# ALUMINIUM LOOS IN THE PROCESS OF Ti-6Al-7Nb SMELTING

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## Abstract
In the paper, results of experimental smelting of the Ti-6Al-7Nb alloy in a vacuum induction furnace are presented. The experiments were performed at 5-1000 Pa and 1973-2023 K. For the analysed alloy, a significant impact of pressure on aluminium loss was observed. Pressure reduction in the device from 1000 Pa to 5 Pa was accompanied by Aluminium content decrease from the initial value of 5.5 % mass to a value even below 3.2 % mass. Moreover, aluminium elimination was enhanced when the smelting temperature increased. Additionally, values of a so-called evaporation coefficient ($\Omega$) were determined. In terms of titanium and niobium, $\Omega_{Al/Ti}$ and $\Omega_{Al/Nb}$ values suggest that, thermodynamically, aluminium loss may result from its intense evaporation from the investigated alloy.

**Keywords:** Ti-Al-Nb alloys, VIM technology, evaporation

## 1 Introduction
At present, each industrial branch focuses on innovations which are seen as alterations and a chance for a future success. The subjects of innovative activities are usually products, technological processes, company organisation and management systems. Innovative activities are mostly forced by the market and, regarding their beneficial results, they add to improvements in product quality and production output as well as cost reduction and a less negative impact of a specific technological process on the environment.
Moreover, innovations hold a clear position in the area of new material manufacturing. Advancements in this field are currently far more frequently observed than in the past due to new design technologies, new research methods and modern production technologies. Examples of development of such materials are light titanium-based alloys. In recent years, increasingly more applications of these alloys have been observed. At present, the materials are utilized in the civil aviation and military aircraft; energy, chemical and automotive industries as well as in medicine and even in the construction and shipbuilding industries [1-6]. Increased interest of the contemporary industry in titanium alloys is best illustrated by the structure of this material utilization in modern airplanes (**Table 1**) [7].
In the process of melting of titanium and its alloys, arc, plasma, electron-beam and induction furnaces are used. Major problems with smelting of these materials are related to their strong reactivity in the liquid phase with virtually all melting pot materials, including particularly resistant Th and Ca oxides [8–9]. Therefore, smelting processes should be performed in chilled,

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copper melting pots with a cold-wall melting pot ("skull crucible"), obtained from molten material during intensive heat evacuation, being particularly convenient.

**Table 1** The structure of material utilization in Boeing 777-200 and Boeing 787 – Dreamliner airplanes [7]

| Material | Boeing 777-200 [%] | Boeing 787 – Dreamliner [%] |
|---|---|---|
| Aluminium | 70 | 20 |
| Steel | 7 | 7 |
| Titanium | 6 | 14 |
| Other | 7 | 9 |
| Glass fiber reinforced polymer (GFRP) | 3 | 2 |
| Carbon fiber reinforced polymer (CFRP) | 7 | 43 |
| Other Composites | - | 5 |

Another problem regarding titanium alloy smelting is an unfavourable process of alloy component evaporation due to a high melting temperature and significant differences in vapour pressures of the alloy individual components. It is clearly seen during Ti-Al-X alloy smelting and casting processes where reduction in aluminium content is observed. Study results available in the literature mostly concern aluminium loss during titanium-aluminium-vanadium alloy smelting are available [10–14], while there are no data on the kinetics of this metal evaporation from Ti-Al-Nb alloys. The available reports only regard Ti-25Al-25Nb and Ti-13Al-29Nb alloys which are smelted by means of the VIM-skull melting method [15, 16]. Results of the experiments on aluminium loss during the process of Ti-6Al-7Nb alloy smelting in the vacuum induction furnace are presented below.

## 2 Experimental materials and methods

In the experiments, the Ti-6Al-7Nb alloy was used (see **Table 2** for its composition).

