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Improving of Manufacturing of Hot-Extruded Pipes from Ni-Based Alloys

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ABSTRACT

The paper shows the reasons for the growing demand for pipes made of materials with special properties, which include Ni-base alloy CrNi60WoTi. The article is dedicated to results of complex research of opportunity to improve outside surface quality of Ni-base alloy hot extruded pipe. The paper presents analysis of scientific and technical information to determinate the characteristic features of deformation of Ni-based alloys. In work presents the results of plastometric research of samples of metal from an alloy CrNi60WoTi, which made it possible to receive data of value of deformation resistance. According to the results of plastometric tests at the *Gleeble 3800* thermo-mechanical process simulator using the module *Hydrawedge*, metal flow curves were constructed. Using the selected dependence in the work, an approximation of the experimental data is shown based on this information, in the article presents results of calculation technological parameters of pipe extrusion process. This information was used on the factory to product of pilot industrial batch of pipes with an improved quality of outside surface that meets the requirements of Technical conditions (TC) 14-3R-85 without turning the outer surface.

1. INTRODUCTION

From the point of view of processing Ni-based alloys, can be divided into two groups. The first of these groups includes nylon alloys, which mainly consist of solid solutions and are hardened only to a very small extent due to the formation of titanium and chromium carbides in them. The second group consists of all other alloys of this type, which are hardened by the release of intermetallic compounds of titanium and aluminum. Most of the hot working operations are carried out within the temperature range in which the intermetallic compounds of the second group of alloys are in solid solution, resulting in significantly reduced strength and increased ductility of the alloy. These changes are favorable in terms of workability. Thus, all nimonic-type alloys tend to equalize properties at a rational hot working temperature, although the allowable temperature ranges are narrowed significantly for more complex alloys. Practically the above provisions mean that in the processing of more complex alloys, precise temperature control plays a more important role and that for these alloys, the degree of compression between the heating should be reduced. Due to the increased deformation resistance of complex alloys, more powerful equipment is required to conduct their hot processing.

The key to successful hot processing of nimonic alloys lies mainly in accurate temperature control and in observing the narrow temperature range of hot deformation. The grain size and mechanical characteristics obtained after heat treatment largely depend on the temperature of the last stages of hot processing, as well as on the cooling rate.

Currently, there is a significant increase in the consumption of pipe products by the leading, in terms of contribution to the gross domestic product, domestic industries [1]. Complex scientific and technical development of the oil, gas and energy sectors, dictates new, increasingly high requirements for pipe products [2]. At first, this is due to need for pipes made of materials with special characteristic, also with maximum possible ability to resist destruction under influence of aggressive corrosive environments, with the ability of pipes to resist hard operating conditions in general, high heat resistance, fatigue resistance etc. One of these materials that meet modern requirements are complex alloys, in particular, Ni-based alloys. The need for pipes made of Ni-based alloys always remains high in the early 80s of the XX century, it amounted to more than 500 thousand linear meters pipes per year. However, high alloying (simultaneously with an improvement in physicochemical and technological characteristic) often reduces ductility and the temperature range of maximum ductility to such an extent that it complicates the hot deformation of these alloys by rolling.

The process providing high deformability of metals and producing large deformation in one processing cycle, characterized by the best stress state scheme (comprehensive non-uniform compression) is hot extruding. However, successful (without destruction) extruding of highly alloyed Ni-based alloys is possible only if the temperature-deformation conditions are observed during all the time of technological process.

It has shown, in the researches of Russian scientists L. Prozorov, V. Jolobov, V. Ostrenko, S. Borisov, L. Stepanskiy, A. Pritomanov, Yu. Manegin and others, that heat-resistant alloys have a number of features that have a significant effect on the conditions of deformation: low plastic characteristics during deformation; high deformation resistance and high heating of the metal in the deformation zone.

In his works, Prof. I. Pavlov connected the cause of cracks in the metal with the formation of "hard ends". The formation of a "hard end" leads to equalization of the flow velocities of the inner and outer layers of the metal. Since the latter, under the action of external friction forces, tend to lag behind, and this is prevented by the integrity of the metal, internal tensile stresses arise in them. The accumulation of these stresses in the peripheral layers and can lead to the destruction of products.

