Research of Technology For Production Deformed Semi-Finished Products From Chip Waste of Aluminum Alloys And Study Properties of The Obtained Products

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Abstract

The results of studies of some methods of obtaining longish deformed semi-finished products in the form of rods and wires from chips of aluminum alloys 6063 and AlSi12 excluding the melting process during their implementation are presented. At the same time, the main methods used powder metallurgy (briquetting), metal forming (extrusion and drawing), and heat treatment (annealing). Using the developed general technological scheme of thermal deformation processing of chip waste from aluminum alloys, experimental studies of the technology of production of longish deformed semi-finished products from high-quality chips of alloys 6063 and AlSi12 have been carried out. The mechanical properties of metal obtained from shavings of experimental alloys of briquettes, rods, and wires were determined. The change in the structure of semi-finished products at all technological stages of processing was investigated. Computer simulation has been carried out, according to the results of which the regularities of temperature change, degree of deformation, and relative density in the volume of the deformation zone for semi-finished products obtained by the method of combined rolling-extrusion of a porous billet from briquette chips of 6063 alloy. As well as the degree of deformation, average normal and tangential stresses in the zone have been established. Deformation depends on the conditions of contact friction when drawing a wire from this alloy. Using the results of computer simulation, the proposed routes for drawing wire from extruded rods of chips of 6063 and AlSi12 alloys were experimentally tested and with their help, experimental batches of products were obtained for various industrial purposes.

Introduction

The increased interest in the metallurgy of secondary aluminum in recent years is expressed in the relatively rapid development of the specified production due to high technical and economic indicators in the structure of the cost of production and the possibility of its implementation in environmentally friendly options [1–13].

About 90% of the produced secondary aluminum is used in the automotive industry as casting alloys, and the rest is wrought aluminum alloys, from which products are obtained by metal forming [13–32]. The main method used to obtain billets for subsequent deformation is chip briquetting [13, 16, 18, 20, 21, 23, 24, 29]. The most common metal forming process for this type of product is hot extrusion [13–17, 19, 26–28, 30–32]. There is also a possibility of obtaining deformed semi-finished products from aluminum chips by rolling [13, 15], hot stamping [13, 18, 20, 21], drawing [19], and combined methods (such as Conform) [13]. An urgent task is the mathematical modeling of metal forming processes during chip recycling [22]. The issues of processing waste generated in one form or another play a significant role in the cycle of manufacturing products from aluminum and its alloys. The volume of processed metal has been constantly increasing in recent years. Therefore, the creation of new, more advanced technologies for involving the generated waste into the production turnover is an important task of energy and resource-saving. This is due to the fact that the current system of processing non-ferrous metal waste through their remelting does not fully meets the requirements of economy and rational use of secondary metals and alloys [5, 6, 10, 11, 13]. Insufficient efficiency of traditional technology in the processing of various types of waste is due to factors such as increased waste of metal, reduced yield due to the transition of a part of the metal into slag, significant energy consumption for remelting, high labor intensity during basic operations, increased volume of gas and dust emissions [10, 11].

This is especially true for the waste of aluminum and its alloys in the form of chips generated in the machine-building, metallurgical and other industries since their amount significantly exceeds the volume of such waste of other non-ferrous metals and alloys.

Thus, the improvement of the technology for processing waste chip materials by eliminating the stage of remelting and based only on the use of methods of powder metallurgy and metal forming processes should be recognized as an urgent scientific and technical problem. The main developments of the authors in this area of research are given in the monograph [33].

As is known [34], of all types of industrial waste supplied to metallurgical plants for processing the maximum share falls on bulk waste such as chips, which is about 40%.

Secondary aluminum metallurgy has its specifics since aluminum oxide formed during storage or remelting is not reduced. Consequently, the aluminum included in its composition is irretrievably lost. In addition, alumina is difficult to completely separate from the molten metal, although it does not dissolve in the base metal. However, the presence of oxide in alloys, usually in the form of solid inclusions, adversely affects the properties of products.

Due to the developed surface, the chips are oxidized especially intensively. In the chips not prepared for melting the average metal content is 73-75%. In some batches, it ranges from a few percent (the chips were in the air for a long time) to 85-90% (for clean, just formed chips).

Waste losses are about 5% when smelting under production conditions. With an increase in oil, moisture, dirt, a mechanical admixture of iron, and other foreign materials in the chips, the metallurgical yield, which, in addition, depends on the size of the chips, is significantly reduced. Therefore, when melting "dirty" chips it is necessary to introduce an increased amount of flux into the furnace not only to protect the metal from oxidation but also to absorb the oxide film, dirt, and dust. This leads to additional costs for flux, complicates the work of smelters, reduces the productivity of furnaces and labor, increases the amount of slag to be downloaded, and increases the loss of aluminum.

Therefore, special attention of researchers is directed to the development of methods for returning the generated chip waste into production circulation, bypassing the melting process. In a generalized schematic form, possible options for processing chip waste into products for various purposes are shown in Fig. 1. As can be seen from Fig. 1, in most cases chips in one form or another, despite the negative aspects noted, are ultimately introduced into the metal melt anyway. But, in contrast to its traditional use as one of the components of the charge raw material prepared for remelting, the option of endowing the semi-finished product introduced into the melt with certain specific functions such as a deoxidizer, modifier, or alloying component seems to be more promising.

Examples of the practical implementation of the proposed approach are sometimes given in specially printed sources. For example, in [35] the possibility of using granular aluminum obtained by mechanical crushing of scrap was investigated as a deoxidizer. Experiments on the deoxidation and alloying of steel in a vacuum induction furnace did not reveal differences between the types of aluminum that were processed, both during deoxidation and when determining the purity of the metal by oxygen. At the same time, it was found that granules of lesser sphericity and with a large number of particles per unit of bulk material mass form accumulations on the surface of the melt, as a result of which their mobility decreases, and the dissolution time increases. This reduces the efficiency of the deoxidation process.

The work [36] shows the possibility of using special technological processes and equipment for powder and granular metallurgy to obtain aluminum briquettes intended for steel deoxidation. The technological scheme provides for the possibility of plasma spraying of metal waste of various types to obtain granules of a certain type and their subsequent static cold compaction into briquettes of a given shape. Technologically important is the possibility of transferring a specially made spraying object to the plasma processing facility, which can be continuous tubular billets, formed from pre-prepared chips from machining industries.

Studies on the production of aluminum briquettes intended for deoxidation showed [37] that it is necessary to take into account the peculiarities of the formation of powder aluminum briquettes, associated, first of all, with the fact that aluminum granules are always covered with a thin, thermodynamically very stable film of aluminum oxide. Plastic deformation of aluminum granules destroys oxide films, and the formed contacts of juvenile metal-to-metal surfaces provide mechanical and/or physical contact. The implemented method of pressing in rigid molds should ensure obtaining a briquette with the highest possible density. This is achieved either by briquetting at a pressure of about 400-800 MPa with the preliminary application of a lubricant of a certain composition to the working surfaces of the mold, or by introducing an additional operation such as extrusion (squeezing out) of the compacted mass through the die point into the technological scheme. It is also important that the aluminum chips used for briquette correspond in chemical composition to one of the alloys specified in State Standard 295-98 "Aluminum for deoxidation, production of ferroalloys, and aluminothermy".

It is also known [38] that to improve the structure, increase the mechanical and technological properties of aluminum alloys, they are modified before pouring the corresponding melts. According to one of the theories reflecting a relatively new approach to the description of the modification mechanism and based on the concept of the cluster structure of a liquid crystallizing metal [39], it is assumed that the grain refinement of a solid solution is possible due to the introduction of modifier rods made of the same alloy as the material being modified. First of all, such modifiers do not contain specially introduced elements. And secondly, when the rods are dissolved in the crystallizing metal, their ability to influence the state of the cluster structure of the crystallizing ingot is used, which ensures the modification of the alloy. Along with this, the use of a bar made from chip waste for modification solves the problem of more efficient use of a large amount of production waste generated during the machining of semi-finished products from the same alloy.

The cluster theory of modification upon the introduction of rods into the melt, for example, from silumin chip waste [40], makes it possible not only to explain the grinding mechanism of silicon particles in the Al+Si eutectic but also confirms the fact that the reason for the formation of a modified structure in the AlSi12 alloy is the introduction of traditional modifiers such as aluminum-titanium-boron and aluminum-strontium. The desire to increase the number of crystallization centers based on the introduction of more dispersed silicon made it possible to assume that it would be much more efficient to use as a master alloy not a pressed bar, but a wire obtained by cold drawing. With an increase in the degree of deformation, the structure of the metal becomes more uniform and dispersed, the particles of the alloying component decrease in size, and a greater number of them are placed in a unit volume. This can favorably affect the structure of the clusters formed upon the dissolution of the ligature and affect the structure of the crystallizing melt. The expediency of feeding longish deformed semi-finished products into the melt as a deoxidizer or modifier instead of loosely poured or briquette chips can be explained by the fact that it is much easier to introduce rods wound into coils into the melt, for which the industry uses special installations for their automatic feeding.

Despite the fact that the works of many domestic and foreign scientists [41–59] are devoted to the creation of metal recycling technologies, the problem of finding an energy-efficient technology for manufacturing deformed semi-finished products from aluminum alloy wastes has not yet been solved. The process of chip formation and its subsequent remelting and compacting were studied in [49]. The production of briquettes is discussed in [49, 53]. The process of chips extrusion is considered in works [41, 44, 46, 49, 54]. Assessment of properties and influence of pores during compaction was studied in works [42, 49–51]. The possibility of drawing non-compact materials is presented in works [43–45, 54]. Modeling the formation of chips and their behavior during processing is also of great importance [51, 52]. Also, the authors have developed methods and devices for processing non-compact materials [47, 48]. In the course of prospecting studies, the possibility of processing aluminum shavings by combined metal forming methods, such as combined rolling-extruding (CRE), was studied [55–60].

