A. R. TOLEUOVA, A. M. DOSTAYEVA, O. M. ZHARKEVICH,
S. A. ABDULINA, M. A. ADILKANOVVA, D. SERIKBAYEV

ISSN 0543-5846
METABK 59(4) 543-546 (2020)
UDC – UDK 546.621.831.72.28:66.065:66.082:518.5.001.1:536.425=111

CALCULATING AND EXPERIMENTAL STUDYING PHASE TRANSFORMATIONS IN THE Al-Zr-Fe-Si SYSTEM ALLOYS

Received – Primljeno: 2020-03-26
Accepted – Prihvaćeno: 2020-06-30
Preliminary Note – Prethodno priopćenje

The paper presents the results of calculating phase transformations in Al–Zr–Fe–Si alloys. It is urgent to develop a fundamentally new class of aluminum alloys in which the required level of hardening would be ensured by means of alloying them with transition elements and dispersion hardening during heterogeneous annealing, eliminating the hardening operation during their heat treatment. In this case, it becomes possible to maintain the obtained structure stability and high heat resistance at elevated temperatures.

Keywords: Al–Zr–Fe–Si system, crystallization, concentration, computer program, phase transformations

INTRODUCTION

At present, aluminum alloys are widely used due to the valuable combination of mechanical, physical, and corrosion properties, high workability, as well as significant natural reserves and low cost of aluminum. Aluminum possesses high electrical conductivity, so it is widely used for manufacturing electrical products, in particular, wires of high-voltage overhead power lines.

Since adding other elements reduces the electrical conductivity to one degree or another, the wire is still made of technical aluminum (A5E or A7E grades) or low alloys of the Al-Si-Mg system (ABE).

The wire rod obtained after continuous casting and rolling of alloys serves as the initial billet for producing aluminum wires. According to the 2013 data, the volume of production of wire rod using primary aluminum (A5E and A7E grades) in the world is about 250 thousand tons per year. The bulk of the wire rod goes to the production of bare wires of power lines.

Recently, in manufacturing semi-finished products and electrical products, much attention has been paid to alloys with zirconium additives. It is assumed that zirconium can significantly increase the temperature of aluminum recrystallization.

This in turn should ensure the workability of wires for overhead power lines at temperatures up to 300 °C. To ensure the required level of electrical resistivity and Al–Zr wire strength, it is necessary to form a specified microstructure of the wire rod by optimizing the chemical composition of the alloys and their melting and casting modes, as well as the deformation-heat treatment modes of the wire rod.

EXPERIMENTAL PART AND DISCUSSING THE RESULTS

To analyze the phase composition of alloys by calculation using the Thermo-Calc program, the phase diagram of the Al–Zr–Fe–Si system was studied. There were built the projections of the liquidus and solidus surfaces (Figures 1, 2). As it is seen in Figure 1, starting already with small concentrations of zirconium, Al_3Zr aluminide crystallizes primarily. The projection of the solidus is characterized by a very small extent of the multiphase region.

Adding zirconium to binary alloys is known to lead to the formation of the Al_3Zr phase [1-5]. The effect of zirconium on the boundaries of the intermetallic phase primary crystallization in this quaternary system at a constant concentration of one of the components is shown in Figure 1. In this Figure, there is shown the selecting of maximum concentrations of these elements.

At 1 % Fe, the region of primary crystallization (Al) decreases significantly.

It should be noted that in this case, the minimum liquidus temperature (at the point of the triple eutectic $L \circledR Al_3Fe+Al_8Fe_2Si-\alpha+(Al)$ increases.

Zirconium is known to increase greatly the liquidus temperature in binary alloys. The calculation shows that the presence of zirconium affects the degree of this increase, as it is shown by the polythermal sections in Figure 4 [6-8].

