3D modelling of combined rolling-extrusion of alloying rods of Al – Ti – B

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Based on the finite element analysis for the combined rolling-extrusion process, the stress-strain state, force on the tool, and the moments on the rolls are calculated as a function of the tool temperature and the rotational speed of the rolls.
The calculations are performed for an Al – Ti – B system alloy containing 5% titanium and 1% boron, widely used in the industry for melt modification when casting ingots of aluminum alloys. The authors proposed ligature rods from this alloy to be produced by the method of combined rolling-extruding (CRE), which has significant advantages in comparison with the traditional technologies of continuous casting-rolling and discrete extruding. Therefore, for the design of technology and equipment for combined processing, it is necessary to have preliminary design data on the temperature-velocity conditions and energy-force parameters of the metal deformation process. For 3D modeling in a software package SolidWorks® the model of the combined rolling-extruding process was created, which was imported into the package DEFORM™. The simulation process of producing a rod diameter of 9.5 mm by installing rolls with diameters of 462 mm and a protrusion stream 394 mm with rolling reduction of 50% drawing ratio during extruding 6.2 at the rotation speed of 9 rpm data obtained by the temperature distribution metal, strain rates, normal contact stresses on the tool and internal stresses in the metal. In addition, graphs of the change in the forces and moments of rolling acting on the rolls are plotted, depending on the rotational speed of the rolls and the required power of the drive motor is calculated. The obtained data were used in the design of new industrial equipment for combined rolling-extruding of aluminum alloys and experimental studies, which confirmed the adequacy of the obtained modeling results.

Key words: ligature, rolling-pressing, rolls, tension, speed, temperature, deformation, force.

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Introduction

In recent times, for production of long-length deformed semi-finished products of aluminum alloys, new energy-saving technologies of combined casting and metal forming such as continuous casting-rolling and rolling-extrusion, as well as continuous casting and rolling-extrusion [1–4], have been actively used and applied. Their application is particularly relevant for production of Al – Ti – B alloying rods which are widely used in Russia and abroad for inoculation of bars of aluminum alloys for the purpose of fine-grain structure and reduction of gas porosity [5–8]. Rods made of Al – Ti – B alloy with 5% titanium and 1% boron [9–16] are the most in demand for grain refinement.

The relevance of this ligature is also emphasized by the fact that it was used for the preparation of new aluminum-scandium alloys, casting large-sized ingots of them and obtaining deformed semi-finished products with an increased level of operational and mechanical properties in the course of the project 03.G25.31.0265 "Development of economically alloyed high-strength Al – Sc alloys for use in road transport and navigation" within the framework of the Program for the implementation of complex projects for the creation of high-tech production, approved by the Government of the Russian Federation dated April, 2010 № 218 [17].

On the basis of finite element analysis, for the process of combined rolling-extrusion of a rod with a diameter of 9.5 mm from Al – Ti – B alloy, calculations of the change of stress-strain state, the forces acting on tools and the torques of rolls depending on the temperature of the tools and rotation speed of the rolls were made. A software package DEFORM™-3D was used for 3D modeling. The data of deformation resistance of alloy AlTiB1 [3] was imported to the software package DEFORM™-3D.

Methodology

Geometric three-dimensional models of extrusion components of a CRE unit and an aluminum feedstock were built with a software package SolidWorks® (Fig. 1).

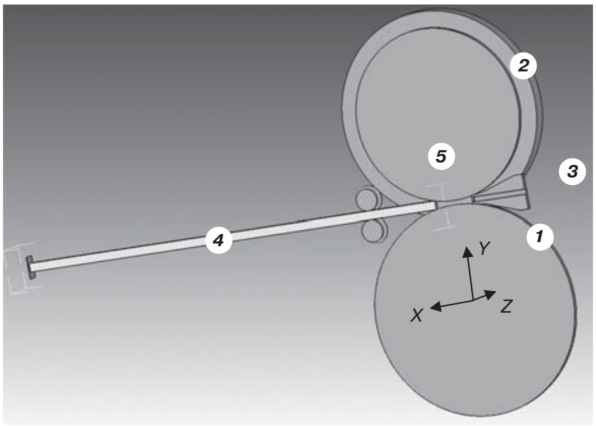

Fig. 1. 3D model of combined rolling-extrusion (CRE) process
1 — the roll with a protrusion; *2* — the roll with a groove; *3* — the die; *4* — a feedstock; *5* — the feed rolls

