



Received: 08/02/2026

Revised: 23/04/2026

Accepted: 26/06/2026

Published online: 30/06/2026

Original Research Article



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UDC 531.43; 621.8

A UNIFIED ANALYTICAL MODEL FOR DEFORMATION RESISTANCE OF METAL UNDER THERMOPLASTIC PROCESSING CONDITIONS

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Abstract. A unified analytical framework is developed to describe the deformation resistance of metals under thermoplastic processing conditions. The proposed approach is based on the Hansel-Spittel constitutive equation and establishes a direct relationship between yield stress and the key thermomechanical parameters of deformation, including strain, strain rate, and temperature. An analytical solution of the spatial plasticity problem is obtained using harmonic functions, enabling the determination of stress intensity at any point within the deformation zone. The formulation integrates the Huber-Mises plasticity criterion with frictional and geometric factors, resulting in a closed-form expression that links the local stress strain state to process parameters. The model accounts for non-uniform and multi-stage deformation characteristic of rolling and contact loading processes. Its applicability is demonstrated for thermoplastic loading of surface layers in tribological contacts, where deformation resistance plays a decisive role in wear and fatigue damage accumulation. The developed analytical model provides an efficient tool for predicting energy-force parameters and assessing surface layer behavior under complex thermomechanical loading. The proposed framework can be directly applied in engineering calculations, process optimization, and the design of metal forming and tribological systems.

Keywords: deformation resistance; thermoplastic processing; plasticity theory; tribological contact; surface layer damage.

1. Introduction

In thermoplastic processing of metallic materials, including rolling, forging, and contact loading in tribological systems, deformation resistance is one of the key parameters governing energy consumption, force characteristics, and the resulting service performance of components. Accurate prediction of deformation resistance is essential for the rational design and optimization of metal forming processes, as well as for assessing wear and fatigue damage in surface layers subjected to complex loading conditions [1].

Deformation conditions play a decisive role in shaping both the mechanical response of the material and the evolution of its microstructure. Variations in strain, strain rate, and temperature directly affect hardening, recovery, and dynamic recrystallization processes, which in turn determine the stress strain state within the deformation zone. As a result, reliable models describing the dependence of deformation resistance on thermomechanical parameters are required to ensure adequate prediction of energy-force parameters and material behavior under real processing conditions.

In recent years, numerical simulation methods, particularly finite element modeling, have become widely used for analyzing thermoplastic deformation processes [2, 3]. However, the accuracy of such simulations strongly depends on the quality of the constitutive description of the material. In addition to precise

characterization of physical and chemical properties, it is necessary to establish analytical relationships that adequately reflect the evolution of mechanical characteristics during deformation. In many engineering applications, the absence of closed-form solutions complicates rapid parametric analysis and limits the applicability of numerical models at early design stages.

Deformation resistance is commonly treated as a rheological characteristic of metals, representing the stress required to sustain plastic flow under specific thermomechanical conditions [4, 5]. In technological processes such as continuous rolling, this parameter determines the stress level in the deformation zone and significantly influences the mechanical properties of the final product. Therefore, the development of physically substantiated and mathematically tractable models for deformation resistance remains an important engineering task.

Existing experimental and semi-empirical approaches provide valuable insights into the dependence of yield stress on deformation parameters; however, the reported results are often inconsistent, particularly with respect to strain rate sensitivity and temperature effects [6]. Moreover, many available models are limited to monotonic deformation paths and do not fully capture the non-uniform and multi-stage nature of real industrial processes [7, 8]. Under such conditions, yield stress may increase, decrease, or remain nearly constant depending on the balance between hardening and softening mechanisms, highlighting the need for more flexible constitutive descriptions.

The rolling process represents a generalized case of thermoplastic loading, characterized by spatially non-uniform stress and strain distributions within the deformation zone. For sheet and section rolling, as well as for contact loading in tribological joints, an analytical solution of the three-dimensional plasticity problem is particularly valuable, as it allows the stress state to be evaluated at any material point rather than relying on averaged parameters.

2. Materials and methods

The most common methods of theoretical research of technological processes of processing metals by pressure, both hot and cold, are mathematical and simulation modeling.

