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LOSS OF ALUMINIUM DURING THE PROCESS OF Ti-Al-V ALLOY SMELTING IN A VACUUM INDUCTION MELTING (VIM) FURNACE

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In the present paper, results of the study on changes in basic Ti-6Al-4V alloy component contents during smelting in the vacuum induction melting (VIM) furnace are presented. The experiments were performed at 5 – 1 000 Pa and 1 973–2 023 K. Assuming that the observed loss of aluminium from the alloy during smelting is the effect of evaporation, an additional thermodynamic analysis was performed aimed at determining evaporation coefficients.

Key words: Ti-Al-V alloys, VIM technology, evaporation of Al, coefficient of evaporation.

INTRODUCTION

At present, the aim of each industrial branch is implementation of new solutions which mostly regard applied technologies as well as new organisation and management methods. Thus, development and implementation of innovations under global economy conditions have become the most urgent issue. In the field of new material production, development work basically focuses on adjustment of products and their quality to the market requirements, modernisation of existing technological processes and implementation of new solutions in terms of reduced material and energy consumption during production as well as introduction of devices that shorten the production cycle. Also, it should be noted that in many cases technological modifications are forced by a change of raw material resources: primary raw materials are replaced by secondary materials. It is particularly important for metal production processes where traditional ores are replaced by such metalliferous materials as scrap, powder or sludge. Qualitative development in the field of new constructive materials refers to i.a. light titanium-based alloys, which primarily results from their low densities and very good mechanical properties. Titanium alloys are modern constructive materials applied in the aerospace industry, medical technology, chemical engineering etc. [1 - 5]. Ti-Al-X alloys are excellent examples of these materials; however, their manufacturing processes are very complicated due to their high reactivity with melting pot materials and a potential significant alteration of the alloy chemical composition during smelting and casting. The latter is caused by evaporation of the basic alloy component, i.e. aluminium. The evaporation rate depends on many factors. The major ones are: smelting temperature, smelting device pressure, alloy composition and broadly defined system hydrodynamics of the process [6, 7]. In the paper, results of the study on changes in basic Ti-6Al-4V alloy component contents during smelting in the vacuum induction furnace are discussed.

EXPERIMENTAL PART

In the experiments, Ti-6Al-4V alloy samples (see Table 1 for its chemical composition) were investigated. All experiments were performed with the use of a one-chamber VIM 20 - 50 vacuum induction furnace manufactured by SECO - WARWICK. The scheme of the device is presented in Figure 1.

Table 1 **Chemical composition of the Ti-6Al-4V alloy used in the study**

The content of the basic alloying elements / % mass							
Ti	Al	V	Fe	Mo	Si	Zr	Pd
90,42	5,50	3,77	0,08	0,12	0,07	0,02	0,02

Each experiment began with introducing an alloy sample (of pre-specified mass) to the graphite melting pot placed in the induction coil of the furnace. After closing the furnace, pre-specified vacuum was generated by the pump system of the device. The pressure was generated with the use of mechanical and Roots pumps as well as the diffusion pump, if necessary. During the next stage of experiment, the charge material was heated up to the set temperature, at which liquid metal was held for 10 minutes. In exactly defined time intervals, metal samples were collected. For temperature measurements, a pyrometer and a PtRh-Pt thermocouple (as a control device) were used. When the test was completed, liquid metal was poured into the graphite ingot mould. When it solidified and the furnace cooled down,

