Microstructure and mechanical properties of extruded bars manufactured from aluminum chips

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A comparative analysis of the microstructure and mechanical properties of extruded bars produced from chips by solid-phase consolidation was carried out using two aluminum alloys of different alloying systems: the AD31 alloy and the experimental “Calmar” alloy based on the Al – Ca – Mn system. Chips were produced from ingots by turning with equal cutting conditions for both alloys. The dimensions of the chips (both for AD31 and “Calmar” alloys) were: thickness 1–6 mm, length 2–15 mm, height 2–5 mm. It was shown that under identical briquetting conditions, the calculated density of briquettes produced from the “Calmar” alloy is closer to the calculated density of the ingot compared to the AD31 alloy: 89.5% vs. 85.2%. It was established that direct extrusion of briquettes makes it possible to obtain defect-free bars with high strength and ductility, which are not inferior to those produced from ingots under similar conditions. For the “Calmar” alloy, the UTS is 152–179 MPa and the elongation is 15.2–18.2%. The microstructure of bars produced from chips is characterized by a more favorable morphology of eutectic phases and their more uniform distribution compared to bars produced from ingots. This effect is especially pronounced in the experimental alloy, in which the volume fraction of such phases reaches about 10% (compared to about 2% in the AD31 alloy). It was shown that the experimental “Calmar” alloy exhibits superior mechanical properties compared to the AD31 alloy. This indicates that eutectic-type alloys are more promising for solid-phase consolidation than alloys with a low content of secondary phases.

Key words: chips of aluminum alloys, system Al – Ca – Mn, extruded bars, microstructure, mechanical properties

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Introduction

The production and consumption of aluminum alloys is constantly increasing, which is due to the unique combination of their operational and technological properties with a broad raw material base [1–4]. The production of aluminum alloys using recycled raw materials as the main charge is much more attractive in terms of environmental impact and cost-effectiveness compared to the use of primary aluminum. This is due not only to the fact that primary aluminum is more expensive than aluminum scrap, but also to the fact that its production is associated with substantial environmental burden [5–10].

In the total volume of scrap, a significant share is occupied by machining chips, which are formed in the process of mechanical processing of products and, as a rule, are sent for remelting [10]. However, chip remelting is accompanied by technological and economic disadvantages, such as metal losses due to oxidation, burn-off of alloying elements, the need for sorting and removal of contaminants, as well as additional energy costs. In this regard, in recent years, there has been an increasing interest in alternative methods of chip waste processing based on solid-phase consolidation processes, in particular, hot pressing and subsequent plastic deformation [11, 12].

One of the main parameters of the efficiency of the use of briquetted billets for obtaining finished products (bars, forgings, stampings) is the amount of energy spent to obtain the initial blank for deformation processing. In the paper [13], it is shown that for the liquid-phase process of obtaining a workpiece for deformation treatment, it is necessary to spend specific energy of at least 1353 kJ/kg or 376 kWh/t, but only 2% of these costs are required for consolidating chips.

Obtaining finished products by deformation treatment of chip briquettes also has several technological advantages: stable chemical composition, as well as potentially finer microstructure, which is due to the method of mechanical processing when obtaining chips. As is known, machining operations are characterized by plastic deformation, which changes the structure and properties of the material [14], while the strain imposed on the chips significantly depends on the technological parameters of the cutting process: cutting speed, machining method, geometric parameters of the tool, etc. [15–17].

To obtain suitable products from briquettes, the issues of formation of microstructure and mechanical properties of extruded bars from aluminum chips of various alloying systems remain insufficiently studied and require experimental confirmation. To eliminate this gap, in this work the task was set to carry out work aimed at substantiating the possibility of obtaining extruded bars from aluminum alloy shavings, which have mechanical properties at the level of semi-finished products, obtained using traditional technology from ingots.

