Modelling of combined thermomechanical processing of stainless steel wire

Irina E. Volokitina; Andrey V. Volokitin, Evgeniy A. Panin
Karaganda Industrial University, Temirtau, Kazakhstan
e-mail: irinka.vav@mail.ru

Abstract: *In this article, a number of theoretical studies have been conducted on a new combined process of multicycle thermomechanical processing, including wire drawing and subsequent cooling in liquid nitrogen. When analyzing the deformation, it was found that the presence of intermediate heating to ambient temperature allows calculating the force according to the Krasilshchikov formula and the well-known nomogram of the tensile strength of AISI-316 steel at 20°C with minimal errors. The lack of heating leads to the fact that the second and third drawing cycles take place at partially negative temperatures in the workpiece section. This leads to an increase in the difference in the force values obtained by calculation and during modeling. To be able to use the Krasilshchikov formula and the nomogram of the tensile strength of AISI-316 steel at 20°C, it is necessary to adjust the resulting force values by increasing by about 30% for a diameter of 6 mm and 20% for a diameter of 9 mm in the absence of heating of the workpiece and by 35% for a diameter of 6 mm and 25% for a diameter of 9 mm in in case of preheating the workpiece.*
KEYWORDS: *WIRE, MODELLING, STEEL, STRESS-STRAIN STATE, CRYOGENIC COOLING.*

1. Introduction

Currently, combined technologies are one of the most promising areas for improving innovative technologies for producing long-length semi-finished products [1-2]. Such technologies contribute to the development of new processes that improve production efficiency, as well as significantly increase labor productivity as a result of reducing the number of low-productivity operations. Also, the combination of innovative modern technologies helps to reduce production space. Over the past few years, scientists have been interested in materials that are characterized by ultrafine-grained and nano-structures, due to the fact that they have high strength properties. But usually a significant increase in strength, resulting from the accumulation of a volume fraction of the surface boundaries of grains, leads to a parallel decrease in plastic properties. As a result, the scope of application of such metals will be significantly reduced. And the ever-increasing demands that are now being placed on today's materials are pushing to improve their manufacturing technologies. It is necessary to achieve this goal with a winning combination of high strength and plasticity. As a result of the above, the development of a technology that allows to increase the strength and performance properties of austenitic chromium-nickel steel wire by thermomechanical processing is an urgent task.

Wire was always one of the main types of rolled metal, since it is made of various profiles, but most often round, according to the shape of the cross section. With the development of modern industry, which has occurred at the moment, metals are becoming more and more in demand. The wire production technologies currently used by Kazakhstan companies can be safely called outdated, since they are characterized by such negative factors as high energy consumption and low productivity. The annual global production of austenitic corrosion-resistant steels is about 22 million tons per year, which accounts for 80% of the global market for all corrosion-resistant steels [3]. The main advantage of such steels is their high performance characteristics: corrosion resistance, ductility and strength. Therefore, austenitic corrosion-resistant steels are widely used as a structural material in metallurgy, instrument engineering, various branches of mechanical engineering, etc. An important property of such steels is that after quenching they have a purely austenitic structure and undergo a γ-α transformation during plastic deformation. And the higher the concentration of martensite, the lower the deformation temperature and the higher the deformation degree.

Despite the fact that, as a rule, even after very intense deformation, a part of austenite may not turn into martensite [4,5]. Therefore, in the production of wire made of AISI-316 steel and its analogues with high strength properties, a deformation of 90-92% is recommended [6,7]. And even with such compressions, only 75% of martensite is formed in the structure. And also the best combination of plastic and strength properties is obtained. When deforming medium and large cross-sections of wire, the use of such high compressions is not advisable, since the resulting wire diameter always has its limitations. The use of drawing always leads to a significant reduction in the diameter of such a wire.

Recently, there has been great interest in the use of cryogenic cooling during deformation by metal forming using liquid nitrogen [8,9]. In this case, the processing is not accompanied by recrystallization or dynamic return. This makes it possible to grind the microstructure more intensively. Another advantage of such deformation is a strong increase in strength properties at lower deformation degrees compared to traditional metal forming methods.

There are studies [8,9] that have been conducted in the field of cryogenic deformations, which confirm the effectiveness of such treatment in terms of grinding structural components. Thus, in [8,10] it was proved that the microstructure of the initial coarse-grained copper and aluminum after cryogenic deformation differs in significantly smaller grain size than after conventional cold deformation. Therefore, it is proposed to use cryogenic cooling immediately when the wire leaves the drawing using liquid nitrogen, which will give a more favorable compromise between the strength and ductility of the material. This can be achieved due to the increased mobility of dislocations and, at the same time, their increased density. When the martensitic transformation takes place at a temperature below the temperature of the beginning of the martensitic transformation, a large difference in free energies occurs, which leads to a sharp decrease in grain size compared with stable growth.

