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# Deformations in the nonstationary stage of aluminum alloy rod extrusion process with a low elongation ratio

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**ABSTRACT**

**Introduction.** It is noted that extrusion is the main procurement process in the aluminum alloys forming operations. At the same time, the process has such a disadvantage as the nonstationarity of the metal plastic flow. **The work aim** is to establish the inhomogeneity deformation level of the pressed rod front part by numerical simulation using the finite element method. The study objectives are to formulate the extrusion process boundary conditions, to obtain a solution and to evaluate the inhomogeneity degree. **Research methods:** the finite element method was used to evaluate the deformed state. The actions sequence included the creation of primary deformation zone shape and the tool configuration. The mutual movement of the tool and the deformable material is set using the appropriate boundary conditions. The deformable medium is a ductile material with power-law hardening, the physical and mechanical properties correspond to the aluminum alloy of the 6000 series. **Results and discussion:** It is revealed that the strain degree in the pressed rod front part is extremely nonuniform distributed; differences above 300% are recorded. The strain degree distribution dependences in the rod cross sections are constructed depending on the distance from the front end at different relative radial coordinates. It is revealed that the rod central layers acquire a constant level of the strain degree earlier than the peripheral layers. The stationary process is achieved with less metal motion. **The work result application scope** is the technological study of rational metal cutting of aluminum alloys at the extrusion final stage in order to use recyclable waste more rationally. **Conclusions.** In the extrusion process with a low elongation ratio, the strain degree is distributed nonuniform both along the press rod cross and along its length. The rod front part remains weakly deformed both at the periphery and in the center in the nonstationary initial extrusion stage. It often forces to send for remelting due to the insufficiently developed metal structure. At the same time, if the limits on the minimum possible degree of deformation are set, then using the results of the calculation by the finite element method, the minimum length of the metal to be removed can be set, thereby reducing the mass of waste sent for remelting.

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## Introduction

Extrusion is one of the main procurement types of forming in the production of semi-fabricated products from aluminum and its alloys along with hot sheet rolling [1, 2]. The process is characterized by increased flexibility: it is often enough to apply a die change for re-conversion. Such speed will not be achieved when using the rolling process, where whole rolls sets will have to be changed. Additionally, in the case

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of aluminum alloys forming process it becomes possible to conduct the deformation process at moderate temperatures in contrast, for example, to the copper or steel forming. As a result, the tooling retains the strength properties, even if it is heated to the deformation point. This brings the process to the isothermal treatment level, which should stabilize the final product properties.

At the same time, extrusion is characterized by increased metal waste in the form of cutoff front and rear parts. It is rejected due to a different deformed condition than the product main part [3]. For example, the rear pressed profile part is characterized by the funnel formation and, as a result, the product is prone to defect [4, 5].

The profile front part is characterized by a low strain degree, which leads to an elaboration lack in the cast metal structure. As a result, the mechanical properties in this place are low and does not correspond the standard requirements. In addition, standards, especially for products made of aluminum alloys for aviation purposes, dictate the requirements for the structural state of the metal, and it may also not be met. The inhomogeneity of the structure and properties of the extruded semi-fabricated products along the length and cross section is the subject of study of the technological services of enterprises and research institutions [6, 7].

The extruded product front part occurs under low plastic deformation conditions. If extrusion process is planned with pre-reduced elongation ratio, then the effect of these two phenomena is summed up and its consequences should be considered. The extrusion process with low elongation ratio was analyzed, for example, by the authors [8] for the aluminum alloy extrusion case. The elongation ratio may be reducing due to the use of ingots with smaller cross-sections. The energy input is reduced since this reduces the plastic deformation level. But at the same time, the issue of bringing plastic deformation to such values remains relevant so that the necessary product properties are obtained. There is a problem of achieving the optimal strain amount, which minimizes energy costs and improves product quality. As a result, technical solutions began to appear to increase the strain during pressing, at least magnesium alloys [9].

Another reason for the poor properties of the front parts of the press products is its cracking after leaving the die. The fact is that the stressed state of the metal near the die differs from the state of the metal in the container of the press. In the latter case, it is a stressed state of all-round compression [10], which increases the plasticity of the metal. However, the metal near the opening of the die has a free surface without forces counteraction. The ductility is reduced for insufficiently plastic aluminum alloys since the metal ductility is a stress state function in the absence compression stresses. It is possible that flaw may appear on the press product front part leaving the extrusion die, which is shown in [11] on the example of large-sized pipes production. Upon transition to the stationary stage of extrusion, the effect of the absence of the front forces counteraction disappears, and the product ceases to destruction.