Two alloys were chosen as objects of study: brand AD31 (GOST 4784–2019) [18] and experimental "Calmar" based on the Al – Ca – Mn system [19]. The choice of the first alloy is because it is one of the most common of the industrial thermally strengthened alloys [20–22]. It is used in various industries and construction, usually in the form of extruded semi-finished products. Most often, window and door profiles, partitions, awnings and canopies are made from this alloy. The choice of the second (non-heat treatable) alloy is because it has a high processability not only in deformation processing, but also in conventional casting processes [19]. In the alloys of this system, strengthening is provided by nanoscale dispersoids Al_6Mn and eutectic particles of Ca-containing phases, mainly Al_4Ca [23, 24]. Dispersoids are formed during the decomposition of the aluminum solid solution (hereinafter (Al)) during heating before and during the deformation process, and the latter during solidification. Thus, their formation does not require homogenization, solution treatment, quenching and aging operations, and the heat resistance of the alloys of this system is much higher than that of heat treatable alloys, including alloys of 6xxx series.

Table 1
Chemical composition of experimental alloys in ingots

Alloy	Concentration, wt.%							
	Al	Si	Mg	Ca	Mn	Fe	Zn	Cu
AD31	Basis	0,40	0,51	<0,01	0,05	0,33	0,05	0,04
"Calmar"	Basis	0,17	<0,01	2,21	1,00	0,20	0,87	0,03

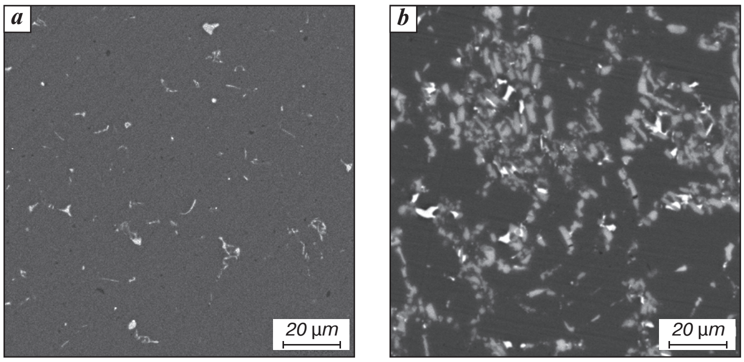

Fig. 1. Microstructure of initial ingots, SEM:
a – AD31 alloy, homogenized; *b* – "Calmar" alloy, as-cast

Experimental

The objects of the study were ingots and bars of two aluminum alloys: grade AD31 and an experimental alloy based on the Al – Ca – Mn system (hereinafter referred to as "Calmar"). Sections cut from an industrial cylindrical ingot manufactured by "Aluminum Alloy Plant JSC" were used as the initial charge of the grade alloy. The experimental alloy was prepared from 99.7 wt.% aluminum with the metallic calcium and scrap addition to obtain the average composition given in the patent [19]. Both alloys were prepared in the PP-10 laboratory electric furnace in a graphite-chamotte crucible at a melt temperature of 720–740 °C. Cylindrical ingots with a diameter of 43.5 mm and a weight of about 1 kg were obtained by casting in a graphite mold. Prior to machining, the ingots made of AD31 alloy were homogenized at 580 °C for 36 h. Ingots of the "Calmar" alloy were not subjected to heat treatment. The actual composition of the alloys is shown in **Table 1**, and their microstructure in the ingots is shown in **Fig. 1**.

Chips were produced from ingots by turning with equal cutting conditions for both alloys. The dimensions of the chips (both for AD31 and "Calmar" alloys) were: thickness 1–6 mm, length 2–15 mm, height 2–5 mm (**Fig. 2, *a*, *b***). The main fraction of chips for briquettes production (more than 80% by weight): thickness 3–4 mm, length 7–10 mm, height 3–4 mm. After chip production, they were briquetted at room temperature with identical pressing forces for both alloys. Briquetting was carried out using a container with a diameter of 50 mm. As a result, briquettes with a diameter of 50 mm, a height of approximately 16 mm were obtained. The weight of the briquettes ranged from 69 to 72 grams. Photographs of the briquettes are shown in **Fig. 2, *c*, *d***. The density of ingot samples and briquettes obtained from them was determined by weighing and measuring geometric dimensions. The values of the calculated density of briquettes were obtained by measuring 7 briquettes. Briquette parameters are presented in **Table 2**.

