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Research article
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Effect of rotary forging on the structure and mechanical properties of two eutectic alloys of the Al–La and Al–Ca–La systems

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Abstract: Recently developed aluminum alloys based on the eutectic composition of the Al–Ca system exhibit excellent casting properties and, unlike silumins, show good deformability. The development of multi-component alloys, where calcium is partially replaced by lanthanum, cerium, nickel, and other eutectic-forming elements, improves their properties by producing a finer eutectic structure and enhancing their heat resistance. These alloys can all be strengthened through deformation, with severe plastic deformations being especially effective. Among these methods, rotary forging is of particular interest due to its ability to produce long billets. Lanthanum, at a specific concentration, significantly improves the alloy's plasticity, making the Al–La system particularly well-suited for deformation processing. This study investigates the effect of rotary forging on the microstructure and mechanical properties of two eutectic alloys, Al–10La and Al–6Ca–3La (wt. %). Billets in the as-cast state were rotary forged from an initial diameter of 20 mm to a final nominal diameter of 5 mm under isothermal conditions: at room temperature for the Al–10La alloy and at 200 °C for the Al–6Ca–3La alloy. The results showed that rotary forging led to an elongated structure in both alloys, with micron-sized grains forming inside the dendrites and eutectic particles being refined. In the Al–10La alloy, the dislocation density was low, while in the Al–6Ca–3La alloy, the dislocation density was higher. The Al–10La alloy showed a slight tendency to soften during rotary forging, whereas the Al–6Ca–3La alloy exhibited a marked tendency to strengthen (its strength doubled). Both alloys retained high plasticity (elongation) after forging. After annealing at 300 °C, the strength of both alloys remained stable. The tensile strength of the Al–6Ca–3La alloy at 300 °C was higher than that of the Al–10La alloy, with values of 53 MPa and 44 MPa, respectively.

Keywords: aluminum alloy, rotary forging, microstructure, mechanical properties.

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Влияние ротационной ковки на структуру и механические свойства двух эвтектических сплавов систем Al–La и Al–Ca–La

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Аннотация: Разработанные в последние годы алюминиевые сплавы на основе эвтектики системы алюминий–кальций обладают превосходными литейными свойствами и, в отличие от силуминов, хорошо деформируются. Создание многокомпонентных сплавов, в которых кальций частично замещен лантаном, церием, никелем и другими эвтектикообразующими элементами, позволяет улучшать свойства сплавов за счет формирования более дисперсной эвтектики, а также повышать их теплостойкость. Все перечисленные сплавы можно упрочнять деформационными методами, при этом особенно эффективны методы больших пластических деформаций. Среди них ротационная ковка представляет наибольший интерес ввиду возможности получения длинномерных заготовок. Лантан в определенной концентрации эффективно повышает пластичность, поэтому сплав системы Al–La является наиболее подходящим для деформационной обработки. Было изучено влияние ротационной ковки на микроструктуру и механические свойства двух эвтектических сплавов: Al–10La и Al–6Ca–3La (мас. %). Ротационную ковку заготовок в исходно литом состоянии с начального диаметра 20 мм на конечный номинальный диаметр 5 мм осуществляли в изотермических условиях: для сплава Al–10La – при комнатной температуре, а для сплава Al–6Ca–3La – при $t = 200$ °C. Установлено, что в результате ротационной ковки структура обоих сплавов становится вытянутой, внутри дендритов формируются зерна микронного размера, а частицы эвтектики измельчаются. При этом в сплаве Al–10La наблюдается низкая плотность дислокаций, в то время как в сплаве Al–6Ca–3La – повышенная. Сплав Al–10La склонен к небольшому разупрочнению в условиях ротационной ковки, в отличие от сплава Al–6Ca–3La, который проявляет заметную тенденцию к деформационному упрочнению (прочность увеличивается в 2 раза); при этом оба сплава в состоянии после ковки сохраняют высокую пластичность (относительное удлинение). Уровень прочности обоих сплавов сохраняется после отжига при $t = 300$ °C. Предел прочности сплава Al–6Ca–3La при температуре испытания 300 °C выше в сравнении со сплавом Al–10La – соответственно 53 и 44 МПа.