At each moment of the technological process of rolling, especially in a continuous process, the metal is in completely different deformation and stress states at a single point of the deformation center [9, 10]. This leads to inhomogeneity of the physical and mechanical properties of the metal, ambiguity in determining the power parameters of the process, energy consumption.

Their is known complex nature of the metal flow curve, presented in Fig. 1 [11].

The dependence is characterized by the growth of σ_s from the yield strength σ_0 to a certain peak value σ_p corresponding to the peak deformation ε_p , then σ_s decreases to the steady-state stress σ_y , at which the equilibrium of the hardening and dynamic recrystallization processes occurs.

On the other hand, the flow curve of the metal also indicates the nature of the change in austenite. In the area of hardening, before the deformation value ε_p is reached, grain refinement occurs, the density of dislocations in the substructure increases, after which the process of dynamic recrystallization develops intensively, and according to, the size of the austenite grain depends exclusively on the stress σ_y .

In his scientific work A. Nadai proposed an equation for determining the resistance to deformation of a metal, taking into account temperature, relative deformation, hardening in time, stress changes, depending on the deformation rate taking into account the viscosity of the metal. The authors in work [11] considered the positive and negative sides of this equation, and established that the laws necessary for solving the equation proposed by A. Nadai are quite complex and require improvement. Thus, in practical applications, the determination of σ_s relies on experimental data, which are presented as discrete values corresponding to specific deformation conditions and steel grades or as approximated dependencies that represent these experimental results.

In various works, experimental studies were carried out that determined the dependence of the yield strength σ_T , yield stress σ_p on the thermomechanical parameters of the process of plastic impact (degree, speed and temperature of deformation). Based on the results of these experimental studies, the authors Cook P.M., Nikolaev V.O. and others [12] proposed their own options for determining the dependence of the flow stress of a metal on the deformation rate. The data presented in the technical literature regarding the dependence of deformation resistance on strain rate for steels are often inconsistent, making it difficult to draw definitive conclusions about the influence of various factors. An inaccurate mathematical representation of yield stress during the design of technological processes can lead to significant errors in calculating the forces and moments involved in plastic deformation.

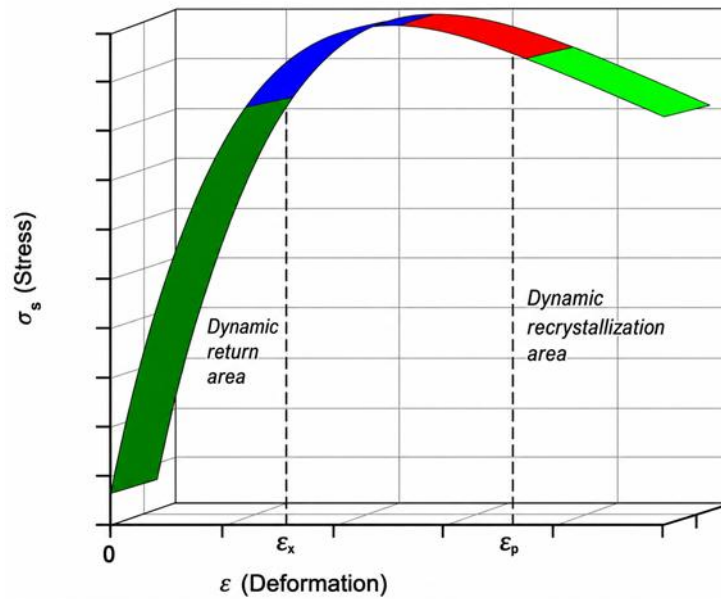


Fig.1. The general view of the flow curve of steel in the presence of dynamic recrystallization

A key distinction between yield strength and yield stress lies in their definition: yield strength characterizes the stress level at which plastic deformation begins under initial loading, whereas yield stress is determined throughout the loading process. The yield stress serves as an indicator of the material's rheological behavior. As a result, existing models and dependencies do not fully capture the rheological properties of the material. Depending on deformation conditions, yield stress may not only increase with greater strain but also decrease or remain constant.