The bars were obtained by direct extrusion on a P-450 hydraulic press. The diameter of the container was ∅50 mm, and the diameter of die was ∅12 mm (extrusion ratio $\mu = 17.4$). Extrusion was carried out at a deformation rate of 1 mm/s. without lubrication. Before pressing, the workpiece and the working tool (container, dummy block, die and backer) were heated together. The design of the working tool allows pressing without significant heat loss. After loading the briquettes into the container, the assembled tooling (container, dummy block, briquettes, die and backer) was loaded into the furnace and heated to the target temperature (400 and 450 °C) for 4 hours.

As a result of extrusion at both temperatures, bars with a diameter of ∅12 mm and a length of ~1200 mm were obtained **(Fig. 2, *d, f*)**.

Microstructural analysis of samples taken from the rods was carried out using a TESCAN VEGA3 scanning electron microscope (SEM) equipped with an OXFORD energy dispersive analyzer and Aztec software that provides micro-analysis (EMPA). Samples preparation was carried out by mechanical polishing. Tensile tests of cylindrical specimens (6 mm in diameter) machined from the bars were performed under uniaxial tension using a QUASAR 50 testing machine in accordance with GOST 10446–80 at a crosshead speed of 5 mm/min. The ultimate tensile strength (UTS) and elongation (El) were determined.

Results and discussion

The microstructure of homogenized ingots of the AD31 alloy, as expected, is characterized by the presence of networks of Fe-containing phases (mainly a-Al_8Fe_2Si) **(Fig. 1, *a*)**. The as-cast microstructure of the "Calmar" alloy looks different, since it contains a fine eutectic structure in the amount of about 20 vol% **(Fig. 1, *b*)**. According to EPMA, this eutectic contains (wt.%): 6.6Ca, 2.0Mn, 1.0Fe, 0.5Si, 1.6Zn. Thus, iron, silicon, and zinc are concentrated in this eutectic. Based on the data reported in [25, 26], the eutectic can be identified as (Al) + + $(Al,Zn)_4Ca + Al_{10}CaFe_2 + Al_2CaSi_2$. It should be noted the absence of needle-like inclusions of Fe-containing phases (in particular, b-Al_5FeSi) in the structure of the "Calmar" alloy, which are known to deteriorate mechanical properties of aluminum alloys. The concentration of manganese in (Al) is 1.1 wt.% (which is close to its nominal content in the alloy, see **Table 1**), and the concentration of other elements is negligible.

When briquetting chips and assessing the density of briquettes, it was revealed that with equal parameters of chip compaction and fractional composition, briquettes made of the "Calmar" alloy have a higher packing density compared to the AD31 alloy **(Table 2)**. The calculated density (ρ_c) of AD31 ingot is 2678.8 kg/m^3, and of the "Calmar" alloy is 2678.1 kg/m^3. Such a "low" value of ρ_c of AD31 alloy (its density is $\rho = 2710$ kg/m^3) obtained during measurements is due to the presence of pores in the central zone of the ingot, formed during casting, and the accuracy of measurements. When comparing the ingot density (ρ_c) with the average calculated density of the briquettes ($\Delta\rho_1 = ((\rho_{ingot} - \rho_{av.briq}) / \rho_{ingot}) \times 100\%$), it is shown that briquettes made of shavings of the "Calmar"