The aim of the research, therefore, was the development of technical and technological solutions to increase the efficiency of processing graded loose chips from aluminum alloys.

To achieve this goal, the following tasks were set and solved:

- analysis of scientific and technical literature in the area under consideration in order to select potential methods for processing bulk waste from aluminum alloys widely used in industry;

- formation of a general technological scheme for the processing of bulk metal waste from chips of 6063 and AlSi12 alloys and development of a technology for obtaining deformed semi-finished products from them using the methods of powder metallurgy and metal forming;

- computer modeling and assessment of the possibility of obtaining longish deformed semi-finished products from pre-briquetted chips using various methods of metal forming;

- experimental studies of the technology for the production of bars and wires from chips of 6063 and AlSi12 alloys obtained by briquetting, discrete (cyclic) and continuous extrusion, as well as cold drawing;

- investigation of the structure and properties of rods and wires obtained from chips of 6063 and AlSi12 alloys by the above processing methods.

Method Of Carrying Out Research

Deformable aluminum alloy 6063 and casting alloy AlSi12, widely used in industry, were chosen as materials for research. The chemical composition of these alloys is given in Table 1.

Table 1
– Chemical composition of the investigated aluminum alloys

Alloy	Mass fraction of the component, %								
	Al	Mg	Si	Cu	Fe	Mn	Zn	Ti	Zr
6063	Basis	0.45-0.90	0.3-0.7	0.1	0.35-0.50	0.1-0.2	0.10-0.15	0.10-0.15	-
AlSi12	Basis	0.10	10.0-13.0	0.6	1.50	0.5	0.30	0.10	0.1

For the research, a certain type of 6063 alloy chips was chosen, which is formed when cutting molded products to measured lengths (Fig. 2a). Chips from the AlSi12 alloy (Fig. 2b) were obtained at one of the technological stages in the production of cast wheel disks.

At the first stage, to solve the set tasks of obtaining deformed semi-finished products with an appropriate level of mechanical properties, the method of hot discrete (cyclic) extrusion was chosen. The processing of chips from the experimental alloys was carried out according to the scheme shown in Fig. 3.

The equipment used was a vertical hydraulic press with a force of 1 MN (Fig. 4a) and a extruding tool (Fig. 4b).

At the second stage of research, a scheme was developed for obtaining deformed semi-finished products from chips of experimental alloys by the method of combined rolling-extruding. [33, 58-60] (Fig. 5).

The production of hot-extruded rods according to this scheme was experimentally realized on the CRE-200 unit [33, 56-59].

Results And Discussion

To determine the influence of the cold briquetting pressure on the density of cylindrical briquettes made of 6063 alloy, depending on the mass of the fill, experimental studies were carried out the results of which are shown in Fig. 6.

It has been found that the minimum required level of the relative density of briquettes for subsequent deformation should be at least 60-70%, for which a briquetting pressure of at least 80-100 MPa must be applied. In this case, the greater the mass of the fill, and, consequently, the higher the height of the resulting briquette, the lower its density and the more significant the inhomogeneity of its distribution. A decrease in porosity and, consequently, an increase in density at the same values of briquetting pressure can be achieved if the chips are compacted in a form heated to a certain temperature. The heating temperature, corresponding in this case to the conditions of hot briquetting, is selected on the basis that the resistance to deformation of the chip material at this temperature should be lower than the level of applied briquetting pressures.

To confirm this fact, experiments were carried out on hot briquetting of the same 6063 alloy chips in a press-form, in one case heated to a temperature of 300±20°C, and in the other - up to 400±20°C. The integral density of the obtained compacts was: at 300°C 2.3-2.4 g/cm^3, which corresponded to the relative density of about 85%, and at 400°C 2.5-2.6 g/cm^3, which corresponded to the relative density of about 90%.

The temperature and deformation rate at which discrete extrusion on a vertical press with a force of 1000 kN took place were identical each time and corresponded to the parameters recommended for extrusion cast billets from 6063 alloy, i.e. when the billet temperature was in the range T = 430-450°C, and the extruding speed V_{extr} = 50-150 mm/s. Compression was used to obtain rods with a diameter of 6 mm (the elongation coefficient μ was $\approx$ 56), 8 mm ($\mu \approx$ 32), and 12 mm ($\mu \approx$ 14). It was revealed that regardless of the extrusion ratio with which extrusion is carried out, the outflow of the rods from the die according to a given temperature and speed regime is quite stable. The maximum extrusion force for the 6063 alloy is about 500 kN, which is in satisfactory agreement with the calculated data obtained using the formula of I.L. Perlin [61].

In the course of practical testing, it was found that preliminary hot or cold briquetting of chips does not have a significant effect on the formation of a given level of mechanical characteristics of wire-rod products. In any case, it is important to provide only the specified temperature and rate conditions of deformation at the moment of the beginning of the outflow of metal from the working hole of the die. In this case, the mechanical properties of the rods after hot extrusion were: ultimate tensile strength R_m = 130-140 MPa, elongation to failure A = 15-17%.

To obtain briquettes from AlSi12 alloy chips, two methods were also used: cold and hot briquetting.

The results of experiments on cold briquetting showed that the maximum relative density, which can be achieved by cold briquetting of chips with a pressure of about 180 MPa, is about 70-75%. At the same time, the use of briquetting pressures below 100 MPa did not allow achieving a stable bound state at all. When removing the briquettes compacted at this pressure from the press-form, they crumbled into separate fragments.

Experiments on hot briquetting of the same chips at different briquetting temperatures were carried out with the following parameters: the weight of the sample of the chips was about 100 g, the diameter of the container was 42 mm, the maximum applied briquetting pressure was 180 MPa, and the holding at this pressure was 5 min.

In the course of briquetting and at the end of it, the value of the current and final integral density of the briquettes was determined, the values of which, depending on the temperature and pressure of briquetting, are shown in Fig. 7. The maximum integral density of the obtained briquettes at a temperature of 400°C was 2.35-2.45 g/cm^3, which corresponded to a relative density of about 90%.

The temperature and speed mode of performing the discrete extrusion operation in this case corresponded to the parameters recommended for extruding rods from hard-to-deform aluminum alloys: billet heating temperature T = 450-470°C, extruding speed V_{extr} = 50-100 mm/s [61]. By extruding, rods with a diameter of 6 mm (μ ≈ 56) and 8 mm (μ ≈ 32) were obtained. A comparative analysis of the achieved mechanical characteristics showed that, regardless of the diameter of the hot-extruded rod, the average values of the considered indicators of the strength and plastic properties of the material differ little from each other. The range of variation of the values of the ultimate tensile strength R_m is from 160 to 170 MPa, the elongation to failure A is from 15 to 17%, the area reduction Z is from 30 to 40%. For example, Fig. 8 shows the typical structures of a rod with a diameter of 6 mm, obtained from chips of silumin AlSi12 by the method of discrete extrusion.

Metallographic analysis showed that the structure in the longitudinal section is row-like, with the light sections of the aluminum phase elongated in the direction of outflow from the die interspersed with darker areas saturated with silicon (Fig. 8). In this case, the concentration, size of silicon particles, and the order of their distribution against the background of the aluminum phase are relatively inhomogeneous.

Computer modeling of the combined rolling-extruding process was carried out in the QForm V8 program in a 3D setting with one plane of symmetry (Fig. 9). The data on mechanical properties required for modeling were taken from works [62–70]. Aluminum alloy 6063 was chosen as the workpiece material. The rolls had different rolling diameters, which made it possible to increase the feasibility of the CRE process [58–60].

Figure 9a shows the distribution of metal temperature along the deformation zone. When in contact with a colder tool, the temperature of the billet decreases, which is explained by its small transverse dimensions and a significant difference between the heating temperatures of the billet and the rolls. The only positive effect of this effect can be that the metal of the billet does not recrystallize and, therefore, does not lose the strength achieved as a result of hardening. The distribution of the degree of deformation shown in Fig. 9b shows a gradual increase in this parameter, starting from the entry of the billet into the rolls with a sharp increase near the surface of the die. In this case, at the entrance to the deformation zone, the distribution of the degree of deformation is asymmetric: the maximum degree of deformation is obtained by the layers adjacent to the roll having a larger diameter (roll with a protrusion).

Figure 10 shows the results of studies of changes in the power parameters of the CRE process and the relative density of the metal. From the graphs of the dependence of the value of the rotation moment of the rolls on the displacement (Figure 10a), it can be seen that the rotation moment of the roll with a protrusion is lower than that of a roll with a small diameter (a roll with a groove). This is explained by the fact that a roll with a groove has a larger contact area with the metal being processed than a roll with a protrusion; therefore, the amount of contact friction is greater.

From the picture of the distribution of the relative density of the billet material along the deformation zone, it can be seen (Fig. 10b) that the compaction process begins immediately at the entrance to the deformation zone, and this process is also asymmetric: on a roll with a protrusion, the process begins earlier. However, as the metal advances in the course of rolling-extruding, the metal layers adjacent to the groove roll are already more compacted. When the metal approaches the die, the highest density is observed closer to the center of the billet. In the plane connecting the axes of the rolls, the compaction process practically ends, and an almost compact material enters the extrusion zone, the relative density of which is close to 100%. With further advancement of the metal, this density no longer changes.

