Pilot-scale industrial research into the modifying capacity of rods made from secondary AD31 alloy waste obtained using a new method of ingotless rolling-extrusion (IRE)

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The article presents the results of studies of the structure and properties of industrial ingots made of AD31 alloy, which are modified with alloying rods obtained using the technology of ingotless rolling and extrusion (IRE) from scrap of extruded profiles made of AD31 alloy. This method and device are described for combining continuous casting, rolling, and extrusion operations in a single unit. As equipment for obtaining rods with a diameter of 9 mm from secondary waste of AD31 alloy, an experimental and industrial installation CRE-400 with a rolling roll diameter of 385 mm was used. For the production of rods, technological parameters of the IRE process obtained as a result of numerical modeling of the studied process were used. To produce ingots, the company used experimental and industrial equipment from United Company Rusal Engineering and Technology Center (RUSAL ETC). In the course of experimental studies, experimental ingots with a diameter of 100 mm were obtained from the AD31 alloy, modified with a rod made using the IRE technology from secondary waste of the AD31 alloy. Tensile tests were performed on these ingots, and the mechanical properties were obtained, as well as the macro- and microstructure of the metal was studied. It has been established that the introduction of a 3–4% AD31 rod made of the same alloy into the melt, obtained by the IRE method from the scrap of extruded profiles of the same alloy, reduces the grain size to 234–349 µm, depending on the conditions of the rod introduction and the choice of ingot casting parameters. Comparison with the initial macrostructure of the unmodified ingot showed that the introduction of a rod of the same composition obtained by the new method leads to the formation of a fine-grained structure of the ingot, which indicates the presence of a modifying effect when using a rod obtained by the IRE method. At the same time, the obtained high level of mechanical properties of the metal of these ingots makes it possible to use them for the production of extruded profiles from the AD31 alloy.

Key words: aluminum alloys, extrusion production waste, high-speed crystallization-deformation, ingotless rolling and extrusion, modification, ingot casting, structure, and mechanical properties.

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Introduction

The fundamentals of the ingotless rolling-extrusion (IRE) process are described in reference [1]. This process was subsequently employed to produce rods from AD31 alloy waste [2–4]. Studies showed that the rapid crystallisation and deformation of the melt using the IRE method enables extruded products with a subgrain structure to be obtained, which can be used to modify ingots during casting.

Based on these studies and the technical solution in reference [5], a method was proposed for producing extruded products from secondary aluminium alloy waste that are suitable for modifying aluminium alloys [6]. This method is analogous to combined casting and rolling-extrusion [1], whereby molten metal is poured into a closed caliber of rotating rolls with a minimum cross-section height of h_1, after which the metal is rolled, pressed and extruded through a die with a height of h_m to produce extruded products (see **Fig. 1**).

Works [7–11] note that combining continuous rolling with high deformation during extrusion has a synergistic effect. Authors [12–19] describe the effectiveness of continuous and combined methods for casting Al – Si – Mg alloy billets, which are widely used for producing deformed semi-finished products. One example is the AD31 alloy, which can be easily processed using casting and plastic deformation methods [20, 21]. However, extruded products from this alloy results in a significant amount of waste in the form of cut ends of deformed semi-finished products.

The aim of this work is to improve the efficiency of the manufacturing process for hot-extruded aluminium alloy rods with high mechanical properties and modifying capacity, including the use of secondary aluminium alloy waste. The technical objective of the research was to obtain modifying rods with high mechanical properties and to reduce the cost of products by incorporating secondary alloy waste into production.

Secondary waste aluminium alloys whose chemical composition corresponds to that of the resulting rods were used as the starting material. AD31 alloy rod production involves melting the material and then overheating it to a temperature of 770–850 °C, which is then held for a period of time. The melt is then fed into rotating rolls at a circumferential speed of 4–14 rpm with a rolling compression of at least 50%. Due to the rolls being water cooled, rolling is accompanied by accelerated crystallisation. The metal is then extruded through a water-cooled die with a draw ratio of at least 10. The diameter of the hot-extruded rods (*d*) is 8–12 mm (see **Fig. 1, *a***).