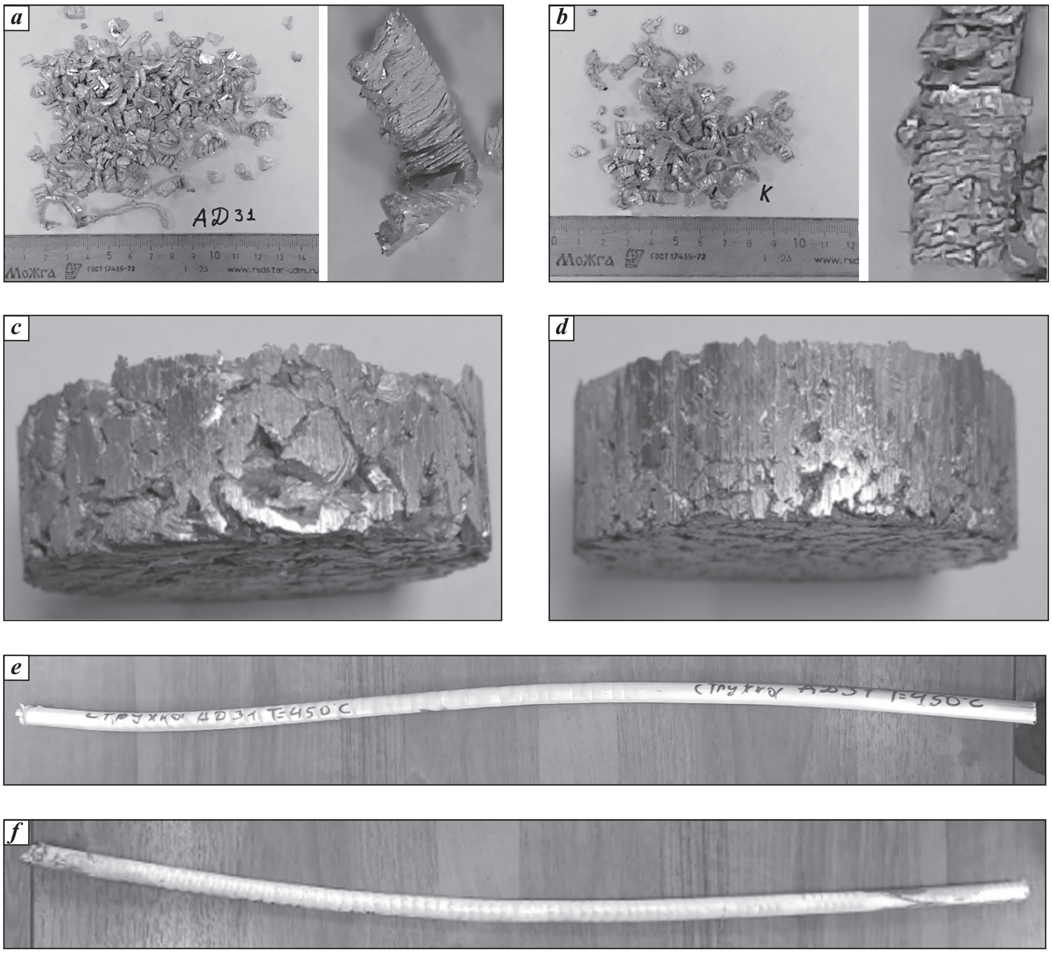

Fig. 2. Appearance of chips (*a*, *b*), briquettes (*c*, *d*) and rods (*d*, *f*) of alloys AD 31 (*a*, *c*, *e*) and "Calmar" (*b*, *d*, *f*) (photo by authors)

alloy have a smaller difference in the calculated density of the briquette from the design density of the ingot. For example, for the AD31 alloy, the $\Delta\rho_1$ value is 14.8%, and for the experimental alloy – 9.5% (85.2% and 89.5% of the calculated ingot density, respectively). Also, briquettes made of the "Calmar" alloy had a more uniform calculated density of briquettes. Thus, the maximum and minimum value of the design density of the AD31 alloy is 2378.8 kg/m^3 / 2153.1 kg/m^3. The relative deviation ($\Delta\rho_2 = ((\rho_{max} - \rho_{min}) / \rho_{max}) \times 100\%$) for AD31 is $\Delta\rho_2 = 10.6\%$. For the "Calmar" alloy, the corresponding values were 2454.7 kg/m^3 / 2355.2 kg/m^3 and $\Delta\rho_2 = 4.1\%$.

