# High-temperature deformation and recrystallization behavior of a high-manganese austenitic TWIP steel: Postprint

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## Abstract

At deformation temperatures of 1223~1423 K and strain rates of 0.01~10 s-1, single-pass compression deformation experiments were conducted using an MMS-300 thermal simulator, combined with characterization techniques such as SEM-EBSD and TEM, to investigate the high-temperature deformation and recrystallization behavior of a high-manganese austenitic twinning-induced plasticity (TWIP) steel, and to analyze and characterize the microstructural evolution behavior during its dynamic recrystallization process and its correlation with the stress-strain curve. The results show that the hot deformation behavior of this high-manganese austenitic TWIP steel is relatively sensitive to strain rate; when the strain rate is lower than 0.1 s-1, dynamic recrystallization occurs during hot deformation; when the strain rate is higher than 1 s-1, dynamic recovery occurs. The hot deformation constitutive equation for this high-manganese austenitic TWIP steel was established through regression analysis, and analysis suggests that the microstructural evolution behavior during dynamic recrystallization is closely related to its stress-strain curve. With increasing strain, grain boundary migration induces recrystallization nucleation; as the strain further increases, a large number of subgrain boundaries are generated; dislocation climb and slip on adjacent subgrain boundaries cause grain boundary merging, leading to the formation of recrystallized grains.

## Full Text

### Hot Deformation at Elevated Temperature and Recrystallization Behavior of a High Manganese Austenitic TWIP Steel

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## Abstract

Single-pass compression tests were conducted on a MMS-300 thermo-mechanical simulator at deformation temperatures of 1223–1423 K and strain rates of 0.01–10 $s^{-1}$ to investigate the high-temperature deformation and recrystallization behavior of a high-manganese austenitic twinning-induced plasticity (TWIP) steel. Microstructural evolution during dynamic recrystallization and its correlation with stress-strain curves were analyzed and characterized using SEM-EBSD and TEM techniques. The results show that the hot deformation behavior of this high-manganese austenitic TWIP steel is sensitive to strain rate. Dynamic recrystallization occurs during hot deformation when the strain rate is lower than 0.1 $s^{-1}$, whereas dynamic recovery takes place at strain rates higher than 1 $s^{-1}$. A constitutive equation for hot deformation was established through regression analysis, revealing a close correlation between microstructural evolution and stress-strain curves during dynamic recrystallization. With increasing strain, grain boundary migration induces recrystallization nucleation. As deformation progresses further, numerous subgrain boundaries form. Dislocation climb and slip on adjacent subgrain boundaries cause boundary merging, leading to the formation of recrystallized grains.

**KEY WORDS** TWIP steel; hot deformation; dynamic recrystallization; constitutive equation; microstructure evolution

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## 1. Introduction

Twinning-induced plasticity (TWIP) steel is primarily based on Fe-C alloys with additions of 15–30 wt% Mn and certain amounts of Al, Si, Ti, Mo, Cu, and other elements. Both C and Mn are major austenite-stabilizing elements in TWIP steel. Carbon provides strong solid solution strengthening, while Mn addition can improve the high-temperature mechanical properties of the alloy. Aluminum addition forms a protective $Al_2O_3$ film on the alloy surface, thereby enhancing oxidation resistance, and trace additions of Si, Ti, Mo, and Cu can improve corrosion resistance to varying degrees. High-Mn TWIP steels (20–30% Mn) can obtain single-phase stable austenite structure at room temperature and exhibit excellent comprehensive properties including superior strength-ductility combinations and good crash energy absorption capability. The product of strength and elongation for TWIP steel generally exceeds $5\times10^{4}$ MPa · %, making it a promising new automotive steel that has attracted widespread attention.

