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STRUCTURE AND PROPERTIES EVOLUTION OF THE AL-CU-MG ALLOY DURING THE "TWIN-ROLL CASTING – HOT DEFORMATION – HEAT TREATMENT" TECHNOLOGICAL PROCESS

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Abstract. *The influence of hot deformation and heat treatment on the wide solidification range 2024 alloy twin-rolled cast sheet billets structure and properties evolution at all stages of the technological process was studied. The maximum strength at a reduction ε = 50 % (σ_B ≈ 450 MPa), and an increase in ductility with the degree of deformation (from 0–2 % in the cast state to 20–22 % after rolling and heat treatment) were established. The resulting mechanical properties of the 2024 alloy strip exceed existing analogs and standard requirements.*
Keywords: *Al-Cu-Mg alloy, Twin-roll casting, hot deformation, harderning, ageing.*

Introduction

In the conditions of highly competition in the metal products market, the priority direction of development for the metallurgical complex of Ukraine is the implementation of modern energy- and resource-efficient technologies.

A proven and economical technology for producing thin aluminium sheets directly from the melt [1–5] is twin-roll casting. This technology reduces capital costs, saves energy, and lowers operational expenses compared to traditional casting methods. The process works by feeding molten metal directly into the gap between two internally water-cooled rolls, where it solidifies and undergoes some hot deformation before emerging as a solid strip or sheet.

Twin-roll casting machines have been used for producing aluminium sheets from the melt for almost 50 years. However, aluminium alloys typically subjected to commercial twin-roll casting have a narrow solidification range, and the sheets are cast at a thickness of approximately 6 mm. The productivity of this process is relatively low, and the range of alloys that can be produced using this method is limited.

The analysis of publications

One of the most promising in this regard is the technology of strip casting-rolling, known as the "CASTRIP-process" [6, 7], for producing sheet blanks with a thickness ranging from 1 to 5 mm, which are immediately rolled into thin sheets. The strip casting of steel differs from traditional methods due to the peculiarities of the structure formation process. The rapid solidification of the melt ensures a uniform distribution of alloying elements and impurities in the solid solution, the formation of a fine-grained structure (the dendrite size decreases by up to 5 times), and also results in less pronounced metal contamination by non-metallic inclusions, high surface cleanliness, and increased mechanical properties [8, 9].

Therefore, expanding the possibilities of using strip casting for non-ferrous metals and alloys, establishing its hereditary influence on the regularities of structure formation and properties of products in subsequent rolling and heat treatment processes, represents an important scientific and practical task.

Data on the formation of structure and mechanical properties complex of low-alloy aluminum alloy EN AW-6082 during strip casting-rolling are known [10–12], however, information regarding the structure formation of more alloyed aluminum alloys, in particular 2024 with a wide solidification range, is limited. Also, there is a lack of data on the influence on the structure formation in 2024 of the complex "strip casting-rolling + hot rolling + heat treatment," which prevents obtaining products with significantly improved mechanical properties.

Thus, establishing the regularities of the complex treatment's influence "strip casting-rolling + hot rolling + heat treatment" with the aim of obtaining high-strength 2024 billets and sheets is relevant.

Objective and task formulation

Research object is the structure formation in wide solidification range aluminum alloy of 2024 type during the production of twin rolled strips after hot deformation by rolling, and subsequent heat treatment.

Objective is to improve the technological parameters to ensure a stable process of obtaining sheet blanks from wide solidification range 2024 aluminum alloy with increased mechanical properties.

Methodology and research results

The chemical composition of the investigated alloys is presented in Table 1.

The research was carried out on an experimental two-roll mill in the conditions of the FTIMA of the NASU. Casting (Table 2) was carried out on a two-roll mill with rollers diameter of 420 mm. The barrel length is 600 mm.

The cooling rate in the inter-roll gap was 10^3 °C/s. The developed technology differs in that the melt is poured into the casting bath with overheating of 10…20 °C from the liquidus temperature, which allows avoiding the leakage of liquid metal from the crystallizer rolls [13]. The level of the melt in the casting bath is maintained constant at the maximum level to ensure uniform sheet thickness.

