Technological parameters for the production of steel and titanium blanks by the method of helical rolling

V N Belyakov¹,² and O S Naumova¹
¹Yaroslav-the-Wise Novgorod State University, ul. B. St. Peterburgskaya, 41, 173003, Veliky Novgorod, Russia
²E-mail: val-belyakov@mail.ru

Abstract. The article is devoted to the technology of producing steel and titanium blanks by the method of cross-helical rolling. The grades of the investigated alloys and technological processing modes are given. Studies of the effect of rolling parameters (deformation temperature, feed angle) on the production of round billets are presented. The general nature of the influence of technological factors of the process on the conditions of metal deformation is established. The change in the microstructure of titanium alloys after hot deformation was investigated. The expediency of using this method is substantiated.

1. Introduction
The desire to reduce the technological losses of expensive materials, to reduce the costs of redistribution has a stable relevance in the production of rods from alloyed metals and expensive alloys. Modern conditions of metal products turnover exacerbate the problem with new requirements. Of particular value is the possibility of prompt production and delivery of quality steel in limited quantities in an expanded brand size assortment.

Stationary helical rolling, naturally and inseparably connecting the discontinuity and continuity with its essence, occupies a uniquely preferable position in the indicated direction. Largely due to this feature, helical rolling is present on the widest range of industrial applications, including: pipe; detail rolling and rolling production.

The use of the process of helical rolling is widely used to produce round solid steel from various materials [1, 2]. The technology is based on the method of helical rolling of continuous billets in a three-roll stand with elevated values of partial reductions, which is achieved mainly by increasing the feed angles. This method allows to obtain during hot rolling in one pass the degree of deformation in the axial zone of the rod up to 130% and the drawing ratio $\mu=2.9$ for steel billets [3].

2. Material and research methods
The paper presents studies of the effect of rolling parameters (deformation temperature, feed angle) on the production of round billets from O9Г2С (O9G2S), 40Х (40KH), 60С2А (60S2A) steels and industrial titanium alloys, the chemical composition of which is given in table 1.
Table 1. The chemical composition of titanium alloys.

| Alloy   | Original structure | Al  | Mn | Mo | V  | Cr | Fe | Zr |
|---------|--------------------|-----|----|----|----|----|----|----|
| BT1 (VT1) | α                 |     |    |    |    |    |    |    |
| BT5 (VT5) | α                 | 5   | -  | -  | -  | -  | -  | -  |
| OT4 (OT4) | Pseudo-α          |    |    |    |    | 3  | 1.5| -  |
| BT20 (VT20) | Pseudo-α         | 5.5–6 | -  | 0.8–1.5 | 1.2 | -  | -  | 2.2 |
| BT22 (VT22) | α + β             | 5   | -  | 4.5 | 4.5 | 1.2 | 1.0 | -  |

The study was carried out on an industrial rolling mill IRM 30/10, in which the rolls are inclined to the rolling axis at an angle of 15 °. Rolling was subjected to billets with a diameter of 15 ... 25 mm with a pre-deformed structure obtained by the method of longitudinal rolling.

Studied the possibility of obtaining maximum compression per pass at a given rolling temperature and feed angle. The degree of deformation (drawing ratio) was varied by calibrating the rolls to a given diameter of the rolled steel, and the conditional speed of rotation of the workpiece – by changing the speed of rotation of the rolls. For helical rolling, working gauges are formed by converting the rolls to a predetermined amount. The degree of maximum compression at each temperature was limited to obtaining high-quality bars, which were evaluated by the state of the surface, the accuracy of geometric dimensions.

3. Results and discussion

According to the research results, the dependences of the maximum compression per pass on the rolling temperature were obtained (figure 1).

Research results show that with increasing rolling temperature, the maximum compression per pass increases and reaches a maximum at a certain temperature for each alloy grade (figure 1). This behavior is explained by an increase in the plasticity of the material with an increase in the deformation temperature in the single-phase region. The decrease in the maximum compression with increasing temperature above $T_{\text{opt}}$ is explained by the fact that due to the high ductility, the metal is squeezed into the gaps between the rollers, the rolling process is disturbed, and ovality is formed in the cross section of the workpiece.