The calculations and experimental studies have shown that, upon rapid cooling under non-equilibrium conditions, the formation of primary crystals of the equilibrium Al_3Zr ($L1_2$) phase directly from the melt is

A. R. Toleuova, A. M. Dostayeva (ardak_erkekyz@mail.ru), O. M. Zharkevich, Karaganda State Technical University
S. A. Abdulina, M. A. Adilkanovva, D. Serikbayev, East Kazakhstan State Technical University, Kazakhstan

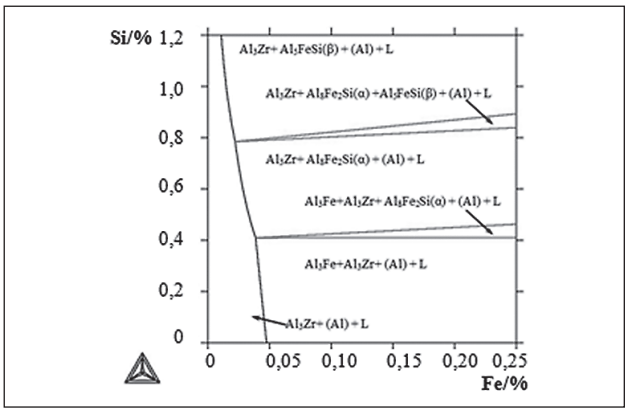

Figure 1 The solidus surface projections of the Al–Zr–Fe–Si system at 0,38 % Zr

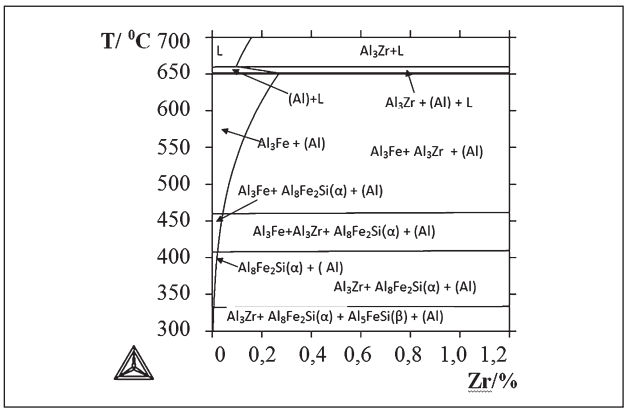

Figure 3 Polythermal section of the diagram of state for the Al-Fe-Si-Zr system with 0,139 % Fe, 0,072 % Si

suppressed, and in the solid state secondary nanosized particles of the Al_3Zr (DO_{23}) phase are released from the supersaturated aluminum solution.

To calculate the polythermal cross sections of the phase diagram of the multicomponent Al–Zr–Fe–Si system, we used the Thermo-Calc program (TCW-5 version, TTAL7 database). From the polythermal section of the Al–Zr–Fe system with the zirconium content of 0,18 %, it follows that the Al_3Fe compound is formed at the temperature of about 630 °C [9]. The ultimate solubility of this element in (Al) is about 0,005 %.

Polythermal sections (Figure 3) show that even small changes in the concentrations of silicon and iron lead to significant changes in the phase composition. As the silicon and iron contents increase, there is formed the Al_8Fe_2Si phase, which is in equilibrium with the aluminum solid solution. Increasing the zirconium content to 0,5 % has a significant effect on the structures of polythermal sections of the diagram of state for the Al–Fe–Si–Zr system.

The temperature effect on the phase composition at different concentrations is reflected in polythermal sections (Figures 4,5). These sections show that Zr increases the liquidus temperature on the aluminum side.

It also follows from polythermal sections that during crystallization and subsequent cooling of the Al–Zr–Fe–Si system alloys in the solid state, multiphase reactions take place with participation of the following phases: (Al), Al_3Zr ($L1_2$), Al_3Fe and other iron-containing complex compounds phases (Al_8Fe_2Si-α, Al_5FeSi-β). According to the calculation, the Al–Zr–Fe–Si system contains the following phase regions: Al_3Zr+L, (Al)+L, Al_3Fe + (Al)+L, Al_3Zr+(Al)+L, Al_3Fe + Al_3Zr+(Al)+L, Al_3Fe + (Al), Al_3Fe + Al_3Zr+(Al), Al_3Fe + Al_8Fe_2Si-α +(Al), Al_3Fe + Al_3Zr+Al_8Fe_2Si-α +(Al), Al_3Zr+Al_8Fe_2Si-α+(Al), Al_8Fe_2Si-α+ Al_5FeSi-β + (Al), Al_3Zr+ Al_8Fe_2Si-α+ Al_5FeSi-β + (Al).

The aluminum solid solution, depending on the composition and temperature, can be in equilibrium with the above phases and participate in multiphase (eutectic, peritectic, eutectoid and peritectoid) reactions.

