Criteria approach in the sphere of manufacturing of composite materials reinforced by particles at multicycle rolling

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Abstract. The article is devoted to considering the possibility of application of criteria system for the definition of parameters of technological process of manufacturing of composite materials reinforced by particles while multicycle rolling.

1. Introduction
Multicycle rolling of composite laminated materials composed of components with different physicochemical and mechanical properties allows to conduct deforming in the conditions when each component is in its own and peculiar for it temperature regime. For example, the matrix component of the composite can be rolled in the conditions of hot deformation and the reinforcing component in the conditions of warm or cold one.

In case of multiple joining of blank parts from the previously rolled ones and repetition of the rolling cycle, the reinforcing material will start to granulate and the item which is being produced will be reinforced with the particles of the smaller size each time a rolling cycle is done [1].

2. Problem formulation
This article describes the investigation of composite material of the aluminum-copper system, where aluminum is the matrix component and copper is the reinforcing element. The blank part consists of 3 layers: two external matrix layers and an internal reinforcing one. Different physicochemical and mechanical properties of the components will lead to granulation of copper and creation of reinforcing particles in the aluminum basis of the material during the multicycle rolling.

Manufacturing of composite materials reinforced by particles of laminated blank parts should meet the following requirements:
- the temperature conditions of the deformation should provide the regimes of hot deformation for matrix material and warm or cold for the reinforcing one;
- in the process of rolling the matrix material deforms in the plastic state and maintains the soundness and the reinforcing one granulates into particles and allocates equally in the volume of the matrix material;
- during the rolling process a solid, indissoluble connection between the materials-components should be provided.
3. Solution

Let us consider the effect of blooming on the example of a spectrum fragment of a mercury low pressure lamp. It can be seen that there is a significant broadening of spectral lines, which leads to considerable difficulties in determining the wavelength of the respective line. It should be noted that in the case of a linear spectrum is also observed the broadening of spectral lines towards the larger wavelengths, i.e. in the direction of charge packet transfer.

With the aim of formalization of the requirements to the parameters of the technological process, the criteria approach was used [2]. In its basis there are criteria expressions which build interconnections between rolling managing parameters (temperature, deformation degree and speed), geometric parameters of the initial laminated blank part, a solid connection between components and allocation of particles in the produced item.

For the process of multicyle rolling there were formulated the following criteria:

3.1. The temperature criteria

The processes of rolling and interoperalational annealing should be conducted in the conditions of hot plastic deformation for matrix material and in the conditions of hot or cold deformation for reinforcing material. The conditions of this criteria can be formulated as follows:

\[ \Delta T_d \cap \Delta T_{htm}, \]
\[ \Delta T_o \cap \Delta T_{htm}, \]

where \( \Delta T_d \) and \( \Delta T_o \) are the temperature intervals of the deformation of the joined laminated blank part, \( \Delta T_{htm} \) is the temperature interval of the hot plastic deformation of the matrix component. Basing on the physicochemical data it is rational to conduct the rolling and annealing at the temperature of 450°C for the compositions aluminum-copper.

3.2. Criteria of formation of solid connection of components

During the first rolling pass it is necessary to receive a composition with a solid connection between all the layers meanwhile the internal layer of copper should maintain its soundness. The value of drafting should on the one hand provide a solid metal connection on the border aluminum-copper and on the other hand it shouldn’t surpass the breaking point of both materials. The following expression allows to define the minimum necessary value of joint deformation degree \( \varepsilon \), at which a solid connection between components \( \sigma_{com} \) is provided:

\[ \sigma_{com} = f(T, \varepsilon, t_d), \]

where \( T \) is the temperature of hot plastic deformation, \( \varepsilon \) is the degree of laminated blank part deformation, \( t_d \) is the time of deformation.

A solid metal connection between components appears during the course of diffusion interaction on their borders during the activation period \( t_a \). It is obvious that \( t_d \geq t_a \). Basing on the geometric parameters of the rolling process and the strain-stress state in the deformation zone, the time of the activation can be defined as follows:

\[ t_a = \sqrt{\frac{\varepsilon_{com} H_0}{n_{roll} \pi N}}, \]

where \( H_0 \) is the thickness of the laminated blank part, mm; \( n_{roll} \) is the radius of the mill rollers, mm, \( N \) is the mill rollers rotation frequency, \( c^{-1} \); \( \varepsilon_{com} \) is the degree of deformation of joined blank during pass, which provides the adhesive interaction of its components, %.

In order to define \( \varepsilon_{com} \) there was conducted a range of experimental rollings of laminated blank parts at different degrees of deformation.