Based on a comparative analysis of the parameters of briquettes ($\Delta\rho_1$, $\Delta\rho_2$), it was noted that the "Calmar" alloy is more susceptible to plastic deformation in comparison with the AD31 alloy, including after the operation of mechanical treatment (local deformation treatment). Visual inspection of the surface of the bars of both alloys **(Fig. 2, *d, f*)**, produced by direct extrusion of briquettes, did not reveal defects in the form of discontinuities, delaminations, longitudinal and transverse cracks. The surface quality in both alloys is satisfactory. It can be assumed that during subsequent deformation (for example, to reduce the diameter of the bar by drawing, etc.), the bars obtained from briquettes will deform under standard modes for these alloys, without significant modification of the deformation processing parameters.

As a rule, during machining, local plastic deformation occurs, which can be characterized and quantified by changes in the geometric parameters of chips, depending on the methods of cutting (turning, milling, etc.), machining modes, etc. [15–17, 27]. The accumulation of plastic deformation leads to microstructural refinement and improved mechanical properties. As a result of combining deformation methods, it is possible to form a set of properties in the finished product. For example, when combining the method of screw rolling and upsetting, due to a change in the nature of the plastic flow, it is possible to improve ductility, impact strength values [28, 29] without reducing the strength characteristics of the material, as well as significantly improve the structure of the metal, eliminate defects formed during casting [30].

It is assumed that the presence of discontinuities in briquettes can affect the deformation forces. Previous experimental work shows that due to deformation treatment, it is possible to create discontinuities (in the form of central porosity) in order to increase process efficiency, which is manifested in a decrease in mandrel force when piercing solid billets in a screw rolling mill, and to obtain defect-free sleeves with high plastic properties, impact toughness, without reducing strength characteristics [31].

Deformation treatment, implemented by combining local deformation in the process of turning and subsequent direct pressing, had little effect on the volume fraction of eutectic phases formed during casting, but changed their morphology and distribution. When compared with the structure of bars obtained from ingots **(Fig. 1)** a higher degree of refinement of eutectic phases is observed. In the AD31 alloy this effect is less pronounced, since their total volume fraction does not exceed 2 vol.% **(Fig. 3)**. In the

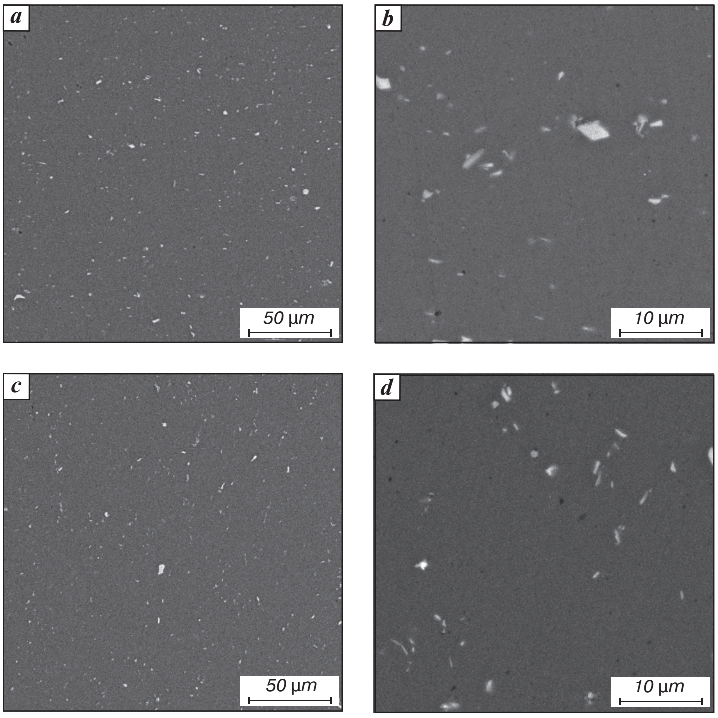

Fig. 3. Microstructure of AD31 alloy bars pressed from briquettes at 400 °C (*a*, *b*) and 450 °C (*c*, *d*), SEM

