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Changes in Ti-Al-Mn alloy compositions during their smelting in a vacuum induction furnace

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ABSTRACT

Purpose: Major problems with smelting of light titanium-based alloys are related to their strong reactivity in the liquid phase with virtually all melting pot materials. Another problem regarding titanium alloy smelting is an unfavourable process of alloy component evaporation due to high melting temperatures of the alloys and significant differences in vapour pressures of their individual components. In the present paper, results of a study on manganese evaporation from the OT4 alloy are presented.

Design/methodology/approach: The OT4 alloy contained 94.29, 3.50 and 1.49 %mass of Ti, Al and Mn, respectively. The experiments were performed at 5 to 1000 Pa for 1973 K and 2023 K. During each smelting experiment, metal samples were collected and analysed for titanium, aluminium and manganese contents.

Findings: During inductive OT4 alloy smelting from the Ti-Al-Mn system at reduced pressure, significant manganese losses from the alloy are observed as a result manganese evaporation. For manganese and titanium, the evaporation coefficient $\Omega_{Mn/Ti}$ values were within 12421–42899, while for manganese and aluminium ($\Omega_{Mn/Al}$), they were within 34 to 52, suggesting that, thermodynamically, there is a potential for intense manganese evaporation from the investigated alloy.

Research limitations/implications: The study findings may be a basis for a full kinetic analysis of Mn evaporation from the OT4 alloy which enables determination of process-controlling stages.

Practical implications: The study results regarding changes in manganese content in the OT4 alloy during its smelting with the use of VIM technology suggest that one of conditions that may limit the unfavourable process of manganese evaporation is shortening the smelting time or performing the process at about 1000 Pa.

Originality/value: In literature, there are no data regarding results of studies on manganese elimination from Ti-Al-Mn alloys during their smelting.

Keywords: Ti-Al-Mn alloys; VIM technology; Evaporation of Mn; Coefficient of evaporation

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

In recent years, a lot of innovations in the field of metallic material production have been observed. This is mainly due to environmental protection issues, necessary reduction in technology-related energy consumption and a change of raw material resources [1,2]. Another very important issue regarding metallic material development is a search for new materials or improvement of existing material properties. Ti-Al-X alloys, becoming increasingly important for many years, are considered promising materials in view of their excellent mechanical characteristics with extremely low densities. However, Ti-Al-X alloys belong to the constructive material class characterized by complicated manufacturing processes [3-7] resulting from high reactivity of the alloy matrix, i.e. titanium, with ceramic materials of the melting pot or ingot mould as well as significant differences in the alloy basic component vapor pressures at melting temperatures. The latter factor, both during alloy smelting and casting, contributes to an unfavorable process of aluminium evaporation. In the present paper, results of studies on manganese elimination during OT4 alloy smelting are presented. The alloy is utilized in the aerospace and energy industries as well as for production of specific chemical equipment components. In recent years, a potential use of the alloy for implant production has been demonstrated [9-10]. In Ti-Al-Mn smelting processes, mostly VIM, EBM and EAR technologies are applied. Each technology is related to low-pressure environment, which promotes an unfavorable process of alloy component evaporation. Other factors that affect intensity of this process are: smelting temperature, its duration and the system hydrodynamics. In the last case, the system can be generally assumed a type of device used for smelting of these alloys [11].

2. Materials and methods

The investigational material was OT4 alloy whose composition is presented in Table 1. The alloy is utilized e.g. in the aerospace and energy industries as well as for production of chemical equipment.

Table 1.
Chemical composition of the OT4 alloy used in the study

Alloy labeling	Basic alloy component contents, %mass					
	Ti	Al	Mn	Fe	Si	Zr
Ti-4Al-2Mn	94.29	3.50	1.49	0.30	0.12	0.30

The smelting experiments were performed with the use of a one-chamber VIM 20-50 vacuum induction furnace manufactured by SECO-WARWICK. It is a modern metallurgic device designed for vacuum metal smelting at maximum 0.01 Pa and maximum 2073 K. The device is equipped with systems meant for introducing alloy additions to the metal bath and in-smelting metal sampling. Metal casting is performed in a pre-heated ingot mould. The scheme of the furnace is presented in Fig. 1.