In this context, the present study aims to develop a unified analytical model describing metal deformation resistance under thermoplastic processing conditions. The proposed approach is based on the Hansel-Spittel constitutive equation and is combined with an analytical solution of the spatial plasticity problem using harmonic functions. By integrating the Huber-Mises plasticity criterion with frictional and geometric factors, a closed form relationship between the local stress strain state and thermomechanical processing parameters is established. The developed framework is intended for practical engineering applications, including prediction of energy-force parameters and assessment of surface layer behavior in metal forming and tribological systems.

3. Results and discussion

A preliminary review of mathematical models proposed by various researchers revealed that the Hansel-Spittel equation is the most suitable for determining yield stress under varying thermomechanical conditions. This equation effectively represents the relationship between stress and thermomechanical parameters, accommodating diverse variations in their values:

$$\sigma_p = \alpha_1 \varepsilon^{\alpha_2} \exp\left(\frac{\alpha_3}{\varepsilon}\right) \exp(\alpha_4 \varepsilon) (1 + \varepsilon)^{\alpha_5 T} u^{\alpha_6} u^{\alpha_7 T} T^{\alpha_8} \exp(\alpha_9 T), \quad (1)$$

where $\alpha_1 \dots \alpha_9$ – empirical coefficients, ε – relative deformation, T – temperature, u – deformation rate

In case of small deformations ($\varepsilon = 0.2 \dots 0.3$), the yield strength increases strongly as the deformation increases. At moderate deformation levels, the increase in yield strength becomes less pronounced, and in some cases, it may even decline with further straining. A distinctive feature of this approximation is that the derived formula allows for consideration of the rheological properties of various steel grades. The relationship between yield stress and deformation can exhibit different trends – it may increase, decrease, or remain constant. This formula enables the calculation of energy parameters and yield stress at any point within the deformation zone.

Moreover, it is necessary to take into account that the inhomogeneity of the deformed state is the main feature of metal products shaped by pressure processes. As a result, the metal of the product has different

mechanical properties and fatigue resistance in its volume. This is important because, in each model, separate elements or zones usually correspond to service characteristics. Thus, for accurate forecasting, it is essential to analyze the deformation of individual material points throughout the entire product volume rather than relying on averaged deformation characteristics. The intensity of tangential stress is used as an indicator [13]:

$$\tau_i = \frac{1}{\sqrt{6}} \sqrt{(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2)} \quad (2)$$

where $\sigma_x, \sigma_y, \sigma_z, \tau_{xy}, \tau_{yz}, \tau_{zx}$ – normal and tangential stresses in space

Real technological processes are characterized by a multi-stage, non-monotonic nature of strain intensity with complex loading. In the theory of small deformations, it is proven that the deformed state of any material point is completely determined by six components: three main components, intensity and type of deformation. At the same time, the total shear deformation is a quantitative characteristic of the degree of change in the shape of the particle under consideration, which is expressed as a dependence through the main components of the deformation [14]:

$$D_i = \sqrt{\frac{2}{3} \left[(\varepsilon_x - \varepsilon_y)^2 + (\varepsilon_y - \varepsilon_z)^2 + (\varepsilon_z - \varepsilon_x)^2 + \frac{3}{2} (\gamma^2 + \gamma) \right]} \quad (3)$$

where $\varepsilon_x, \varepsilon_y, \varepsilon_z$ – degree of deformation in space, γ – shear strain

In general, for finite (significant) deformation, the intensity equation is preserved. For multi-operational (multi-pass) processes Smirnov-Aliaev G.A. proposed a mathematical equation according to which the total (resulting) degree of deformation for the entire technological process is defined as the arithmetic sum of the degrees of deformation of individual operations, the values of which, in the case of a monotonous course of the deformation process, are numerically equal to the intensity of the main deformations. At the same time, it was noted that the intensity is a scalar quantity and the only comparable characteristic of the change in shape, allowing to determine the work spent on it.