Prof. S. Gubkin further developing the theory of crack formation, explore in more detail on the nature of changes in the stress state during extruding. The metal is affected by the main compressive stresses causing deformation and additional internal stresses (tensile at the periphery and compressive in the axial zone) associated with the unevenness of this deformation. Both types of stresses develop in the work. As the metal moves toward the exit from the matrix, the form of the stress state changes, the main ones drop and increase, due to the accumulation of additional internal stresses. Since at the output of the matrix, the main compressive stresses drop to zero, only internal stresses remain in the metal. If the value of internal tensile stresses in the surface layers exceeds the value of the true deformation resistance, a crack will appear in the metal, which will rush into the deformable product.

N. Kurpakov & S. Jemchujniy using the relaxation theory of K. Maxwell in the analysis of the process of extruded solid bodies, found that during the deformation of materials, simultaneously with the emergence and growth of internal stresses, processes of their removal and relaxation proceed. If the growth and stress relieving rates are compensated, then the destruction of bodies in the process of their deformation does not occur. Since relaxation processes occur over time, an increase in the latter leads to a greater release of internal stresses during the deformation itself and contributes to an increase in ductility. N. Kurpacks & S. Jemchujniy expressed the belief that if you change the conditions of deformation, including temperature, you can deform the same material both as a plastic body and a fragile body. The correctness of this thought was confirmed by the works of a number of scientists and practitioners.

Therefore, we conclude that in order to ensure the successful extruding of low-plastic materials, which include Ni-based alloys, it is necessary to find the optimal thermo-mechanical conditions of deformation for these materials and ensure the maximum possible uniformity of outflow. The latter can be achieved, in particular, by improving the conditions of contact friction, through the use of specially selected lubricants.

The conclusion about a limited range of ductility of Ni-based alloys was drawn by the Soviet scientist Vdovin [3] as well as modern research [4, 5]. Direct research on the extruding of hardly deformed heat-resistant alloys were conducted on the basis of the premise that the quality of the extruded products depends on the ratio of the growth rates and the removal of internal stresses that occur during deformation. In the work, the data on the choice of glass lubricants, the rational form of the matrix, and the workpieces set forth in the paper [6] were used. This made it possible to reduce the magnitude of the arising internal stresses by increasing the uniformity of the outflow of metal. An analysis of different methods for determining stress relaxation rates by Vdovin [3] showed that none of them can be used to find relaxation rates at temperatures of 1100 – 1200°C in the course of deformation processes occurring in fractions of a second.

The experimental results of researches to determine the critical ultimate degree of deformation when extrusion pipes from heat-resistant Ni-based alloys are presented in work [3]. The curve of the critical drawing coefficient [3] on the heating temperature is shown in Figure 1.

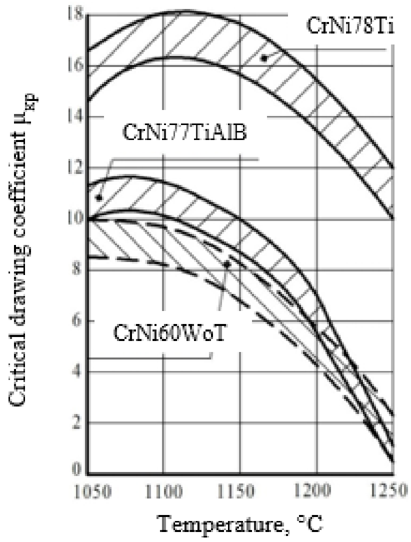


Figure 1. The curve of the critical drawing coefficient on the heating temperature

From Figure 1, constructed according to the regression equations [3], it can be seen that the dependence $\mu_{critical} = f(t)$ is dome-shaped, indicating the presence of a region of maximum ductility in each of the alloys. Figure 1 also shows that the more complex the alloying alloy, the lower the critical drawing coefficient, and the maximum plasticity is more shifted to the region of low billet heating temperatures before extruding. This is explained by the fact that, with an increase in the alloying complexity, the deformation resistance increases, and this, in turn, increases the heating of the metal in the deformation zone.

