Effect of Rolling Temperature and Thickness Reduction on the Strength of a 316L Steel

Marina Odnobokova[1,a)], Andrey Belyakov[2,b)], and Nariman Enikeev[1,c)]

[1] Institute for Physics of Advanced Materials, Ufa State Aviation Technical University, Ufa, 450008 Russia
[2] Belgorod State University, Belgorod, 308015 Russia

[a)] Corresponding author: odnobokova_marina@mail.ru
[b)] belyakov@bsu.edu.ru
[c)] nariman.enikeev@gmail.com

Abstract. The relationship between the microstructural changes and the yield strength of a 316L austenitic stainless steel subjected to plate rolling at temperatures of 200 and 300°C with 40, 65, 85 and 95% rolling reductions was studied. The structural changes during rolling at studied temperatures were characterized by the development of deformation twinning and micro-shear banding that led to a reduction of the transverse grain size. The martensitic transformation hardly developed during rolling at 200°C, when the martensite fraction did not exceed 5% after 95% rolling reduction, and did not occur at all during rolling at 300°C. The grain refinement was accompanied by an increase in the yield strength from 670 to 1240 MPa depending on the rolling regimes. The shape of the stress-strain curves also strongly depended on the rolling temperature and reduction. The shape of the stress–strain curve was characterized by a long plateau-like region right after yielding in the samples subjected to rolling at 300°C with 40 and 65% rolling reductions. A decrease in the rolling temperature and/or increase in the rolling reduction shortened plateau region followed by its disappearance. The effect of rolling conditions on the evolved microstructures and the mechanical properties is discussed in some detail.

INTRODUCTION

An yield strength is one of the most important mechanical properties of advanced structural materials such as austenitic stainless steels. The strength of austenitic stainless steels depends significantly on their microstructures and, primarily, on the grain size. Improvement in yield strength is related to a reduction of grain size through the Hall–Petch relationship [1, 2]. The change in the yield strength is often evaluated by a modified Hall–Petch relationship, which additionally takes into account dislocation strengthening [3–6]. Also an increase in the yield strength of austenitic stainless steels is related to grain boundary segregations [7] or particle hardening [8]. The yield strength of austenitic steels after rolling at 200°C was expressed through true strain [9]. However, an effect of deformation temperature was not considered. The aim of the present paper is establishing a relationship between the yield strength, true strain and deformation temperature in a 316L steel subjected to rolling at 200 and 300°C to various rolling reductions.

EXPERIMENTAL

A 316L austenitic stainless steel with the chemical composition shown in Table 1 was investigated. The ingot of 316L steel was forged at 1100°C to blanks with square cross section. The obtained blanks were plate rolled at 200 and 300°C to rolling reductions of 40, 65, 85 and 95% that corresponds to total true strains of 0.5, 1, 2 and 3, respectively. The microstructural studies after rolling were carried out on a scanning electron microscope, Nova Nanosem 450, using electron backscatter diffraction (EBSD) method. An average grain size was determined with the EBSD data as an equivalent diameter using software of TSL OIM Analysis 6.2 and taking into account only high-angle boundaries (HABs). The flat specimens with a gauge length of 12 mm, thickness of 1.5 mm and width of 3 mm were tensile tested on testing machine, Instron 5882, at ambient temperature.

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TABLE 1. The chemical composition of studied 316L steel

Element	Cr	Ni	Mn	Mo	Si	P	S	C	Fe
wt %	17.3	10.7	1.7	2	0.4	0.04	0.05	0.04	Bal.

RESULTS AND DISCUSSION

Typical deformation microstructures developed in the 316L steel during rolling at temperature of 200 and 300°C to various rolling reductions are shown in Fig. 1. The grid of strain-induced low-angle boundaries (LABs) readily develops during early deformation (40% reduction) at 200 and 300°C. In addition, the rolling at 200°C with 40% rolling reduction is accompanied by the deformation twinning (Fig. 1a). Deformation twins are not observed after rolling at 300°C with 40% rolling reduction, since larger reductions about 65% (Fig. 1e) are required for their development at this deformation temperature. The deformation twinning results in fast subdivision of original grains into fragments surrounded $\Sigma 3^n$ CSL boundaries with misorientations about 60°.

