Influence of rolling modes and the level of accumulated deformation on the mechanical and plastic properties of stainless austenitic steel AISI 304L

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Abstract. The paper presents the results of studies of rolling modes (direct, reverse, cross ones) at 500°C for samples of stainless steel AISI 304L and their influence on mechanical and plastic properties of the material. The stress-strain state was investigated using a numerical simulation program and the deformation parameters of processing were established. The mechanical properties were studied by microhardness measuring and tensile testing methods. The results of the experiment were analyzed and discussed, and conclusions were drawn. The regularities of the effect of strength parameters depending on the modes of processing and accumulated deformation during rolling have been established.

1. Introduction

Stainless steels are widely used in industry, and improvement of their properties is an important task for increasing the reliability of products obtained from them. Recently, to improve the properties of austenitic stainless steels, methods of severe plastic deformation (SPD) have been used, which ensure the accumulation of large degrees of deformation. In this case, it is possible to form a structure with a grain size of down to 1 μm or less with a large proportion or prevalence of boundaries with high-angle misorientation [1-3].

However, these methods have a number of limitations and are not technologically advanced for the production of sheet blanks. Therefore, in the study of sheet materials, including stainless steel, rolling in a wide temperature range and with the accumulation of high degrees of deformation is quite widely used to improve the mechanical properties. In addition, austenitic stainless steels demonstrate efficient grain refinement and hardening during cold and warm working [4-6]. It should be noted that grain refinement in austenitic steels is also associated with deformation twinning and martensitic transformation. A decrease in the rolling temperature promotes significant strengthening due to an increase in the dislocation density and the development of deformation twinning [5, 7].
In this regard, the purpose of this paper is to study the effect of rolling modes on the hardening intensity and plastic properties of austenitic stainless steel AISI 304. Direct, reverse and cross rolling at 500°C, strain rates of 5 s\(^{-1}\) with a relative accumulated deformation of 50 and 70% were used as the modes of rolling. It is assumed that a change in the rolling direction may affect the nature of hardening due to the non-monotonous effect.

2. Material and experimental procedure

AISI-304L steel was used as a material for the study after holding for 1 hour at a temperature of 1050°C and cooling in water. The chemical composition of the steel is shown in table 1. The samples had the shape of a disc with a diameter of 60 mm and a height of 15 mm.

Rolling was carried out on a six-roller strip mill HANKOK M-TECH INDUSTRIES CO LTD with a roll diameter of 70 mm, the total relative deformation was 50 and 70% (which is equal to the true strain \(e = 0.8\) and \(e = 1.1\), respectively). Deformation by rolling was carried out in 15 passes, the relative reduction per pass was 5%. During direct rolling, the samples were rolled in the same direction every pass, while during the inverse and cross ones the sample was rotated to 180° and 90° around the normal direction before each subsequent pass, respectively. The workpieces were preheated in a Nabertherm N321/13 muffle furnace to 500°C before each pass. Samples for measuring the microhardness were cut out transversely to the direction of the final rolling of the sample on an ARTA120 electro-erosion machine.

The Vickers hardness (HV) was measured on a Buehler micro-hardness tester with a load of 100 g and a holding time of 15 sec. The number of measurements for each sample was at least 15. Mechanical tensile testing was carried out at room temperature in accordance with GOST 1497-84, on an Instron 5982 universal testing machine at a crosshead speed of 1 mm / min.

Table 1. Chemical composition of AISI 304L (wt%)

| C  | Si  | Mn  | Ni  | Cr  | P   | S   |
|----|-----|-----|-----|-----|-----|-----|
| 0.024 | 0.516 | 1.063 | 7.64 | 17.04 | 0.022 | 0.032 |

The stress-strain state for each processing mode was investigated by the finite element method in the Deform 3D software package. The rheological characteristics of steel AISI 304L were taken from the database of the software product.

3. Results and discussion

3.1. Computer simulation

As a result of computer simulation in the software product DEFORM 3D, maps and graphs of the strain intensity distribution in the cross-section of the samples received in the studied rolling modes were obtained (figure 1).

The analysis of the obtained images and graphs shows that the deformation during rolling in the studied modes is not uniformly distributed across the section. The surface layers of the workpieces accumulate higher strain values compared to the central region. This indicates that with a relatively small reduction per pass (5%), at the early stages of processing, the surface areas of the samples are deformed first of all. Moreover, after the first cycle of processing, the maximum value of the surface layers is \(e = 1.1\), and the central area it is practically equal to zero. With a further increase in the number of passes up to three, an increase in the accumulated strain occurs in the central region, and with cross-rolling - more intensively.
3.2. Experimental study
Rolling of blanks in three modes showed that after deformation at 500°C, the samples did not exhibit mechanical destruction and the formation of surface defects or cracks with a relative accumulated deformation of up to 70%. The samples obtained during rolling are shown in figure 2.

Figure 2. Initial samples for experimental studies (a), samples obtained by direct, reverse and cross-rolling at a temperature of 500°C and a relative accumulated deformation of 70%.
After direct and reverse rolling, the samples are elongated in the rolling direction and acquire a wavy shape, i.e. lose flatness, and after cross-rolling the sample has a symmetrical shape and looks like a flat plate.

3.3. Study of mechanical properties

The results of studies on the mechanical properties of the specimens in tension after all processing modes are presented in figure 3, and the results of microhardness measurements are given in figure 4. The obtained data show that during rolling there is an increase in ultimate strength and yield stress, and a higher degree of deformation of 70% provides higher values of these characteristics. In this case, the maximum value of the tensile strength of 972 MPa and the yield stress of 938 MPa is observed when using reverse rolling, and the minimum values of the tensile strength of 937 MPa and the yield stress of 911 MPa are observed after cross-rolling. However, while the difference in mechanical characteristics between the modes of rolling is insignificant (only about 35MPa), the elongation of the samples after reverse rolling and cross-rolling differs almost twice.

![Figure 3](image)

**Figure 3.** Tensile data for AISI 304L steel specimens after various treatments.

Measurements of the microhardness HV after three rolling modes presented in figure 4 were performed along the central zone of the sample cross section.
Figure 4. Change in the microhardness of the cross section of the samples after direct (a) reverse (b) and cross rolling (c) when reaching the maximum deformation of 70%.

Analysis of the results on microhardness measurements show that in the case of direct and reverse rolling, a nonuniform distribution of microhardness over the section is observed. Thus, during direct rolling, the surface layers are hardened more intensively up to 320HV, and the difference with the middle layers is approximately 60HV. In reverse rolling, the microhardness distribution is more uniform, and the difference between the middle and surface layers is about 20HV. The maximum microhardness values are shown for the samples after cross rolling - 400 ± 40HV.

4. Conclusions
The influence of rolling modes (direct, reverse, cross) at 500°C and a degree of relative deformation of 50 and 70% on the strength and plasticity of properties has been studied. Thus, an increase of deformation from 50 to 70% allows to increase the mechanical properties by an average of 12% and 30% as compared to the original heat-treated sample. It was found that the use of cross-rolling leads to the formation of higher plastic properties in comparison with other rolling modes, for example, 2 times compared to reverse rolling, with similar strength characteristics. Cross-rolling also provides the most homogeneous and 1.25 times higher microhardness values in comparison with other modes. The study of the deformed state by numerical modeling shows that a high fractional deformation of 5% per pass leads to the formation of an inhomogeneous deformation field with higher deformation values in the surface layers. This is most pronounced in direct rolling.

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