To check the simulation results, experimental studies were carried out on the production of briquettes from the investigated alloys and their deformation by the CRE method. The cross section of the briquette had dimensions of 15×15 mm, the length was 200 mm, and the mass of the fill was taken equal to 130, 150, and 180 g. A special split form was used for briquetting the chips [33]. The general view of the briquettes, as well as the dependence of their density on the pressure of cold briquetting, is shown in Fig. 11. The maximum relative density at p_{br} = 100 MPa was 80%.

The resulting briquettes (3 pieces at the same time) before rolling-extruding were heated to a temperature of 480±20°C in a resistance furnace; the total heating time was about 60 minutes. In parallel, the rolls of the CRE-200 unit were heated to a temperature of T_r = 80-100°C.

Using the CRE method, rods with a diameter of 7 and 9 mm were obtained, the level of strength and plastic characteristics of which turned out to be approximately the same and amounted to: ultimate tensile strength R_m = 180-190 MPa, elongation to failure A = 12-16%, area reduction Z = 38-42%.

Analysis of the results of metallographic studies of rods obtained from 6063 alloy chips (Fig. 12) showed that it is necessary to increase the degree of deformation during extrusion, since it is insufficient to ensure high-quality seizure of the chips particles in the process of their joint deformation. The microstructures show clearly defined interfaces between individual chips, which are surface oxide films, and rather rare discontinuities. There is no fundamental difference between the structures of the samples cut from extruded rods with a diameter of 7 and 9 mm. Bridges of seizure between the chips are not observed, i.e. the formation of physical contact occurs mainly on the microroughnesses of the chips with partial spreading (but not destruction) of the oxide film over the entire contact surface.

Billets made of chips from the AlSi12 alloy for CRE were formed by hot briquetting at a temperature T_{br} = 350 °C and a briquetting pressure p_{br} = 100 MPa, the relative density being 85-87%. The temperature of heating the briquettes before the CRE was chosen equal to 500-520 °C, the total heating time was 60 minutes. As a result, rods with a diameter of 7 and 9 mm were manufactured, and, as before, the level of strength and plastic properties of the resulting rods was practically the same value: ultimate tensile strength R_m = 220 - 230 MPa, elongation to failure A = 5-7%, area reduction Z = 8-9%. The characteristic structures of rods also do not have fundamental features, as in the case of rods made of 6063 alloy chips.

Comparison of the mechanical properties of rods manufactured using discrete extrusion and the CRE method from the same types of chips showed that due to the difference in temperature conditions for the implementation of the processes, it is advisable to pre-anneal the rods obtained by the CRE method before they are cold drawn by drawing according to the following modes:

- for alloy 6063: T_{anneal} = 350 °C; t_{anneal} = 60 min;
- for alloy AlSi12: T_{anneal} = 400 °C; t_{anneal} = 60 min.

After the annealing of the rods, the strength and plastic characteristics of the metal were:

- for alloy 6063: ultimate tensile strength R_m = 125-135 MPa, elongation to failure A = 17-18%, area reduction Z = 50-55%;

- for alloy AlSi12: ultimate tensile strength R_m = 105-115 MPa, area reduction Z = 10-11%.

At the final stage of research, computer modeling of the process of drawing bars obtained by discrete and continuous extrusion from chips of 6063 and AlSi12 alloys, as well as experiments on obtaining wire from them, were carried out [33].

Modeling of the process of drawing a porous rod was carried out in the ABAQUS program. Workpiece material - aluminum alloy 6063, the initial relative density of the material was 90%. The coefficient of friction was chosen as a variable parameter, which varied at four levels: 0.05; 0.1; 0.2 and 0.3.

The effect of the friction coefficient on the compaction process is shown in Fig. 13 (for example, the distribution of the relative density for the friction coefficients of 0.05 and 0.3 is shown). It can be seen that with a small friction coefficient in the direction of the radial coordinate, two zones of compaction can be distinguished, and in the peripheral zone the compaction is greater than in the central zone. With an increase in the friction coefficient, a third zone appears in the center with a density reduced to the initial value, which expands with an increase in the friction coefficient to 0.3.

The results of calculating the distribution of the Pressure value (the value opposite in sign with respect to the hydrostatic pressure) are shown in Fig. 14. It can be seen that at a low coefficient of friction, zones of intense compression are located in the peripheral regions of the billet, adjacent to the surface of the die. At the level of the calibrating band, tensile zones appear which are caused by the action of the pulling force. With an increase in the friction coefficient, the zones of action of compression stresses are increasingly localized near the contact surfaces, without penetrating into the central region. This picture is in qualitative agreement with the density distribution shown in Fig. 13.

The distribution pattern of the degree of deformation PEEQ (Fig. 15) reflects an increase in this value from the entrance to the deformation zone to exit from it and its characteristic non-uniform distribution along the radius.

The maximum value of this indicator is typical for the periphery of the wire, and the smallest for the central area. Thus, qualitatively, the distribution of the degree of deformation also corresponds to the distribution of density.

Additional shear stresses also contribute to the compaction of the deformable material. In the case of axisymmetric deformation, they can be estimated by the stress tensor component σ_{rz}. This component, designated as $S12$, is depicted in Fig. 16 areas and lines of equal level.

This value is characterized by the presence of two signs - "plus" and "minus", which corresponds to a different direction of shear deformation. At the entrance to the deformation zone, a stress extremum with a minus sign is observed, and at the exit - with a plus sign. With an increase in the friction coefficient, the zone of increased shear stresses at the entrance to the deformation zone increases, and at the exit, it decreases. The values of the maximum shear stresses are located closer to the contact surface, i.e., in the regions where the highest density is observed. Therefore, the contribution of increased shear stresses to the effect of increasing density cannot be rejected.

Thus, summarizing the simulation results presented above, it is possible to predict a scenario of deformation development in which the influence of the discontinuities initially embedded in the metal structure will be minimal. This approach can become the next step in the development of ideas about the deformation of porous materials, including according to the technological scheme described above.

Further, in the work, rods from the investigated alloys were drawn on a chain mill with a force of 50 kN, obtained using various versions of the extruding process. Preliminarily, using data on the mechanical characteristics of the metal [70], the parameters of the wire drawing process were determined. Table 2 shows the results of calculating these parameters for the 6063 alloy.

Table 2

– Technological and energy-power parameters of the process of drawing wire obtained from 6063 alloy chips

Drawing process parameters	Pass number							
	1	2	3	4	5	6	7	8
Initial diameter D_i, mm	6	5.5	5.1	4.7	4.35	4.1	3.75	3.4
Final diameter D_{i-1}, mm	5.5	5.1	4.7	4.35	4.1	3.75	3.4	3
Initial cross-sectional area F_i, mm^2	28.3	23.7	20.4	17.3	14.9	13.2	11.0	9.1
Final cross-sectional area F_{i-1}, mm^2	23.7	20.4	17.3	14.9	13.2	11.0	9.1	7.1
Elongation coefficient μ	1.19	1.16	1.18	1.17	1.13	1.20	1.22	1.28
Total relative reduction ε_{Σ}, %	16.0	27.8	38.6	47.4	53.3	60.9	67.9	75.0
Average resistance to deformation $\sigma_{s(av)}$, MPa	150	175	193	206	215	221	227	232
Drawing force P_d, kN	1.21	1.00	1.02	0.88	0.61	0.82	0.76	0.80
Drawing tension K_d, MPa	51	49	59	59	46	74	84	113
Safety factor γ_s	3.0	3.6	3.3	3.5	4.6	3.0	2.7	2.1

The drawing route was taken as a basis: 6.0 mm → 5.5 → 5.1 → 4.7 → 4.35 → 4.1 → 3.75 → 3.4 → 3.0 mm. In this case, preliminary and intermediate annealing was not provided. In the course of drawing, in each case, samples were taken at separate diameters (3 pieces for each diameter) and the mechanical characteristics were determined on a universal testing machine LFM10.

Comparison of the achieved mechanical characteristics was carried out on a cold-deformed wire with a diameter of 4.7 mm (the total relative reduction ε at that time was 39%), a diameter of 4.1 mm (ε = 53%) and a diameter of 3.0 mm (ε = 75%). The results of the mechanical tests carried out in the form of the corresponding diagrams are presented in Fig. 17. Their comparative analysis and comparison with the calculated data obtained from the results of the regression analysis (the formulas (1-4) are given below), indicates a high convergence of the results.

Figure 18 shows the microstructures of a wire made of 6063 alloy of various diameters, obtained from a rod with a diameter of 6 mm. Their analysis showed that with an increase in the relative reduction, the structure is refined with a gradually increasing fragmentation in the near-surface layers of the wire.

The drawing of the bars obtained from the chips of the AlSi12 alloy by the method of discrete extrusion, as before, was carried out on a chain drawing mill with a force of 50 kN. The average unit reduction during drawing was 15-20%, and during intermediate annealing the following regime was used: annealing temperature T_{anneal} = 400 °C, holding time annealing = 1 hour. Taking into account the pre-calculated values of the safety factor, the following drawing route was used: 6.0 mm → 5.5 → 5.0 → 4.35 → 3.85 → 3.3 → 2.8 → 2.4 → 2.1 → 1.7 → 1.5 → 1.2 mm.

The results of mechanical tests of wires of various diameters made of chips of the AlSi12 alloy in comparison with the calculated data are presented in Fig. 19.