Approximate theoretical calculations, based on the estimation of the amplitude of the change in the potential energy of the nucleus during the movement of the dislocation, showed that the minimum tangential stress necessary for the movement of the dislocation is equal to:

$$\tau_n = \frac{2G}{k} e^{-\frac{2\pi a}{k b}}, \quad (4)$$

where a – distance between adjacent sliding planes, b – size of a structure element

This formula indicates that as a increases and b decreases, the value of τ_n becomes smaller. It is established that the value of a is the maximum for densely packed atomic planes, and the smallest value of b corresponds to the most densely packed directions.

Thus, checking the condition $\tau_i > \tau_n$, it is possible to talk about the possibility of dislocation movement. Dislocations that ensure plastic displacement along the directions and planes of the densest atoms are especially mobile. Preventing sliding in these planes in any way, it is possible to cause ego in those planes where the packing of atoms is less dense.

The most clearly marked relationship between metal deformation resistance and thermoplastic processing conditions impact on the surface layer is manifested in the contact interaction in the conditions of friction of parts in tribo-joints. It is obvious that under contact conditions of loading, the near-surface layers of the material are damaged more than the deep ones.

With repeated loading, fatigue microcracks appear on the surface even in the absence of contact loads and are located in the active sliding planes, in which the maximum shear stresses act. The accumulation of defects leading to the formation of microcracks is determined by the characteristic features of the main structural elements of the material. Under the action of multiple impulse loads, the original structure of the deformable material changes significantly. The subsurface zone, extending from a few to several hundred micrometers in depth, consists of a plastically deformed material layer characterized by specific crystallite size and orientation.

The processes of friction and wear, as well as the destruction of the surface layers of the tribocoupling, are determined by the dynamic nature of the application of loads in contact, the amplitudes of mutual displacements, which create specific conditions of contact interaction. At the same time, the majority of tribocoupling work under the conditions of complex three-dimensional dynamic loading: impact and sliding in two mutually perpendicular directions with the effect of both high and low temperatures. Such a complex

of loading conditions causes a complex tense state of the surface layers of contacting pairs. This explains the limited capabilities of the general principles of friction theory, as well as the majority of experimental research results.

As preliminary studies have shown [15-17], complex three-dimensional loading (impact and slip in two mutually perpendicular directions) creates conditions for the formation of surface layer fragments with relatively easy passage of dislocations through these crystallites to their boundaries. This contributes to lowering the level of external stresses required for the action of the rotational plasticity mechanism in the analyzed structures. As a result, a surface layer with a more uniform texture is formed, which is accompanied by increased wear. A change in the nature of loading leads to a change in the state of the surface layer and, as a consequence, a change in the wear resistance of the tribocoupling.

The features and specificity of the mechanism of plastic deformation during friction under multicomponent loading have not yet made it possible to develop the physical foundations and reveal the patterns of surface destruction. Research on the structure and properties of surfaces in tribocoupling components reveals the complexity and variety of surface phenomena involved.

The general case of a diagram of vertical surface and horizontal subsurface cracks during friction with three-dimensional dynamic loading is shown in Fig. 2 [17].

