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Abstract

Increasing demand for automotive vehicles with reduced weight, improved crashworthiness and passengers safety has steamed the research of new Twinning Induced Plasticity (TWIP) steels. In this work the effect of annealing between 400 and 900oC on the microstructure and mechanical properties of hot and cold rolled 0.06C-24Mn-3Al-2Si-1Ni (wt%) steel with TWIP effect was investigated. The results have shown that steel exhibits fast recrystallization kinetics with a low amount of recovery, which results in a high driving force for the former. Mechanical properties were determined using Vickers microhardness and tensile tests. Tensile strength of 670 MPa with 54% of total elongation, and strain hardening exponent of 0.57 were reached after annealing at 900°C.

Keywords

cold, c, low, mn, high, behavior, mechanical, recrystallization, steel, annealed, effect, rolled, twip

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Recrystallization and Mechanical Behavior of High Mn and Low C Cold Rolled and Annealed Steel with TWIP Effect

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Keywords: Annealing, TWIP steel, Recovery, Twinning, Mechanical properties.

Abstract. Increasing demand for automotive vehicles with reduced weight, improved crashworthiness and passengers safety has steamed the research of new Twinning Induced Plasticity (TWIP) steels. In this work the effect of annealing between 400 and 900°C on the microstructure and mechanical properties of hot and cold rolled 0.06C-24Mn-3Al-2Si-1Ni (wt%) steel with TWIP effect was investigated. The results have shown that steel exhibits fast recrystallization kinetics with a low amount of recovery, which results in a high driving force for the former. Mechanical properties were determined using Vickers microhardness and tensile tests. Tensile strength of 670 MPa with 54% of total elongation, and strain hardening exponent of 0.57 were reached after annealing at 900°C.

Introduction

The Twinning Induced Plasticity (TWIP) steel is a promising alternative to meet the demand in the construction of automotive parts, which require a material with high strength, high formability, good toughness and lower density. The shock absorption of TWIP steels is twice that found in conventional high strength steel used for deep drawing. These characteristics led mainly automotive industries to develop the application of this product aimed at fuel economy, passenger safety, reduced weight and decreased emission of pollutant gaseous in the environment [1-4].

In austenitic steels containing about 22-30% Mn, where the Gibbs free energy for martensite reaction is positive (110 to 250 J/mol) and the stacking fault energy (SFE) is low (~16- 25 mJ/m^2), TWIP effect is usually observed. Stable austenitic microstructure is maintained throughout the plastic deformation process [1,2], and its excellent formability (ε = 70%) is the effect of intensive formation of mechanical twins within the grains. These twins act, similar to grain boundaries, as barriers to dislocation slip, refining the microstructure and thus develop, in spite of the high strength, good elongation and high capacity for energy absorption [3,4].

The reorientation of the atoms, with the imposed deformation, has a direct relationship with the composition chemistry and temperature of deformation [5-7]. These factors also determine the SFE and as a result, the possible mechanisms of plastic deformation: slip, strain-induced transformation to martensite or strain-induced twinning. High SFE (>45 mJ/m^2) favours slip, whereas low SFE (<20 mJ/m^2) favours the martensite formation. The high strain rate of high Mn steel during deformation is commonly associated with deformation twinning and contributes significantly to the rapid recrystallization process. The high misorientation between grains or regions of the microstructure and formation of subgrains accelerate this process [5,7].

To achieve tensile strength of 1000 MPa and an elongation of 50%, which is characteristic for TWIP steel, an oriented microstructure and fine grains produced by cold rolling and recrystallization are required. To date studies on TWIP steel focused more on deformation behaviour [1,3-5] with fewer studies on its recrystallization mechanism [7-10]. The aim of this work was to gain a thorough knowledge of 25Mn-3Al-2Si-1Ni-0.06C (wt%) TWIP steel microstructure and mechanical performance after cold rolling and annealing at different temperatures.

