*metals*

MDPI

*Article*

# Deformation Behavior of High-Mn TWIP Steels Processed by Warm-to-Hot Working

**Vladimir Torganchuk [1], Aleksandr M. Glezer [2,*], Andrey Belyakov [1] and Rustam Kaibyshev [1]**

[1] Belgorod State University, Belgorod 308015, Russia; torganchuk@bsu.edu.ru (V.T.); belyakov@bsu.edu.ru (A.B.); rustam_kaibyshev@bsu.edu.ru (R.K.)

[2] National University of Science & Technology (MISIS), Moscow 119049, Russia

* Correspondence: a.glezer@mail.ru; Tel.: +7-495-777-9350

Received: 11 May 2018; Accepted: 1 June 2018; Published: 3 June 2018

check for updates

**Abstract:** The deformation behavior of 18%Mn TWIP steels (upon tensile tests) subjected to warm-to-hot rolling was analyzed in terms of Ludwigson-type relationship, i.e., $\sigma = K_1 \cdot \varepsilon^{n1} + \exp(K_2 - n_2 \cdot \varepsilon)$. Parameters of $K_i$ and $n_i$ depend on material and processing conditions and can be expressed by unique functions of inverse temperature. A decrease in the rolling temperature from 1373 K to 773 K results in a decrease in $K_1$ concurrently with $n_1$. Correspondingly, true stress approached a level of about 1750 MPa during tensile tests, irrespective of the previous warm-to-hot rolling conditions. On the other hand, an increase in both $K_2$ and $n_2$ with a decrease in the rolling temperature corresponds to an almost threefold increase in the yield strength and threefold shortening of the stage of transient plastic flow, which governs the duration of strain hardening and, therefore, manages plasticity. The change in deformation behavior with variation in the rolling temperature is associated with the effect of the processing conditions on the dislocation substructure, which, in turn, depends on the development of dynamic recovery and recrystallization during warm-to-hot rolling.

**Keywords:** high-Mn steel; deformation twinning; dynamic recrystallization; grain refinement; work hardening

## 1. Introduction

High-manganese austenitic steels with low stacking fault energy (SFE) are currently considered as promising materials for various structural/engineering applications because of their outstanding mechanical properties [1–3]. Owing to their low SFE, these steels are highly susceptible to deformation twinning, which results in the twinning-induced plasticity (TWIP) effect. Austenitic TWIP steels are characterized by pronounced strain hardening, which retards the strain localization and cracking during plastic deformation and, therefore, provides a beneficial combination of high strength with high ductility [1]. Deformation twinning, therefore, is the most crucial deformation mechanism governing the mechanical properties of high-Mn TWIP austenitic steels [4]. The deformation twins appear as bundles of closely spaced twins with thickness of tens nanometers, crossing over the original grains [5,6]. The deformation twins prevent the dislocation motion and promote an increase in dislocation density, leading to strain hardening. Frequent deformation twinning develops in steels with SFE in the range of approx. 20 mJ/m$^2$ to 50 mJ/m$^2$, which can be adjusted by manganese and carbon content [4].

The exact values of mechanical properties of austenitic steels, e.g., yield strength, ultimate tensile strength, total elongation, etc., depends on processing conditions. Hot rolling is frequently used as a processing technology for various structural steels and alloys. Final mechanical properties of processed steels and alloys depend on their microstructures that develop during hot working. Metallic materials with low SFE like high-Mn austenitic steels experience discontinuous dynamic recrystallization (DRX) during hot plastic deformation [7]. The developed microstructures depend on the deformation temperature and/or strain rate. Namely, the DRX grain size decreases with a decrease in temperature and/or an increase in strain rate and can be expressed by a power law function of temperature compensated strain rate ($Z$) [8]. A decrease in the deformation temperature to warm deformation conditions results in a change in the DRX mechanism from discontinuous to continuous, leading to a decrease in the grain size exponent in the relationship between the grain size and the deformation conditions, although this relationship remains qualitatively the same as that for hot working conditions [9]. The grain refinement with an increase in $Z$ is accompanied with an increase in the dislocation density in DRX microstructures, irrespective of the DRX mechanisms [10]. Thus, the yield strength of the warm to hot worked semi-products can be evaluated by using various structural parameters. This approach has been successfully applied for strength evaluation of a range of structural steels and alloys, including high-Mn TWIP steels subjected to various thermo-mechanical treatments [5,6,10–12]. On the other hand, the effect of processing conditions on the deformation behavior of high-Mn TWIP steels has not been qualitatively evaluated, although, particularly for these steels, the deformation behavior is one of the most important properties, which manages the practical applications of the steels. It should be noted that the stress-strain behavior of austenitic steels with low SFE cannot be described by any well elaborated models like Hollomon or Swift equations, especially, at relatively small strains because of exceptional strain hardening [13]. Ludwigson modified the Hollomon-type relationship with an additional term to compensate the large difference between experimental and predicted flow stresses at small strains for such metals and alloys [14]. In spite of certain achievements in the application of the Ludwigson-type equation for the stress-strain behavior prediction, the selection of suitable parameters in this equation is still arbitrary in many ways. The aim of the present study, therefore, is to obtain the relationships between the processing conditions, the developed microstructures, and the stress-strain equation parameters in order to predict the tensile deformation behavior of advanced high-Mn TWIP steels processed by warm-to-hot rolling.