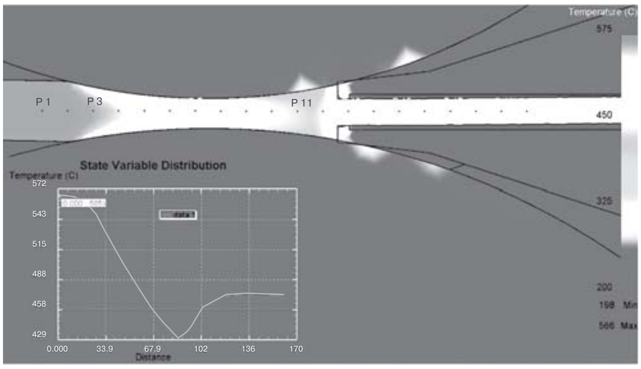

Fig. 2. Metal temperature behavior in deformation zone

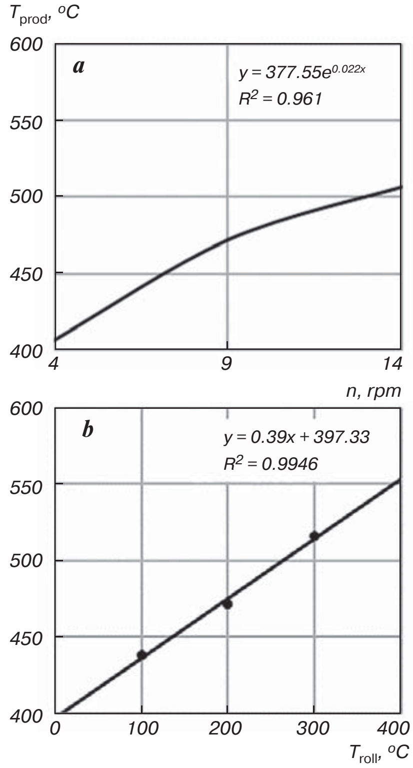

Fig. 3. Impact of rotation frequency of the rolls (*a*) and temperature of the tool (*b*) on temperature of extruded product

Then these geometries were imported in the format*.stl to the software package DEFORM^{TM}-3D.

The following data is selected as input modeling data.

1. Material of feedstock — aluminum alloy AlTiB1, material of the rolls and the die — tool steel;

2. End product is an extruded product with a diameter 9.5 mm;

3. Parameters of the rolls and the die:

– pass width — 22 mm;
– feedstock dimensions — 20×20×500 mm;
– dimensions of the die face — 20×21 mm;
– reduction ratio during extrusion — 6.2;
– diameter of the roll with protrusion — 462 mm;
– diameter of the roll with a groove — 394 mm.

4. Rotation frequency of rolls from 4 to 14 rpm

5. The conditions of contact interaction of the feedstock with the rolls were accepted according to the friction law of Siebel with an index of friction during metal deformation $\psi = 0.5$ and for the die face $\psi = 0.2$.

6. Percent reduction during rolling $\psi = 50\%$.

7. Initial temperature of feedstock $T_{\text{feed}} = 575\ ^{\circ}\text{C}$, heat exchange with environment and the tools occurs;

8. Initial temperatures of the die T_{die} and the rolls T_{roll} were measured from 100 to 300 °C, heat exchange with environment and feedstock occurs respectively. An important factor affecting the value of stress state and conditions of stable flow of rolling-extrusion process is the temperature in plastic deformation zone and the temperature of extruded rod.

