

TITANIUM ALUMINIDES SYNTHESIS BY ALUMINO-CALCIOTHERMIC REDUCTION OF TiO₂

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Abstract: Production of titanium aluminides in TiO₂-Al-Ca system has been investigated. For this purpose, different compositions of raw materials were studied in a special reaction vessel. In a special case, the non-completed reaction of TiO₂ with Al and Ca resulted in the production of granulates of titanium aluminides especially Ti₃Al and other Ti – Al phases as the metallic product and Ca₁₂Al₁₄O₃₃ as the non-metallic product. Remelting of metallic granulates led to production of TiAl ingot.

Keywords: Titanium Aluminide, Titanium Dioxide, Alumino-Calciothermic.

1. INTRODUCTION

Titanium aluminide intermetallic compounds are a new class of advanced materials with unique thermal properties such as high specific strength, excellent oxidation resistance and acceptable mechanical properties at high temperatures [1-2]. Replacement of Ni-based superalloys by γ -TiAl alloys in jet engine components results in considerable reduction of weight and therefore increases of speed and efficiency [3-5]. However, in order to put this material in operation for its wide applications, some challenges must be overcome. The most important challenges are their low toughness at room temperature and technical difficulties in production. The production process of titanium aluminides are divided in two categories: ingot metallurgy and powder metallurgy.

1.1. Ingot Metallurgy

The ingot metallurgy includes technologies such as vacuum arc remelting (VAR) [6], vacuum induction melting (VIM) either in ceramic crucible [7] or in cold crucible [8] and electroslag remelting (ESR) [9]. These processes were used for titanium aluminides productions which all have some limits related to the control of chemical composition and expensiveness of the final product.

1.2. Powder Metallurgy

The powder metallurgy processes for production

of titanium aluminides include non-reactive and reactive sintering. The non-reactive sintering is a process for production of a wide range of materials such as titanium aluminides. “Non-reactive sintering” means that the sintering is carried out only for densification with no chemical reaction. In the case of this process, the raw materials would be pre-alloyed titanium aluminides (Ti_xAl_y) powders. The powders are produced by atomization [10] or mechanical alloying [11-13]. Reactive sintering or self-propagating high temperature synthesis (SHS) or combustion synthesis offers an attractive alternative route for production of titanium aluminides [14]. “Reactive sintering” means that a chemical reaction is occurred during sintering process. In this process, the raw materials are elemental titanium and aluminium or compounds like TiO₂ powders. The SHS process has two different modes: a) plane wave propagation (PWP) mode and b) thermal explosion mode [15]. The PWP technique was adopted to produce gamma titanium aluminide (TiAl) by using of Ti and Al powders as raw materials [14]. Products of this process are a mixture of TiAl and other phases like Ti₃Al, TiAl₃, Ti and Al [14]. However, it seems that the thermal explosion method has not been explored much for producing titanium aluminides. It is noted that economical production is possible when Ti is replaced by a relatively low price raw material such as TiO₂ [16]. This attractive recent

approach is based on the following reaction [17]:
 $3\text{TiO}_2 + 7\text{Al} = 3\text{TiAl} + 2\text{Al}_2\text{O}_3$ (1)

Product of reaction 1 is a composite comprising of titanium aluminide and alumina powders. It is reported that this composite can be a non-expensive alternative for some components in engines [18]. The goal of this research is reduction of TiO_2 with Al in presence of Ca to produce non-composite titanium aluminides.

2. EXPERIMENTAL

2.1. Materials

The elemental powders, Al (merck, $100\mu\text{m}$, 99.95%), TiO_2 (merck, $150\mu\text{m}$, 99.98%), and Ca (merck, granulated, 99.95%) were used as raw materials. The reactions were performed in an Al_2O_3 crucible (99.95%).

2.2. Idea of Research

The reaction between TiO_2 and Al results in the formation of a mixture consisting of alumina and titanium aluminides [17]. According to reaction 1, the product of reaction can be TiAl and Al_2O_3 . The melting point of TiAl is about 1500 °C (Fig. 1) and that of Al_2O_3 is 2000°C [20]. In order to have a metallic and a slag phase in separated form, it is necessary to add an additive to TiO_2 and Al raw materials. In this case, it seems that CaO is a suitable option based on the Al_2O_3 -CaO binary phase diagram (Fig. 2) [21]. Therefore CaO can be used as an additive to reduce the melting point of slag. In order to bring CaO into the reaction system, Ca powder can be added to raw materials.

