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EFFECTS OF A BATH COMPOSITION ON ALUMINIUM LOSS DURING Ti-Al ALLOY SMELTING IN A VACUUM INDUCTION FURNACE

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In the paper, results of a kinetic analysis of aluminium evaporation from binary Ti-Al alloys during their smelting in a vacuum induction furnace are presented.

Keywords: Ti-Al alloy, evaporation, vaccum induction furnace, kinetic analysis

INTRODUCTION

Titanium alloys belong to a group of the most modern metal materials applied in many industrial branches, which mainly results from their specific properties, i.e. small density, high strength and good corrosion resistance. Contrary to a majority of other metal materials, during smelting and casting of these alloys many technological problems arise. Their reasons are as follows: high chemical activity of titanium, high viscosity with a relatively small density of alloy matrix, a high melting point as well as a high reactivity of these materials with a melting furnace lining and mould materials. Moreover, for these alloys, the process of melting is commonly accompanied by unbeneficial evaporation of their basic components, e.g. aluminium or manganese. [1 - 10]. In the paper, results of a kinetic analysis of aluminium evaporation from binary Ti-Al alloys during their smelting in a vacuum induction furnace are presented.

MATERIALS AND EQUIPMENT

For experiments, Ti-Al alloys containing up to 50 % mass aluminium were used. All the experiments were performed using a SECO-WARWICK VIM 20 - 50 vacuum induction furnace. The device ensures alloy sampling during the smelting process. At the beginning of each experiment, an alloy sample (about 1000 g) was placed in a melting pot located inside the induction coil of the furnace. When the device chamber was closed, the working pressure was lowered to the set level and the charge was heated up to the specified temperature. The alloy was held at that temperature for 600 s. During smelting, alloy samples were collected and subjected to a chemical analysis for aluminium content. All experiments were performed at 1 973 K, 2 023 K, 1 000 Pa and 5 Pa.

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STUDY RESULTS AND DISCUSSION

In Table 1, Al concentrations after each smelting process and values of Al loss rate are presented. Moreover, basic parameters for each experiment, i.e. temperature and pressure in the measuring system, are listed. Based on the Table 1 data, it is seen that the level of Al loss rate in all experiments was 11 % to 20 % and it increased with temperature and lowered pressure in the device. However, no effects of the alloy composition on the aluminium loss rates were observed.

The changes in aluminium concentration in the alloy were used for a kinetic analysis of the investigated process which included:

- determination of the aluminium overall mass transfer coefficient;
- estimation of the coefficient of aluminium mass transfer in the liquid phase and the substitutional evaporation rate constant.

Table 1 **Final alloy compositions following the smelting process**

No.	Temp., / K	Pressure, / Pa	Initial Al content, /%mass	Final Al content, /%mass	Al loss, / %
1	1 973	1 000	6,52	5,78	11,34
2	2 023	1 000	6,52	5,71	12,42
3	1 973	5	6,52	5,34	18,09
4	2 023	5	6,52	5,21	20,09
5	1 973	1 000	24,11	20,76	13,89
6	2 023	1 000	24,11	20,53	14,84
7	1 973	5	24,11	20,13	16,50
8	2 023	5	24,11	19,31	19,90
9	1 973	1 000	48,32	43,22	10,55
10	2 023	1 000	48,32	40,59	15,99
11	1 973	5	48,32	39,69	17,66
12	2 023	5	48,32	39,41	18,43

The value of overall mass transfer coefficient, k_{Al}, was determined using the following equation:

$$2{,}303 \log \frac{C^k_{Al}}{C^o_{Al}} = -k_{Al} \frac{F}{V} \cdot t \quad (1)$$

where:

C^k_{Al} and C^o_{Al} – initial and final aluminium concentrations in the alloy, respectively

t – time

F – evaporation area

V – bath volume.

Based on the equation (1), it is seen that for correct determination of the k_{Al} coefficient, the evaporation area, F, must be known. For crucible furnaces, it is mostly assumed equal to the inner cross-section of the crucible. In the analysed case, however, a meniscus is formed in the liquid metal, which results in increased evaporation area. To determine the liquid titanium meniscus area for the experimental conditions of the study, a methodology based on the coupled model of the electromagnetic field and the hydrodynamic field of liquid metal was used. [11 - 13]. The hydrodynamic calculations were performed based on the VOF method which is also commonly used for a description of e.g. a process of liquid steel casting. [14]. The evaporation area, determined using this method, was 0,0068 m^2.