When combining crystallisation with metal deformation, it is important that the process is carried out at a stable speed. This is determined by the circumferential speed of the rolls during rolling. Studies of combined casting and deformation processes for aluminium alloys show that the crystallisation–deformation process is stable at roll circumferential speeds ranging from 4 to 14 rpm. At speeds below 4 rpm, the deformation rate is too low for the metal structure to acquire a cluster structure. Consequently, the number of crystallisation centres when modifying ingots with such a rod is insufficient to achieve effective modification. Conversely, at speeds greater than 14 rpm, the metal in the rolls does not have time to fully crystallise, resulting in a mixed metal structure consisting of cast and deformed areas. This reduces the grain refining effect in aluminium alloy ingots when modified using these rods.

Since the strain during extrusion is determined by the ratio of the area of the billet extruded in front of the die to the area of the extruded product, in order to ensure the specified drawing ratios during extrusion of more than 10, it is necessary that the height of the metal pressed in front of the die $h_м$ be no less than the height of the workpiece crystallised in the rolls h_0 (see **Fig. 1, *a***). If this condition is not met, it will not be possible to achieve the specified drawing ratios, and the task of obtaining modifier rods will not be solved.

In industrial conditions, devices for feeding rods of a certain diameter d (most often 9 mm) are used to modify aluminium alloys. the declared range of rod diameters covers all possible options for their use, including large-diameter rods (up to 12 mm), if further processing operations (e.g., scalping or drawing) are envisaged.

Materials and methods

The material studied was scrap from extruded AD31 alloy profiles obtained in industrial conditions after removing the front and rear ends of the profiles. The chemical composition of the alloy according to GOST 4784–2019 is given in **Table 1**.

The research used the results of numerical modelling and proprietary methods for determining the energy-force parameters of the process under study [2, 3].

The metal structure was studied using a Stemi 2000-C stereomicroscope, an Observer.A1m light microscope (Carl Zeiss), and an EVO50 scanning microscope with an Energy 250 energy-dispersive spectrometer. The mechanical properties were determined using an LFM 400 testing machine. The grain size was determined using the random secant method, in accordance with GOST 21073.3–75. Quantitative analysis of the microstructure was performed using the Axio Vizion digital image analysis software from Carl Zeiss. Spectral analysis of samples to determine their chemical composition was performed on a Spectrolab optical emission spectrometer.

To obtain modified rods, a IRE device was used (**Fig. 1, *a***), the practical implementation of which was carried out on a pilot industrial installation SPP-400 [1] (**Fig. 1, *b***). The installation parameters are given in **Table 2**.

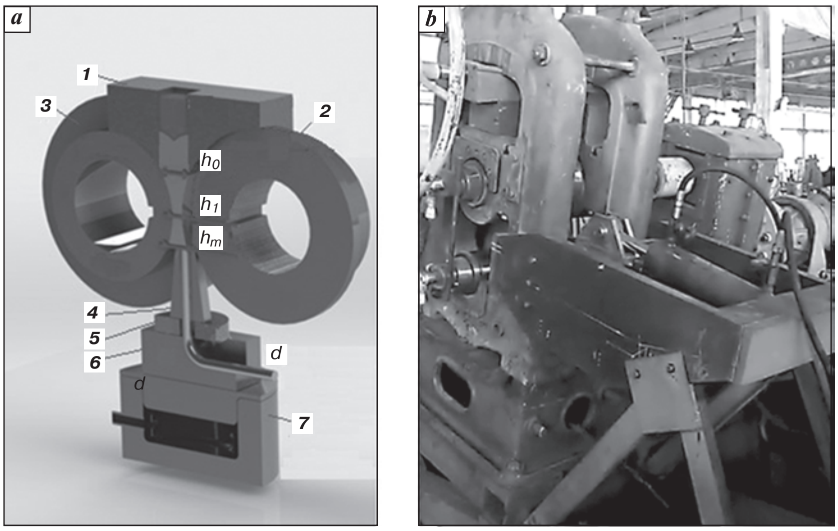


Fig. 1. Device for implementing the ingotless rolling-extrusion method (*a*) and CRE-400 installation (*b*):
1 – filling groove, *2* – roller with protrusion; *3* – roller with groove; *4* – die; *5* – die holder; *6* – slide; *7* – hydraulic clamp (*photo by authors*)