In recent years, research has been conducted on the correlation between processing parameters and mechanical properties of TWIP steels with different chemical compositions. Beyond conventional mechanical properties, studies on oxidation resistance and corrosion resistance of TWIP steels have also drawn attention. Our previous work found that in typical Fe-Mn-Al-C austenitic steels, small additions of Cr and N can improve oxidation and corrosion resistance to some extent while maintaining mechanical properties. This suggests that TWIP steels with new compositions based on traditional TWIP steel chemistry but with certain amounts of Cr and small amounts of N added could potentially partially replace stainless steels in applications.

The variation of flow stress is a comprehensive reflection of internal microstructural evolution and also serves as the basis for equipment selection and verification during material plastic processing. Therefore, studies on material flow stress and its influencing factors have attracted great attention. Additionally, investigating the high-temperature deformation behavior of metallic materials and establishing accurate mathematical models for flow stress are of great significance for the formulation of hot processing technologies.

Currently, there have been reports on flow stress characteristics and constitutive relationships during isothermal compression deformation of TWIP steels. However, research correlating the characteristics of different stages of flow stress curves during high-temperature deformation with the deep-seated mechanisms of dynamic recrystallization microstructural evolution, particularly regarding the mechanisms of dynamic recrystallization processes, is still lacking. Therefore, this work focuses on a newly designed high-manganese austenitic TWIP steel. Through single-pass compression thermo-simulation experiments, true stress-strain curves under different hot deformation conditions were obtained. The plastic flow behavior and microstructural evolution of the new high-manganese austenitic TWIP steel during high-temperature deformation were investigated, and a correlation analysis was performed between the microstructural evolution during dynamic recrystallization and the characteristics of different stages of the flow stress curve, aiming to provide a theoretical basis for formulating the hot processing technology for this steel grade.

## 2. Experimental

The high-manganese austenitic TWIP steel used in this study was melted in a 20 kg vacuum induction furnace. The main chemical composition (wt%) was: C 0.34, Mn 22.30, Al 3.12, Cr 2.96, N 0.01, Fe balance. After cold rolling and annealing, the steel exhibits room temperature tensile strength exceeding

700 MPa and elongation over 50%. The cast ingot from the vacuum induction furnace was forged into a slab with dimensions of 35 mm × 100 mm × 120 mm at 1473 K. Cylindrical thermo-simulation specimens with dimensions of Φ8 mm × 12 mm were then cut from the forged slab using wire electrical discharge machining.

Uniaxial compression tests were conducted on an MMS-300 multifunctional thermo-mechanical simulator. Specimens were heated to 1473 K at a rate of 20 K/s, held for 180 s, then cooled to the deformation temperature at 20 K/s and held for temperature equalization. The deformation temperatures were 1223, 1273, 1323, and 1423 K; strain rates were 0.01, 0.05, 0.1, 1, 5, and 10 $s^{-1}$; and the true strain was 0.7. Additionally, under the condition of 1323 K and 0.05 $s^{-1}$, compression tests were performed to various true strains ranging from 0.05 to 0.70. After hot deformation, specimens were immediately water-quenched to preserve the high-temperature deformation microstructure.

The deformed specimens were sectioned along the compression axis. After mechanical grinding and polishing, metallographic specimens were prepared for microstructural observation using a Quanta 600 scanning electron microscope (SEM). For electron backscatter diffraction (EBSD) analysis, specimens were electropolished and then examined using a Supra 55 field-emission SEM equipped with an HKL Channel 5 analysis system to characterize grain boundary evolution. For transmission electron microscopy (TEM), specimens were mechanically ground to 50 m thickness, then further thinned using a twin-jet electropolishing unit with an electrolyte of 10% perchloric acid + 90% ethanol (by volume) at 248 K and 40 V. The microstructural evolution of specimens deformed at 1323 K and 0.05 $s^{-1}$ to various strains was observed and analyzed using a Tecnai G2 F20 transmission electron microscope.

