Investigation of the structure and mechanical properties of stainless steel alloyed with silver

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Abstract.
The paper contains information of the development of technology for smelting stainless steel for application in the manufacture of medical devices. Smelting was carried out in electric arc vacuum furnaces. The technology has been developed for producing sheets with a thickness of 1 ÷ 1.25 mm for further research of mechanical properties. To study the structure, thin sections of the alloys were obtained by melting and further rolling. The mechanical properties of the samples and their structure have been studied. The results show that the addition of a small amount of silver decreases the mechanical properties of the steel. In the ingots, a dendritic structure is observed, and after warm rolling, the structure has a pronounced fine-grained austenitic structure.

1. Introduction
Today, stainless steel has taken one of the leading places among the most important materials in the world. Its composition has been repeatedly modified and improved to acquire novel and enhanced properties. One of the most popular and applied grades among stainless steels is 316L austenitic stainless steel. The range of its application is incredibly wide. It has high corrosion resistance, good mechanical strength, and ductility, which can guarantee long-term and high-quality operation of products from this steel. It is used in many industries such as medical, food, petrochemical, mining, automotive, aerospace and other fields. The scope of application of 316L stainless steel is constantly growing in new areas of the economy, such as biotechnology and others [1-5].

Due to its high performance properties, stainless austenitic steel has long been used for the manufacture of various medical devices, such as orthopedic prostheses, dental implants, cardiovascular stents / valves, and other medical devices [6]. Often, stainless steel implants are used to fix bone fractures [7]. However, the biological environment in the human body is very corrosive to metals and can lead to protein adsorption, biofilm formation (attachment of microorganisms / bacteria to the surface of the material), and corrosion. Steel itself is able to become a source of bacterial contamination [8].
Alloying, coating and many other methods are applied to increase the biocompatibility of stainless steels. Recent studies have shown that the addition of Ag to stainless steels can impart antibacterial properties without the necessity for further surface modification [9].

In this work, 2 ingots of stainless steel with and without the addition of 0.2% Ag were smelted, plates were obtained from these ingots by the method of warm rolling, and the structure and mechanical properties were investigated.

2. Methods and materials

Two compositions of stainless steel were melted with a carbon (C) content of less than 0.3%, 17% chromium (Cr), 10% nickel (Ni), 2% manganese (Mn), 2% molybdenum (Mo), silicon (Si) less than 0.5%, phosphorus (P) less than 0.05%, sulfur (S) less than 0.01%, nitrogen (N) less than 0.08% (ingot № 1 composition). Ingot № 2 was also added with 0.2% Ag.

The weighed portions were melted in an electric arc vacuum furnace with an LK200DI non-consumable tungsten electrode from LEYBOLD-HERAEUS (Germany). Samples were placed in a water-cooled copper crystallizer, after which the working chamber was hermetically closed and evacuated to a pressure of 1 * 10^{-2} mm. rt. Art. After that, argon was poured into the chamber to a pressure of 0.4 atm.

In the first remelting process, a single ingot was obtained. The shape of the ingot was obtained in the form of a biconvex lens, 30-35 mm in diameter, 10-15 mm in height. The next 2 remelts are aimed at obtaining a uniform chemical composition throughout the ingot. The duration of each melting of one ingot is 1-1.5 minutes. The getter was melted before of the fusible ingot. An ingot of iodide titanium weighing 15-20 g was used as a getter. The mass of the ingots was 45 to 50 grams.

Further, under these conditions, the resulting ingots are melted into single ingots weighing 180-200 g for 2 remelts. The final ingot has a length of 90-100 mm, a width of 20-25 mm, and a height of 10-15 mm.

The primary deformation (rolling) of cast billets 10-15 mm thick was carried out by warm rolling on a DUO-300 twin-roll mill with partial absolute reductions per pass: 1–2 mm to a billet thickness of 4 mm, then 1.0 mm to a billet thickness of 2.0 mm, further 0.5 mm to the final thickness of the workpiece - 1-1.25 mm. The blanks were heated before deformation in a muffle furnace for 25 minutes at a temperature of 1100 °C. Heating was carried out in a KYLS 20.18.40 / 10 furnace from HANS BEIMLER with a maximum temperature of 1350 °C.

The tensile strength study was carried out on an INSTRON 3382 universal testing machine with a tensile speed of 1 mm / min. Flat specimens with heads were made from plates and cut by EDM cutting along and across the plate (Figure 1). This shape is necessary to minimize the influence of gripping on the results of the study of samples.

![Figure 1. Drawing of flat specimens for the study of mechanical properties](image-url)

The structure study was carried out for samples in the form of ingots after smelting and plates after plastic deformation. The pressing occurred on an IPA 40 pneumohydraulic press at a temperature of 175°C and holding for 10 minutes, at a pressure of 3 bar. The samples obtained were grinded and polished.
Sample preparation was carried out on a Buehler Phoenix 4000 installation by sequential grinding after pressing on a P320 grinding wheel (15 min) and Aka-Alegran-3 with a 3 μm diamond suspension (10 min). The samples were polished using a rayon polishing wheel (Aka-Napal) using a diamond suspension (1 μm) for 5 min.

The surface of the samples was etched with a mixture of acids for high-alloy steels, consisting of 20% nitric acid (HNO₃), 10% sulfuric acid (H₂SO₄), 5% hydrofluoric acid (HF), and 65% water (H₂O). The etching time for ingots was 9 minutes, for samples of rolled plates 11 minutes.