Table 1
Chemical composition of AD31 alloy according to GOST 4784–2019

Mass fraction of an element, %										
Al	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	V	B
Base	0.2–0.6	0.5	0.1	0.1	0.45–0.90	0.10	0.2	0.15	0.05	0.05

Table 2
Geometric parameters and technical characteristics of the CRE-400 installation

Parameter	Value
Diameter of roller with comb, mm	385
Diameter of the roller with groove, mm	385
Minimum calibre height, mm	10
Caliber width, mm	22.5
Roll rotation speed, rpm.	2; 4; 4.8
Matrix clamping force, kN	400
Permissible rolling force, kN	600
Electric motor power, kW	45

Results and discussion

Based on the obtained simulation data and analytical calculations [2–4], a tool was designed and technological parameters were selected for conducting experimental studies on obtaining 9 mm diameter rods from AD31 alloy extruded profile trimmings using the proposed combined processing method. The technological parameters of the IRE process for implementing this process were as follows: melt temperature 760 ± 10 °C; tool temperature 100 °C; roll rotation speed 4.8 rpm; degree of deformation during rolling 50%; draw ratio during extrusion 9.7.

The resulting 17 kg of rods were used to modify industrial ingots during casting.

To determine the modifying ability of rods obtained from AD31 alloy extruded profile trimmings using the IRE method, studies were conducted at the casting section of the pilot industrial casting complex of RUSAL ETC LLC (**Fig. 2**). The manufactured rods were continuously fed into the melt in the metal tract upstream of the foam ceramic filter at a rate of 3–4% of the melt volume.

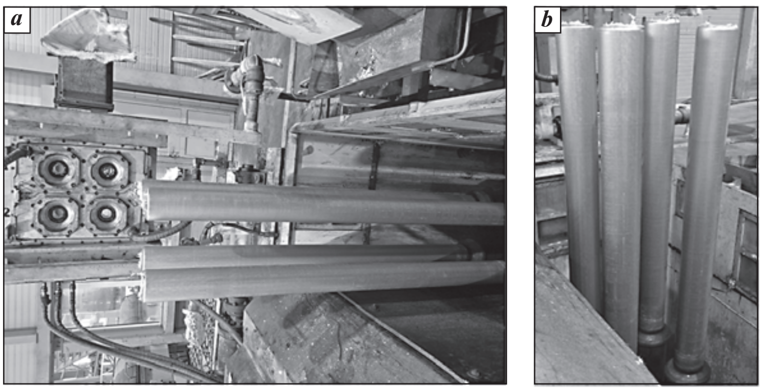


Fig. 2. View of the casting complex (*a*) and the ingots obtained (*b*) (*photo by authors*)

The melt was prepared in a furnace for experimental smelting based on primary aluminium grade A7. Before smelting, the melt was treated with a flux preparation and allowed to settle for 30 minutes. The temperature of the melt in the furnace before casting was 760 ± 3 °C.

The chemical composition of the alloy (**Table 3**) was determined by spectral analysis.

To study the macrostructure and evaluate the grain structure parameters of ingots subjected to modification with experimental rods, templates were selected from the ingots obtained.

For casting ingots, a melting complex with a capacity of 350 kg of aluminium, a foam ceramic filter, a trough system with heating elements, a semi-continuous vertical casting screw machine, and a set of casting equipment manufactured by Wagstaff were used (**Fig. 2, *a***).

Ingots with a diameter of 100 mm and a length of up to 1500–1600 mm were cast using a pilot modifier in the form of rods obtained by the IRE method from secondary AD31 alloy waste, in accordance with the production casting regulations. Four ingots were cast simultaneously (**Fig. 2, *b***).

Analysis of the macrostructure of ingot No. 1 (**Fig. 3, *a***), obtained without the use of a modifier, showed that a significant area in the structure of this ingot is occupied by fan-shaped crystals, and a granular structure with an average size of about 3.5 mm was formed only in a small part of the ingot. The largest grains reached a size of up to 10 mm, and equiaxed crystals with a size of 2–3 mm were observed in the crust zone of the ingot.