Conducting rolling with a lower degree of deformation per pass leads to the formation of a structure that is not uniform across the cross section. The structure of the workpiece across the cross section is unevenly worked out, the metal is quickly cooled down and, as a result, surface defects appear (flaws); the productivity of the rolling process is reduced. When setting a greater degree of deformation per pass during rolling, uneven heating of the rod occurs, which also causes structural heterogeneity of the metal and instability of the mechanical properties of the cross section of the rod.
We should note the extreme nature of the temperature dependence of the limiting coefficient of drawing with a maximum at a rolling start temperature 80 ... 100° C below the temperature of the maximum plastic properties, determined by plastometric tests [4]. This indicates intense deformation heating and its noticeable effect on the deformation conditions of the metal.

It should be noted that there is a dependence of the maximum compression on the conditional speed of rotation of the workpiece for materials with low thermal conductivity (such as alloy BK22 (VK22)). An increase in the rotational speed leads to localization and intensification of the deformation heating in the zone of maximum velocities and a decrease in the degrees of deformation. Reducing the speed of rotation of the workpiece contributes to the weakening of the non-uniformity of the temperature field, reducing local maxima near the area of ring failure due to more complete completion of heat transfer processes and obtaining higher quality rolled products [5].

One of the most important technological parameters affecting the processing performance and the quality of the resulting blanks is the feed angle $\beta$, which is set by the angle of the rolls to the axis of the workpiece and the calibration of the working part of the roll.

In studies, the feed angle was changed by changing the calibration of the mushroom-shaped rolls within 10 ... 22°. It was established that with an increase in the feed angle, an increase in the axial movement of the workpiece in the rolling process, and, accordingly, an increase in the productivity of
the process, occurs. But on the other hand, an increase in the feed angle impairs the process of metal capture by the rollers and does not allow to obtain maximum reduction values in a single pass. The positive effect of large feed angles on the rolling capacity of the workpieces reflects a significant increase in the uniformity of the distribution of strain-rate and temperature conditions in the deformation zone. This is facilitated by the growth of private reductions and reduction in the number of deformation cycles. The analysis of the parameters of shaping showed, in particular, that an increase in the feed angle from 12 to 20° when rolling a bar with a diameter of 18 mm from a billet with a diameter of 25 mm leads to an increase in the maximum partial reduction from 12.5 to 15.6%, to a reduction in the number of deformation cycles of 1, 67 times. A decrease in the depth of the axial extension of the end face of the workpiece by 13% also indirectly indicates a decrease in the non-uniformity of deformation. When rolling steel O9Г2С40X the optimum feed angle is in the range of 16–18°.

The process of helical rolling of all the studied steels and alloys on conic calibrations of rolls with a tilt angle of 10 ... 15 ° forming to the rolling axis is characterized by high stability during the seizure of blanks and in the steady state with a wide range of feed angles (12 ... 24°) and coefficients of extracts per pass (1.1 ... 4.5). Increasing the feed angles to 20 ... 25° worsens the gripping conditions, violates the stability of rotation and axial movement of the deformable workpiece.

The general nature of the established laws of the influence of technological factors of the process on the conditions of metal deformation was noted when studying the characteristics of helical rolling of other alloys [6, 7]. The individual characteristics of a particular material are manifested mainly in the choice of the temperature range of rolling and the level of deformability. Direct experiments have shown for the first time the possibility of defect-free deformation of billets in the process of helical rolling according to the modes presented in table 2.