**Table 2** Chemical composition of the investigated alloy

| **Alloy type** | **Basic alloy component fractions [% mass]** | | | | |
|---|---|---|---|---|---|
| | Al | Nb | Fe | Ta | Ti |
| Ti-6Al-7Nb | 5.5 – 6.5 | 6.5 – 7.5 | ≤0.25 | ≤0.5 | Last fraction |

All experiments were performed in a vacuum induction furnace which enables smelting of metals under high vacuum. Additionally, it is equipped with an in-smelting sampling system. Each experiment began with loading an alloy sample (about 1000 g) into a graphite melting pot placed in the induction coil of the furnace. After closing the furnace, the pre-specified vacuum was generated with the use of a pump system, i.e. a diffusion pump and a Root's pump. When the pressure level was stabilized, the melting pot was heated up to the required temperature and the metal bath was held for 600 s. During each smelting experiment, metal samples were collected and analysed for titanium, aluminium and niobium contents. The experiments were performed at 5–1000 Pa for 1973–2023 K.

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## 3 Results

In **Table 3**, sample final post-smelting alloy compositions are presented. **Fig. 1** and **2** show graphic interpretations of aluminium content changes during smelting for selected experiments, while in **Fig. 3**, the final Al concentrations in the alloy vs. the furnace operating pressure are presented.

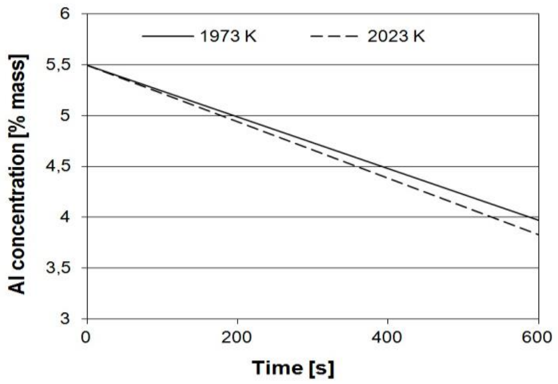


**Fig. 1** Aluminium concentration changes during smelting at 1000 [Pa]

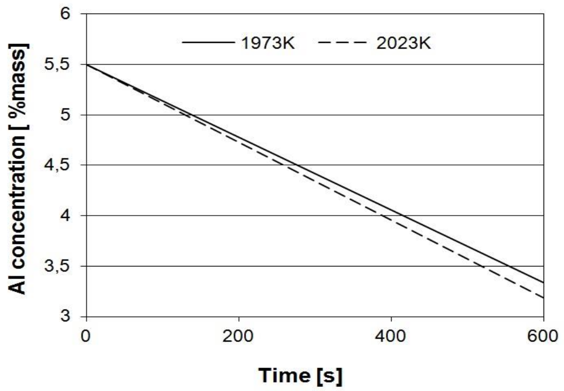


**Fig. 2** Aluminium concentration changes during smelting at 5 [Pa]

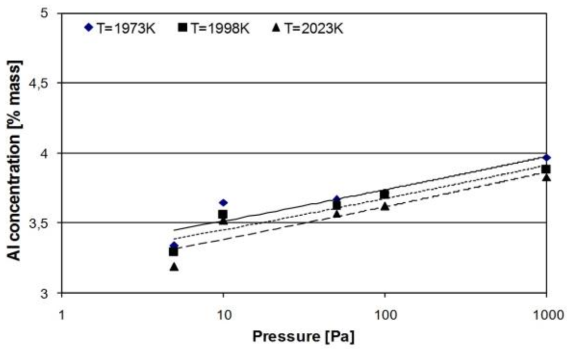


**Fig. 3** Final aluminium concentrations in the alloy after smelting at 5–1000 [Pa]

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**Table 3** Final Ti-6Al-7Nb compositions for selected experiments