The results of the research and their discussion

Fig. 2 shows temperature behavior in deformation zone under the following conditions: $T_{\text{roll}} = T_{\text{die}} = 200\ ^{\circ}\text{C}$, $T_{\text{feed}} = 575\ ^{\circ}\text{C}$, rotation speed of rolls – 9 rpm. As can be seen from picture 2 there is an intensive temperature drop from 566 °C down to 429 °C in the area of rolling, then the temperature slightly increases due to deformational heating. Such temperature pattern has a significant influence on stress state, as will be illustrated below.

Fig. 3 shows temperature change of an extruded product T_{prod} at the exit of the die mouth depending on

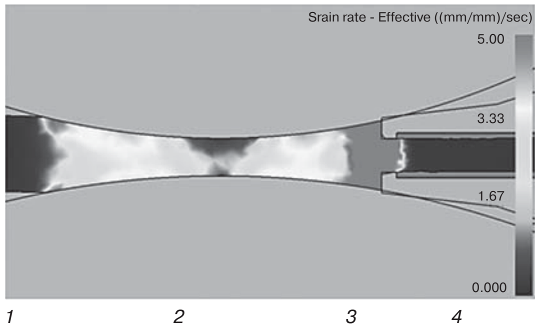

Fig. 4. Deformation rate behavior during CRE:
1 — area of feedstock gripping; *2* — rolling area; *3* — pressing-out area; *4* — extrusion area

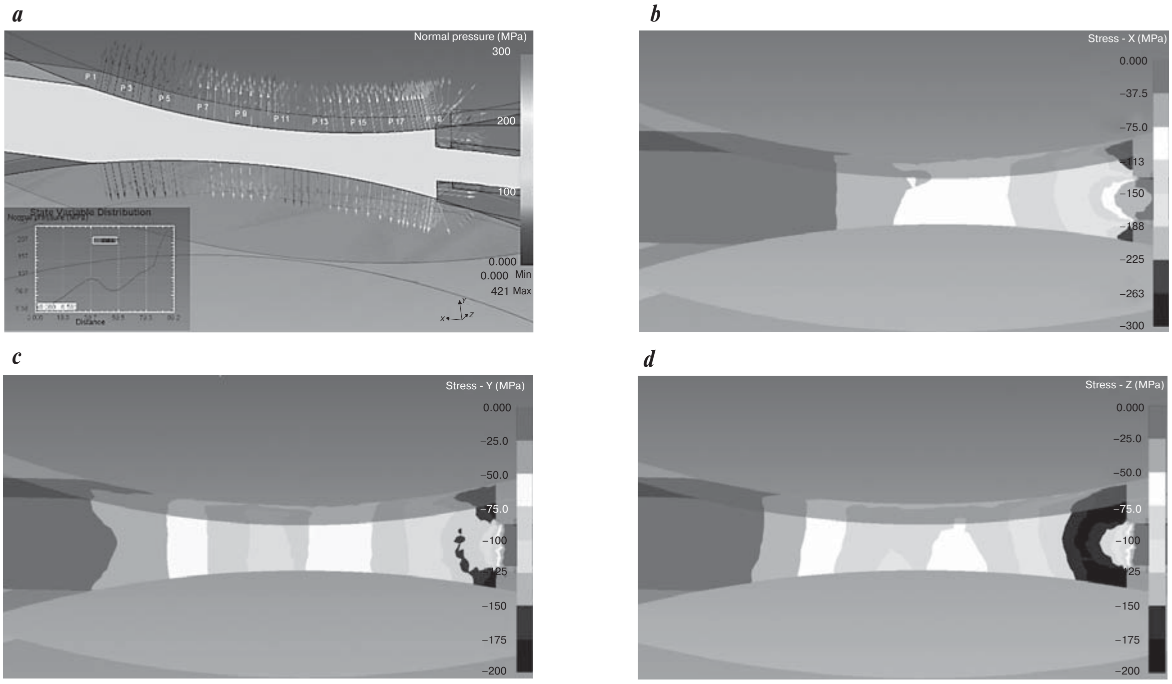

Fig. 5. Distribution of normal contact stresses on the tool (*a*) and internal stresses in metal along axes X (*b*), Y (*c*), Z (*d*)

