UDK 621.77.01: 621.771.8

ENGENEERING PROCEDURE OF OPTIMIZATION CALCULATION OF MODES OF CLADDING BY ROLLING

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Purpose. To develop the engineering procedure for calculation of optimal modes of production of bimetal sheets or wide strips by cladding by rolling. As optimality criterion of modes of cladding the connection quality of layers in the composition is accepted. **Methodology.** The proposed procedure is based on the laws of physical and chemical processes in the formation of connection of heterogeneous metals in the solid phase at their joint plastic deformation, the theory of joint rolling of heterogeneous metals, the deformation of multilayer bodies at rolling. The main points of the previously developed model of temperature-speed conditions of deformation of bimetals such as "low-alloy pearlitic steel – austenitic steel" at cladding by rolling are also based for an engineering procedure of calculation of optimum modes of cladding. **Results.** According to the proposed procedure, a combination of metals of composition defines process fluid of cladding (in air, in a neutral process fluid, in a vacuum), and the conditions of cladding determine the rational ranges of relative deformation and of temperature at cladding by rolling. **Originality.** For the first time, we have offered the sequence of calculation, which is connecting as the input parameters – combination of metals in composition and the regulated parameters of cladding by rolling, and as the results of the calculation – the range of rational values of relative deformation and the range of rational temperatures of heating of billets. **Practical value.** The proposed procedure allows us to generalize the model of temperature-speed conditions of cladding by rolling of corrosion-resistant bimetal to any combination of joined metals and conditions of cladding by rolling.

Key words: cladding, rolling, bimetal, procedure, calculation.

ІНЖЕНЕРНА МЕТОДИКА ОПТИМІЗАЦІЙНОГО РОЗРАХУНКУ РЕЖИМІВ ПЛАКУВАННЯ ПРОКАТКОЮ

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Представлено інженерну методику розрахунку режимів, оптимальних з точки зору якісного з'єднання шарів, отримання плакуванням прокаткою біметалевих листів або широких смуг. Запропонована методика заснована на закономірностях фізико-хімічних процесів при утворенні з’єднання різнорідних металів у твердій фазі при їх спільній пластичній деформації, теорії спільної прокатки різнорідних металів, деформації багатошарових тіл при прокатці. Основні положення розробленої раніше моделі температурно-швидкісних умов деформування біметалів типу «низьколегирована перлітна сталь – аустенітна сталь» при плакуванні прокаткою також покладені в основу інженерної методики розрахунку оптимальних режимів плакування. Згідно з методикою, поєднання металів композиції визначає середовище плакування (на повітрі, в нейтральному середовищі, в вакуумі), а умови плакування визначають раціональні діапазони відносної деформації і температур при плакуванні прокаткою.

Ключові слова: плакування, прокатка, біметал, методика, розрахунок.

PROBLEM STATEMENT. In accordance with the experience of production and operation, the layered metal compositions (in most cases, bimetals) are one of the prospective directions of the development of metallurgy [1].

A general decline in production that accompanied the end of the last century and the beginning of this one also affected the production of bimetals. However, in recent years there is a tendency to increase the volume of bimetals production and consumption.

At the peak (late 80's – early 90-ies of the last century) of the domestic production of the main types of bimetallic rolled stock the production of the corrosion-resistant bimetals made a quarter of the total volume and ranked second in volume (after the wear-resistant bimetals). The largest part of the corrosion-resistant bimetal that was produced in the Soviet era accounted for the bimetal having a base of carbon or low-alloyed steel and the cladding layer of the corrosion-resistant steel, in most cases, austenitic or ferritic.

In the period of the bimetallic product mass production, the packet rolling was the main method of their production, in which a metallic bond is formed between sheets or strips that are the components of the package.

It should be noted, in comparison to the times of the intensive development of the corrosion-resistant bimetals production technologies, when up to 80% of them were produced by the packet rolling, by preent, the development of the alternative technologies (primarily cladding by explosion) has slightly reduced the proportion of the packet rolling in the total volume of the production of bimetals [1, 2].

The use of the low-alloyed steel of high strength (supplied in a heat treated state) instead of the carbon steel as a basic layer of the corrosion-resistant bimetals provides a higher level of mechanical properties of these compositions, as a rule, than that of the cladding layer material [2].