Experimental Procedures

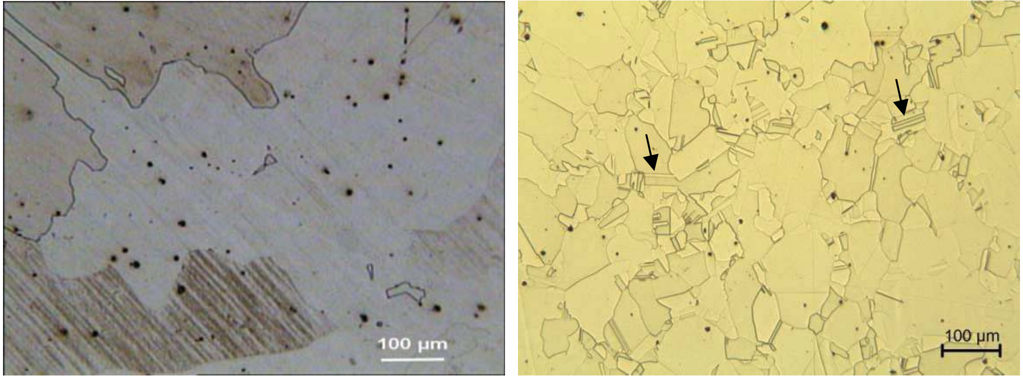
The pieces of 100x80x30 mm were cut from the induction cast plate (300x200x30 mm), then homogenized at 1100°C for 2 h and water quenched. These plates were reheated at 1100ºC before hot rolling, which was conducted to 50% reduction in four passes of equal reduction. The scale was removed by machining before cold rolling. Cold rolling was carried out in a sequence of 9 passes in order to reach a reduction of 52%. The final thickness of a strip was 6.1 mm.

Annealing of cold-rolled strip was conducted at temperatures from 400 to 900°C. The total soaking time was 300 s at each temperature. For examination, the samples were cut along the normal direction to the rolling direction. After mechanical grinding and polishing, the samples were etched with 2% Nital. The annealed samples were characterized by optical microscopy, scanning electron microscopy (SEM) and Electron Backscattering Diffraction (EBSD).

The austenite grain area, due to its small size, was measured from SEM micrographs by image analysis. Two hundred grains were measured per sample. The square root of the average value corresponds to the austenite grain size. The volume fraction of recrystallized grains was measured by optical microscopy using point count method. The microhardness was measured with 500 g load. The average value of twenty indentations per sample was calculated. The softening fraction was calculated based on the results of microhardness tests, being equal to the ratio of the difference between the hardness of the sample fully hardened and hardness of the sample in question, to the difference between the sample fully hardened and the sample fully recrystallized [7]. To complement the optical metallography some images were obtained by EBSD to better reveal the distribution of recrystallized grains. After annealing, the samples were subjected to tensile testing at room temperature with a strain rate of 10^{-3} s^{-1} in an MTS machine equipped with interface TestStar. The sub-sized samples of 4 mm in diameter and 25 mm gage length were machined according to ASTM A-370.

Results and Discussion

The homogenized and hot rolled microstructures are shown in Fig. 1. After hot rolling, a typical austenitic microstructure with smaller grain size compared to homogenized microstructure (Fig. 1(a)) and annealing twins was produced (Fig.1(b)), as a result of static recrystallization during hot working. X-ray diffraction (Fig. 2) has confirmed that the microstructure of the samples after both hot rolling and cold rolling was fully austenitic.



(a) (b)

Fig. 1. Optical micrographs showing austenite and non-metallic inclusions after homogenization (a) and after hot rolling (b). Arrows indicate annealing twins.