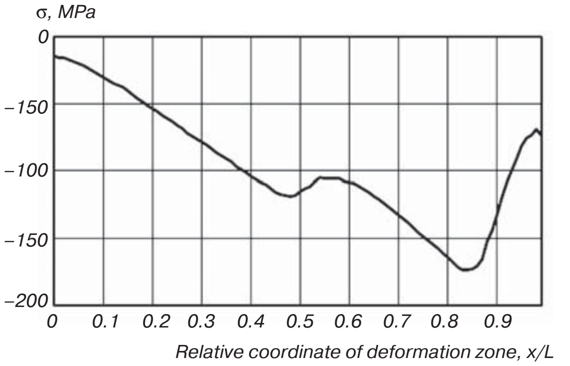

Fig. 6. Change of average normal stress along deformation zone

rotation frequency of the rolls (Fig. 3, *a*) and temparature of the rolls (Fig. 3, *b*). It is seen that with increase of rotation frequency of the rolls, the temperature of product at the exit of the die grows because deformation rate increases (Fig. 4), resistance to deformation grows, and therefore heat generation increases too. And the time for heat transfer between the metal and the rolls decreases, consequently the temperature drop of the feedstock in the area of rolling and pressing-out decreases.

Analysis of the dependences shows it is possible to control thermal conditions by regulating the temperature of the rolls and the die through their initial heating and subsequent cooling during combined rolling-extrusion. Moreover, the product temperature can be reduced by reducing rotation frequency of the rolls.

Analysis of deformation rates at $T_{\text{roll}} = T_{\text{die}} = 200\ ^{\text{o}}\text{C}$, $T_{\text{feed}} = 575\ ^{\text{o}}\text{C}$ and rotation frequency of the rolls 9 rpm shows that in the areas of gripping and rolling, deforamtion rate is not higher than 2.5^{-1}. In the section of the roll centers, defromation rate decreases down to 0.1–0.3 s^{-1}, further in the area of pressing-out the rate has a slight increase, and then suddenly it reaches its maximum values up to 130 s^{-1} in the area of extrusion.

The behavior of deformation rates and temperatures under the same parameters impacts distribution of both contact stresses (Fig. 5, *a*) affecting on the rolls and the die, and internal stresses in the metal (Fig. 5, *b–d*). Analysing the data one can note that in the areas of gripping and rolling of the feedstock, an increase of normal contact stresses is observed, and the stresses reach their maximum values in the plane passing through the common axis of the rolls.

In the area of pressing-out, normal contact stresses at first decrease and then increase, thus significantly non-monotone character of their change along the deformation zone is observed. This can be explained by non-monotone character of deformation along the deformation zone, and also by the fact that in the area of pressing-out the effect of active and reactive friction forces increases. In the area of pressing-out, the stresses reach their upper value.

Analysis of axial stresses in metal (Fig. 5, *b–d*) showed a constant increase of stresses σ_x up to the extrusion area, and their decrease in the area of rod outflow from the extrusion area. Behaviour of stresses σ_y repeats nonmonotone distribution of normal contact stresses. Stresses σ_z change also non-monotonically and have maximum values in the area of extrusion.

As it appears from the analysis of stress distribution, a very favourable pattern of the stress state is formed during rolling-extrusion which is confirmed by the diagram of distribution of average normal stress σ (Fig. 6).

Based on the data it can be concluded that during extrusion of metal by combined method of rolling-extrusion, an additional type of deformation appears — alternating deformation in which every elementary volume of metal first undergoes vertical deformation and horizontal deformation of elongation, and after passing the minimum roll gap, the deformation of opposite sign. Such deformation behavior contributes to creation of a favourable pattern of stress state and higher ductility, especially of as cast metal, and also increase of the maximum allowable extrusion rate [1–3].