Estimation of the coefficient of mass transfer in the liquid metal phase is only possible for several hydrodynamic systems in metallurgical devices, including liquid metal barbotage with inert gas [15 - 18] and inductive metal stir. In the latter case, a value of this coefficient can be determined based on the following equation:

$$\beta^l_{Al} = \left(\frac{8D_{Al} \cdot V_m}{\pi \cdot r_m} \right)^{\frac{1}{2}} \quad (2)$$

where:

v_m – near-surface velocity of inductively stirred liquid metal

r_m – radius of a liquid metal surface

D_{Al} – Al diffusion coefficient in liquid alloy.

In the present paper, to determine a liquid titanium mean velocity, a mathematical model of liquid metal melting and heating in the induction furnace, considering the electromagnetic field and hydrodynamic field coupling, was applied [19 - 20]. The near-surface velocity values, determined using this method, were within 0,135 – 0,154 m·s^{-1}.

To determine the coefficient of aluminium diffusion in the liquid phase, the Darken's equation was used, assuming the aluminium and titanium self-diffusion activation energies to be, respectively: 52,8 and 24,1 kJ·mol^{-1} [21]. The determined coefficients of aluminium diffusion in liquid titanium were: 0,88 to 1,79 · 10^{-9} m^2·s^{-1}.

To determine the value of substitutional evaporation constant, k^e_{Al}, the following equation was applied:

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

where:

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

where:

γ_{Al} – coefficient of Al activity in liquid alloy

p^o_{Al} – 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.

To determine values of activity coefficient for individual components of the alloys, equations presented in the paper [22] were applied.

The values of k_{Al}, β_{Al} and k^e_{Al} coefficients, determined based on equations (1) - (3), are presented in Table 2. The data show that increased content of aluminium in the alloy does not cause a significantly increased value of the aluminium overall mass transfer coefficient.

The determined values of k_{Al}, β_{Al} and k^e_{Al} coefficients allowed for defining stages that determined the investigated process. For all experiments, the level of resistance related to mass transfer in the liquid phase did not exceed 15 %. At the same time, the ratio of resistance related to evaporation to the overall process resistance for all experiments exceeded 50 %, which means that the investigated process was kinetically controlled. The obtained results are consistent with findings of Su and Guo who observed identical control for processes of aluminium evaporation from Ti-Al alloys (above 24 % of Al) using the induction skull melting technology. [23, 24].

The experiments demonstrated a potential use of granulates made of fine-grained carboniferous materials as reducers in the process of copper oxide slag smelting. However, it should be noted that with respect to application of these granulates, an appropriate agglomeration technology and studies on the granulate effects on the environment during their combustion should be developed and conducted, respectively.

Table 2 **Values of k_{Al}, β_{Al} and k^e_{Al} coefficients**

No.	k_{Al}·10^{-5} / m·s^{-1}	β_{Al}· 10^{-5} / m·s^{-1}	k^e_{Al}·10^{-5} / m·s^{-1}
1	0,88	11,6	1,70
2	1,00	11,5	1,91
3	1,46	11,6	1,70
4	1,64	11,5	1,91
5	1,11	10,2	1,83
6	1,20	10,1	2,01
7	1,34	10,2	1,83
8	1,66	10,1	2,01
9	1,12	8,34	1,99
10	1,30	8,30	2,15
11	1,47	8,34	1,99
12	1,53	8,30	2,15

SUMMARY

While investigating the process of aluminium evaporation from Ti-Al alloys molten in the vacuum induction furnace, the following have been observed:

- The Al loss rates for all experiments were 11 % to 20 %; they increased with temperature and lowered pressure in the device.
- No significant effects of the alloy composition on the aluminium loss rates are observed.
- The investigated process is kinetically controlled, i.e. its rate is determined by the rate of evaporation which occurs on a liquid metal surface

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