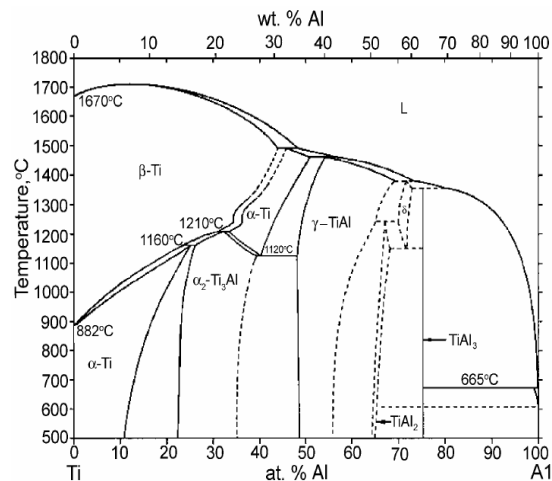


Fig. 1. Ti-Al phase diagram [8].

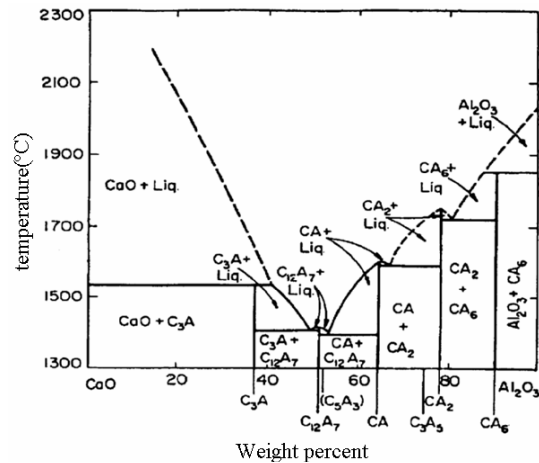


Fig. 2. CaO- Al_2O_3 phase diagram [12].

2.3. Procedures

The powders of raw materials were combined and mixed by a mixer. The mixed powders were placed in an alumina crucible and pounded by a mallet. The crucible then sealed by means of a ceramic bung. The crucible was placed in a flanged steel vessel where the empty space within the vessel was filled with MgO or Al_2O_3 powder. The presence of MgO or Al_2O_3 powders is desirable for preventing damage to ceramic crucible which may occur as a result of severe shocking during the reaction and also preventing oxygen diffusion to the crucible. The steel vessel was sealed by means of screwing with a steel bung (Fig. 3). The steel vessel then was placed into an electric furnace. The heating of the furnace was carried out with the rate of 20°C/min to 1000 °C. After 20 minutes when the reaction was completed, furnace was turned off. After ensuring the cooling of vessel to about room temperature, the vessel was removed. The detail of this process has been explained elsewhere [19].

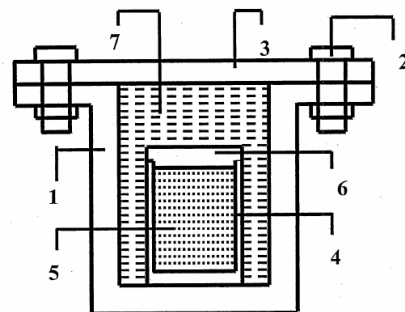


Fig. 3. The experimental setup. 1: steel vessel, 2: screw, 3: steel bung, 4: crucible, 5: mixed charge, 6: alumina crucible bung, 7: ceramic powder.

Table 1. Amount of raw materials according to different reactions and obtained product.