When modeling the force actions during combined rolling-extrusion, the rolls and the die were put into coordinate system so that the direction of rolling and extrusion would be opposite to the direction of axis OX (see picture 1). Forces affecting on the rolls and the die along axes *X*, *Y*, *Z* were calculated in Deform™-3D for such system.

Fig. 7 shows variation graphs of forces on the rolls and the die depending on the time of the process at the following conditions:

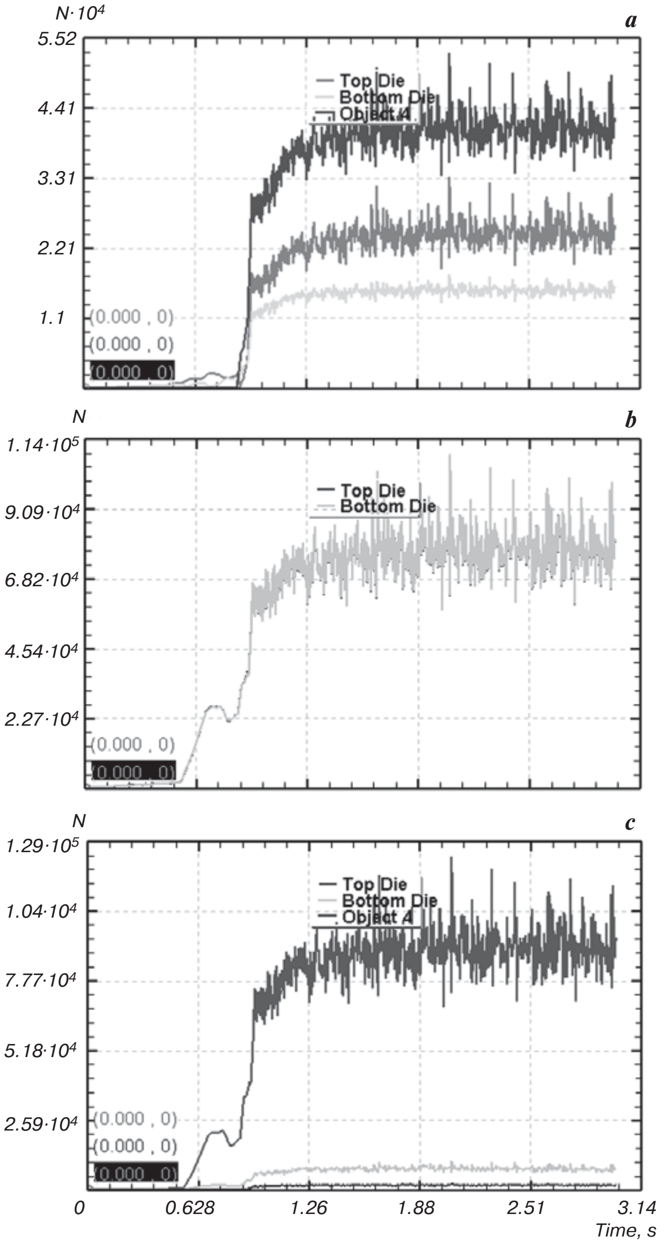

Fig. 7. Variation graphs of forces on the rolls and the die depending on time:
a — along axis X; *b* — along axis Y; *c* – along axis Z