Therefore, the determination of the deformed state of the front part of the pressed product, especially in conditions of deformation with low elongation ratio, is an urgent task.

Physical modeling can be used to analyze the stress-strain state during extrusion [12], but recently the finite element method implemented in various software products has been most often used: *QFORM* [13, 14], *FORGE* [15], *DEFORM* [16-18], *RAPID* [19] et al. This makes it possible to evaluate the situation at each elementary point of the deformable metal. At the same time, it is possible to consider a variety of the deformable materials properties and boundary conditions in production situations. The work aim is to establish the extruded rod front part strain inhomogeneity level by numerical simulation using the finite element method.

## Research methodology

The direct extrusion process is carried out by pushing the ingot metal 1, located in the container 2, by the hob force 3 through the extrusion die hole 4 (Fig. 1). As a result, the rod front part 5 first extruded die hole, then a process stationary stage occurs, and the entire ingot is extruded with the extrusion discard exception.

It should be noted that the diagram shows the strain with a light reduction, which is not typical for the extrusion process, where the elongation ratio reaches 1,000 or more. In the extrusion theory, the elongation ratio question assigning at least 5 for semi-fabricated products intended for subsequent forming (the first option) and at least 10 for semi-fabricated products not subsequently processed by forming (the second option) is considered. Such limitations are due to the press product core non-processing possibility due to the localization of plastic deformation in the peripheral layers [20].

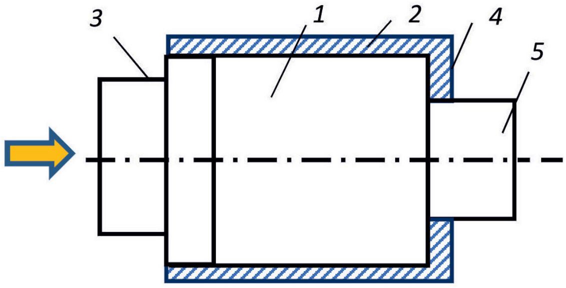



*Fig. 1.* Scheme of direct extrusion:

*1* – ingot; *2* – container; *3* – punch with a pressure pad; *4* – die; *5* – the front of the rod; arrow – direction of tool motion

Equations are provided for the elongation ratio $\lambda$ conversion into other strain indicators, as well as for the relationship between it:

– for reduction rate:

$$\varepsilon_{\%} = 100 \times (\lambda - 1)/\lambda, \tag{1}$$

– for strain (sometimes called logarithmic strain)

$$\varepsilon = \ln \lambda \tag{2}$$

or

$$\varepsilon = -\ln (1 - \varepsilon_{\%} / 100) \tag{3}$$

Calculation by equations (1) and (2) gives the minimum values $\varepsilon_{\%} = 80$ %, $\varepsilon = 1.61$ for the first option $\varepsilon_{\%} = 90$ %, $\varepsilon = 2.30$ for the second option. The strain indicators are large and often it is not achievable in individual rolling passes, as an alternative process even though the elongation ratio values are minimal.

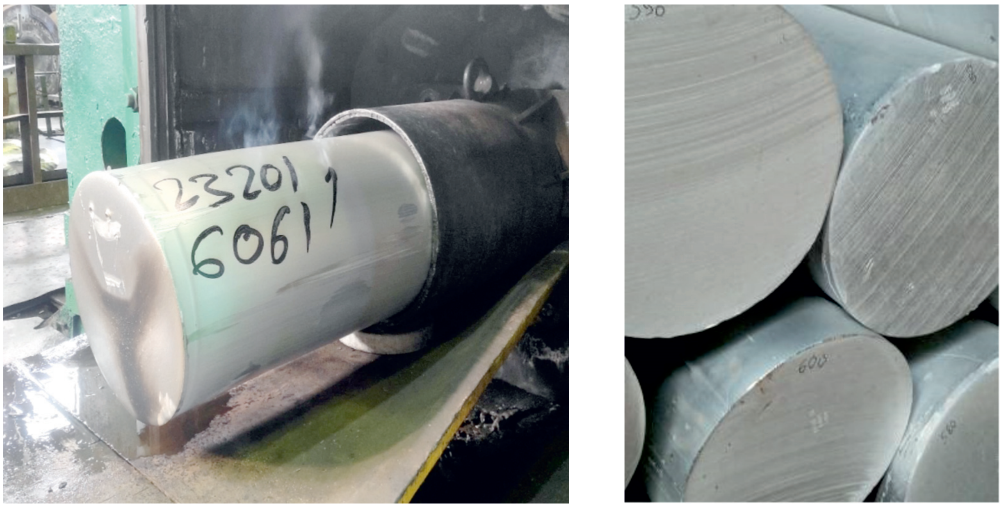
The extrusion process is carried out on horizontal hydraulic presses. The extrusion tool in the form of a pressure pad and an extrusion die form is heated to 380 °C in a separate furnace and mounted in the extrusion line. The container temperature is 450 °C and is stabilized by a heating device. After leaving the extrusion die, the rods get on the press rack, and then are cut into measured lengths, while the rod front part is separated. Metal structure is considered insufficiently developed by plastic deformation. There are general recommendations in extrusion production, based on which the front part of the extruded press product on a plate approximately equal to two diameters is considered to be defective. For example, if an extruded large-sized rod diameter is 360 mm, it is necessary to cut off the front part with a length of 720 mm and a mass of 198 kg. When the mass of the original ingot is about 2 tons, the waste of this type is ~10%. Such large wastes arise precisely when extrusion with low elongation ratio, since the resulting rod length turns out to be low and in comparison with it the metal proportion being cut turns out to be significant. Fig. 2, a show the rod front part as it leaves the extrusion die, and Fig. 2, b shows the rod cutting surface.