| | Considered Reaction | Amount of raw material (g) | | | Ca/TiO ₂ mole ratio | Product |
|---|--|----------------------------|------|------|--------------------------------|--------------------------------------|
| | | TiO ₂ | Al | Ca | | |
| 1 | 19TiO ₂ + 43Al + 2Ca = 2CaAl ₁₂ O ₁₉ + 19TiAl | 10.55 | 8.05 | 0.55 | 0.105 | powder |
| 2 | 7TiO ₂ + 15Al + 2Ca = 2CaAl ₄ O ₇ + 7TiAl | 10.87 | 7.86 | 1.54 | 0.286 | Powder |
| 3 | 2TiO ₂ + 4Al + Ca = CaAl ₂ O ₄ + 2TiAl | 10.66 | 7.20 | 2.66 | 0.500 | Powder |
| 4 | 33TiO ₂ + 61Al + 24Ca = 2Ca ₁₂ Al ₁₄ O ₃₃ + 33TiAl | 12.56 | 7.82 | 4.56 | 0.727 | Metallic and non-metallic granulates |
| 5 | 3TiO ₂ + 5Al + 3Ca = Ca ₃ Al ₂ O ₆ + 3TiAl | 12.00 | 4.05 | 6.00 | 1 | powder |

2.4. Analyzing of Products

Characterization of products was performed by X-ray diffraction (Siemens Kristalloflex 810 equipped with a copper anode operated at 40KV and 30mA, with graphite curved monochromatic on the diffracted beam). The microscopic study was performed by using optical microscopy and scanning electron microscopy (SEM) equipped with EDX analyser. The samples were etched in a solution of modified knoll's reagent (5%HF, 15%HNO₃, 80%H₂O).

3. RESULTS AND DISSCUTION

3.1. Alumino-Calciothermic Reduction of TiO₂

TiAl and calcioaluminates can be formed during the reaction between TiO₂, Al and Ca according to Table 1. It can be found from Table 1 that only in reaction 4, the product comprised the metallic and non-metallic granulates. In other cases, powder products were obtained. X-ray diffraction patterns of products of reaction 1, 2, 3 and 5 (Table 1) are presented in Fig. 4. In Fig. 4, The XRD labeled to "0" is related to "3TiO₂+7Al = 3TiAl+2Al₂O₃". The product of

different reactions according to Fig. 4 is shown in Table 2.

It is seen from Table 2 that according to reaction 1,2,3 and 5, powders comprising of some titanium aluminides and calcioaluminates were produced with adding of Ca to TiO₂+Al raw materials. With increasing of Ca, in reaction 5, an intermediate phase of Al-Ca (Al₄Ca) also was formed. Therefore some of the reactant that can contribute in production of titanium aluminides was consumed. On the other hand, as it is seen in Table 2, heating of raw materials according to reaction 4 caused to formation of metallic and non-metallic granulates.

This experiment was repeated with different amount of raw materials and same results were obtained (Table 3). One of the products in reaction 4 was Ca₁₂Al₁₄O₃₃. This phase has the lowest melting point in CaO-Al₂O₃ phase diagram. Therefore the released heat during the reaction 4 was resulted in the partially fusion of the slag and metallic product. The presence of Ca₁₂Al₁₄O₃₃ as a major peak in products is due to the partially fusion and therefore partially completion of reaction.

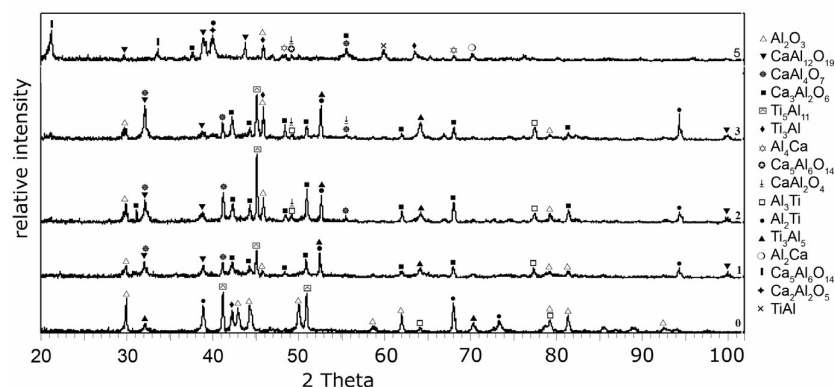


Fig. 4. X-ray diffraction patterns of products of reaction 1, 2, 3 and 5 (Table 1).