It is seeming, the above results of various researches confirm that the development of technology for the production of pipes from Ni-based alloys (including CrNi60WoTi) is limited by a narrow range of temperature-deformation conditions. In order to develop rational technological regimes for the manufacture of hot-extruded pipes from a Ni-base alloy CrNi60WoTi a plastometric research was carried out.

2. METHOD FLOW

According to the results of a number of studies of the influence of temperature and the degree of deformation on the hot extrusion force of pipes made of Ni-based alloys, it was determined that the value of specific pressure is influenced more by the deformation resistance than the drawing coefficient. According to the developed mathematical model, the authors obtained dependence for determining the specific pressure on the press washer, and, accordingly, the hot extrusion force of Ni alloys with high accuracy. It is established that the mathematical dependence of Prof. Prozorov L.V. gives the best convergence with experimental data in the range of drawing coefficients from 7.4 to 10.4. The mathematical dependence of J. Sejourne should be used only when determining peak forces of extrusion process.

The aim of this work is to study the properties of uniaxial precipitation of samples of Ni-based alloy CrNi60WoTi grade used for the production of hot-extruded pipes.

The methodology for plastometric studies included welding to the central part of the sample a control chromel-alumel thermocouple, placing the sample in a working chamber with vacuum, and directly testing.

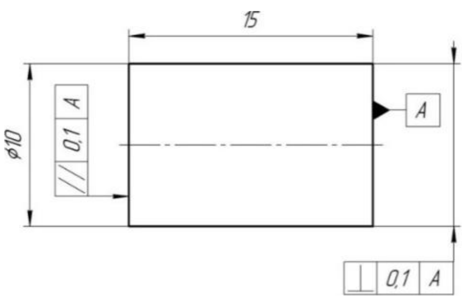
In order to avoid melting the sample to the surface of the working tool (carbide die), a 0.1 mm thick molybdenum foil was placed between the sample and the hammer. A sample placed in a working chamber with vacuum was heated by direct transmission of electric current. The samples were heated to a deformation temperature at a rate of 5 °C/sec., followed by isothermal exposure for 3 minutes to equalize the temperature over the volume of the sample. The methodology for plastometric studies considered in detail in the papers [7–9].

3. EXPERIMENTAL PART

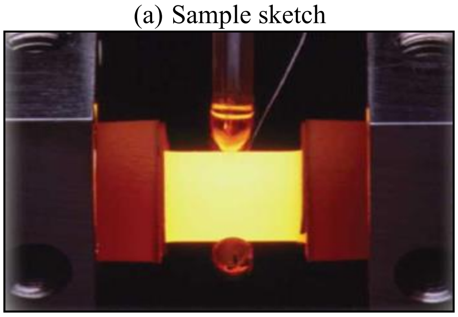
Hot deformation was modeled by uniaxial compression (upsetting) on the *Gleeble 3800* thermo-mechanical process simulator using the module *Hydrawedge* (Figure 2). Modes of plastometric research are presented in Table 1.

Compression deformation was carried out to the maximum value ε=1.2 ... 1.3 for the type of testing on the *Hydrawedge* module. Figure 3 shows the results of tests for uniaxial compression (upsetting) of an alloy CrNi60WoTi.

The predominantly good reproducibility of the deformation curves is observed (the spread is no more than 20 MPa) for each temperature-speed deformation mode: the curves corresponding to the samples cut in the transverse direction (highlighted in blue in Figure 3) are located at the same level as the curves corresponding to specimens cut in the longitudinal direction (highlighted in red in Figure 3). The exception is 1100°C; 1.0 sec.$^{-1}$, in which, for specimens cut in the longitudinal direction, lower yield stresses and higher values of the hardening coefficient are observed in comparison with specimens cut in the transverse direction.