For the investigation of the influence of hot rolling on the structure and mechanical properties of the alloy, samples were deformed on a four-roll mill with a working roller diameter of 90 mm and a barrel width of 200 mm. The rolling speed was 2 m/min. The preheating temperature before rolling for the alloy was 400 °C. The relative deformation ε per pass was approximately 30 %.

To determine the effect of heat treatment on the 2024 alloy structure formation after twin-roll casting, it underwent heat treatment in both the cast state and after hot deformation by rolling according to the following regimes:

Regime HT1: annealing at T=415°C for t=2 hours + cooling with the furnace to 150°C + further air cooling;

Regime HT2: heating at T=495°C for t=30 minutes + quenching in water + ageing at room temperature for more than 3 days;

Regime HT3: heating at T=495°C for t=30 minutes + quenching in water + ageing for one day in the furnace at T=120°C + air cooling.

At each stage of the technological process, the microstructure was studied, and the mechanical properties of the alloy were determined. The influence of technological parameters on the structure quantitative characteristics was analyzed: E – the intermetallic phases fraction; D – the intermetallic crystals size; A – the intermetallics shape parameter, defined as the ratio of the larger crystal size to the smaller one; R – the dendritic cells size; Ar – the dendritic cells shape parameter.

For the alloy's microstructure investigation, samples were etched with 0.1% HF for 10 seconds followed by rinsing in flowing water. The microstructure was studied using an AXIOVERT 200-MAT microscope.

To determine the mechanical characteristics, materials were tested for tensile strength on a universal testing machine UTM-100 according to ДСТУ EN 10002-1:2006.

The 2024 aluminum alloy microstructure in the cast state after twin-roll casting (Figure 1) is represented by dendrites of α-Al solid solution of various degrees of branching, the dendritic cells of which are more or less axisymmetric throughout the sample volume. Eutectics α-Al-θ($CuAl_2$)-S(Al_2CuMg)-Mg_2Si [14] are located in the interdendritic spaces (Figure 1a).

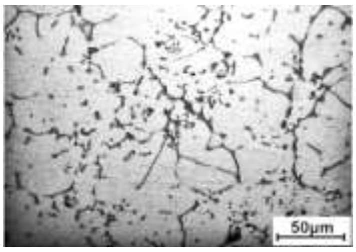
Processing the alloy according to the "strip casting + hot rolling" scheme changes its microstructure, which significantly depends on the degree of deformation. Plastic deformation during hot rolling with compression ε = 50 % leads to the primary α-Al crystals orientation in the rolling direction and a decrease in their size in the plane perpendicular to the sheet surface (Figure 1b). Increasing the compression degree to ε = 67.5–75% causes further deformation, intermetallics refinement, which are predominantly located along the boundaries of dendritic cells and are oriented in the rolling direction together with primary α-Al crystals. Intensification of these processes at ε = 87.5 % is accompanied by the formation of a band microstructure (Figure 1 c)

Table 1 – Chemical Composition of Investigated Alloy

Alloy		Alloy elements, % mass						
		Si	Fe	Cu	Mn	Mg	Cr	Zn
2024	Standart	< 0,5	< 0,5	**3,8–4,9**	0,3–0,9	1,2–1,8	<0,1	<0,25
	Experiment	0,36	0,45	**4,61**	0,72	0,94	-	-

Table 2 – Experimental Data on Casting Strips from Aluminum Alloys

Alloy	T casting, °C	Casting speed, m/s	Strip thickness, mm
2024	645	0,32	3,5
	650	0,50	2,2–2,5
	645	0,68	2,0



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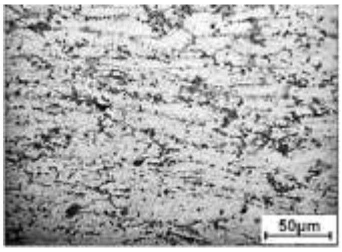

