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# Effect of multiple forging and annealing on microstructure and mechanical properties of a high-manganese steel

P D Dolzhenko<sup>1\*</sup>, R Z Valiev<sup>2</sup>, A N Belyakov<sup>1</sup>, E V Bobruk<sup>2</sup> and M S Tikhonova<sup>1</sup>

<sup>1</sup>Belgorod State National Research University, Pobeda, 85, Belgorod, 308015, Russia

<sup>2</sup>Ufa State Aviation Technical University, K. Marxa, 12, Ufa, 450008, Russia

\*Corresponding author: dolzhenko\_p@bsu.edu.ru

**Abstract.** The effect of multiple forging and annealing on the microstructure and mechanical properties of a high-manganese steel is considered. An austenitic high-manganese steel, Fe-0.03C-28Mn-1.5Al (all in wt.%), with an average grain size of about 37  $\mu\text{m}$  was used as the initial material in this study. Multiple forging at room temperature was carried out up to a total true strain of 2. Multiple forging was accompanied by deformation twinning and resulted in significant strengthening. The steel samples subjected to multiple forging demonstrate an increase in the strength properties with an increase in the total strain, while elongation decreases. After multiple forging to a total strain of 2, the samples were annealed at temperatures from 673 to 1073 K for 30 minutes. An increase in the annealing temperature leads to a decrease in the strength and a significant increase in plasticity. Annealing at temperatures of  $T \geq 873$  K leads to the formation of a recrystallized microstructure.

## 1. Introduction

Austenitic high manganese steels exhibiting the twinning-induced plasticity (TWIP) effect are of great interest in materials science and are considered advanced structural materials for use in the automotive industry [1,2]. TWIP steels exhibit an excellent combination of mechanical properties due to the fact that the twins nucleated during the plastic deformation act as obstacles, reducing the dislocation mean free path during deformation, leading to high strain hardening rates [3]. However, the widespread use of TWIP steels is limited. This is partly due to their relatively low yield stress compared to other advanced high strength steels (AHSS) [4]. Many works are devoted to such methods of improving the yield strength as cold rolling and annealing [4–6] in a wide temperature range, as well as high-pressure torsion (HPT) [7] and other methods of austenitic steel processing [8]. However, the multiple forging of high-manganese steels at room temperature and subsequent annealing in a wide temperature range has received little attention. In this paper, we investigate the effect of multiple forging and subsequent annealing on the microstructure and mechanical properties of a high-manganese TWIP steel.

## 2. Experimental

High-manganese TWIP steel with a chemical composition of Fe-0.03C-28Mn-1.5Al (all in wt.%) was subjected to annealing at 1423 K for 1 hour followed by rolling at 1423 K with about a 60% reduction. Then, the prismatic steel samples with the initial dimensions of  $10 \times 12 \times 15$  mm<sup>3</sup> were subjected to multiple forging at room temperature to a total strain of 2. Multiple forging was carried out with a change in the deformation axis by 90 degrees at a true strain of 0.4 per pass. After multiple forging, the samples

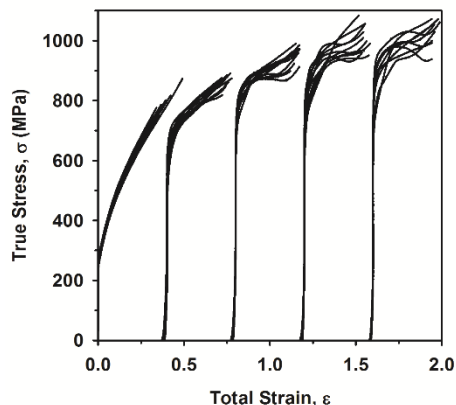


were annealed at temperatures in the range from 673 to 1073 K for 30 minutes. Microstructure studies were carried out using a scanning electron microscope (SEM). The specimens for structural investigations were electro-polished using an electrolyte containing 10% perchloric acid and 90% acetic acid at a voltage of 20 V at room temperature. The average grain size was estimated by the intercept line method. The tensile tests of the flat-type specimens with a gauge length of 4 mm and a cross section of  $1.0 \times 0.5$  mm were carried out at room temperature and at an initial strain rate of  $10^{-3} \text{ s}^{-1}$ .

### 3. Results and discussion

#### 3.1. Deformation behavior

Several true stress-strain curves for five sequential forgings to a total strain of 2 at room temperature are shown in figure 1. Following the yielding at about 245 MPa, the first compression pass is characterized by a gradual increase in the flow stress to about 820 MPa. Further deformation leads to a gradual increase in the flow stresses, which tends to saturate at a level of about 1000 MPa after total strains exceeding 1.6.