(a) Sample sketch



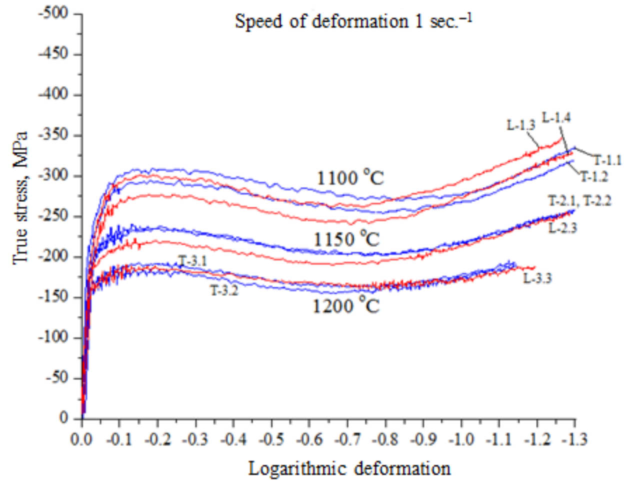
(b) Compression load scheme

Figure 2. Compression sample sketch and compression load scheme

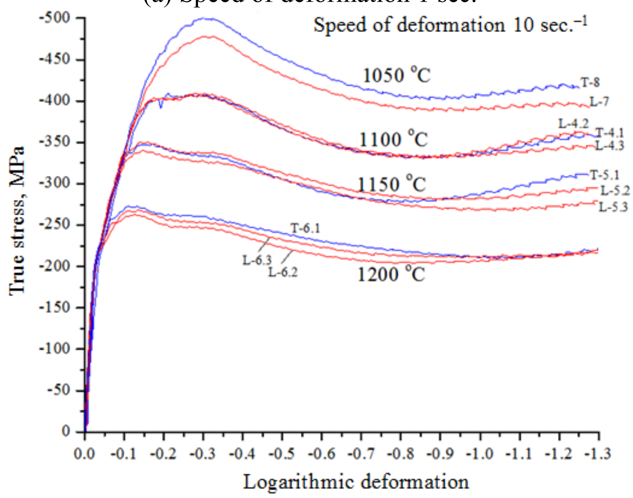
Table 1. Modes of the plastometric research

Deformation's speed, sec.$^{-1}$	Temp., °C	Sample's nu., pcs	Sample labeling[1]
1	1100	3	T-1.1, T-1.2, L-1.3, L-1.4[2]
	1150	3	T-2.1, T-2.2, L-2.3
	1200	3	T-3.1, T-3.2, L-3.3
10	1100	3	T-4.1, L-4.2, L-4.3
	1150	3	T-5.1, L-5.2, L-5.3
	1200	3	T-6.1, L-6.2, L-6.3
10	1050	1	L-7
	1050	1	T-8

Notes: 1. *L* – longitudinal sample, *T* – transverse sample. 2. An additional sample of *L*-1.4 was tested at the initiative of the performer in connection with the observed high variation in mechanical characteristics for the given regime.



(a) Speed of deformation 1 sec.$^{-1}$



(b) Speed of deformation 10 sec.$^{-1}$

Figure 3. Curve of deformation alloy CrNi60WoTi

The shape of the deformation curves is typical of Ni-based alloys at high temperatures: there is stage of hardening, followed by softening after reaching the peak stress value. Softening may be due to various factors: dynamic return and / or recrystallization, polygonization, structural transformations, etc. (additional microstructural researches are needed to establish a specific mechanism). In addition, for high deformation rates, the softening effect is exerted by deformation heating.

On Figure 4 are presented typical photos of samples Ni-bases alloy CrNi60WoTi after deformation (deformation degree ~1.3).

Figure 4. Photos of samples allow CrNi60WoTi after hot upsetting with deformation degree ~1.3: *T*=1050°C, U_c=10.0 sec.$^{-1}$, longitudinal and transverse (from left to right)

The performed plastometric study indicates the following features of the deformation.

During deformation at a rate of 1 sec.$^{-1}$ at a temperature of 1100°C, there is a significant variation in the values of deformation resistance (within 50 MPa for all samples and within 25 MPa for samples of the same orientation). At such a strain rate, a significant decrease in temperature is observed (the absence of deformation heating), which in turn causes an increase in stresses at which the anisotropy of the material properties is most pronounced. This is also evidenced by the presence of slight ellipticity on samples T-1.1, T-1.2, L-1.3, L-1.4. For a strain rate of 10 sec.$^{-1}$, which corresponds to the design speed of the stamp during the pressing process of 190…200 mm/sec., the anisotropy of the plastic properties is much lower, the spread does not exceed 15 MPa (regardless of the orientation of the sample).

