Effect of the processing parameters of the hot rolling of a stainless austenitic steel on the processes of structural and phase transformation

G I Raab¹, V I Semenov¹, P La² and S V Dobatkin³,⁴

¹ Institute of Physics of Advanced Materials, Ufa State Aviation Technical University, 12 K. Marx st., Ufa 450008 Russia
² State Key Laboratory of Advanced Processing and Recycling of Nonferrous Metals, Lanzhou University of Technology, Lanzhou, China
³ Baikov Institute of Metallurgy and Materials Science RAS, 49 Leninskiy pr., Moscow 119334 Russia Institute of Physics of Advanced Materials, Ufa State Aviation Technical University, 12 K. Marx st., Ufa 450008 Russia
⁴ National University of Science and Technology “MISIS”, 4 Leninskiy pr., Moscow 119049 Russia

E-mail: giraab@mail.ru

Abstract. We studied the mechanism of structure formation of the stainless austenitic steel with the composition 0.09%C, 17.5%Cr, 11.6%Ni, 0.5%Ti (a close analogue of the AISI 304 steel) during hot deformation by rolling at a temperature of 900 °C, strain rates of 0.5–5 s⁻¹ and strains of about 10–60%. It was demonstrated that with increasing strain the fraction of polygonized volumes grows, and inside them the fraction of equiaxed subgrains grows.

1. Introduction
In the papers [1-3] studying the structure formation processes during the hot deformation by compression of stainless austenitic steels, the authors determined a pattern of softening mechanisms depending on the temperature, strain and strain rate, and built maps of the structural states determining the regions of acting dynamic processes of polygonization and recrystallization under steady-state deformation in the coordinates «deformation temperature – strain rate».

In terms of the deformation pattern, hot compression is close to rolling, which is widely used in the industrial cycles of high-temperature thermomechanical treatment of austenitic stainless steels. Therefore, the established regularity in the change of the softening mechanisms during hot deformation by compression can also be characteristic of the processes of hot rolling. For example, to control the strengthening-softening processes the authors of the paper [4] proposed a method for the deformation-thermal treatment of austenitic stainless steels which includes plastic deformation by hot rolling to a strain of 1-2 with subsequent annealing and additional cold rolling to a true strain of 3.5-4. A decrease in the temperature of rolling [5] is accompanied by a considerable strengthening due to an increase in dislocation density and development of deformation-induced twinning. This leads to the emergence of shear bands with increasing strain. Subsequent annealing leads to the occurrence of the recovery and recrystallization processes, their kinetics depending on the preceding strain value and...
annealing temperature. Such approaches enable producing a set of balanced strength and ductility characteristics. Another area of research for the control of the strengthening-softening processes is to produce specified ultrafine-grained (UFG) states in austenitic stainless steels by means of severe plastic deformation processing [6-7].

It follows from the above that the study of the strengthening-softening mechanisms influencing actively the formation of a set of properties in austenitic steels is a relevant task in the physics of strength, and it is of great practical interest.

The aim of the present work is to study the features of structural transformations in the austenitic stainless steel with the composition 0.09% C, 17.5% Cr, 11.6% Ni, 0.5% Ti (a close analogue of the AISI 304 steel and the Russian steel 0.8Kh18N12T) during hot deformation by rolling depending on the temperature 900 °C, strain rate 0.5-5 s⁻¹ and strain in a range of 10-60%.

2. Material and experimental procedure
As the material for the study, we used the steel (0.09% C, 17.5% Cr, 11.6% Ni, 0.5% Ti) after cooling in water from a temperature of 1050 °C (exposure for 1 hour). Rolling was performed on a Hankook six-high strip-rolling mill for the hot rolling of sheets with strain rates of 0.5 and 5 s⁻¹, strains of 10, 20 and 60% (corresponding to true strains of 0.11, 0.22 and 0.92, respectively) for one pass at a temperature of 900 °C. The grain size and the fraction of recrystallized grains were determined using light microscopy, and the subgrain size, the fraction of equiaxed subgrains and the distance between elongated sub-boundaries were found using electron microscopy. The pole density of the X-ray lines {111}, {200}, {220}, {311}, {222} of the steel with the composition 0.09% C, 17.5% Cr, 11.6% Ni, 0.5% Ti in the process of hot deformation by rolling at \( \dot{\varepsilon} = 5 \) s⁻¹ was determined using a DRON-4 diffractometer.