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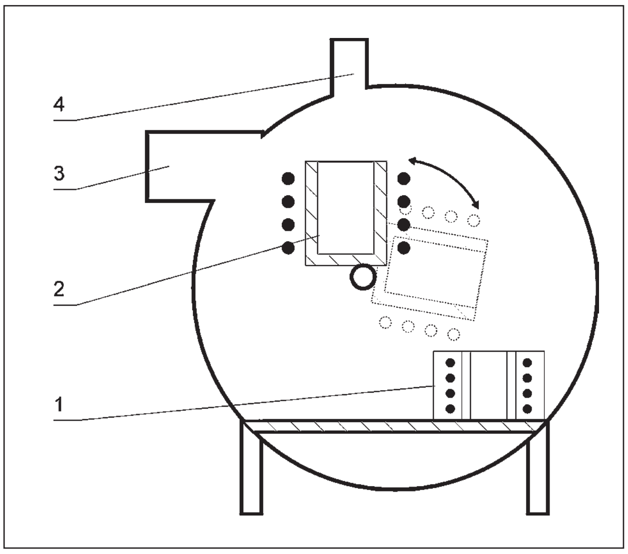

Figure 1 The scheme of experimental device used in the study: 1 – an ingot mould with a heating system, 2 – an inductor with a ceramic melting pot, 3 – an outlet to vacuum pumps, 4 – a mounting point for the system for temperature measurements and sample collection

the furnace chamber was opened and the alloy sample was analysed for aluminium, vanadium and titanium contents. The experiments were performed at 5 to 1 000 Pa and 1 973 – 2 023 K. The sample mass was about 1 000 g.

EXPERIMENT RESULTS

Final titanium, aluminium and vanadium fractions in the alloy with regard to each experiment are listed in Table 2. Additionally, in Figures 2 – 4, graphic interpretations of observed changes in these metal fractions during smelting are presented.

Table 2 **Final alloy compositions following the VIM smelting process**

Temp. /K	Pressure /Pa	Final metal fractions in the alloys / % mass		
		Ti	Al	V
1 973	1 000	91,100	4,707	3,797
1 973	1 000	91,167	4,720	3,830
2 023	1 000	91,533	4,383	3,817
2 023	1 000	91,500	4,450	3,800
1 973	50	91,600	4,307	3,763
1 973	50	91,800	4,200	3,750
2 023	50	91,767	4,230	3,750
2 023	50	91,900	4,160	3,720
1 973	10	91,800	4,220	3,710
1 973	10	91,900	4,170	3,720
2 023	10	91,933	4,110	3,707
2 023	10	91,900	4,100	3,710
1 973	5	91,833	4,063	3,820
1 973	5	91,800	4,080	3,870
2 023	5	92,000	4,017	3,723
2 023	5	92,100	3,960	3,700

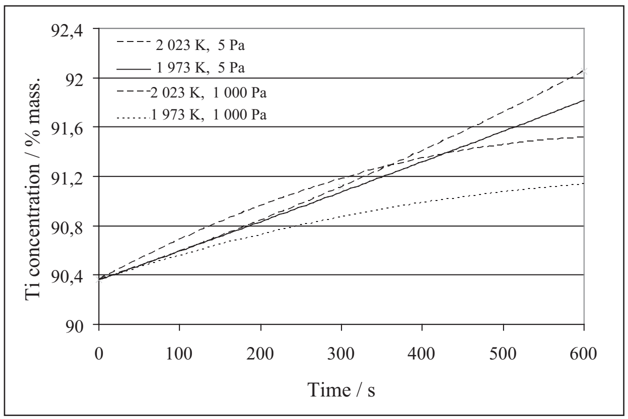

Figure 2 Changes in the titanium fraction in the Ti-6Al-4V alloy during smelting

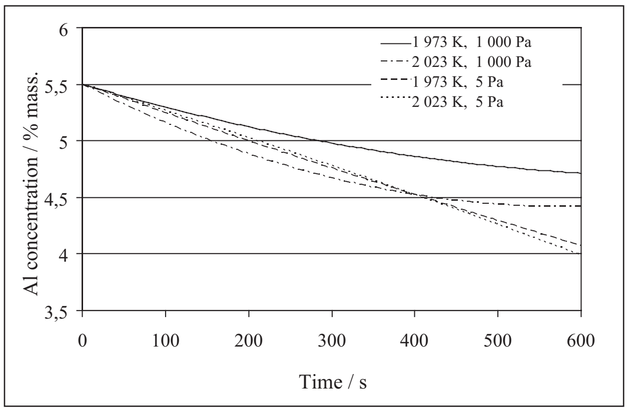

Figure 3 Changes in the aluminium fraction in the Ti-6Al-4V alloy during smelting