The study of the microstructure (Fig. 20) using the example of a wire with diameters of 6.6 and 5.0 mm, each of which was drawn from the corresponding rod with a total relative reduction of 30%, shows that as the diameter of the wire decreases, though not quite uniform length, but a noticeable crushing of silicon. The boundaries between the individual shavings practically do not appear, that is, we have obtained an almost homogeneous solid material, which is a uniformly distributed siliceous phase over the body of a α-solid solution of aluminum.

To assess the results obtained and automate the calculation of the parameters of the drawing process using the methods of full factorial experiment and least squares, regression equations were derived to determine the ultimate tensile strength R_m and elongation to failure A during cold drawing of wire obtained from chips of 6063 and AlSi12 alloys, depending on total relative reduction ε_{Σ}, expressed as a percentage.

For the 6063 alloy, these equations are:

$R_m = 132.9 + 2.177 \cdot \varepsilon - 0.011 \cdot \varepsilon^2$; (1)

$A = 15.8 - 0.226 \cdot \varepsilon + 0.001 \cdot \varepsilon^2$. (2)

For alloy AlSi12:

$R_m = 167.2 + 2.747 \cdot \varepsilon - 0.016 \cdot \varepsilon^2$; (3)

$A = 14.4 - 0.272 \cdot \varepsilon + 0.002 \cdot \varepsilon^2$. (4)

Possible areas of practical application of wire-rod products made from waste chips of the investigated alloys are their use as modifiers or deoxidizers, as well as welding wire made of AlSi12 alloy for soldering special-purpose structures made of aluminum alloys.

Summary

Thus, as a result of the research, the following main results were obtained:

- a general technological scheme of thermal deformation processing of chip waste of aluminum alloys was developed, including the stages of preparing chips for compaction, its briquetting, discrete and continuous extrusion, as well as drawing and heat treatment.

- experimental studies have been carried out and a technology has been developed for the production of wire-rod products from high-quality chips of 6063 and AlSi12 alloys using various extrusion methods;

- using standard techniques to study the structure and properties of the obtained prototypes of longish semi-finished products from the investigated alloys, the features of structure formation and the regularities of the formation of mechanical properties of deformed semi-finished products made from chips have been studied;

- using computer simulation, the process of combined rolling-extruding of a porous billet from compacted chips of 6063 alloy was analyzed, as a result of which the distribution of temperature, degree of deformation and relative density in the volume of the deformation zone was determined, as well as the energy-power parameters of the process;

- a simulation of the process of drawing a rod from 6063 alloy with residual porosity was carried out, according to the results of which the regularities of the change in the degree of deformation, average normal and tangential stresses in the deformation zone, depending on the conditions of contact friction, were determined.

- routes for drawing wire from extruded rods of chips of alloys 6063 and AlSi12 were developed, pilot batches of wire were obtained and their mechanical properties were determined, using the data on which regression equations were obtained to determine the ultimate tensile strength and elongation to failure of the metal;

- recommendations are given on the use of rods and wires obtained from chips of 6063 and AlSi12 alloys in industry.

Declarations

Ethical Approval

The work contains no libelous or unlawful statements, does not infringe on the rights of others, or contain material or instructions that might cause harm or injury.

Consent to Participate

The authors consent to participate.

Consent to Publish

The authors consent to publish.

Authors Contributions

The authors declare that they are all participants in the work and none of them performed only administrative functions.

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Competing Interests

The authors declare about the absence of competing interests.

Availability of data and materials

The model was developed using the commercial software package QForm (a trademark of QForm Group) and ABAQUS (a trademark of Dassault Systemes). The authors completed the calculation work of QForm and ABAQUS at Ural Federal University named after the first President of Russia B.N. Yeltsin.

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Figures

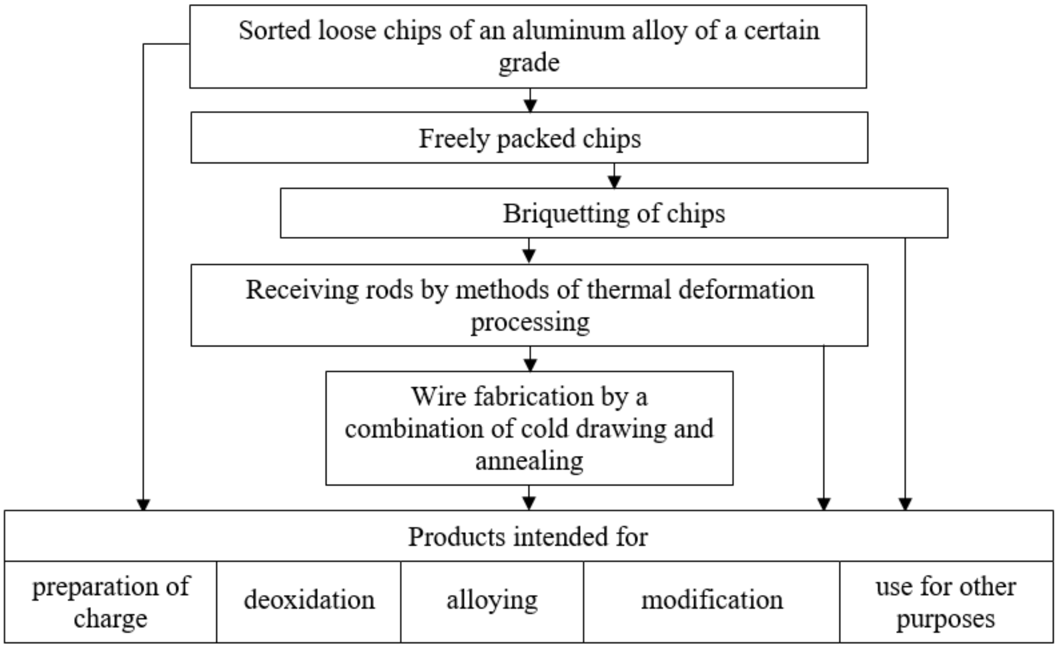


Figure 1

Options for recycling chip waste into products for various purposes

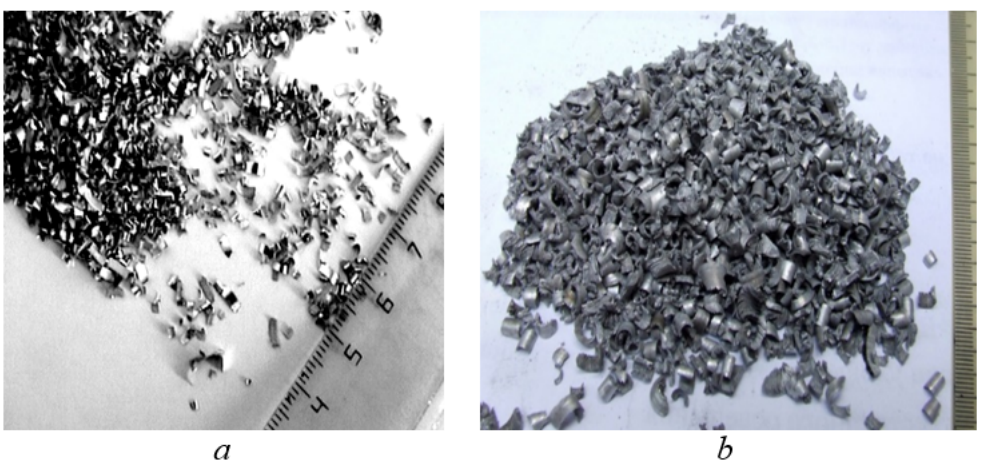


Figure 2

Type of chips from 6063 alloy (a) and AlSi12 alloy (b)

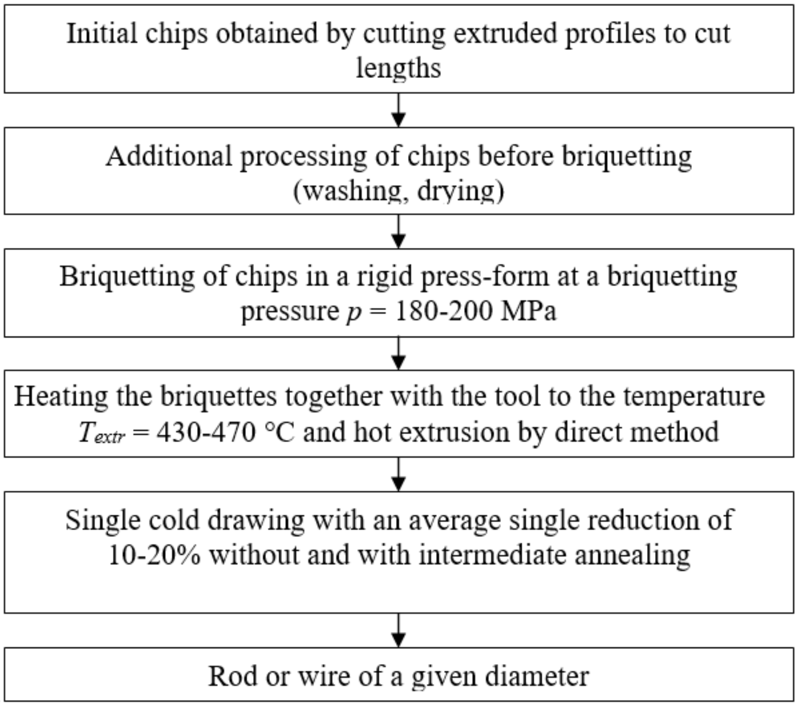


Figure 3

Technological scheme for obtaining deformed semi-finished products using the method of discrete extrusion

