



Regular article

Recovery of tensile properties of twinning-induced plasticity steel via electropulsing induced void healing

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ABSTRACT

The effects of electropulsing treatment (EPT) and annealing on the tensile behaviors of twinning-induced plasticity (TWIP) steel after interrupted tension are compared. It is found that EPT effectively restores the tensile property of specimens with macro voids completely, while annealing could not. The selective heating and thermal compressive stress induced by EPT around voids make them readily to be healed while keeping the matrix unchanged. The healing effect of voids improves the strain-hardening capability of TWIP steels and leads to the recovery of strength and elongation of the EPT specimen, relative to those annealed counterparts.

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Twinning-induced plasticity (TWIP) steel exhibits an outstanding combination of tensile strength and uniform elongation [1–3], making it a potential structural material for auto and aerospace industry [4]. Previous studies [5, 6] have shown that the high strength and ductility of TWIP steels can be attributed to the high strain-hardening capacity, which is caused by deformation twinning [7–9]. Whereas, microvoids always initiate in TWIP steels during plastic deformation [10, 11], which will weaken the strain-hardening capability of TWIP steels and lead to the premature initiation of necking [12]. Therefore, the mechanical properties of TWIP steels are severely harmed by the existence of macro voids [13–15].

Fortunately, plenty of studies [16–18] have reported that cracks in steels can be effectively healed by electropulsing treatment (EPT). The crack-healing effect of EPT may be attributed to two aspects [19]: 1) the elevated temperature near the crack and 2) the thermal compressive stress around the crack. The thermal effect near a crack is much larger than that far away from the crack during EPT. A previous study [20] has shown that the temperature rise near a crack can be 3–4 times higher than that of the whole specimen during EPT, that is, the materials near a crack might be molten while the whole specimen stays solid. Furthermore, the compressive stress around a crack is caused by the high temperature near the crack [21]. The materials around a crack will expand as the temperature around the crack

increases, whereas the material far away from the crack will not expand that much. Thus, the outwards expanding of the materials around a crack may be restricted by the surrounding materials and then the melted metal is compressed into the crack. Therefore, cracks might be healed after cooling. Similar to the crack-healing effect of EPT, the healing of the macro voids through EPT can also be expected, which will effectively improve the mechanical properties of TWIP steels. Besides, another advantage of EPT is that its duration is very short with an order of ~ 0.1 ms, which ensures its efficiency in industrial applications.

Previous studies have reported the effect of EPT on the mechanical behavior of boron steel [24] dual-phase steel [25] and stainless steel [26]. This study presents the effect of EPT on the mechanical behavior of TWIP steel with macro voids, comparing with the effect of annealing. It is interesting to find that both the strength and plasticity of the TWIP steels with defects were synchronously recovered by EPT, while those of the annealed ones did not.

High-Mn TWIP steels with the composition of Fe-22Mn-0.9C produced by induction furnace melting were used in this study. The cast ingot was kept at 1000 °C for 2 h, and then immediately hot forged to square rod with a final dimension of 25×25 mm² at 800–1000 °C. After that, the rod was subjected to solution annealing at 1050 °C for 1 h followed by water quenching. The specimens for tensile tests were sparking cut along the axial direction with gauge sectional dimensions of $15 \times 4 \times 3$ mm³. Before tensile tests, all the specimens were electropolished in a mixed solution of perchloric acid and glacial acetic acid with a ratio of 1:9 for 1 min at 15 °C and 12 V, in order to produce a strain-free and smooth surface. Tensile tests were carried out at a strain rate of 10^{-3} s⁻¹ by an INSTRON 5982 testing machine at room

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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. Interrupted tensile tests at a true strain of $\sim 37.5\%$ were carried out with four identical TWIP steel specimens, marked as #1, #2, #3 and #4, respectively, in order to introduce macro voids into these specimens [12]. After beforehand tension, the four TWIP steel specimens experienced different treatments that will be described below. Final tensile tests were conducted with the four TWIP specimens after different treatments.

