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# Evaluation of the level of hardening of aluminum alloy chips intended for subsequent pressure treatment

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**ABSTRACT**

**Introduction**. It is noted that the chip is an undesirable type of metal scrap, because it has a developed surface, which creates conditions for more intense interaction with the surrounding atmosphere. This creates conditions for oxidation and gas saturation, especially at elevated temperatures typical of remelting processes. Therefore, the process of chip utilizing is considered, bypassing the remelting stage. The aim of the work is to establish the level of work hardening of chips during the processing of aluminum alloys and to predict its effect on the subsequent processing process. **Research methods**: to assess the deformed state, the finite element method was applied, implemented in the RAPID-2D software package. The sequence of actions included the creation of the initial shape of the deformation region and the configuration of the tool. The mutual displacement of the tool and the deformable material is specified using the corresponding boundary conditions. The deformable medium is a viscous-plastic material with power-law hardening, the physical and mechanical properties correspond to an aluminum-magnesium alloy. **Results and discussion**: the solution obtained shows that the degree of shear deformation in the chips can reach a value of more than 2. In this case, a higher level of deformation is localized on the side of the convex part of the chip. The comparison of the solution with those obtained earlier by other authors is carried out and its similarity is shown. In the considered solution, the difference in the degree of work-hardening of the chips along its thickness is 36 %. A variant of the sequence of processing the workpiece first by cold deformation, and then by cutting is considered. The field of application of the results of the work is the development of methods for the processing of technogenic formations. **Conclusions**. During the cutting process, the plastic deformation of the chips reaches significant values. In this paper, the difference in the degree of shear deformation in the chip thickness is established, depending on the proximity of the cut layer to the surface of the cutting tool. It is proposed to take this difference into account at the subsequent stages of chip processing. The presence of the marked inhomogeneity of mechanical properties leads to consequences in the form of an inhomogeneous distribution of the temperature of the beginning of recrystallization during subsequent operations of heat treatment or hot deformation treatment. The principle of additivity of the degree of deformation obtained by the metal at the stage of plastic shaping of the workpiece and the shaping of the chip itself is introduced.

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## Introduction

The processes of pressure treatment produce a smaller amount of waste compared to cutting treatment, and the waste itself is less dispersed than the chips, which allows them to be remelted with fewer losses. However, not all processes of giving products the desired shape can be performed by pressure treatment.

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The cutting processes that lead to the formation of chips occupy a significant segment in mechanical engineering [1]. Chips are a second-rate type of scrap metal because they have a developed surface, which creates conditions for more intensive interaction with the surrounding atmosphere. If the chips are transferred to the melt state, the oxide films appear on the surface as a result of heating, or there occurs gas saturation of the metal. These circumstances forced the developers to work out chip recycling avoiding the remelting stage [2,3]. For this purpose, pressure treatment methods are used, such as compaction in a closed container, rolling-pressing, hot pressing with subsequent cold processing of the product, etc. [4]. An additional difficulty arises when remelting aluminum chips: unlike heavy non-ferrous metals or even ferrous metals, which can be restored during melting using various reducing materials, aluminum oxides can be converted to a metal state only by electrolysis processes. Hence, there was a limitation to applying only solid-phase recycling processes [5-7]. In the liquid-phase process of aluminum remelting, oxide films are formed on the metal surface; the density of the films is almost the same as the density of the liquid phase, which impedes the separation of these phases due to gravity. The solid phase cannot be separated due to floating on the surface of the melt or settling on the surface of the hearth of melting furnaces.

