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THE EFFECTS OF MASS TRANSFER IN THE LIQUID PHASE ON THE RATE OF ALUMINIUM EVAPORATION FROM THE Ti-6Al-7Nb ALLOY

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Preliminary Note – Prethodno priopćenje

In the present paper, the rate of aluminium evaporation from the Ti-6Al-7Nb alloy during smelting with the use of VIM method at 5 to 1 000 Pa and 1 973 to 2 023 K has been discussed. It has been observed that pressure reduction and temperature rise affect aluminium elimination from the alloy. Based on the determined values of overall mass transfer coefficients and mass transfer coefficients in the liquid phase, it has been found that the resistance related to aluminium mass transfer in the liquid phase is about 8 % of the overall process resistance.

Keywords: Ti-6Al-7Nb alloy, aluminium evaporation, VIM technology, mass transfer coefficient

INTRODUCTION

Titanium alloys belong to the group of metallic materials whose applications markedly increase, primarily due to their small densities and high strength levels. A critical property of these materials is also their corrosion resistance. Titanium alloy products are mainly applied in the aerospace, shipbuilding and automotive industries as well as in medicine. They are also frequently used for construction purposes – basically due to the corrosion resistance mentioned.

In developed and currently utilised technologies of titanium alloy production, melting devices that work at lower pressures are mostly used, i.e. induction furnaces (VIM technology), arc furnaces (VAR technology) and electron beam furnaces (EBM technology). Smelting and casting of such metallic materials may pose various problems due to large differences in the melting points of alloy components and high reactivity of the matrix component, titanium, with gases or ceramic materials of melting pots or the furnace lining [1, 2]. Another disadvantageous process that may occur during the discussed alloy smelting is evaporation of its components. For instance, during Ti-Al-V alloy smelting intense aluminium evaporation is observed with losses reaching even 40 % of the metal [3-7]. Similarly, during Ti-Al-Mn alloy smelting, intense evaporation of manganese is observed [8, 9]. It should be noted that alloy overheating and too high vacuum levels in the smelting system may significantly intensify the disadvantageous evaporation process. To prevent this, knowledge on the process kinetics is necessary as for various vacuum ranges, the stage that controls its rate may change. Regarding results of the studies on aluminium evaporation from Ti-Al-Nb alloys, available in the literature, the only findings are related to the alloy containing 25 % mol Al and 25 % Nb, smelted in the induction furnace with the use of skullmelting technology [10]. Based on a thermodynamic analysis and own investigations, the authors of the paper demonstrated that individual components of the alloy show a tendency for evaporation in the Al>>Ti>>Nb order.

However, the authors did not perform a complete kinetic analysis of the process based on their own findings. In the present paper, the rate of aluminium evaporation from the Ti-6Al-7Nb alloy during smelting with the use of VIM method, at 5 to 1 000 Pa, has been discussed.

RESEARCH METHODOLOGY

For the investigations, the Ti-6Al-7Nb alloy was used (see Table 1 for the chemical composition). The alloy is an important biomaterial utilised for implant and biomedical engineering.

Table 1 **Chemical composition of the investigated alloy**

Basic alloy component fractions / %mass				
Al	Nb	Fe	Ta	Ti
5,5 – 6,5	6,5 – 7,5	≤0,25	≤0,5	The other fraction

All smelting experiments were performed in a single-chamber vacuum induction furnace VIM-20 manufactured by SECO-WARWICK. Each experiment began with introducing an alloy sample (about 1 000 g) into

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the melting pot placed in the induction coil. After closing the furnace chamber, the precisely determined vacuum was generated by the diffusion and Root's pump system. When the required vacuum level was reached, the melting pot was heated up to the assumed temperature and the liquid alloy sample was held under the set conditions for 600 sec. Next, the furnace was cooled. During the experiment, alloy samples were collected and their chemical analysis was performed. All experiments were performed at 5 – 1 000 Pa and 1 972 – 2 023 K. In Table 2, basic process parameters and final aluminium fractions in the alloy are presented.

RESULTS

While analysing the kinetics of aluminium evaporation, its three essential stages were considered:

- transfer of aluminium in the liquid phase to the interface (liquid metal surface),
- evaporation reaction on the liquid Al.(l) – Al(g) surface,
- transfer of gaseous aluminium mass from the evaporation surface to the core of gaseous phase.

