New approaches to the definition of power parameters of rolling based on finite volume method

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Abstract
New approaches to the definition of power parameters of rolling on the basis of the finite volume method are suggested. The approach is the development of a Finc method, based on the definition of the displaced volume. Results of theoretical and experimental studies of the volume transformation in the deformation zone are the basis of the new approach. The method for the direct determination of the rolling moment was developed, it is based on new patterns of the metal volume shifts and the principle of equality of works of external and internal forces.

Key words: FINITE VOLUME METHOD, FINC METHOD, TRANSFORMATION, ROLLING MOMENT, FORCE

Evaluation of the reliability and durability level of the equipment can not be considered credible if the real conditions of its loading are not known. The knowledge, above all, of rolling torque and force are necessary for the conditions of rolling production. Determination of rolling power parameters is a challenge even for simple cases, there are no theoretical solutions for the production of shaped sections, the lack of theory is compensated by the achievements of practice, which are based on experimental data.

The aim of the study is the analysis and development of methods for determining the power parameters during rolling. Investigations of volumetric displacements of metal during rolling and detection, in particular, of displaced volume are the basis of the proposed approach to their determination.

The existing theoretical methods for determining the power parameters in rolling by their physical approaches can be represented by two groups. The methods of the first group are based on volumetric signs of metal displacements within the deformation zone. The founder of the first group methods is Fink, the principle of the displaced volume is the basis of his approach. The proposed by Fink logarithmic dependence is simple in its structure and inaccurate at the same time. This caused the need to search new solutions, which resulted in the creation of a group of methods. Fink had a lot of followers, there are a lot of studies in this area, the authors are: G. Preisler, L. Weiss, I.A. Time, E. Kirchberg, V. Tafel, A.P. Herman, E. Siebel, Grashof, G. Caudron, I. Pupe, A.P. Vinogradov, A.P. Gavrilenko, M.S. Vereschagin, G. Liss, S.M. Petrov and others. There were proposed semi-empirical dependences, containing all kinds of correction coefficients, and eventually the original physical value of volume, that Fink gave to his well-known formula was lost. The group of methods was formed, they are based, along with the displaced volume on other features, designed to assess the metal volumes, expressed as ratios and not always having specific names or definitions. Created methods of were inaccurate and the continuing search for new solutions resulted in the creation of the second group of methods.

The basis of the second group methods is contact interaction between the metal and rolls and the contact voltages, coefficient of external friction, values characterizing the relative displacement of metal and rolls - forward flow, sliding and a neutral angle are involved in the definition of power parameters. The definition of each parameter is always connected with uncertainties, as a result, the required accuracy of calculations becomes unattainable. Methods of the second group received a greater development and spread, despite the fact that they are set in dependence on many factors, which in turn, are not well defined and not always unambiguous. In the methods of the second group the physical substance of mentioned characteristics is not always reflected quite correctly. The coefficient external friction in rolling has no clear physical meaning [13, 7] because of the fact that there are two types of external friction on the contact - rest and slip (slip and attachment zones). The neutral angle, as one of the signs of the first group methods is also a not enough unambiguous value because its demonstration is made dependent on the forward flow when rolling, which is considered to be dependent on conditions of contact interaction [26, 1, etc.]. The lack of consensus about the mechanism of formation of forward flow and its relation with other parameters [4, 2, 3] makes it difficult to use the methods of the second group.

The state of the plastic friction theory, divisiveness of provisions of the nature of forward flow, neutral angle and the role of the last one [16] indicate that the accuracy of power parameters by methods of the second group can not be sufficiently high, in particular, there are difficulties in determining of rolling torque and operation through the force of force external friction and neutral angle.