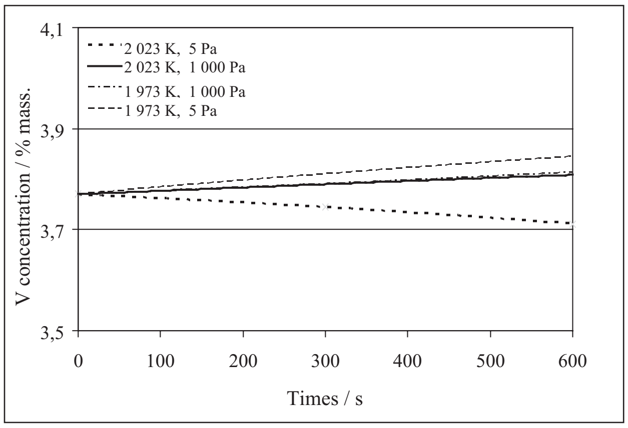

Figure 4 Changes in the vanadium fraction in the Ti-6Al-4V alloy during smelting

DISCUSSION OF RESULTS

In order to perform a full analysis of results with regard to changes in the investigated alloy composition during smelting, vapour pressures of individual alloy components over the metal bath were calculated with the use of the following relation

$$p_i = p_i^o \cdot a_i = p_i^o \cdot \gamma_i \cdot X_i = \left[\exp\left(-\frac{\Delta_p G_i^o(T)}{RT}\right)\right] \cdot \gamma_i \cdot X_i (1)$$

where:

p_i – ‘i’ alloy component pressure over the solution

X_i – a molar fraction of the 'i' component in the solution
R – the gas constant
T – the absolute temperature
$\Delta pGi(T)$ – standard free enthalpy of the evaporation reaction

The free enthalpy values for the analysed Ti-Al-V system were obtained from the HSC Chemistry 6 thermodynamic database (Table 3).

Table 3 **Free enthalpies of the titanium, aluminium and vanadium evaporation reaction**

Selected evaporation reaction	ΔG / KJ·mol^{-1}			
	1 973 / K	1 998 / K	2 023 / K	2 073 / K
$Ti_{(l)} = Ti_{(g)}$	195	192	189	182
$Al_{(l)} = Al_{(g)}$	88	85	82	77
$V_{(l)} = V_{(g)}$	223	220	216	209

For the calculations, the titanium reactivity coefficient was assumed 1, while the aluminium and vanadium activity coefficients were assumed $\gamma_{Al} = 0,12$ and $\gamma_V = 0,89$, respectively [8].

In Figure 5, determined values of titanium, aluminium and vanadium equilibrium vapour pressures over the pure bath are presented, while Figure 6 shows determined changes in vapour pressures of these metals over liquid Ti-6Al-4V alloy versus temperature.

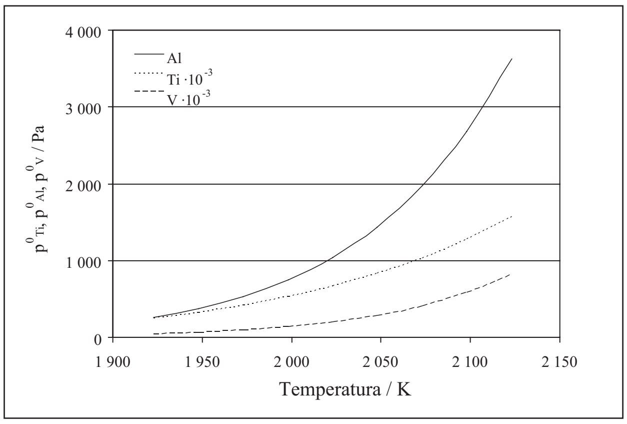

Figure 5 Changes in titanium, aluminium and vanadium equilibrium vapour pressures over the pure bath versus temperature