An excellent picture, from the one described above, is observed for a deformation temperature of 1150°C. In this case (Figure 4**)**, at a lower strain rate, the scatter of values is practically absent, in contrast to a strain rate of 10 sec.$^{-1}$. This is probably due to the place of sampling, which was not taken into account in this study, since the uniformity of the properties is estimated by the metallographic method.

At a deformation temperature of 1050°C, a rougher lateral surface of the samples and significant yield stresses (up to 500 MPa) are observed; therefore, the indicated temperature is not rational when assigning heating modes.

From the point of view of a rational heating temperature, when the degree of deformation is 1.3, any damage and chips on the samples are not destroyed, but taking into account the experience known in scientific and technical practice [3–5], the critical drawing coefficient decreases with increasing heating temperature.

4. RESULTS PROCESSING

In the article, experimental data were processed [10, 11] (obtained curves of metal flow). As a dependence approximating the experimental data was selected the function:

$$\sigma_s = k_0 \varepsilon^{k_\varepsilon} u^{k_u} exp(k_\theta \theta) \quad (1)$$

ε − logarithmic degree of deformation;
u − speed of deformation;
θ − temperature of deformation;
$k_0, k_\varepsilon, k_u, k_\theta$ − rheological coefficients.

In accordance with the data processing, the tabular value of the Cochran's statistic for data series ($G_{\text{т}}$) at a significance level α=95%, degrees of freedom $f_1 = N = 8$ и $f_1 = \gamma - 1 = 2$ is equal 0,5157 [8]. The actual value of the Cochran's statistic for data series ($G_{\text{э}}$):

$$G_{\text{э}} = \frac{S^2(Y_u)_{max}}{\sum_{u=1}^{8} S^2(Y_u)} = 0{,}3294 \quad (2)$$

$G_{\text{э}}$ − Cochran's statistic coefficient;
S − progressive dispersion;
Y_u − arithmetical mean of progressive dispersion.

Because $G_{\text{э}} < G_{\text{т}}$ the measurements are homogeneous with a probability level of 95%. According to the results of processing experimental data, the methodology of which was discussed in detail in the paper [9], with the error $S_{\bar{y}}$ =1,13% the following expression was obtained:

$$\sigma_s = 15\,170\, \varepsilon^{0{,}016} u^{0{,}67} exp(-0{,}0042\theta) \quad (3)$$

σ_s − deformation resistance;
ε − logarithmic degree of deformation;
u − speed of deformation;
θ − temperature of deformation.

At a deformation temperature of 1050°C, a rougher lateral surface of the samples and significant yield stresses (up to 500 MPa) are observed. This temperature is not rational when assigning heating modes.

From the point of view of a rational heating temperature, when the degree of deformation is ~1.3, any damage and chips on the samples are not destroyed, but taking into account the experience known in scientific and technical practice [3–6], with an increase in the heating temperature, the critical drawing coefficient declining. For example, the data of Figure 1 indicate the value of the critical drawing coefficient of ~6.0 at a temperature of 1200°C. In project technology, the drawing coefficient for extruding pipe's sizes 89.0×11.0 mm is ~ 7.37. The rational temperature range is from 1110 to 1140°C. Taking into account the smaller height of the gauge section of the matrix in comparison with that reflected in the experimental data [12] (6 mm instead of 15 mm) and taking into account the best lubricating properties of glass-lubricant materials, the rational temperature range of heating the billets for extruding can be shifted upward (from 1130 to 1160°C) in order to reduce the extruding force.

To assess the level of energy-power parameters, taking into account the design technology for manufacturing hot-extruded pipes, the maximum (peak) extruded force was determined by the equation of Sejournet et al. [12, 13]:

$$P_{\max} = \frac{\pi}{4}\left(D_{con.}^2 - d_{ex.need.}^2\right) \cdot \sigma_S \cdot \ln(\mu) e^{\frac{4fl}{D_{con.} - d_{ex.need.}}} \quad (4)$$

$D_{con.}$ − diameter of pipe-extruding's container;
$d_{ex.need.}$ − diameter of an extruding needle;
f − coefficient of friction on metal-tool contact surfaces;
l − length of the sleeve after pre-extruded state.

