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FUNCTIONAL PROPERTIES OF PLASTIC DEFORMATION RESISTANCE OF 12KH18N10T STEEL

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Abstract. The resistance of metals and alloys to plastic deformation has functional properties, since it depends on the history of the development of deformation over time. This is especially true for hot deformation processes. At the same time, complexity of the mathematical description and lack of the necessary experimental equipment for a long time did not allow us to design functionals of this type. Currently, due to the emergence of multifunctional research complexes like Gleeble, such an opportunity has appeared. Accordingly, a methodology was developed to study the functional properties of the resistance of metals and alloys of plastic deformation, which was applied to the study of 12Kh18N10T steel. The choice of steel grade is due to the fact that the behavior of austenitic stainless steel during plastic deformation differs significantly from carbon steels. On the other hand, at present, more and more attention is being paid to the production of metal products from stainless steels. This is due, on the one hand, to the tightening of the operating conditions of metal products, the development of new areas of their application and, on the other hand, a fairly high share of imports in the market of products made of austenitic stainless steels. Therefore, the study of the technological properties of such metals and alloys is relevant. At the same time, it should be noted that the most significant functional properties of the metal resistance to plastic deformation are manifested during hot deformation under continuous rolling conditions. Therefore, in this paper, the temperature range of hot plastic deformation is investigated. The results obtained can be used to determine the energy-power parameters in such processes as continuous rolling of strips in the finishing groups of strands and continuous rolling of sleeves in the lines of modern pipe rolling units.

Keywords: continuous rolling, metal resistance to plastic deformation, hot deformation, history of deformation, austenitic class, technological properties of metal, energy-power parameters

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ФУНКЦИОНАЛЬНЫЕ СВОЙСТВА СОПРОТИВЛЕНИЯ ПЛАСТИЧЕСКОЙ ДЕФОРМАЦИИ СТАЛИ 12Х18Н10Т

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Аннотация. Сопротивление металлов и сплавов пластической деформации имеет свойства функционала, так как зависит от истории развития деформации во времени. Особенно это характерно для процессов горячей деформации. Вместе с тем сложность математического описания и отсутствие необходимого экспериментального оборудования долгое время не позволяли конструировать функционалы подобного типа. В настоящее время в связи с появлением многофункциональных исследовательских комплексов типа Gleeble такая возможность появилась. Соответственно была разработана методика исследования функциональных свойств сопротивления металлов и сплавов пластической деформации, которая была применена для исследования стали 12Х18Н10Т. Выбор марки стали обусловлен тем, что поведение нержавеющей стали аустенитного класса при пластическом деформировании существенно отличается от углеродистых сталей. С другой стороны, в настоящее время вопросам производства металлоизделий из нержавеющих марок стали уделяется все больше внимания. Это связано, с одной стороны, с ужесточением условий эксплуатации металлоизделий, освоением новых областей их применения и, с другой стороны, достаточно высокой долей импорта на рынке изделий из нержавеющих марок стали аустенитного класса. Поэтому исследование технологических свойств подобных металлов и сплавов является актуальным. При этом следует отметить, что наиболее заметно функциональные свойства сопротивления металла пластической деформации проявляются при горячем деформировании в условиях непрерывной прокатки. Поэтому в данной работе исследован температурный интервал горячей пластической деформации. Полученные результаты могут быть использованы для определения энергосиловых параметров в таких процессах, как непрерывная прокатка полос в чистовых группах клетей и непрерывная раскатка гильз в линиях современных трубопрокатных агрегатов.

Ключевые слова: непрерывная прокатка, сопротивление металла пластической деформации, горячая деформация, история деформирования, аустенитный класс, технологические свойства металла, энергосиловые параметры

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Introduction

The most productive and efficient method for manufacturing long metal products is continuous rolling. Recently, this method has been widely used in the production of rolled sections, strips, and pipes [1 – 3]. On the other hand, the quality of the final product rolled on continuous mills is significantly influenced by the adjustment of the mill's rate mode, which, in turn, determines the level of energy-power parameters. Therefore, to establish an optimal rate mode for the continuous rolling process, it is necessary to have relationships that link the kinematic parameters with the forces acting on the deformation zone boundaries.