2. Material and research methodology

The developed technology of thermomechanical wire processing is a combined process that includes successive stages of wire drawing and cooling in a special chamber with liquid nitrogen.

At the theoretical stage of research on deformation processes which have a drawing scheme, a study of force parameters is usually carried out, since the very possibility of deformation of the wire depends on the force magnitude. The drawing force depends on various geometric and technological factors, such as the mechanical properties of the deformable material, the amount of compression, external friction, the shape and size of the drawing, the drawing speed, the presence or absence of tension at the front and rear ends of the workpiece, as well as the transverse area of the resulting profile. For solid round profiles, you can use the Krasilshchikov formula, which was obtained on the basis of numerous experimental data:

$$P = 0,6 d_0^2 \sqrt{\frac{d_0^2 - d_1^2}{d_0^2}} \cdot \sigma_{TAV} \tag{1}$$

where σ_{TAV} – average tensile strength, equal to the arithmetic mean of tensile strength of the material before and after pass, MPa; d_0 – diameter of the wire before pass, mm; d_1 – diameter of the wire after pass, mm.

The determination of the average tensile strength during drawing is carried out according to nomograms constructed based on the results of experimental tensile tests after a series of draws at different compressions. In particular, for austenitic stainless steel AISI-316, deformable at 20°C, it is necessary to use the nomogram shown in Fig. 1.

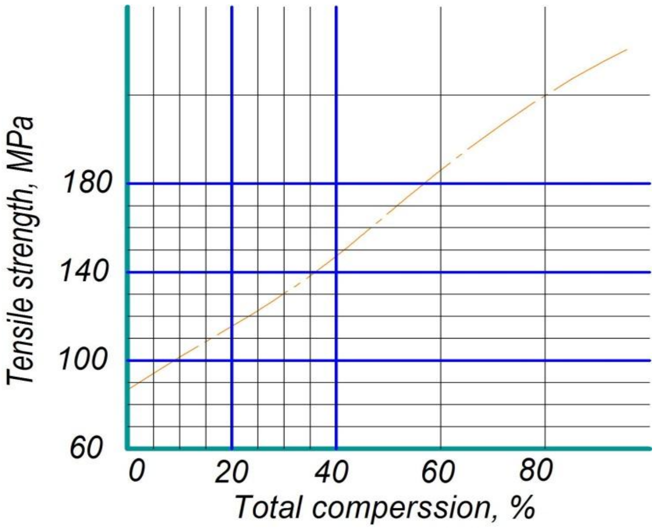


Fig. 1. *Nomogram of the tensile strength of AISI-316 steel during drawing at 20°C*

The thermomechanical processing route was carried out in two variants, in each variant the workpiece was deformed to a predetermined diameter, after which it fell into a container with liquid nitrogen.

In the first variant, the workpiece was heated in air to a temperature of 20 ° C after each treatment with liquid nitrogen. In the second variant, this heating was absent. For the first option, the nomogram in Figure 1 is completely suitable, since before each stage of drawing, the workpiece is evenly heated to room temperature.

Given that in the second variant, the workpiece will have a negative temperature after nitrogen treatment, the usual Deform material database will not be suitable for such modeling, since the standard lower temperature limit is 20°C. In [11], FEM modeling of this steel under cryogenic cooling was carried out. For this purpose, a new database was developed, which included the rheological properties of AISI-316 steel up to -200°C.

3. Experimental results

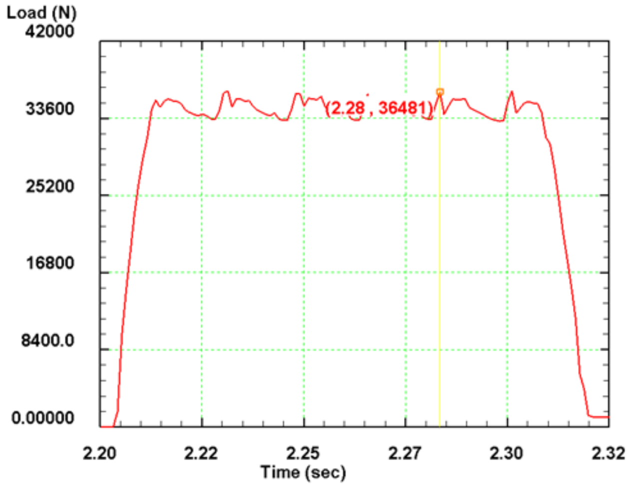
Using formula (1), when drawing a wire with a diameter of 6 mm, the following force values were obtained:
- on the first pass from 6 mm to 5.6 mm = 44201 N.
- on the second pass from 5.6 mm to 5.3 mm = 37326 N.
- on the third pass from 5.3 mm to 5 mm = 36144 N.