The values of these variables for calculating the extruding force of pipe's sizes 89.0×11.0 mm is presented in Table 2. The performed calculations require observance of the technology for applying lubricants to the workpieces in order to provide the coefficient of friction (*f*) indicated in Table 2.

The list of the main technological operations in the production of pipes on the extrusion press-line with an effort of 20.0 MN is presented on Figure 5.

Table 2. The values of the variables of the dependence of Sejournet to calculate the extruding force

Size of pipes, mm	89.0×11.0
$D_{con.}$, mm	176
$d_{ex.need.}$, mm	68.4 / 37.6 (groove)
f [3, 12, 13]	0,02
l, mm	≈ 620
σ_s, MPA	330,0…360,0
μ	7,37 / 4,34 (reduction efforts)

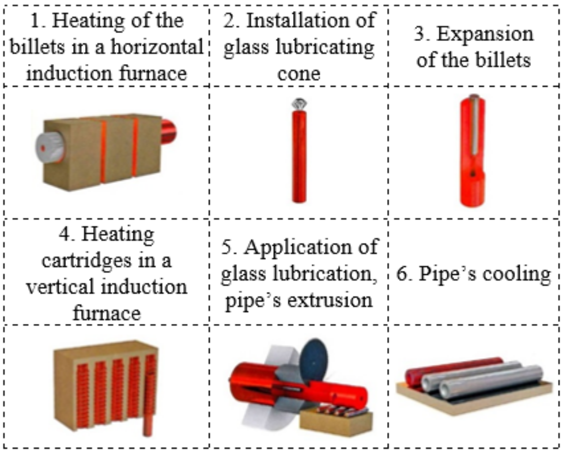


Figure 5. The list of the main technological operations in the production of pipe's extrusion

Table 3. The results of the calculation of the peak extruding force of pipe's sizes 89.0×11.0 mm

Temperature of plastic deformation, °C	Before reduction efforts, MN	After reduction efforts, MN
1140	23.5	17.5
1160	21.5	16.0

Table 3 presents the results of calculating the pipe extruding force as a function of the deformation temperature.

Based on the calculation practice, the peak extruding force is on average 15% [7–9, 13, 14] higher than the calculated values using real values of deformation resistance. Therefore, it is worth accepting the level of peak efforts from 19.0 to 20.0 MN, according to the principle presented by Zhang et al. [15]. Pipe's cooling may be carried out in various ways, including as shown by Driss et al. [16].

As can be seen from the calculated data of Table 3, according to the actual values of the deformation resistance, the selected temperature range makes it possible to produce pipes from an alloy CrNi60WoTi with dimensions 89.0×11.0 mm using technology with the removal of the peak force on a wall with a thickness of 26,0 mm.

Using the temperature and speed regime, a pilot batch of pipe's sizes 89.0×11.0 mm was produced from an alloy CrNi60WoTi, the purpose of which was to improve the quality of the surface of pipes with the exception of the operation to circumvent the outer surface.

5. DISCUSSION

The fundamental factors for ensuring the competitiveness of products are the quality and costs of production, which form the cost and price. In the cost of production of steel pipes, the bulk of the cost falls on metal - from 75…80%.

Cost-effective management of technological processes involves the development of relevant consumption rates for any type of material resources, including metal, established taking into account the current level of technology, the introduction of advanced methods and techniques.

Therefore, the results of studies of the deformation characteristics of Ni-based CrNi60WoTi are of value for the development of an individual technology for a working metallurgical enterprise.

Equation of Sejournet et al. [12, 13] for calculating the maximum extrusion force has proven itself when used with pipes made of steel and alloys. Therefore, it is one of the sufficient parts of the mathematical apparatus for predicting the loads on the deforming tool of the press.

