PHYSICAL METALLURGY AND HEAT TREATMENT / МЕТАЛЛОВЕДЕНИЕ И ТЕРМИЧЕСКАЯ ОБРАБОТКА

UDC 669.017
https://doi.org/10.17073/0021-3438-2023-2-49-56

Research article
Научная статья

Mechanical properties and electrical conductivity of Al–Y–Sc–Er cold worked alloy

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Abstract: Aluminum alloys alloyed with rare earth and transition metal are promising materials for electric energy transportation due to their high properties of strength, thermal stability, and electrical conductivity. The features of strengthening, their mechanical properties and electrical conductivity of Al–0.2Y–0.2Sc–0.3Er alloy after cold rolling have been established. The alloy as a cast structure is presented by aluminum solid solution (Al) and dispersed eutectics with τ_2 ($Al_{75-76}Er_{11-17}Y_{7-14}$) phase upon complete dissolution of scandium in (Al), and a content of yttrium and erbium at the level of 0.2–0.3 % each. Cold rolling the ingot accelerates strengthening upon annealing at 270 and 300 °C, reducing the time of achieving peak hardness. The maximum strengthening due to precipitation of $L1_2$ dispersoid of Al_3(Sc,Y,Er) phase with the average particle size up to 10 nm is achieved after 7 h of annealing at 300 °C after cold rolling. This shows the prevailing heterogeneous mechanism of nucleation due to defects accumulated during cold rolling which stimulates strengthening. The eutectic particles are located mainly along the boundaries, elongated in the rolling direction. Irrespective of the mode of sheet fabrication, the alloy demonstrates high thermal stability up to 400 °C. During annealing of the sheets to 450 °C, their non-recrystallized structure is retained. Ingot annealing at t = 300 °C in 7 h and cold rolling with subsequent annealing under the same conditions provide a high level of mechanical properties and electrical conductivity: $\sigma_{0.2}$ = 194 MPa, σ_u = 210 MPa, δ = 12.1 % and IACS – 60,1 %. The alloy has demonstrated high yield stress up to 100 h of annealing at t = 300 °C.

Keywords: aluminum alloys, scandium, yttrium, recrystallization, mechanical properties, electrical conductivity

Acknowledgments: This work was supported by the grants НШ-1752.2022.4 and МК 3457.2022.4.

For citation: Gorlov L.E., Glavatskikh M.V., Barkov R.Yu., Pozdniakov A.V. Mechanical properties and electrical conductivity of Al–Y–Sc–Er cold worked alloy. *Izvestiya. Non-Ferrous Metallurgy*. 2023;29(2):49–56. https://doi.org/10.17073/0021-3438-2023-2-49-56

Механические свойства и электропроводность холоднодеформированного сплава Al–Y–Sc–Er

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Аннотация: Алюминиевые сплавы, легированные редкоземельными и переходными металлами, являются перспективными материалами для транспортировки электроэнергии ввиду высоких показателей прочности, термической стабильности и электропроводности. В работе определены особенности упрочнения, механические свойства и электропроводность сплава

Al–0,2Y–0,2Sc–0,3Er после холодной прокатки. Литая структура сплава представлена алюминиевым твердым раствором (Al) и дисперсной эвтектикой с фазой τ_2 ($Al_{75-76}Er_{11-17}Y_{7-14}$) при полном растворении скандия в (Al) и содержании иттрия и эрбия на уровне 0,2–0,3 % каждого. Холодная прокатка слитка ускоряет упрочнение при отжиге при температурах 270 и 300 °С, уменьшая время достижения пиковой твердости. Максимальное упрочнение за счет выделения $L1_2$-дисперсоидов фазы Al_3(Sc,Y,Er) со средним размером частиц до 10 нм достигается после 7 ч отжига при температуре 300 °С после холодной прокатки, что говорит о превалировании гетерогенного механизма зарождения за счет дефектов, накопленных в процессе холодной прокатки, стимулирующих упрочнение. Частицы эвтектики располагаются преимущественно вдоль границ, вытягиваясь в направлении прокатки, и вне зависимости от режима получения листа сплав демонстрирует высокую термическую стабильность до 400 °С. В процессе отжига листов до 450 °С сохраняется нерекристаллизованная структура. Отжиг слитка при t = 300 °С в течение 7 ч и холодная прокатка с последующим отжигом в тех же условиях обеспечивают высокий уровень механических свойств и электропроводности: $\sigma_{0,2}$ = 194 МПа, $\sigma_в$ = 210 МПа, δ = 12,1 % и IACS – 60,1 %. Сплав продемонстрировал высокую стабильность предела текучести вплоть до 100 ч отжига при t = 300 °С.