## 3. Results and Discussion

**3.1 Flow Stress Behavior** The true stress-true strain curves of the high-manganese austenitic TWIP steel under different deformation conditions are shown in [Figure 1: see original paper]. As seen in Figures 1a and 1b, when the strain rate is 0.1 $s^{-1}$, stress increases rapidly with increasing strain and reaches a peak in the initial deformation stage. Subsequently, stress decreases with further strain increase, indicating that dynamic recrystallization occurs during deformation. When the strain rate is \$ 1*s*^{-1}\$, as shown in Figures 1c and 1d, stress reaches a peak and then enters a steady state, suggesting that dynamic recovery occurs in the experimental steel.

In the initial deformation stage, stress increases rapidly to a peak with increasing strain because lattice distortion generated during plastic deformation causes work hardening. Lattice distortion hinders dislocation slip, and the more severe the distortion, the more difficult the plastic deformation and the greater the work hardening rate. However, the work hardening rate does not continue to increase with deformation degree. During deformation, dislocations generated by deformation move through cross-slip and climb, causing some dislocations to disappear or rearrange, resulting in recovery softening of the metallic material. In cases controlled by dynamic recovery, no nucleation and growth of new grains occur, and dynamic recrystallization does not happen. Under specific deformation conditions, when the deformation reaches a certain level, the distortion energy accumulated by the dislocation stress field becomes sufficient to trigger dynamic recrystallization.

The curves in [Figure 1: see original paper] also show that the peak stress during hot deformation decreases with increasing deformation temperature and decreasing strain rate. This is because higher deformation temperature increases the driving force for dislocation cross-slip and climb, while lower strain rate extends the time for accumulation of distortion energy and dislocation annihilation, which is beneficial for softening behaviors such as dynamic recrystallization.

**3.2 Hot Deformation Microstructure Analysis** SEM images of the high-manganese austenitic TWIP steel deformed at 1223 K with strain rates of 0.1 and 0.01 $s^{-1}$ are shown in [Figure 2: see original paper]. [Figure 2: see original paper]a shows that when the strain rate is 0.1 $s^{-1}$, the deformed microstructure consists of elongated subgrains with recrystallized grains appearing at grain boundaries. When the strain rate is 0.01 $s^{-1}$, the microstructure after deformation consists of equiaxed recrystallized grains ([Figure 2: see original paper]b).

[Figure 3: see original paper] shows SEM images of the high-manganese austenitic TWIP steel deformed at various temperatures with a strain rate of 0.1 $s^{-1}$. It can be seen that when the deformation temperature is 1223 K, the microstructure consists of deformed austenite grains. At 1323 K, recrystallized grains appear at the boundaries of deformed original austenite grains. At 1423 K, dynamic recrystallization is complete.

Evidently, when deformed at higher strain rates (\$ $0.1s^{\{-1\})andlowertemperatures(\ 1323K),dynamicrecrystallizationisinc}$ 1})*andhighertemperatures*( \$1423 K), dynamic recrystallization occurs, which is consistent with the characteristics of the true stress-strain curves. Thus, the features of flow curves can accurately reflect microstructural changes.

**3.3 Hot Deformation Constitutive Relationship** The relationship between flow stress ($\sigma$), strain rate ($\dot{}$), and temperature (T) for austenitic alloys can be expressed as follows:

$$Z = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right) = A[\sinh(\alpha\sigma)]^n \tag{1}$$

where A and $\alpha$ are material constants; n is the stress exponent; Q is the deformation activation energy (kJ/mol), reflecting the difficulty of hot deformation; R is the gas constant (R = 8.314 J/(mol · K)); Z is the Zener-Hollomon parameter ($s^{-1}$), i.e., the temperature-compensated strain rate parameter; and $\sigma$ can represent peak stress, steady-state stress, or flow stress at a specified strain. In this study, peak stress was used.

