G. SIWIEC, J. MIZERA, D. JAMA, A. SZMAL, R. BURDZIK

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THE EFFECTS OF TEMPERATURE ON THE KINETICS OF ALUMINIUM EVAPORATION FROM THE Ti-6Al-4V ALLOY

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In the paper, results of the study on temperature effects on the rate of aluminium evaporation from the Ti-6Al-4V alloy during smelting in a vacuum induction furnace are presented. During smelting at 1 973 – 2 023 K, 10 Pa and 100 Pa, up to 26 % reduction in the aluminium content in the alloy compared to the initial value is observed. The determined values of overall mass transport coefficient are $1{,}48 \cdot 10^{-5}$ m·s^{-1} – $1{,}95 \cdot 10^{-5}$m·s^{-1}.

Key words: Ti-6Al-4V alloy, vacuum induction furnace, smelting, overall mass transport coefficient

INTRODUCTION

Titanium alloys belong to the class of metallic materials which recently have been of increasing interest in many industries, mainly due to their specific properties, such as small densities, high tensile strength and good corrosion resistance in many chemically aggressive environments. These properties ensure the use of alloys for production of e.g. implants, endoprostheses and components of systems used in cardiovascular surgery, such as cardiac pacemakers and valves. The Ti-6Al-4V is an example of increasing applications of titanium alloys. One of its production methods is smelting in a vacuum induction furnace (a conventional technology) or with the use of 'skull melting' technology. The process of smelting is very often associated with two disadvantageous effects. The first effect is metal bath contamination due to a reaction of the matrix component, i.e. titanium, with the ceramic materials of the melting pot. The other effect is a potential for significant aluminium elimination due to its evaporation which is caused by a large difference in vapour pressures of aluminium and titanium. Aluminium loss is also induced by low pressures in the smelting system [1 - 5].

In the paper, results of the study on the temperature effects on the rate of aluminium evaporation from the Ti-6Al-4V alloy during smelting in the vacuum induction furnace are presented.

G. Siwiec - Silesian University of Technology, Faculty of Materials Engineering and Metallurgy, Katowice, Poland
J. Mizera - Warsaw University of Technology, Faculty of Materials Engineering Warszawa, Poland
D. Jama - Silesian University of Technology, Faculty of Applied Mathematics, Gliwice, Poland
A. Szmal - Silesian University of Technology, Faculty of Organization and Management, Zabrze, Poland
R. Burdzik - Silesian University of Technology, Faculty, Faculty of Transport, Katowice, Poland

EXPERIMENTAL PART

For the experiments, a Ti-6Al-4V alloy containing Al 5,5 %mass was used. The smelting system was a VIM-20 - 50 vacuum induction furnace manufactured by Seco - Warwick. It is a modern device which ensures smelting at a broad range of operating pressures due to a system of vacuum pumps consisting of e.g. a diffusion pump and a Roots pump. The time of liquid alloy holding at a given temperature and pressure was 10 minutes. During each experiment, alloy samples were collected and subjected to a chemical analysis to determine titanium, aluminium and vanadium contents. The experiments were performed at 1 972 – 2 023 K, 10 and 100 Pa.

Changes in the aluminium content in a liquid bath were determined with the use of the following equation:

$$-\log\frac{C_{Al}^{k}}{C_{Al}^{0}} = A \cdot t \qquad (1)$$

where: C_{Al}^{k} and C_{Al}^{0} - initial and final aluminium concentrations in the alloy, respectively

t – time,

A – constant.

Examples of changes in aluminium concentration in the alloy are presented in Figures 1 and 2.

DISCUSSION OF RESULTS

While analysing the process of aluminium evaporation, it was assumed to be determined by the first-order rate equation [6 - 8]. Thus, in order to determine the overall mass transfer coefficient, the following equation was used:

$$2{,}303 \quad \log\frac{C_{Al}^{k}}{C_{Al}^{o}} = -k_{Al}\frac{F}{V}\cdot t \qquad (2)$$

where:

k_{Al} – overall mass transfer coefficient,

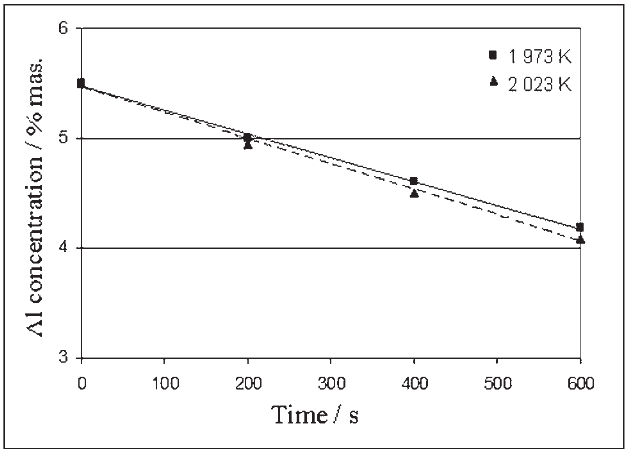

Figure 1 Changes in aluminium concentration during Ti-6Al-4V melting at 100 Pa, 1 973 K and 2 023 K