Ключевые слова: алюминиевые сплавы, скандий, иттрий, рекристаллизация, механические свойства, электропроводность

Благодарности: Работа выполнена при финансовой поддержке грантов НШ-1752.2022.4 и МК 3457.2022.4.

Для цитирования: Горлов Л.Е., Главатских М.В., Барков Р.Ю., Поздняков А.В. Механические свойства и электропроводность холоднодеформированного сплава Al–Y–Sc–Er. *Известия вузов. Цветная металлургия.* 2023;29(2):49–56.
https://doi.org/10.17073/0021-3438-2023-2-49-56

Introduction

Strengthening Al—Sc alloys during annealing of ingots provides formation of structured $L1_2$ dispersoids [1—11]. Additional doping with zirconium leads to an increase in thermal stability of the precipitates due to formation of $L1_2$ dispersoids of $Al_3(Sc_xZr_y)$ phase [12—19]. In this way, high strength conductive alloys were developed on the basis of Al—Sc—Zr system [20, 21]. Al—0.35Sc—0.2Zr[1] alloy after heat deformation treatment is characterized by a good combination of strength (σ_u = 210 MPa), plasticity (δ = 7.6 %), and electrical conductivity (IACS — 60.2 %) [20]. A less expensive alloy containing 0.06 % Sc has lower strength (194 MPa) at higher electrical conductivity (IACS — 61 %) [21].

In recent years much attention has been paid to other rare earth metals (REM), in particular, to Y, Yb, Er, and Gd [22—34]. Minor amounts during crystallization are present in aluminum solid solution. Upon annealing in alloys with scandium they substitute in $L1_2$ dispersoids, thus increasing the density of their precipitation and mechanical properties of the alloys [22—31]. Thus, for example, Al—0.2Y—0.2Sc alloy after rolling and annealing demonstrated a good combination of the properties: the yield stress up to 183 MPa, the ultimate strength up to 202 MPa, the relative elongation up to 15.8 % at the electrical conductivity of 60.8—61.5 % [31]. Further strengthening was achieved after additional doping with 0.3 % ytterbium [32]. As a consequence, in Al—0.2Y—0.2Sc—0.3Yb alloy the ultimate strength increased to 244 MPa with a decrease in plasticity to 7.6—11.9 % and electrical conductivity to 57—57.7 % [32]. Approximately the same level of properties was obtained in the sheets from Al—0.3Er—0.2Sc—0.2Yb alloy due to precipitation of dispersoids with the size of 4—8 nm [33]. For the aim of comparison, dispersoids of Al_3(Er,Y,Zr) phase in scandium free Al—0.3Er—0.2Y—0.2Zr alloy provide lower strengthening ($\sigma_u \leq$ 156 MPa) at the same electrical conductivity [34].

In [35], a significant influence of annealing before deformation on mechanical properties and electrical conductivity of new Al—0.2Y—0.2Sc—0.3Er alloy was demonstrated. Ingot annealing, hot and cold rolling with subsequent annealing provide the following combination of properties: $\sigma_{0.2}$ = 191 MPa, σ_u = 207 MPa, δ = = 14 % and IACS — 59.7 %.

The aim of this work is to establish the influence of heat treatment on the properties of cold deformed conductive Al—0.2Y—0.2Sc—0.3Er alloy.

