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Original Article

Investigation the structure and properties of deformed semi-finished products produced from chips of Al–Mg alloys system alloyed with scandium

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A B S T R A C T

The article presents the results of studies that make it possible to solve the problem of processing secondary waste from expensive aluminum alloys without irretrievable loss of metal. For this purpose, tasks were set and solved for the development of technological schemes for obtaining longish deformed semi-finished products from chip waste of Al–Mg alloys 01570 and 1580 alloyed with scandium using methods of powder metallurgy and metal forming. For their experimental verification, the operations of chip briquetting, combined rolling-extrusion (continuous extrusion), sectional rolling, hot extrusion and drawing in combination with heat treatment were applied. According to these schemes, semi-finished products in the form of rods and wires were obtained. Structure and mechanical properties were investigated. It has been revealed that when hot-extruded rods are obtained from chip briquettes of alloy 01570 on a vertical hydraulic press, even with significant degrees of deformation during extrusion, the margin of plastic properties is small and makes it possible to obtain a wire with a diameter of only 4.2 mm after drawing. The processing of briquettes from 1580 alloy chips using the combined rolling-extrusion method makes it possible to obtain after cold deformation a wire with a diameter of up to 3 mm. At the same time, the influence of the annealing process on the structure and properties of deformed semi-finished products from the investigated alloys was studied. It is shown that due to the low plasticity of the investigated material cold working of the rods must be carried out with small degrees of deformation, alternating it with intermediate annealing according to the proposed regime. An analysis of the physical and mechanical properties of the wire obtained using combined processing showed that its strength and plastic properties are comparable to the properties of the wire obtained from a cast billet, and the structure is characterized by a high degree of elaboration and compactness.

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Thus, as a result of the research, technological schemes have been developed and processing parameters have been determined for the production of rods and wire from graded chip waste of alloys 01570 and 1580 using compaction, discrete and continuous extrusion, as well as cold drawing.

1. Introduction

Secondary waste in the form of chips, especially from aluminum alloys, which accumulate in large volumes during machining by cutting in metallurgical profile enterprises, are now advantageously processed by remelting. This leads to significant losses of metal during waste and, ultimately, to a decrease in the cost of finished products from these alloys. This is especially important for alloys containing expensive elements in their chemical composition such as scandium. Considering the issues related to the application of technological schemes for the processing of high-quality waste chips of aluminum alloys, excluding melting, and its economic feasibility, experts in this field recommend using hot pressing (extrusion) as one of the key and mandatory operations.

Cislo and authors [1] evaluated a direct recycling route for machining chips via pulsed electric current sintering (PECS). W. Abdullah with authors [2] investigated the process of obtaining profiles by direct recycling of aluminum chips in hot extrusion process using preheating. Majer with authors [3] focused on the different possibilities of recycling aluminium chips and chips from aluminium alloys. Authors of work [4] described direct recycling of aluminum chips using different methods of severe plastic deformation. In research [5], the use of a combined method (sintering + thixoforging) has been proposed. Works [6–8] provide an intensive review on past and current research works in solid state recycling of aluminium chips and its alloys. Powder metallurgy methods of aluminum chips recycling described in work [9]. New methods and techniques of chip recycling described in works [10,11]. The authors [12] investigated effect of hot extrusion parameters on tensile strength and fracture behavior in direct recycling of alloy 6061 chips. Friction stir back extrusion process for alloy AA1090 chips described in Ref. [13]. Microhardness and microstructure of aluminium alloy chips when subjected to various settings of preheating temperature and preheating time in hot extrusion process shown in works [14,15]. The effect of the extrusion ratio and temperature on the microstructure evolution, the physical properties and the mechanical properties of the products from AA6061 chips were studied in work [16]. Hot press forging of AA6061 chips described in work [17]. Optimization of aluminum chips hot extrusion process investigated in work [18]. Authors of work [19] shown application of cold extrusion after hot extrusion for recycling of AA6060 aluminum alloy machining chips. Optimization of hot press forging parameters in direct recycling of AA 6061 chip investigated in work [20]. Operating methods of temperature for hot press forging process of aluminum chip shown in work [21]. Hot extrusion of mixed materials (1050 and 6060 aluminum alloys chips) investigated in work [22]. Hot extrusion with subsequent hot rolling of 6061 chip described in work [23].

It is most practical to use vertical or horizontal hydraulic presses, given their disadvantages. First of all, this is the cyclical nature of the extrusion process, which leads to a noticeable decrease in the productivity of the process, as well as a relatively low yield [24]. The search for energy-efficient technologies for manufacturing deformed semi-finished products from aluminum alloy waste using thermal deformation processing methods has been carried out by the authors for a number of years, and the main research results are published in Refs. [24–30]. Deformation resistance of porous materials described in works [25,26]. Manufacturing Mmethods of alloyed rod production from chip without its remelting shown in Ref. [27]. Works [28,29] described manufacturing technique of fibrous structure wire from the facing of Al–Mg–Si alloy. Developed device [30] for producing wires and profiles from non-compact materials allows producing wire and profiles by continuous extrusion from non-compact metal materials: chips, powders, granules, etc.

The advent of continuous extrusion methods gave a new impetus to the development of such technologies, with the key being the use of combined rolling-extrusion (CRE) units for the processing of secondary wastes of aluminum and its alloys [24,31,32]. When adapting their work to address the issues of chip waste processing, it must be taken into account that the briquetting stage is necessarily preceded by the CRE process. Its task is to form a billet-briquette of the appropriate shape, size and density level, sufficient to ensure its capture by rolls and the implementation of the rolling process. Ideally, it is desirable to combine the processes of briquetting and deformation in a single cycle, but for this it is necessary to modernize the CRE unit by supplying it with a unit for continuous supply of preheated and briquetted chips directly to the deformation zone. One of the solutions to this problem can be the application of the invention [30] proposed by the authors. The results of previous studies [24] on the development of technologies for obtaining deformed semi-finished products from aluminum alloy chips using combined processing methods suggest that the expediency of obtaining rods and wires from such non-compact materials using them is obvious and has undeniable technical and economic advantages.

When choosing a processing object, as a rule, they are guided by considerations of obtaining products that, in terms of properties, could to some extent serve as an analogue of similar products made in the traditional way from a cast billet. But at the same time, the cost of production can be significantly reduced if secondary waste is used in the form of chips, which accumulate in large volumes during machining. In particular, this is expedient for processing chip wastes of aluminum alloys, additionally alloyed with rare-earth group metals and having a relatively high cost [33,34], for example, alloys of the Al–Mg system alloyed with scandium [35].