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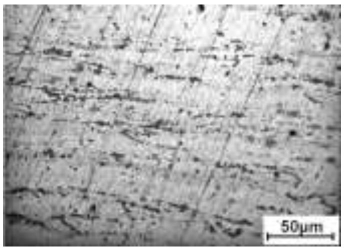
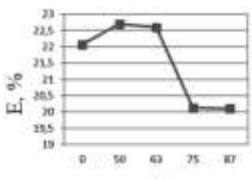


c

Fig. 1. Microstructure of 2024 alloy after twin-roll casting and hot deformation with different degrees of deformation: a – cast; b – ε = 50 %; c – ε = 87.5 %

This is due to the increase in the length of α-Al solid solution dendritic cells and their shape parameter (Fig. 2 c, d). At the same time, the reduction in size and increase in the volume intermetallics fraction (Fig. 2 a, b) are likely a result of partial dissolution during heating under rolling and during the rolling process itself.



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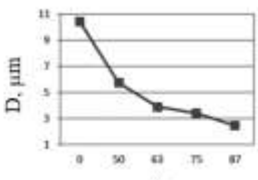

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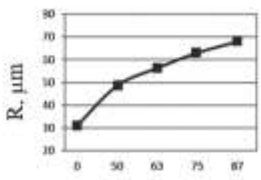

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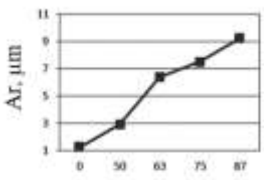
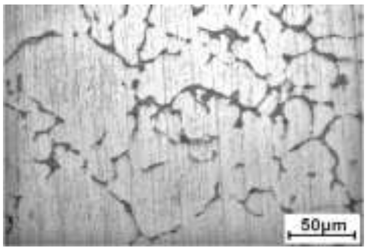


d

Fig. 2. Quantitative characteristics of the 2024 alloy specimens structure after strip twin-roll casting and hot rolling with various degrees of deformation

The microstructure of the alloy after twin-roll casting with subsequent heat treatment under various regimes is shown in Figure 3, and its quantitative characteristics are shown in Fig. 4. Compared to the cast state, annealing at T=415 °C for τ=2 hours leads to a decrease in the volume fraction and average size of intermetallic phase crystals (Fig. 3 a, b; Fig. 4 a, b). The size of α-Al dendritic cells slightly increases (Fig. 3 a, b; 4 c) with a slight decrease in their shape parameter (Fig. 4 d).



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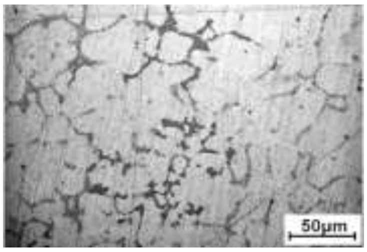

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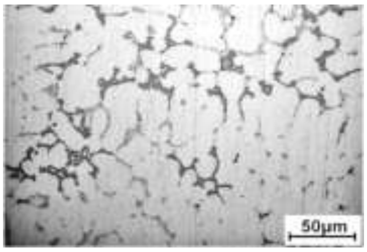

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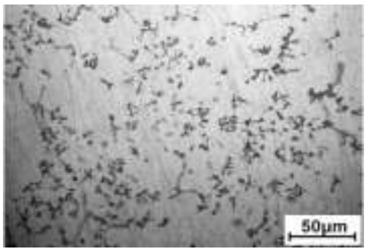


d

Fig. 3. Microstructure of 2024 alloy after twin-roll casting and heat treatment under different conditions: a – as-cast state; b – HT1 (heat treatment, regime 1); c – HT2: d – HT3

The microstructure of the alloy quenched from 495 °C and aged at room temperature (Fig. 3 c) is characterized by the presence of intermetallics with rounded growth forms, which can be explained by spheroidization and coagulation processes. Similar to annealing, quenching followed by aging at room temperature leads to a decrease in the intermetallics volume fraction and size (Fig. 4 a, b).