Experimental

Al—0.2Y—0.2Sc—0.2Er (AlYScEr) alloy was smelted in a resistance furnace from aluminum with a purity of 99.99 %, and dopants: Al—9Y, Al—2Sc and Al—10Er. The ingots were 40 mm wide, 20 mm thick and 120 mm height, and obtained by crystallization in copper water cooled mold at the cooling rate of ≈15 K/s. Rolling of ingots in a cast state (T1) and after annealing at t = 300 °C in 7 h (T2) was carried

[1] Hereinafter the contents of components are in wt.%, if not otherwise mentioned.

out at ambient temperature to the thickness of 1 mm. The microstructure studies were carried out using an Axiovert 200MMAT optical microscope (OM) (Carl Zeiss, Germany), a TESCAN VEGA 3LMH scanning electron microscope (SEM) (Czech Republic), a JEM 2100 transmission electron microscope (TEM) (Japan). Samples for PEM were prepared using a Struers Tenupol-5 facility of electrolytic pulsing (Denmark). Vickers hardness was measured using a Wilson/Wolpert 930N hardness meter (Germany) at the load of 5 kg.

Uniaxial tensile tests were carried out using a Zwick/Roell Z250 facility (Germany) at a deformation rate of $3\cdot10^{-3}$ s^{-1}. Samples with an operating length of 20 mm and width of 6 mm were cut out from a sheet in the rolling direction.

Electric resistance was measured on samples with a length of 70 mm and a width of 5 mm, cut from sheets using the double bridge method on an INSTEK GOM-802 ohmmeter (China).

Results and discussion

The initial ingot microstructure and phase composition of AlYScEr alloy were studied in detail in [35]. Aluminum solid solution (Al) and dispersed eutectics with τ_2 ($Al_{75\text{-}76}Er_{11\text{-}17}Y_{7\text{-}14}$) phase are presented in the as cast structure. Herewith, scandium is totally dissolved in (Al), and the content of yttrium and erbium is at a level of 0.2—0.3 %. The maximum strengthening due to precipitations of $L1_2$ dispersoids of Al_3(Sc,Y,Er) alloy was achieved after 7 h annealing at 300 °C.

Figure 1 illustrates the microstructure of alloy ingot after annealing providing the maximum hardness. The size of the precipitates does not exceed 10 nm. The particles of Al_3(Sc,Y,Er) phase are highlighted in TEM images, the diffraction pattern contains respective reflections located between main ones from the lattice (Al).

Figure 2 illustrates the microstructure and distribution of dopants between the phases in the highlighted

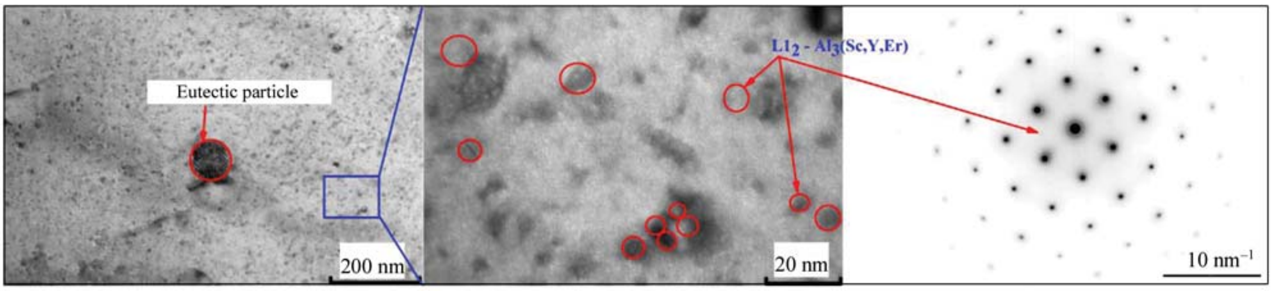

Fig. 1. Microstructure (TEM) and diffraction pattern of AlYScEr alloy after annealing at t = 300°C in 7 h

Рис. 1. Микроструктура (ПЭМ) и микроэлектронограмма сплава AlYScEr после отжига при t = 300 °C в течение 7 ч