Studies have shown that modifying the melt with an AD31 alloy rod obtained by the IRE method contributes to the elimination of fan-shaped crystals and the refinement of the grain structure of the AD31 ingot, subject to compliance with the specified casting parameters and modification conditions. Thus, ingots No. 2–4 formed a fairly fine grain structure with no defects (**Fig. 3, *b*, *c*, *d***). During experimental melting, larger grains were formed in ingot No. 2 (**Fig. 3, *b***) than in ingots No. 3 and No. 4 (**Fig. 3, *c*, *d***), which is explained by the difference in the variation of casting conditions and methods of modifier introduction.

Thus, in order to obtain a stable modifying effect when using AD31 alloy rod obtained by the IRE method from secondary waste, it is necessary to strictly observe the conditions for introducing the rod and select the parameters for casting ingots.

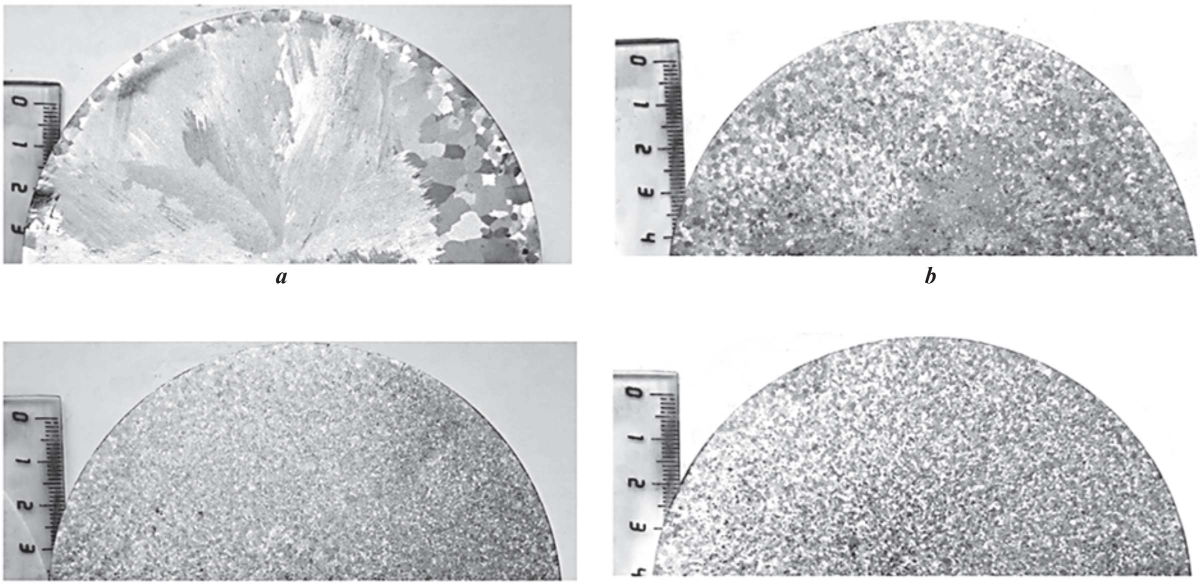
Table 3
Chemical composition of AD31 alloy during experimental smelting

Mass fraction of an element, %										
Al	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	V	Impurities, summ
Base	0.43	0.32	0.002	0.004	0.68	0.002	0.015	0.007	0.014	0.017

Micro-*X*-ray spectral analysis of AD31 alloy ingots in their initial state and after modification with a rod obtained by IRE from secondary waste (**Fig. 4**) showed that the structure consists of an aluminium solid solution (**Fig. 4, *a***, spectra 3, 7; **Fig. 4, *b***, spectra 3, 8, 9). Since magnesium partially dissolves in aluminium, a certain amount of it is observed in the spectra shown.