| No. | Temperature [K] | Pressure [Pa] | Final metal fractions in the alloy [% mass] | | |
|---|---|---|---|---|---|
| | | | Ti | Al | Nb |
| 1 | 1973 | 1000 | 85.40 | 3.97 | 9.63 |
| 2 | 1998 | 1000 | 85.26 | 3,88 | 9.86 |
| 3 | 2023 | 1000 | 85.80 | 3.83 | 9.30 |
| 4 | 1973 | 100 | 86.16 | 3.72 | 9.32 |
| 5 | 1998 | 100 | 85.23 | 3.70 | 9.97 |
| 6 | 2023 | 100 | 86.33 | 3.62 | 9.11 |
| 7 | 1973 | 50 | 86.16 | 3.67 | 9.07 |
| 8 | 1998 | 50 | 86.90 | 3.62. | 9.15 |
| 9 | 2023 | 50 | 86.80 | 3.57 | 8.99 |
| 10 | 1973 | 10 | 85.97 | 3.65 | 9.18 |
| 11 | 1998 | 10 | 85.10 | 3.56. | 9.01 |
| 12 | 2023 | 10 | 84.93 | 3.52 | 10.11 |
| 13 | 1973 | 5 | 85.07 | 3.34 | 9.99 |
| 14 | 1998 | 5 | 84.77 | 3.29 | 10.12 |
| 15 | 2023 | 5 | 84.43 | 3.19 | 10.34 |

## 4 Discussion

As the components of Ti-Al-Nb alloy show high vapour pressure differences, it was assumed that Al elimination from the alloy is a result of its evaporation. The process of metal bath volatile component evaporation depends on many factors, including the alloy temperature and composition, the smelting system pressure and the system hydrodynamics [17–19].

Thermodynamically, a parameter that determines a potential for liquid metal alloy component evaporation is a so-called evaporation coefficient described by the following equation [9]:

$$\Omega = \frac{\gamma_i \cdot p_i^o}{\gamma_j \cdot p_j^o} \tag{1.}$$

where: $p_i^o$ [Pa] – 'i' alloy component vapour pressure over pure bath,

$\gamma_i$ – the 'i' alloy component activity coefficient in the solution (liquid Ti-6Al-7Nb)

When the $\Omega = 1$ condition is met, it is assumed that the alloy composition does not change during smelting. When $\Omega > 1$, the 'i' component loss (evaporation) from the alloy is observed versus the 'j' component, while with $\Omega < 1$, there is a reversed situation.

In order to obtain the **Ω** value, equilibrium pressures of the basic alloy components over pure metal bath were determined with the use of HSC Chemistry thermodynamic database. The data are presented in **Table 4** and changes in titanium, aluminium and niobium equilibrium pressures over pure bath versus temperature are presented in **Fig. 4**.

**Table 4** Determined $p_i^o$ values for titanium, aluminium and niobium

| Selected evaporation reaction | $p_i^o$ [Pa] | | | | | |
|---|---|---|---|---|---|---|
| | 1973 [K] | 1998 [K] | 2023 [K] | 2048 [K] | 2073 [K] | 2098 [K] |
| $Ti_{(1)}=Ti_{(g)}$ | 0.5292 | 0.7448 | 1.0389 | 1.43688 | 1.9709 | 2.6822 |
| $Al_{(1)}=Al_{(g)}$ | 415.6439 | 526.3900 | 662.6251 | 829.2764 | 1032.035 | 1277.444 |
| $Nb_{(1)}=Nb_{(g)}$ | 1.76E-07 | 3.11E-07 | 5.41E-07 | 9.28E-07 | 1.57E-06 | 2.63E-06 |

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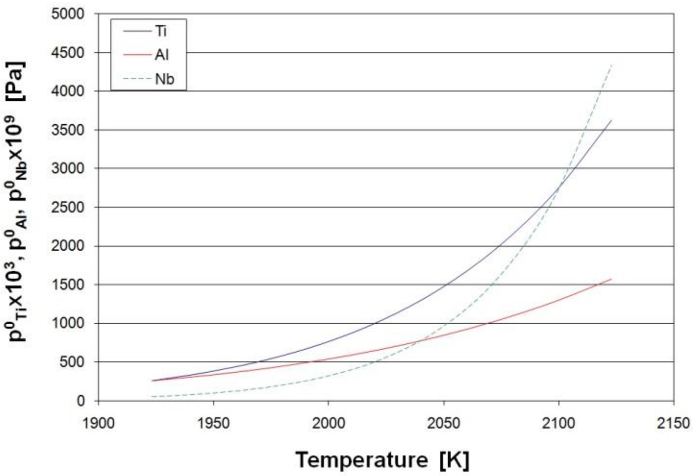