The combination of the low-alloyed high-strength steel as the core layer (such as 09Г2С, 10Г2ФР, 12Х1МФ) with the corrosion-resistant steel (particularly for steel 12Х18Н10Т which is the most common steel of the cladding layer in the corrosion-resistant bimetal) gives a noticeable increase in the strength of the layered composition compared to the metal of the cladding layer [3].

At the development of the production technology of a particular layered metal composition, its required properties are often received by selection of technological regimes by experiments. This is due to the insufficient knowledge of the formation nature of the metals connection in the solid phase, and to the complexity of joint plastic deformation of heterogeneous metals.

Therefore, studying the behavior of the compositions formation and the change of their properties both upon production of the compositions and during their treatment and exploitation is the most important task of improving the technology of production of layered compositions. This task is inseparably linked with the study of the processes that determine the formation of compounds of metals and their joint plastic deformation.

Controlling of the parameters of process of cladding by rolling of the bimetal (in case of composition «low-alloyed pearlitic steel – austenitic steel» is possible by finding the optimal temperature-speed conditions of deformation of bimetals of this type at cladding by rolling on the basis of the previous developed model [4].

The representation of the basic postulates of the model in the form of the engineering procedure for finding the optimum parameters of the cladding is a logical continuation of such modeling.

The purpose of the paper is the development of the engineering procedure of calculation of the operating conditions of production of cladding by rolling of bimetal sheets or wide strips which are optimum in terms of the layers connection quality.

EXPERIMENTAL PART AND RESULTS OBTAINED. Models of process three stages are proposed, which based on the experimental and theoretical analysis of the physico-chemical processes occurring in the contact zone of the connected metals [4–6]:

1. Model of a physical contact formation.
2. Model of contact surfaces activation.
3. Model of bonding.

It is noted [4–6] that the practical usefulness of the first stage model is that it is possible with its help to determine the optimal parameters of bonding of metals by calculating the physical contact area at a given duration of the process in accordance with the predetermined scheme. For this purpose the data of creep for the connected metals are necessary.

The possibility of using the constructed model of the physical contact formation to determine the optimum connection parameters depends on how close the calculated and experimentally obtained values [5] are.

In accordance with classification [5], cladding by rolling belongs to the group of bonding methods with a medium-intensive force action, whereas the explosion cladding belongs to the methods with a high intensity power influence.

The cladding by rolling is a highly efficient process [3]. On the other hand, cladding by rolling belongs to the methods of joining metals with a forced deformation [5], for which the rate of plastic deformation of the metal in the joint area in the connection process remains constant or varies according to a certain program, and the flow stress obeys the dependence P = P (T, u, ε, θ), where T – the temperature, u – the deformation rate, ε – the magnitude (degree) of deformation, θ – the structural factor that takes into account the joined metal resistance to plastic deformation.

During cladding by rolling the connection is formed under the conditions of a forced deformation and short duration of the interaction [5].

At the beginning, there is the crushing of microirregularities and increasing of the contact surfaces due to a significant drawing, resulting in thinning and partial destruction of the oxide films.

The possibility of a further increase of the number and area of the bonding areas is determined by the development of the adsorption process of residual gases by the metal. The bonding areas are expanding under the additional plastic deformation as the gas is absorbed by metal, zones of interaction are formed, and the connection border is transformed into a continuous interfacial boundary.

The formation of the connection finishes with the bonding of the contact surfaces and stress relaxation to the extent necessary to preserve the resulting interatomic bonds.

The cladding by rolling is a typical representative of the group of the ways in which the plastic deformation and the effect of the compressive stresses finish at the same time. In this case, it is necessary that the stresses in the joined metals during their plastic deformation don't reach the level of σ* (the stress in the deformed metal, which is able to destroy formed connection) [5].

Consider the behavior of conditional volume of a metal bounded by cross-sections AB and CD, when rolling from the beginning of deformation until it ends (Fig. 1) [7].

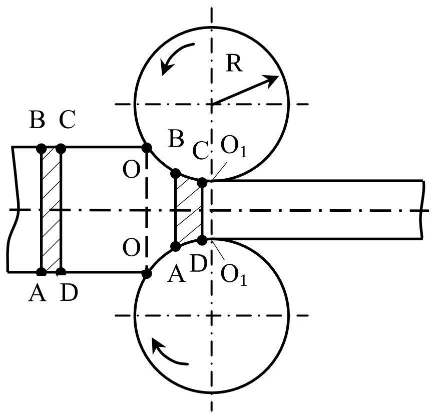

Figure 1 – Diagram of the deformation process of the conditional volume of a rectangular strip metal under lengthwise rolling

The plastic deformation of the connected blanks begins when the conditional volume of a metal reaches the section OO of the entrance to the rolls.