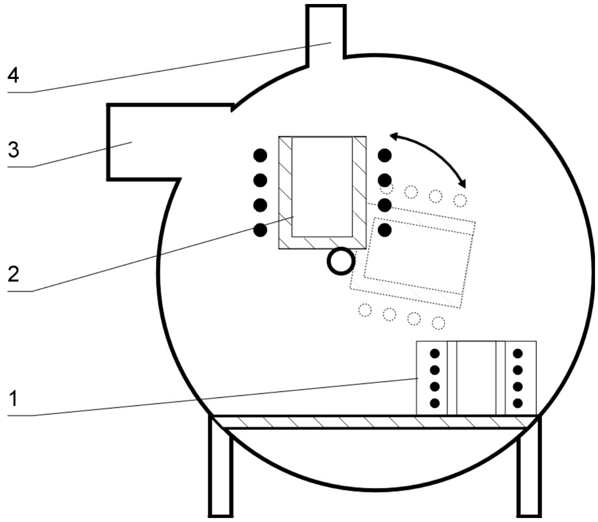

Fig. 1. The scheme of experimental device: 1 - an ingot mould with a heating system; 2 - an inductor with a ceramic melting pot; 3 - an outlet to vacuum pumps; 4 - a mounting point for the system for temperature measurements and sample collection

Each experiment began with introducing an alloy sample (about 1000 g) to the graphite melting pot placed in the induction coil. After closing the furnace chamber, assumed vacuum was generated by the pump system. When the vacuum level was stabilized, the melting pot was heated up to the required temperature and the liquid metal sample was held under the set conditions for 600 sec. During smelting, metal samples were collected and analyzed for titanium, aluminium and manganese contents. The experiments were performed at 5-1000 Pa for 1972 K and 2023 K.

The final alloy compositions with regard to each experiment are listed in Table 2. Figs. 2-4 show sample graphic interpretations of observed changes in individual alloy component fractions during smelting performed at 5 Pa and 1973, 2023 K.

Table 2.
Final alloy compositions after smelting in the vacuum induction furnace

No.	Temperature, K	Pressure, Pa	Final metal fractions in the alloys, %mass		
			Ti	Al	Mn
1	1973	1000	95.433	2.633	1.330
2	2023	1000	95.367	2.643	1.21
3	1973	100	96.000	2.867	0.693
4	2023	100	96.100	2.743	0.313
5	1973	50	96.067	2.767	0.494
6	2023	50	96.367	2.750	0.349
7	1973	10	96.333	2.990	0.079
8	2023	10	96.491	2.843	0.037
9	1973	5	96.433	2.807	0.039
10	2023	5	96.511	3.023	0.032

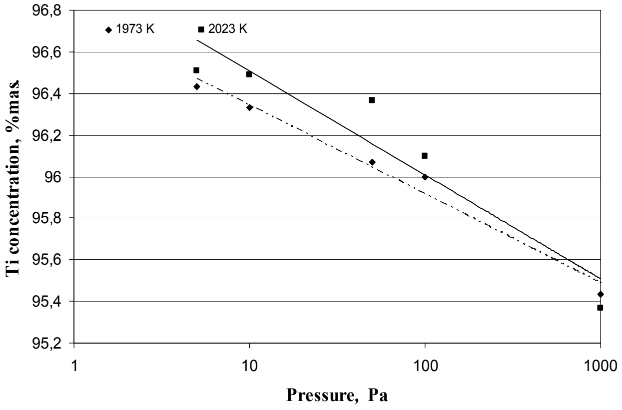

Fig. 2. Changes in the alloy Ti fraction related to the VIM chamber pressure during smelting

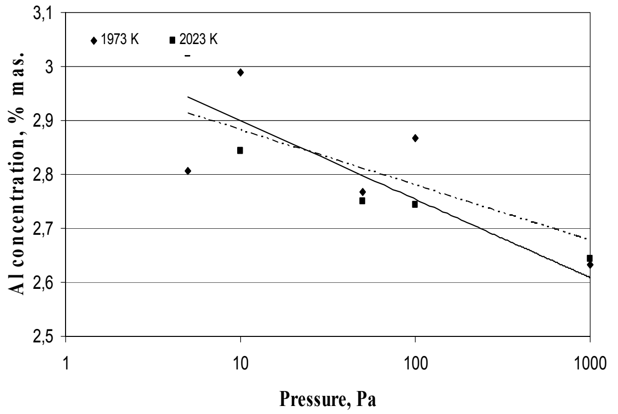

Fig. 3. Changes in the alloy Al fraction related to the VIM chamber pressure during smelting