The development of new nanosized grains with HABs is promoted by microshear bands, which appear as narrow regions of localized shear after rolling at 200 and 300°C with 65 and 85% rolling reductions, respectively. Further rolling at 200 and 300°C with 95% rolling reduction leads to substantial grain refinement and the formation of a microstructure consisting of a mixture of elongated grains and nanosized grains/subgrains [3, 9]. It should be noted that the martensitic transformation takes place only during rolling at 200°C, and the fraction of martensite grains does not exceed 5 after 95% rolling reduction [9]. Thus, the deformation twinning and the micro-shear banding are the main mechanisms of grain refinement during rolling at 200 and 300°C. The development of these mechanisms depends on deformation temperature and thickness reduction.

The stress–strain curves for 316L steel subjected to rolling at 200 and 300°C to various rolling reductions are shown in Fig. 2a. The stress-strain curves are characterized by a long plateau-like region right after yielding in the samples subjected to rolling at 200 and 300°C with 40 and 40–65% rolling reductions, respectively. It should be noted that the average grain size in these samples was more than 1 μm (Table 2).

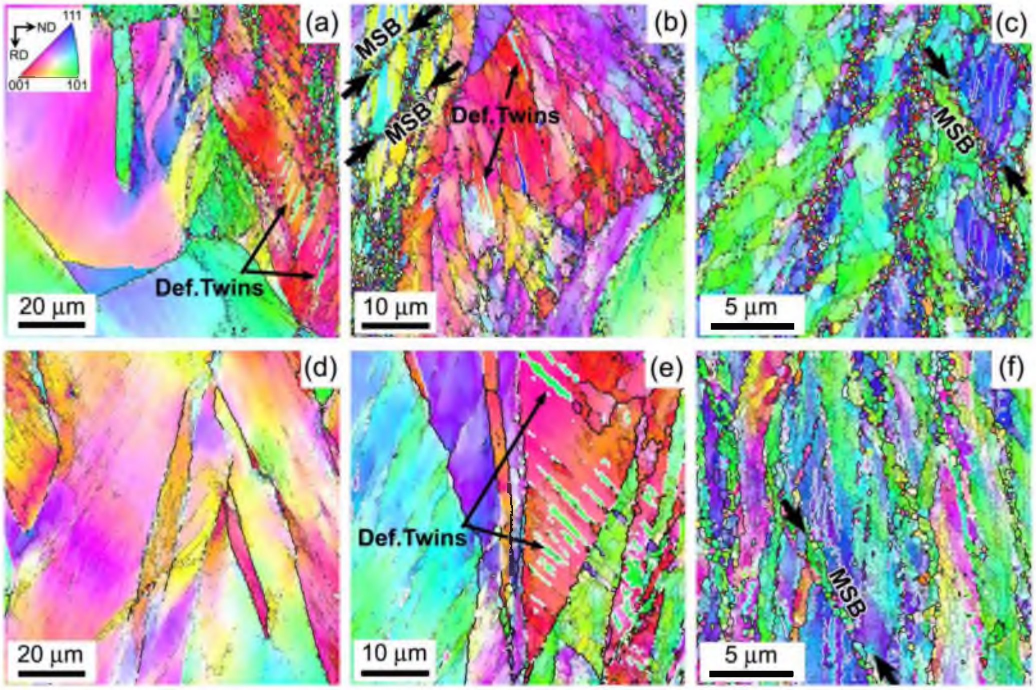

FIGURE 1. OIM images of deformation microstructures evolved in a 316L steel after rolling at 200 (a–c) and 300°C (d–f) to total reductions of 40 (a, d), 65 (b, e), and 85% (c, f). The colors of OIM images are shown for the normal direction (ND). HAB—thick black lines, LAB—thin black lines, twin boundaries—white lines, MSB—microshear band and Def.Twins—deformation twins.