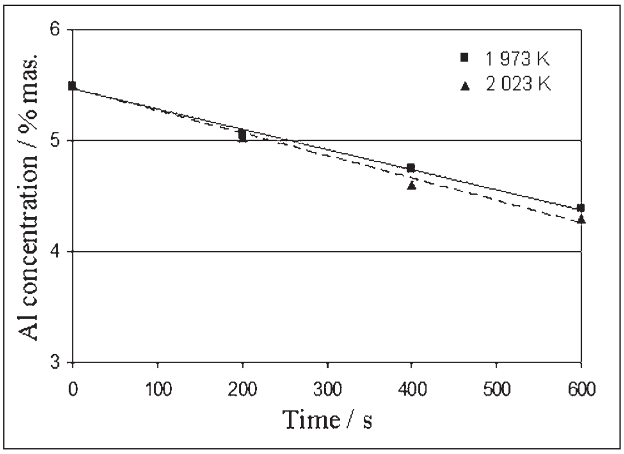

Figure 2 Changes in aluminium concentration during Ti-6Al-4V melting at 10 Pa, 1 973 K and 2 023 K

F – evaporation area assumed as the inner surface area of the melting pot,
V – bath volume.

In order to determine the k_{Al} value from equation (2), the value of 'A' slope in equation (1) was used. In Table 1, the overall mass transfer coeffi cient values, deter - mined from the experimental results, are presented.

In order to determine the effects of liquid phase-gaseous phase physical change rate (on the interface) on the overall process rate, the values of apparent evaporation rate constant were estimated with the use of the following equation:

$$\frac{\alpha\varphi}{(2\pi RTM_{Al})^{0,5}} = k_{Al}^{e'} \quad (3)$$

where:

$$\varphi = \frac{p_{Al}^{o} \cdot \gamma_{Al} \cdot M_{Ti}}{\rho_{Ti}} \quad (4)$$

where:
γ_{Al} – coefficient of Al activity in liquid alloy,
p_{Al}^{o} - vapour pressure of Al over pure bath,
M_{Ti} – titanium molar mass,
M_{Al} - aluminium molar mass,
ρ_{Ti} – liquid titanium density,
α=1 – constant [9].

Table 1 **The values of pressure, temperature, average flux of Al loss, overall mass transfer coeffcien t, apparent evaporation rate constant for aluminum evaporation process from Ti-6Al-4V alloy**

Pressure /Pa	Temp /K	Average flux of Al loss /g·cm^{-2}·s^{-1}	Overall mass transfer co-efficient k_{Al} /m·s^{-1}	Apparent evaporation rate constant $k^{e'}_{Al}$ /m·s^{-1}
100	1 973	6,30·10^{-5}	1,48·10^{-5}	1,90·10^{-5}
100	1 973	6,31·10^{-5}	1,48·10^{-5}	1,90·10^{-5}
100	1 998	6,26·10^{-5}	1,57·10^{-5}	2,37·10^{-5}
100	1 998	6,24·10^{-5}	1,57·10^{-5}	2,37·10^{-5}
100	2 023	6,22·10^{-5}	1,64·10^{-5}	2,97·10^{-5}
100	2 023	6,21·10^{-5}	1,62·10^{-5}	2,97·10^{-5}
10	1 973	6,08·10^{-5}	1,52·10^{-5}	1,90·10^{-5}
10	1 973	6,01·10^{-5}	1,52·10^{-5}	1,90·10^{-5}
10	1 998	6,00·10^{-5}	1,86·10^{-5}	2,37·10^{-5}
10	1 998	5,92·10^{-5}	1,95·10^{-5}	2,37·10^{-5}
10	2 023	5,92·10^{-5}	1,94·10^{-5}	2,97·10^{-5}
10	2 023	5,91·10^{-5}	1,93·10^{-5}	2,97·10^{-5}

In Table 1, the estimated values of apparent rate constant $k_{Al}^{e'}$ and average flux of Al loss are presented.

The determined k_{Al}, and $k_{Al}^{e'}$ values allowed for defining the contribution of mass transfer resistance related to the evaporation process to the overall resistance of the process using the following relation:

$$U_e = \frac{\frac{1}{k_{Al}^{e'}}}{\frac{1}{k_{Al}}} \cdot 100\ \% \quad (5)$$

The results have shown that for both pressures, the contribution of resistance related to the evaporation process, U_e, to the overall process resistance exceeds 50 %, which means that the investigated process is kinetically controlled (Figure 3).