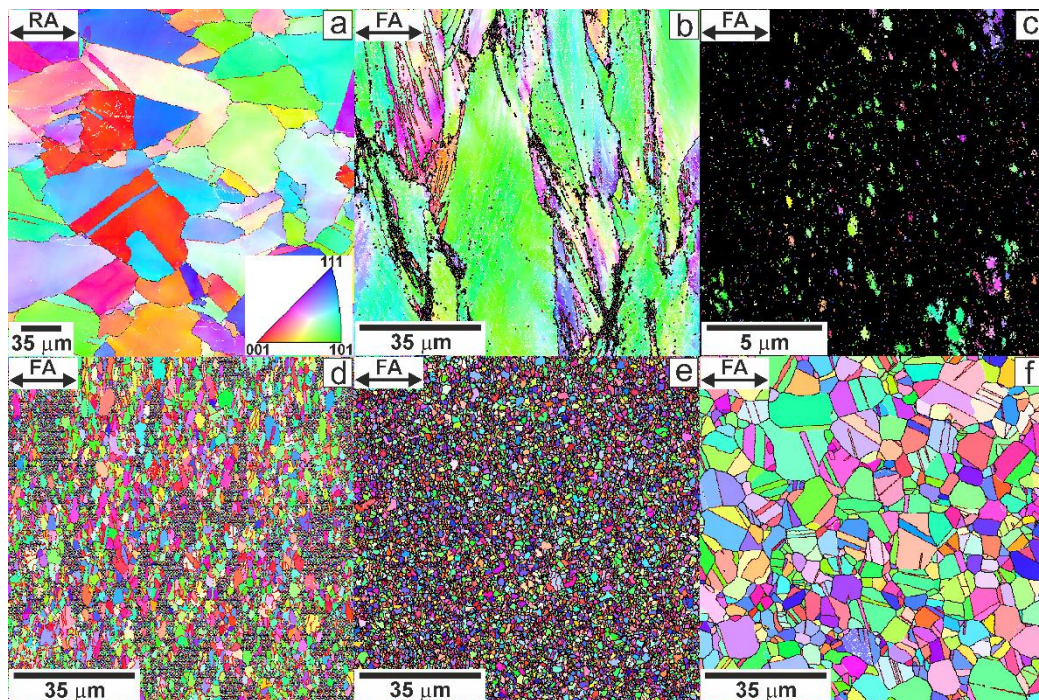
**Figure 1.** True stress–strain curves obtained during multiple forging of high-Mn steel at room temperature.

#### 3.2. Microstructures

The microstructure of high-manganese TWIP steel in the initial state (figure 2a) is characterized by equiaxed austenite grains with an average size of about  $37 \mu\text{m}$ . The fraction of high-angle boundaries (HAB) in this state is 0.67, and the fraction of  $\Sigma 3$  CSL boundaries is 0.30. The CSL boundaries have a misorientation angle of  $60^\circ$  and are associated with annealing twins [8]. In the process of multiple forging to a true strain of 0.4 (figure 2b), a network of low-angle boundaries (LAB) with a misorientation angle of less than  $15^\circ$  is formed, the fraction of high-angle boundaries (HAB) decreases by a factor of 2. The deformation twins form bundles with individual twin thickness of 470 nm.

An increase in the total strain to 2 (figure 2c) is also accompanied by mechanical twinning and, as a result, the refinement of structural elements to sizes less than 50 nm. Heat treatment at 673K and 773K for 0.5 h does not change remarkably the microstructure evolved during multiply forging. An increase in the annealing temperature to 823K results in a partially recrystallized microstructure as shown in figure 2d. New fine austenitic grains with a size of  $1 \mu\text{m}$  with quite a low dislocation density, as well as work hardened regions with high density of deformation twins were found in the microstructure after 0.5 h of annealing at 823 K. The fraction of  $\Sigma 3$  CSL boundaries is 0.14. An increase in the annealing temperature to 873K leads to the formation of a recrystallized structure with an average grain size of 900 nm (figure 2e), as a result of static recrystallization, while the fraction of special  $\Sigma 3$  boundaries increases by 2 times, and the HAB fraction is 0.98.