The overall mass transfer coefficient (k_{Al}) in the analysed evaporation process was determined by the following equation:

$$\frac{1}{k_{Al}} = \frac{1}{\beta^l} + \frac{1}{\varphi k_e} + \frac{RT}{\varphi \beta^g} \qquad (1)$$

where:

$$\varphi = \frac{p_i^o \cdot \gamma_i \cdot M_m}{\rho_m} \qquad (2)$$

where:

β^l – mass transfer coefficient in the liquid phase,
β^g – mass transfer coefficient in the gaseous phase,
k_e – evaporation rate constant,
R – gas constant,
T – temperature,
M_m, ρ_m – respectively: the molar mass and density of the basic alloy component, titanium,
p^0_i, γ_i – respectively: aluminium vapour pressure over pure bath and its reactivity coefficient in liquid alloy.

In order to determine the overall mass transfer coefficient for aluminium from the experimental data, the following equation was applied:

$$2{,}303 \log \frac{C^t_{Al}}{C^0_{Al}} = -k_{Al} \cdot \frac{F}{V}(t - t_0) \qquad (3)$$

where:

F – evaporation areas (the interface),
V – liquid metal volume,
$(t - t_o)$ – process duration,
C^t_{Al} – aluminium concentration in the alloy after time t (Table 2),
C^0_{Al} – initial aluminium concentration in the alloy.

In Table 3, values of the experimental coefficient k_{Al}, determined from equation (3), are presented.

Table 2 **Basic experiment parameters and final Al fractions in the alloy**

Test no.	Temp. / K	Pressure / Pa	Final Al concentration in the alloy, / %mass
1	1 973	1 000	3,94
2	1 973	100	3,77
3	1 973	50	3,67
4	1 973	10	3,66
5	1 973	5	3,34
6	1 998	1 000	3,88
7	1 998	100	3,69
8	1 998	50	3,63
9	1 998	10	3,56
10	1 998	5	3,30
11	2 023	1 000	3,86
12	2 023	100	3,62
13	2 023	50	3,57
14	2 023	10	3,48
15	2 023	5	3,19

In order to determine the contribution of resistance related to mass transfer in the liquid Ti-Al-Nb alloy to the overall evaporation process resistance, values of the mass transfer coefficient, β^l, were determined with the use of Machlin's equation which describes mass transfer in the liquid metal phase, inductively stirred. The equation is as follows:

$$\beta^l = \left(\frac{8 D_{Al} \cdot v_m}{\pi \cdot r_m} \right)^{0,5} \qquad (4)$$

where:

v_m – near surface velocity of inductively stirred liquid metal,
r_m – radius of the liquid metal surface (assumed to be the melting pot inner radius),
D_{Al} – Al diffusion coefficient in the liquid alloy.

According to this Author, the v_m value does not depend on the type of inductively stirred alloy or the electrical parameters of the furnace operation and equals 0,1 $m \cdot s^{-1}$ for devices where up to 1 Mg of metal is smelted. However, many studies have shown that this value depends on a lot of factors, i.e. density and viscosity of the metal as well as the electrical parameters of furnace operation, including current frequency, device power and current intensity in the induction coil [11]. For the investigated alloy, the following v_m values were assumed: 0,080 $m \cdot s^{-1}$ for T=1 973, 0,093 $m \cdot s^{-1}$ for 1 998 K and 0,105 $m \cdot s^{-1}$ for T=2 023 K. The values were determined based on the data presented in the paper [10]. In order to determine the aluminium diffusion coefficient in the liquid phase, the equation [12] was used:

$$D_{Al} = 10^{-8} \exp\left[\frac{250\ 000}{R} \left(\frac{1}{1\ 925} - \frac{1}{T} \right) \right] \qquad (5)$$

In Table 3, the values of aluminium mass transfer coefficient in the liquid phase, determined with the use of equation (3), are presented.