These include alloys 01570 (0.17–0.27 wt% scandium) and 1570C (0.18–0.26 wt% scandium), which have high corrosion resistance and excellent weldability [36,37]. Rolled plates and sheets, thin-walled spherical shells, welding wire and other products used in rocket and space technology are made from them. In recent years, as an alternative to these alloys, a new alloy of the Al–Mg system with a reduced content of scandium in the range of 0.05–0.14% was developed, which received the designation 1580 [35]. Deformed semi-finished products from this alloy have a high level of strength and plastic properties [38–43], comparable with the properties of products made from 01570 to 1570C alloys, and a relatively lower cost, which can be further reduced by returning secondary waste in the form of chips to production.

Therefore, the main task of this work was to search for and develop alternative technologies to remelting, which make it possible to obtain deformed semi-finished products from scandium-doped aluminum alloys using powder metallurgy and metal forming methods. The research was also focused on the possibility of obtaining deformed semi-finished products in the form of rods and wires from chip waste of alloys 01570 and 1580 and a comparative analysis of their structure and properties.

2. Material recycling processes and tooling

In the work, this goal was achieved through the use of two main technological processing schemes [24]: in the first case, for alloy 01570, the operations of briquetting round-section billets and subsequent hot extrusion of rods from them and cold drawing. And for alloy 1580, in the second case, briquetting operations, combined rolling-extrusion to obtain rods, as well as their subsequent rolling and drawing to make wire. This approach was tested in relation to the processing into rods and wires of chip waste from alloys of the Al–Mg system alloyed with scandium, resulting from machining (turning or milling) of cast billets. Chips before compacting were not subjected to additional preparation in the form of cleaning from impurities and contaminants, that is, they corresponded to the production conditions for its production. The general view of the chips is shown in Fig. 1(a). The chemical composition of the alloys is given in Table 1.

The experimental research methodology was as follows.

The process of briquetting chips from alloy 01570 was carried out at a temperature of 400 °C with a weight of a loaded sample of 135 g, as a result of which a round briquette with dimensions $d \times h = 42$ mm × 38 mm was obtained, having a density of 2.57 g/cm^3. The briquetting pressure was 180 MPa. Briquettes of alloy 01570 were placed in a container with a diameter of 45 mm and subjected to hot pressing on a vertical hydraulic press with a force of 1 MN [24] with a drawing ratio of 44 at a temperature of 450 °C, as a result of which rods with a diameter of 7.0 mm were produced. Rods were then subjected to cold drawing to a diameter of wire 4.2 mm. The total degree of deformation during the processing of a briquette with a diameter of 45 mm was 99.1%.

To obtain briquettes from chips of alloy 1580, a special mold was used (Fig. 2(b)), including upper and lower punches, a split die, and a holder with inclined contact surfaces. The cross section of the obtained briquette had the dimensions $h \times b = 14.5$ mm × 14.5 mm, the length was 200 mm, and the mass of the filling was taken equal to 80 g (Fig. 1(a)). The results of measurements of the density of 1580 alloy briquettes showed that at a cold briquetting pressure of about 100 MPa, it was 1.42 g/cm^3.

To ensure a more stable flow of material in the implementation of the subsequent processing, it is desirable that the density of the briquettes was somewhat higher. This requires either increasing the briquetting pressure or preheating the chips before briquetting. Further, hot-extruded rods with a diameter of 9 and 7.5 mm were made from these briquettes on the CRE-200 unit [24,31], from which, after the use of sectional rolling in square gauges and drawing, a wire with a diameter of 3 mm was obtained. The total degree of deformation during processing of a briquette with dimensions of 14.5 mm × 14.5 mm was 96.6%.

To assess the nature of structure formation and the level of mechanical properties of the obtained semi-finished products, samples were taken from the middle part of each of them, which were subsequently subjected to tensile tests on a universal machine LFM 400 and metallographic studies according to existing standard methods.

The structure of deformed and annealed semi-finished products was studied using an Observer.A1m, Carl Zeiss light microscope at various magnifications and an EVO 50 scanning electron microscope using an Energy 250 energy-dispersive spectrometer. The study of recrystallization processes was carried out on samples after deposition of an oxide film in polarized light mode. The grains in the structure of the alloys were identified and evaluated by the contrast of the oxide film associated with the crystallographic orientation of the grains.

Sampling for evaluation of mechanical characteristics was carried out on several intermediate sizes of deformed semi-finished products. The amount of deformation reported to the rods and wire by this moment was estimated by the indicator of the total compression

$$\varepsilon = \frac{F_0 - F}{F_0} \cdot 100\% \tag{1}$$

where F_0 – cross-sectional area of the rod after CRE, mm^2; F – the cross-sectional area of the profile after the corresponding stage of cold deformation, mm^2.

Metal microhardness (HV) was determined using a DM8 digital microhardness tester at a load of 200 g for 10 s.

Fig. 1. General view of chips (a) and molds for its briquetting (b).

Table 1
The chemical composition of experimental alloys of the Al–Mg system alloyed with scandium.

Alloy	The content of components in the alloy, % (wt.)										
	Mg	Mn	Si	Sc	Zr	Ti	Cr	Fe	Cu	Zn	Ni	Al
01570	5.20	0.60	0.20	0.25	0.10	0.02	0.16	0.20	0.01	0.10	–	balance
1580	5.27	0.49	0.13	0.12	0.13	0.02	0.15	0.16	0.011	0.01	0.006	balance