Presumably, in both cases, this is associated with their partial dissolution in the α-Al solid solution.

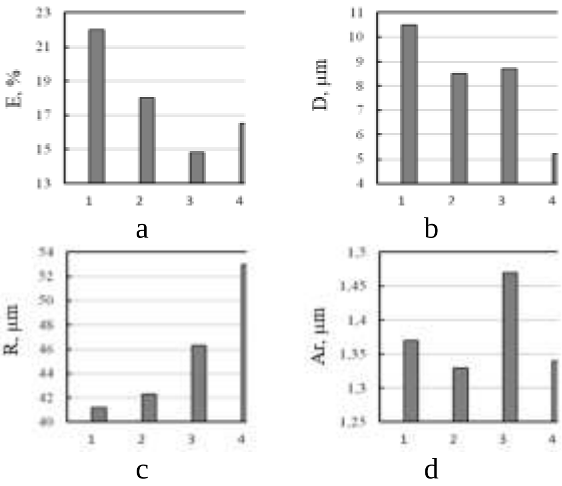


Fig. 4. 2024 alloy quantitative structure characteristics depending on technological factors according to the scheme "twin-roll casting + heat treatment": 1 – As-cast state; 2 – HT1; 3 – HT2; 4 – HT3

In the structure of the alloy, quenched from 495 °C and aged at 120 °C, along with a large number of fine-grained aging products, there are branched crystals of Mg_2Si phase with sizes up to 20 μm. These phases are located both along the boundaries of dendritic cells, which may indicate their crystallization genesis, and within the dendrite plane.

The latter is undoubtedly a result of the high-temperature aging process, during which not only the precipitation of this phase from the aluminum solid solution occurred but also its rather intense growth.

As for the as-cast state, the size of α-Al dendritic cells in the rolling direction monotonically increases from the annealed sample to the quenched one. The largest dendritic cell shape parameter is observed in the case of quenching from T=495 °C with subsequent aging at room temperature.

Investigations of the 2024 alloy structure in relation to the influence of technological factors in the " twin-roll casting + hot rolling (ε = 75 %) + heat treatment" technological process under the specified regimes showed that it consists of α-Al dendrites and intermetallics. These structural components are oriented in a plane parallel to the direction of hot rolling. The intermetallics are fragmented (Fig. 5).

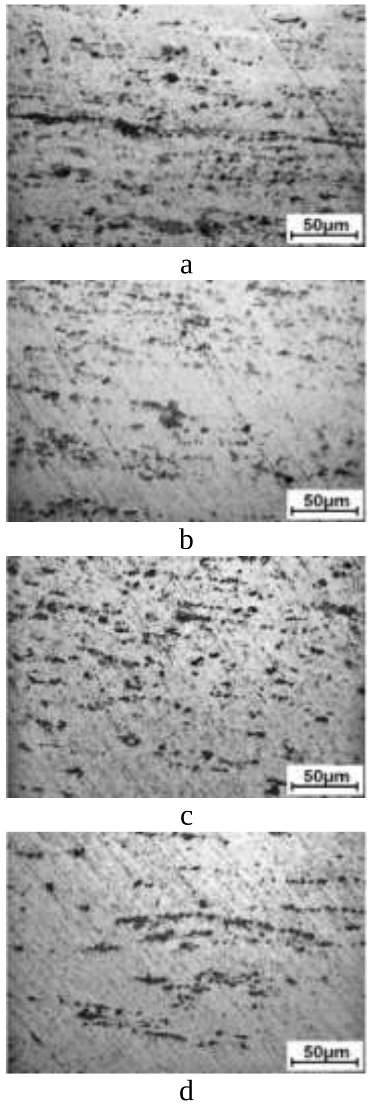


Fig. 5. Microstructure of 2024 alloy depending on the influence of technological factors in the " twin-roll casting + hot rolling (ε = 75 %) + heat treatment": a – as-cast + hot rolling; b – as-cast + hot rolling + HT1; c – as-cast + hot rolling + HT2; d – as-cast + hot rolling + HT3

Heat treatment leads to partial α-Al recrystallization and intermetallics spheroidization, indicated by rounded boundaries between intermetallics and α-Al.