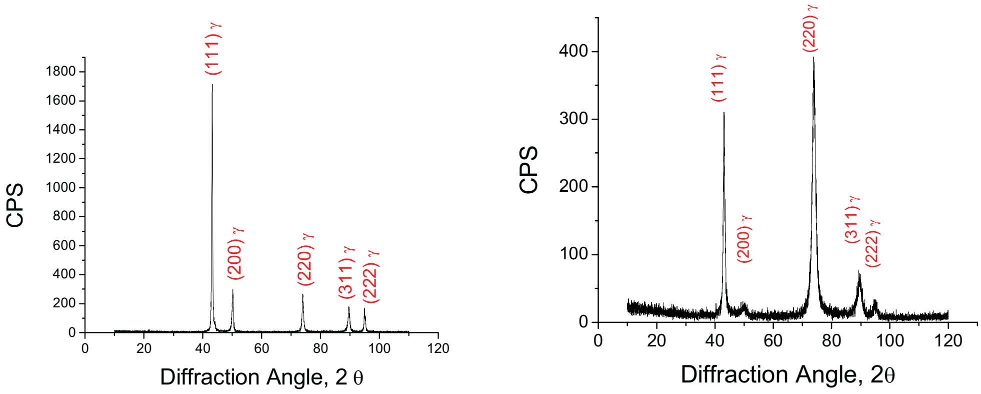
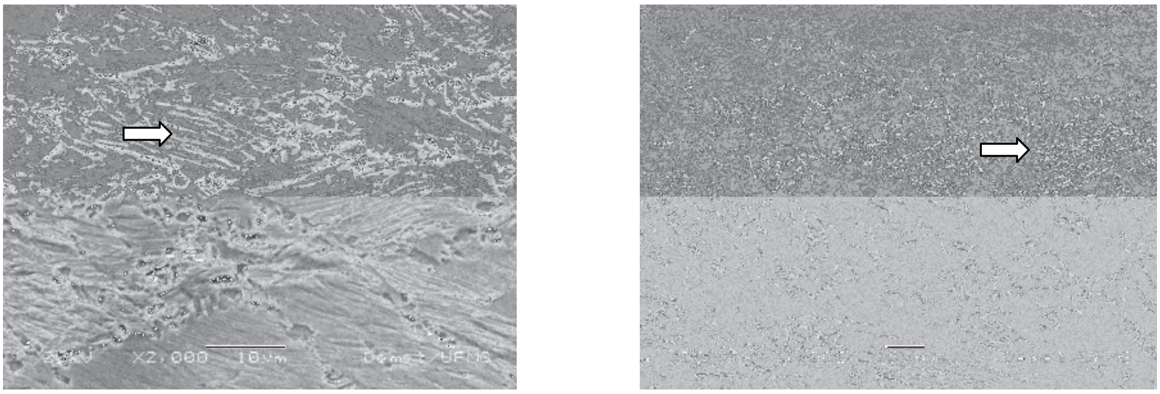


Fig. 2. X-ray diffraction of hot rolled sample (a) and cold rolled sample (b).

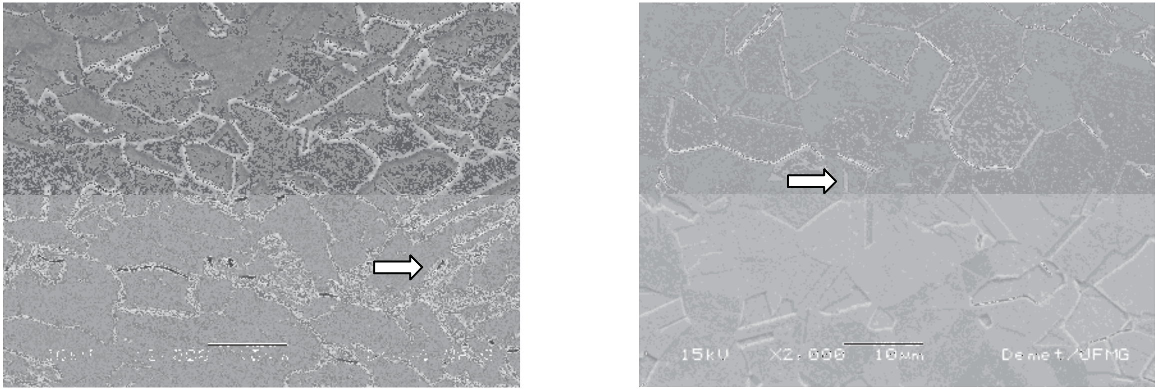
SEM micrographs of samples annealed at different temperatures are presented in Figs. 3(a-d). A significant advance in recrystallization is visible in the microstructure after annealing at 700°C. In remaining deformed grains, the presence of deformation twins (or deformation substructure) is evident. During annealing the rearrangement of defects takes place (formation of dislocation cells, microbands, annihilation of dislocations, etc.) in order to reduce the stored energy of the material. Such process is termed recovery. It follows by recrystallization, which manifests itself in appearance of defect-free grains [11].