Several studies [4 – 6] describe a methodology for determining such relationships. Analysis of the results obtained using this methodology for calculating rolling forces in continuous rolling has shown that the calculated values correspond quite well to actual values but are consistently underestimated. It should be noted that the rolling force is directly proportional to the metal's resistance to plastic deformation [7]. Further research has revealed that commonly used methods for calculating the resistance of metals to plastic deformation [8; 9] provide underestimated results when calculating the technological parameters of continuous rolling processes. This discrepancy arises because these methods do not account for the actual transformation of strength properties, particularly the residual strengthening after rolling in the previous stand of the mill. The effect of deformation history on the resistance of metals to plastic deformation during continuous hot strip rolling is also noted in [10]; however, the modeling employs expressions similar to those mentioned earlier. The above observations highlight the need for additional research into the resistance to plastic deformation of various steel grades.

One of the most in-demand types of metal products is seamless pipes made from stainless steel grades, particularly 12Kh18N10T [11]. Since continuous rolling is the most productive and economically efficient process for shell rolling in the production of seamless pipes [12; 13], studying the patterns of plastic deformation resistance formation in 12Kh18N10T steel during continuous rolling is highly relevant.

Research methods

In this study, experiments were conducted using the modern universal testing system Gleeble 3800 [14 – 16] in a vacuum environment (low vacuum) on the PocketJaw module, with chromel-alumel thermocouples welded to the samples (for temperature control during heating and measurement of deformation-induced heating). The samples were heated at a rate of 5 °C/s to the test temperature, followed by a 5-min hold, using electric current. High-temperature sensors for longitudinal and transverse deformation were used to measure deformation.

To determine the strain hardening rate of the steel, tensile tests were conducted at room temperature. The working hypothesis assumed that softening processes were absent under these conditions.

The behavior of metal resistance to plastic deformation during testing depends on its initial value, which, in turn, is influenced by the heating temperature. Therefore, a separate series of tensile tests was conducted on 12Kh18N10T steel samples at temperatures ranging from 800 to 1200 °C in 100 °C increments.

To determine the softening rate, stepwise tensile testing of cylindrical samples was performed with varying pause durations at temperatures from 800 to 1200 °C in 100 °C increments. It was assumed that during the pauses, no hardening processes occurred, and the decrease in stress characterized the softening rate.

All experimental data were processed using the least squares method in accordance with the methodology presented in [17].

Results

The general appearance of the strain hardening curves for 12Kh18N10T stainless steel, obtained from uniaxial tensile tests at various temperatures, is shown in Fig. 1.

The approximation of the strain hardening curve was based on results obtained at a temperature of 25 °C (Table 1).

In [18], it is noted that a power-law relationship is well-suited for approximating the dependence of the plastic deformation resistance of metals and alloys on strain

Table 1. **Plastic deformation resistance of 12Kh18N10T steel at 25 °C**

Таблица 1. **Сопротивление пластической деформации стали 12Х18Н10Т при температуре 25 °С**

Logarithmic strain	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Stress, MPa	380	530	600	720	790	900	980	1100	1170	1270

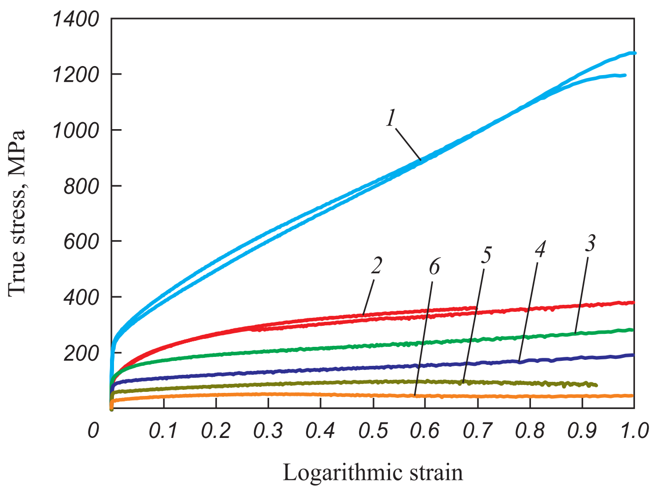

Fig. 1. Influence of logarithmic strain measure and temperature on plastic deformation resistance of 12Kh18N10T steel at temperature, °C:
1 – 25; *2* – 800; *3* – 900; *4* – 1000; *5* – 1100; *6* – 1200

Рис. 1. Влияние логарифмического показателя деформации и температуры на сопротивление пластической деформации стали 12Х18Н10Т при температуре, °С:
1 – 25; *2* – 800; *3* – 900; *4* – 1000; *5* – 1100; *6* – 1200

level in cold conditions. Processing the experimental data using the least squares method yielded the following equation for 12Kh18N10T steel

$$\sigma_{s0} = 200 + 1064\varepsilon^{0.78},$$

where ε is the logarithmic strain.