## 2. Materials and Methods

Two steels, Fe-18%Mn-0.4%C and Fe-18%Mn-0.6%C, have been selected in the present study as typical representatives of high-Mn TWIP steels. The steel melts were annealed at 1423 K, followed by hot rolling with about 60% reduction. The steels were characterized by uniform microstructures consisting of equiaxed grains with average sizes of 60 μm (18Mn-0.4C) and 50 μm (18Mn-0.6C). The steels were subjected to plate rolling at various temperatures from 773 K to 1373 K to a total rolling reduction of 60%. After each 10% rolling reductions, the samples were re-heated to the designated rolling temperature. Structural investigations were carried out using a Quanta 600 scanning electron microscope (SEM), equipped with an electron backscattering diffraction (EBSD) analyzer incorporating orientation imaging microscopy (OIM). The SEM samples were electro-polished at a voltage of 20 V at room temperature using an electrolyte containing 10% perchloric acid and 90% acetic acid. The OIM images were subjected to a clean-up procedure, setting the minimal confidence index of 0.1. The tensile tests were carried out using Instron 5882 testing machine with tensile specimens with a gauge length of 12 mm and a cross section of $3 \times 1.5$ mm$^2$ at an initial strain rate of $10^{-3}$ s$^{-1}$. The tensile axis was parallel to the rolling axis.

## 3. Results and Discussion

### 3.1. Developed Microstructures

Typical deformation microstructures that develop in the high-Mn steels during warm to hot rolling are shown in Figure 1. The mechanisms of microstructure evolution operating in austenitic steels during warm to hot working and the developed microstructures have been considered in detail in previous studies [10]. The deformation microstructures in the present high-Mn steels subjected to warm to hot rolling at temperatures of 773–1323 K can be briefly characterized here as follows. The temperature range above 1073 K corresponds to hot deformation conditions. Therefore, the deformation microstructures evolved during deformation in this temperature range result from the development of discontinuous DRX. The uniform microstructures consisting of almost equiaxed grains with numerous annealing twins are clearly seen in the samples hot rolled at temperatures above 1073 K (Figure 1a,b). The transverse DRX grain size decreases from 50–80 μm to 5–10 μm with a decrease in the rolling temperature from 1323 K to 1073 K.

In contrast, DRX hardly develops during warm rolling at temperatures below 1073 K. The deformation microstructures composed of flattened original grains evolve during warm rolling (Figure 1c,d). It is worth noting that the transverse grain size in the deformation microstructures developed during warm rolling does not remarkably depend on the rolling temperature. Relatively low deformation temperature suppresses discontinuous DRX. In this case, the structural changes are controlled by dynamic recovery. Under conditions of warm working, continuous DRX, which is assisted by dynamic recovery, can be expected after sufficiently large strains [7]. The present steels, however, are characterized by low SFE of 20–30 mJ/m$^2$ [4]. Such a low SFE makes the dislocation rearrangements during plastic deformation difficult and slows down the recovery kinetics. Therefore, 60% rolling reduction as applied in the present study is not enough for continuous DRX development in high-Mn steels. The final grain size, therefore, seems to be dependent on the original grain size and the total rolling reduction.