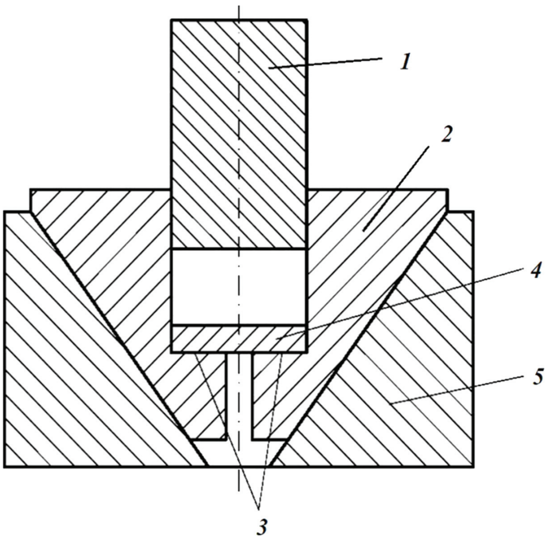
The chips have a certain degree of cold work hardening, which is recognized by all researchers. This degree of hardening has little effect on the melting temperature, but it strongly affects the recrystallization temperature; for some metals, it is possible to lower it to room temperature, which allows transferring the metal to a soft state. Conversely, metal hardening should be taken into account in the processes of chip compaction since it causes additional energy consumption.

Recent studies have been aiming at determining the properties of chips depending on the cutting conditions [8], including the ones for cutting various aluminum alloys [9], as well as the properties of semi-finished products obtained from the chips [10].

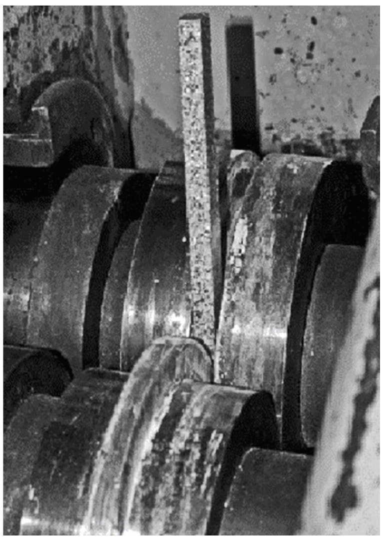
The aim of this work is to establish the degree of chip deformation during the aluminum alloys processing by cutting and to predict its impact on the subsequent recycling. The objectives of the study are to formulate the boundary conditions of the cutting process, to obtain a solution, and to adapt the conclusions to the chip recycling process.

## Methodology of Experimental Research

The aluminum alloy chips 2 were briquetted in a mold (Fig. 1, *a*), which consists of the upper *1* and lower *4* movable dies, a detachable matrix *3*, and a cage *5* with inclined contact surfaces.




*a*



*b*

*Fig. 1.* Scheme of cold pressing of a billet made of chips (*a*) and a photo of subsequent hot processing on a combined rolling-pressing process unit (*b*)

The experiments demonstrated that to ensure the briquettes' relative integral density of 70...80 %, briquetting pressure should not be lower than 80...100 MPa. The use of the stated pressures is common for compacting installations; usually, this level is not exceeded to avoid the danger of increased wear of the tool working surfaces. In the case of aluminum alloys, tool wear is caused by a thin protective film of aluminum oxide surrounding each chip fragment. The hardness of aluminum oxide is very high; the edges of its protruding parts continuously scratch the tool and cause wear. The danger of aluminum sticking to these surfaces aggravates the situation.

An important factor in the disposal of aluminum chips is known to be the development of shear deformations that allow crushing the oxide film surrounding each metal fragment, which enables consolidating the metal [11, 12]. Therefore, for the further processing of the obtained briquettes, a combined rolling-pressing unit (CRP) was used (Fig. 1, *b*). The rolls of the unit were heated to a temperature of 80...100 °C. The briquettes were set into rolls and deformed to obtain a rod with a final size of 7 and 9 mm, which corresponded to the values of the reduction ratios during pressing 8 and 5. Studies of the obtained rods microstructure led to the conclusion that in some cases the chip elements do not form a continuous connection, despite certain conditions created for this, such as high temperature and significant shear deformations.

The reason for this phenomenon could be that after removal by the cutter the chips have increased strength properties, which prevents the process of their consolidation during cold briquetting. A low level of compaction at this stage leads to a high level of residual porosity after hot deformation. Mathematical simulation of the cutting process is proposed to apply for assessing the level of chip hardening. It is carried out in the next part of the work.