Methods based on the metal volume displacements have more promising opportunities in comparison with the methods of the second group; a prerequisite for their successful use is physically correct definition of metal displacement signs in the deformation zone, which include the displaced volume. Fink formula generally has the following form:

$$A = \sigma_Y V_{disp} \quad , \qquad (1)$$

where σ_Y - the average in terms of deformation volume yield stress of the wrought metal,

V_{disp} - displaced volume:

$$V_{disp} = ln \frac{h_0}{h_1} \quad , \qquad (2)$$

In modern scientific literature, there are two forms of Fink formulas writing, one has the form:

$$A = \sigma_Y V\, ln \frac{h_0}{h_1} \qquad (3)$$

In such form, the expression (3) is given, for example, in studies [1, 29, 31]; in [31], the author refers to an earlier source (Tonkov. Rolling and Calibration, Mining Journal, vol. 1, 1901). The author [31, p. 67], commenting the relationship of parameters, states the following: "... the power of rolling depends on the value of the critical angle γ , that is, on the forward flow." (Here the author [31], admits the inaccuracy, saying that power depends on the forward flow. The forward flow can not be characterized as a self-existing phenomenon, it appears as a result of deformation, accompanies it).

Another form of the Fink formula is:

$$A = P_{av} V\, ln \frac{h_0}{h_1} \qquad (4)$$

It is considered that the inclusion in the formula (4) the average pressure P_{av} instead of the average in terms of volume yield stress σ_Y reflects the influence of external friction on the deformation work. One of the reasons to use the average pressure P_{av} in the Fink formula is a controversial opinion in parameter σ_Y evaluation. Along with the notion of "yield stress" in the rolling theory, there are also the other: "deformation resistance" [26], "useful deformation resistance" and "complete deformation resistance" [29], "forced yield strength" [6, 9], "true yield stress" [9] and others ("physical yield stress", "physical resistance to plastic deformation", "linear deformation resistance"). Moreover, there is the different physical meaning embedded in the mentioned notions. One can disagree with the statement that σ_Y in the expression (3) does not reflect the participation of friction on the metal contact with roll. Yield stress σ_Y , being the average volume characteristic, should cover the whole amount of the deformation zone, including contact surfaces. And therefore, σ_Y by quantity should reflect the participation of friction on the metal contact with roll. In well the form of (4) the volume problem is limited by the metal contact interaction with roll and is not enough in its form, because no longer fully reflects the work of internal forces. The fact that the volume conversion in the plastically deformed body should be characterized by yield stress is mentioned, for example, in study [12]. If to estimate with position of the MF theory, the Fink approach is a simplified solution of the integral expression of internal forces work, which includes the intensity of stresses, which in turn can be represented as the average in terms of volume yield stress [30]:

$$A_{\mathrm{int}\,ern} = \sigma_T \iiint\limits_V \varepsilon_{in}\, dV \qquad (5)$$

The expression (4) is fixed in the modern theory of rolling. One of the reasons for this is that P_{av} is used in the derivation of Fink formula for upending and this event is moved to the rolling process. The researchers analyzed deeply the applicability of the P_{av} parameter and there were not attempts to create the independent methods of σ_Y determination. Generally speaking, the use of Fink formula as the expression (4) is acceptable, since σ_Y, as the volume-average characteristic of stresses includes both P_{av} implicitly (or at least, must include) as boundary conditions. At least, their numerical equality ($\sigma_Y \approx P_{av}$) is permissible, if we talk about the physical nature, the more the expression (3) corresponds to it.

Describing the Fink formula as an insufficiently precise one for rolling conditions I.M. Pavlov in study [24, p. 432] notes on this subject as follows: "It must be recognized that the Fink formula is correct only in relation to the simplest cases of deformation (prism clenching, prism extraction) which are used for its derivation. In the process of rolling this formula can only serve to account the part of work that meets these simple deformations, and can not reflect the whole complex set of rolling forces, very different from the elementary circuit which is used for Fink derivation (parallelepiped compression)." Insufficient applicability of Fink formula in its original form for the rolling process was established soon after its inception and this was the reason for the search of new solutions. Tafel in one of his works gives the expression (4) as follows:

$$V_{disp=Vln}\,\lambda \qquad (6)$$

In this form the expression (6) becomes known under the name of Kisselbah-Gulst formula, it is considered that it takes into account the spreading. Preisler attempted to take into account the work of complex forming, a result he got an expression of the form:

$$A = \sigma_Y V ln\,\frac{h_1 b_1 l_1}{V} \qquad (7)$$

Expression (7) can be reduced to the Fink formula.