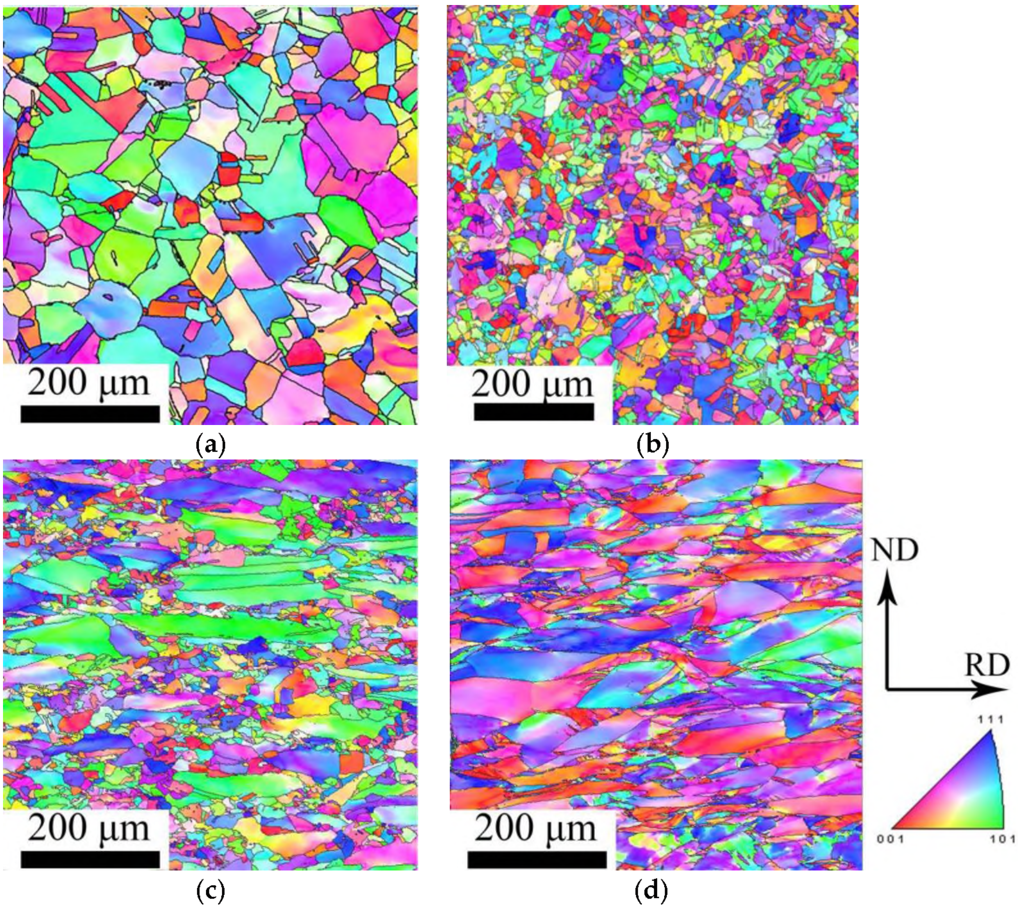



**Figure 1.** Typical OIM (orientation imaging microscopy) micrographs for deformation microstructures evolved in the Fe-18%Mn-0.4%C steel during hot-to-warm rolling at 1273 K (**a**), 1173 K (**b**), 1073 K (**c**) and 973 K (**d**). Colored orientations are shown for the transverse direction (TD).

### 3.2. Mechanical Properties

The stress-elongation curves obtained by tensile tests of the high-Mn steels processed by warm-to-hot rolling at different temperatures in the range of 773–1373 K are shown in Figure 2. A decrease in the rolling temperature results commonly in an increase in the strength and a decrease in the plasticity. The effect of the rolling temperature on the tensile tests properties is more pronounced for the warm working domain, i.e., rolling at temperatures below 1073 K, than that for hot working conditions, i.e., rolling at temperatures above 1073 K. A decrease in the temperature from 1373 K to 1073 K results in an increase in the yield strength ($\sigma_{0.2}$) by about 130 MPa while the ultimate tensile strength (UTS) does not change remarkably. In contrast, further decrease in the rolling temperature from 1073 K to 773 K leads to almost twofold increase in $\sigma_{0.2}$, which approaches about 900 MPa, and increases UTS by about 200 MPa. Correspondingly, the strengthening by warm to hot rolling is accompanied by a degradation of plasticity. It is interesting to note that total elongation gradually decreases with a decrease in the rolling temperature for Fe-18%Mn-0.6%C steel, where as that in Fe-18%Mn-0.4%C steel exhibits a kind of bimodal temperature dependence. The total elongation in the Fe-18%Mn-0.4%C steel tends to saturate at a level of 60–65% as the rolling temperature increases above 1073 K, following a rapid increase from 30% to 55% with an increase in the rolling temperature from 773 K to 1073 K.

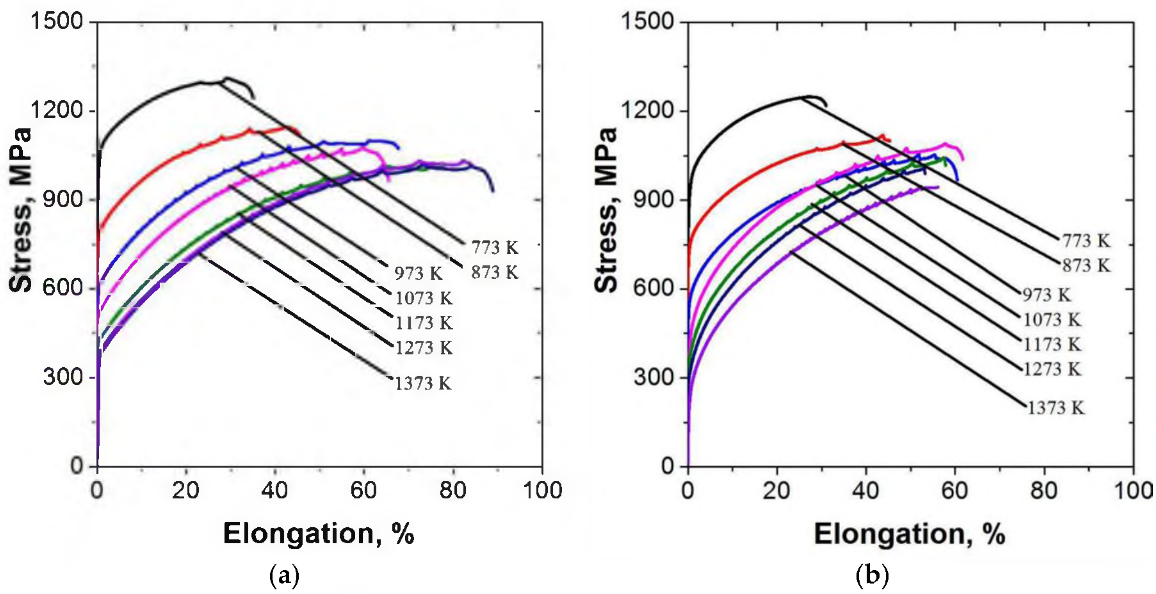



**Figure 2.** Engineering stress vs elongation curves of the Fe-18%Mn-0.6%C (**a**) and Fe-18%Mn-0.4%C (**b**) steels subjected to rolling at the indicated temperatures.