Ключевые слова: алюминиевый сплав, ротационная ковка, микроструктура, механические свойства.

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Introduction

Aluminum alloys based on the Al—Me eutectic system (where Me = Ca, Ce, La, Ni, Fe) feature a composite structure comprising an aluminum matrix and eutectic phases. These alloys exhibit excellent casting properties and good deformability [1—6]. Additionally, alloys such as Al—La, Al—Ce, Al—Ni, and, in some cases, Al—Fe demonstrate enhanced heat resistance [7; 8]. While these alloys have similar strength levels, their plasticity varies significantly, as it directly depends on the composition of the eutectic. Lanthanum, in certain concentrations, effectively increases plasticity [9], making the Al—La system particularly suitable for deformation processing. The elongation at fracture for the eutectic composition of Al—10La (wt. %) is approximately 22 % [9]. However, increasing the lanthanum content beyond this level reduces plasticity [10]. A drawback of lanthanum is its high cost. On the other hand, among the alloys mentioned above, Al—Ca alloys are the most cost-effective. Therefore, the use of small amounts of lanthanum in complex eutectic compositions, such as Al—Ca—La-based alloys, is of interest. Complex eutectics have been studied in several works [11—13].

All these alloys can be effectively strengthened using both traditional deformation methods, such as rolling, and severe plastic deformation techniques [6; 9; 11; 14—16]. Among these techniques, rotary forging stands out due to its ability to achieve high deformation levels while also enabling the production of long billets [17—19].

Building on this, the present study examines the effect of lanthanum in the eutectic composition on the strength and plasticity of the Al—6%Ca—3%La aluminum alloy under rotary forging conditions. For comparison, the eutectic alloy Al—10%La was selected as a reference.

Materials and methods

Two alloys near the eutectic composition, Al—6Ca—3La and Al—10La (wt. %), were studied. Castings with a length of 200 mm and a diameter of 22 mm were turned on a lathe to a final diameter of 20 mm and then subjected to rotary forging. The as-cast billets were forged to a final nominal diameter of 5 mm using a rotary forging machine (RKM1, model V2129.01) in multiple passes, with the reduction per pass ranging from 5 % to 22 % (averaging 13 %). Before each pass, billets of the Al—6Ca—3La alloy were heated to 200 °C in an electric-tube furnace and held at this temperature for 10—15 min, whereas billets of the Al—10La alloy were forged without preheating. For larger diameters (greater than 10 mm), the billets were fed manually, while for subsequent passes, automatic roller feeding was employed. This ensured billet alignment and more uniform deformation distribution along the billet's length. The final diameters of the Al—6Ca—3La and Al—10La alloy billets were 5.5 mm and 5.4 mm, respectively, corresponding to an equivalent strain of $e = 2.6$.

The characterization of the specimens was carried out using transmission electron microscopy (TEM) (JEM-1400 and JEM-2100 microscopes, JEOL, Japan), Vickers microhardness measurements (Micromet 5101, Buehler, USA), and tensile testing. Two types of specimens were prepared for tensile tests: cylindrical specimens with a gauge section of $\varnothing 4\times10$ mm and flat specimens with a gauge section of $5\times1{,}5\times1$ mm. Tensile tests at room temperature were conducted on both cylindrical and flat specimens using Instron 5569 and Instron 5966 testing machines (Instron Corp., USA), respectively. Tests at 300 °C were performed exclusively on cylindrical specimens using an Instron 3382 machine. The strain rate during tensile testing was maintained at 0.002 s^{-1}.