## The methodology of the computational experiment

To estimate the deformed state, we used the finite element method implemented in the RAPID 2D software package (© E.G. Polishchuk, D.S. Zhirov); the description and application of the software product are given in the book [13]. The sequence of actions included the creation of the initial shape of the deformation focus and the configuration of the tool (Fig. 2). The scheme of the deformed state is flat. Thus, only the near-surface layer of the material is considered. This layer experiences the cutting stresses. The physical and mechanical properties of the deformable material correspond to the AMg1 alloy and are taken from the library of the program module. The presence of viscous properties of aluminum alloys in the cold state was proved in [14–16]. The cutter is presented as an absolutely rigid body, so the characteristics of the material from which it is made were not taken into account.

The mutual movement of the tool and the deformable material is set using the appropriate boundary conditions. The deformable medium is viscoplastic with power-law hardening. The speed of mutual displacement of the workpiece and the cutter is set at 2 m/s. Usually, the Siebel law of friction is set in

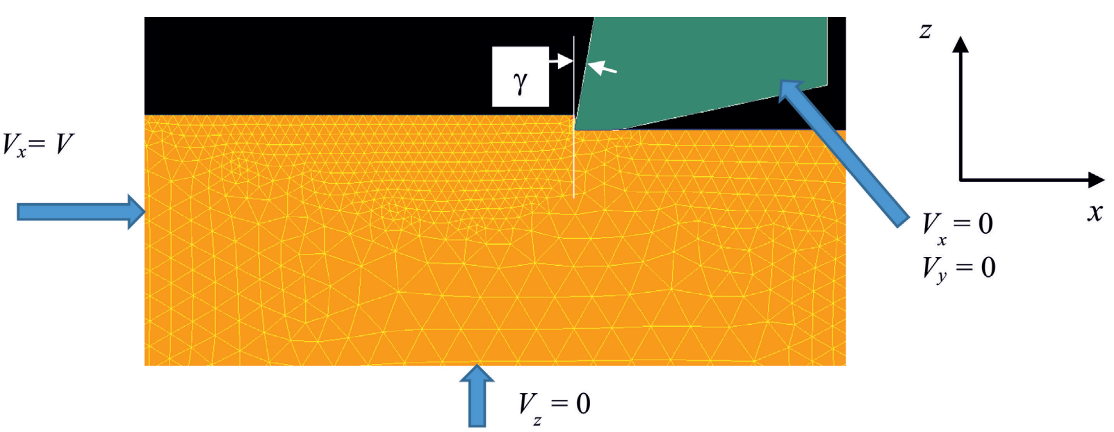



*Fig. 2.* Boundary conditions in the formulation of the problem and the coordinate system, γ – tool rake angle

processes with high normal stresses on the contact surface; it is also implemented in this formulation. The coefficient of friction is assumed to be equal to 0.1.

The RAPID 2D software package allows operating with dimensional values at the millimeter level and above, which is not always typical for chip removal. Therefore, we used the following technique: the dimensional values were increased by an order of magnitude, bearing in mind the subsequent transition after the implementation of calculations to dimensionless values. The dimensionless representation of information makes it more versatile for use.

A layer of metal with a thickness of 25 mm is considered. The thickness of the metal removal is assigned at 1 mm. The dimensions are chosen conditionally, it is the ratio between them that is important. The finite element grid at the places of the assumed increased strain gradients is made with a smaller step.

The deformation hardening of a metal is estimated by invariant values: either by the degree of deformation ε (equivalent deformation) or by the degree of shear deformation Λ, with the correlation between them, $\Lambda = 1{,}732\ \varepsilon$.

Areas of equal level (Fig. 3) show that the degree of shear deformation in the chip can reach values higher than 2; this value is higher on the convex part of the coil. This can be explained by the fact that the convex part of the chip undergoes a greater elongation relative to the concave surface.