An apparent saturation for the total elongation of the Fe-18%Mn-0.4%C steel with an increase in the rolling temperature above 1073 K can be associated with a variation in the deformation mechanisms operating during tensile tests. The steel with lower carbon content has somewhat lower SFE [4] and, thus, may involve the strain-induced martensite upon tensile tests at room temperature. This difference in deformation mechanisms has been considered as a reason for the difference in plasticity [10]. The Fe-18%Mn-0.4%C steel subjected to hot rolling at temperatures above 1073 K exhibits the maximal plasticity, which can be obtained in the case of partial ε-martensitic transformation, whereas the Fe-18%Mn-0.6%C steel demonstrates increasing plasticity, which is improved by deformation twinning, with an increase in the rolling temperature. On the other hand, the strength properties, which depend on the grain size and dislocation density, are certainly affected by the rolling temperature, even in the range of hot working.

The Fe-18%Mn-0.6%C steel exhibits higher strength and elongation than the Fe-18%Mn-0.4%C steel after rolling warm to hot rolling in the studied temperature range. This additional strengthening of the Fe-18%Mn-0.6%C steel can be attributed to the difference in carbon content, which has been considered as the contributor to the yield strength of high-Mn TWIP steels [15]. The difference in 0.2 wt % carbon should result in about 85 MPa difference in the yield strength [15].

### *3.3. Tensile Behavior*

Generally, the strength and plasticity during tensile tests depends on strain hardening, which, in turn, depends on the operating deformation mechanisms [1]. The plastic deformation of austenitic steels with low SFE at an ambient temperature is commonly expressed by the Ludwigson relation [14]:

$$\sigma = K_1 \cdot \varepsilon^{n1} + \exp(K_2 - n_2 \cdot \varepsilon), \tag{1}$$

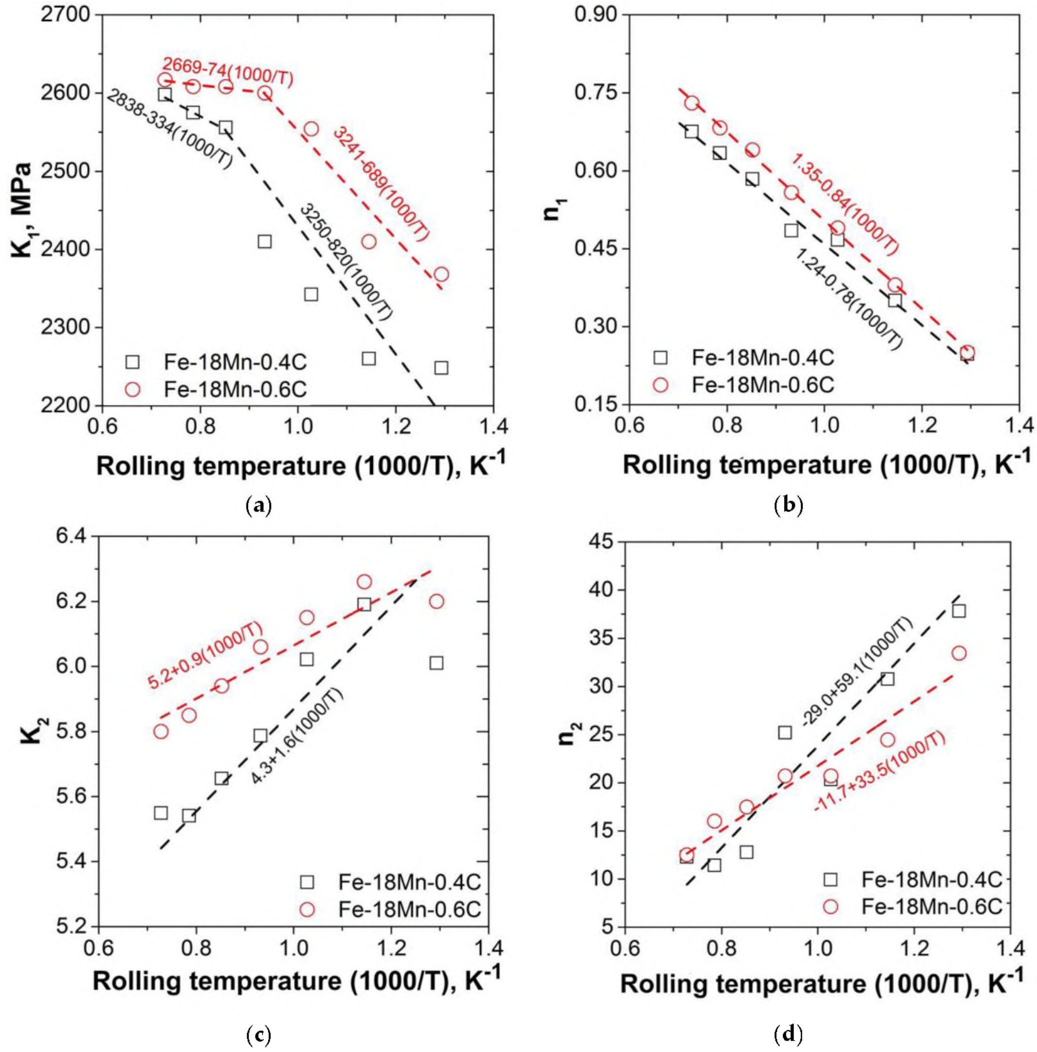
where the first term with the strength factor of $K_1$ and strain hardening exponent $n_1$ represents Hollomon equation and the second term has been introduced by Ludwigson to incorporate the transient deformation stage, which differentiates the deformation behavior of fcc-metals/alloys with low-to medium SFE from other materials at relatively small strains. The stress of $\sigma = \exp(K_2)$ is close to the stress of plastic deformation onset and an inverse value of $n_2$ corresponds to the transient stage duration.