Ni-based complex alloys have an extremely narrow range of ductility (temperature range and interval of critical degrees of deformation), which distinguishes these alloys, for example, from chromium-nickel. For an alloy of the CrNi60WoTi grade, the maximum value of the drawing coefficient obtained by extrusion pipes without breaking is in the range from 8 to 9. This is due to the fact that with an increase in the drawing coefficient, the non-uniformity of the degree of shear strain along the pipe wall thickness increases. At actual extrusion temperatures of the CrNi60WoTi alloy (1100…1150°C) and drawing coefficients from 8 to 10, the strain heating reaches from 120 to 165°C.

It is possible that in the development of the topic of studying the deformation feature of Ni-based alloys, it will be of further interest to carry out physical modeling of the tensile process of samples using the multifunctional complex *Gleeble 3800*. Then it is possible to compare the results.

6. CONCLUSIONS

The paper presents the results of improving of manufacturing of hot-extruded pipes from Ni-based alloys by the scientific research at improving the manufacturing technology of hot extruded pipes from the Ni-based alloy CrNi60WoTi grade on existing equipment of the, while ensuring the required according to the normative quality documentation [17] of finished pipe parameters.

It is shown in the work that plastic deformation of a hard-deformed heat-resistant of Ni-based alloy CrNi60WoTi grade is accompanied by high values of the force parameters of the pressing process that go beyond the maximum allowable. At the same time, this alloy has a limited range of deformation temperatures, at which it is possible to obtain the required surface quality of the hot-pressed pipes.

As a result of the experiment and technical information, the following characteristic features of the deformation of Ni-based alloy CrNi60WoTi by hot deformation were determined.

(1). Complex alloyed Ni-based alloys as CrNi60WoTi have an extremely narrow ductility interval (narrow temperature range and interval of critical degrees of deformation), which distinguishes these alloy's group.

(2). The analytical determination of the limiting degree of deformation indicates the following features:

- the degree of shear deformation reaches its maximum value at the exit from the deformation zone;

- the degree of shear deformation is uneven in the thickness of the pipe wall and on the inner surface is higher than on the outer. This suggests that the inner surface of the pipe is in more severe conditions than the outer, and therefore more susceptible to cracking;

- with an increase in the drawing coefficient, the unevenness of the degree of shear deformation along the wall thickness increases;
- with an increase in the coefficient of friction at the metal-tool contact, the degree of shear strain on the inner surface of the pipe increases.

Thus, according to the analysis results, the main features of hot plastic deformation of Ni-based alloys are established, in particular, by hot extrusion on horizontal hydraulic pipe's extrusion presses. The indicated deformation features were taken into account during the subsequent development of the technology of hot extrusion pipes from an alloy of the grade CrNi60WoTi.

It is seems, that with a systematic approach to the development of production technology, a pilot batch of hot-extruded pipes with an improved quality of the outer surface was obtained, which eliminated the labor-consuming operation of turning and the outer surface and ensured compliance with the requirements of TC 14-3R-85 [17].

Explanations and conclusions on the results of manufacturing hot extrusion pilot batch of pipe's sizes 89.0×11.0 mm was produced from an alloy CrNi60WoTi:

(1). Actual metal savings in the preparation section compared to the plan, in the amount of 1.7 kg/t, are caused by a slight difference in the cutting of the received rods.

(2). The actual metal savings in the pressing section compared to the plan, in the amount of 3.2 kg/t, is due to an insignificant difference in the actual parameters of the press balances compared to the planned ones.

(3). In fact, the resulting metal loss during pickling and chemical treatment of pipes fully corresponds to the planned value.

(4). The planned input coefficient of metal for finishing includes only trimming of defects during pipe repair, in the amount of 4%. Finishing operations, such as trimming the front thickened end, sampling for quality control at the pipe finishing section, trimming the pipe ends, as well as defective pipes, are completely transferred to the production facilities of the customer.

(5). The actual metal savings in the pipe finishing section compared to the plan, in the amount of 9.9 kg/t, are due to the lower volume of waste generated during pipe repair relative to the planned one.

(6). In general, over the entire technological cycle, the actual indicators of metal consumption are close in comparison with the planned ones.

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