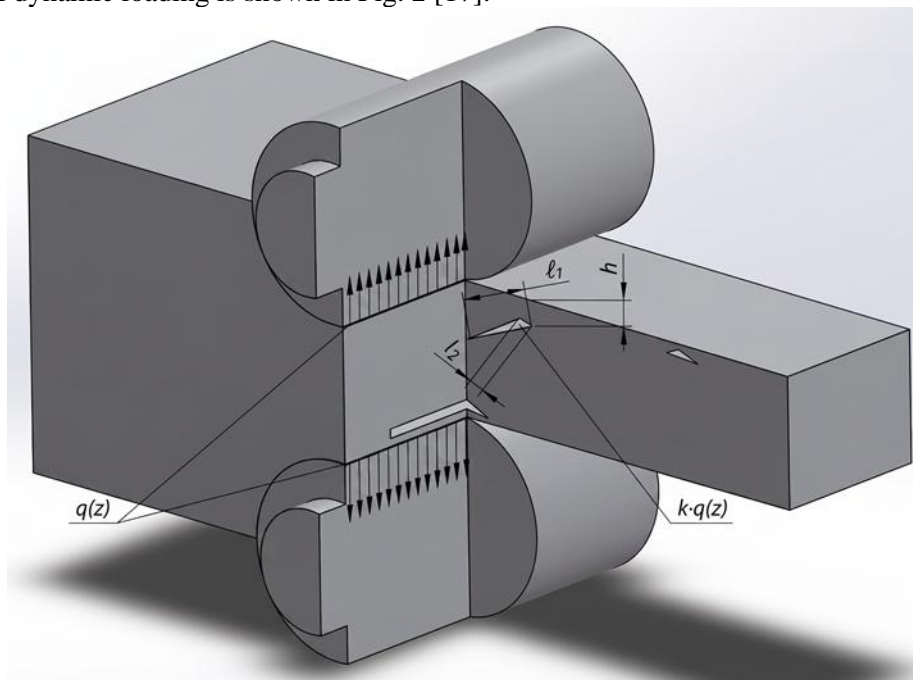


Fig. 2. Scheme cracks arrangement during friction with three-dimensional dynamic loading: l_1 – conditional length of the defect, l_2 – conditional width of the defect, h – depth of the defect, $kq(z)$ – conditional area of the defect, $q(z)$ – normal alternating stress (rolling stress)

The surface is loaded with normal alternating stress $q(z)$ under impact loading and tangential stresses τ_x and τ_y under reciprocating sliding in two mutually perpendicular directions of the counter-specimen.

Studies using microscopic methods have shown that as a result of plastic deformation, a developed cellular structure oriented along the friction direction is formed in the surface layers. Fracture is initiated by the cell faces perpendicular to the sliding direction, and the initial crack passes along these faces. Therefore, with relative sliding of surfaces, the initiation of differently oriented cracks is possible [18-19]. Especially in the case of friction with sliding in two mutually perpendicular directions.

Overall, the development and propagation of microcracks under cyclic loading are heavily influenced by both the material's structural condition and the number of loading cycles N . To describe the development of microstructurally short cracks, the equation presented in [20] is applicable:

$$\frac{db}{dN} = C(\Delta\gamma)^m(d - b) \quad (5)$$

where b – crack depth; $\Delta\gamma$ – shear strain range; d – characteristic size of a structure element; C and m – experimentally determined material constants.

It follows from this equation that as the crack grows to the grain size, its speed decreases down to zero. At stresses above the endurance limit, the crack does not stop, but only slows down its growth or may stop for some time.

Moreover, the nature of deformation accumulation under the action of multiple pulse and pulsating loads is approximately the same. Thus, under impact loading, the dependence of contact deformation on the number of cycles is nonlinear with three sections: in the first section – the hardening stage (approximately up to $N = 20$) contact deformation occurs; in the second section, slow accumulation of contact deformation at an approximately constant speed (up to $N = 103 \dots 104$); in the third section, a significant increase in deformation and intense destruction of the surface are observed [21].

It has been established [22] that wear under impact loading is a nonlinear function of the number of cycles and normal stress:

$$W = BN^n \sigma^m, \quad (6)$$

where B , n , m – coefficients determined experimentally.

In this case, the normal stress σ and the maximum contact pressure N are determined by the impact force, which in turn depends on the speed, geometry of the contact and the properties of the material.

Cyclic stresses lead to the occurrence of fatigue damage, both on the surface and at some depth. Surface fatigue occurs as a result of the normal collisions between microroughnesses, which generate tangential stresses beneath the roughness features, extending to a depth roughly corresponding to the height of the protrusions (in the micrometer range). The maximum tangential stress acts under the protrusion:

$$\tau'_m = \left(E' / \pi^2 \right) \rho, \quad (7)$$

where E' – reduced modulus of elasticity; ρ – angular coefficient of protrusion.