After the beforehand tension, the #2 specimen was annealed at 500°C for 10 min, #3 was annealed at 1000°C for 10 min and #4 was electropulsing treated and #1 specimen did not experience any treatment. The annealing was conducted under the protection of argon environment. EPT was carried out by a self-made equipment with a capacitor bank discharge circuit at ambient temperature. The experimental discharge voltage was chosen 3 kV and the current pulse duration was 400 ns. The specimen was connected to two copper electrodes during EPT. Then the #4 specimen was cooled at room temperature.

In order to characterize the microstructure of the specimens after beforehand tension and various treatments, another four Fe-22Mn-0.9C TWIP steel samples were prepared following the same treatments conducted with the above four tensile specimens. The microstructures of the samples after different treatments were characterized by a LEO Supra 35 field emission scanning electron microscopy (SEM) equipped with an electron backscattered diffraction (EBSD) detector and an FEI Tecnai F20 transmission electron microscopy (TEM). Furthermore, a Versa XRM-500 three-dimensional X-ray tomography (3D-XRT) was used to detect the macro voids before and after EPT.

Fig. 1 shows the results of the tensile tests conducted with the Fe-22Mn-0.9C TWIP steel specimens. The stress-strain curves of the four identical TWIP steel specimens strained to a true strain of $\sim 37.5\%$ are exhibited in Fig. 1(a), which strongly suggests that the tensile behaviors of the four TWIP steel specimens are congruent with each other. Almost the identical microstructures, thus, can be expected in the four TWIP steel specimens. It should be mentioned that macro voids can be introduced to the TWIP steel specimens after beforehand tension according to the previous study [12] which demonstrates that some macro voids can be detected in the Fe-22Mn-0.9C TWIP steel specimens strained to 25%. Fig. 1(b) shows the final stress-strain curves of the four Fe-22Mn-0.9C TWIP steel specimens after different treatments. The yielding strengths (YS) of the four specimens decrease ~ 400 MPa, ~ 800 MPa and ~ 700 MPa after 550°C annealing, EPT and 1000°C annealing, respectively. That is, the YS of the electropulsing treated specimen sets between those of the 550°C and 1000°C annealed specimens. For the annealed specimens, the ultimate tensile strength (UTS) and uniform elongation (UE) exhibit a trade-off relationship, i.e. as the UTS decreases, the UE increases. Whereas, the UTS and UE of the electropulsing treated specimen break this trade-off relationship. That is, the UTS and UE of the electropulsing treated specimen were improved

synchronously compared to the annealed counterparts. The stress-strain curves of the #1 specimen (without any treatment) and #4 specimen (after EPT) are presented in Fig. 1(c), where the joint of the two stress-strain curves (red and black) of #1 specimen illustrates the tensile stress-strain behavior of the initial Fe-22Mn-0.9C TWIP steel specimen before the interrupted tension. It is indicated that the tensile properties, such as YS, UTS and UE, of the electropulsing treated specimen are in line with those of the initial void-free specimen. That is to say, the EPT may remove the influence of the macro voids after the beforehand tension, which will be further discussed below.