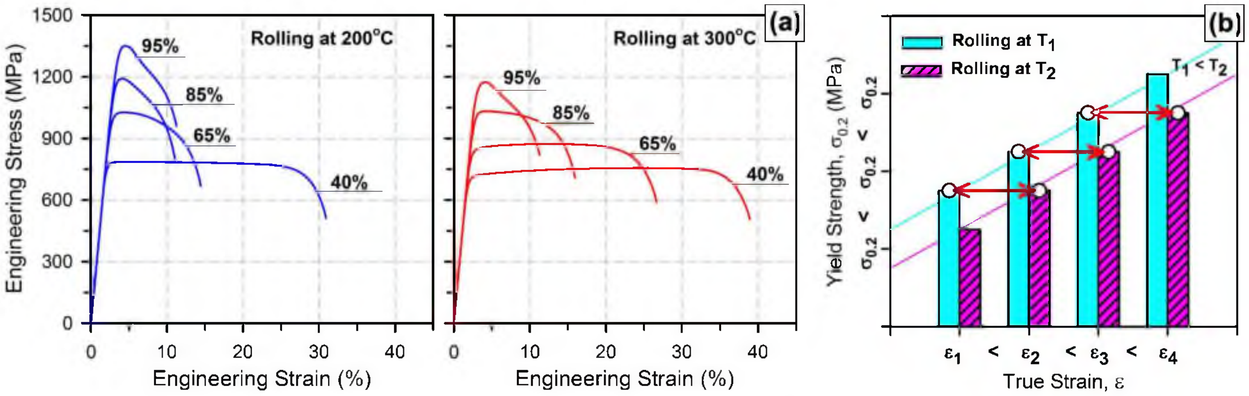

FIGURE 2. The stress–strain curves for 316L steel subjected to rolling at 200 and 300°C to various rolling reductions (a) and the effect of rolling temperature *T* and true strain ε on the yield strength (b).

A decrease in the rolling temperature and/or increase in the rolling reduction results in strengthening (Table 2) and shortening of plateau region followed by its disappearance (Fig. 2a). The rolling at 200 and 300°C with rolling reduction of 95% results in the yield strength about 1240 and 1080 MPa, respectively, with total elongation about 9%. The required rolling strain to achieve a certain increase in the yield strength ($\sigma_{0.2}$) increases with an increase in the rolling temperature (Fig. 2b). This strengthening can be represented by the following function:

$$\Delta\sigma_{0.2} = f\left(\varepsilon \exp\frac{Q}{RT}\right), \tag{1}$$

where ε is a true strain, *T* is rolling temperature, *Q* is the activation energy and *R* is the gas constant. Using the Ludwik relation [10], the yield strength can be expressed as follows:

$$\sigma_{0.2} = \sigma_0 + k\varepsilon^n, \tag{2}$$

where σ_0 is the strength of initial (undeformed) steel sample, *k* and n are constants. Combining Eqs. (1) and (2), the strengthening increment can be represented as follows:

$$\sigma_{0.2} - \sigma_0 = k\varepsilon^n = k^*\left(\varepsilon \exp\frac{Q}{RT}\right)^n. \tag{3}$$

The equation (3) after logarithmic transformation can be expressed in the form of the equation of a plane:

$$\ln(\sigma_{0.2} - \sigma_0) = \ln(k^*) + n\ln(\varepsilon) + \frac{nQ}{RT}. \tag{4}$$

TABLE 2. The grain size *D*, the yield strength $\sigma_{0.2}$, the ultimate tensile strength UTS and total elongation δ of 316L steel subjected to rolling at 200 and 300°C to various rolling reductions

Rolling reduction	Rolling strain	*D*, µm	$\sigma_{0.2}$, MPa	UTS, MPa	δ, %
		Rolling at 200°C			
40%	0.5	1.6 ± 0.4	750 ± 30	790 ± 20	30 ± 3
65%	1	0.55 ± 0.05	950 ± 20	1030 ± 20	13 ± 2
85%	2	0.25 ± 0.05	1110 ± 10	1190 ± 10	9 ± 2
95%	3	0.15 ± 0.03	1240 ± 10	1350 ± 10	9 ± 2
		Rolling at 300°C			
40%	0.5	10.4 ± 1.2	670 ± 20	760 ± 20	38 ± 2
65%	1	1.2 ± 0.2	790 ± 20	870 ± 20	25 ± 2
85%	2	0.35 ± 0.1	950 ± 10	1030 ± 10	14 ± 2
95%	3	0.18 ± 0.03	1080 ± 10	1180 ± 10	9 ± 2