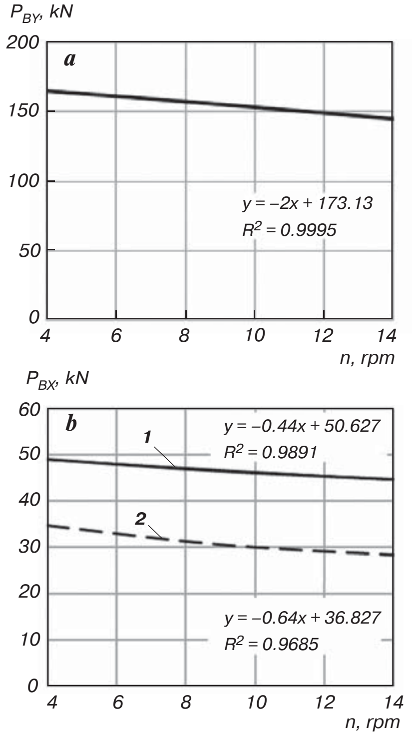

Fig. 8. Variation graphs of forces acting on rolls PBY (*a*) and PBX (*b*) depending on rotation frequency of the rolls:
1 — a roll with a groove; *2* — a roll with a tongue

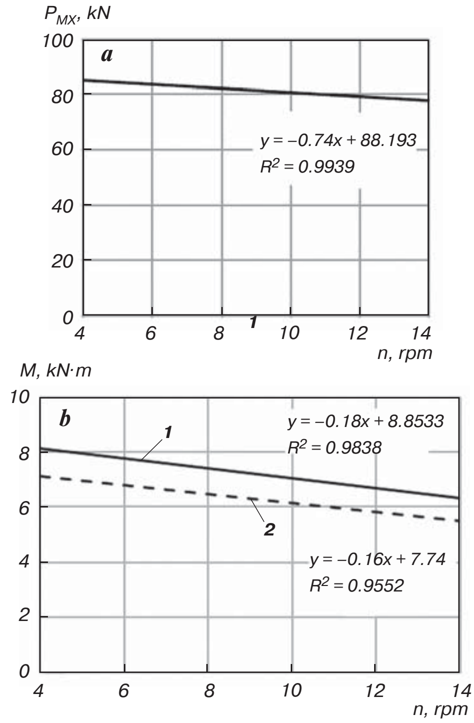

Fig. 9. Variation graphs of force PMX (*a*), acting on die, and moments (*b*) of the rotational speed of the rolls:
1 — a roll with a groove; *2* — a roll with a tongue

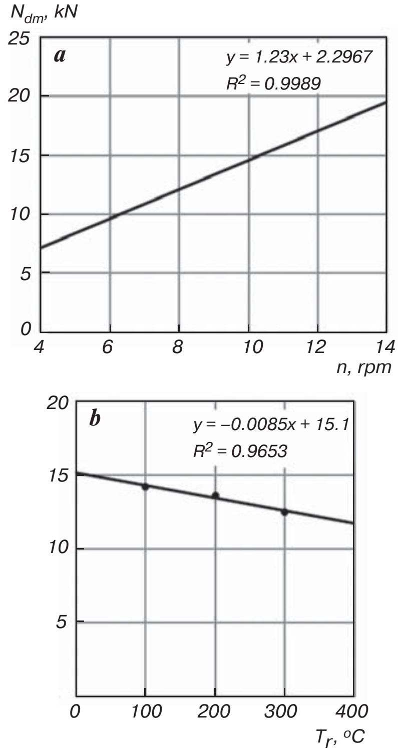

Fig. 10. Variation diagram of the required power of a drive motor depending on rotation frequency of the rolls (*a*) and temperature of the roll (*b*)

$T_r = T_d = 200$ °C, $T_{\text{feed}} = 575$ °C, rotation frequency of the rolls — 9 rpm.

Fig. 8 shows dependences of forces acting on the rolls along axis OY (P_{BY}) and OX (P_{BX}) on initial temperature of the feedstock, the tools and rotation frequency of the rolls. With increase of rotation speed of the rolls, the temperature of the feedstock falls in the areas of rolling and pressing-out. It causes decrease of forces acting on the rolls and along axis OY, at the same time force P_{BY} is practically identical for both of the rolls.

Along axis OX, force P_{BX} is acting on the rolls, which leads to undesired displacement (separation) of the rolls. The value of this force for the roll with a groove is 1.4–1.6 times higher than for the roll with a tongue. It can cause uneven “pressing-back” (detachment) of the rolls from the die resulting in metal getting into a gap between them.