3. Research results and their discussion
Indeed, in the process of rolling of the austenitic steel 0.09% C, 17.5% Cr, 11.6% Ni, 0.5% Ti at \( T_{\text{def}} = 900 \) °C and strain rates 0.5 and 5 s⁻¹ (up to a strain of \( \varepsilon = 0.92 \)) dynamic recrystallization does not take place, as it was also observed for compression [9, 10]. With increasing strain and strain rate grains become more elongated (table 1).

Study by TEM electron microscopy shows that at \( T_{\text{def}} = 900 \) °C small areas are observed with a substructure typical of hot-work hardening (figure 1a), characterized by a high density of free dislocations, the presence of dislocation pile-ups and a cell substructure. In the whole volume a polygonized structure prevails, with both elongated (figure 1b) and equiaxed (figure 1c) subgrains having imperfect sub-boundaries and an increased density of free dislocations.

![Figure 1](image)

**Figure 1.** Structure (TEM) of the steel 0.09% C, 17.5% Cr, 11.6% Ni, 0.5% Ti after hot deformation by rolling at a temperature of 900 °C and a strain rate of 0.5 s⁻¹: a) \( \varepsilon = 0.11 \); b, c) \( \varepsilon = 0.92 \).

With increasing strain, the fraction of polygonized volumes grows, and inside them the fraction of equiaxed subgrains grows (table 1). At \( T_{\text{def}} = 900 \) °C and \( \dot{\varepsilon} = 0.5 \) s⁻¹ the fraction of polygonized areas increases from 29% (at \( \varepsilon = 0.11 \)) to 42% (at \( \varepsilon = 0.22 \)) mainly due to the formation of elongated
subgrains. When a strain of 0.92 is reached, the polygonized areas occupy about 90% of the whole volume, 60% of them being equiaxed subgrains (table 1).

| Material | $T_{\text{def}}$, °C | $\dot{\varepsilon}$, s$^{-1}$ | $\varepsilon$, % | $\bar{d}$, μm | $K_r$, % | $V_r$, % | $V^*$, % | $V^{**}$, % | Distance between sub-boundaries in elongated subgrains, μm | Size of equiaxed subgrains, μm |
|----------|------------------|-----------------|--------|--------|--------|--------|--------|--------|-------------------|--------------------|
| Steel    | 0.09%C, 17.5%Cr, 11.6%Ni, 0.5%Ti | 1060 Quenching | 32.1±4.5 | 29 | 22 | 42 | <5 | 60 | - | - |
|          | 900              | 0.5             | 27.1±4.0 | 0 | 0 | 29 | <5 | 0.35±0.02 | 0.41±0.02 |
|          | 20               | 26.5±3.8 | 22 | 42 | <5 | 0.35±0.02 | 0.41±0.02 |
|          | 60               | 19.1±3.9 | 28 | 90 | 60 | 0.48±0.06 | 0.30±0.04 |
|          | 5                | 34.4±4.8 | 28 | 69 | - | 0.37±0.07 | 0.56±0.05 |
|          | 20               | 34.4±4.8 | 28 | 69 | - | 0.37±0.07 | 0.56±0.05 |
|          | 60               | 19.5±5.2 | 36 | 90 | 59 | 0.34±0.05 | 0.60±0.05 |

where $T_{\text{def}}$ is the deformation temperature, $\dot{\varepsilon}$ is the strain rate, $\varepsilon$ is the degree of deformation, $\bar{d}$ is the grain size, $V_r$ is the fraction of recrystallized grains, $V^*$ is the fraction of polygonized volumes, $V^{**}$ is the fraction of oriented subgrains.

An increase in strain rate at $T_{\text{def}} = 900$ °C from 0.5 s$^{-1}$ to 5 s$^{-1}$ results in an increase in the fraction of polygonized volumes. The size of equiaxed subgrains and the distance between the sub-boundaries of the elongated subgrains is 0.3-0.6 μm and 0.3-0.5 μm, respectively (table 1). The fraction of equiaxed subgrains after a strain of $\varepsilon = 0.92$ at both strain rates is 55-60%. In addition, the electron microscopy studies revealed individual recrystallized grains with a size of 2-5 μm, having a low density of free dislocations, which apparently indicates the static nature of their formation.