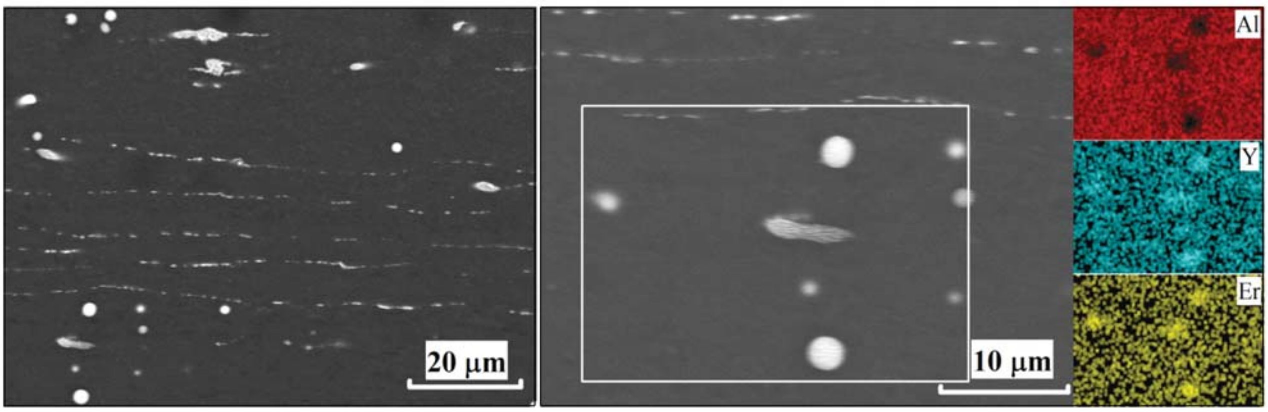

Fig. 2. Microstructure (SEM) and distribution of dopants between the phases in highlighted region in cold rolled state as exemplified by mode T1

Рис. 2. Микроструктура (СЭМ) и распределение легирующих элементов между фазами в выделенной области в холоднокатаном состоянии на примере режима T1

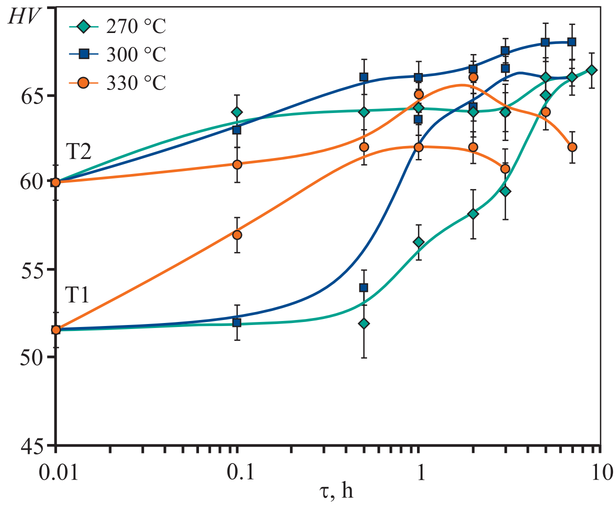

Fig. 3. Hardness as a function of annealing time at various temperatures

Рис. 3. Зависимости твердости от времени отжига при разных температурах

region in a cold rolled state, as exemplified by a sheet fabricated according to mode T1. The eutectic particles are located mainly along the boundaries, being elongated in the rolling direction.

After rolling, the sheets were annealed at 270—330 °C. Figure 3 illustrates hardness as a function of annealing time. In the sheets fabricated according to mode T1 (cold rolling of ingot), significant strengthening occurs. With an increase in the temperature from 270 to 300 °C, the same maximum hardness of 66 HV is achieved after 7 and 3 h, respectively. For the aims of comparison, in an ingot during annealing at t = 300 °C the maximum hardness (61 HV) is achieved in 7 h, and at 270 °C in 24 h [35].