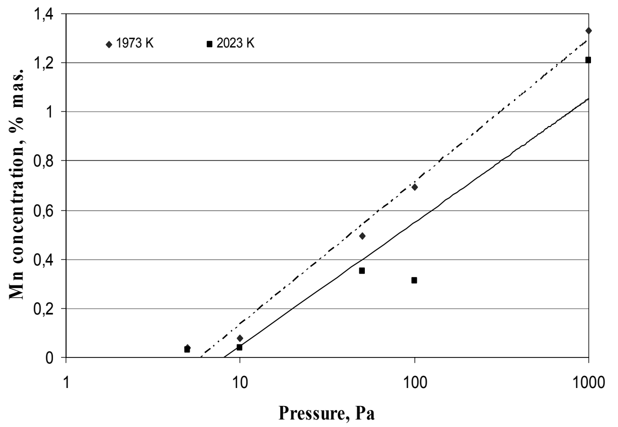

Fig. 4. Changes in the alloy Mn fraction related to the VIM chamber pressure during smelting

2.1. Thermodynamic analysis of the OT4 component evaporation

Assuming that observed manganese losses during smelting result from its evaporation, vapor pressures of individual OT4 components over the metal bath were calculated in order to perform a full analysis, using the following relation:

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

where:
p_i - ‘i’ alloy component pressure over the solution
p^o_i - ‘i’ alloy component vapor pressure over pure bath
X_i - a molar fraction of the ’i‘ -component in the solution
R - the gas constant
T - the absolute temperature
$\Delta_p G^0_i(T)$ - standard free enthalpy of the evaporation reaction

The equilibrium pressures over pure Ti, Al and Mn components were determined based on known standard free enthalpies of the evaporation reactions ,$\Delta_p G^0_i$ (T). The values were obtained from the HSC Chemistry 6 thermodynamic database (Tab. 3). The determined values of vapor pressure $p^o i$ were listed in Table 3 and presented in Fig. 5.

Table 3.
Free enthalpies of the titanium, aluminium, manganese evaporation reactions and their equilibrium pressures

Metal	Equilibrium pressure p^o_i, Pa		Change in the standard free enthalpy $\Delta_p G^0_i$ (T), kJ mol^{-1}	
	1973 K	2023 K	1973 K	2023 K
Titanium	0.53	1.04	195.19	189.03
Aluminium	415.63	662.63	88.20	82.77
Manganese	10547	15114	36.31	31.31

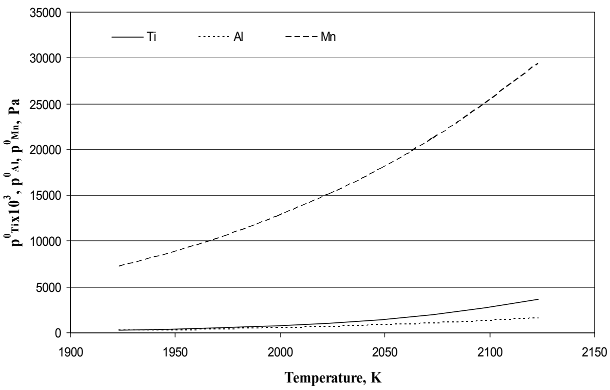

Fig. 5. Titanium, aluminium and manganese pressures over the pure component at 1923-2123 K

For estimations of the p_i values of the basic alloy components from Equation (1), activity coefficients $\gamma_{Ti} = 1.01$, $\gamma_{Al} = 0.83$ and $\gamma_{Mn} = 1.53$ were assumed. They were determined based on the data collected by Kostowa and Żivkovic [12]. Titanium, aluminium and manganese equilibrium pressures over liquid OT4 alloy versus temperature are presented in Fig. 6.

Additionally, based on the equilibrium pressures of titanium, aluminium and manganese vapors over pure components, values of so-called evaporation coefficient were determined, described in the following relation [7]:

$$\Omega = \frac{\gamma_i \cdot P_i^0}{\gamma_j \cdot P_j^0} \tag{2}$$

When the $\Omega > 1$ condition is met, 'i' component loss is observed (due to evaporation). Fig. 7 shows changes in the Ω values versus temperature for three basic alloy components, i.e. Ti, Al and Mn.