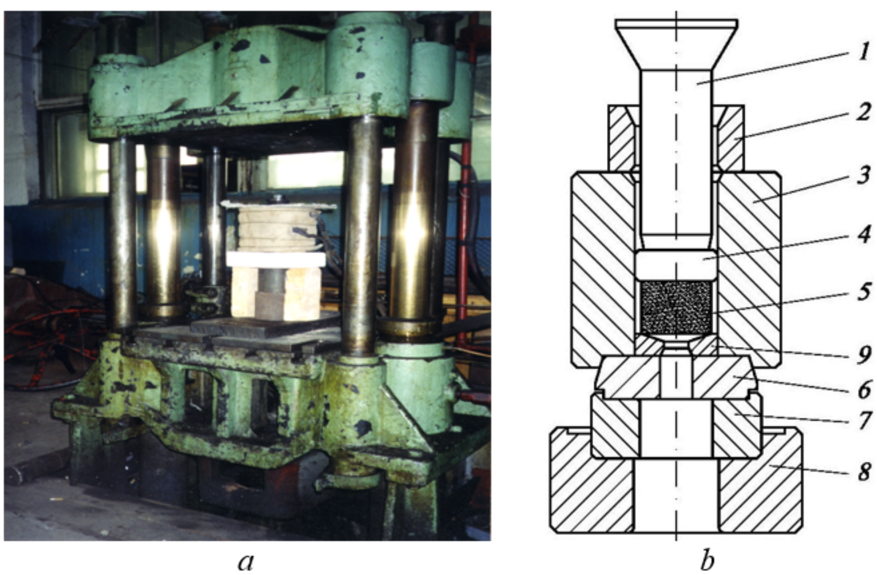


Figure 4

View of hydraulic press (a) and assembly scheme of extruding tool (b) for hot discrete extrusion: 1 – punch; 2 – travel stopper; 3 – container; 4 – press spacer; 5 – billet; 6 – bolster; 7 – die holder; 8 – base; 9 – die

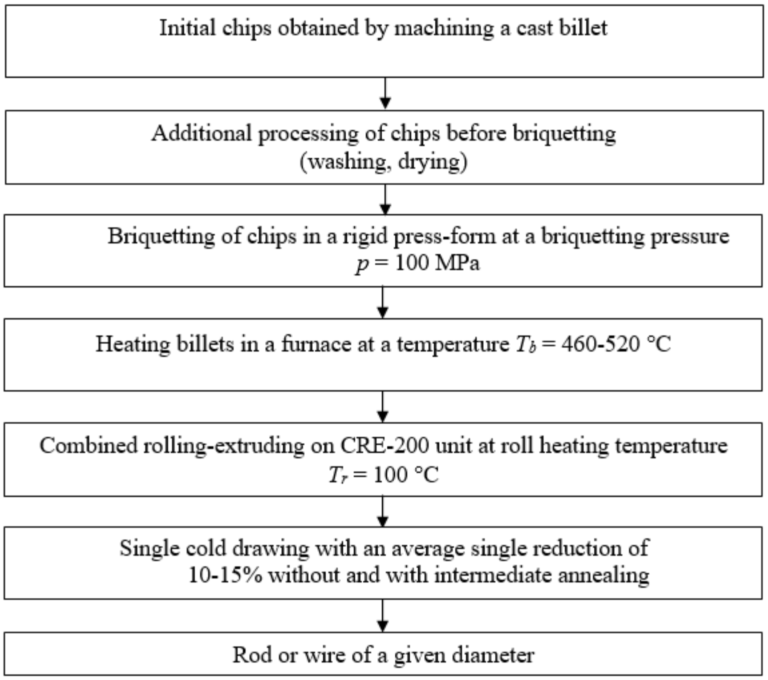


Figure 5

Technological scheme for obtaining deformed semi-finished products from aluminum alloy chips using the combined rolling-extruding method

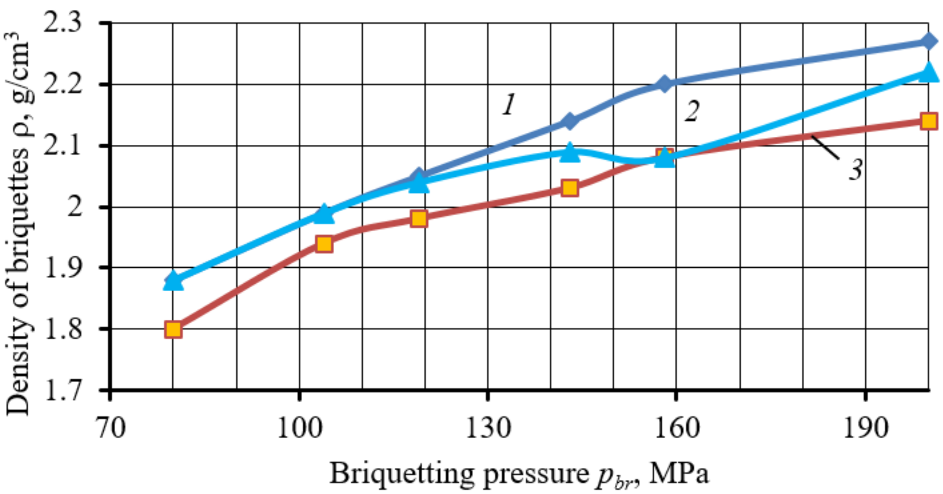


Figure 6

Dependence of the density ρ on the pressure of cold briquetting pbr of semi-finished products from the 6063 alloy chips at various values of the mass of the fill, g: 1 – 80; 2 – 100; 3 – 120

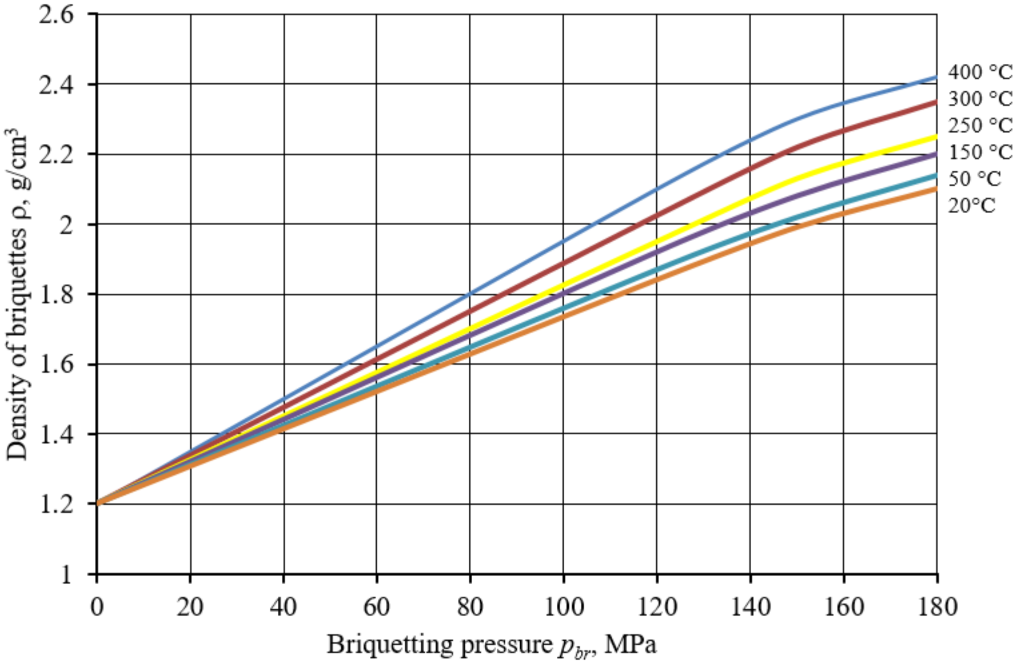


Figure 7

Dependence of the density ρ on the briquetting pressure pbr of semi-finished products from the AlSi12 alloy chips at different temperatures

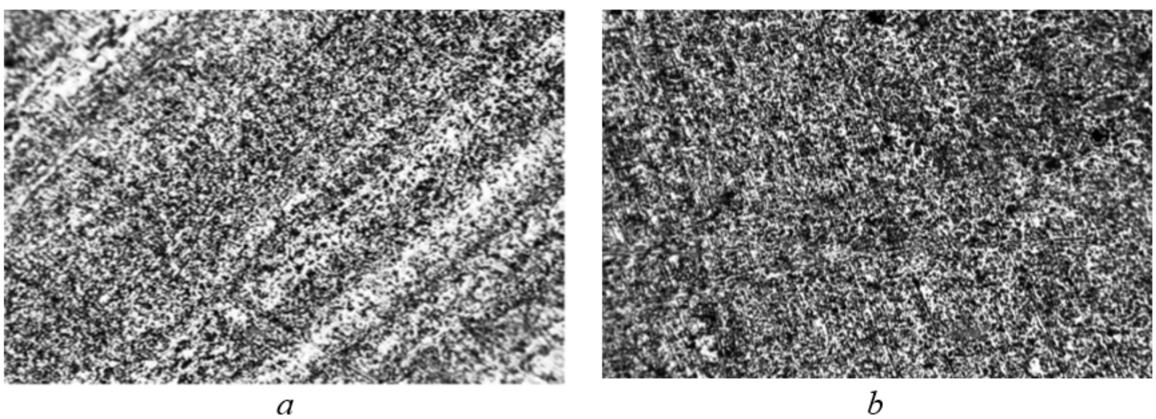


Figure 8

Typical microstructures of extruded rod with a diameter of 6 mm made of chips of AlSi12 alloy in longitudinal (a) and transverse (b) sections, x320