Table 3 **Determined values of the k_{Al} and β^l coefficients**

Test no.	Coefficient k_{Al} / m·s^{-1}	Coefficient β^l / m·s^{-1}
1	0,0000220	0,000334
2	0,0000232	0,000334
3	0,0000247	0,000334
4	0,0000252	0,000334
5	0,0000269	0,000334
6	0,0000242	0,000368
7	0,0000250	0,000368
8	0,0000259	0,000368
9	0,0000277	0,000368
10	0,0000309	0,000368
11	0,0000253	0,000404
12	0,0000261	0,000404
13	0,0000274	0,000404
14	0,0000301	0,000404
15	0,0000374	0,000404

DISCUSSION

As demonstrated by the results of experimental Ti-6Al-7Nb alloy smelting in the vacuum induction furnace, the temperature rise from 1 973 K to 2 023 K and working pressure reduction from1 000 Pa to 5 Pa are accompanied by significantly higher aluminium loss from the alloy. At the same time, increased overall mass transfer coefficient (k_{Al}) values from 0,0000220 to 0,0000374 m·s^{-1} are observed. It is illustrated by the data presented in Figure 1.

The determined k_{Al} and β^l values allowed for defining the contribution of mass transfer resistance in the liquid phase to the overall resistance of the process. The contribution of mass transfer resistance in the liquid phase was determined with the use of the following equation:

$$U_l = \frac{\dfrac{1}{\beta^l}}{\dfrac{1}{k_{Al}}} \cdot 100\,\% \tag{6}$$

The contribution of resistance related to mass transfer in the liquid phase did not exceed 8 % for the whole pressure range. It is illustrated by the data presented in Figure 2.

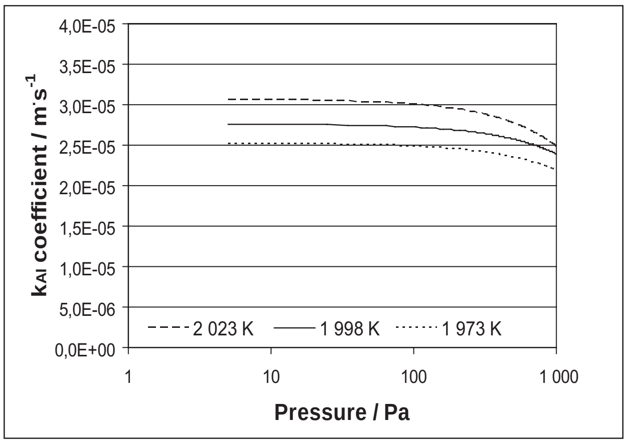

Figure 1 Changes of the overall mass transport coefficient, k_{Al}, depending on the furnace working pressure

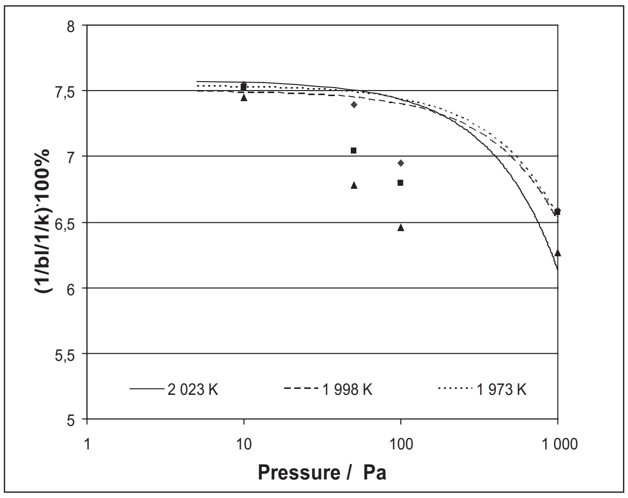

Figure 2 The contribution of resistance in the liquid phase to the overall process resistance depending on the pressure

CONCLUSION

Based on the investigations, the following was demonstrated:

- Final aluminium concentrations in the alloy, following the process, range from 3,19 to 3,94 % mass depending on the process conditions (the initial Al fraction was 5,5–6,5 % mass). The most marked reduction in Al content in the alloy was observed for the process conducted at 2023 K and 5 Pa.
- The aluminium mass transfer coefficient increases with the temperature rise and pressure reduction in the smelting device; its values range from 0,0000220 to 0,000034 m·s^{-1}.
- The resistance related to aluminium mass transfer in the liquid phase is about 8 % of the overall process resistance, which means that this stage does not determine the rate of the whole process

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Note: The responsible for English language is the lecture from Silesian University of Technology, Katowice, Poland