**Fig. 4** Equilibrium pressures of titanium, niobium and aluminium over pure bath

As the values of aluminium and niobium activity coefficients in liquid Ti-Al-Nb alloys were not available in the literature, they were estimated based on the equations for binary Ti-Al and Ti-Nb alloys [20], as follows:

$$\log \gamma_{Al} = -8340/T + 1.07 \quad (2.)$$

$$\log \gamma_{Nb} = 66/T - 0.008 \quad (3.)$$

**Fig. 5** shows changes in Ω values versus temperature for three basic alloy components, i.e. Ti, Al and Nb.

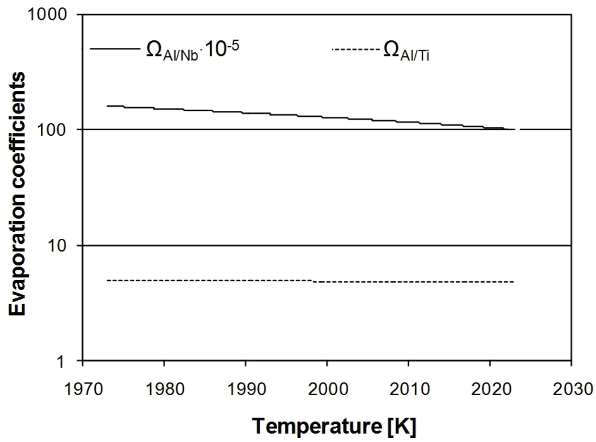


**Fig. 5** Changes $\Omega_{Al/Nb}$ and $\Omega_{Al/Ti}$ value at 1973–2023 [K]

The data presented in **Fig. 5** show that for aluminium and titanium, the $\Omega_{Al/Ti}$ value was above 5, while for aluminium and niobium, the $\Omega_{Al/Nb}$ value exceeded $10^6$. It means that, thermodynamically, there is a potential for intense aluminium evaporation from the investigated alloy, which was confirmed by the results of investigations on Ti-6Al-7Nb smelting in the

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vacuum induction furnace. A change in aluminium content in the alloy from 5.5 % mass in the initial material to 3.19 % mass in the alloy smelted at 5 Pa was observed. In each experiment, pressure reduction was accompanied by decrease in the $C^{k}_{Al/Ti}$ value (**Fig. 6**), suggesting that the vacuum rise enhances the aluminium evaporation process.

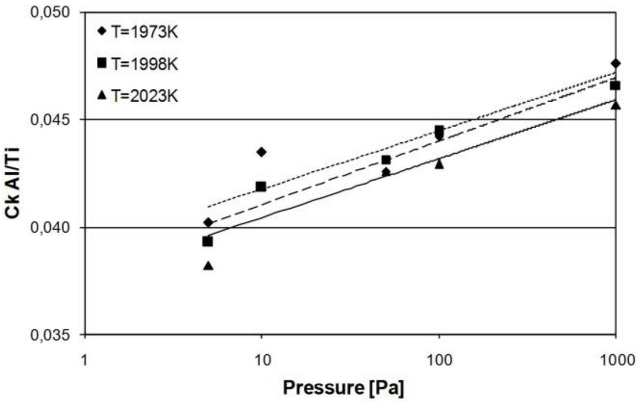


**Fig. 6** Changes in $C^{k}_{Al/Ti}$ values at 5–1000 [Pa]

## 5 Conclusion

During inductive Ti-6Al-7Nb alloy smelting at reduced pressure, significant aluminium loss from the alloy is observed which results from its evaporation. Pressure reduction in the device from 1000 Pa to 5 Pa was accompanied by Al content decrease from the initial value of 5.5 % mass to the value even below 3.2 % mass. Moreover, aluminium evaporation was enhanced when the smelting temperature increased. The aluminium loss from the alloy was related to the niobium content rise up to above 10 % mass. A similar situation was observed during the Ti-25Al-25Nb alloy smelting experiments performed in the vacuum induction furnace with the use of skull melting technology where aluminium loss from 25 % at to 21 %. In order to limit this unfavourable process, it appears advisable to reduce the smelting process duration or conduct the process at pressures above 1000 Pa.

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