At the exit of the rolls (when the cross-section CD reaches the exit cross-section from the rolls O_1O_1) to the metal in this conditional section is affected by the compressive stresses, which are approximately equal to the initial level $\sigma_н$ of stresses corresponding to the initial moment of the relaxation time.

When cladding by rolling the duration of the stress relaxation is considered the duration of the deformation, after the end of which the equality is the following

$$\sigma_н \prec \sigma^*, \quad (1)$$

where σ* – the level of critical stresses in the relaxation process, in which the formed in the connection area interatomic connections are not destroyed.

The formation of the connection in this case ends with the bonding of the contact surfaces and stress relaxation to the extent necessary to preserve the resulting interatomic bonds. The duration of the complete bonding of these surfaces is determined by the duration of their activation [5].

Despite the fact that the modelling of the kinematic parameters of the longitudinal rolling process, including the laminated metals, were sufficiently covered in numerous works, it should be noted that there is no uniform approach to the application of the calculation method of the parameters of cladding by rolling, which consists either in purely theoretical constructions, or experimental confirmation of the theory for some specific combinations of metals and thickness in a composition.

It is proposed in the basis of engineering procedure of optimization calculation of operating conditions of production of cladding by rolling of bimetal sheets or wide strips to put the known laws of physical and chemical processes in the formation of joining heterogeneous metals in the solid phase at their joint plastic deformation.

We propose the following algorithm:

1. The combination of connected metal determines the conditions of cladding by rolling – in the air, in a neutral process fluid, in a vacuum.

Thus, the layered composition of easily oxidized high-melting, rare and precious metals, in some cases to get by rolling on vacuum mills [8, 9].

Depending on the conditions (process fluid) of cladding is set an area of active site S, cm^2, defined by process cutting of stress fields around the dislocations, the values of which for cladding by rolling may vary from 10^{-13} to 10^{-11} cm^2 [7].

The maximum area of the active center is determined by the circumcision of the fields of the elastic distortions of the neighboring dislocations [5]. Therefore, the maximum radius of the active center will be half the value of the path of the dislocations movement.

Since the field of elastic distortions around dislocations has a circular symmetry, the value of the area S of the active centers is equal to the area of a circle with the radius r, that is S= $8 \cdot 10^{-11}$ cm^2. Such values of S are fair for the case where the cladding is performed under vacuum conditions [5].

In case when the cladding is carried out by rolling in the air, in determining S, we assume that the active centre is limited by the area around the core of the dislocation due to the fact that the potential barrier is very large (the joined surface is covered with an oxide layer).

According to [5], such a focus of interaction has a radius of

$$r \approx 15b, \quad (2)$$

where b – the module of the Burgers vector. Taking b = $3 \cdot 10^{-8}$ cm [5], the value of r is equal to $4{,}5 \cdot 10^{-7}$ cm.

Considering that the field of elastic distortions around the dislocations has a circular symmetry, S will be equal to the area of a circle with the radius r, that is S= $6{,}4 \cdot 10^{-13}$ cm^2.

2. The relative deformation (reduction) at the cladding by rolling should be based on conditions [5, 7]:

$$\varepsilon_{\min} \le \varepsilon \le [\varepsilon]_{\max}, \quad (3)$$

where ε – relative deformation (reduction), $\varepsilon = \Delta h/h_0$; Δh – absolute deformation (reduction), $\Delta h = h_0 - h_1$, where h_0 and h_1 – the thickness of the rolled package before and after rolling.

Value of ε is limitated by ε_{min} – the minimum value of deformation and $[\varepsilon]_{max}$ – the maximum acceptable value of relative deformation.

3. The minimum relative deformation ε_{min} is determined from dependence [5]

$$\varepsilon_{\min},\% \;\ge\; \frac{100 \cdot b \cdot L}{S}, \quad (4)$$

where L – the path of dislocation movement to the obstacle. The path L of the movement of the dislocation to the barrier and the density ρ of the dislocations in the metal are linked by ratio [5]

$$L = \frac{1}{\sqrt{\rho}}. \quad (5)$$

A strong connection for each combination of metals of layers at cladding by rolling is formed when certain minimum values of relative deformation. Thus, for the most common corrosion-resistant bimetal minimum value ε must be at least 45 %, and the range of rational reductions is 45...65 % [11].