Cold rolling significantly accelerates decomposition of (Al), allowing a greater hardness in sheets to be achieved, in comparison with ingots. Defects accumulated during cold rolling stimulate strengthening due to precipitation of $L1_2$ dispersoids, thus showing the prevailing heterogeneous mechanism of nucleation. The same argument can be confirmed by analysis of hardness evolution of samples fabricated according to mode T2. The annealing of sheets annealed before rolling to maximum hardness at 270—300 °C leads to increase in hardness by 6—8 HV. Thus, thermal stimulus is insufficient for complete decomposition of solid solution upon ingot annealing. In combination with the subsequent cold rolling and annealing at t = = 300 °C in 5—7 h, AlYScEr alloy demonstrates maximum hardness: 68 HV. During annealing at t = 330 °C, a certain strengthening is also observed, which in ≈1 h is superseded by polygonization processes leading to

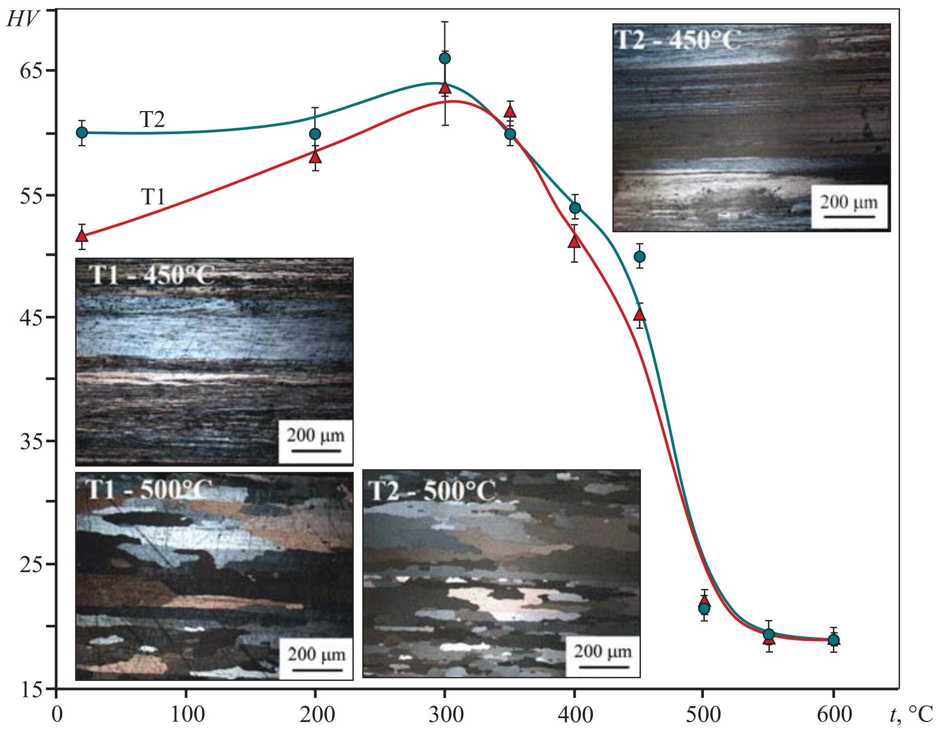

Fig. 4. Hardness as a function of temperature of 1 h annealing and granular structure (OM) of sheets

Рис. 4. Зависимости твердости от температуры 1-часового отжига и зеренная структура (СМ) листов decrease in the hardness together with coarsening of dispersoids.

Figure 4 illustrates the hardness as a function of temperature of 1h annealing, and the granular structure of sheets in the range of recrystallization temperature. During annealing to 450 °C, the non-recrystallized structure retains in the alloy, the hardness decreases insignificantly (to 45 and 50 HV) in the sheets fabricated according to modes T1 and T2, respectively. A greater hardness in the sample according to mode T2 (annealing before rolling) evidences formation of more disperse and homogeneous polygonised structure. Similar results were achieved in [35] for the same alloy exposed to preliminary annealing, hot and cold rolling. A sharp decrease in the hardness to 19 HV occurs after 1 h annealing at t = 550 °C, when the structure is completely recrystallized. Irrespective of the mode of sheet fabrication, the alloy demonstrates a high thermal stability up to 400 °C, the hardness is 51—54 HV.

Table 1 summarizes the experimental results of uniaxial tensile tests of samples of AlYScEr alloy fabricated according to different modes. After rolling (mode T1), the ingot has a yield stress $\sigma_{0.2}$ = 167 MPa. During annealing at t = 300 °C, this property increases to 192 MPa in 4 h and actually does not decrease upon subsequent increase in annealing time to 100 h.