Research results

The as-cast Al—10La alloy exhibited a predominantly eutectic structure [(Al) + $Al_{11}La_3$] with a small fraction of aluminum dendrites (Fig. 1, *a*). As a result of rotary forging, the structural elements of the alloy were elongated along the billet axis. Additionally, ultrafine grains smaller than 1 μm were formed within the dendrites (indicated by arrows in Fig. 2, *a*), and the eutectic particles were fragmented into pieces approximately 100—200 nm in length due to cleavage. This is evidenced by the flat boundary between two fragmented particles (Fig. 2, *b*). Evidently, in certain areas of the structure, mixing of dendrites and eutectic phases occurs as a result of mass transfer. TEM images show that the dislocation density in the alloy is low.

The difference in the microstructure of the as-cast Al—6Ca—3La alloy compared to the Al—10La alloy lies in the presence of shorter and wider eutectic particles (Fig. 1, *b*). According to [20], the Al—Ca—La system forms a ternary eutectic [(Al)+Al_4(Ca,La) + + Al_{11}(La,Ca)$_3$]. During rotary forging of the Al—6Ca—3La alloy, similar to the Al—10La alloy, mixing

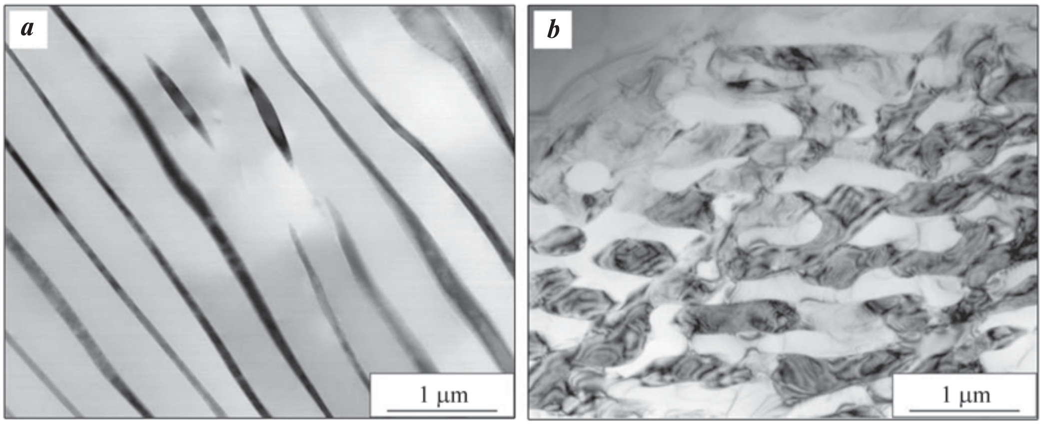

Fig. 1. Microstructure of the as-cast Al–10La (***a***) and Al – 6Ca – 3La (***b***) alloys (bright-field TEM images)

Рис. 1. Микроструктура сплавов Al–10La (***a***) и Al–6Ca–3La (***b***) в литом состоянии (светлопольные изображения ПЭМ)

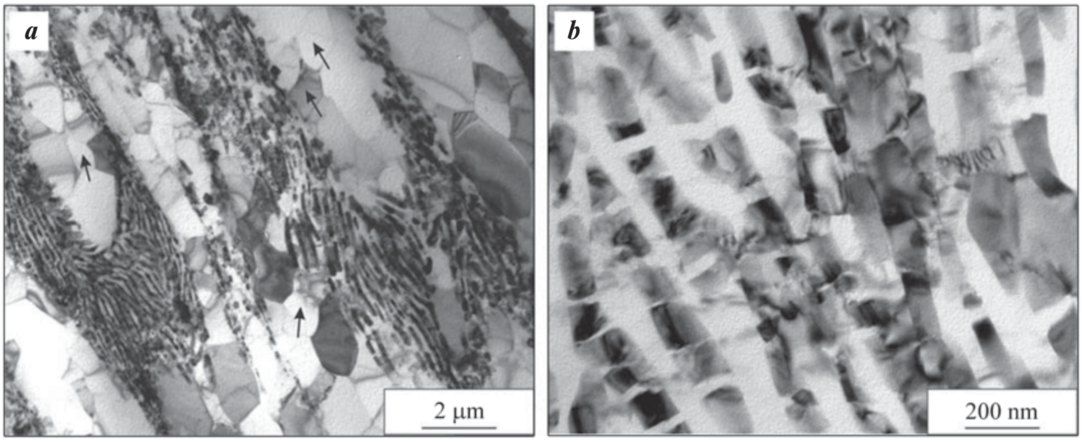

Fig. 2. Microstructure of the Al–10La alloy after rotary forging (bright-fields TEM images)