When drawing a wire with a diameter of 9 mm, the following force values were obtained:
- on the first pass from 9 mm to 8.2 mm = 175051 N.
- on the second pass from 8.2 mm to 7.5 mm = 158087 N.
- on the third pass from 7.5 mm to 7 mm = 122863 N.

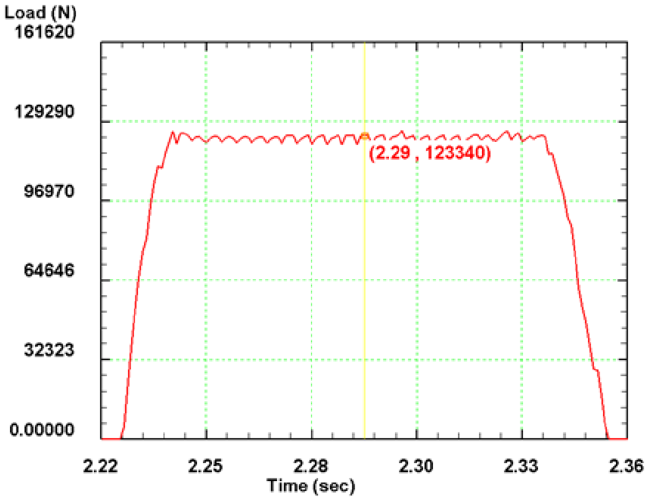
To verify the correctness of the received data, it was decided to carry out verification using finite element modeling. Figures 2-3 show graphs of forces when drawing workpieces with diameters of 6 and 9 mm using heating and without using at speeds of 500 mm/s and 1000 mm/s.

Comparing the values obtained during calculation and modeling, it is necessary to note a high level of error, which is approximately 35% for a diameter of 6 mm and 25% for a diameter of 9 mm. The decrease in error with an increase in the workpiece thickness is due to the fact that with an increased thickness and a constant cooling time in nitrogen, a higher temperature gradient occurs when the central layers are cooled less intensively.

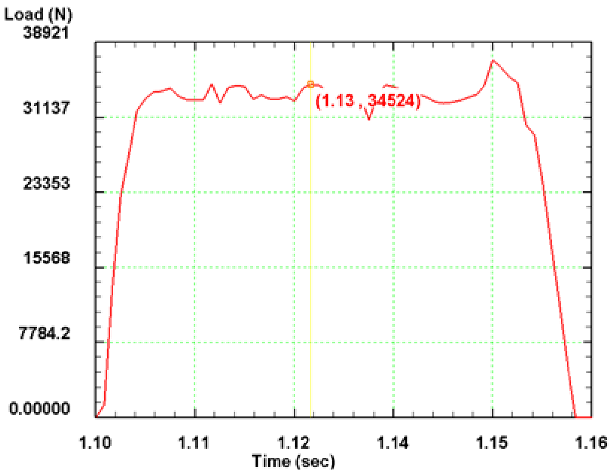
At the same time, all calculated values are lower than the values obtained during modeling, which is the result of deformation at a reduced temperature. Taking into account the results obtained, it can be recommended to increase the calculated values by about 35% for a diameter of 6 mm and by 25% for a diameter of 9 mm when using a calculation technique and a nomogram to obtain correct values.