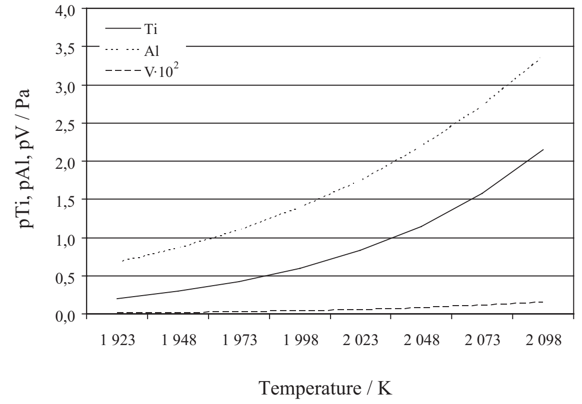

Figure 6 Changes in titanium, aluminium and vanadium vapour pressures over liquid Ti-6Al-4V alloy versus temperature

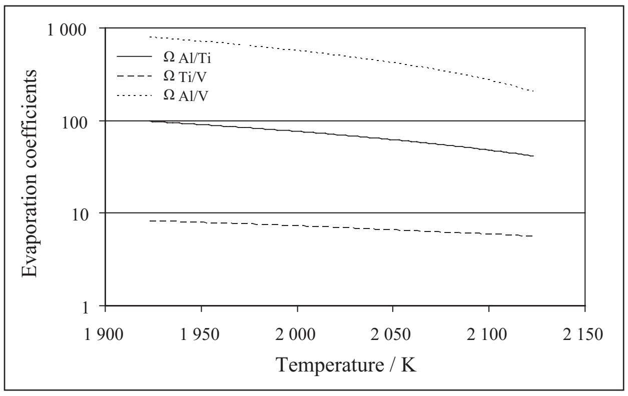

Figure 7 Changes in the coefficient Ω values versus temperature for the basic alloy components, i.e. Ti, Al, V

Based on the equilibrium vapour pressures of titanium, aluminium and vanadium over pure components, a so-called evaporation coefficient was determined, described in the following relation [9]:

$$\Omega = \frac{\gamma_i \cdot P_i^0}{\gamma_j \cdot P_j^0} \qquad (2)$$

When the $\Omega = 1$ condition is met, it is assumed that the alloy composition does not change during smelting. When $\Omega > 1$, 'i' component loss in the alloy is observed (due to evaporation) versus the 'j' component. When the $\Omega < 1$ condition is met, the situation is reversed. Figure 7 shows changes in the Ω values versus temperature for the three basic alloy components, i.e. Ti, Al and V. For aluminium and vanadium, the $\Omega_{Al/V}$ values were within 257 - 859, while for aluminium and titanium ($\Omega_{Al/Ti}$), they were within 45 – 103.

Thus, the analysis showed that, thermodynamically, there is a potential for aluminium evaporation from the Ti-6Al-4V alloy during its smelting at decreased pressure. This was confirmed by the results of investigations performed with the use of the vacuum induction furnace.

A change in aluminium content in the alloy from 5,5 % mass in the initial material to 3,96 % mass in the 5 Pa-smelted alloy was observed. In each experiment, pressure reduction was accompanied by reduction in the $C^k_{Al/v}$ and $C^k_{Al/Ti}$ ratios (Figures 8 – 9), suggesting that with the vacuum value increase, the aluminium evaporation process is intensified.