Plastic deformation during chip removal ends at the place where it is separated from the tool. The scheme presented in Fig. 3 allows estimating the transition from the non-strengthened state $\Lambda = 0$) to the hardened one, but the gradient of the deformation degree in the chip itself cannot be adequately displayed. Therefore, in Fig. 4, the range of displaying the degree of shear deformation is shifted to 2...2.8.

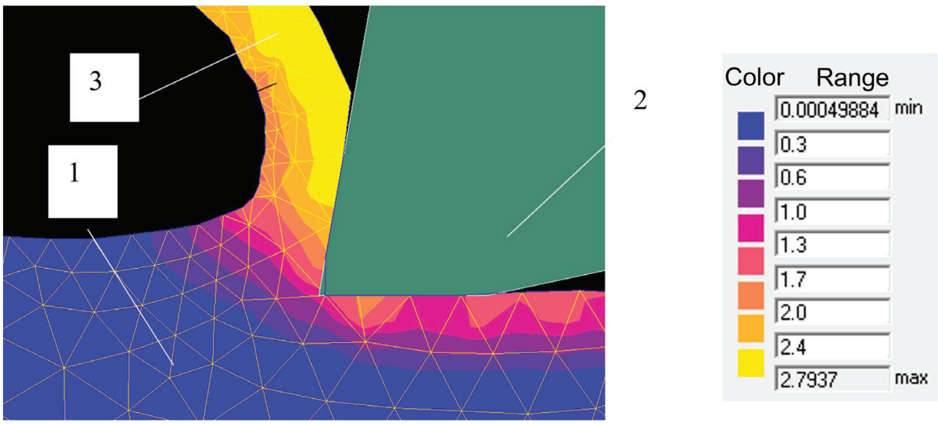



*Fig. 3.* Solution of the problem of separation of chips at an angle of γ = 10 ° and a nominal removal depth of 1 mm:

*1* – workpiece from AlMg1 alloy; *2* – cutter; *3* – chips; on the right is a color key for the of shear strain Λ

The maximum value of the shear deformation degree is $\Lambda = 2.69$. This value can be correlated with the value of the reduction of the cross-sectional area ε, for example, when drawing a rod, using the formula

$$\Lambda = 1.732 \cdot \ln\left(F_0/F_1\right) = 1.732 \cdot \ln\left[F_0/\left(F_0 - \Delta F\right)\right] = 1.732 \cdot \ln\left[1/\left(1 - \varepsilon/100\right)\right], \quad (1)$$

where $F_0$, $F_1$, $\Delta F$ are the initial and final cross-sectional areas, as well as their change, respectively.

From here

$$\varepsilon = 100\left[1 - \exp\left(-\Lambda/1.732\right)\right]. \quad (2)$$

At $\Lambda = 2.69$, the value $\varepsilon = 79\%$.

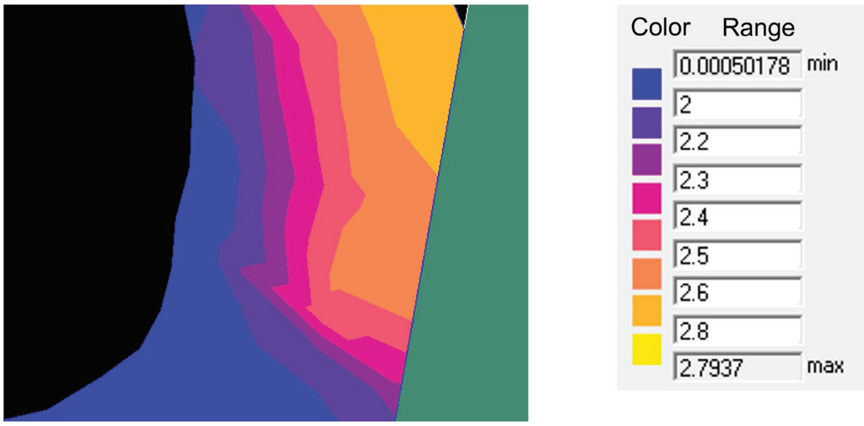



*Fig. 4.* Field of the of shear strain Λ in the place of separation of the chips from the cutter, on the right with a color key

To estimate the numerical values of the strain distribution, a relative coordinate $x/\delta$ is introduced, where $x$ is the current horizontal coordinate, $\delta$ is the chip thickness. The graph of the dependence $\Lambda = f(x/\delta)$ is shown in Fig. 5.