Optical microscopy was carried out on a Carl Zeiss JENA Germany NEOPHOT 2 microscope, with which microimages were obtained and processed using the AmScope MU1403 camera and the AmScope 3.1 software.

3. Results and discussion

For mechanical tests, 5 samples were tested per one experimental point. Determined the values of the relative elongation, conventional yield stress and ultimate strength. The results can be found in Table 1. For convenience, a bar chart was constructed (Figure 2).

Table 1. Mechanical properties

| Alloy            | Elongation (%) | Yield strength (MPa) | Ultimate tensile stress (MPa) |
|------------------|----------------|----------------------|-------------------------------|
| №1 (across rolled) | 48±0,5         | 492±8               | 682±8                         |
| №1 (along the rental) | 54±0,5         | 456±8               | 690±8                         |
| №2 (across rolled) | 42±0,5         | 506±8               | 675±8                         |
| №2 (along the rental) | 52±0,5         | 398±8               | 682±8                         |

Figure 2. Diagram mechanical properties.

Based on the data obtained, it can be concluded that all samples have good plasticity (from 42% to 54%) and strength (from 675 to 690 MPa). The nominal yield stress also varies depending on the alloy composition and the direction of the rolled product in the range from 398 to 506 MPa.

The results show that the addition of a small (0.2% Ag) amount of silver slightly reduces the mechanical properties of the steel. The minimum strength and ductility were found for the sample across the rolled steel with the addition of 0.2% silver and amounted to 42% and 675 MPa,
respectively. The maximum characteristics were for the specimens cut along the rolled stock without the addition of silver and amounted to 54% in terms of elongation and 690 MPa in terms of ultimate strength. It should also be noted that the direction of the rolling also affects the properties. The tensile strength and relative elongation are slightly higher for specimens cut along the direction of rolling, however, the yield stress is lower than for specimens cut across the direction of rolling.

Optical microscopy of melted ingots and plates was carried out on an optical microscope Carl Zeiss JENA Germany NEOPHOT 2. The structure can be found in Figure 3.

| Ingot Composition №1 | Plate Composition №2 |
|----------------------|-----------------------|
| ![Ingot Composition №1](image1.png) | ![Plate Composition №2](image2.png) |
| ![Ingot Composition №2](image3.png) | ![Plate Composition №2](image4.png) |

**Figure 3.** Microstructure of the steel.

The obtained micrographs show that the structure of the ingots is a dendritic structure, and in the plates the structure has a pronounced fine-grained austenitic structure.

4. **Conclusion**
Technology has been developed for smelting stainless steel for use in the production of medical products in electric arc vacuum furnaces and a technology for producing sheets with a thickness of 1 ÷ 1.25 mm for further research of mechanical properties. To study the structure, thin sections of the alloys were obtained after melting and after rolling. The mechanical properties of the samples and their structure have been studied. The results show that the addition of 0.2% Ag silver does not significantly reduce the mechanical properties of the steel. In the ingots, a dendritic structure is observed, and in the ingots after warm rolling, the structure has a pronounced fine-grained austenitic structure.

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References

[1] Grabco D. et al. Microstructures generated in AISI 316L stainless steel by Vickers and Berkovich indentations //Materials Science and Engineering: A. – 2020. – C. 140597.

[2] Kirsankin, A. A., Kalaida, T. A., Kaplan, M. A., Smirnov, M. A., Ivannikov, A. Y., & Sevostyanov, M. A. Characterization of spherical stainless steel powders prepared by electric arc spraying process // IOP Conference Series: Materials Science and Engineering, 2020, Volume 848, 012033, p.1-5, doi: 10.1088/1757-899X/848/1/012033

[3] Smirnov M.A., Kaplan M.A., Kirsankin A.A., Kalaida T.A., Nasakina E.O., Sevostyanov M.A. Investigation of the properties of heat-resistant spherical powders // IOP Conference Series: Materials Science and Engineering, 2019, Volume 525, 012076, DOI:10.1088/1757-899X/525/1/012076

[4] Kaplan M.A., Kirsankin A.A., Smirnov M.A., Kalaida T.A., Baranov E.E., Ustinova Yo.O., Sevostyanov M.A. Properties of spherical stainless steel powders // IOP Conference Series: Materials Science and Engineering, 2019, Volume 525, 012075, DOI:10.1088/1757-899X/525/1/012075

[5] Smirnov M.A., Kaplan M.A. and Sevostyanov M.A. Receiving finely divided metal powder by inert gas atomization // IOP Conference Series: Materials Science and Engineering, 2018, Volume 347, 012033, DOI:10.1088/1757-899X/347/1/012033

[6] Virtanen S. et al. Special modes of corrosion under physiological and simulated physiological conditions // Acta Biomater. 2008. Vol. 4, № 3. p. 468–476

[7] Brooks E.K., Brooks R.P., Ehrensberger M.T. Effects of simulated inflammation on the corrosion of 316L stainless steel // Mater. Sci. Eng. C. 2017. Vol. 71. P. 200–205

[8] Chen Q., Thouas G.A. Metallic implant biomaterials // Mater. Sci. Eng. R Reports. 2015. Vol. 87. P. 1–57

[9] Sreekumari K.R. et al. Silver containing stainless steel as a new outlook to abate bacterial adhesion and microbiologically influenced corrosion // ISIJ Int. 2003. Vol. 43, № 11. P. 1799–1806