The parameters of $K_1$, $K_2$, $n_1$, $n_2$ providing the best correspondence between Equation (1) and experimental stress-strain curves are listed in Table 1. Note here, similar values for parameters of Ludwigson relation have been reported in other studies on low SFE austenitic steels [14,16–18]. The larger values of $K_2$ and $K_1$ for the present 0.6%C steel as compared to those for the 0.4%C steel reflect the higher stress levels of the former at early deformations and at large tensile strains, respectively. On the other hand, the $n_1$ values for both steels are close, suggesting similar strain hardening at large tensile strains, irrespective of some differences in the carbon content and SFE. The $n_2$ values are also close for both steels, indicating the same effect of the rolling temperature on the transient deformation stage during subsequent tensile tests.

**Table 1.** Parameters of the Ludwigson equation for the Fe-18%Mn-0.4%C and Fe-18%Mn-0.6%C steels processed by warm-to-hot rolling.

| Steel | Rolling Temperature (K) | $K_1$ (MPa) | $n_1$ | $K_2$ | $n_2$ |
|---|---|---|---|---|---|
| Fe-18%Mn-0.4%C | 773 | 2248 | 0.24 | 6.0 | 37.8 |
| Fe-18%Mn-0.4%C | 873 | 2260 | 0.35 | 6.2 | 30.8 |
| Fe-18%Mn-0.4%C | 973 | 2342 | 0.46 | 6.0 | 20.3 |
| Fe-18%Mn-0.4%C | 1073 | 2410 | 0.48 | 5.8 | 25.2 |
| Fe-18%Mn-0.4%C | 1173 | 2556 | 0.58 | 5.7 | 12.8 |
| Fe-18%Mn-0.4%C | 1273 | 2575 | 0.63 | 5.5 | 11.4 |
| Fe-18%Mn-0.4%C | 1373 | 2598 | 0.67 | 5.5 | 12.3 |
| Fe-18%Mn-0.6%C | 773 | 2368 | 0.25 | 6.2 | 33.5 |
| Fe-18%Mn-0.6%C | 873 | 2410 | 0.38 | 6.3 | 24.5 |
| Fe-18%Mn-0.6%C | 973 | 2554 | 0.49 | 6.2 | 20.7 |
| Fe-18%Mn-0.6%C | 1073 | 2600 | 0.55 | 6.1 | 20.7 |
| Fe-18%Mn-0.6%C | 1173 | 2608 | 0.64 | 5.9 | 17.5 |
| Fe-18%Mn-0.6%C | 1273 | 2608 | 0.68 | 5.9 | 16.0 |
| Fe-18%Mn-0.6%C | 1373 | 2617 | 0.73 | 5.8 | 12.5 |

The monotonous changes of obtained parameters with rolling temperature suggest unique relationships between all parameters and deformation conditions. The effects of processing temperature on the parameters of Equation (1) are represented in Figure 3. Except for $K_1$, all parameters can be expressed by unique linear functions of the inverse rolling temperatures (Figure 3). The bimodal temperature dependencies obtained for $K_1$ with inflection points at 1073 K in Figure 3 are associated with the transition from warm to hot rolling conditions at this temperature, which reflects clearly on the deformation microstructures (see Figure 1). Using the indicated (Figure 3) linear relationships between the parameters of Ludwigson relation and the inverse rolling temperatures, the true stress vs strain curves calculated by Equation (1) are shown in Figure 4, along with the experimental curves obtained by tensile tests. Figure 4a,c show a general view of the stress-strain curves to validate the first term of Equation (1), whereas Figure 4b,d are plotted in double logarithmic scale to display the deformation behaviors at relatively small strains, which are described by the second term of Equation (1). The clear correspondence between the calculated and experimental plots testifies to the proposed treatments above.




(a) (b) (c) (d)

**Figure 3.** Effect of the rolling temperatures on the parameters of Ludwigson equation, $K_1$ (**a**), $n_1$ (**b**), $K_2$ (**c**), and $n_2$ (**d**).

The tensile deformation behavior of the steel samples should indeed be closely related to the steel microstructures, which were evolved by previous thermo-mechanical treatment. In turn, the developed microstructures depend on the processing conditions, i.e., rolling temperature, as the main processing variable in the present study. Generally, the deformation microstructures including the mean grain size and dislocation density that develop in metallic materials during warm-to-hot working can be expressed by power law functions of Zener-Hollomon parameter (temperature-compensated strain rate); $Z = \varepsilon \cdot \exp(Q/RT)$, where $Q$ and $R$ are the activation energy and universal gas constant, respectively [7,12]. Such microstructural changes are associated with thermally activated mechanisms of microstructure evolution in metallic materials. Therefore, the unique linear relationships in Figure 3 between the parameters of the flow stress predicting equation and the inverse rolling temperature suggest exponential relationships between the flow stress and the microstructures developed by warm-to-hot rolling. The second (exponential) term in Equation (1) predicts the flow stresses at relatively small strains (transient deformation), when the deformation behavior is associated with the dislocation ability to planar glide [14]. Thus, the stress-strain relationship of the high-Mn TWIP steels depends on their microstructures, namely, dislocation densities, evolved by previous thermo-mechanical treatments. Similar conclusions about a dominant role of dislocation density in the yield strength [10] and the work-hardening rate [19] were drawn in other studies on TWIP steels.