The changes in the quantitative characteristics of the 2024 alloy structure due to the action of technological factors in the " twin-roll casting + hot rolling (ε = 75 %) + heat treatment under different regimes" are presented in Fig. 6.

These data indicate the following:

- the quantity of intermetallics decreases monotonically due to partial dissolution in the α-Al, and hot rolling promotes intermetallic phases fragmentation, stimulating their dissolution (Fig. 5 a, b);

- heat treatment after deformation contributes to the reduction in size and shape parameter of intermetallics, especially in the case of quenching followed by aging;

- the nature of the change in size and shape parameter of α-Al dendritic cells indicates a possible influence of recrystallization processes occurring during heating of the deformed alloy (Fig. 6 c, d).

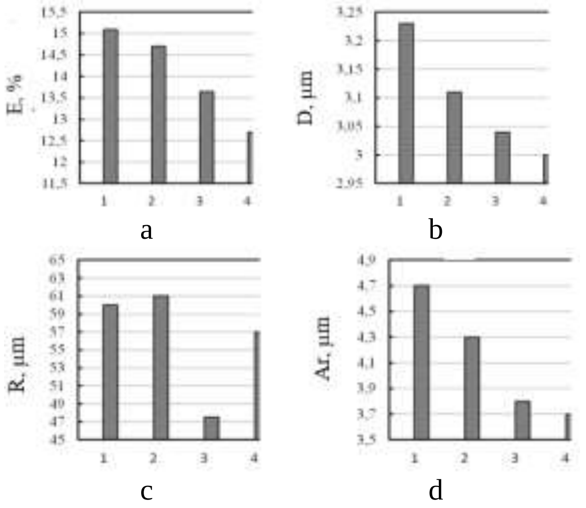


Fig. 6. Quantitative characteristics of the 2024 alloy structure, depending on technological factors in the "twin-roll casting + hot rolling + heat treatment" technological process: 1 – casting + hot rolling; 2 – HT1; 3 – HT2; 4 – HT3

The evolution of the 2024 alloy cast strip structure, which occurs under the influence of external technological factors, also affects the mechanical properties level (Fig. 7), namely the ultimate strength (σ_B) and relative elongation (δ) depending on the degree of compression $\sum_i = \frac{h_0}{h_i}$, where h_0 – is the cast strip thickness, h_i is the strip thickness after the *i-th* compression.

The data in Figure 7 indicate that the cast strip (Σ = 1.0) is characterized by low strength properties (σ_B) – 250±50 MPa and relative elongation (δ) – 0...2 %. Hot rolling leads to an increase in mechanical properties. The highest level is achieved at a compression of ε = 50 % (Σ = 2.0), after which the ultimate strength σ_B reaches its maximum value (≈ 450 MPa). This is probable due to the dissolution of intermetallic phases and, consequently, an increase in the saturation of the aluminum solid solution. At the same time, the ductility properties (δ) significantly increase with increasing degree of deformation, accompanied by a decrease in the size and shape parameter of both aluminum solid solution crystals and intermetallic phases, including secondary ones formed after the decomposition of the solid aluminum solution.