Siebel in study [27] gives the dependence of the form:

$$dA = V\,\frac{dh}{h}\,k_f\,, \qquad (8)$$

where $k_f = \sigma_1 - \sigma_3$.

Other researchers were also attended in the definition of the volumetric signs of metal flow that reflect the amount of power consumption during rolling. I.M. Pavlov, referring to A.P. Vinogradov in study [24] gives the structurally generalized formula:

$$A = p\,V\,f(\partial)\cdot \qquad (9)$$

All these expressions and others existing do not characterize fully the volumetric characteristics reflecting the metal volumetric displacements, they all include static parameters. Inaccuracies in the first group methods are expressed in definition of the actual displaced volume, since all approaches are simplified and do not represent, as mentioned above, a true picture of the metal displacement in the deformation zone. Authors of critical remarks about Fink formula do not give conclusive evidence (experimental, computational, or other), which would show the limits of its applicability for the rolling conditions. The approaches (and recommendations) to the determination of the base volume value – value V in (2) - (4) were not also created.

The search for new approaches to the definition of rolling power parameters does not stop and recently there are studies, which retain an interest to the Fink method. This, in particular, is mentioned in the study [8, p. 67]: "All the published later materials on definition of rolling work repeat the structure of Fink formula. Sustained interest in its use for practical purposes is related to the fact that the use of, for example, the formula to calculate the rolling torque of the form $M_r = 2Pl\Psi$, where P - rolling force, MN; l - capture arc length, m; ψ – rolling force arm, is not correct due to the lack of precise calculation dependencies of rolling force arm ψ."

One of the reasons for the emergence of the second group methods, was the lack of sufficient clarity, what should be a basic volume V_0^* and, accordingly, the displaced in the Fink formula. The second reason - the lack of a direct opportunity to determine the torque and force of rolling based on Fink approach. The mentioned restrictions came from the lack of knowledge at that time about the features of metal volume displacement in the deformation zone. All this, in turn, did not allow to move from deformation work by Fink to the definition of rolling force and torque. Volume conversions in rolling are hidden and inaccessible for direct studying, for this reason, a lot of conclusions regarding the volume displacements are carried out on the basis of patterns of contact interaction and are often qualitative in nature. Such data are incomplete and because of lack of information, the conclusions are not always adequately reflect the the phenomena occurring in the volume of the deformation zone. The consequence of the foregoing are unsolved problems [4, 14], disputed provisions and contradictions [2, 3, 16] in the modern theory of rolling.

Typical volumetric indications (parameters) of the deformation zone were established only recently, they have been found theoretically and confirmed experimentally [19]. It has been found that the deformation zone includes several specific, objectively existing, volumes of deformation (natural) origin. This allows to approach to the modeling of the rolling process through the use of these characteristics volumes and produced (subordinate) volumes of subsequent levels. From the combination of signs the approach is characterized as a finite volume method [23, 17]. It involves the final macrovolumes, they are of natural origin and their size is commensurate with the volume of metal in the deformation zone borders. Another type - elementary finite volumes, they are created by the user, the number of them can be quite arbitrary and it is dictated by the conditions of problem. The notion “displaced volumes” is also introduced, this are mostly macrovolumes that do not include features of the displaced volume, as well as other auxiliaries and additives. A common feature of all types of volumes is their numerical constancy in variable form, thereby, the principle of incompressibility and continuity is respected. Fink formula can be converted to a form that would reflect the totality of the basic volumetric rolling parameters, involved in the formation of the displaced volume. For this the new notions: “single volume”, “basic volume”, “initial volume”, “single displaced volume” are created and used. The mentioned values are basic for the characteristics of all processes for longitudinal rolling, they have well-defined numerical values for simple cases (flat rolling), for complex cases of rolling the additional parameters are introduced.