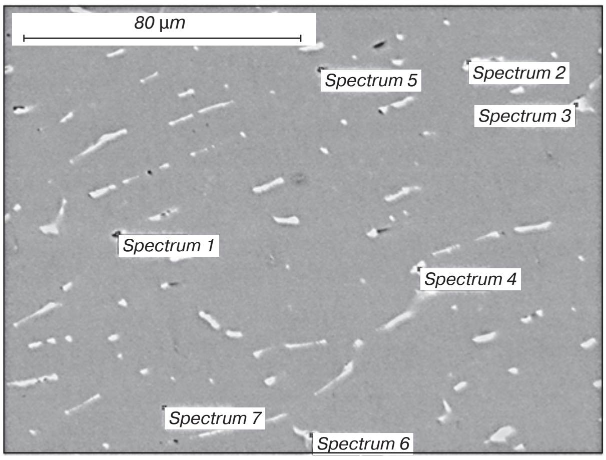
Excess phases are mainly located at the boundaries of dendritic cells. EDS analysis of the phases showed that they contain Al, Fe, and Si, which may correspond to the Fe_2SiAl_8 phase (**Fig. 4, *a***, spectra 2, 4; **Fig. 4, *b***, spectra 1, 4, 5). Dark inclusions are also present in the alloy structure, which presumably correspond to the Mg_2Si phase (**Fig. 4, *a***, spectra 1, 5; **Fig. 4, *b***, spectra 6, 7). Micro-*X*-ray spectral analysis of the structure of the ingots before and after modification did not reveal any significant differences in the chemical composition of the phases.

To determine the quantitative parameters in the ingots after modification, studies of the microstructure of the samples were carried out in polarised light (**Fig. 5**).



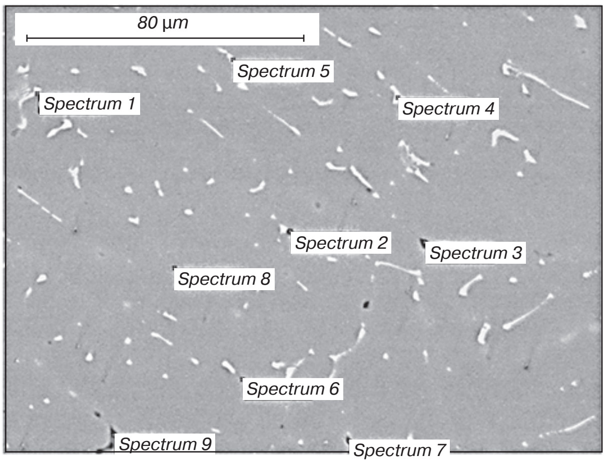
a ***b*** ***c*** ***d***

Fig. 3. Macrostructure of ingots:
a – ingot No. 1; *b* – ingot No. 2; *c* – No. 3; *d* – No. 4



Spectrum	Mg	Al	Si	Fe
Spectrum 1	6,44	89.13	4.43	
Spectrum 2	0.90	92.14	2.97	3.99
Spectrum 3	0.80	99.20		
Spectrum 4	0.66	91.42	4.58	3.34
Spectrum 5	6,21	89.50	4.28	
Spectrum 6	1.29	96.15	2.55	
Spectrum 7	1.15	98.85		

a



Spectrum	Mg	Al	Si	Fe
Spectrum 1	1.13	87.96	5.14	5.77
Spectrum 2	0.72	97.65	1.63	
Spectrum 3	0.74	99.26		
Spectrum 4	0.99	87.05	4.01	7.96
Spectrum 5	1.01	90.94	3.03	5.02
Spectrum 6	7,6	80.87	11.53	
Spectrum 7	9,24	84.26	6.50	
Spectrum 8	0.52	99.48		
Spectrum 9	1.02	98.98		

b

Fig. 4. Electronic image and results of micro-*X*-ray spectral analysis of ingots:
a – without modification; *b* – after modification with AD31 rod obtained by IRE

Table 4
Grain size and mechanical properties of experimental ingots made of AD31 alloy

Ingot No.	Condition	Grain size, μm	Yield strength, MPa	Ultimate tensile strength, MPa	Elongation to failure, %
1	Without modifier	3000 ± 590	80 ± 3	163 ± 3	20
2	Modification with a rod made from secondary AD31 alloy waste obtained by the IRE method	349 ± 90	122 ± 2	197 ± 2	25
3		303 ± 96	139 ± 2	235 ± 2	26
4		234 ± 61	147 ± 2	243 ± 2	25