The statistical processing of experimental data (Table 2) also made it possible to determine the nature of the temperature's influence on the initial resistance of 12Kh18N10T steel to plastic deformation.

The resulting empirical relationship can be represented as:

$$\sigma_{s0}(\theta_0) = 200\left(\frac{1350-\theta_0}{1325}\right)^{0.87},$$

where θ_0 is the heating temperature of the sample.

It should be noted that the plastic deformation resistance of 12Kh18N10T steel in tensile tests has been previously studied. For example, in [19], based on extensive experimental research, an original methodology was proposed. According to this methodology, regardless of the steel grade, the ratio of the actual value of the metal's plastic deformation resistance σ_s to the average σ_{sc} for a given strain ε remains constant. The average plastic deformation resistance value is determined experimentally. Specifically, at South Ural State University, using this methodology and a cam plastometer, the following relationship was obtained for 12Kh18N10T steel:

$$\sigma_{sc} = 1892u^{0.0974}\varepsilon^{0.2637}\exp(-0.0022t),$$

where u is the strain rate; t is the heating temperature.

At the same time, it should be noted that the reliability of the results obtained thus far requires verification, as the equipment, methodologies, and measurement techniques used had certain errors.

On the other hand, the capabilities of modern research equipment significantly enhance the accuracy of results and broaden their applicability. In particular, stepwise loading of samples now enables the study of softening behavior during inter-deformation pauses. Similar studies using the Gleeble 3800 universal testing system are known [20], although they primarily focus on examining the metal structure. Therefore, stepwise tensile tests were conducted to obtain the relationship of the softening coefficient [8] as a function of temperature. As an example, Fig. 2 shows a record of the changes in the metal's plastic deformation resistance, taking into account the inter-deformation pause.

As a result, processing the presented experimental data using the least squares method yielded the following relationship:

$$k = 4.75\frac{1350-t}{t-25} - 0.93.$$

Table 2. **Initial value of plastic deformation resistance of 12Kh18N10T steel at different temperatures**

Таблица 2. **Начальное значение сопротивления пластической деформации стали 12Х18Н10Т при различных температурах**

Parameter	Temperature, °C				
	800	900	1000	1100	1200
Stress, MPa	100	100	60	40	30
Calculated value, MPa	93.07	78.16	62.81	46.87	30.05
Error, %	6.9	21.8	4.7	17.2	0.2

Analysis and discussion of results

The investigation of the plastic deformation resistance of 12Kh18N10T steel confirmed the existing information regarding the intensive strain hardening of this steel grade during cold deformation. The hardening behavior is accurately described by a power-law relationship.

The proposed new relationship for the initial plastic deformation resistance of 12Kh18N10T steel as a function of heating temperature provides a satisfactory qualitative and quantitative description of this dependence. A relatively large error is observed at a temperature of about 900 °C. However, on the other hand, the shell rolling process occurs at higher temperatures, where the proposed relationship shows good agreement with the actual data. Nevertheless, the search for a more suitable regression equation remains an open question.

The temperature dependence of the softening coefficient for 12Kh18N10T steel was determined for the first time. Previously, no attempts had been made to include a constant term in this equation. An analysis of the proposed relationship revealed that, according to calculations, the softening coefficient may take negative values at higher temperatures. This outcome lacks physical validity, as the softening coefficient represents the time required for the metal to fully soften. To address this issue, the constant term in the formula should be set to zero or higher. However, calculations indicate that this adjustment compromises the accuracy of the approximation at lower temperatures. Therefore, it is suggested to retain the current formula but assign a value of zero to the softening coefficient in cases where negative values are calculated. Alternatively, a more suitable regression equation could be developed to address this issue.

The investigation of the softening behavior of 12Kh18N10T steel at high temperatures revealed a distinct characteristic: it exhibits more intense softening between reductions compared to, for instance, ferritic-pearlitic steels [8].

As previously demonstrated [17], to determine the actual value of metal plastic deformation resistance while accounting for its time-dependent evolution, the entire duration of the deformation process, including pauses between reductions, is divided into discrete time intervals. For each i-th time interval, the plastic deformation resistance is calculated using a recursive formula.