New approaches in part of the definition of displaced volume are realized not quite difficult for the simple case of flat rolling. The initial one is volume V_0^*, located within the borders of entry planes into the deformation zone and delivery out of it (Fig. 1), upper and lower borders are within the height of piece h_0. The metal, located within the borders of the deformation zone, occupies a volume called the single (volume V_S). The volume of metal released from the deformation zone during the period of shaft rotation at an angle of contact α is indicated as V_1. The volume V_0^* becomes a value alternative to a height h_0 in the Fink formula, it follows from the following assumptions. The volume V_0^* is numerically equal to:

$$V_0^* = h_0\, b_0 R \sin\alpha \quad (10)$$

From where

$$h_0 = V_0^*/b_0\, R \sin\alpha \quad (11)$$

The height of piece h_1 will be expressed using the volume V_1:

$$h_1 = V_1/b_1\, R\,\alpha \quad (12)$$

The expression for determining a single displaced volume on the basis of Fink formula is converted and in its final form takes the following form:

$$V_d = V_s \ln \frac{V_0 b_1 \alpha}{V_1 b_0 \sin\alpha} \quad (13)$$

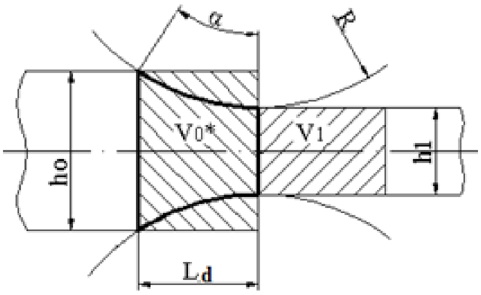

Figure 1. Specific volumes in definition of the displaced volume

Volumes V_0^* and V_1 become quantities alternative to height h_0 and h_1, accordingly, unlike Fink formula, using expression (13), it becomes possible to consider the transverse displacement of the metal (spreading). Expression (13) is applicable for the cases of flat rolling of rectangular (strip) profiles for smooth barrel rolling, for complex cases of rolling Fink formula retains its initial structure in new approaches, but it has its own characteristics, in particular, for definition of displaced volume. It becomes necessary to determine the position of piece in rolls of unequal diameter or asymmetric caliber, it is based on the principle of minimum work involving vertical displaced volumes [20, 19, 15].

The displaced volume is a kind of "power filler" of rolling process - to create the the displaced volume the related power consumption is necessary. Its detection allows differentially to approach to the measurement of the rolling work, that is, to allocate some work, corresponding to the characteristic displaced volume. In this regard, it became justified the introduction of notions "single work" and "single displaced volume", which correspond to the period of rotation of the work roll in the contact angle α. In turn, this allows to have a fundamentally new approach to the definition of rolling torque and force. The principle of equality of works of external A_{extern} and internal forces A_{intern} is used, which generally takes the form:

$$A_{extern} = A_{intern} \tag{14}$$

The work of external forces in the rolling is carried by the torque at flat rolling, the work of internal forces (deformation work A_{def}) is created by tensions in the volume of deformable body. The work of external forces in rolling is formed by external friction, namely it is the underlying factor. This differs the rolling process from other types of metal forming, wherein the external friction is a contributing factor, and it arises due to the action of internal forces. For example, at upending the increase of external forces on the magnitude becomes a necessary condition to overcome the external friction forces and the energy balance equation has the form [30, 5]:

$$A_{extern} = A_{def} + A_{fr}. \tag{15}$$

Some authors, such as [29], spread the expression (15) on the rolling process, considering A_{fr}. the work of sliding frictional forces. This approach is physically not justified by anything. A.I. Tselikov otherwise characterizes the friction part in the energy balance of rolling process. The study [28] gives the following expression:

$$M_{dv}=M_r/i+M_{fr}+M_{idl}+M_{din}, \tag{16}$$

Where M_{dv} – "rolling torque, i.e. the torque that is required to overcome the resistance of the rolled metal and with arising metal friction forces on the roll surface" [28, p. 199];