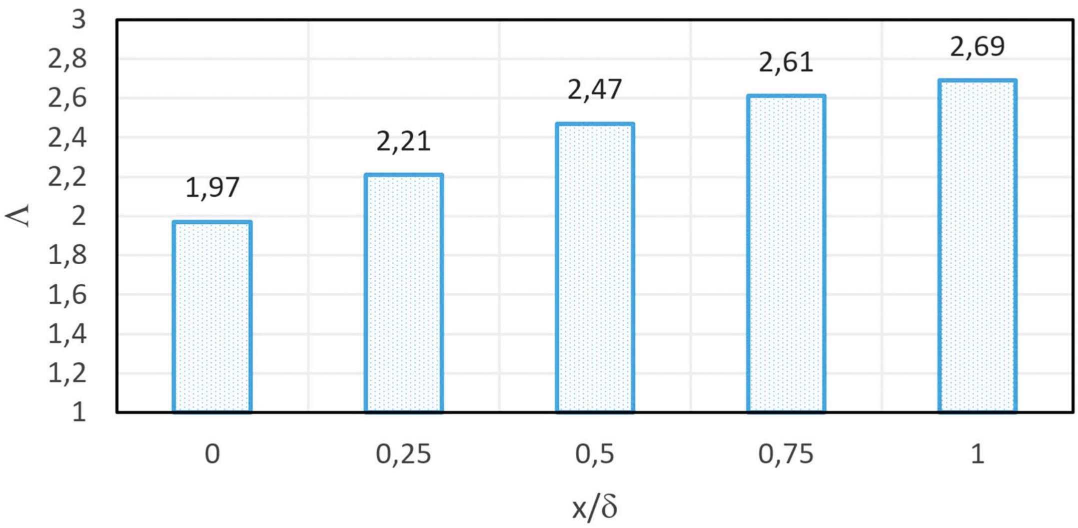



*Fig. 5.* Dependence of the of shear strain on the relative coordinate $x/\delta$

Here it can be seen that in this case, the difference in the degree of chip peening by its thickness is 100(2.69 – 1.97)/1.97 = 36 %. Further calculations showed that as the chip thickness increases, this difference will increase, i.e. the chip becomes an increasingly heterogeneous material.

## Results and discussion

Notably, a qualitatively similar solution to the problem was obtained in a joint study of the United States, the Republic of Korea, and the United Kingdom [17]. The problem was solved by the finite element method in the Abaqus/Explicit software package for calculating a plane strain state. The task of separating the chips from the workpiece was not always solved successfully by researchers since it required allowance for the beginning of metal destruction, while the continuity hypothesis adopted for constructing a system of equations of the plasticity theory hindered it. However, this is overcome in the article [18], where a significant hardening of the chip metal is shown.

A large degree of deformation localized in the chips leads to physical phenomena, which include the structure refinement; paper [19] argues that the grain size decreases from about 60 μm to 1...3 μm, i.e. by

20...60 times. A greater effect is achieved in the metal layers on the convex surface of the chip, and a smaller effect is achieved on the concave surface, which corresponds to the resulting deformation distribution.

A specific factor that has to be taken into account when assessing the chip deformed state is the degree of deformation achieved at the previous stages of processing since the parts are often cut after preliminary cold deformation. The level of this deformation is set by the engineering specifications for using high-strength metal in the part.

Additionally, the cold-worked metal is characterized by a higher level of brittleness, which yields loose chips instead of drain chips. The latter is easier removed from the cutting zone as fragmented material.