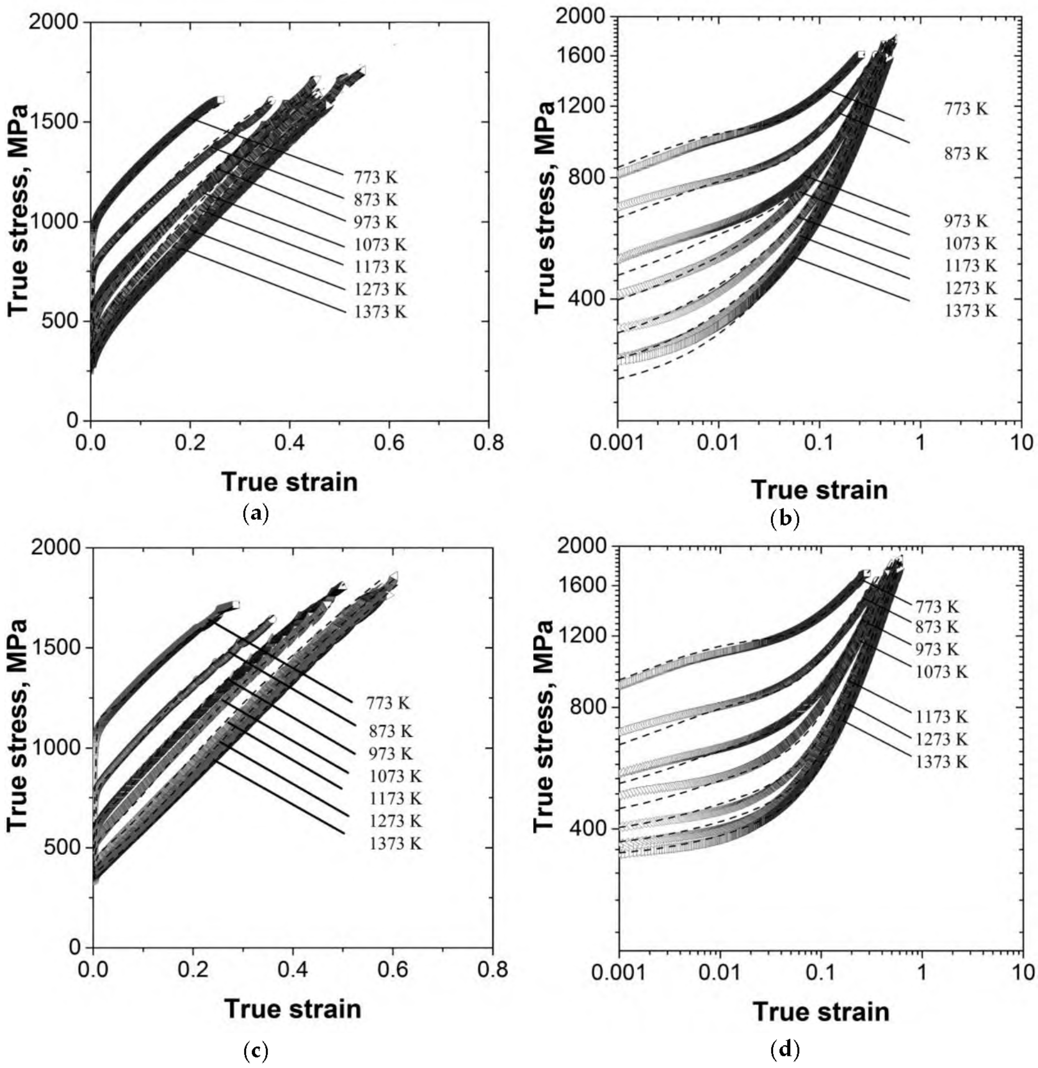



**Figure 4.** True tensile stress vs strain plots for Fe-18%Mn-0.4%C steel (**a**,**b**) and Fe-18%Mn-0.6%C steel (**c**,**d**) subjected to warm-to-hot rolling at indicated temperatures. The stress-strain curves obtained by tensile tests are shown by thick gray-scaled lines and those calculated by Equation (1) are shown by dashed lines.

It is worth noting in Figure 4 that maximal true stresses during tensile tests comprise about 1750 MPa for all steel samples, irrespective of the previous rolling conditions. Such gradual change in the altitude and slope of the true stress-strain curves can be represented by a gradual decrease in $K_1$ concurrently with $n_1$. An apparent saturation for the true stresses can be attributed to the strain-hardening ability owing to dislocation accumulation.

The strain, at which the transient deformation stage decays ($\varepsilon_L$) can be evaluated from the following relation [14]:

$$\exp(K_2 - n_2 \cdot \varepsilon_L)/(K_1 \varepsilon_L{}^{n1}) = r, \tag{2}$$

setting an arbitrary small value for $r$. According to the original Ludwigson treatment [14], $r = 0.02$ is selected in the present study. The values of $\varepsilon_L$ calculated by Equation (2) for the present steels subjected to warm-to-hot rolling are shown in Figure 5 as functions of the rolling temperature. Formally, this strain ($\varepsilon_L$) limiting the transient deformation duration can be considered as a critical point below which, the plastic flow cannot be adequately described by Hollomon-type relation, i.e., the first term in Equation (1). The flow stresses during the transient deformation can be calculated taking into account the second term in Equation (1). The strain of $\varepsilon_L$ can be roughly related to a strain when cross slip and dislocation rearrangements, which are closely connected with dynamic recovery, impair the strain hardening [14]. Therefore, an increase in $\varepsilon_L$ should promote plasticity, including both uniform and total elongations.