The results of the study on the plastic deformation resistance of 12Kh18N10T steel allow for the proposal of the following recursive equation for determining this resistance within the temperature range of 900 – 1200 °C

$$\sigma_{si} = 200\left(\frac{1350-\theta_0}{1325}\right)^{0.87} + $$
$$+\sum_{i=1}^{m}\left\{1064\left(\varepsilon_i^{0.78}-\varepsilon_{i-1}^{0.78}\right)+\left(\sigma_{s(i-1)}-\sigma_0\right)\times\right.$$
$$\left.\times\left[\exp\left(-\frac{\Delta\tau_i}{4.75\dfrac{1350-t}{t-25}}\right)-1\right]\right\},$$

where i is the number of the time interval into which the deformation time is divided; m is the total number

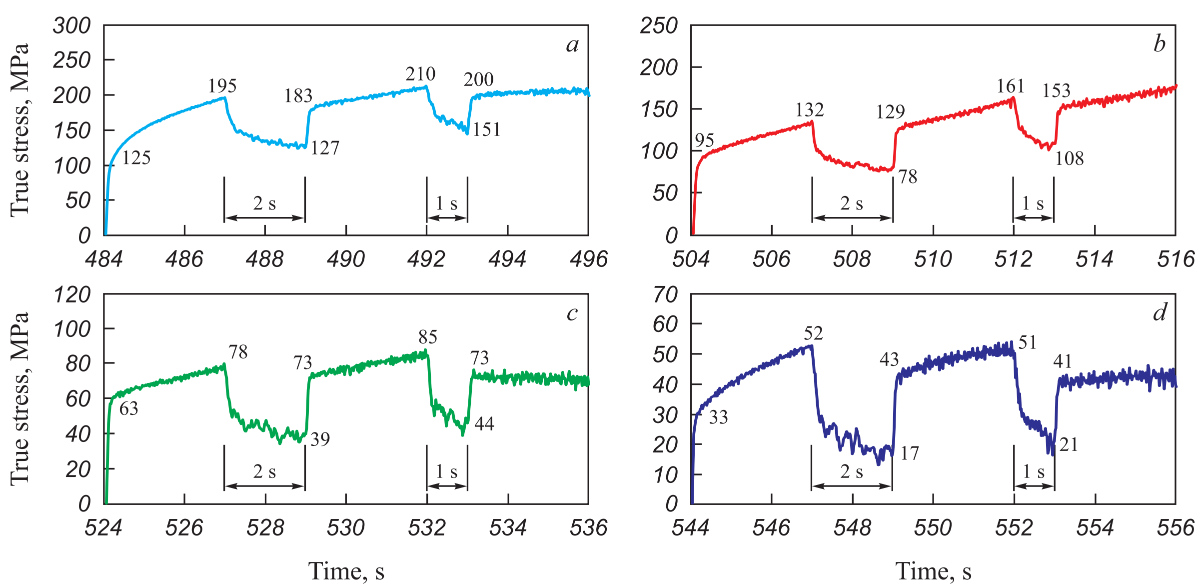

Fig. 2. Change in plastic deformation resistance of 12Kh18N10T steel under stepwise tension at temperature, °C: *a* – 900; *b* – 1000; *c* – 1100; *d* – 1200

Рис. 2. Изменение сопротивления деформации стали 12Х18Н10Т при ступенчатом растяжении при температуре, °С: *а* – 900; *b* – 1000; *c* – 1100; *d* – 1200 of time intervals into which the deformation time is divided; $\Delta\tau_i$ is the duration of the time interval.

Conclusions

The plastic deformation resistance of 12Kh18N10T steel in the hot state was studied. In addition to determining specific empirical coefficients, a notable characteristic of stainless steel deformation was identified – a significantly higher softening rate compared to ferritic-pearlitic steels.

The extensive experimental data collected can be used to calculate the deformation parameters and energy-power characteristics of the continuous shell rolling process for austenitic stainless steels on mills equipped with a controlled moving mandrel.

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Contribution of the Authors

A. V. Vydrin – developing theoretical principles of functional properties of metal resistance to plastic deformation.

A. V. Krasikov – generalization of results.
A. A. Korsakov – processing experimental data.
E. A. Geim – conducting experimental studies.

Вклад авторов

А. В. Выдрин – разработка теоретических принципов функциональных свойств сопротивления металла пластической деформации.
А. В. Красиков – обобщение полученных результатов.
А. А. Корсаков – обработка экспериментальных данных.
Е. А. Гейм – проведение экспериментальных исследований.

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