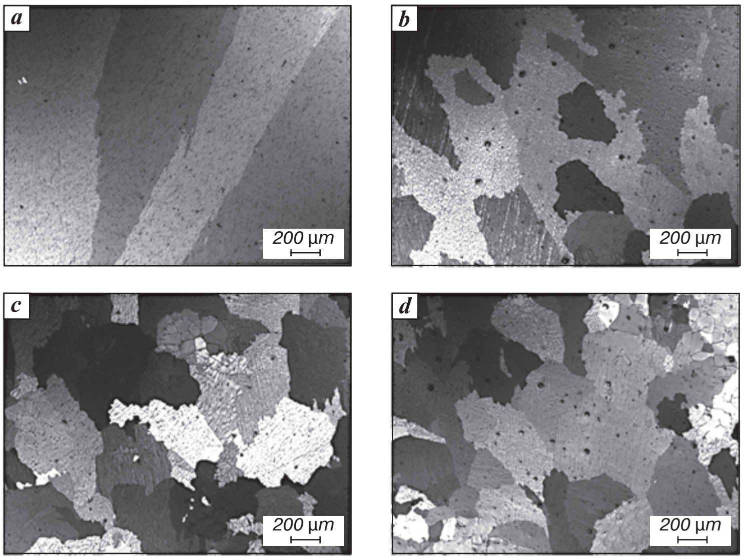


Fig. 5. Microstructure of AD31 alloy ingots in polarised light: *a* – ingot No. 1; *b* – ingot No. 2; *c* – No. 3; *d* – No. 4

Metallographic studies showed that in its initial state, ingot No. 1 contained elongated large crystals, the size of which is difficult to estimate as they do not fit in the field of view (**Fig. 5, *a***). The studies confirmed that modification with a rod obtained using IRE technology from AD31 alloy waste leads to the formation of equiaxed crystals in ingots No. 2-4 (**Fig. 5, *b–d***). Depending on the casting conditions, the modification with the AD31 alloy rod results in a fine-grained structure of the ingots, with the grain size varying in the range of 234–349 μm (**Table 4**). When casting ingot No. 2, modification with a rod manufactured using the IRE method allowed the formation of a structure with an average grain size of about 349 μm (see **Table 4**). For ingot No. 3, the average grain size was 303 μm, and for ingot No. 4, it was 234 μm. To determine the mechanical properties of the metal, samples were taken from the experimental ingots. Analysis of the results of determining the mechanical properties of the samples before and after modification (see Table 4) showed that for modified ingots No. 2-4, the strength properties were higher than for unmodified ingot No. 1, which is consistent with the general ideas of modification theory and the results of studies by other authors [22–25].

Thus, analysis of the results of pilot industrial studies showed that adding 3–4% of AD31 rod made of the same alloy, obtained by the IRE method from the trimmings of extruded profiles of the same alloy, to the melt reduces the grain size to 234–349 μm (see **Table 4**). A comparison with the initial macrostructure of the unmodified ingot showed that the introduction of a rod of the same composition obtained by the new method leads to the formation of a fine-grained structure of the ingot, which indicates the presence of a modifying effect when using a rod obtained by the IRE method. At the same time, the high level of mechanical properties of the metal of these ingots (**Table 4**) allows them to be used to manufacture extruded profiles from AD31 alloy.

Conclusion

Thus, the studies conducted using the authors' new scientific and technical solutions, the results of which are presented in works [1–6], confirm the conclusion that rods made from secondary waste from the extrusion production of AD31 aluminium alloy in the form of extruded profile trimmings, obtained by a method using ingotless rolling-extrusion process, provide effective modification of aluminium alloys and make it possible to obtain a grain size in industrial ingots of up to 234 μm. The quantitative parameters of the ingot casting process and the method of introducing modifying rods into the melt have been established. At the same time, these ingots have a sufficiently high level of mechanical properties: ultimate tensile strength 197–243 MPa; yield strength 122–147 MPa; elongation to failure 25–26%. Therefore, it is also possible to predict the mechanical properties required by GOST [26] for AD31 alloy in the hardened and naturally aged state (ultimate tensile strength 127 MPa, yield strength 69 MPa, elongation to failure 13%) for hot-extruded profiles made from these ingots.

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