Рис. 2. Микроструктура сплава Al–10La после ротационной ковки (светлопольные изображения ПЭМ)

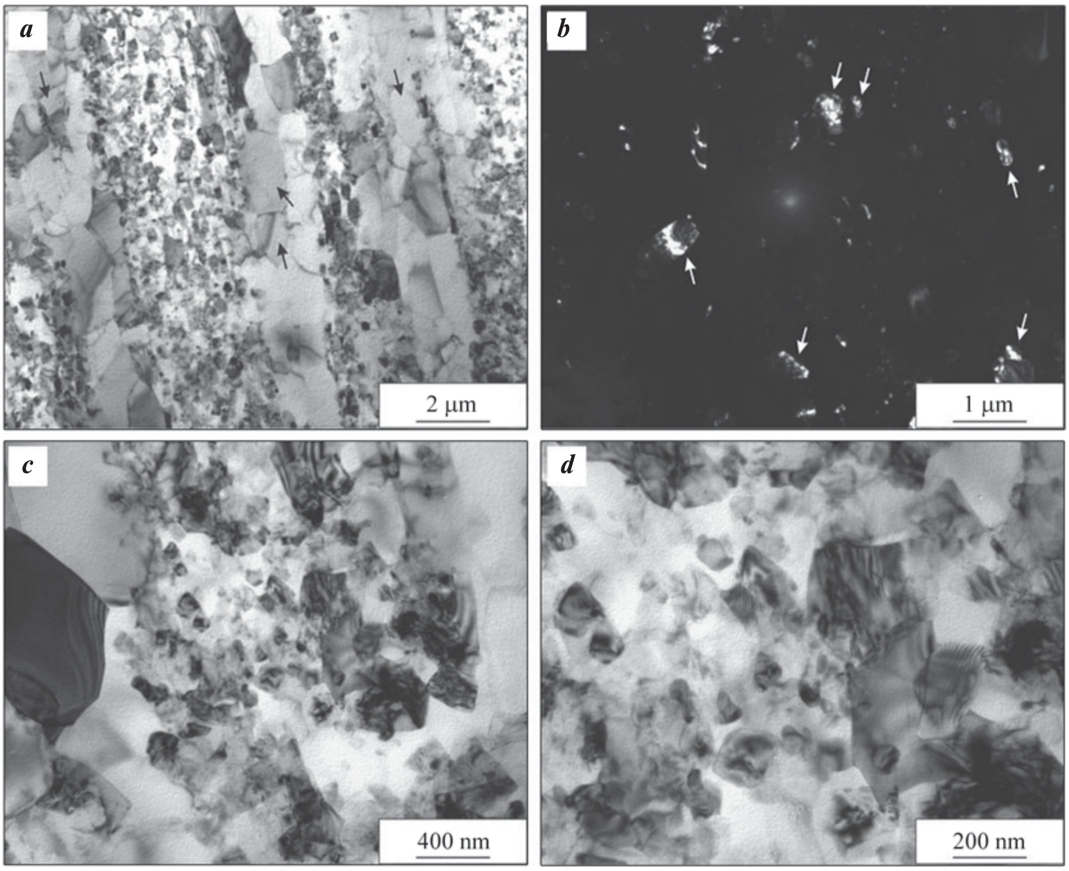

Fig. 3. Microstructure of the Al–6Ca–3La alloy after rotary forging
a, ***c***, ***d*** – bright-field TEM images; ***b*** – dark-field TEM image in (Al) reflections