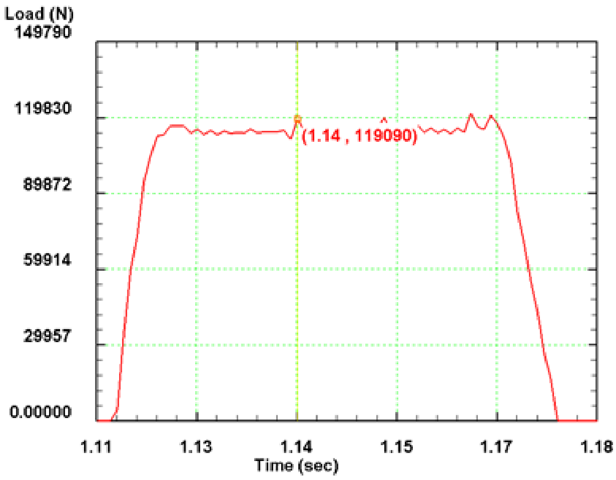
a



b

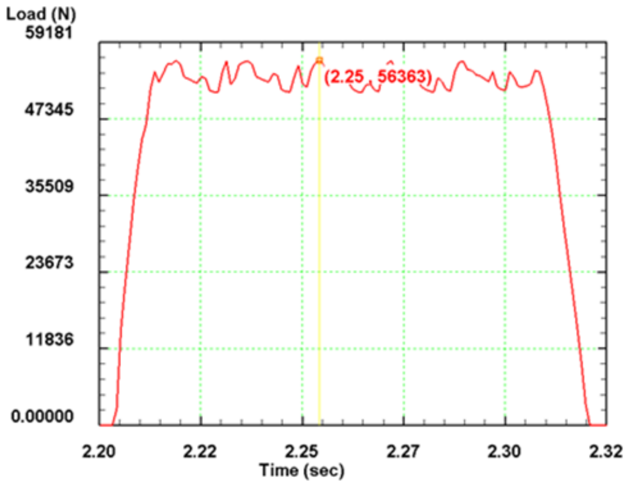


c

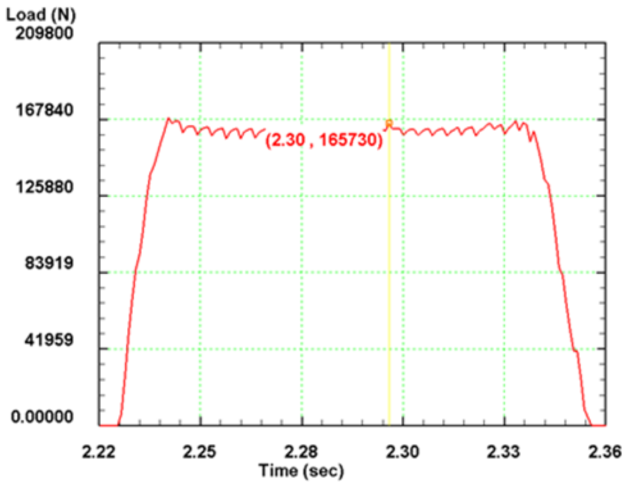


d

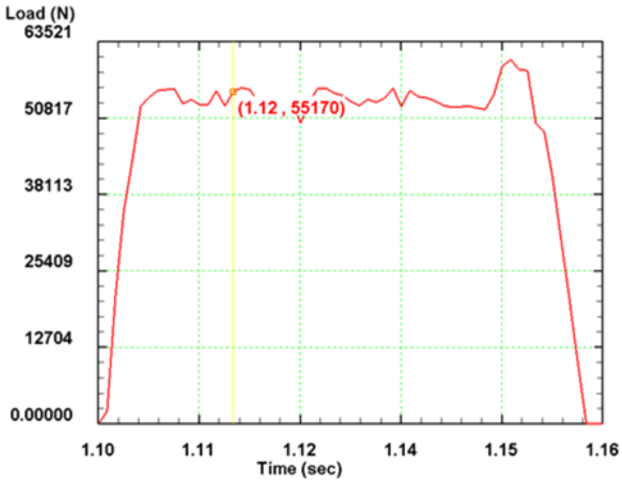
Fig. 2. *Graphs of drawing forces after 3 passes (with workpiece heating): a – diameter of 6 mm at a speed of 500 mm/s, b – diameter of 9 mm at a speed of 500 mm/s, c – diameter of 6 mm at a speed of 1000 mm/s, d - diameter of 9 mm at a speed of 1000 mm/swith*



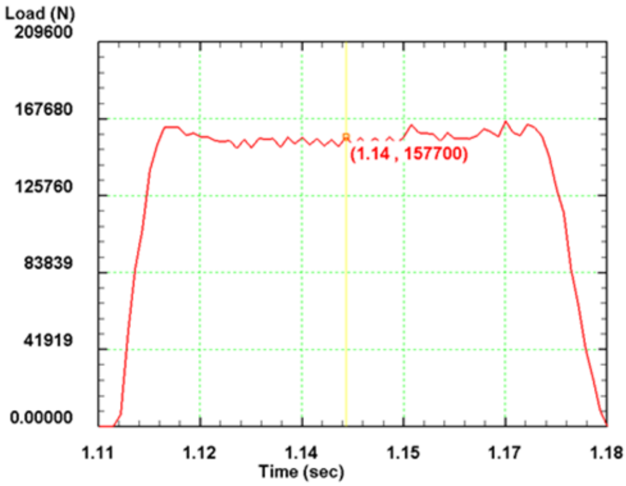
a



b



c



d

Fig. 3. *Graphs of drawing forces after 3 passes (without workpiece heating): a – with a diameter of 6 mm at a speed of 500 mm/s, b – with a diameter of 9 mm at a speed of 500 mm/s, c – with a diameter of 6 mm at a speed of 1000 mm/s, d - with a diameter of 9 mm at a speed of 1000 mm/s*