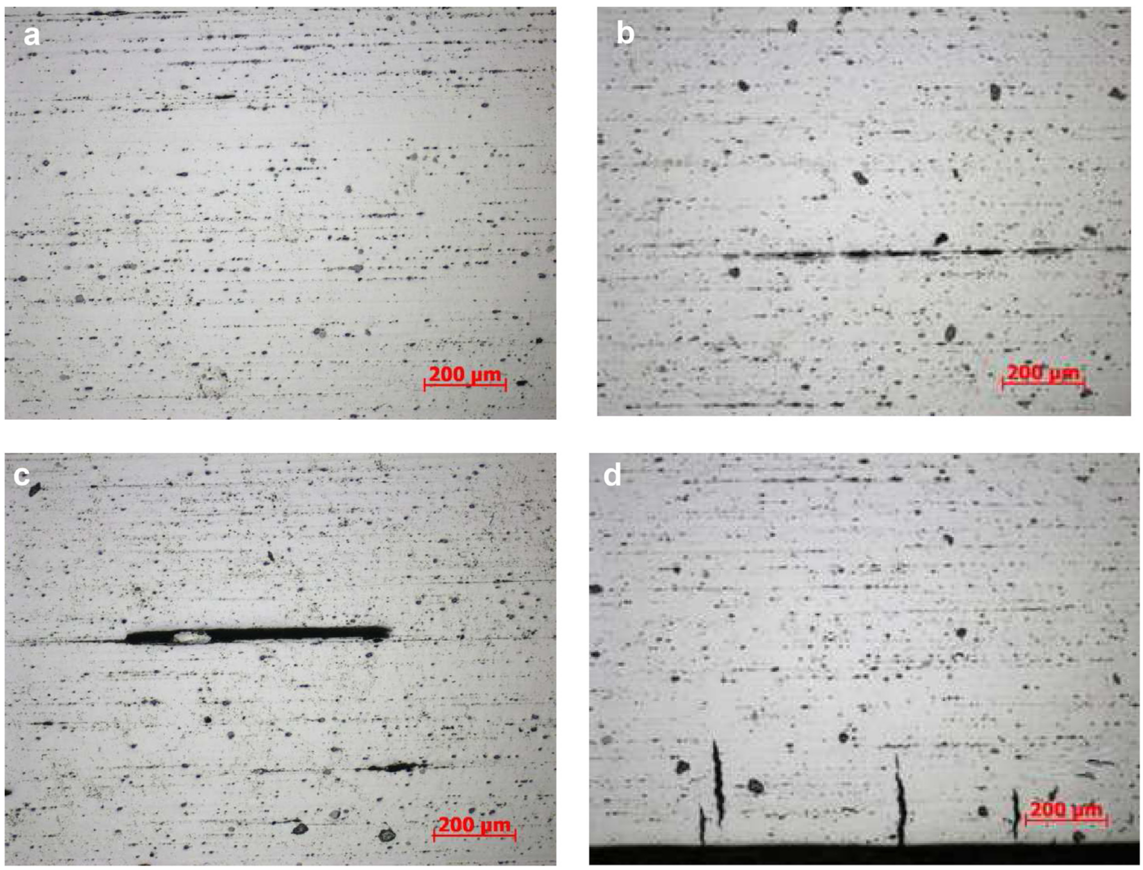


Fig. 2. Microstructure of a rod with a diameter of 7.0 mm made of chips from alloy 01570. (a)–(c) – the central part of the rod; (d) peripheral part of the rod, ×100.

3. Experimental results

Rods obtained by hot extrusion from alloy 01570 using the first processing scheme were of low quality and had quite a lot of defects, which is clearly demonstrated by the results of metallographic studies of the sample, taken at a distance of 100 mm from the front end of the rod (Fig. 2). However, in the main volume of the sample structure, the boundaries of individual chips are not detected, which indicates a good interaction of metal chips in these areas (Fig. 2(a)).

The microstructure is grains elongated along the direction of deformation, along the boundaries of which inclusions of excess phases are located. In the central zones of the rod, there are areas in which there are discontinuities associated with poor interaction between adjacent metal layers due to chip contamination (Fig. 2(b) and (c)). This defect is non-systemic in nature and is the result of the demonstration of the stress-strain state scheme acting in this case. The sizes of individual discontinuities exceed 800 μm. On some peripheral sections of the rod, transverse cracks are observed, up to 200 μm in size (Fig. 2(d)).

To determine the elemental composition of the phases of the 01570 alloys, an X-ray microanalysis (EDS) of the microstructure of the rods was carried out. The electronic images of the structure and the chemical composition of the spectra are shown in Fig. 3.

X-ray microspectral analysis of the sample obtained from the chips of alloy 01570 showed that the main phase is an aluminum solid solution, which contains the alloying element Mg (Fig. 3 spectrum 5), Sc and Zr were not detected in the solid solution. Element-by-element analysis of dispersed excess phases located along the direction of deformation revealed the content of Al, Mg, Fe, and Mn in them (Fig. 3 spectrum 4). The structure of the alloy contains dark inclusions containing Mg and Si, which correspond to the Mg_2Si phase (Fig. 3 spectrum 6).

Light particles of regular shape, up to 15–20 μm in size, contain the elements Al, Sc, Zr, Ti (Fig. 3 spectrum 1–3), the proposed composition of these phases corresponds to the compounds Al_3(Sc, Ti, Zr) and Al_3(Sc,Zr). The presence of brittle intermetallic compounds with Sc and Zr in the structure of the rods can complicate the further deformation of the alloy when obtaining semi-finished products of a smaller size and lead to premature failure.

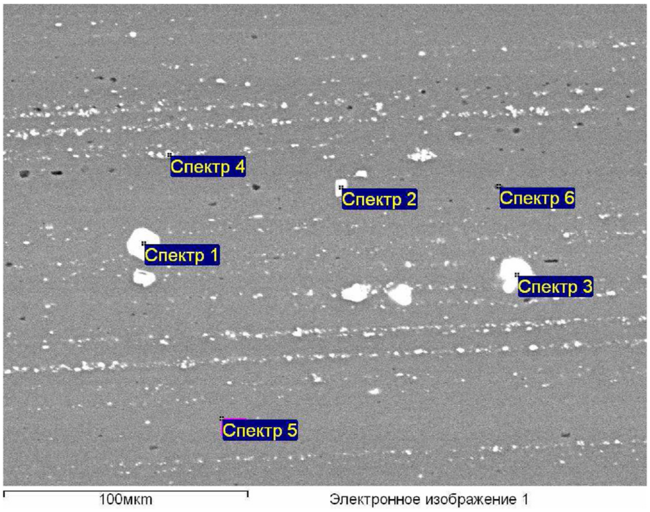


Fig. 3. Electronic image and MRSA results of a bar with a diameter of 7.0 mm from chips of alloy 01570.

Further cold working using a chain drawing mill was carried out along the route: 7.0–6.5-5.9–5.6-5.3-5.1-4.5–4.2 mm, during wire annealing on diameters 5.3 mm and 4.5 mm. The heat treatment mode included heating the metal to a temperature of 400 °C and holding for 3 h. After annealing, it was possible to obtain a wire with a diameter of 4.2 mm. The ultimate tensile strength of the metal for it was 340 MPa, and the elongation to failure did not exceed 3%.

An analysis of the microstructure of a wire with a diameter of 4.2 mm (corresponds to its central part) in a deformed state from alloy 01570 (Fig. 4) showed that a fibrous structure and a row arrangement of excess phases are observed in the structure. The gaps shown in Fig. 4(b) are, apparently, a consequence of the development of those discontinuities that take place in the structure of the extruded rod mentioned above.

Discontinuities remain in some sections of the structure of the rods (Fig. 4(b)), associated with poor interaction between the metal layers of the original rod with a diameter of 6.8 mm.

Further drawing of a semi-finished product with a diameter of 4.2 mm, despite the use of annealing, led to the destruction of the metal during deformation. In this regard, it was concluded that the deformation resource of the material is completely exhausted. Thus, the total relative reduction during cold deformation of metal from alloy 01570 between intermediate annealings did not exceed 39–40%, and single reductions during drawing reached 10–15%.