In the mechanics of plastic deformation, there is a hypothesis that plastic deformations achieved in various processes have the property of additivity, i.e. they can be summed up. Then the resulting degree of shear deformation $\Lambda_\Sigma$obtained by the chip is the sum of the degrees of shear deformation accumulated by the workpiece at the preliminary stages of its processing $\Lambda_1$, $\Lambda_2$, ..., $\Lambda_{i-1}$, and the degree of shear deformation obtained by cutting $\Lambda_d$:

$$\Lambda_\Sigma = \Lambda_1 + \Lambda_2 + \ldots + \Lambda_{i-1} + \Lambda_d. \quad (3)$$

Pure aluminum rarely acts as a structural material. It is usually considered a functional material and used as a conductor of electric current or a heat transfer element. Accordingly, chips rarely occur in the manufacture of wire or conductive tires since these products are obtained by drawing.

Thermally non-hardenable aluminum alloys are hardened by cold plastic deformation. Thermally hardenable alloys undergo the stages of quenching and subsequent natural or artificial age-hardening, with the possibility of additional hardening by cold or warm plastic deformation. The metal that has undergone these stages of hardening can be processed by cutting with the formation of chips. The degree of deformation to failure depends on the type of alloy and can exceed 90 % [20].

An additional degree of shear deformation $\Lambda_{i-1}$, which the workpiece metal underwent during the cutting operation, causes a decrease in the temperature of the recrystallization beginning. This circumstance will have to be taken into account for the heat treatment or hot deformation treatment operations [21]. In particular, the recrystallization temperature decrease may be inhomogeneous within the workpiece due to the inhomogeneities of the chips themselves. As a result, the formation of a multi-grained structure is not excluded, which, in turn, will cause heterogeneity in the distribution of the physical and mechanical properties of the finished product.

Another factor that has to be taken into account when assessing the chip condition concerns the thermal processes that occur during cutting. The process itself can be carried out in various conditions. The cutting work is converted into heat; as a result, the chips are heated. This process coincides with the process of cooling it by the lubricoolant supplied to the cutting center. At the same time, at high cutting speeds, heat may not have time to be removed, so the heating temperature may exceed the recrystallization temperature, which will lead to the annealing of the metal. However, a large number of aluminum alloys have a very high recrystallization temperature, which allows obtaining cold-worked metal in such operations as pressing. Thus, although pressing is usually referred to as hot processing, for aluminum alloys it is often a cold or, in extreme cases, warm processing. As a result, a semi-finished product is obtained, for example, a rod that enters the cutting operation with a residual level of accumulated deformation. Here, the same situation develops as in the case of processing a cold-formed semi-finished product: to assess the hardening of the resulting chips, the degrees of shear deformation must be summed up.

The paradox is that an increased degree of deformation, in this case, leads to a decrease in the recrystallization temperature of the chip material, i.e. the process of the chips' hot deformation can be carried out at lower temperatures. Importantly, the recrystallization temperature for aluminum chips also depends on the deformation rate: when it increases, the recrystallization temperature decreases. Therefore, if a less durable state of aluminum chips is required, the recommended process of hot briquetting is better performed at high loading speeds, which contradicts the concept of high-speed hardening characteristic of other metals. Further research can be aimed at the study of the structural consequences for the chips to be used as a raw material for the manufacture of semi-finished products.

## Conclusion

During the cutting process, the plastic deformation of the chips reaches significant values. The paper shows the difference in the degree of shear deformation in the chip thickness depending on the proximity of the cut layer to the surface of the cutting tool. This difference is proposed to be considered at the subsequent stages of chip processing. The noted inhomogeneity of mechanical properties leads to an inhomogeneous temperature distribution of the recrystallization beginning during subsequent operations of heat treatment or hot deformation treatment. The additivity principle of the degree of deformation obtained by the metal at the stage of plastic shaping of the workpiece and the shaping of the chip itself is introduced.

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## Conflicts of Interest

The authors declare no conflict of interest.