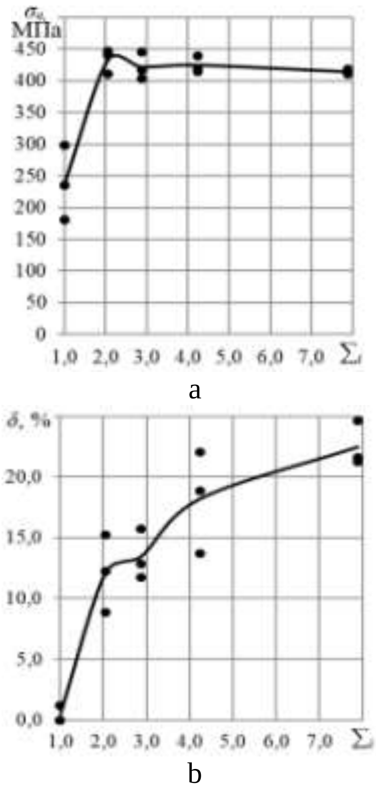
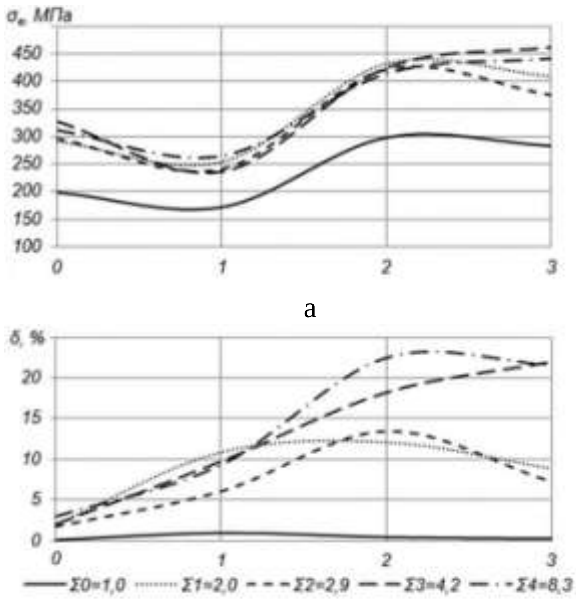


Fig. 7. Experimental data of the dependence of 2024 alloy strip ultimate strength σ_B (a) and relative elongation δ (b) on the compression degree *Σi* during hot rolling.

Heat treatment significantly affects the mechanical properties of the deformed strip (Fig. 8). The alloy achieves maximum relative elongation (δ = 20...22 %) after 6...8 compressions followed by quenching and natural aging at room temperature. The maximum ultimate strength (σ_B = 442...462 MPa) of the alloy after quenching is almost the same for both natural and artificial aging.

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

- at each stage of the technological process "twin-roll casting – hot rolling – heat treatment," significant changes occur in the structure of the cast strip;
- the strip structure evolution during twin-roll casting, hot rolling, and heat treatment leads to consistent changes in mechanical properties;
- hot rolling of strips obtained by the twin-roll casting method significantly increases their mechanical properties: the ultimate strength of the strip reaches a maximum (≈ 450 MPa) at a deformation degree of 50 % (Σ = 2); the relative elongation (δ=20...22 %) – with 6...8 compressions;
- the obtained mechanical properties of the 2024 alloy strip exceed existing analogs and are significantly higher than standard requirements.



b

Fig. 8. Effect of heat treatment regimes on ultimate strength (a) and relative elongation (b) of the 2024 alloy strip at different compression degrees *Σ:* 0 – after hot rolling; 1 – annealing; 2 – quenching with natural aging; 3 – quenching with artificial aging

Conclusions

The technological parameters for obtaining sheet blanks have been developed and tested on an experimental two-roll casting-rolling mill, allowing for the first time in metallurgical practice to obtain a cast strip with a thickness of 2–3 mm from 2024 aluminum alloy with a wide solidification range (130 °C).

The influence of hot deformation and heat treatment on the structure and properties of the obtained sheet blanks at each stage of the technological technological process "continuous casting – hot rolling – heat treatment" has been investigated:

- after casting-rolling, the structure of 2024 alloy consists of dendrites of α-Al solid solution of various branching degrees and intermetallic compounds;

- hot deformation by rolling results in the orientation of primary α-Al crystals in the rolling direction. Increasing the deformation degree to ε≥87.5 % leads to the formation of a banded structure, with the quantity of intermetallic compounds decreasing monotonically due to their partial dissolution in the solid solution;

- heat treatment (quenching with aging) after deformation contributes to a reduction in the size and shape parameter of intermetallic compounds. The nature of the changes in the size and shape parameter of dendritic α-Al crystals upon heating of 2024 alloy after its deformation indicates possible recrystallization processes.