It is obvious that microscopic (second kind) maximum shear stresses can indeed be the cause of the formation of embryonic cracks under the surface. The contact area between two bodies is influenced by the prevailing conditions:

$$\begin{cases} \tau_{xy} = -q(z) \sqrt{\psi_x^2 + \psi_y^2} + \left(E'_m / \pi^2 \right) \rho, \\ \sigma_z = -q(z) \end{cases} \quad (8)$$

Based on the solution of plane problems in analytical form presented in works [14, 23, 24], it is necessary to comply with the formulas:

$$\tau_{xz} = k_1 \cdot \sin A_1 \Phi_1, \quad \tau_{yz} = k_2 \cdot \sin A_2 \Phi_2, \quad (9)$$

where A_1 and A_2 – constants that determine the parameters of a plastic medium; Φ_1 and Φ_2 – unknown coordinate functions determined by the solution of the problem; k_1 , k_2 – resistance to plastic shear deformation along the X and Y axes, depending on the coordinates of the deformation zone:

$$k_1 = C_{\sigma 1} \cdot \exp \theta_1', \quad k_2 = C_{\sigma 2} \cdot \exp \theta_2', \quad (10)$$

where $C_{\sigma 1}$, $C_{\sigma 2}$ – constants that determine the dimension of shear resistance in the directions of the X and Y axes; θ_1 , θ_2 – coordinate unknown functions determined by solving the problem along the same axes. Based on the equilibrium equation, we obtain analytical dependencies for normal stresses. The components of the stress tensor have the form:

$$\begin{aligned} \sigma_x &= -2 \cdot C_{\sigma 2} \cdot \exp \theta_2' \cdot \cos A_2 \Phi_2 - C_{\sigma 3} \cdot \exp \theta_3' \cdot \cos A_3 \Phi_3 + C, \\ \sigma_y &= -C_{\sigma 2} \cdot \exp \theta_2' \cdot \cos A_2 \Phi_2 - 2 \cdot C_{\sigma 3} \cdot \exp \theta_3' \cdot \cos A_3 \Phi_3 + C, \\ \sigma_z &= -3 \cdot C_{\sigma 2} \cdot \exp \theta_2' \cdot \cos A_2 \Phi_2 - 3 \cdot C_{\sigma 3} \cdot \exp \theta_3' \cdot \cos A_3 \Phi_3 + C, \\ \tau_{yz} &= C_{\sigma 2} \exp \theta_2' \cdot \sin A_2 \Phi_2, \\ \tau_{zx} &= C_{\sigma 3} \exp \theta_3' \cdot \sin A_3 \Phi_3 \end{aligned} \quad (11)$$

The integral characteristic of the stress state of a point is the intensity of normal stresses according to equation (2). Substituting (11) into (2), we obtain an equation convenient for conducting analysis:

$$\sigma_i = \sqrt{3} \cdot \sqrt{\left(C_{\sigma 2} \cdot \exp \theta_2' \right)^2 + \left(C_{\sigma 3} \cdot \exp \theta_3' \right)^2 + \left(C_{\sigma 2} \cdot \exp \theta_2' \cos A_2 \Phi_2 \right) \left(C_{\sigma 3} \cdot \exp \theta_3' \cos A_3 \Phi_3 \right)} \quad (12)$$

Based on the condition of plastic deformation, in accordance with the Huber-Mises hypothesis on the equality of the intensity of normal stresses and yield stress, it is possible to write in relative values:

$$\frac{\sigma_i}{\sigma_T} = \frac{\sigma}{\sigma_T}, \quad (13)$$

where σ – yield stress; σ_T – yield stress in unhardened condition.

On the one hand, we have a characteristic of the stress state of the medium, depending on the friction coefficient, the shape factor, on the other, a physical quantity determined by the degree and speed of deformation, temperature, chemical composition. Thus, the Huber-Mises plasticity condition is a link that allows us to establish a connection between the parameters of the stress state of a point and the thermomechanical characteristics of the process.

Taking into account all of the above and the results of the experimental part, we finally get:

$$\sigma_p = 0,00008 \varepsilon^{0,52} \exp\left(\frac{-0,00016}{\varepsilon}\right) \exp(1,114\varepsilon) (1+\varepsilon)^{-0,0034T}. \quad (14)$$

$$\dot{\varepsilon}^{-0,217} \dot{\varepsilon}^{0,00034T} T^{2,97} \exp(-0,00495T)$$

The obtained equation allows us to connect the parameters of the stress state of a point (friction coefficient, shape expresfactor) with the thermomechanical parameters of the process (degree, speed and temperature of deformation). Thus, an analytical connection has appeared that directly connects the factors of production and loading [24-25]. By setting the parameters of the stress state, with known coefficients a_i , it is possible to determine, using different calculation methods, the thermomechanical parameters of the process.

