ratio of the three layers of the IF steel/TWIP steel/IF steel was 1:6:1.

Disks of 10.0 mm in diameter for HPT process were machined from the 1.0 mm thick layered sheet. The HPT process was applied to the disks under 6 GPa of pressure at a rotation speed of 1 RPM. The disks were then processed with the different number of turns, 1/16, 1/8, 1/4, 1/2, and 1 turns, with a set of semi-constrained dies. In addition, as a reference material, a single TWIP steel disk without cladding was

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http://dx.doi.org/10.1016/j.scriptamat.2016.06.009
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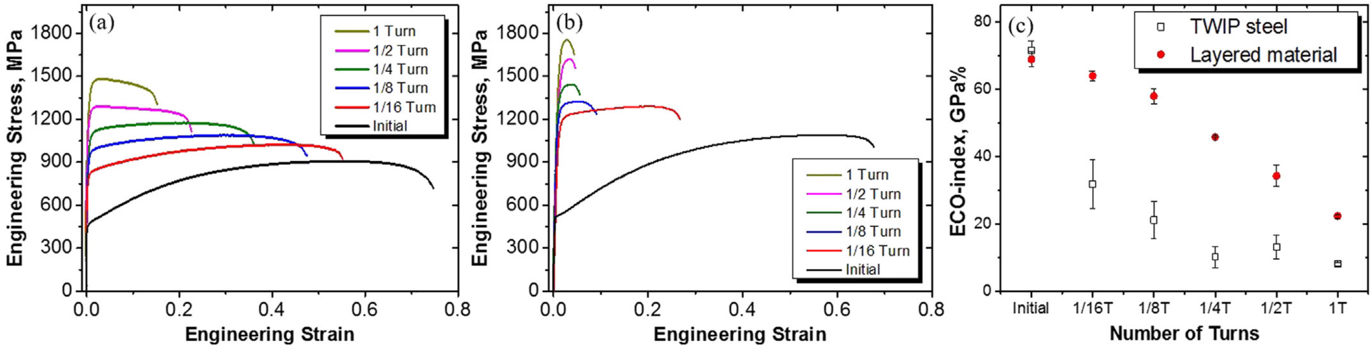

Fig. 1. Stress-strain curves of (a) the layered material and (b) the pure TWIP steel after 1/16, 1/8, 1/4, 1/2, and 1 turns of high-pressure torsion. The curves of the initial layered material and the initial TWIP steel without the IF layers (before deformation) are plotted for references. The ECO-indices (UTS ∗ fracture elongation) obtained from the stress-strain curves are shown in (c).

processed under the same HPT condition in order to investigate the effect of multiple layers on mechanical properties. The reference TWIP steel and the TWIP steel in the layered materials had the identical chemical composition. All disks were processed at 298 K, and the correlation between the mechanical properties and the microstructural features was investigated by experiments after HPT.

A plate-type dog-bone tensile specimen with a gage length of 1.5 mm was machined at the mid-radius point of the disk to measure mechanical properties. Before the tensile tests, the rough surfaces of the IF steel sheath layers produced by contact asperity with the upper and the lower die during HPT process were removed by polishing. Therefore, the thickness of the tensile samples decreased by approximately 20 μm. All the tensile tests in the study were performed at room temperature with an initial strain rate of 10^{-3} s^{-1} using a universal testing machine (Instron 5582, Instron Corp., Canton, MA, USA). The strain during the tensile tests was measured using a digital image correlation (DIC) method with a vision strain gage system (ARAMIS v6.1, GOM Optical Measuring Techniques, Germany). Micro-hardness testing (FM-700, Future Tech, Japan) was conducted at 50 gf for the IF steel and 300 gf for the TWIP steel for 10 s.

Microstructural characterization of the samples was performed using electron backscatter diffraction (EBSD) for the initial samples and HPT-processed ones. The EBSD images after HPT were taken from a position 2.5 mm away from the center of the disks. All points having confidence index (CI) lower than 0.09 were eliminated for a reliable microstructural study. Grain sizes smaller than five times the step size were removed in grain size calculation. Misorientation angles smaller than 5° were also excluded in plotting grain boundary maps.