M_{fr}, M_{idl}, M_{din} - torques of friction in transfer handling gears, of idling and the dynamic torque, respectively;

i– gear box ratio in the line of main drive.

The authors [28] unambiguously assign a direct role to external friction at rolling in the formation of external forces (include its effect in M_{dv}) and do not allocate the friction work into a separate article. And If to consider the actual deformation zone (exclude the dynamic torque and losses in the mill main line), the equation (16) at i=1 is identically transformed into the expression (14).

During the period of shaft rotation at an angle φ the external forces work will be:

$$A_{extern}=M\phi \tag{17}$$

The work in the volume of deformable body based on the expression (4) will be:

$$A_{intern} = P_{av}V_{disp} \tag{18}$$

Equating the right sides of equations (17) and (18), we obtain:

$$M\varphi = P_{av}V_{disp} \tag{19}$$

With regard to the conditions of the shaft rotation angle α the expression (19) takes the form:

$$M\alpha = P_{av}V_{av} \tag{20}$$

The right side of equation (16) is a single work A_s for the period of roll rotation at an angle α :

$$A_s = P_{av}V_{av} \tag{21}$$

Rolling torque is based on a single work:

$$M = \frac{A_s}{\alpha}. \tag{22}$$

On the basis of rolling torque the resultant of tangential forces at the metal contact with roll is determined:

$$T = M/R \tag{23}$$

To determine the rolling force P the known dependencies $P=P_{av}F_t$ or $P=M/a$ can be recommended. The last one contains the coefficient of moment arm f . Another well-known relation can be used:

$$P = M/Rf. \tag{24}$$

However, the use of dependence (24) causes difficulties connected with determining the average on the contact rate (indicator) of friction f . The coefficient (index) of friction is an ambiguous value due to its lack of physical definition [13, 7]. It does not reflect the characteristics of plastic friction, in particular, it does not take into account the change of the kinematic characteristics in the volume of a deformable metal and on its contact with the instrument. For this reason, in terms of the kinematic variability along the contact arc the energy approach to the estimation of friction parameters can be promising. This approach is given in the study of author [12, p.]: “... the kinematic friction should be described by work rather than force.” By its physical origin (connection of normal and tangential forces) the eternal plastic friction index is close to the friction coefficient of solids [10, 32], and thus, the Amonton friction law can be the basis. Given the above, the creation of value having an energy basis - the “energy plastic friction index.” becomes promising to assess the friction conditions in rolling.

Conclusions

New approaches to the definition of power parameters of rolling based on finite volume method were suggested. The approach is the development of Fink method, based on the definition of displaced volume. The basis of new approach is the results of theoretical and experimental studies of volume conversions in the deformation zone. The objectively existing specific volumes were revealed. The components of the approach are finite volumes of two types - the macrovolumes and elementary ones. A feature of volumes of both types is the stability of their numerical values in the variable form, thereby the conditions of continuity and incompressibility are complied.

On the basis of a new approach the further developing got the method of calculating the rolling work on the basis of volume parameters, the definition of the single displaced and basic volume is based on the method.

The method of direct determination of rolling torque is developed, it is based on identified patterns of metal volumetric displacements, the principles of equality of works of external and internal forces and the single work.

The suggested approaches and developed methods are applicable for complex cases of rolling: in rolls of unequal diameter, in simple and multiroller flange passes.

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