The changes in the texture during hot deformation by rolling and during compression have a certain similarity (figure 2) [10]. In the conditions providing the formation of a dynamically polygonized structure (at $T_{\text{def}} = 900$ °C), with increasing strain the deformation texture becomes enhanced – the component $\{220\}_\gamma$ grows (figure 2a) [10]. Unlike high-temperature compression, the formation of a dynamically polygonized structure during hot rolling is accompanied by a smaller change in the respective texture components (figure 2) [10]. This is apparently related to the partial static recrystallization during slower cooling after rolling, as indicated by the increased pole density of the component $\{311\}_\gamma$ (figure 2) [10].

**Figure 2.** Variation in the pole density of the X-ray lines for the steel 0.09%C, 17.5%Cr, 11.6%Ni, 0.5%Ti in the process of hot deformation by rolling ($\dot{\varepsilon} = 5$ s$^{-1}$): $T = 900$ °C.
4. Conclusions
1. In the process of rolling at $T_{\text{def}} = 900 \, ^{\circ}\text{C}$ with increasing strain and strain rate grains become more elongated.
2. With increasing strain the fraction of polygonized volumes grows, and inside them the fraction of equiaxed subgrains grows, e.g. at $\varepsilon = 0.5 \, \text{s}^{-1}$ the fraction of polygonized areas increases from 29% (at $\varepsilon = 0.11$) to 42% (at $\varepsilon = 0.22$), mainly due to the formation of elongated subgrains. When a strain of 0.92 is reached, polygonized areas occupy about 90% of the whole volume, 60% of them being equiaxed subgrains. Thus, in the process of rolling of the steel 0.09%C, 17.5%Cr, 11.6%Ni, 0.5%Ti at $T_{\text{def}} = 900 \, ^{\circ}\text{C}$ with $\dot{\varepsilon} = 0.5$ and 5 $\text{s}^{-1}$ softening takes place practically only via the mechanism of dynamic polygonization.
3. It has been found that in the conditions providing the formation of a dynamically polygonized structure (at $T_{\text{def}} = 900 \, ^{\circ}\text{C}$), with increasing strain the deformation texture becomes enhanced – the component $\{220\}_\gamma$ grows.

Acknowledgements
The work was performed in the framework of a joint Russian-Chinese research project funded by the Russian Foundation for Basic Research (project No. 19-53-53022) and the National Natural Science Foundation of China (51911530119).

References
[1] Kaputkina L M, Dobatkin S V and Zhdanovich T K 1985 Bull. Acad. Sci. USSR: Metals 3 122 [in Russian]
[2] Dobatkin S V and Kaputkina L M 2001 Phys. Met. Metallog. 91 79
[3] Gorelik S S, Dobatkin S V and Kaputkina L M 2005 Recrystallization of Metals and Alloys (Moscow: MISIS) [in Russian]
[4] Beljakov A N, Shakhova J E and Kajbyshev R O 2013 Russian Federation patent No. 2482197
[5] Shakhova I, Dudko V, Belyakov A, Tsuzaki K and Kajbyshev R 2012 Mater. Sci. Eng. A 545 176
[6] Dobatkin S V, Rybal’chenko O V and Raab G I 2007 Mater. Sci. Eng. A 463 41
[7] Dobatkin S V, Kaputkina L M, Rybal’chenko O V and Komlev V S 2012 Metally 5 28 [in Russian]
[8] Bernshtein M L, Kaputkina L M, Prokoshkin S D and Dobatkin S V 1982 Bull. Acad. Sci. USSR: Metals 2 94 [in Russian]
[9] Bernshtein M L, Kaputkina L M, Prokoshkin S D and Dobatkin S V 1985 Acta Metall. 33 247
[10] Bernshtein M L, Kaputkina L M, Prokoshkin S D and Dobatkin S V 1989 Diagrams of Hot Deformation, Structure and Properties of Steels (Moscow: Metallurgiya) [in Russian]