| Table 2. Modes of helical rolling of steels and titanium alloys. |
|---------------------------------------------------------------|
| Steel /alloy type  | Rolling temperature,°C | Feed angle, degrees | Maximum compression per pass, % |
|-------------------|------------------------|--------------------|--------------------------------|
| O9Г2C (09G2S)     | 1000                   | 15                 | 45                             |
| 40X (40 KH)       | 1050                   | 16                 | 40                             |
| 60C2A (60S2A)     | 1060                   | 16                 | 37                             |
| BT1 (VT1)         | 900                    | 14                 | 35                             |
| BT5 (VT5)         | 980                    | 12                 | 33                             |
| OT4 (OT4)         | 950                    | 12                 | 33                             |
| BT20 (VT20)       | 950                    | 12                 | 31                             |
| BT22 (VT22)       | 960                    | 12                 | 30                             |

The limitation of the maximum rolling temperature is determined not only by the conditions for obtaining rolled products of the correct geometric shape, but also by obtaining the necessary structure of the material. With an increase in the heating temperature, the speed of the oxidation process increases, the depth of the decarburizing layer increases, which is especially important for medium and high carbon steels.
Experiments show that when heated to a temperature of 1100° C and held for an hour for samples of 30 mm in diameter from 60C2A (60S2A) steel, the size of the decarburizing layer is 0.6 mm. Therefore, when choosing the optimal rolling temperature, it is necessary to take into account both the plastic properties and the structural features of the steel.

Microstructure studies have shown that heating titanium alloys to temperatures below phase transformations and the subsequent rolling at these temperatures have virtually no effect on grain growth. After rolling BT1 and BT5 (VT5) alloys at a temperature of 900° C and a degree of reduction of 40%, the average grain size was 0.1–0.2 mm, which corresponds to 4.5 type of macrostructure in a ten-point system. The initial structure of the samples annealed at 850° C was 5 points of the macrostructure. An increase in the rolling temperature of the BT5 (VT5) alloy to 1000° C made it possible to increase the degree of reduction to 80%, but the average grain size accordingly increased to 0.25+0.3 mm (6 point of the macrostructure).

It should be noted that in the temperature range of 1000-1100° C, the plastic properties of the metal deteriorate sharply in the entire speed range of deformation, which is associated with overheating of the metal. This is confirmed by a sharp increase in grain size. In addition, at temperatures above 900° C, a brown scale, which is titanium dioxide, is formed on the surface. The depth of the oxide layer at 1000° C and holding for 10–15 min reached 0.1–0.15 mm.

Rolling alloys OT4 (OT4), BT20 (VT20) with a pseudo-α structure showed that at a temperature of 850–900° C, the alloys have the least ductility, which increases dramatically when passing through the polymorphic transformation point. However, an increase in the rolling temperature to 1050° C led to an increase in the macrograin to 0.25 with an initial structure of 0.1 mm.

Based on the research obtained on the microstructure of titanium alloys, the following can be noted:

1. The grain size and the microstructure score after rolling substantially depends on the nature of the initial structure of the sample.
2. At temperatures of hot deformation located below the polymorphic α + β ⇔ β transformations, the macrostructure score practically does not increase, the macrograin is noticeably crushed.
3. At temperatures of hot deformation above the point of polymorphic α + β ⇔ β transformation, a significant growth of micrograin is observed and the macrostructure score increases. The deformation here significantly affects the grain size. The increase in deformation crushes the grain, but with deformations of 80-90% it is not possible to obtain a fine structure, which is easily achieved with small deformations in the temperature range below the polymorphic transformation limit.
4. Significant grinding of the initial coarse macrostructure is possible only at the deformation temperature below the polymorphic transformation point.

With correctly selected modes of helical rolling, it was established that in the macro- and microstructure of the metal rolled according to the new technology, there are no discontinuities of deformation origin.

The specific nature of the development of metal forming, accompanied by intense shear deformations on the background of general compaction, has a positive effect on almost all levels of the metal structure. In carbonaceous alloyed steels 40X (40KH), 60C2A (60S2A), high dispersion and uniformity of isolated particles of the carbide phase were recorded, practically in the absence of mesh and line formations [8]. Such a structure of carbides differs sharply from the characteristic carbide streakiness obtained by rolling in calibers, forging, and approaches the structure of carbides in steels obtained by quenching and subsequent tempering.