Taking logarithms of both sides of Equation (1) and taking partial derivatives with respect to ln ˙ and 1/T yields:

$$n = \frac{\partial \ln[\sinh(\alpha\sigma)]}{\partial \ln \dot{\varepsilon}} \tag{2}$$

$$Q = Rn\frac{\partial \ln[\sinh(\alpha\sigma)]}{\partial(1/T)} \tag{3}$$

From Equations (1), (2), and (3), it is clear that to obtain the values of n, $\beta$, and Q, the value of $\alpha$ must first be determined. The relationship between the residual sum of squares of n and $\alpha$ obtained from experimental data is shown in [Figure 4: see original paper]. When $\alpha$ is 0.007 $\mathrm{MPa}^{-1}$, the residual sum of squares of n reaches a minimum value, thus $\alpha = 0.007\ \mathrm{MPa}^{-1}$ can be determined.

Under constant temperature conditions, the relationship between $\ln[\sinh(\alpha\sigma)]$ and ln ˙ is linear, with its reciprocal slope being n. Linear regression of the experimental data for $\ln[\sinh(\alpha\sigma)]$ versus ln ˙ yields [Figure 5: see original paper]a, from which n = 6.41 is obtained for the experimental steel. Similarly, under constant strain rate conditions, $\ln[\sinh(\alpha\sigma)]$ and 1/T also satisfy a linear relationship. Linear regression of the corresponding experimental data yields [Figure 5: see original paper]b, from which the slope $\beta = 7.53$ is obtained.

Substituting the values of $\alpha$, n, and $\beta$ into Equation (3) yields Q = 399.76 kJ/mol. Substituting parameters under different hot deformation conditions into Equation (1) gives a set of A values, whose average is A = $2.11 \times 10^{14}$. Accordingly, the hot deformation constitutive equation for this high-manganese austenitic TWIP steel in the temperature range of 1223–1423 K can be established as:

$$\dot{\varepsilon} = 2.11 \times 10^{14}[\sinh(0.007\sigma)]^{6.41} \exp\left(-\frac{399760}{RT}\right) \tag{4}$$

The Z parameter has been widely used to represent the combined effect of deformation temperature and strain rate on the deformation process. Based on Equation (1), the Z parameter under different deformation conditions can be calculated, and the scatter plot and linear regression curve of $\ln[\sinh(\alpha\sigma)]$ versus ln Z can be plotted, as shown in [Figure 6: see original paper]. The linear correlation coefficient $R^2 = 0.9845$. Therefore, the hot deformation constitutive relationship for this high-manganese austenitic TWIP steel in the temperature range of 1223–1423 K can be described by Equation (4).

### 3.4 Microstructural Evolution During Dynamic Recrystallization

EBSD grain boundary maps of the high-manganese austenitic TWIP steel deformed at 1323 K and 0.05 $s^{-1}$ to various strains are shown in [Figure 7: see original paper]. [Figure 7: see original paper]a shows that prior to high-temperature deformation, the microstructure consists of equiaxed austenite grains containing numerous annealing twins with relatively smooth grain boundaries. As deformation proceeds, original grains are compressed axially, grain boundaries become non-straight, and some boundaries bulge. Additionally, fine equiaxed recrystallized grains form at austenite grain boundaries ([Figure 7: see original paper]b), indicating the initiation of dynamic recrystallization. With increasing strain, original grains become elongated. Under applied stress, twin boundaries also bend and become non-straight, twins gradually decompose, and deformation bands composed of low-angle grain boundaries form within grains. [Figure 7: see original paper]c shows that numerous original austenite grain boundaries develop serrated structures, meaning deformation-induced subgrains form near original austenite grain boundaries, which exert a pinning effect on high-angle grain boundary migration. Thus, serrated structures provide conditions for nucleation of recrystallized grains, which form at original austenite grain boundaries. Furthermore, as seen in [Figure 7: see original paper]c–e, the number of recrystallized grains increases with continued deformation. When deformation is complete, the recrystallization process is essentially finished, and the microstructure consists of relatively fine austenitic recrystallized grains compared with the original austenite structure ([Figure 7: see original paper]f).