The structure formation of the of the 2024 alloy cast strip under the influence of technological factors "continuous casting – hot rolling – heat treatment" significantly affects the level of mechanical properties (ultimate strength and relative elongation). The highest level of ultimate strength is achieved with a deformation of ε = 50 % (from σ_B ≈ 200 MPa in the cast state to σ_B ≈ 450 MPa). The relative elongation increases significantly with increasing degree of deformation (from δ = 0…2 % in the cast state to δ = 20…22 % after rolling and heat treatment), which is associated with a decrease in the size and shape parameter of α-Al solid solution and intermetallic phases. The obtained mechanical properties of the 2024 alloy strip exceed existing analogs and significantly exceed standard requirements.

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Еволюція структури та властивостей сплаву A-Cu-Mg під час технологічного процесу «розлив-прокатка – гаряча деформація – термічна обробка»

Анотація. Проблема. *Розлив-прокатка знижує капітальні витрати, економить енергію і зменшує експлуатаційні витрати порівняно з традиційними методами лиття. Проте алюмінієві сплави, що добувають методом розливу-прокатки, мають вузький інтервал кристалізації, що обмежує номенклатуру сплавів, які можна виробляти зазначеним методом. Наразі відсутня інформація про формування структури більш легованих алюмінієвих сплавів, зокрема сплаву 2024, який має широкий інтервал кристалізації. Також бракує інформації про вплив комплексу процесу "розлив-прокатка + гаряча прокатка + термічна обробка" на структуроутворення сплаву 2024, що ускладнює отримання продуктів із істотно покращеними механічними властивостями.*
Мета. *Установлення раціональних параметрів технологічного процесу "розлив-прокатка + гаряча прокатка + термічна обробка" для забезпечення стабільного отримання листових заготовок зі сплаву 2024 із широким інтервалом кристалізації та підвищеними механічними властивостями.*
Методологія. *Дослідження проводили на експериментальному двовалковому стані в умовах ФТІМС НАН України. Для вивчення впливу гарячої прокатки на структуру та механічні властивості сплаву зразки деформували на чотирициліндровому стані зі швидкістю прокатки 2 м/хв і температурою попереднього нагріву 400 °С. Для визначення впливу термічної обробки на формування структури сплаву 2024 після розливу-прокатки та гарячої деформації прокаткою було проведено термічну обробку за різними режимами. Мікроструктуру сплаву 2024 досліджували за допомогою оптичного мікроскопа AXIOVERT 200-MAT. Для визначення механічних характеристик матеріали випробовували на розтягнення на універсальній випробувальній машині UTM-100 згідно з ДСТУ EN 10002-1:2006.*
Результати. *Установлення закономірностей впливу параметрів обробки в технологічному процесі «розлив-прокатка – гаряча деформація – термічна обробка» на структуру та властивості експериментального сплаву системи Al-Cu-Mg дало змогу досягти значного одночасного підвищення міцності (від $\sigma_B \approx 200$ МПа у литому стані до $\sigma_B \approx 450$ МПа) та пластичності (від $\delta = 0…2$ % у литому стані до $\delta = 20…22$ % після прокатки та термічної обробки).*
Новизна. *Уперше в металургійній практиці отримано литу стрічку зі сплаву 2024 завтовшки 2 мм з широким інтервалом кристалізації 130 °С.*
Практичне значення. *Механічні властивості стрічки зі сплаву 2024 перевищують наявні аналоги та значно перевершують вимоги стандарту. Матеріал може бути використаний в автомобільній, ракетобудівній та суднобудівній промисловості для високовідповідальних виробів завдяки підвищеній стійкості до руйнування, високій міцності та пластичності.*
Ключові слова: *сплав Al-Cu-Mg, розлив-прокатка, гаряча деформація, зміцнення, старіння*.

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