4. Conclusions

FEM simulation of a new combined process of multicycle thermomechanical processing, including wire drawing and subsequent cooling in liquid nitrogen have been conducted. It was found that the presence of intermediate heating to ambient temperature allows calculating the force according to the Krasilshchikov formula and the well-known nomogram of the tensile strength of AISI-316 steel at 20°C with minimal errors. The deformation without intermediate heating leads to the negative temperatures in the workpiece section in the second and third drawing cycles. To be able to use the Krasilshchikov formula and the nomogram of the tensile strength of AISI-316 steel at 20°C, it is necessary to adjust the resulting force values by increasing by certain percent values.

5. Financing

This research was funded by the Science Committee of the Ministry of Education and Science of the Republic of Kazakhstan (Grant № AP19576369).

6. References

1. Andreev V.A., Yusupov V.S., Perkas M.M., Prosvirnin V.V., Shelest A.E., Prokoshkin S.D., Khmelevskaya I.Yu., Korotitskii A.V., Bondareva S.A., Karelin R.D. Mechanical and Functional Properties of Commercial Alloy TN-1 Semiproducts Fabricated by Warm Rotary Forging and ECAP // Russian Metallurgy (Metally). – 2017. – Vol. 10. – P. 890–894.

2. Naizabekov A., Volokitina I., Volokitin A., Panin E. Structure and mechanical properties of steel in the process "pressing-drawing // Journal of Materials Engineering and Performance. – 2019. – Vol. 28. – P. 1762-1771.

3. Cunat, P.J. Aciers inoxydables: Propriétés, résistance à la corrosion / P.J. Cunat // Techniques de l'ingénieur. – 2000. - № M 4541. – C. 1-16.

4. S. S. Kazemi, M. Homayounfard, M. Ganjiani, N. Soltani. Numerical and Experimental Analysis of Damage Evolution and Martensitic Transformation in AISI 304 Austenitic Stainless Steel at Cryogenic Temperature. Progress in Materials Science. 2019, Vol. 53, 9 pp. 893-979.

5. M. Glatt, H. Hotz, P. Kölsch, A. Mukherjee, B. Kirsch, .J.C. Aurich. Predicting the martensite content of metastable austenitic steels after cryogenic turning using machine learning. The International Journal of Advanced Manufacturing Technology 2021, V.115, 749–757.

6. Xu, W. Modelling and characterization of chi-phase grain boundary precipitation during aging of Fe-Cr-Ni-Mo stainless steel / W. Xu, D. S. Martin, P.E.J. Rivera D'iaz del Castillo, S. van der Zwaag // Materials Science and Engineering A. 2007. V. 467. P. 24-32.

7. Bidulský R., Bidulská J., Gobber F.S., Kvačkaj T., Petroušek P., Actis-Grande M., Weiss K-P., Manfredi D., Case Study of the Tensile Fracture In-vestigation of Additive Manufactured Austenitic Stainless Steels Treated at Cryogenic Conditions // Materials. – 2020. – Vol. 13. № 3328.

8. Panigrahi S.K., Jayaganthan R., Pancholi V., Gupta M. A DSC study on the precipitation kinetics of cryorolled Al 6063 alloy // Materials Chemistry and Physics. - 2010. - № 12. - C. 188-193.

9. Volokitina I., Siziakova E., Fediuk R., Kolesnikov A. Development of a Thermomechanical Treatment Mode for Stainless-Steel Rings // Materials. - 2022, – Vol.15 - 4930.

10. Ramesh Kumar S., Kondaiah Gudimetla, Tejaswi B., Ravisankar B. Effect of Microstructure and Mechanical Properties of Al–Mg Alloy Processed by ECAP at Room Temperature and Cryo Temperature // Transactions of the Indian Institute of Metals. - 2017. - Vol. 70. - P. 639-648.

11. Volokitin, A., Volokitina, I., Panin, E., Naizabekov, A., Aksenov, S., Kuis, D. (2022). Finite element method (FEM) simulation of processing of AISI-316 austenitic stainless steel by high-pressure torsion (HPT) process at the cryogenic cooling. Metalurgija, 61 (1), 237-240.