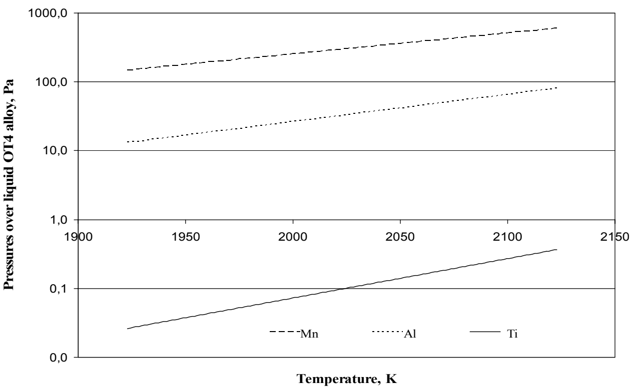

Fig. 6. Titanium, aluminium and manganese pressures over liquid OT4 alloy

3. Discussion of results

The data presented in Fig. 7 show that for manganese and titanium, the $\Omega_{Mn/Ti}$ values were within 12421-42898, while for manganese and aluminium ($\Omega_{Mn/Al}$), they were within 34-52, suggesting that, thermodynamically, there is a potential for intense manganese evaporation from the investigated alloy.

This was confirmed by the results of studies on OT4 alloy smelting in the vacuum induction furnace. A change in manganese content in the alloy from 1.48 mass% in the initial material to 0.032 %mass in the 5 Pa-smelted alloy was observed. In each experiment, pressure reduction was accompanied by reduction in the $C^k_{Mn/Al}$ and $C^k_{Mn/Ti}$ ratios (Figs. 8-9), suggesting that with the vacuum value increase, the manganese evaporation process is intensified.

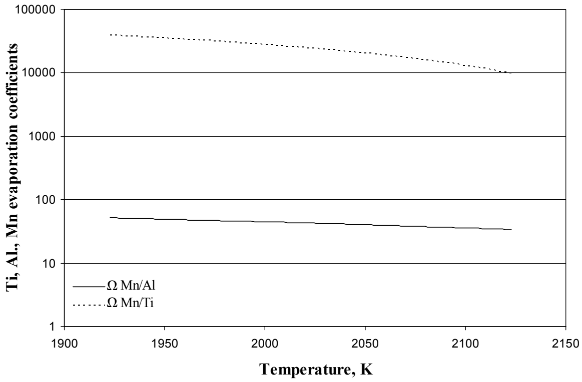

Fig. 7. Changes in the coefficient Ω values versus temperature for the basic alloy components

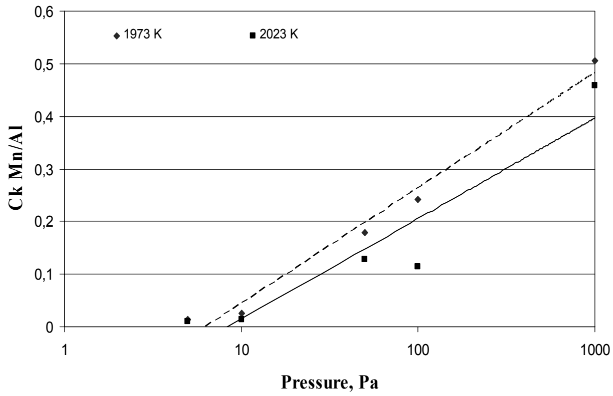

Fig. 8. Changes in the $C^k_{Mn/Al}$ values at 5-1000 Pa

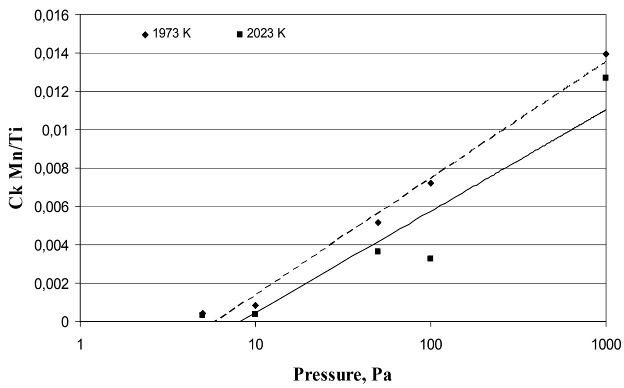

Fig. 9. Changes in the $C^k_{Mn/Ti}$ values at 5-1000 Pa

4. Summary

With regard to the Ti-Al-Mn system, during inductive OT4 alloy smelting at reduced pressure, significant manganese loss from the alloy is observed, which results from its evaporation.

Pressure reduction in the device to the pressure range from 1000 Pa to 5 Pa was accompanied by Mn content reduction from the initial value of 1.49% mass to the value even below 0.04% mass. Also, with the smelting temperature rise, aluminium evaporation was intensified. In order to reduce this unfavorable process, it appears advisable to shorten smelting time or perform the process at about 1000 Pa.

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