To obtain a wire with a diameter of 3 mm, the second processing scheme using combined rolling-extrusion to obtain rods from alloy 01570 chips was not used, since the drawing ratio during extrusion by the CRE method was significantly lower than during hot extrusion on a vertical press. Therefore, the low ductility margin of the deformed semi-finished products from the 01570 alloy in this case would not have made it possible to obtain a wire of a given size using the CRE method.

The implementation of the rolling-extrusion process of rods from alloy 1580 in accordance with the second processing scheme was carried out on a CRE-200 unit mounted on the basis of a two-roll mill with an initial roll diameter of 200 mm [24]. It included a deforming assembly (Fig. 5) and a drive with an AC motor with a power of 20 kW at a rotation speed of 900 rpm, gearbox, gear stand and two-stage reducer provided 3 levels of rotation frequency of rolls having different rolling diameters and forming a closed box caliber with dimensions in the smallest Section 7 mm ×15 mm (Table 2).

The deforming unit (Fig. 5) consisted of two steel frames of a closed type, fastened together with tie bolts and mounted on a common base with an engine, gearbox, and gear stand.

Axles were installed in pillows on bronze plain bearings, on which the rolls were fixed (Fig. 6). By means of a hydraulic cylinder, a die was tightly pressed against the rolls (Fig. 7), blocking the pass and directing the metal flow into the calibrating hole. The working tool (rolls and die) was made of 5CrNiMo steel with hardness HRC 48 ÷ 50.

The resulting briquettes were heated to a temperature of 450 ± 10 °C in a resistance furnace before rolling-extrusion, trying to avoid overheating, which in some cases led to their warping and destruction even before being removed from the working zone of the furnace. The total heating time was 30–40 min. The number of simultaneously heated briquettes was 3.

At the same time, the rolls of the CRE unit were heated, which could only be heated to a temperature of $T_r = 80 \div 100$ °C. In the course of experimental studies, it was found that the heating of the rolls should be carried out to higher temperatures (about 200 ÷ 300 °C), since in this case the rates of heat exchange between a hotter billet and a less heated tool decreases. The supply of briquettes heated to a temperature of 450 ± 10 °C into a closed caliber formed by rolls (Fig. 5(a)) was carried out sequentially one by one, trying to minimize the pauses between their entry into the deformation zone. This provided better welding between the briquettes and the continuity of their processing to obtain a longish rod.

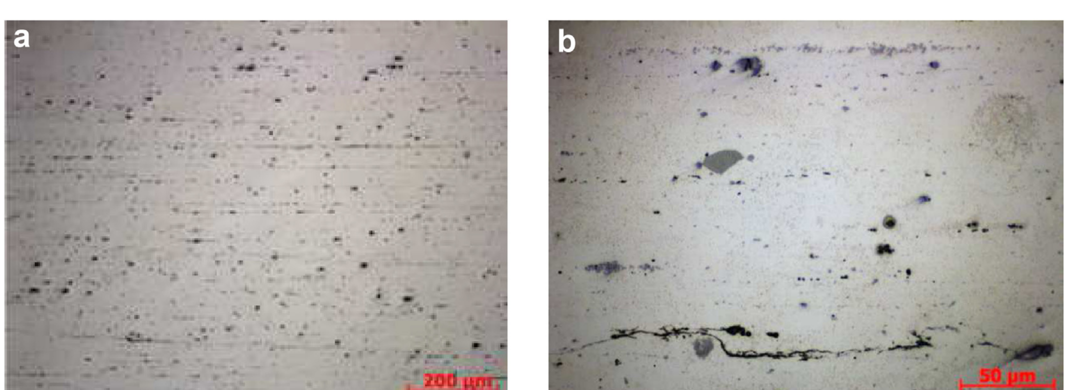


Fig. 4. The microstructure of a wire with a diameter of 4.2 mm from chips of alloy 01570. (a) ×100, (b) ×500.

Fig. 5. Deforming unit of the CRE-200 unit: (a) roll assembly and briquette, set into rolls; (b) hydraulic device for clamping the die.

Table 2
Technical characteristics of the CRE-200 unit.

Parameters	Value
Initial diameter of rolls, mm	200
with a protrusion, mm	214
with the groove, mm	164
Roll barrel length, mm	240
Diameter of the neck of the shaft, mm	100
Caliber dimensions in the smallest section, mm	7 × 15
Number of roll rounds, rpm	4; 8; 14
Gear ratio of the gearbox	40
Electric motor power, kW	20
Torque on the output shaft, kN·m	10
Operating pressure of the hydraulic station, kgf/cm^2	200–500
Maximum clamping force, kN	300

The gap between the rolls in the minimum section of the caliber, which is 7 mm, provided compaction of the briquette at the rolling stage to a relative density of the order of $\rho = 0.85 \div 0.90$. This led to a more uniform deformation of the metal during rolling in the cross-section of the pass and its depressurization. As a result of the experiments, it was also found that a decrease in the minimum height of the caliber is inappropriate due to a decrease in the second volume of metal passing through the minimum cross-section of the caliber. An increase in the gap had a negative effect on the rolling-extrusion process, since when an insufficiently compacted mass of the briquette entered the pre-pressing zone; the pre-pressing proceeded unstable or was completely absent.

The remoteness of the mirror of a flat die covering the pass from the common axis of rolls having different rolling diameters

Fig. 6. Rolls of CRE-200 unit.

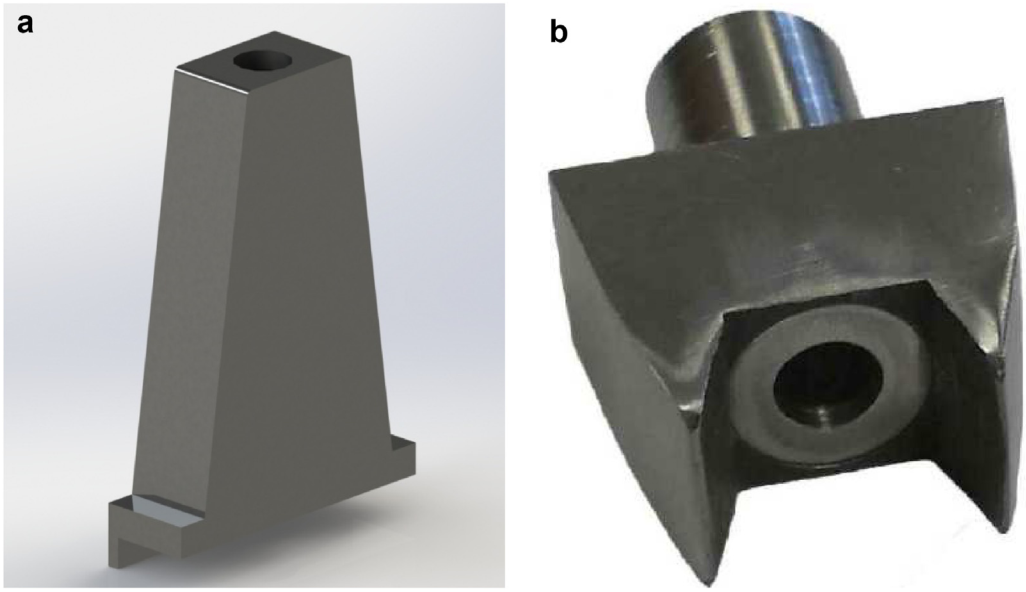


Fig. 7. Dies for combined rolling-extrusion process: (a) flat die, (b) conical die.