Under equilibrium cooling conditions, complex four-phase: (Al_3Fe+Al_3Zr+(Al)+L, Al_3Fe+ Al_3Zr+Al_8Fe_2Si-α+(Al), Al_3Zr+ Al_8Fe_2Si-α+ Al_5FeSi-β+(Al)), as well as three-phase: (Al_3Fe+(Al)+L, Al_3Zr+(Al)+L, Al_3Fe + Al_3Zr+(Al), Al_3Fe + Al_8Fe_2Si-α +(Al), Al_3Zr+Al_8Fe_2Si-α+(Al), Al_8Fe_2Si-α+ Al_5FeSi-β + (Al)) transformations take place in the alloys of this system.

The calculations and experimental studies have shown that, upon rapid cooling under non-equilibrium conditions, the formation of primary crystals of the

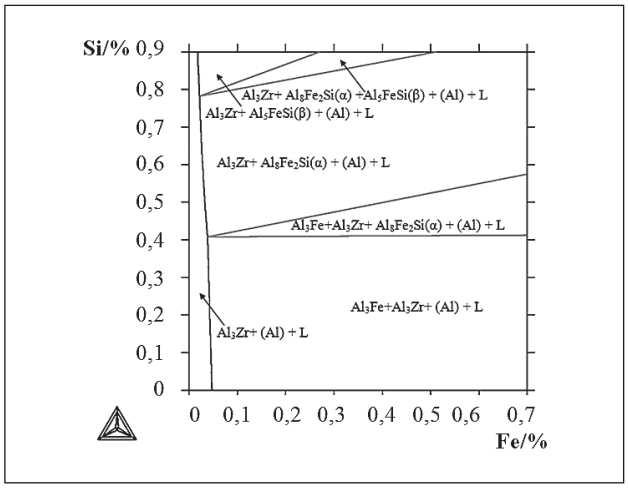

Figure 2 The solidus surface projections of the Al–Zr–Fe–Si system at 0,48 % Zr

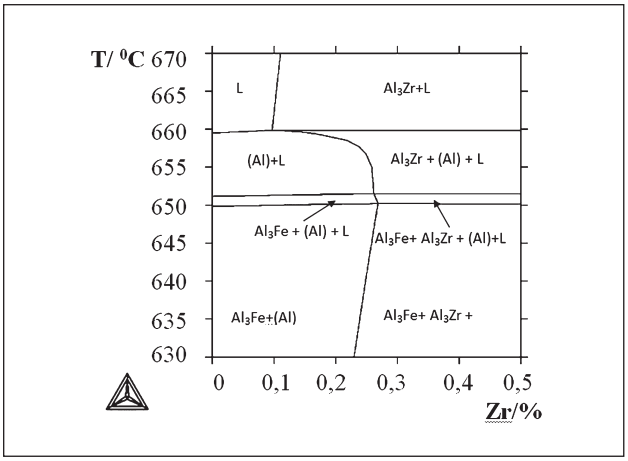

Figure 4 Polythermal section of the diagram of state for the Al-Fe-Si-Zr system, 0,139 % Fe, 0,072 % Si, above 600 °C

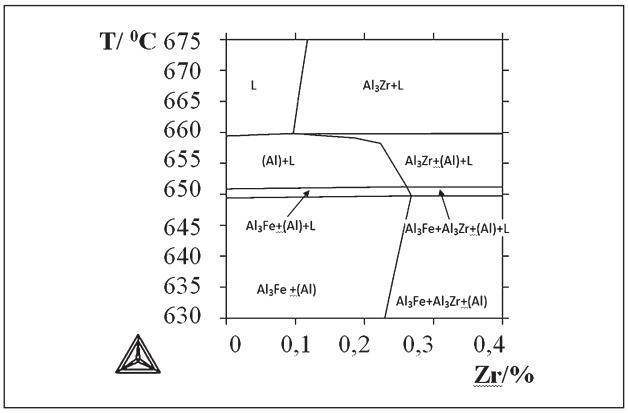

Figure 5 Polythermal sections of the diagram of state for the Al-Fe-Si-Zr system, 0,14 %Fe, 0,08 % Si, above 600 °C