Рис. 3. Микроструктура сплава Al–6Ca–3La после ротационной ковки
a, ***c***, ***d*** – светлопольные изображения ПЭМ; ***b*** – темнопольное изображение ПЭМ в рефлексах (Al)

of dendrites and eutectic phases occurs, the structural elements become elongated, and ultrafine grains form within the dendrites (indicated by arrows in Fig. 3, *a*, *b*). The eutectic particles are fragmented to a greater extent, reaching sizes of 50—100 nm, with evidence of diffusion processes indicated by the rounded shapes of the fragmented particles (Fig. 3, *c*, *d*). The former eutectic structure exhibits a higher dislocation density, as reflected by the characteristic contrast in the TEM images.

The mechanical properties of the aluminum alloys in as-cast and forged conditions, obtained at room temperature, are presented in Table 1. The yield strength ($\sigma_{0.2}$) and ultimate tensile strength (σ_u) of the as-cast Al—10La alloy were 113 MPa and 173 MPa, respectively, with a total elongation (δ) ~22 %. For the as-cast Al—6Ca—3La alloy, the values were $\sigma_{0.2}$ = 109 MPa, σ_u = 194 MPa, and δ = 20 %.

Typical tensile curves obtained during testing of cylindrical specimens of forged alloys are shown in Fig. 4. The main difference between testing flat and cylindrical specimens of the Al—10La alloy is the significantly higher elongation of the latter (by a factor of 2, as shown in Table 1). In contrast, for the Al—6Ca—3La alloy, the difference in mechanical properties between cylindrical and flat specimens is negligible (Table 1).

After rotary forging of the Al—10La alloy, its yield strength remains unchanged or increases by no more than 10 %, while its ultimate tensile strength decreases by 18 %. At the same time, the total elongation increases slightly (Table 1). Additionally, the shape of the tensile curve changes: the uniform plastic deformation region (up to necking) decreases significantly, from 8 % to 1.5 %. As a result, nearly all of the specimen's elongation occurs in the localized deformation region (Fig. 4, *a*).

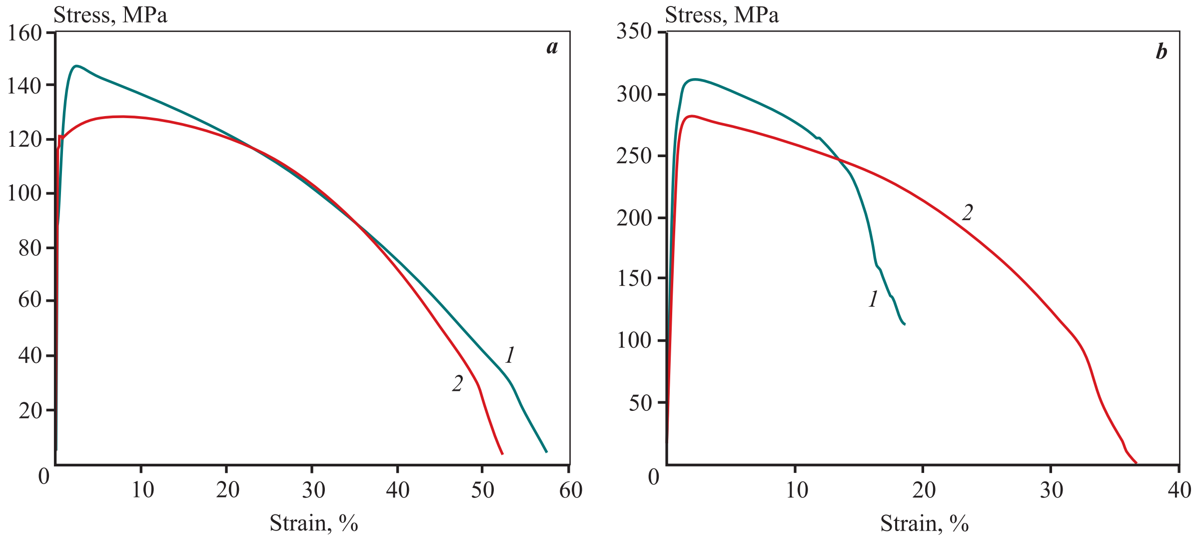

Fig. 4. Tensile curves at room temperature for specimens of Al–10La (***a***) and Al–6Ca–3La (***b***) alloys after rotary forging (***1***) and after subsequent annealing at *t* = 300 °C (***2***)