(Table 2) was determined according to the recommendations from Ref. [31]. It was taken equal to 30 mm, while the area of the die mirror was 300 mm^2. The calibrating holes of the dies were selected taking into account the thermal shrinkage of the metal and ensured the production of rods with a diameter of 7.5 and 9.0 mm, which corresponded to the values of the elongation ratio coefficients during extrusion 7 and 5. The value of the calibrating belt of the dies was 2 mm.

The mesdoses installed in certain places of the working stand made it possible to fix the maximum values of the forces developed in the course of the work on the rolls and on the die. Upon receipt of a rod with a diameter of 9.0 mm, the force on the rolls was 290 ÷ 300 kN, and on the die was 200 ÷ 210 kN. When manufacturing a rod with a diameter of 7.5 mm, the force on the rolls increased to 350 ÷ 360 kN, and on the die up to 225 ÷ 230 kN. The speed of rotation of the rolls in both cases was 4 rpm.

4. Discussion

4.1. Microstructure investigation of the rods

Fig. 8 shows the microstructures of deformed and annealed rods from alloy 1580 with diameters of 9 and 7.5 mm in the longitudinal direction along their outflow from the die. The structure consists of an α-solid solution of aluminum and excess phases, predominantly oriented in the direction of deformation and elongated into lines. The microstructure contains areas with a vortex direction, which is explained by the specifics of the structure of the initially used material. The structure of the rods was influenced by the purity of the material used, as well as the heating temperature of the briquette. Therefore, the microstructure of the investigated rods in the deformed and annealed states contains some defects, such as extended oxide films and discontinuities between the chips. The investigated alloy is weakly subject to self-welding and its surface is quickly covered with a film during heating, in connection with which these defects probably formed.

However, the results of metallographic analysis also showed that, unlike other aluminum alloys [24], in the microstructure of the metal of the 1580 alloy processed according to the technological scheme using the combined rolling-extrusion method, even at high magnification (Fig. 8), the boundaries of individual chips, which indicates a good elaboration of the metal.

The annealing carried out after CRE at a temperature of 400 °C and holding for 3 h was aimed at increasing the ductility of the metal during further cold working of the rods by sectional rolling and drawing, which occurred due to the processes of recrystallization of the metal structure.

Fig. 9 shows the microstructures of the rods before and after annealing in polarized light. Analyzing the research results, it can be concluded that in rods obtained with a higher degree of deformation (7.5 mm in diameter), recrystallization processes to which the surface layers are more susceptible, proceed much more intensively due to the large number of introduced dislocations. Oxidation of the samples also made it possible to trace the direction of metal flow. The near-surface layers of the bar are mainly oriented along the direction of deformation, which cannot be said about the central ones, where vortex orientation is observed, which is especially noticeable in a rod with a diameter of 9.0 mm.

4.2. MRSA of the rods

The X-ray microspectral analysis of the samples obtained from the chips of the 1580 alloy (Fig. 10) showed that the structure consists of an aluminum solid solution containing the alloying element Mg (Fig. 10(a) spectrum 5; Fig. 10(b) spectrum 1, 7). EDS analysis did not reveal the presence of Sc and Zr in the solid solution due to their low content in the alloy.

Intermetallic particles containing Sc and Zr in the structure of the samples were not found. The dispersed phases are arranged in lines along the grain boundaries. EDS analysis of excess phases showed that they contain: Al, Mn, Fe (Fig. 10*a* spectrum 1, 4; Fig. 10*b* spectrum 6); Al, Mn, Fe, Si (Fig. 10*a* spectrum 2; Fig. 10*b* spectrum 2, 4, 5); Al, Mg, Mn, Cr (Fig. 10*a* spectrum 3). The structure of the alloy also contains dark inclusions containing Mg and Si, which correspond to the Mg_2Si phase (Fig. 10*a* spectrum 6). It is difficult to determine the exact stoichiometric composition of the excess phases because of the small size of the inclusions.