Microhardness results in Fig. 4(a) show the recovery stage of steel during annealing between 400 and 600°C. For cold rolled (work hardened) sample, the microhardness is equal to 380HV, whereas the microhardness of fully recrystallized sample is reduced by approximately 50%, to 175HV. Fig. 4(a) shows that recovery reach a significant extent detectable by microhardness at 600C, which is translating by small drop in hardness. Fig. 4 (b) shows evolution of softening as annealing temperature increases. In Figs. 3 (b-d) the evolution of recrystallization in the steel could be followed which is accompanied by appearance of new equiaxed grains and disappearance of the deformed areas containing deformation twins. The recrystallized fraction increased with annealing temperature up to complete recrystallization at 850°C, Fig. 3 (d) and Fig. 4 (b). These values for recovery and recrystallization are compatible with those of Bracke *et al.*, who found 600 and 700°C respectively, for a Fe-22Mn-0.6C TWIP steel, cold rolled to 50% reduction [7]. The higher temperatures encountered in this work are due to higher amount of alloying elements in the studied steel, which retard the progress of recrystallization by solute drag effect. Mi *et al.* [8] found for a steel of similar composition that complete recrystallization takes place after 60% cold rolling and annealing at 800ºC for 1.8 ks. For annealing temperatures above 850°C, the recrystallization was complete and the grain growth took place Fig. 5(a). Fig. 5(a) shows the influence of annealing temperature on the evolution of grain size. In principle this grain growth is heterogeneous, Fig. 5(b), and then became homogeneous above 850ºC, reaching a value around 10 µm at 900°C annealing (Fig. 5(a)). This low grain growth rate (2 to 10 µm) is due to high concentration of alloying elements in steel, which reduced the rate of grain boundary migration.

It is noteworthy that there are two types of twinning. First, the ones visible in Fig 3(a,b), and indicated by arrows, are called deformation twins and their formation is discussed in several models [1,6]. A common feature among them is the need for migration of the grain boundary for their formation [11]. The second is annealing twin, Fig. 3 (d). Nucleation is the beginning of recrystallization process and occurs mainly in places with high difference in orientation (grain boundaries, triple junctions) or regions of high stored energy, e.g. dislocations accumulation [7,11], which explain why the recrystallization does not occur evenly in this steel microstructure. In metals that exhibit the formation of mechanical twins and transition shear bands, the nucleation will also occur preferentially at the intersections of these heterogeneities or next to them [5,7].



(a) 700ºC (b) 750ºC



(c) 800ºC (d) 850ºC

Fig. 3. SEM micrographs showing evolution of recrystallization with annealing temperatures. Arrows indicate deformation twins in (a,b) and annealing twins in (c,d).

The micrographs of Fig. 3 show clearly how the recrystallization starts in specific regions and seems to have difficulties to start in others, resulting in the inhomogeneity of the microstructure (Figs, 3 (b,c).

As the recrystallization tends to occur in regions with high difference in orientation [11], the great difference between twin bands shown in Fig. 3(a,b) results in a partial recrystallization occurred for annealing at 750°C and almost complete at 800°C. Figs. 3(c) and 5(b) further illustrates the different crystallographic orientations of recrystallized grains and the heterogeneity of the microstructure.

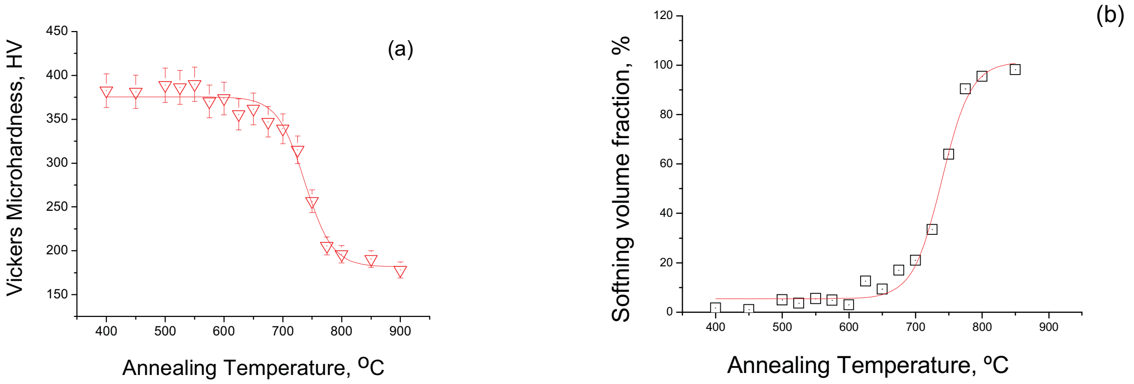


Fig 4. Microhardness as function of each annealing temperature (a) at temperature. Softening as function of annealing temperature (b).