During hot deformation, recrystallization nucleation results from the synergistic action of multiple mechanisms. At small strains, due to the deformation inhomogeneity in single-pass compression tests, adjacent grains exhibit large differences in dislocation density. As shown in [Figure 8: see original paper]a, one side of a grain boundary shows a cellular dislocation structure with high dislocation density, while the other side has extremely low dislocation density. This large difference in dislocation density between adjacent grains leads to a unidirectional driving force at the grain boundary, causing a small segment of the boundary to suddenly bulge toward the side with higher dislocation density ([Figure 8: see original paper]b). The stored energy in the swept region is completely released, forming a recrystallization nucleus, similar to results reported in the literature. [Figure 8: see original paper]c and d show that with increasing deformation, numerous new subgrain boundaries form, distributed both near original grain boundaries and within grains, due to the activation of slip systems in different directions within grains that divide original grains into different regions. [Figure 8: see original paper]d shows that subgrain boundaries in the hot-deformed microstructure are merging, with original subgrain boundaries disappearing. This occurs because dislocations on adjacent subgrain boundaries move through climb and slip mechanisms to surrounding grain boundaries or subgrain boundaries, a phenomenon also reported in the literature. Through position adjustment and atomic diffusion, the orientations of a group of subgrains eventually become consistent, forming a recrystallization nucleus. With further increase in deformation, subgrain boundaries disappear and recrystallized grains form ([Figure 8: see original paper]e). When the true strain reaches 0.7, recrystallization is complete, and the recrystallized structure consists of equiaxed polygonal grains ([Figure 8: see original paper]f).

In summary, the microstructural evolution process of the high-manganese austenitic TWIP steel in this work shows a clear direct correspondence with the variation trend of the stress-strain curve. Based on [Figure 1: see original paper]a, under deformation conditions of T = 1323 K and ˙ = 0.05 $s^{-1}$, the peak strain = 0.067. It is generally accepted that the critical strain _c = 0.83 , which gives _c = 0.05, consistent with the strain at which dynamic recrystallization begins in [Figure 7: see original paper]b and [Figure 8: see original paper]a. When the true strain is 0.15–0.25, the flow stress remains relatively stable. At this stage, numerous subgrain boundaries exist within original austenite grains. Although dynamic recrystallization nucleation continues during strain accumulation, the dynamic recovery mechanism remains dominant. When the true strain reaches 0.45, recrystallization nucleation is essentially complete, the dynamic recrystallization mechanism gradually becomes dominant, the softening effect becomes more pronounced, and flow stress decreases. When strain reaches 0.7, new austenite grains are distributed throughout the deformed microstructure, and flow stress reaches a steady state.

## 4. Conclusions

1. For the high-manganese austenitic TWIP steel investigated in this work, the flow stress curve with increasing deformation can be divided into two stages. In the initial deformation stage, stress increases rapidly with strain and reaches a peak due to work hardening caused by plastic deformation. Subsequently, with further deformation, stress enters a continuous steady state or decreases to a certain level before reaching a steady state due to softening from recovery and recrystallization. The hot deformation behavior of this steel is sensitive to strain rate: dynamic recrystallization occurs when the strain rate is lower than 0.1 $s^{-1}$, while dynamic recovery occurs when the strain rate is higher than 1 $s^{-1}$.

2. The hot deformation constitutive equation for this high-manganese austenitic TWIP steel in the temperature range of 1223–1423 K has been established as:

$$\dot{\varepsilon} = 2.11 \times 10^{14} [\sinh(0.007\sigma)]^{6.41} \exp\left(-\frac{399760}{RT}\right)$$

3. Two recrystallization nucleation mechanisms exist during hot deformation of this high-manganese austenitic TWIP steel. At small strains, recrystallization nuclei form through a bulging mechanism. With increasing

deformation, numerous new subgrain boundaries form, and dislocation climb and slip on adjacent subgrain boundaries cause boundary merging, leading to nucleation through a coalescence mechanism.

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