The value of ρ, according to the model of A. Seeger [5] for ε = 45...65 % is approximately 10^{10} cm^{-2}. Thus, when the relative deformation ε = 45...65 % L = 10^{-5} cm.

It should be noted that due to the large geometric heterogeneities of joined surfaces in cladding by rolling in the connection area dislocation density ρ in the contact volume can reach limit values [5]. In this case, the dislocation density in the contact volume should be about 10^{11} cm^2, hence L = $3{,}16 \cdot 10^{-6}$ cm.

4. It is determined duration of staying of the metal in the deformation zone (duration of the interaction between the joined metals, determined the duration of force action on the joined metals) $t_в$, sec, is at the cladding by rolling [7]

$$t_в = \frac{l}{v}, \quad (6)$$

where l – the length of arc of contact, v – the speed of rolling.

The length of arc of contact it is determined from the expression [10]

$$l = \sqrt{0{,}5 \Delta h D}, \quad (7)$$

where D – the diameter of rolls (it is assumed that the rolls of the same diameter).

The speed of rolling [10]

$$v = \pi D n, \quad (8)$$

where n – the rotational frequency of rolls.

After transformations it will be

$$t_в = \frac{19{,}1}{n}\sqrt{\frac{0{,}5h_0\varepsilon}{D}}\ . \tag{9}$$

Thus, the calculation dependence includes controlled parameters of cladding by rolling [7]: the rotational frequency of rolls n, the diameter of rolls D, absolute Δh or relative ε deformation (reduction). Also, these parameters include the temperature of billets before rolling T.

The rolling speed v, the length of arc of contact l, the speed of deformation in the deformation zone u are derived from these parameters.

Substituting in the relation (9) the value of ε_{min} that found the dependence (4) instead ε for specific values h_0, D and n, define the $t_в$.

5. It is checked the received value $t_в$ through the ratio

$$t_в \ge t_a \ge t_p\ , \tag{10}$$

where $t_в$ – the duration of the interaction determined by the duration of the force effect on the connected metals; t_a – the duration of activation of the entire contact surface, i.e. the duration in which all the atoms of the contact surfaces form an inter-atomic bonding; t_p – the duration of the stress relaxation in the contact zone.

The expression (10) is the condition for the formation of a quality connection at the cladding by rolling [7]. It should be noted, that to form a high-quality joint the filfulment of the expression (10) is sufficient at the cladding by rolling of homogeneous metals, which include carbon (or close to them by the composition and properties low-alloyed) and austenitic steels.

The duration of the formation of the active centers t_a will be determined from the expression [5]

$$C = \lambda t_a\ , \tag{11}$$

where C – the number of the active centers; λ – the frequency of appearance of the active centres in the zone of the physical contact.

It is known the expression for the relative strength of the joint obtained by cladding by rolling [5]

$$\bar{\sigma} = CS\ , \tag{12}$$

where S – the area of the active centres, in which the inter-atomic bonding is formed.

Relative strength is determined by the relation

$$\bar{\sigma} = \frac{\sigma_{отр\ соед}}{\sigma_{в\ м.п}}\ , \tag{13}$$

where $\sigma_{отр.\ соед}$ – strength of the connection on peeling, $\sigma_{в\ м.п}$ – tensile strength of less durable metal of composition.

It should be noted [11] that in the production of layered metal composites it is necessary to provide a durable connection of the layers over the entire area of contact under the given ratio of thicknesses of layers, the required structure and properties.

In the assumption of the dislocation origin of the active centers the value of λ is determined by the dependence [5].

$$\lambda = \frac{u}{L \cdot b}\ , \tag{14}$$

where u – the speed of deformation of the metal in the connection area.

Speed of deformation [10]

$$u = \frac{v}{l}\ln\frac{h_0}{h_1}\ . \tag{15}$$

Taking in dependence (13) $\bar{\sigma}$ = 1 (the condition of the maximum strength of the connection) and taking into account dependences (12) and (14), it will be obtained

$$t_a = \frac{L \cdot b}{u \cdot S}\ . \tag{16}$$

The duration of the relaxation of stresses in the connection zone can be expressed by time dependence [5]:

$$t_p = t_0 e^{\frac{E}{RT}}\ , \tag{17}$$

where t_0 – the period of the natural oscillations of the atom, $t_0 \approx 10^{-13}$ sec [12]; E – the activation energy of the process controlling the relaxation of stresses in a more ductile metal; R – the universal gas constant, R = 8,31 J/(mol·K); T – absolute temperature of process.