The *DEFORM-2D* software module was used to evaluate the situation arising at the extrusion initial stage and the following statement of the boundary value problem was formulated. The stress-strain state is axisymmetric. The extrusion tool material is rigid, the ingot material is considered as ductile.

The parameters of the computational statement are set: the mesh elements number is 26,000, the element size in the ingot volume is 1.0–1.2 mm; near the tool is 0.5–0.7 mm.

Thermal boundary conditions are as close as possible to production indicators: ingot temperature is 470 °C; container temperature is 450 °C; extrusion die and a pressure pad temperature is 380 °C, environmental temperature at the extrusion die exit is 20 °C; convection coefficient into the environment is 0.02 N/s/mm/°C, heat transfer ratio – 11 N/s/mm/°C, the coefficients and its dimensions are borrowed from the software module interface.

The velocity boundary conditions are also tied to the production environment: the extrusion punch velocity is 3.66 mm/s, another parts of press tool are stationary. The friction boundary conditions are set with




*a* *b*

*Fig. 2.* The front of the rod at the exit of the die (*a*) and the cutting surface of the rods (*b*)

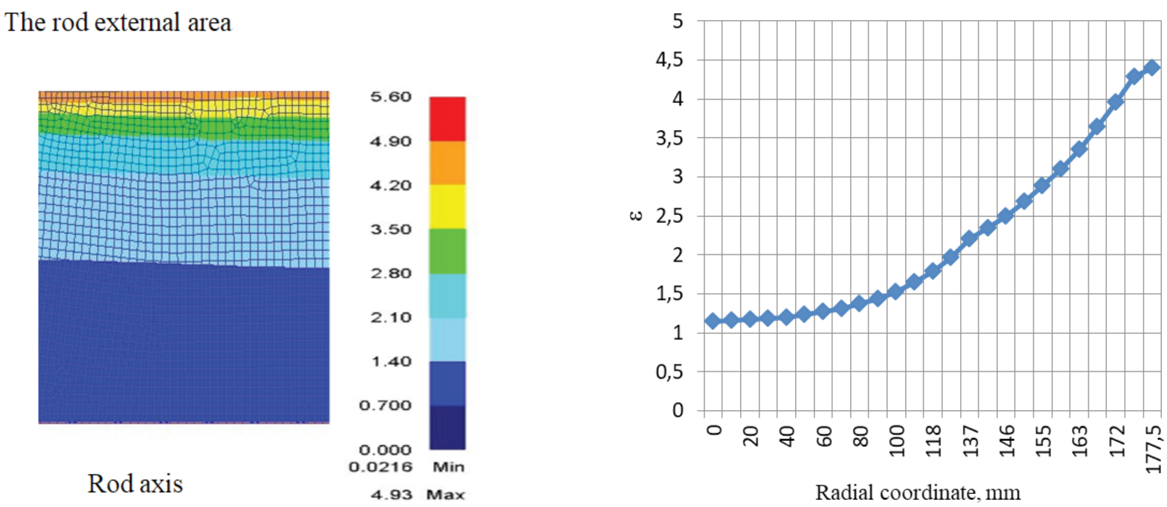
a friction index equal to 0.7 [21] by *Siebel's* law, which is due to the high level of normal stresses characteristic for extrusion [22, 23], in contrast to rolling, where *Coulomb's* law is applied.

The diameter of a container is 800 mm, the extrusion die diameter is 355.6 mm, and the elongation ratio in this process is 5.06. It is extrusion with a light reduction. In accordance with equations (1) and (2) other deformation indicators can be estimated: $\varepsilon = 1.62$, $\varepsilon_{\%} = 80$ %.