Table 2
Parameters of briquettes made of AD 31 alloys (Fig. 1, *c*) and "Calmar" (Fig. 1, *d*)

Material condition	Calculated density ρ_c, (kg/m^3))			Deviation factors, %	
	Max.	Min.	Average*	$\Delta\rho_1$	$\Delta\rho_2$
Ingot AD 31	–	–	2686.8	–	–
Ingot "Calmar"	–	–	2678.1	–	–
Briquettes made from chips of AD 31 alloy	2378.8	2153.1	2289.3	14.8 (85.2% of ingot ρ_c)	10.6
Briquettes made from chips of "Calmar" alloy	2454.7	2355.2	2395.2	9.5 (89.5% of ingot ρ_c)	4.1

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*Average for 7 briquettes.

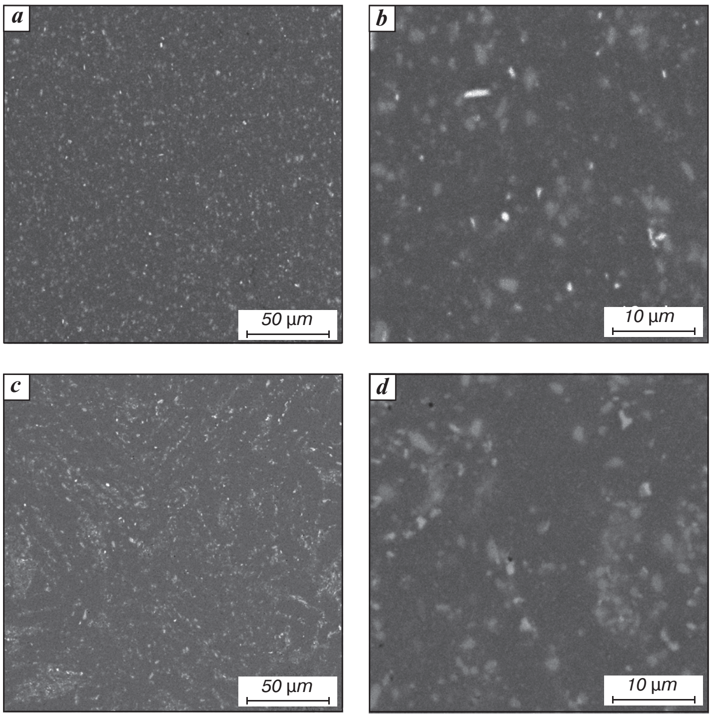

Fig. 4. Microstructure of “Calmar” alloy bars extruded from briquettes at 400 °C (*a*, *b*) and 450 °C (*c*, *d*), SEM