In the process of stationary helical rolling and subsequent standard heat treatment of alloyed titanium alloys BT20 (VT20), BT22 (VT22), a dense uniform macrostructure is formed with an almost complete absence of different grain sizes over the cross section and bar length [9].

It was established that, along with high surface quality, the deformation scheme for helical rolling allows to steadily obtain rods with a cross section ovality of less than 0.5% of the nominal diameter and
a curvature of no more than 0.75 mm per meter. The obtained results provide the possibility of increasing the yield ratio and the efficiency of redistribution as a whole by reducing the volume or eliminating the repair of intermediate blanks and finished bars.

It is especially important to note that when solving all the above problems, the process of helical rolling, as a method of deformation, is applied in its rational form without significant corrections to the properties of the material. Technological recommendations for a particular material are mainly reduced to the definition of a rational heating temperature, taking into account the above-noted features of the temperature mode, allowable reductions per pass and the frequency of rotation of the rolls [10].

The properties of a particular steel or alloy are present in the process modes in the form of a temperature range of processing, a permissible degree of compression of the coefficient per pass, or in the number of passes for a given total deformation and frequency of rotation of the rolls. And the rational configuration of the deformation center, the roll calibration and the parameters of the internal trajectories are practically unrelated, both with compression per pass and the number of passes performed, i.e. have a high degree of invariance with respect to material properties. In addition, in rational form-changing modes, there are no restrictions on maximum crimps on the conditions of natural gripping and rotation of the workpiece, and minimum on filling the caliber and stability of the roll due to their concomitant implementation.

4. Conclusion
Thus, when determining the optimal rolling parameters, it is necessary to take into account the technological features of the helical rolling, roll calibration, the structure and properties of the rolled alloy. These circumstances create the basis for the development of the principle of stationary helical rolling into a new constructive-technological quality, specifically focused on the production of bars of small sections.

References
[1] Ivanov M, Penkin A, Kolobov Yu, Golosov E, Nechaenko D and Bozhko S 2010 Warm cross-helical rolling in tapered rolls as a method of intense plastic deformation Deformation and fracture of materials 9 13–18
[2] Miyazaki T, Terada D, Miyajima Y, Suryanarayana C, Murao R, Yokoyama Y, Sugiyama K, Umemoto M, Todaka Y and Tsuji N 2011 Synthesis of non-equilibrium phases in immiscible metals mechanically mixed by high pressure torsion Mater. Sci V 46 42964301
[3] Galkin S, Khartonov E and Mikhailov V 2003 Reverse radial-shear rolling. Essence, opportunities, advantages Research methods Titanium 1 39–43
[4] Bogatov A, Panov E 2013 The effect of the stress-strain state during helical rolling on the structure and plasticity of metals and alloys Metallurg 63–69
[5] Naydenkin E, Mishin I and Ratochka I 2015 The effect of helical rolling and subsequent annealing on the structure and mechanical properties of titanium alloy BT22 Deformation and fracture of materials 4 32–46
[6] Roh J-H, Seo J-J, Hong S-T, Kim M-J, Han H and Roth J 2014 The mechanical behaviour of 5052-H32 aluminum alloys under a pulsed electric current Int. J. Plasticity Vol 58 84–89
[7] Derevyagina L, Gordienko A and Pochivalov Yu 2018 The effect of helical rolling on the fracture characteristics of low carbon steel at negative temperatures. Deformation and fracture of materials 2 32–46
[8] Naizabekov A, Arbuz A 2015 Effect of the helical rolling on the microstructure of steel 40X Bulletin of KazNTU Engineering science 5 249–255
[9] Ivanov K, Naydenkin E, Lykova O, Ratochka I, Mishin I and Vinokurov V 2017 Evolution of the structure and mechanical properties of the alloy BT6 during the helical rolling and subsequent deformation and heat treatments University Bulletin Physics 60(7) 126–132

[10] Tekoglu C, Hutchinson J and Pardoen T 2015 On localization and void coalescence as a precursor to ductile fracture Phil Trans R A Vol 373 20140121