The deformable medium properties are described by a model from the program interface: *AL6061 Machining-Johnson*, the strain range: 0-5; the strain rate range: 0-100,000 $s^{-1}$; the temperature range: 20–550 $^{o}$C. Additionally, these data are verified with the properties given in the source [24].

## Results and discussion

Fig. 3, *a* shows the result of solving the problem in the form of equal strain areas in the extrusion stationary stage for the rod longitudinal section. Accordingly, Fig. 3, *b* shows a strain distribution graph along the radial coordinate *r*. The strain is distributed nonuniform: in the rod center, the strain is equal to 1.1, and on the periphery is 4.5; the difference is 100·(4.5–1.1)/1.1 = 309 %.




*a* *b*

*Fig. 3.* Distribution of the strain degree ε in the longitudinal section of the pressed rod in the stationary stage (*a*) and the graph of the distribution of this value along the radial coordinate (*b*)

This part of the solution is given to evaluate the difference in the metal properties in the cross section when using an extrusion scheme with low elongation ratio.

Fig. 4 shows the solution of the problem in the form of equal-level areas for the transition process from the initial non-stationary stage to the stationary stage.

If the strain remained constant along the rod length in the stationary stage (Fig. 3), then this condition is not fulfilled for the rod front part. The minimal strain is localized in the rod front end center. The maximum strain is localized closer to the periphery, but it barely reaches the value of 0.7. It should be noted that the strain determined through the cross-sectional areas was 1.62, which is 2.3 times higher than the previously mentioned value. The graphs are plotted in Fig. 5 to evaluate the resulting inhomogeneity. Relative radial coordinate *r/R* is introduced, where *r* is the current rod radius; *R* is the rod external area radius equal to half of rod diameter.

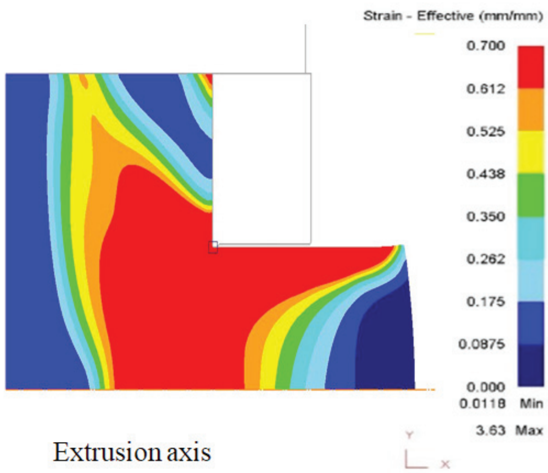



*Fig. 4.* Distribution of the strain degree in the longitudinal section in the nonstationary initial stage

The course of the curves on the graph shows that as the distance from the end increases, the values of the strain degree increase from zero to the level of the stationary stage of extrusion. The curves for the rod central part are most densely located, which indicates the minimal gradient in this zone. The lines are located more rarely closer to the periphery. This corresponds to the graph aggregation manner on Fig. 3, *b*, which was obtained for the stationary stage, however, with significantly different nominal parameter values.

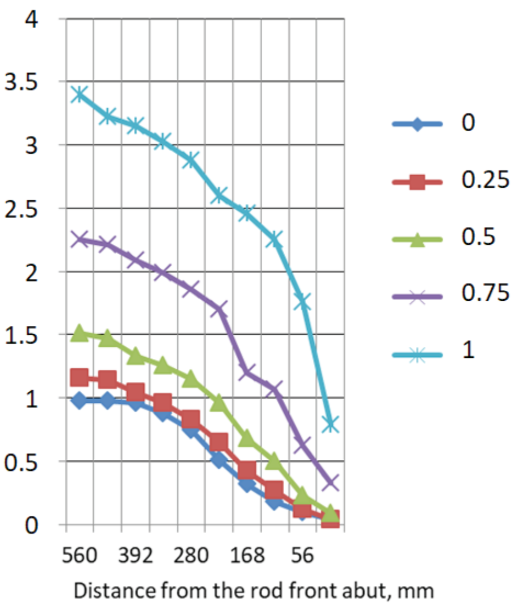



*Fig. 5.* Graph of the distribution of the strain degree in the cross sections of the rod depending on the distance from the front end at various relative radial coordinates *r/R*

The graph analysis in Fig. 5 also shows that the rod central layers obtain a strain constant level earlier than the peripheral layers. The stationary process is achieved with less metal motion.