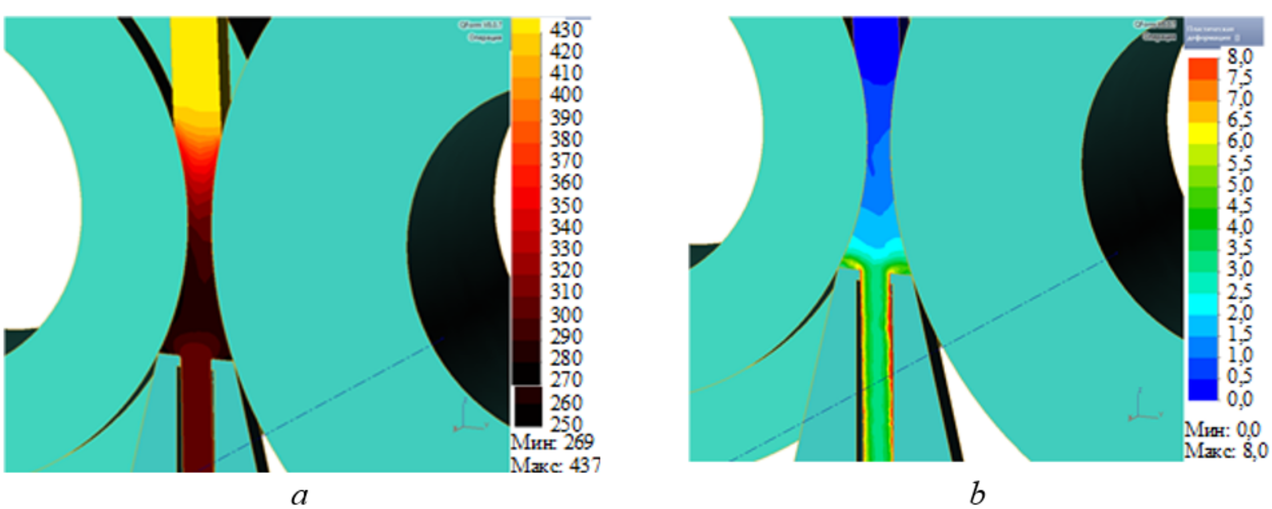


Figure 9

Change in metal temperature (a) in the deformation zone and distribution of the magnitude of the degree of deformation (b) during combined rolling-extruding of rods made of 6063 alloy

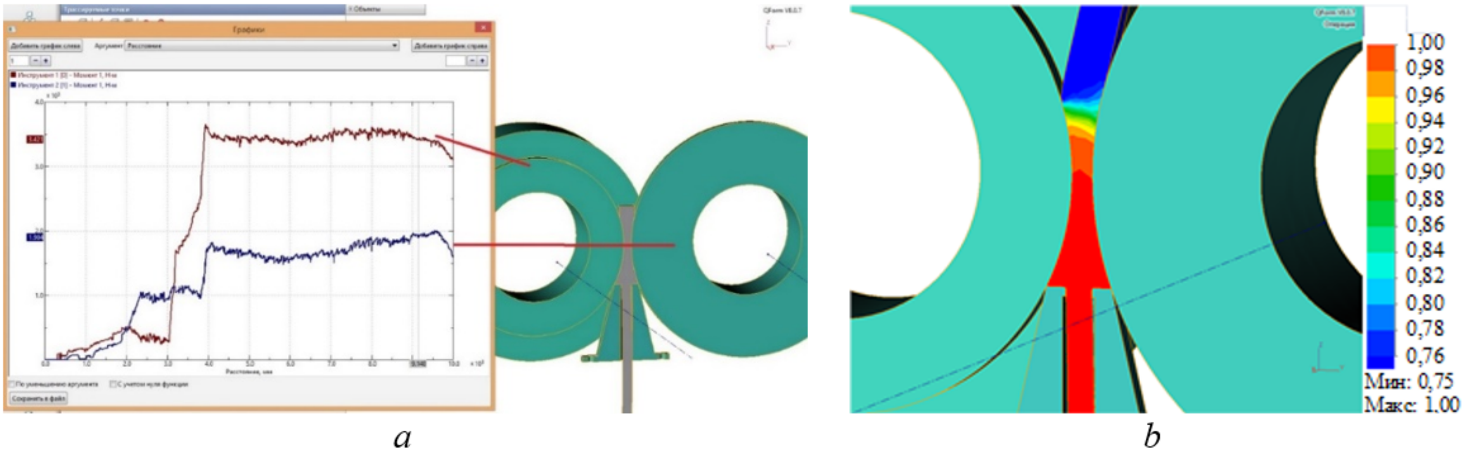


Figure 10

Diagram of the dependence of the moment of rolling on rolls (a) on the magnitude of displacement (the upper curve for a roll with a groove, the lower one for a roll with a protrusion) and a picture of the distribution of the relative density (b) in the process of CRE for the 6063 alloy

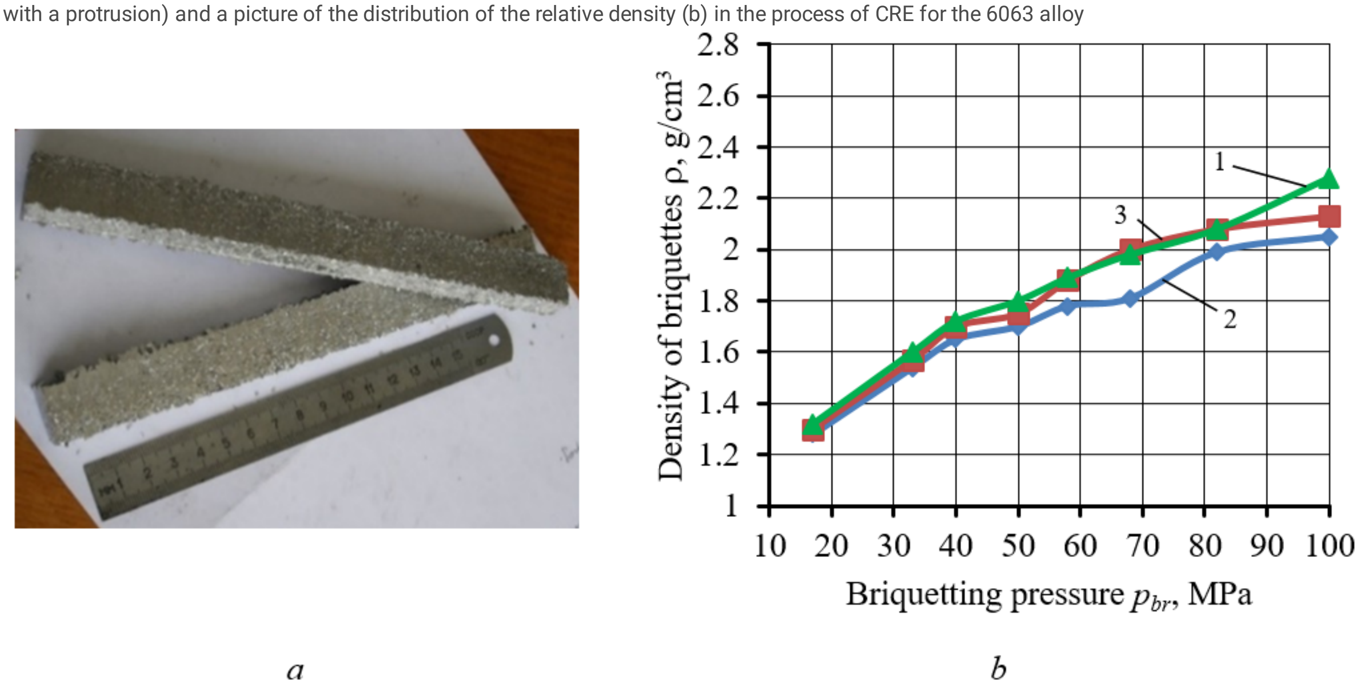


Figure 11

General view (a) and the dependence of the density of briquettes from 6063 alloy chips on the pressure of cold briquetting (b) at various values of the mass of the fill, g: 1 – 130; 2 – 150; 3 – 180

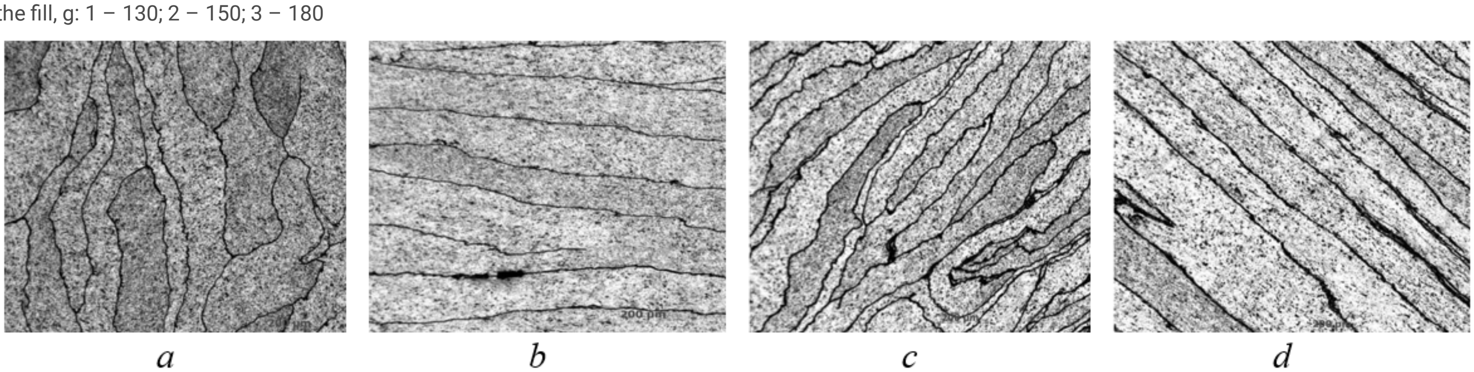


Figure 12

Microstructure of rods made of 6063 alloy chips in the transverse (a, c) and longitudinal (b, d) directions: a, b – a rod with a diameter of 9 mm; c, d – rod with a diameter of 7 mm, x160