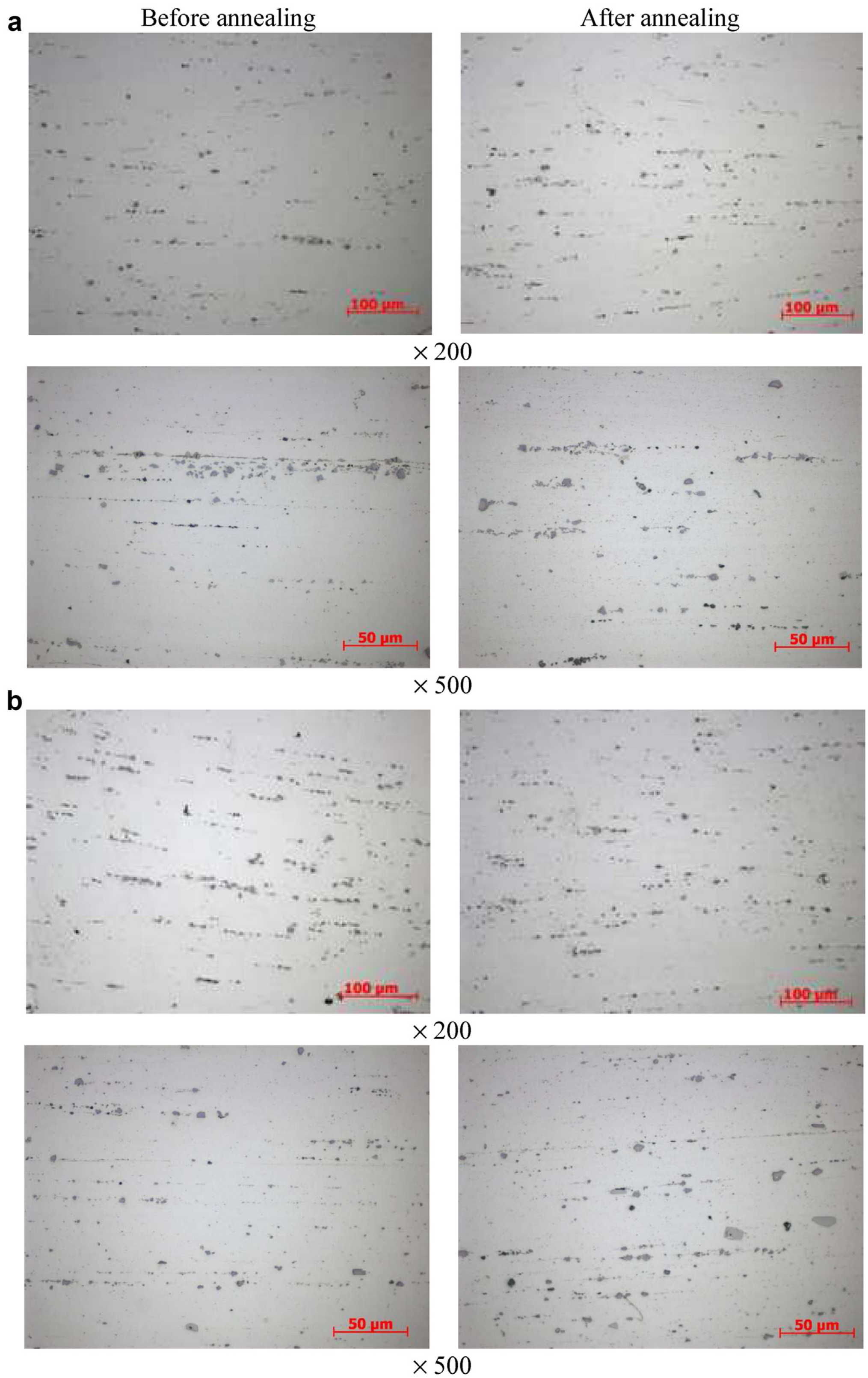


Fig. 8. Microstructures of deformed rods from alloy 1580 with a diameter of 9.0 mm (a) and 7.5 mm (b) at different magnifications before and after annealing.

4.3. Microhardness investigation of the samples

To evaluate the properties of rods in the deformed and annealed states, the microhardness was measured. At least 30 measurements were carried out on one sample, and then the value was averaged and entered in Table 3. For measurements, a place was chosen that was visually free from secondary phases, i.e. actually measured the microhardness of the solid solution. The results given in Table 3 are

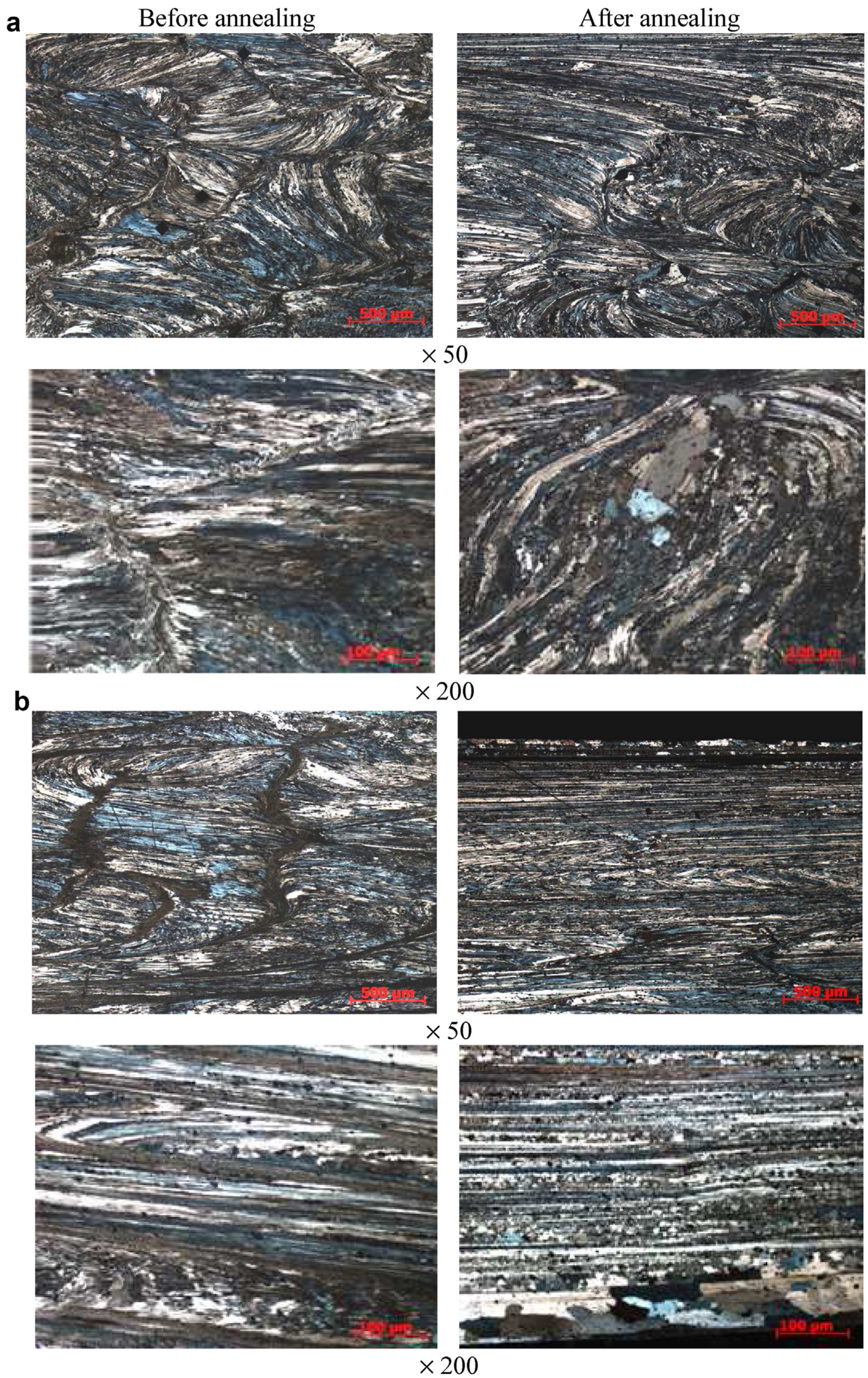
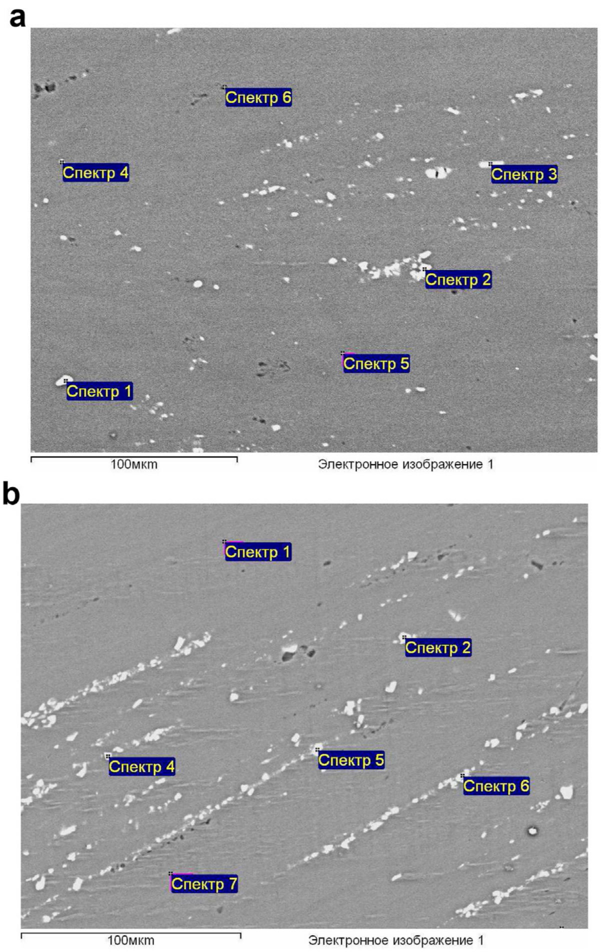