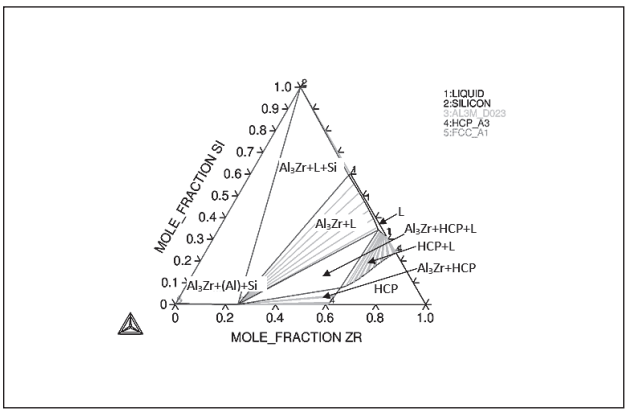

Figure 7 Isothermal sections of the phase diagram for the Al-Zr-Si system at 450 °C

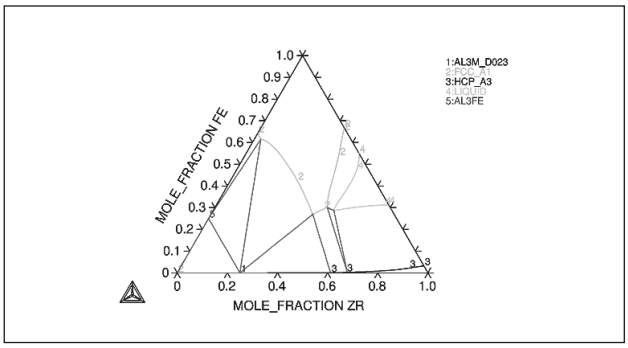

Figure 6 Isothermal sections of the phase diagram for the Al-Zr-Fe system at 450 °C

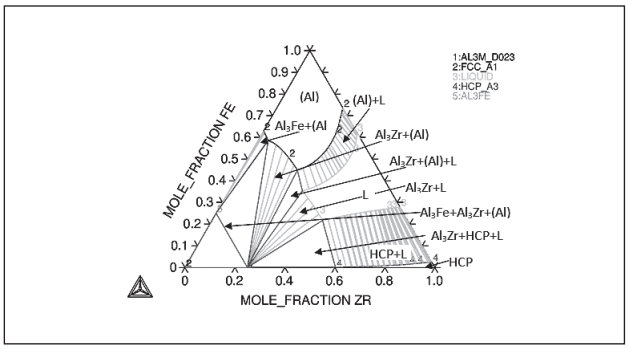

Figure 8 Isothermal sections of the phase diagram for the Al-Zr-Fe system at 600 °C

equilibrium Al_3Zr ($L1_2$) directly from the melt are suppressed, and in the solid state, secondary nanosized particles of the Al_3Zr (DO_{23}) phase are released.

The effect of zirconium reflects the section at 0, 140 % Fe and 0, 080 % Si, in which it is seen that new phases Al_8Fe_2Si, Al_5FeSi, Al_3Fe are crystallized in a relatively small temperature range (lower than 10 °C). Already at 0, 283 % Zr, the Al_3Zr phase appears.

The alloy with 0,18% Zr at 400 °C falls into the (A1)+$A1_3Fe$ phase region. The phase composition of alloys with 0,2 % Zr and 0,3 % Zr consists of the $A1_5FeSi$ and (Si) phase.

The isothermal section at 450 °C (Figure 6) shows that, with the content of more than 0,18 % Zr, the alloys are below the liquidus temperature, and they fall into the Al_3Zr+L+Si region. With increasing the temperature, the liquid region increases. Figure 7 shows that the melting and casting temperature (above 650 °C) typical of aluminum alloys is unacceptably low for the alloy with zirconium addition.

The isothermal sections of the Al–Fe–Si–Zr system in the solid state are characterized by the presence of the following phase regions: (Al), Al_3Fe+(Al), Al_3Fe+ Al_3Zr+(Al). With decreasing the temperature, the single-phase region narrows.

It can be seen in the isothermal sections in Figure 8 that already small changes in the concentrations of silicon and iron can lead to significant changes in the phase composition. For example, the alloy of 0,18 % Zr at 600 °C falls into the (Al)+Al_3Fe phase region, and the 0,28 % Zr alloy (with a high zirconium content) falls into the (Al)+Al_8Fe_2Si region.

Zirconium is distributed between (A1) and $A1_3Zr$(Ll_2). It has been shown in [2, p. 217] that its presence in aluminum solid solution (A1) most negatively affects electrical resistance, and secondary precipitates of the $A1_3Zr$ phase determine its thermal stability [3, 4].