Рис. 4. Кривые растяжения при комнатной температуре образцов сплавов Al–10La (***a***) и Al–6Ca–3La (***b***) после ротационной ковки (***1***) и последующего отжига при *t* = 300 °C (***2***)

Table 1. **Mechanical properties of aluminum alloys in various conditions at room temperature**

Таблица 1. Механические свойства алюминиевых сплавов в различных состояниях при комнатной температуре

Alloy	Material condition	Specimen type	$\sigma_{0.2}$, MPa	σ_u, MPa	δ, %	δ_u, %
Al–10La	As-cast	Flat	113 ± 2	173 ± 3	22 ± 1	8 ± 1
	RF*	Flat	126 ± 3	142 ± 1	27 ± 2	1.5 ± 0.5
		Cylindrical	101 ± 2	147 ± 3	58 ± 2	2.5 ± 0.5
	RF + annealing at 300 °C	Cylindrical	123 ± 2	131 ± 2	52 ± 2	8 ± 1
Al–6Ca–3La	As-cast	Flat	109 ± 2	194 ± 3	19.5 ± 1.3	8.5 ± 0.5
	RF	Flat	252 ± 4	303 ± 3	23.5 ± 0.5	2.5 ± 0.3
		Cylindrical	285 ± 3	312 ± 6	21.6 ± 1.5	3.0 ± 0.5
	RF + annealing at 300 °C	Cylindrical	250 ± 6	283 ± 6	37 ± 2	2.0 ± 0.5

* RF – rotary forging.

In the case of the Al—6Ca—3La alloy, rotary forging results in a 2.3-fold increase in its yield strength and a 1.6-fold increase in its ultimate tensile strength, while the total elongation increases only slightly, from 19 % to 23 % (Table 1). However, the uniform elongation of the forged specimen also decreases, from 8.5 % to 2.5 % (Fig. 4, *b*).

The tensile test results correlate well with the measured microhardness values (Fig. 5). The average microhardness of the as-cast Al—10La and Al—6Ca—3La alloys was 52 ± 2 HV and 58 ± 1 HV, respectively. After rotary forging, the microhardness decreased to 42 ± 1 HV (softening) for Al—10La and increased to 82 ± 2 HV (strengthening) for Al—6Ca—3La. The microhardness was uniformly distributed across the cross-section of the billets for both alloys.

Annealing of specimens of both alloys at 300 °C for 1 h reduces their strength by no more than 10 % (see Table 1 and Fig. 4). For the Al—10La alloy, the total elongation remains essentially unchanged, but the uniform deformation increases significantly (up to 8 %). Conversely, for the Al—6Ca—3La alloy, the total elongation increases to 37 %, while the uniform deformation remains unchanged. The retention of a high combination of mechanical properties in both alloys after annealing at 300 °C demonstrates their high thermal stability.

Table 2 presents the mechanical properties of the forged aluminum alloys tested at 300 °C, and Fig. 6 shows the corresponding tensile curves. Increasing the test temperature from room temperature to 300 °C causes significant softening in both alloys. For