External aluminum layers of the blank part consisted of alloy 1013 with a thickness of 2 mm, the internal layer was of copper C12000, with a thickness of 0.5 mm. The temperature of rolling was 450°C, the deformation degrees were 20, 25, 30, 40 and 50%. Were applied mill rollers with the radius of 145 mm, with rotation frequency of 0.3 \( c^{-1} \).
With an aim of evaluation of solidness of components layers connection there were conducted metallographic analysis of the surfaces of the tearing-off zones, which showed that the relief, corresponding to a solid metal connection (figure 1), is observed at the deformation degree of 50%, with the estimated activation time of 0.066 sec.

![Figure 1](image)

**Figure 1.** Results of metallographic analysis of the surfaces of the tearing-off zones after rolling with drafting of 50%: (a) – surface of the copper layer tearing-off, (b) – surface of the aluminum layer tearing-off.

### 3.3. Criteria of maintenance of soundness of matrix component and destroying of reinforcing component

In the course of rolling cycles it is needed to provide the safety of soundness of matrix component and granulate the reinforcing one. This condition can be formulated as follows:

The condition of maintenance of soundness during all the rolling cycles should be met for the matrix component:

\[
\sigma_{i\text{com}}^j < \sigma_{\text{вм}},
\]

where \(\sigma_{i\text{com}}^j\) is the real stress, appearing in the layers \(i\) of the component at \(\varepsilon = \varepsilon_{\text{com}}\), \(\sigma_{\text{вм}}\) is the breaking point of the matrix component material; \(j\) – is number of rolling cycle.

For the reinforcing component the condition of soundness maintenance is met only at the first cycle of rolling:

\[
\sigma_{i\text{com}}^1 < \sigma_{\text{вa}},
\]

(6)

where \(\sigma_{\text{вa}}\) – is the breaking point of the reinforcing component material.

On the following cycles the condition transforms into an opposite variant:

\[
\sigma_{i\text{com}}^j \geq \sigma_{\text{вa}},
\]

(7)

The level of required stress \(\sigma_{i\text{com}}^j\) in the components was defined by method of quantitative mathematical modelling by means of software Deform.

The results of modelling of the first rolling cycle in the case of a blank part with already formed connection between components, showed that the stress values in the matrix and reinforcing layers differ considerably, herewith the maximum of these values are achieved in the neutral section of 178 MPag and 38 MPag relatively.

The above mentioned stress values do not surpass the breaking points of the components and do not lead to their demolition. Nevertheless the temperature of rolling of 450°C will guarantee the passing of recrystallization annealing in the aluminum matrix layers meanwhile in the reinforcing layers of copper the initial plasticity will not recover and due to the cold work the reinforcing layer will start to granulate into particles at the following cycles. The size of particles will be smaller each time the number of rolling pass increases.
4. Experimental revision of solutions
In order to confirm the values, calculated in the criteria system, a rolling consisting of 6 cycles was conducted.

The results of the microstructure analysis showed that the initial laminated structure of the blank part maintained soundness during 3 rolling cycles, though the thickness of copper layer was decreasing considerably from cycle to cycle.

The process of granulation of copper layers starts after the fourth cycle (figure 2a) and with the increase of the rolling cycle the average area of the section of reinforcing particles decreases by almost 2 times at every following cycle.

After the sixth rolling cycle (figure 2b) the structure of the received material represents a matrix in which the reinforcing copper particles are allocated homogeneously, herewith the average area of these particles accounted for 714 $\mu$m$^2$.

![Figure 2](image1.jpg)

**Figure 2.** Microstructure of composite after 4th (a) and 6th (b) rolling cycles (x200).

5. Conclusions
The investigation of structural peculiarities of the manufactured composite showed that the fracture strength characteristics grow as increases the quantity of rolling cycles and achieve values of 97-130 MPag (figure 3). The plastic characteristics after each rolling cycle change in reverse proportion to the breaking point and by the end of the 6th cycle of rolling achieve the value of 2.5%, which is considerably lower than of the initial materials (20% - copper C12000 and 40% - aluminum 1013) (figure 4).

![Figure 3](image2.jpg)

**Figure 3.** The dependence of tensile strength on number of rolling cycles.
The presented methodology, based on a complex approach, which includes the application of criteria system, mathematical modelling results and experimental rollings, allowed to develop a multicycle rolling technology of composite material reinforced by particles. This methodology can be considered multifunctional for projecting of technological processes of manufacturing of materials, reinforced by particles.

References
[1] Galkin V I, Evseev P S and Paltievich A R 2017 Russian metallurgy (Metally) 1 70–7
[2] Galkin V I, Yakushev V A and Afonin V E 2013 Steel 11 94–6