It is clearly seen in Figure 5 that $\varepsilon_L$ increases from about 0.08 to 0.24 with an increase in the rolling temperature from 773 K to 1373 K; this suggests an improvement in plasticity with increase in rolling temperature. A decrease in SFE promotes planar slip and, thus, should increase $\varepsilon_L$. Indeed, the 0.4%C steel is characterized by a larger $\varepsilon_L$ than the 0.6%C steel after hot rolling at temperatures above 1300 K (Figure 5), although the hot rolled steel with higher carbon content exhibits larger total elongation. This relatively low plasticity of the Fe-18%Mn-0.4%C steel is associated with an ε-martensitic transformation [10]. Commonly, transformation-induced plasticity (TRIP) steels demonstrate lower plasticity than TWIP steels [20,21]. After rolling at temperatures below 1300 K, the values of $\varepsilon_L$ for the Fe-18%Mn-0.4%C steel are smaller than those for the Fe-18%Mn-0.6%C steel processed under the same conditions (Figure 5). This can be attributed to the effect of warm-to-hot rolling at the evolved dislocation density. The latter has been shown to increase as rolling temperature decreases [10]. Therefore, the transient deformation stage upon the tensile tests is shortened because of the previous plastic deformation during warm-to-hot rolling, which partially consumed the dislocation ability to planar glide.

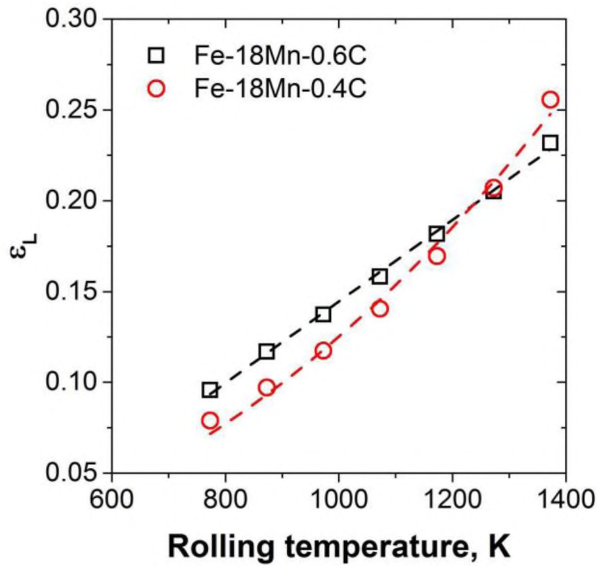



**Figure 5.** Effect of the rolling temperature on the strain for transient deformation during tensile tests of the Fe-18%Mn-0.4%C and Fe-18%-0.6%C steels.

## 4. Conclusions

The deformation behavior during tensile tests of Fe-18%Mn-0.4%C and Fe-18%-0.6%C steels subjected to warm to hot rolling was studied. The main results can be summarized as follows.

1. The hot rolling at temperatures above 1073 K was accompanied by the development of discontinuous dynamic recrystallization, leading to a decrease in the transverse grain size with a decrease in the rolling temperature. On the other hand, microstructure evolution during warm rolling at temperatures below 1073 K was controlled by the rate of dynamic recovery, which slowed down with a decrease in the rolling temperature.
2. The true stress-strain curves obtained by tensile tests at ambient temperature can be correctly represented by the Ludwigson-type relationship—$\sigma = K_1 \cdot \varepsilon^{n1} + \exp(K_2 - n_2 \cdot \varepsilon)$—where parameters of $K_i$ and $n_i$ depended on material and processing conditions and can be expressed by unique functions of inverse temperature of previous warm-to-hot rolling. A decrease in the rolling temperature from 1373 K to 773 K resulted in a decrease in $K_1$ (from approx. 2600 MPa to 2300 MPa) concurrently with $n_1$ (from approx. 0.7 to 0.25). Correspondingly, the true stress approached a level of about 1750 MPa during tensile tests, irrespective of the previous warm-to-hot rolling conditions. On the other hand, an increase in both $K_2$ and $n_2$ with decrease in the rolling temperature corresponded to an almost threefold increase in the yield strength and analogous degradation of plasticity.
3. The stage of transient plastic flow providing initial strain hardening and, therefore, controlling the total plasticity increases from about 0.08 to 0.24 with an increase in the rolling temperature from 773 K to 1373 K. The Fe-18%Mn-0.4%C steel is characterized by smaller values of $\varepsilon_L$ than the Fe-18%Mn-0.6%C steel subjected to warm-to-hot rolling at the same temperatures below 1300 K, although the former should possess lower stacking fault energy. The shortening of the transient deformation stage upon tensile tests of the steels subjected to warm-to-hot rolling can be attributed to previous deformation, which partially consumed the dislocation ability to planar glide.

**Author Contributions:** Conceptualization, A.M.G. and R.K.; Methodology, V.T. and A.B.; Investigation, V.T.; Writing-Original Draft Preparation, A.B.; Writing-Review & Editing, A.M.G. and R.K.; Visualization, V.T.; Supervision, R.K.

**Funding:** This work was performed partly under the State Order of the Ministry of Education and Science of the Russian Federation No. 20'7/113 (2097).