The alloy fabricated according to mode T1 is characterized by high thermal stability. The sheet preliminary annealed before rolling (T2) has $\sigma_{0.2}$ = 195 MPa. With an increase in the annealing time at t = 300 °C from 1 to 7 h, the yield stress actually does not change and after 100 h it insignificantly decreases to 180 MPa. Herewith, the relative elongation (δ) increases with an increase in the annealing time due to depletion (Al) and decrease in the concertation of defects.

For the same reasons, the electrical conductivity increases in sheets with increase in annealing duration at t = 300 °C (Table 2). After 100 h annealing, the electrical conductivity of the new alloy is close to that of the electrotechnical alloy 1350 (A5E), which has a significantly lower yield stress (110 MPa) [36]. The mode T2 provides better electrical conductivity. For the aims of comparison, the conductive alloy A5E has lower ultimate strength in annealed state σ_u = 120÷160 MPa, at approximately the same electrical conductivity IACS — 60.5 % (specific electric resistance: 0.0285 $\Omega \cdot mm^2/m$) [37].

Table 1. **Experimental results of tensile tests of sheets from AlYScEr alloy fabricated according to different modes**

Таблица 1. Результаты испытаний на растяжение листов сплава AlYScEr, полученных по разным режимам

State	T1			T2		
	$\sigma_{0.2}$, MPa	$\sigma_в$, MPa	δ, %	$\sigma_{0.2}$, MPa	$\sigma_в$, MPa	δ, %
Deformed	167±1	174±1	11±1	195±1	205±1	7±1
After annealing						
t = 300 °C, 1 h	186±2	198±2	8±1	198±3	212±2	7±2
t = 300 °C, 4 h	192±2	204±1	9±1	195±2	210±1	13.5±1.5
t = 300 °C, 7 h	190±1	205±1	12±4	194±1	210±1	12.1±0.5
t = 300 °C, 100 h	189±1	205±1	13±1	180±1	197±1	12.8±0.8

Table 2. **Electrical conductivity of sheets from AlYScEr alloy, aluminum, and electrotechnical alloy 1350 (A5E)**

Таблица 2. Электропроводность листов сплава AlYScEr, алюминия и электротехнического сплава 1350 (A5E)

State	IACS, %			
	T1	T2	Al (99,99%) [36]	1350 [36]
Deformed	54.4	58.1	64.5	61
After annealing				
t = 300 °C, 1 h	57.7	59.0		
t = 300 °C, 4 h	59.4	59.8		
t = 300 °C, 7 h	59.6	60.1		
t = 300 °C, 100 h	59.8	60.5		

Conclusions

The strengthening features, the mechanical properties, and the electrical conductivity of Al—0.2Y—0.2Sc—0.3Er alloy after cold rolling were determined.

1. The cold rolling of ingots accelerates strengthening upon annealing at t = 270 and 300 °C, thus decreasing the time to achieve peak hardness from 24 and 7 h for an ingot to 7 and 3 h for a sheet, respectively. The defects accumulated during cold rolling stimulate strengthening due to precipitation of $L1_2$ dispersoids. This shows the prevailing heterogeneous mechanism of dispersoid nucleation.

2. During the annealing of sheets to 450 °C, the non-recrystallized structure retains. The hardness of sheets produced according to modes T1 (ingot rolling) and T2 (rolling after annealing to maximum hardness) equals to 45 and 50 HV, respectively. The greater hardness of a sample fabricated according to mode T2 shows evidence of the formation of more disperse and homogeneous polygonised structure in it.

3. Ingot annealing at t = 300 °C in 7 h and cold rolling with subsequent annealing at 300 °C in 7 h provides a high level of mechanical properties and electrical conductivity: $\sigma_{0.2}$ = 194 MPa, σ_u = 210 MPa, δ = 12.1 % and IACS — 60.1 %.

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The article was submitted 06.10.2022, revised 13.12.2022, accepted for publication 20.12.2022

Статья поступила в редакцию 06.10.2022, доработана 13.12.2022, подписана в печать 20.12.2022