Fig. 9. Microstructures of deformed rods with a diameter of 9.0 mm (a) and 7.5 mm (b) after the deposition of an oxide film at different magnifications before and after annealing.



Spectrum	Mg	Al	Si	Cr	Mn	Fe	Total
Spectrum 1	2.14	77.62			7.04	13.19	100
Spectrum 2	2.25	72.96	3.49		7.88	13.42	100
Spectrum 3	10.0	76.63		5.71	7.66		100
Spectrum 4	3.86	85.51			3.45	7.18	100
Spectrum 5	4.98	95.02					100
Spectrum 6	9.22	76.49	14.29				100

All results in weight %

Spectrum	O	Mg	Al	Si	Mn	Fe	Total
Spectrum 1		5.58	94.42				100
Spectrum 2			69.59	2.87	9.82	17.72	100
Spectrum 4		2.93	77.77	2.66	5.98	10.67	100
Spectrum 5	7.78	1.78	66.90	4.21	7.46	11.89	100
Spectrum 6		3.32	81.81		6.39	8.48	100
Spectrum 7		4.96	95.04				100

All results in weight %

Fig. 10. Electronic image and MRSA results of rods from 1580 alloy chips. (a) diameter 9.0 mm; (b) diameter 7.5 mm.

Table 3
Microhardness of deformed and annealed semi-finished products.

Alloy	Type of semi-finished product	Microhardness (HV), kgf/mm^2	
		Deformed	Annealed
1580	Rod with diameterм 9.0 mm	111 ± 2	98 ± 2
	Wire with diameter 3.0 mm	117 ± 2	94 ± 1
	Rod with diameterм 7.5 mm	113 ± 2	99 ± 3
	Wire with diameter 3.0 mm	115 ± 2	92 ± 2
01570	Rod with diameterм 7.0 mm	81 ± 2	–
	Wire with diameter 4.2 mm	90 ± 2	–

confirming the assumption that during annealing, recrystallization occurs in the structure of the rods and the microhardness after annealing decreases, which indirectly indicates an increase in the plasticity of semi-finished products.

4.4. Technological schemes for producing wire from rods and heat treatment

After combined rolling-extrusion and annealing to obtain a wire with a final diameter of 3 mm from alloy 1580, cold sectional rolling and cold drawing of hot-extruded rods were used, which were carried out on a sectional rolling mill and a chain drawing mill with an average reduction $\varepsilon_{av} = 15 \div 20\%$. Therefore, the next stage of research was the implementation of technological schemes for cold deformation of the metal, shown in Fig. 11.

As a result, it was found that with a given route of cold sectional rolling, due to the dimensions of the rolling mill calibers, it was possible to obtain a square section rod with a side 4.2 ÷ 4.6 mm from a billet with a diameter of 9.0 mm without visible defects (total reduction by this moment was $\varepsilon_\Sigma = 74 \div 78\%$). Sectional rolling of a billet with a diameter of 7.5 mm using the same calibers allowed a rod with a square side of 4.0 ÷ 4.2 mm (total reduction $\varepsilon_\Sigma = 69 \div 71\%$). Thus, annealing of hot-extruded rods with a diameter of 7.5 mm and 9.0 mm did not have a significant effect on the behavior of the material during sectional rolling; therefore, it is not necessary to carry out it immediately after the CRE. It has also been found that the limiting value of the total relative reduction during sectional rolling of 1580 alloy rods should not exceed 70%.

Subsequently, all semi-finished products were subjected to intermediate annealing at a temperature of 400°C and holding time for 3 h, after which they were subjected to drawing to the minimum possible diameter $d_{min} = 3.0$ mm. It was found that the annealing of a rod with a side of 4.2 ÷ 4.6 mm from a billet with a diameter of 9.0 mm had no significant effect on increasing the deformability of the metal. After it was carried out, it was possible to reach the wire only up to $d_{min} = 3.75$ mm, after which frequent breaks began. During mechanical tensile tests, this wire was stratified into separate fragments. The same was observed when trying to stretch a square with a side of 4.0 ÷ 4.2 mm from a workpiece with a diameter of 7.5 mm. This indicates that the effect in increasing the