**Acknowledgments:** The authors are grateful to the personnel of the Joint Research Centre of "Technology and Materials", Belgorod State University, for their assistance with instrumental analysis.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Bouaziz, O.; Allain, S.; Scott, C.P.; Cugy, P.; Barbier, D. High manganese austenitic twinning induced plasticity steels: A review of the microstructure properties relationships. *Curr. Opin. Solid State Mater. Sci.* **2011**, *15*, 141–168. [CrossRef]
2. De Cooman, B.C.; Estrin, Y.; Kim, S.K. Twinning-induced plasticity (TWIP) steels. *Acta Mater.* **2018**, *142*, 283–362. [CrossRef]
3. Kusakin, P.S.; Kaibyshev, R.O. High-Mn twinning-induced plasticity steels: Microstructure and mechanical properties. *Rev. Adv. Mater. Sci.* **2016**, *44*, 326–360.
4. Saeed-Akbari, A.; Mosecker, L.; Schwedt, A.; Bleck, W. Characterization and prediction of flow behavior in high-manganese twinning induced plasticity steels: Part I. mechanism maps and work-hardening behavior. *Metall. Mater. Trans. A* **2012**, *43*, 1688–1704. [CrossRef]
5. Kusakin, P.; Belyakov, A.; Haase, C.; Kaibyshev, R.; Molodov, D.A. Microstructure evolution and strengthening mechanisms of Fe–23Mn–0.3C–1.5Al TWIP steel during cold rolling. *Mater. Sci. Eng. A* **2014**, *617*, 52–60. [CrossRef]

6. Yanushkevich, Z.; Belyakov, A.; Haase, C.; Molodov, D.A.; Kaibyshev, R. Structural/textural changes and strengthening of an advanced high-Mn steel subjected to cold rolling. *Mater. Sci. Eng. A* **2016**, *651*, 763–773. [CrossRef]
7. Sakai, T.; Belyakov, A.; Kaibyshev, R.; Miura, H.; Jonas, J.J. Dynamic and post-dynamic recrystallization under hot, cold and severe plastic deformation conditions. *Prog. Mater. Sci.* **2014**, *60*, 130–207. [CrossRef]
8. Tikhonova, M.; Belyakov, A.; Kaibyshev, R. Strain-induced grain evolution in an austenitic stainless steel under warm multiple forging. *Mater. Sci. Eng. A* **2013**, *564*, 413–422. [CrossRef]
9. Tikhonova, M.; Enikeev, N.; Valiev, R.Z.; Belyakov, A.; Kaibyshev, R. Submicrocrystalline austenitic stainless steel processed by cold or warm high pressure torsion. *Mater. Sci. Forum* **2016**, *838*, 398–403. [CrossRef]
10. Torganchuk, V.; Belyakov, A.; Kaibyshev, R. Effect of rolling temperature on microstructure and mechanical properties of 18%Mn TWIP/TRIP steels. *Mater. Sci. Eng. A* **2017**, *708*, 110–117. [CrossRef]
11. Morozova, A.; Kaibyshev, R. Grain refinement and strengthening of a Cu–0.1Cr–0.06Zr alloy subjected to equal channel angular pressing. *Philos. Mag.* **2017**, *97*, 2053–2076. [CrossRef]
12. Yanushkevich, Z.; Dobatkin, S.V.; Belyakov, A.; Kaibyshev, R. Hall-Petch relationship for austenitic stainless steels processed by large strain warm rolling. *Acta Mater.* **2017**, *136*, 39–48. [CrossRef]
13. Choudhary, B.K.; Isaac Samuel, E.; Bhanu Sankara Rao, K.; Mannan, S.L. Tensile stress-strain and work hardening behaviour of 316LN austenitic stainless steel. *Mater. Sci. Technol.* **2001**, *17*, 223–231. [CrossRef]
14. Ludwigson, D.C. Modified stress-strain relation for fcc metals and alloys. *Metal. Trans.* **1972**, *2*, 2825–2828. [CrossRef]
15. Kusakin, P.; Belyakov, A.; Molodov, D.A.; Kaibyshev, R. On the effect of chemical composition on yield strength of TWIP steels. *Mater. Sci. Eng. A* **2017**, *687*, 82–84. [CrossRef]
16. Mannan, S.L.; Samuel, K.G.; Rodriguez, P. Stress-strain relation for 316 stainless steel at 300 K. *Scr. Metall.* **1982**, *16*, 255–257. [CrossRef]
17. Satyanarayana, D.V.V.; Malakondaiah, G.; Sarma, D.S. Analysis of flow behaviour of an aluminium containing austenitic steel. *Mater. Sci. Eng. A* **2007**, *452*, 244–253. [CrossRef]
18. Milititsky, M.; De Wispelaere, N.; Petrov, R.; Ramos, J.E.; Reguly, A.; Hanninen, H. Characterization of the mechanical properties of low-nickel austenitic stainless steels. *Mater. Sci. Eng. A* **2008**, *498*, 289–295. [CrossRef]
19. Liang, Z.Y.; Li, Y.Z.; Huang, M.X. The respective hardening contributions of dislocations and twins to the flow stress of a twinning-induced plasticity steel. *Scr. Mater.* **2016**, *112*, 28–31. [CrossRef]
20. Song, W.; Ingendahl, T.; Bleck, W. Control of strain hardening behavior in high-Mn austenitic steels. *Acta Metall. Sin. (Engl. Lett.)* **2014**, *27*, 546–555. [CrossRef]
21. Lee, Y.-K.; Han, J. Current opinion in medium manganese steel. *Mater. Sci. Technol.* **2015**, *31*, 843–856. [CrossRef]