In order to understand the different effects of annealing and EPT on the microstructure of TWIP steels, SEM and TEM observations were conducted. Fig. 2 shows the EBSD and TEM images of four Fe-22Mn-0.9C TWIP steel samples experienced the same beforehand tension and various treatments as mentioned above. Fig. 2(a) and (b) are the EBSD and TEM images of #1 specimen which was strained to a true strain of $\sim 37.5\%$ without any further treatment. As shown in Fig. 2(a), the grain size of #1 specimen after beforehand tension is $\sim 20\ \mu\text{m}$ and the orientation of grains distribute uniformly. Besides, large amounts of deformation twins and second twins spread uniformly in #1 specimen and the thickness of the deformation twins is ~ 10 nm as exhibited in Fig. 2(b) with the selected area electron diffraction (SAED) pattern inserted. Fig. 2(c) and (d) are the EBSD and TEM images of #2 specimen which is strained to a true strain of $\sim 37.5\%$ followed by annealing at 550°C . After annealing, deformation twins disappear and a few annealing twins can be observed. Besides, the average grain size of the #2 specimen reduced to $\sim 5\ \mu\text{m}$, which may be mainly due to recrystallization. Fig. 2(d) presents the configuration of annealing twins and corresponding SAED pattern. Fig. 2(e) and (f) are the EBSD and TEM images of the #3 specimen which is strained to a true strain of $\sim 37.5\%$ followed by annealing at 1000°C . The grain size of the #3 specimen increases obviously to $\sim 50\ \mu\text{m}$ and the distribution of grain orientation is also uniform, as shown in Fig. 2(e). Meanwhile, abundant annealing twins can be observed and the thickness of the annealing twins is ~ 100 nm, as exhibited in Fig. 2(f). Fig. 2(g) and (h) are the EBSD and TEM images of the #4 specimen which is strained to a true strain of $\sim 37.5\%$ followed by EPT. Both large grains and small grains can be observed, which may be formed by grain growth and recrystallization, respectively. Besides, different from the thick annealing twins observed in the annealed specimens, thin twins can be observed in the #4 specimen after EPT, as exhibited in Fig. 2(h). These thin twins should be formed by the beforehand tension, that is, deformation twins can be retained during EPT. As is well known, twin boundary is a coherent boundary with relatively lower electric resistance and then the temperature rise around twin boundaries during EPT should be small. Therefore, EPT seems to more like a selective annealing method: heating the parts with higher electric resistance, while retaining the parts with lower electric resistance. This selective annealing effect of EPT is of great significance in industrial applications: it maintains the microstructure and then the mechanical properties of the matrix while repairs damages.

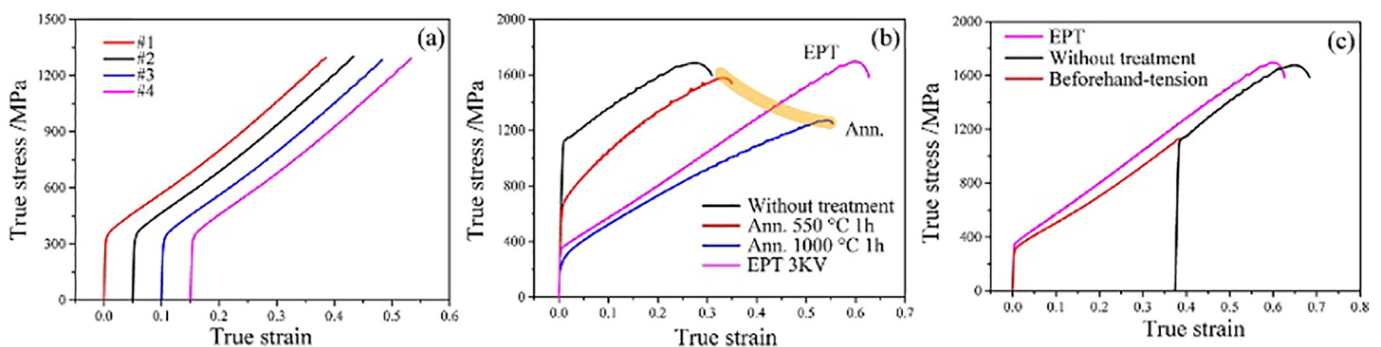


Fig. 1. (a) The beforehand tensile curves of four identical Fe-22Mn-0.9C TWIP steel specimens with a true strain of $\sim 37.5\%$, (b) The final tensile curves of the four TWIP steel specimens and (c) compare the tensile behaviors of the electropulsing treated specimen to the initial specimen.

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