The discussed phenomenon of aluminium evaporation from Ti-Al-V alloys occurs even more intensively during the smelting process when the EBM technology is applied. For instance, in the study [10], this technology yielded aluminium content reduction to 3,11 % mass. in only 300 seconds. Comparable results were obtained by Nakamura and Mitchell [11] and Isawa et al. [12]. Greater aluminium loss from the Ti-6Al-4V alloy during EBM smelting compared to observed losses dur-

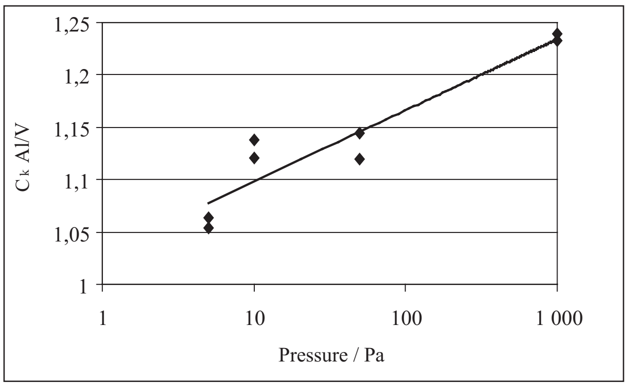

Figure 8 The effect of pressure on final aluminium and vanadium fractions in the alloy (temperature 1 973 K)

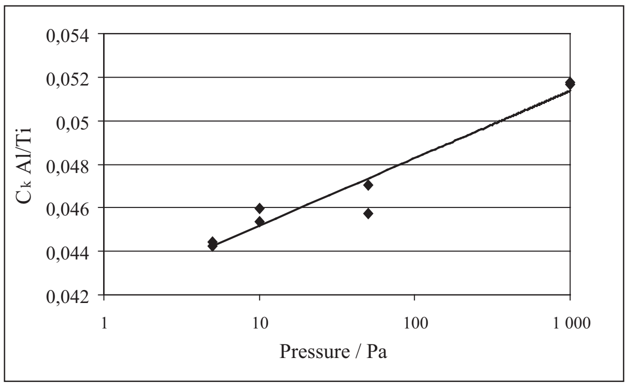

Figure 9 The effect of pressure on final aluminium and titanium fractions in the alloy

ing the VIM process is affected by two factors. Firstly, the EBM technology is characterised by considerably lower operation pressure in the device than in vacuum induction furnaces. Secondly, significant liquid metal temperature rises (even by 100 degrees) are observed compared to virtually stable temperature during the VIM processes.

SUMMARY

During VIM smelting of the Ti-6Al-4V alloy, significant evaporation of aluminium was observed. Pressure reduction in the device from the atmospheric pressure to the range from 1 000 Pa to 5 Pa was accompanied by Al content reduction from the initial value of 5,5 % mass to the value even below 4 % mass. Also, smelting temperature rise intensified aluminium evaporation. However, aluminium losses are smaller than those observed during the EBM processes.

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REFERENCES

[1] K. Pałucha: Metalurgija 51 (2012), 3, 357-360.
[2] M. Czapla, M. Karbowniczek, A. Michaliszyn: Archives of Metallurgy and Materials 53 (2008), 2, 559–565.
[3] P. Folęga: Archives of Materials Science and Engineering 51 (2011), 1, 55–60.
[4] R. Burdzik, Z. Stanik, J. Warczek: Archives of Metallurgy and Materials 57 (2012), 3, 409–416.
[5] M. Niklewicz, A. Smalcerz: Przegląd Elektrotechniczny 86 (2010), 5, 333-335.
[6] L. Blacha, J. Łabaj: Metalurgija 51 (2012), 4, 529-533.
[7] C. Kolmasiak: Metalurgija 51 (2012), 3, 317-320.
[8] Z. Yan, Y. Yanging, S. Jun: Trans. Nonferrous Met. Soc. China 14 (2004), 5, 876-879.
[9] G. Jingjie, L. Guizhong, S. Yanqing, D. Hongsheng, J. Jun, F. Hengzhi: Trans. Nonferrous Met. Soc. China 12 (2002), 4, 587-591.
[10] S. Watakabe, K. Suzuki, K. Nishikawa: ISIJ International 32 (1992), 5, 625-629.
[11] H. Nakamura, A. Mitchell: ISIJ International 32 (1992), 5, 583-592.
[12] T. Isawa, H. Nakamura, K. Murakami: ISIJ International 32 (1992), 5, 607-615.

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