The proposed analytical model can be directly applied in engineering practice for the rapid estimation of deformation resistance and energy-force parameters in thermoplastic metal processing. The closed-form relationships obtained allow efficient parametric analysis without extensive numerical simulations, making the approach suitable for preliminary process design, optimization of rolling and forming regimes, and assessment of surface layer behavior in tribological contacts. The model can also be integrated into computational workflows as a constitutive sub-model, improving the accuracy and reliability of engineering calculations under complex thermomechanical loading conditions.

When performing the experimental part of the study using a Gleeble 3800 thermomechanical simulator, cylindrical specimens of microalloyed steel 10HFTBch with a diameter of 10 mm and a height of 12 mm were used. The samples were placed in a sealed chamber, where air was evacuated to create a vacuum environment in order to prevent oxidation during high-temperature deformation.

During thermomechanical loading, yield stress and logarithmic strain were recorded at predefined deformation intervals. The temperature of the central region of the specimens was monitored using thermocouples. The maximum temperature reached during hot deformation was 952 °C, ensuring deformation within the austenitic region. To analyze microstructural evolution during thermomechanical processing of microalloyed steel 10HFTBch, phase transformation behavior during continuous cooling after plastic deformation was investigated. The specimens in the as-delivered condition were heated to 950 °C and subjected to 30% plastic deformation in the austenitic region below the recrystallization temperature, while the deformation rate did not exceed 100 s⁻¹. Subsequently, the samples were cooled to 20 °C. To evaluate the effect of prior plastic deformation on subsequent structural formation, the specimens were reheated to 950 °C under identical thermal conditions.

Analysis of the results of calculating the intensity of normal stresses from the parameters of shape and friction coefficient shows that it is possible to increase this parameter compared to unhardened metal. There is an increase in this indicator by 1.13...2.0 times [17]. This means that, based on the Huber-Mises's hypothesis, the physical quantity, that is, the yield strength, also increases by 1.13...2.0 times. With an increase in the friction coefficient and shape parameters, we determine the yield stress, which in this case, through the temperature factor and recrystallization diagrams, makes it possible to establish structural transformations corresponding to a given stress state. The experimental data obtained from these thermomechanical tests were used to calibrate and validate the proposed universal analytical model describing metal deformation resistance under thermoplastic processing conditions.

4. Conclusions

A unified analytical model describing the dependence of metal deformation resistance on thermoplastic processing conditions has been developed. The proposed formulation combines the Hansel-Spittel constitutive equation with an analytical solution of the spatial plasticity problem, enabling a closed-form description of the stress strain state under non-uniform and multi-stage deformation.

The integration of the Huber-Mises plasticity criterion with frictional and geometric factors provides a direct analytical link between local stress intensity and the key thermomechanical parameters of the process,

including strain, strain rate, and temperature. This approach allows deformation resistance to be evaluated at any point within the deformation zone, overcoming the limitations of averaged or purely empirical models.

The developed framework is particularly effective for analyzing thermoplastic loading of surface layers in rolling and tribological contact conditions, where complex stress states govern wear and fatigue damage accumulation. The analytical nature of the solution makes it suitable for rapid parametric studies and preliminary engineering calculations without the need for extensive numerical simulations.

Overall, the proposed model enhances the accuracy of energy-force parameter prediction and provides a practical tool for process optimization, material behavior assessment, and the design of metal forming and tribological systems operating under complex thermomechanical loading conditions.

Conflict of interest statement

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

CRedit author statement

Tsyganov V.: Conceptualization, Resources; **Sheyko S.:** Methodology, Supervision; **Hrechanyi O.:** Project administration, Writing – review & editing, **Vasilchenko T.:** Data Curation, **Hrechana A.:** Writing - Original Draft. The final manuscript was read and approved by all authors.

Statement on the use of Artificial Intelligence.

The authors declare that no artificial intelligence tools were used to generate scientific content, results, or conclusions of this article.

Data Availability Statement

The data that support the findings of this article are openly available.

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