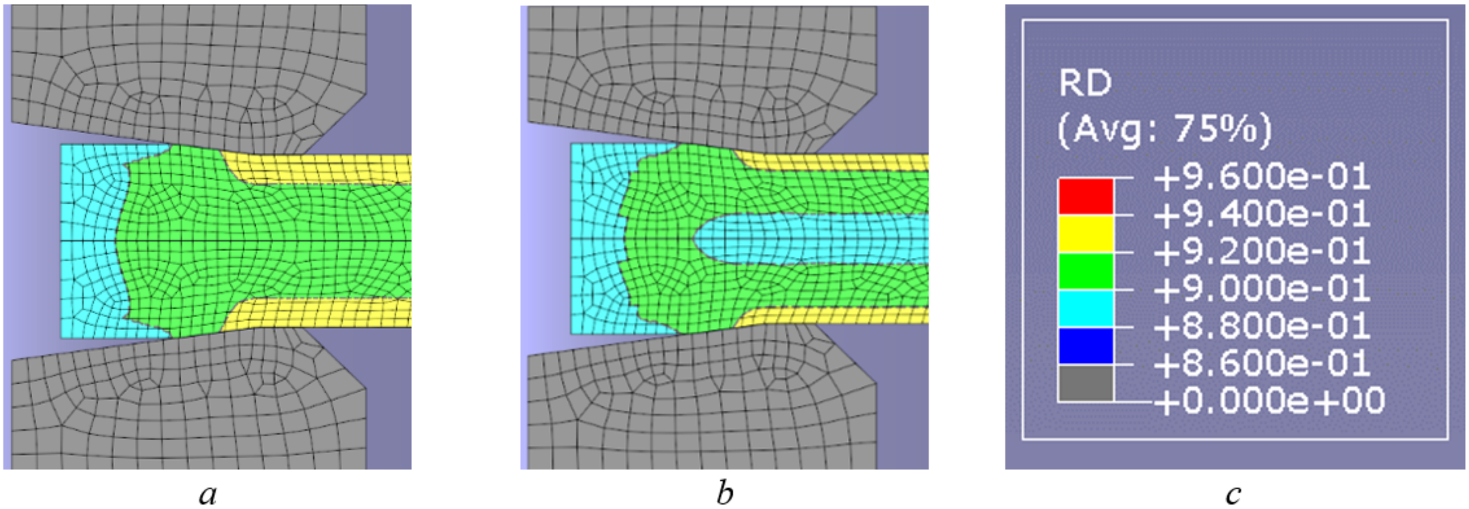


Figure 13

Distribution of the relative density (RD) in the process of drawing the rod with the coefficients of friction: a – 0.05; b – 0.3; c – color key

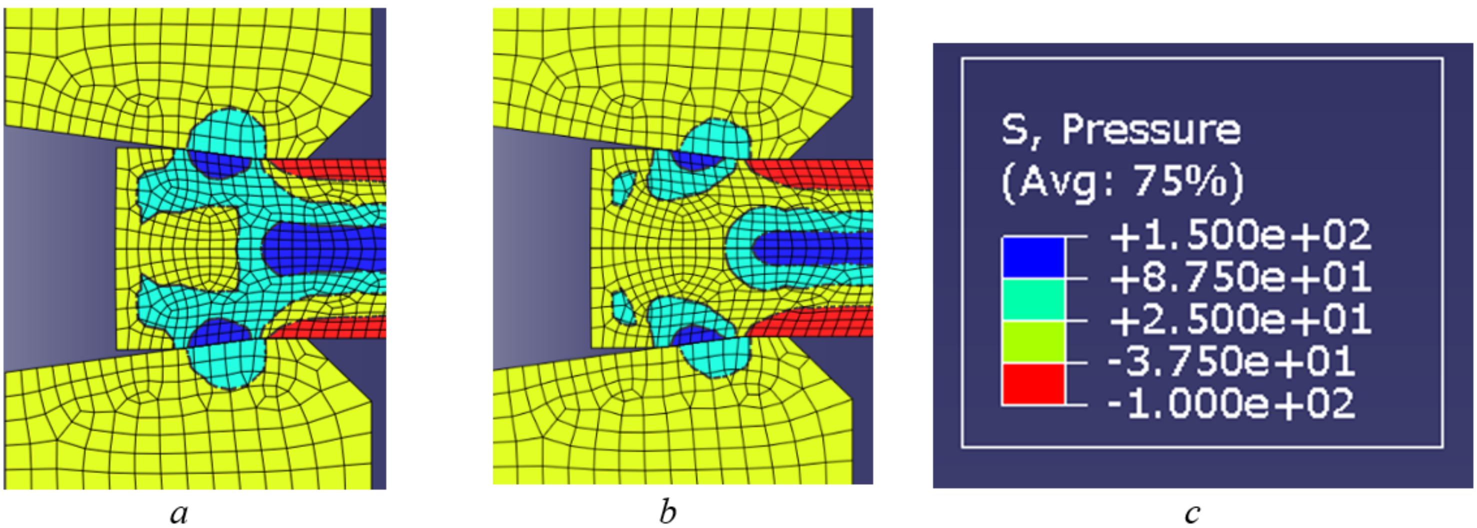


Figure 14

Distribution of the Pressure value at various coefficients of friction: a – 0.05; b – 0.3; c – color key

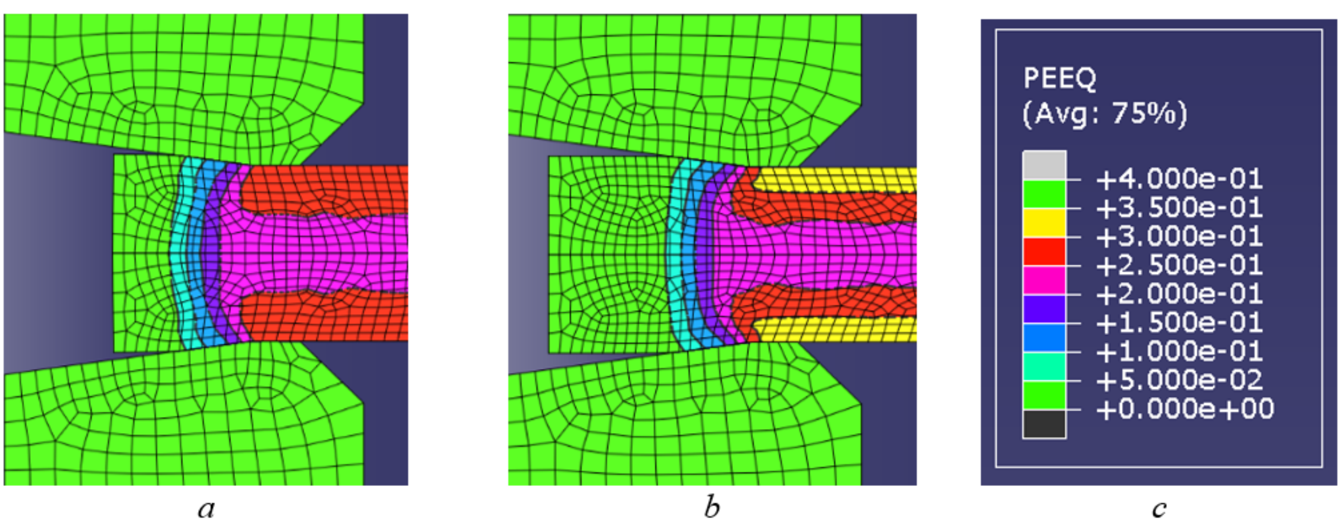
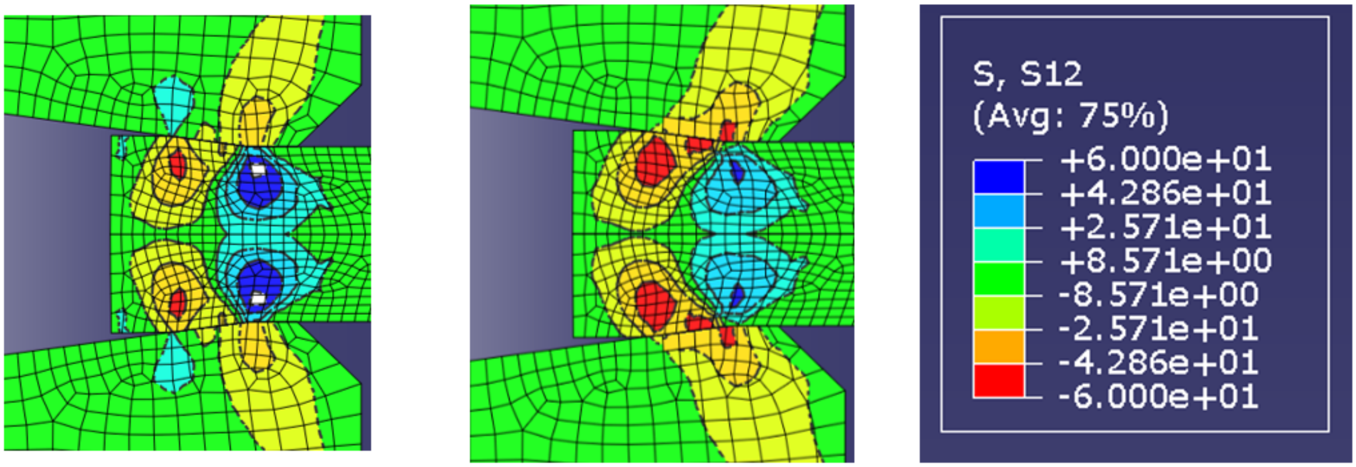