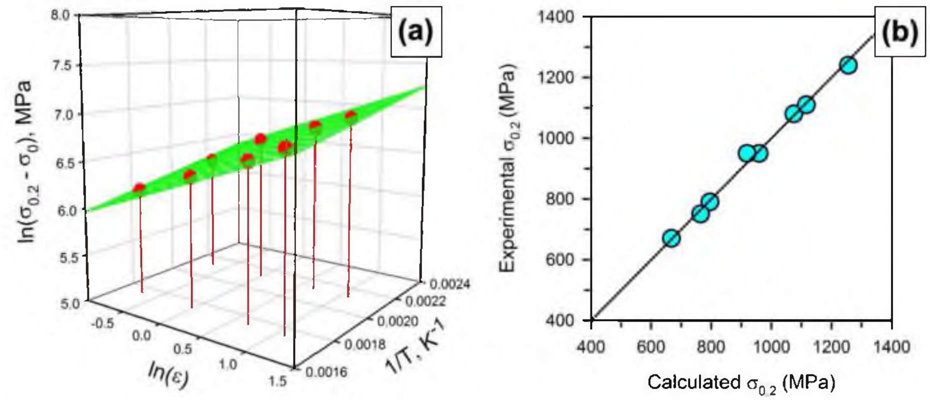

FIGURE 3. The relationship between the yield strength, rolling strain, rolling temperature (a) and the calculated versus experimental yield strength (b) in 316L steel subjected to rolling at 200 and 300°C to various rolling reductions.

The relationship between the yield strength, rolling true strain and rolling temperature can be approximated by a plane as shown in Fig. 3a, using Eq. (4) and taking $\sigma_0 = 200$ MPa [3, 9]. The best fit by a plane in Fig. 3a is obtained with $k^* = 240$ MPa, $n = 0.35$ and $Q = 12$ kJ mol^{-1}.The yield strengths calculated by Eq. (3) are coincident with the experimental yield strengths in 316L steel subjected to rolling at 200 and 300°C (Fig. 3b). Thus, the proposed approach can be used to predict the yield strength with a change in rolling temperature and/or true strain.

CONCLUSION

The microstructural changes and the tensile behavior of a 316L austenitic stainless steel subjected to plate rolling at temperatures of 200 and 300°C with various rolling reductions were studied. The rolling at 200 and 300°C with large thickness reductions resulted in the development of ultrafine-grained structure with a transverse grain size of about 150–200 nm. The deformation twinning and the micro-shear banding contributed to grain refinement during rolling. The rolling at 200 and 300°C with thickness reduction of 95% provided an increase in the yield strength to 1240 and 1080 MPa, respectively. The relationship between the temperature compensated rolling strain and the yield strength was elaborated.

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REFERENCES

1. E. O. Hall, Proc. Phys. Soc. **64**, 742–747 (1951).
2. N. J. Petch, J. Iron Steel Inst. **174**, 25–28 (1953).
3. M. Odnobokova, A. Belyakov, and R. Kaibyshev, Adv. Eng. Mater. **17**, 1812–1820 (2015).
4. L. Zhu, H. Ruan, A. Chen, X. Guo, and J. Lu, Acta Mater. **128**, 375–390 (2017).
5. J. A. Munoz, A. Komissarov, M. Avalos, and R. E. Bolmaro, Mater. Sci. Eng. A **792**, 139779 (2020).
6. R. Singh, S. Agrahari, S. D. Yadav, and A. Kumar, Mater. Sci. Eng. A **812**, 141105 (2021).
7. M. M. Abramova, N. A. Enikeev, R. Z. Valiev, A. Etienne, B. Radiguet, Y. Ivanisenko, and X. Sauvage, Mater. Lett. **136**, 349–352 (2014).
8. S. A. Akkuzin, I. Yu. Litovchenko, and A. N. Tyumentsev, AIP Conf. Proc. **2310**, 020009 (2020).
9. M. Odnobokova, A. Belyakov, N. Enikeev, R. Kaibyshev, and R. Z. Valiev, Metals **10**, 1614 (2020).
10. P. Ludwik, *Elemente der Technologischen Mechanik* (Springer-Verlag, Berlin, 1909), pp. 11–57.