In accordance with the classification of the possible mechanisms of diffusion [12], in our case (diffusion in metals at high temperatures), we assume that the stress relaxation at the dislocation density in $10^{10}...10^{11}$ cm^{-2}, controls the displacements of atoms by vacancies and bivacancies.

The temperature of the heating of bullets for the most common corrosion-resistant bimetal combination of «carbon (or low-alloy) steel + corrosion-resistant steel» is 1200...1250 °C [11].

It is known [5] the dependence of the effective energy of activation E of speed of deformation u (table. 1).

Table 1 – Dependence of the energy of activation of the diffusion process from the speed of deformation

Speed of deformation u, sec^{-1}	Energy of activation of the diffusion process E, kJ/mol
2	10,7
5	10,3
10	9,3
20	7,7
30	7,2
40	7,7

6. It is determined the temperature T of heating of the bullets before rolling [5]

$$\varepsilon_{max} \le t_в^{0{,}33}\left[\frac{\sigma^*}{k \cdot \exp\left(\frac{E}{RT}\right)}\right]^2 , \tag{19}$$

where k – the coefficient, k = 70,4 [5].

In this case the maximum acceptable value of the relative deformation $[\varepsilon]_{max}$ should slightly exceed the value ε_{min}, found from the dependence (4).

As the level of critical stresses σ* in a relationship (18) is proposed to substitute the value $\sigma_{в\ м.п}$ – tensile strength of less durable metal of composition.

If the value of T can not be applied (not included in the range of applied temperatures of heating), it is necessary to increase the $t_в$ by reducing n roll speed when a constant diameter D.

For large values ε_{min} (while rolling in the air) condition $\varepsilon_{max} > \varepsilon_{min}$ can not be performed even at very high temperatures of heating of billets at cladding by rolling and rational values of D and n. In this case, the calculation should be carried out at first, by increasing the value S, which corresponds to the cladding by rolling in neutral process fluid or in vacuum.

CONCLUSIONS. 1. The universal analytic dependence suitable for the calculation of the technological modes of the cladding by rolling is difficult obtained due of complexity of the joint plastic deformation of heterogeneous metals and the formation of joint of metals in the solid phase.

2. The engineering procedure of optimization calculation of modes of production of bimetal sheets or wide strips by rolling by cladding is developed. The procedure is based on the laws of physical and chemical processes in the formation of joining heterogeneous metals in the solid phase at their joint plastic deformation.

3. The initial data for calculation are a combination of metal composition, it determines the process fluid of cladding (in an air, in a neutral process fluid, in a vacuum) and adjustable parameters of rolling (the speed of the rolls, diameter of the rolls, the absolute deformation (reduction) at rolling). The results are rational range of the relative deformation and efficient temperature range at cladding by rolling. The relative deformation is related to the minimum acceptable value of the relative deformation. From the calculated minimum value of relative deformation also depends on maximim acceptable value of relative deformation. In the case of irrational results envisaged adjustment of initial conditions of process of cladding.

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ИНЖЕНЕРНАЯ МЕТОДИКА ОПТИМИЗАЦИОННОГО РАСЧЕТА РЕЖИМОВ ПЛАКИРОВАНИЯ ПРОКАТКОЙ

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Представлена инженерная методика расчета режимов, оптимальных с точки зрения качественного соединения слоев, получения плакированием прокаткой биметаллических листов или широких полос. Предлагаемая методика основана на закономерностях физико-химических процессов при образовании соединения разнородных металлов в твердой фазе при их совместной пластической деформации, теории совместной прокатки разнородных металлов, деформации многослойных тел при прокатке. Основные положения разработанной ранее модели температурно-скоростных условий деформирования биметаллов типа «низколегированная перлитная сталь – аустенитная сталь» при плакировании прокаткой также положены в основу инженерной методики расчета оптимальных режимов плакирования. Согласно методике, сочетание металлов композиции определяет среду плакирования (на воздухе, в нейтральной среде, в вакууме), а условия плакирования определяют рациональные диапазоны относительной деформации и температур при плакировании прокаткой.

Ключевые слова: плакирование, прокатка, биметалл, методика, расчет.

Стаття надійшла 25.11.2016.