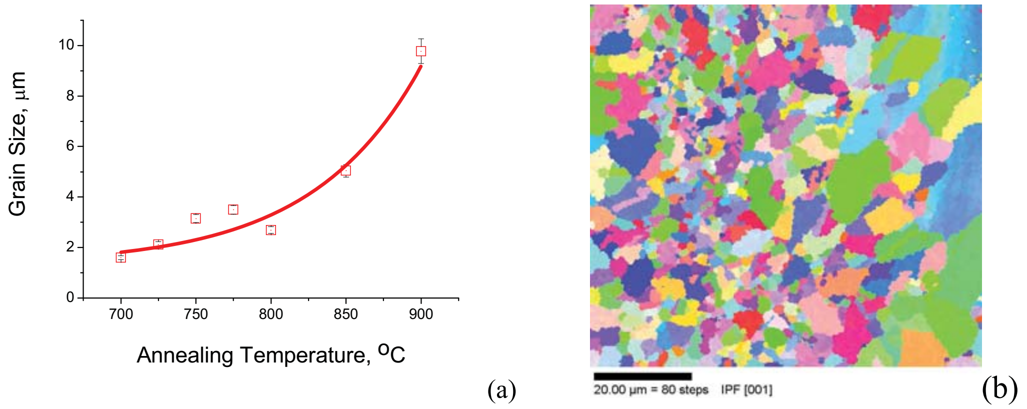


Fig. 5. Grain size as a function of annealing temperature (a). Sample annealed at 800ºC. Areas containing a mixed grain size distribution (b). EBSD image.

The results from tensile tests are listed in Table 1. They show quite favorable properties for the samples annealed at 850ºC or 900ºC. An example of engineering and true stress-strain curves are shown in Figs. 6(a,b) to illustrates the determination of the strain hardening exponent calculated using the Considère's criterion (dσ/dε=σ) and indicated by arrow. As material recover and recrystallize the strain hardening exponent increases and the strength decreases. It is related to a highest degree of recrystallization for high temperatures and uniformity of the microstructure.

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Table 1. Mechanical properties

Annealing Temperature	Yield Strength (MPa)	Tensile Strength (MPa)	Total Elongation %	Strain Hardening Exponent, n
500ºC	850	1200	10	0.25
700ºC	650	1000	23	0.24
850ºC	390	650	55	0.58
900 ºC	400	670	54	0.57

During the tensile test, the steel is subjected to plastic deformation and, as intrinsic characteristic of this material, deformation by twinning and slip happens simultaneously. The microtwins act as grain boundaries contributing to the high value of strain hardening exponent and also ductility [1,3,4,6].

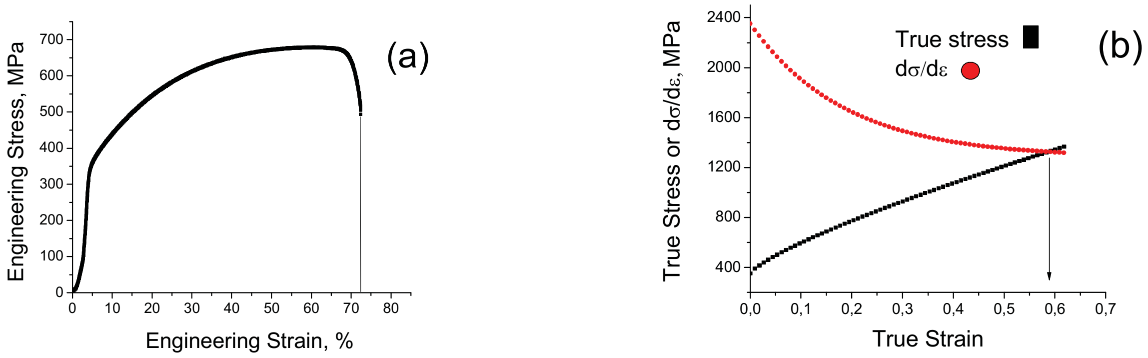

Fig. 6. Engineering stress-strain curve (a) and calculation of the strain hardening exponent (b) of the TWIP steel annealed at 850ºC after 52% cold rolling.

Summary

The recrystallization in the studied TWIP steel after cold rolling with 52% reduction starts at 650°C and was complete above 800ºC. For annealing above 850°C grain growth took place. For 850 or 900°C annealing temperatures the material shows a total elongation of ~55% and tensile strength equal to 659 and 670 MPa, respectively, and a strain hardening exponent of 0.58. The TWIP effect during plastic deformation is responsible for the high mechanical properties level.

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Recrystallization and Grain Growth IV

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