CONCLUSION

1) Using the Thermo-Calc program (TTAl7 base), polythermal and isothermal sections of the Al–Zr–Fe–Si system have been calculated and built in the concentration range 0–0,15 % Fe, 0–0,09 % Si, 0–0,47 % Zr (wt.%). The calculations have shown that during crystallization and subsequent cooling of the Al–Zr–Fe–Si system alloys in the solid state, in addition to the solid solution based on aluminum (A1) and the known Al_3Zr phase, a number of new phases are formed: $A1_3Fe$, α -$A1_8Fe_2Si$, β-$A1_5FeSi$ and others.

The aluminum solid solution, depending on the alloy composition and the temperature, can be in equilibrium with the above phases and participate in multiphase (eutectic, peritectic, eutectoid and peritectoid) reactions.

2) Under the equilibrium cooling conditions in the alloys of this system complex four-phase: (Al_3Fe+Al_3Zr+(Al)+L, Al_3Fe+ Al_3Zr+Al_8Fe_2Si-α+(Al),

Al_3Zr+ Al_8Fe_2Si-α+ Al_5FeSi-β + (Al)) and three-phase: (Al_3Fe+(Al)+L, Al_3Zr+(Al)+L, Al_3Fe + Al_3Zr+(Al), Al_3Fe + Al_8Fe_2Si-α +(Al), Al_3Zr+Al_8Fe_2Si-α+(Al), Al_8Fe_2Si-α+ Al_5FeSi-β + (Al)) transformations take place.

3) Calculations of phase transformations in the Al–Zr–Fe–Si system alloys under equilibrium and non-equilibrium cooling conditions have shown that iron and silicon impurities do not form phases with zirconium. This allows analyzing their effect on the basis of the ternary Al-Fe-Si system. The calculated curves of non-equilibrium crystallization in the form of the temperature dependence of the molar fraction of solid phases (Q) show that four phases can form in the alloys of this system depending on the concentrations of Fe and Si; Al_3Fe, Al_8Fe_2Si, Al_5FeSi and a solid solution based on silicon (Si).

4) The calculations have shown that upon rapid cooling under non-equilibrium conditions, the formation of primary crystals of the Al_3Zr ($L1_2$) equilibrium phase directly from the melt is suppressed, and in the solid state secondary nanosized particles of the Al_3Zr (DO_{23}) phase are released from the supersaturated aluminum solution.

REFERENCES

[1] Du, Q., Poole, W. J., Wells, M. A., Parson, N. C. Microstructure evolution during homogenization of Al-Mn-Fe-Si alloys: Modeling and experimental results(Article) Acta Materialia, 61 (2013) 13, 4961-4973

[2] Zakharov A. M. Industrial alloys of non-ferrous metals. Phase composition and structural components. - M.: Metallurgy, 1980. - 256 p.

[3] Jones S. A., Kaufman M. J., Phase equilibria and transformations in intermediate titanium-aluminum alloys, Acta Metallurgica et, Materialia 41, (1993) 2, 387-398

[4] Cassell M., Robson J. D., Race C. P., Eggeman A., Besel M. Dispersoid composition in zirconium containing Al-Zn-Mg-Cu (AA7010) aluminium alloy, Acta Materialia 169 (2019), 135-146

[5] Hai-Lin, Qing Chen, Anders Engström Chen Development and applications of the TCAL aluminum alloy database // Calphad 62, (2018) 154-171

[6] Amenova A., Belov N., Smagulov D., Toleuova A. Perspective high strength aluminium alloys of new generation based on Al–Ni–Mn–Fe–Si–Zr system, Materials Research Innovations 18 (2013), 550-553

[7] Jae-Gil Jung, Young-Hee Cho, Jung-Moo Lee, Hyoung-Wook Kim, Kwangjun Euh Designing the composition and processing route of aluminum alloys using CALPHAD: Case studies, Calphad 64, (2019) 236-247

[8] Hai-Lin Chen, Qing Chen, Johan Bratberg, Anders Engström Predictions of Stable and Metastable Phase Formations in Aluminum Alloys Materials Today: Proceedings, Volume 2, Issue 10, Part A, (2015), 4939-4948

[9] Belov, N. A., Dostaeva, A. M., Shurkin, P. K., Korotkova, N. O., Yakovlev, A. A. Influence of annealing on electrical resistance and hardness of hot-rolled aluminum alloy sheets containing up to 0.5% Zr//.Russian Journal of Non-Ferrous Metals 57 (2016) 5, 429-435

Note: The responsible for England language is Natalya Drak, Karaganda Kazakhstan