The resulting strain distribution extends to the initial and boundary problem conditions. There is a wide variety of parameter ratios in production. Machine time cost was about two weeks without considering the time for debugging the system for several months. Therefore, sorting through all possible variants of production technologies and processing techniques is a rather expensive procedure. In this case, recommendations were developed for the considered option, but an attempt has been made to extend it to a class of technologies related to the extrusion with light reduction.

The consideration of the strain fields helps to determine the accumulated value of the hardening characteristic. But it is not clear here, why this effect is achieved. Therefore, Fig. 6 shows the stain rate field ($s^{-1}$).

Since the degree of deformation is an integral of the strain rate along the trajectory of the elementary particle, there are two ways to form a field of increased strain rates – either due to high strain rates, or due to the long-term use of moderate strain rates. The figure shows that an extremely high strain rates zone *W* is formed near the parallel land front part of extrusion die. At this point there is a sharp change in the metal motion direction and the strain tensor shear component increases significantly.

It can be concluded that there is a minimum strain that is needed to study the metal structure. The reduction rate calculated by the equation (2) is 80 % as shown previously. If only 40 % reduction rate is sufficient to achieve the properties and obtain the desired structure, then, in accordance with equation (3), the degree of deformation is $\varepsilon = 0.51$. As can be seen from the graph in Fig. 5, this value is already achieved at a distance of

224 mm from the end of the extruded rod, which is 63 % of the rod diameter. At the same time, the established recommendations include the removal of metal at a length of up to 200 % of the rod diameter.

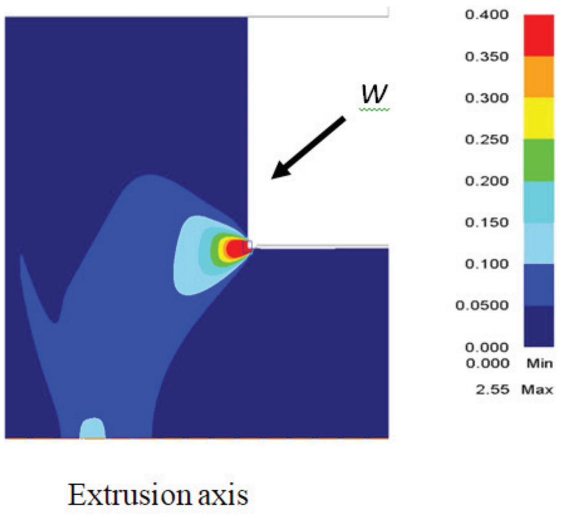



*Fig. 6.* Strain rate distribution (1/sec) in the longitudinal section (shape of the deformation zone); *W* – maximum point

It should be noted that the low strain field in the press product front (output) part has been repeatedly confirmed by experimental studies carried out by the coordinate mesh method [22, 23]. However, these studies were carried out on a model material, such as lead, as well as with much smaller geometric parameters.

The finite element method application made it possible to set the real workpieces dimensions and the real deformable material properties for the solution.

The practical value of the presented study lies in the fact that, according to the data obtained as a calculation result, it is possible to estimate the strain obtained by the rod in the initial non-stationary stage of extrusion and decide whether it is possible to use this metal for further forming or it should be sent for remelting.

One of the problems that arise after the end of the extrusion process is that it is necessary to evaluate the finished product mechanical properties. This should be done by selecting a template that is located at a certain distance from the rod front end. This distance is regulated by the standard. What are the product properties at a smaller or greater distance from the specified location remains unknown. It is possible that a part of the extruded rod has the necessary physical and mechanical properties level, but there is nothing to measure it with. It can be concluded that an easier way out is to send a potentially good metal to remelting. A solution to the problem by the finite element method allows building a strain distribution picture and linking this distribution with the properties distribution in the presence of pre-known functional dependencies.

Another way to use the resulting solution is to use the extruded rod front part for re-extrusion on a lower power press to obtain a product of a lower diameter. In this case, as a first approximation, the strain degree in the two stages of extrusion can be added using the additivity principle. The higher product properties will be achieved with a greater strain.

## Conclusions

In the extrusion process with a low elongation ratio, the strain is distributed inhomogeneously both along the press product cross section and along its length. The difference between the strain (logarithmic) in the central part (on the axis) and on the extruded rod periphery may be higher than 300%. In the non-stationary initial extrusion stage the rod front part remains weakly deformed both at the periphery and in the center. It is often forces to send this part to remelting due to the insufficiently developed metal structure. At the same time, if boundary conditions are set on the minimum possible strain degree, it is possible to set the minimum metal length to be removed with using the calculation results by the finite element method, thereby reducing the waste mass sent to the remelting.

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## Conflicts of Interest

The authors declare no conflict of interest.