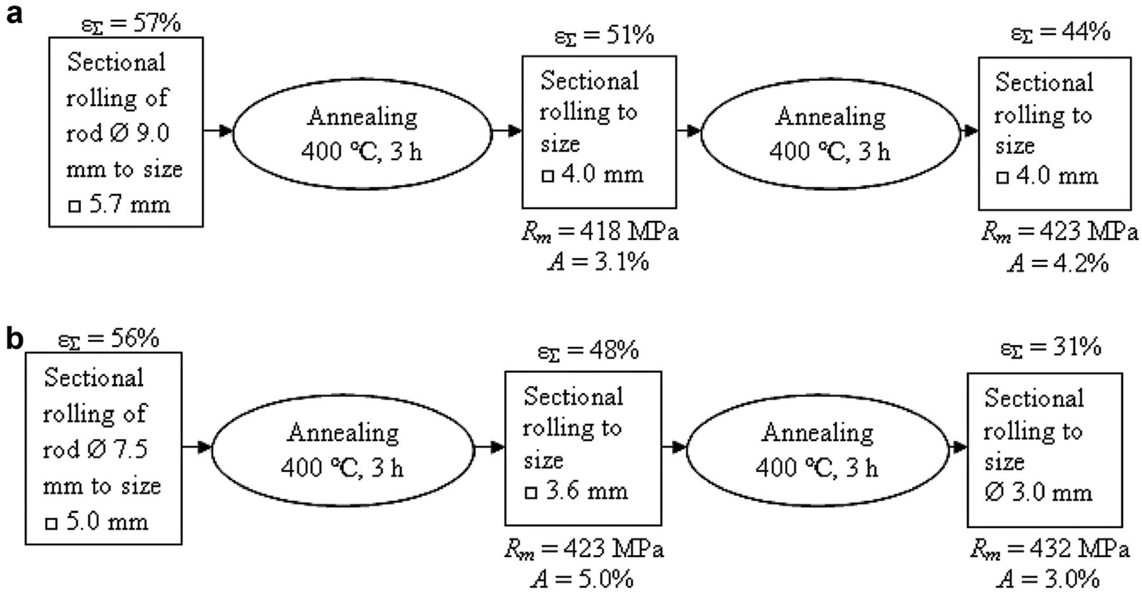


Fig. 11. Technological schemes of cold deformation for 1580 alloy rods obtained by the CRE method: (a) 9.0 mm, (b) 7.5 mm. ε_Σ – total deformation, %; R_m – ultimate tensile strength, MPa; A – elongation to failure, %.

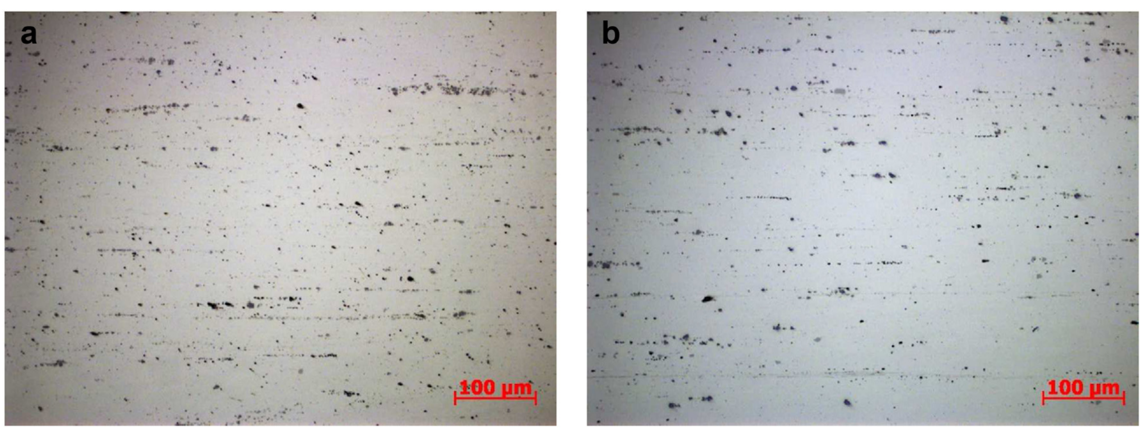


Fig. 12. Microstructure of a wire with a diameter of 3 mm from alloy 1580 obtained from rods with a diameter of 9.0 mm (a) and 7.5 mm (b), ×200.

deformability resource from annealing after significant degrees of deformation imparted to the material becomes minimal. This is quite consistent with the proposition known from the theory of metal forming on reducing the possibility of material damage by microdefects during annealing with an increase in the degree of deformation imparted to it before that.

A wire with a diameter of 3 mm from alloy 1580 was obtained by intermediate annealing on the dimensions of semi-finished products with a square section of 5.7 and 5.0 mm. The diagrams above (Fig. 11) indicate the processing modes, the distribution of the phased values of the total relative reductions, and the values of the mechanical characteristics of the metal of the intermediate and final semi-finished products. It can be seen that the ultimate tensile strength is in the range of 423–432 MPa, and the elongation to failure is 3.2–4.2%. The microhardness of the wire in the deformed and annealed states is given in Table 3. These indicators are comparable with the mechanical characteristics of the wire obtained from the cast billet of this alloy [44], which makes it possible to recommend the obtained products for use in industry, for example, for soldering structures made of aluminum alloys.

The results of metallographic studies of the microstructure of the wire with a diameter of 3 mm from alloy 1580, obtained from billets with diameters of 9.0 and 7.5 mm, are shown in Fig. 12.

The microstructure of the wire obtained according to different technological schemes is identical and consists of grains elongated along the direction of deformation, along the boundaries of which inclusions of excess phases are located. The boundaries of individual chips in the structure are practically not detected, which indicates a good interaction of metal chips and obtaining a continuous material.

5. Conclusions

Thus, on the basis of the results of the research, the following conclusions can be drawn:

– It has been found that rods from high-quality chip waste of alloys 01570 and 1580 of the Al–Mg system alloyed with scandium can be obtained using hot extrusion and combined rolling-extrusion operations;

– To reduce the probability of manifestation of various kinds of defects in the final wire of the investigated alloys, increased requirements for the quality of the initial billet and the parameters of chip briquetting should be observed, while the cold briquetting pressure of about 90 ÷ 100 MPa leads to an increase in density up to 1.40 ÷ 1.42 g/cm^3;
– To obtain a billet (rod) for wire drawing from alloy 01570, it is necessary to use hot extrusion of briquettes with increased density and the use of hot chip compaction;
– To obtain a billet (rod) for wire drawing from alloy 1580, it is advisable to use a more efficient method of combined rolling-extrusion;
– Application of the parameters of the temperature-deformation regime for the implementation of the CRE process (heating temperature of the billet 450 ± 20°C and rolls up to 100°C, drawing ratio during extrusion up to 7) ensures the production of rods from alloy 1580 chips with microhardness (HV) in the deformed state of about 111–113 MPa, and in annealed 98–99 MPa;
– Total relative reduction during cold deformation of metal from alloy 1580 between intermediate annealings should not exceed 60–70%, and single reductions during the processes of sectional rolling and drawing should not exceed 15–20%;
– The structure of the metal after drawing is characterized by compactness, and the boundaries of individual chips in the structure are practically not detected, while the values of the mechanical characteristics of the obtained wire from the chips of alloy 1580 are comparable to the similar values of the wire from this alloy obtained by the CRE method from a cast billet.

The obtained research results make it possible to recommend the developed technologies for the production of longish deformed semi-finished products from chips of aluminum alloys alloyed with scandium for industrial use (for example, in the form of modifier rods and welding wire). Further research may lead to the emergence of new areas of use for such semi-finished products, the cost of which is much lower than the cost of products made from compact materials in various industries.

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.

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Authors contributions

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

Conflict of Interest

The authors declared that no conflict of interest exists for this work.

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