Fig. 1 shows the mechanical properties of the HPT-processed layered sheets and the single TWIP steel samples under the different HPT conditions of 1/16, 1/8, 1/4, 1/2, and 1 turns. The stress-strain curves of both materials, i.e., the layered material and the single TWIP steel, before HPT are also plotted together as references. It should be noted that the thickness of the samples decreased as the number of turns increased due to material outflow during HPT. The thickness variation of the samples was an important factor in plotting the stress-strain curves of the layered materials, and thus was circumspectly recorded for a more reliable analysis. The thickness of the samples gradually decreased as the imposed strain kept increasing, but the difference between the specimen thicknesses before and after 1 turn of HPT was less than 10% in all samples; the thickness values were averagely distributed from 0.98 mm to 1.03 mm.

The stress-strain curves of the layered material in Fig. 1a demonstrate that the yield stress (YS) and the ultimate tensile stress (UTS) were greatly improved as the strain imposed on the samples increased during HPT process. The YS values rose from 467 MPa in the initial specimen to 822, 936, 1071, 1246, and 1447 MPa after 1/16, 1/8, 1/4, 1/2, and 1 turns of HPT, respectively. With regard to elongation, the initial specimen fractured at the engineering strain of 73% and the elongation values were gradually reduced to approximate values of 55%, 46%, 35%, 21%, and 14% as the respective deformation proceeded to 1/16, 1/8, 1/4, 1/2, and 1 turns of HPT. It is important to note that the elongation values themselves far exceeded those of other HPT-processed metals reported thus far [5]. Above all, the yield strength of the samples after 1/16 turn of HPT roughly doubled and after 1/8 turn, the value became more than doubled, compared with that of the initial one. In terms of strain-hardening behavior, the samples processed at less than 1/4 turn of HPT showed reasonable amount of work hardening. However, as the HPT process exceeded 1/4 turn, softening occurred and the ductility decreased steadily, although the upward trend of the strength continued.

As represented in Fig. 1b, the single TWIP steel sample without cladding showed drastic downward trends in its hardening ability and ductility even in the early stages of HPT as compared with the stress-strain

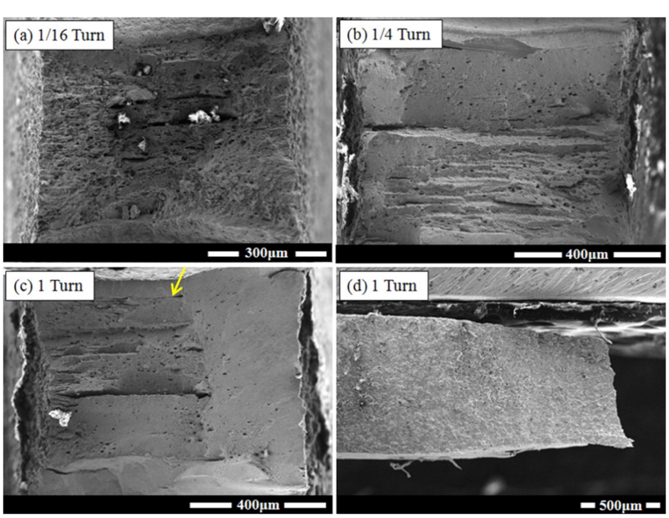

Fig. 2. Fracture surface of the tensile samples after (a) 1/16 turn, (b) 1/4 turn and (b) 1 turn of HPT. (d) The side view of the fractured gage region after 1 turn of HPT.

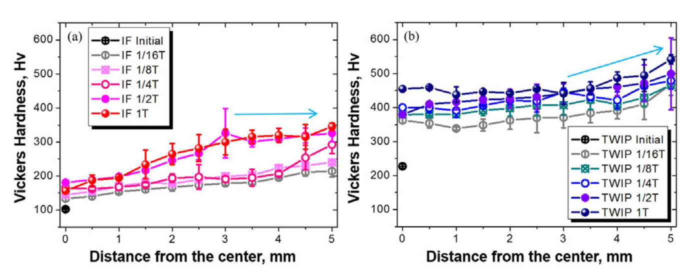

Fig. 3. Vickers hardness of the layers of (a) IF steel and (b) TWIP steel.