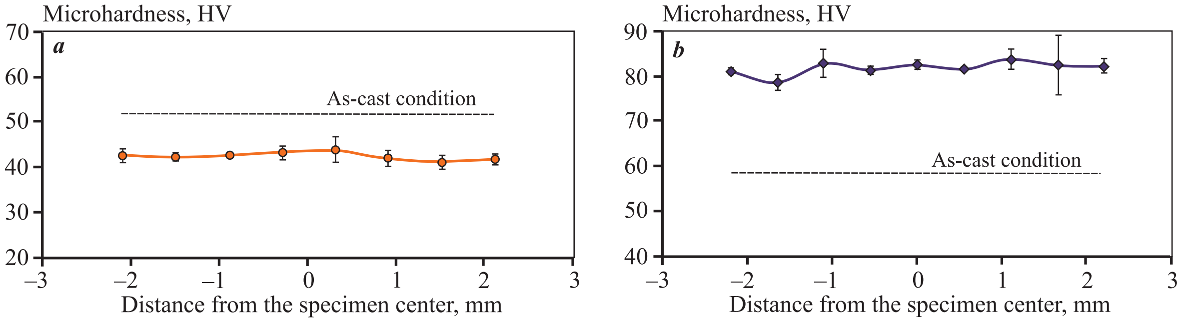

Fig. 5. Microhardness distribution across the cross-section of specimens of Al–10La (***a***) and Al–6Ca–3La (***b***) alloys before and after rotary forging

Рис. 5. Распределение микротвердости в поперечном сечении образцов сплавов Al–10La (***a***) и Al–6Ca–3La (***b***) до и после ротационной ковки

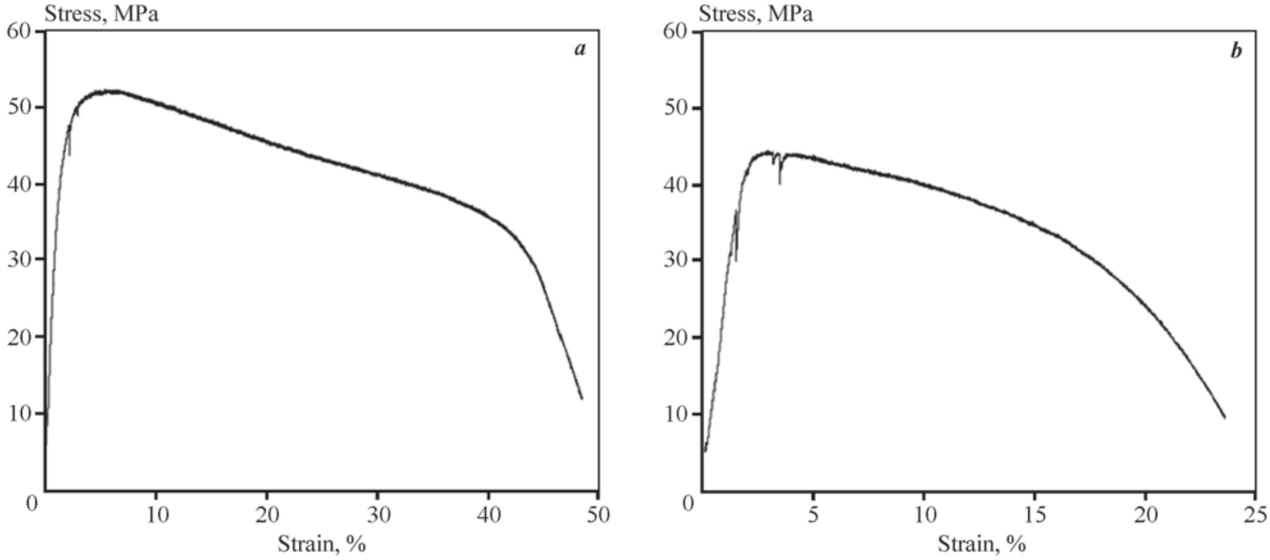

Fig. 6. Tensile curves at a test temperature of 300 °C for forged Al–6Ca–3La (***a***) and Al–10La (***b***) alloys

Рис. 6. Кривые растяжения при температуре испытания 300 °C кованых сплавов Al–6Ca–3La (***a***) и Al–10La (***b***)

Table 2. **Mechanical properties of forged aluminum alloys at a test temperature of 300 °C**