In order to confi rm that the investigated process is kinetically controlled, the value of its activation energy was determined with the use of Arrhenius equation:

$$\ln k_{Al} = \frac{-E_A}{R \cdot T} \quad (6)$$

where:
E_A – activation energy of the process

In Figure 4, Arrhenius relationships and changes in the overall mass transfer coeffi cient (k_{Al}) value versus temperature are presented in the coordinate system.

For both operating pressures, the estimated activation energies are far above 100 kJ/mol, which is typical of kinetically controlled processes. For instance, the activation energy values were 200 kJ/mol and 161 kJ/mol for 100 Pa and 10 Pa, respectively. In the case of diffusion control in the liquid phase, these values are far smaller and comparable to the diffusion activation energies in liquids. For example, the dif fusion activation energy value for cobalt and iron in liquid copper is 11 kJ/mol, while for chromium, nickel, manganese and vanadium in liquid iron, it is 15 to 25 kJ/mol.

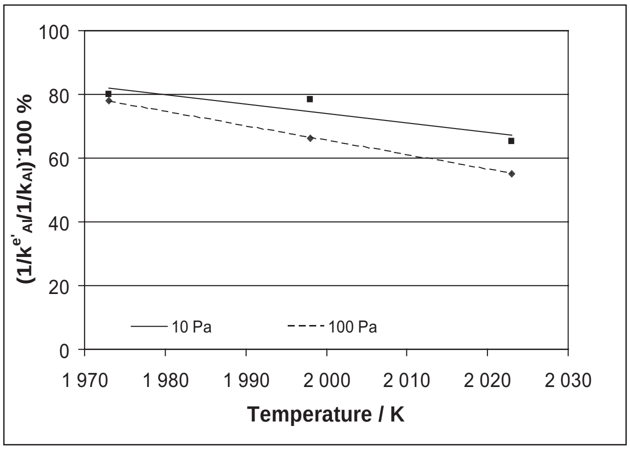

Figure 3 Changes in the contribution of resistance related to evaporation to the overall process resistance depending on the pressure

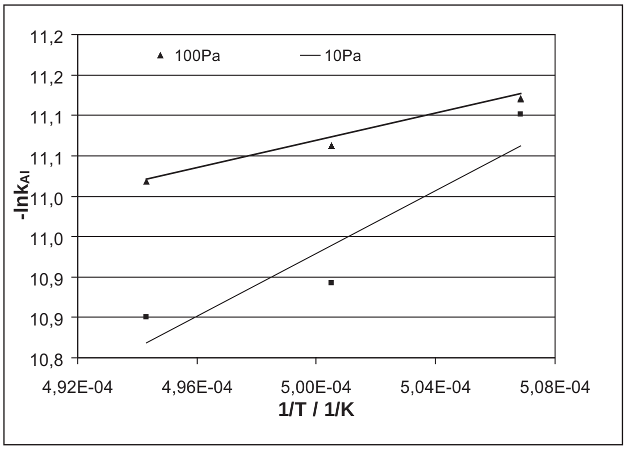

Figure 4 The overall mass transport coefficient, k_{Al}, versus temperature

CONCLUSIONS

Based on the experimental results of Ti-6Al-4V smelting in the vacuum induction furnace at 1 973 – 2 023 K, 10 and 100 Pa as well as the kinetic analysis findings, it was demonstrated that:

- Temperature rise from 1 973 K to 2 023 K at 100 Pa is accompanied by aluminium loss from the alloy: 20 % to 22 % compared to the initial concentration (5,5 % mass).

Simultaneously, the value of overall mass transfer coefficient, k_{Al}, increases from $1,48 \cdot 10^{-5}$ m·s^{-1} to $1,64 \cdot 10^{-5}$ m·s^{-1}.

- The temperature rise from 1 973 K to 2 023 K at 10 Pa is accompanied by aluminium loss from the alloy: 23 % to 26 % compared to the initial concentration. Simultaneously, the value of overall mass transfer coefficient, k_{Al}, increases from $1,52 \cdot 10^{-5}$ m·s^{-1} to $1,95 \cdot 10^{-5}$ m·s^{-1}.
- Kinetically, it has been shown that for the whole pressure range, the contribution of resistance related to the evaporation process to the overall process resistance exceeds 50 %, which means that the process is kinetically controlled. It is confirmed by determined values of the activation energy of the process which are over 160 kJ/mol.

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Note: Nowak P. is responsible for English language, Katowice, Poland