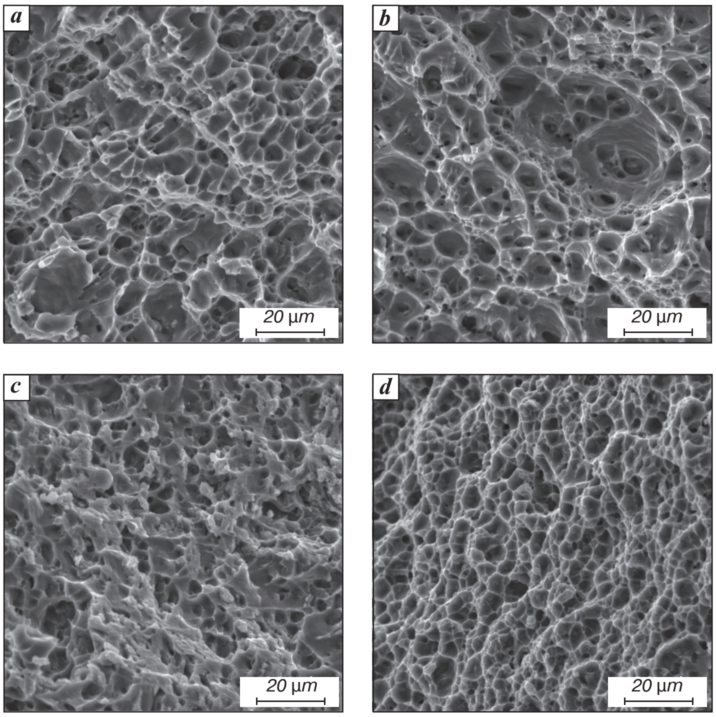

Fig. 5. Fractograms of tensile specimens of AD31 (*a*, *b*) and “Calmar” alloys (*c*, *d*) extruded from briquettes at 400 °C (*a*, *c*) and 450 °C (see Table 3), SEM

“Calmar” alloy, the difference is very significant, which can be seen when comparing the microstructures shown in **Fig. 4**. It can be assumed that eutectic-type alloys are more promising for solid-phase consolidation than alloys with a low content of excess phases.

Table 3
Tensile properties of extruded bars, manufactured from briquett

Alloy	T^*, °C	UTS, MPa	El, %
AD 31	400	137	21.2
	450	117	8.8
	GOST 21488–2025**	>90	>15
“Calmar”	400	179	15.2
	450	152	18.9

*Temperature of extrusion.
**Without heat treatment [33].

The results of tensile tests of hot extruded bars demonstrate superior properties of the experimental alloy in comparison with the grade alloy at both temperatures **(Table 3)**. It should be noted that pressing at 400 °C leads to better mechanical properties for both alloys than pressing at 400 °C. This is consistent with the results of the work [32], which considered a similar method of solid-phase consolidation for obtaining bars from chips in relation to AA6082 alloy (an analogue of AD35). In this work, it was shown that pressing at 350 °C leads to better strength properties compared to pressing at 425 and 500 °C.

It should be noted that the mechanical properties of bars obtained from chips are not inferior to those of bars obtained from ingots of these alloys, at the same values of temperatures and experimental conditions. For the “Calmar” alloy, the UTS value of bars obtained from briquettes is 152–179 MPa, and the elongation is 15.2–18.2%. The corresponding values for bars obtained from an ingot are: UTS = 159–165 MPa, El = 9.6–14.7%. Fracture surfaces of the tensile specimens of both alloys indicate ductile fracture, which is characterized by uniformly distributed fine dimples **(Fig. 5)**.

Thus, the combination of a simplified processing route with increased heat resistance indicates the potential of using the non-heat-treatable alloy “Calmar” based on the Al – Ca – Mn system to produce extruded bars using conventional industrial equipment.

Conclusions

1. A comparative analysis of the microstructure and mechanical properties of extruded bars produced from chips by solid-phase consolidation was carried out using two aluminum alloys of different alloying systems: wthe AD31 alloy and the experimental “Calmar” alloy based on the Al – Ca – Mn system.

2. It was shown that under identical briquetting conditions, the calculated density of briquettes produced from

the "Calmar" alloy is closer to the calculated density of the ingot compared to the AD31 alloy: 89.5% vs. 85.2%.

3. It was established that direct extrusion of briquettes makes it possible to obtain defect-free bars with high strength and ductility, which are not inferior to those produced from ingots under similar conditions. For the "Calmar" alloy, the UTS is 152–179 MPa and the elongation is 15.2-18.2%.

4. The microstructure of bars produced from chips is characterized by a more favorable morphology of eutectic phases and their more uniform distribution compared to bars produced from ingots. This effect is especially pronounced in the experimental alloy, in which the volume fraction of such phases reaches about 10% (compared to about 2% in the AD31 alloy).

5. It was shown that the experimental "Calmar" alloy exhibits superior mechanical properties compared to the AD31 alloy. This indicates that eutectic-type alloys are more promising for solid-phase consolidation than alloys with a low content of secondary phases.

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