Figure 15

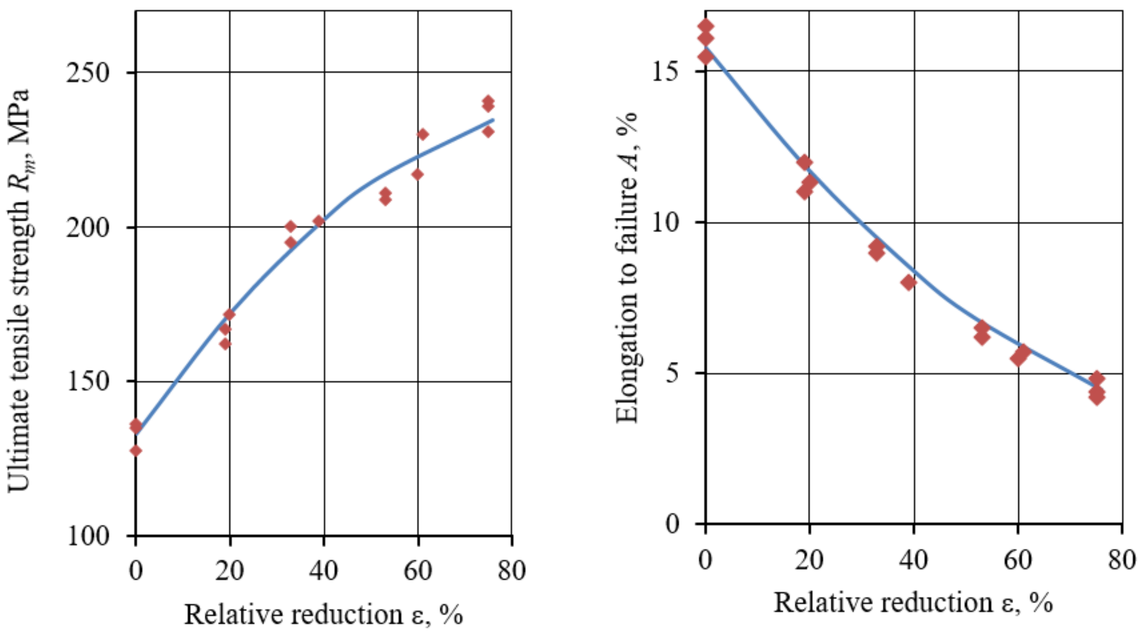
Distribution of the degree of deformation PEEQ at various coefficients of friction: a – 0.05; b – 0.3; c – color key



a *b* *c*

Figure 16

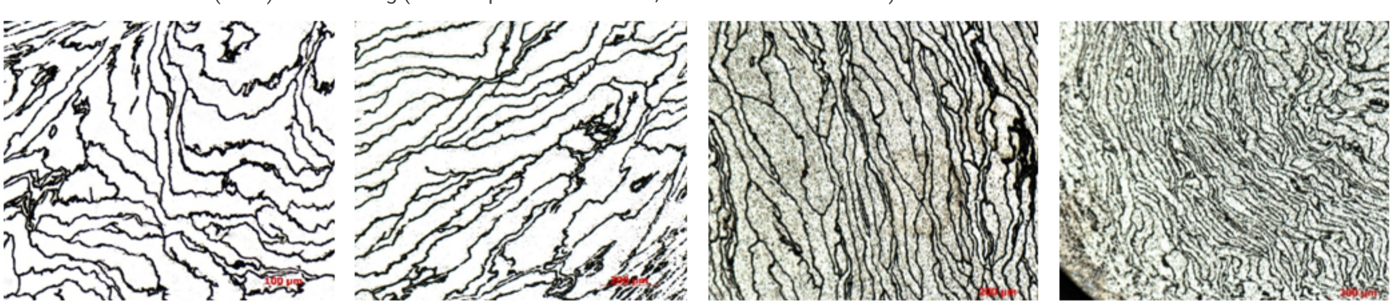
Distribution of shear stresses S12 in the process of drawing a rod at various coefficients of friction: a – 0.05; b – 0.3; c – color key



a *b*

Figure 17

Dependences of ultimate tensile strength (a) and elongation to failure (b) on the total degree of deformation of semi-finished products from 6063 alloy chips after discrete extrusion (ε = 0) and drawing (dots - experimental values, lines - calculated values)



a *b* *c* *d*

Figure 18

Microstructure of the cross-section of a wire made of 6063 alloy chips with diameters of 5.0 (a), 3.7 (b), 2.8 (c) and 1 mm (d), obtained from a rod with a diameter of 6 mm (x160)

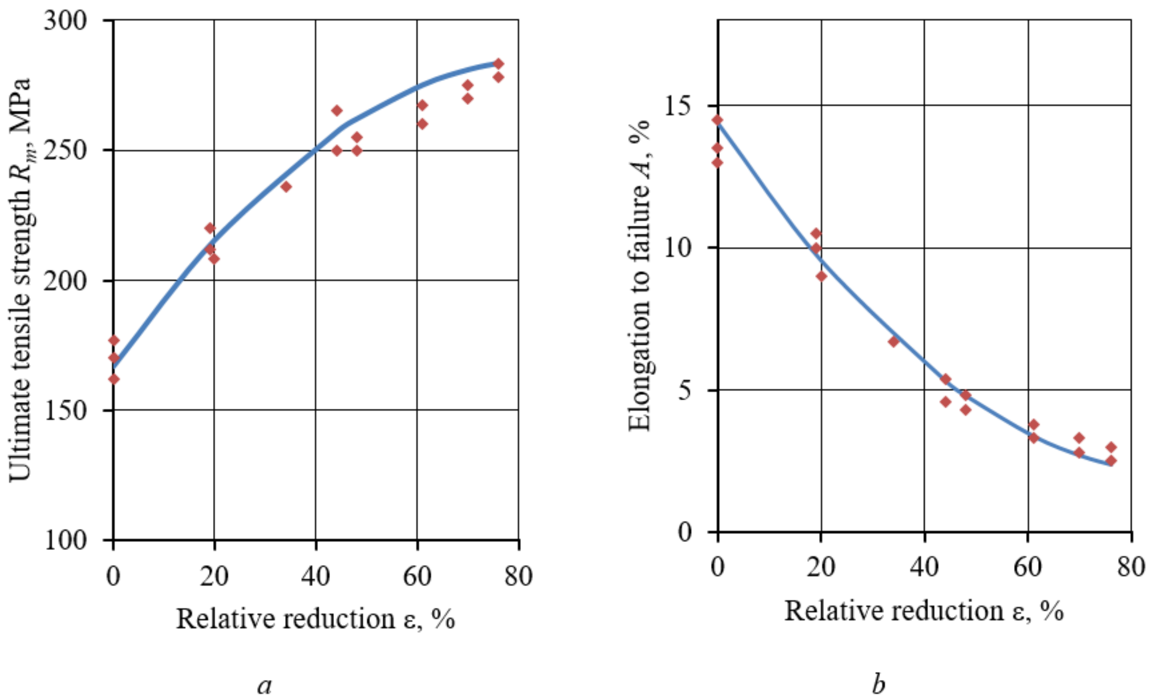


Figure 19

Change in ultimate tensile strength (a) and elongation to failure (b) of semi-finished products made of AlSi12 alloy chips after discrete extrusion (ε = 0) and drawing (dots - experimental values, lines - calculated values)

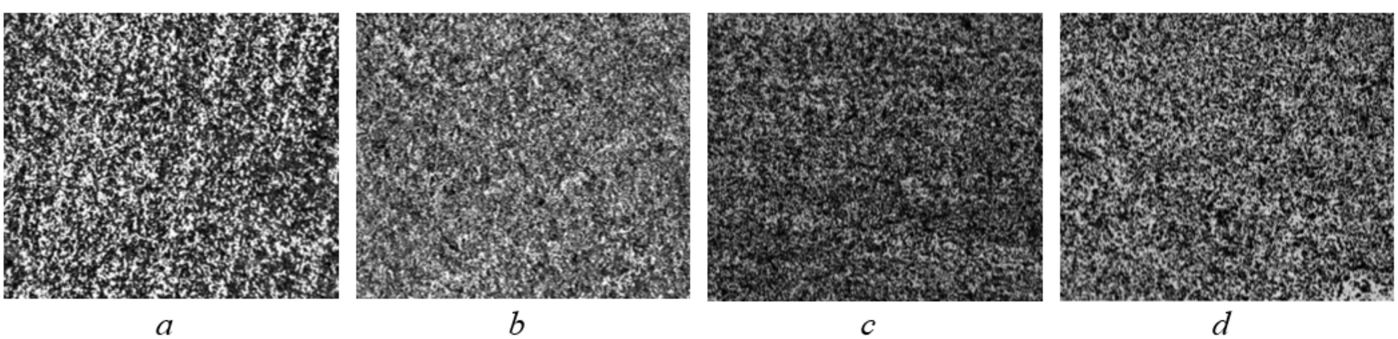


Figure 20

Typical microstructures of wires with diameters of 5 mm (a, b) and 6.6 mm (c, d) obtained from extruded rods with diameters of 6 and 8 mm, respectively: a, c – longitudinal section; b, d – transverse section, (x320)