For secure CRE process it is necessary to know during designing of CRE plants, the value of force PMX acting on the die along axis OX and distribution of torques on the rolls. Fig. 9 shows dependence of the force and the torques acting on the rolls with a groove and with a tongue upon rotation frequency of the rolls. Analysis of the dependences at $T_{\text{feed}} = 575$ °C and at rotation frequency of the rolls 9 rpm shows that the value of torque for the roll with a groove is different from the value of torque for the roll with a tongue which is explained by different effective diameter of rolls. Maximum values of torques should be taken into account during design of a pinion stand and selection of gearboxes and motors.

Based on the obtained results the required power Ndm of a drive motor was calculated considering the efficiency coefficient of a gearbox (0.96) and a pinion stand (0.95). The obtained dependences on rotation frequency of the rolls and temperature of the tools are shown in Fig. 10.

Conclusion

Thus, in the program complex Deform™ 3D for the adopted conditions for the combined treatment of an Al – Ti – B alloy with 5% titanium and 1% boron, modeling was performed and the temperature of the resulting product was obtained from the speed of rotation of the rolls and the temperature of the tool; forces and stresses acting on the instrument; moments on the rolls and the required power of the drive motor. These results of the calculation are confirmed by the data of experimental studies [1–4] and were used later in the design of technology and equipment for combined rolling-extrusion of aluminum alloys.

***E. V. Gladkov took part in this work.**

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NFM

3D modelling of the large-capacity ingots of an Al – Mg system aluminium alloy doped with scandium rolling process

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Implemented has been analysis of strain-stress and temperature states during hot rolling process for ingots of an Al - Mg system aluminium alloy doped with scandium. It has been shown that in case of hot rolling of the large-capacity ingots without using vertical (edger) stands under nonuniform deformation conditions, changes of breakdown bar geometry take place, especially on the first rolling passes. This nonuniformity of a metal flow is caused by intensive deformation of the ingot's outer layer and insignificant metal deformation in the central area, which result in formation of concave edges with a convex near-edge region at front end of the ingot. Metal failure in different zones of the billet may be also caused by casting defects, since essentially nonuniform deformation and stress distribution over thickness as well as that of temperature is typical for hot rolling process, especially during first passes. The metal temperature calculation has shown that sequential deformation is favourable to gradual temperature increase about 5–10 °C by pass, but heat abstraction from the central part of an ingot rises as the billet thickness is decreasing and time of pauses between passes is increasing. At the same time, the edges of a strained half-finished product are the very cold areas. A breakdown bar temperature essentially differs over both surface and volume (up to 10–12 °C), especially at first passes, and on further rolling, their difference is increasing when temperature on the surface and in the center rise and amount to 25–30 °C in comparison with the edge temperature. Based on the Cockroft-Latham criterion, ascertained are the breakdown bar areas with the greatest probability of crack propagation, which is confirmed by results of experimental investigation in an industrial environment. Analysis of changes of the Cockroft-Latham criterion values through passes has demonstrated that values of this criterion at the breakdown bar edge exceed critical value of 1 in pass No. 15 at total deformation of 68.3%.

Key words: hot rolling, large-capacity ingots, scandium, strain-stress state, temperature, Cockroft-Latham failure criterion.

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Introduction

Recently, aluminium alloys doped with rare-earth and transition metals are being increasingly commercialized [1]. One of the ways of their application in aircraft, shipbuilding and motor-car industries is manufacturing plates and sheets of scandium-doped Al – Mg system alloys. Topicality of producing such alloys and developing technologies for their processing is emphasized by implementation of the present work in accordance with the project 03.G25.31.0265 “Development of sparingly alloyed high-strength Al – Sc alloys for application in motor vehicle transport and shipping industry” in the framework of the Program on realization of complex projects in high-tech production organization approved by the resolution of the Government of the Russian Federation No. 218 dated April 9, 2010.