Таблица 2. Механические свойства кованых алюминиевых сплавов при температуре испытания 300 °C

Alloy	Specimen type	$\sigma_{0.2}$, MPa	σ_u, MPa	δ, %
Al–10La	Cylindrical	34 ± 1	44 ± 1	22.9 ± 0.5
Al–6Ca–3La	Cylindrical	36 ± 1	53 ± 1	47.7 ± 0.5

the Al—10La alloy, the yield strength and ultimate tensile strength decrease to 34 MPa and 44 MPa, respectively, which is a 3-fold reduction, while the total elongation decreases by a factor of 2.5. For the Al—6Ca—3La alloy, the yield strength and ultimate tensile strength decrease to 36 MPa and 53 MPa, respectively, representing reductions by factors of 8 and 6. However, the total elongation, in contrast, doubles. This level of strength is comparable to D18 or AMts alloys and slightly lower than AMg2 alloy. Despite undergoing more intense softening, the Al—6Ca—3La alloy exhibits slightly higher strength at a test temperature of 300 °C compared to the Al—10La alloy.

Discussion of results

According to the microhardness measurements and tensile test results, the Al—10La alloy exhibits slight softening under rotary forging conditions, in contrast to the Al—6Ca—3La alloy, which demonstrates a significant tendency for deformation strengthening. Additionally, in both alloys, uniform deformation (up to necking) decreases after deformation processing, while total elongation to fracture increases. The low strength of the Al—10La alloy after rotary forging, comparable to its as-cast condition, is supported by the low dislocation density observed in its microstructure (see Fig. 2, *a*), which may be attributed to recovery processes. On the other hand, the low dislocation density in the alloy's structure contributes to its high plasticity. Previous studies have shown that eutectic $Al_{11}La_3$ particles, due to their specific crystallographic relationship with the aluminum matrix, are easily cut by dislocations [9], which also positively affects plasticity. Interestingly, despite the low dislocation density in its structure, the uniform deformation of the Al—10La alloy is only about 2 %, with elongation mainly occurring in the localized deformation region, i.e., after necking begins.

In contrast, the Al—6Ca—3La alloy accumulates a high dislocation density and undergoes significant eutectic particle refinement as a result of rotary forging, leading to a substantial increase in strength. Despite its high strength, the alloy also retains high plasticity (with elongation primarily occurring in the localized deformation region, similar to the Al—10La alloy). This behavior may be attributed to the presence of ultrafine aluminum grains (which, being defect-free, form layers between the former eutectic, see Fig. 3, *a*) that promote stress relaxation, as well as the positive effect of lanthanum in the complex eutectic on dislocation slip processes.

Conclusion

Rotary forging was performed on billets of the eutectic aluminum alloys Al—10La and Al—6Ca—3La in the as-cast condition, reducing their initial nominal diameter of 20 mm to a final nominal diameter of 5 mm. It was found that as a result of forging, the structure of both alloys becomes aligned along the billet axis, with new ultrafine grains (less than 1 μm) forming within the dendrites and eutectic particles becoming refined (to 100—200 nm in the Al—10La alloy and 50—100 nm in the Al—6Ca—3La alloy). In the Al—10La alloy, a low dislocation density was observed, while the Al—6Ca—3La alloy exhibited a high dislocation density. The structural changes in the alloys significantly affect their mechanical properties: the Al—10La alloy undergoes slight softening under rotary forging, while the Al—6Ca—3La alloy exhibits a pronounced tendency for deformation strengthening, with its strength doubling. The ultimate tensile strength of the forged Al—10La and Al—6Ca—3La alloys was approximately 150 MPa and 300 MPa, respectively. Both alloys retained high plasticity after forging, with total elongation exceeding 20 %. The strength of both alloys remained stable after annealing at 300 °C. At a test temperature of 300 °C, the ultimate tensile strength of the Al—6Ca—3La alloy slightly exceeded that of the Al—10La alloy, at 53 MPa and 44 MPa, respectively.

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