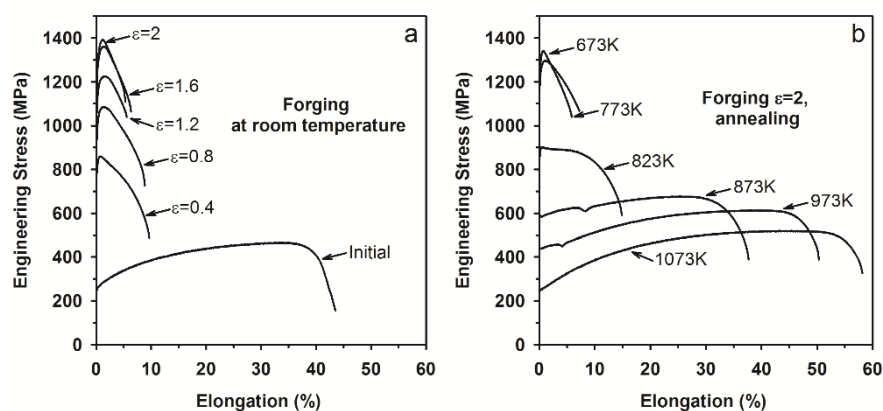
Annealing at a temperature of 1073 K for 0.5 h leads to the formation of austenite grains with an average size of  $5.7 \mu\text{m}$  (figure 2). This microstructure consists of equiaxed grains with numerous annealing twins. The fraction of  $\Sigma 3$  CSL boundaries comprises 0.42.



**Figure 2.** Microstructure of high-Mn steel in the initial state (a), deformation microstructures after multiple forging at room temperature to total strains of 0.4 (b), 2 (c), and microstructures after multiple forging to a total strain of 2 and 30 min annealing at 823 K (d), 873 K (e) and 1073 K (f). The colors correspond to the crystallographic direction along the forging axis (FA) or the rolling axis (RA). High-angle boundaries, low-angle sub-boundaries, and twin boundaries are shown with bold black lines, thin white lines, and red lines, respectively.

### 3.3. Tensile properties

This steel in the initial state demonstrates a yield strength equal to 255 MPa, and a tensile strength equal to 465 MPa with an elongation of 44% (figure 3a). Forging to a true strain of  $\epsilon = 0.4$  leads to an increase in yield stress to 810 MPa, the sample exhibits little uniform elongation and necking soon after reaching the yield stress, and the total elongation is 9%.



**Figure 3.** Tensile stress-elongation curves at room temperature for austenitic high-Mn steel subjected to multiple forging at room temperature to the indicated total true strains from  $\epsilon = 0.4$  to  $\epsilon = 2.0$  (a), and then annealed for 30 min at the indicated temperatures following multiple forging to  $\epsilon = 2$  (b).

The samples subjected to multiple forging to larger total strains show similar behavior in the tensile stress-elongation curves, necking occurs almost immediately upon reaching the yield point. As the total forging strain increases, the strength characteristics increase, and the elongation decreases. After  $\varepsilon = 2$ , the yield strength is 1260 MPa, the ultimate strength is 1390 MPa, and the elongation is 5%.

Annealing at temperatures of 673 K and 773 K does not lead to significant changes in the tensile properties of TWIP steel subjected to multiple forging to a total strain of 2. An increase in the annealing temperature to 823 K leads to an increase in the elongation up to 15%. A further increase in the annealing temperature leads to an expansion of the region of uniform elongation, while the strength characteristics decrease. On the tensile curves of high-manganese steel annealed at temperatures of 873 K and 973 K, there is a tooth characterized by a drop in flow stresses when reaching 635 MPa and 468 MPa, respectively. The nature of this phenomenon should be studied in further research. Annealing at a temperature of 1073 K leads to a decrease in the yield point and ultimate strength to 245 MPa and 520 MPa, respectively, with an elongation of 58%.

#### 4. Conclusion

The present study elaborates further the urgent task of obtaining structural materials with a combination of high strength and good plasticity by means of ultrafine grain refinement by severe plastic deformation [9]. The main results can be summarized as follows:

1. Multiple forging of high-manganese steel is accompanied by a gradual increase in the flow stress as the total true strain increases. The flow stress reaches saturation of about 1000 MPa at total strains above 1.6.

2. Multiple forging is accompanied by the formation of deformation twins and a network of low-angle subboundaries. Ultrafine structural elements with a size below 50 nm evolve as the total strain increases to 2. These microstructures do not remarkably up on subsequent annealing for 30 min at temperatures of  $T \leq 773$  K, whereas an increase in the annealing temperature to 823 K leads to the development of recrystallization process. A completely recrystallized microstructure develops during 30 min of annealing at  $T \geq 873$  K.

3. The steel samples subjected to multiple forging demonstrate an increase in the strength properties with an increase in the total forging strain while elongation decreases. The yield stress reaches 1260 MPa at a total strain of 2. Annealing for 30 min at  $T \leq 773$  K does not lead to significant changes in the mechanical properties, whereas annealing at higher temperatures decreases the yield stress and increases elongation.

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