Table 2. The product of different reactions.

| Reaction Number (table1) | Considered Reaction | Product | | |
|--------------------------|---|--|--|-------------------------|
| | | Titanium Aluminides | Calcium Aluminates | Other phases |
| 0 | $3\text{TiO}_2 + 7\text{Al} = 3\text{TiAl} + 2\text{Al}_2\text{O}_3$ | $\text{TiAl}_2\text{-Ti}_3\text{Al}_5\text{-TiAl}_3$ | - | Al_2O_3 |
| 1 | $19\text{TiO}_2 + 43\text{Al} + 2\text{Ca} = 2\text{CaAl}_{12}\text{O}_{19} + 19\text{TiAl}$ | $\text{Ti}_3\text{Al}_5\text{-TiAl}_2$ | $\text{CaAl}_{12}\text{O}_{19}\text{-Ca}_3\text{Al}_2\text{O}_6$ | Al_2O_3 |
| 2 | $7\text{TiO}_2 + 15\text{Al} + 2\text{Ca} = 2\text{CaAl}_4\text{O}_7 + 7\text{TiAl}$ | $\text{Ti}_3\text{Al}_5\text{-TiAl}_2\text{-TiAl}_3$ | $\text{Ca}_3\text{Al}_2\text{O}_6\text{-CaAl}_4\text{O}_7\text{-CaAl}_{12}\text{O}_{19}$ | Al_2O_3 |
| 3 | $33\text{TiO}_2 + 61\text{Al} + 24\text{Ca} = 2\text{Ca}_{12}\text{Al}_{14}\text{O}_{33} + 33\text{TiAl}$ | $\text{Ti}_3\text{Al}_5\text{-TiAl}_2\text{-TiAl}_3\text{-Ti}_5\text{Al}_{11}$ | $\text{CaAl}_4\text{O}_7\text{-Ca}_3\text{Al}_2\text{O}_6\text{-CaAl}_{12}\text{O}_{19}$ | Al_2O_3 |
| 5 | $3\text{TiO}_2 + 5\text{Al} + 3\text{Ca} = \text{Ca}_3\text{Al}_2\text{O}_6 + 3\text{TiAl}$ | $\text{Ti}_3\text{Al-TiAl}$ | $\text{CaAl}_{12}\text{O}_{19}\text{-Ca}_5\text{Al}_2\text{O}_5$ | Al_4Ca |

Table 3. The product of reaction 4 (Table 2).

| Composition of raw materials | | | Products |
|------------------------------|-------|-------|--|
| TiO ₂ (g) | Al(g) | Ca(g) | |
| 210 | 131 | 76 | $\text{Ca}_{12}\text{Al}_{14}\text{O}_{33}, \text{CaO}, \text{Ti}_2\text{O}_3, \text{TiO}_2, \text{Ti}_3\text{Al}, \text{Al}, \text{Ti}, \text{Al}_5\text{Ti}_3$ |
| 264 | 165 | 96 | $\text{Ca}_{12}\text{Al}_{14}\text{O}_{33}, \text{TiO}, \text{TiO}_2, \text{CaO}, \text{Ti}_3\text{Al}, \text{Ti}$ |
| 290 | 181 | 105 | $\text{Ca}_{12}\text{Al}_{14}\text{O}_{33}, \text{TiO}_2, \text{TiO}, \text{CaO}, \text{Ti}_3\text{Al}, \text{Ti}$ |
| 320 | 200 | 116 | $\text{Ca}_{12}\text{Al}_{14}\text{O}_{33}, \text{TiO}, \text{Ti}_2\text{O}_3, \text{Ti}_3\text{Al}, \text{Al}_5\text{Ti}_3$ |
| 350 | 218 | 127 | $\text{Ca}_{12}\text{Al}_{14}\text{O}_{33}, \text{TiO}, \text{Ti}_2\text{O}_3, \text{CaO}, \text{Ti}_3\text{Al}, \text{Ti}$ |
| 380 | 237 | 138 | $\text{Ca}_{12}\text{Al}_{14}\text{O}_{33}, \text{TiO}, \text{CaO}, \text{Ti}_3\text{Al}, \text{Ti}$ |

3.2. Thermodynamic Considerations

Situation of different calcoaluminates products of reactions (according to table1) in CaO-Al₂O₃ phase diagram is seen in Fig. 5. According to this figure, melting point of slag is decreased with increasing of CaO/Al₂O₃ ratio in calcoaluminate products in reactions 1 to 4. Ca₁₂Al₁₄O₃₃ compound in reaction 4 has the lowest melting point. But, more increasing of CaO/Al₂O₃ ratio in slag, leads to increasing of its melting point.

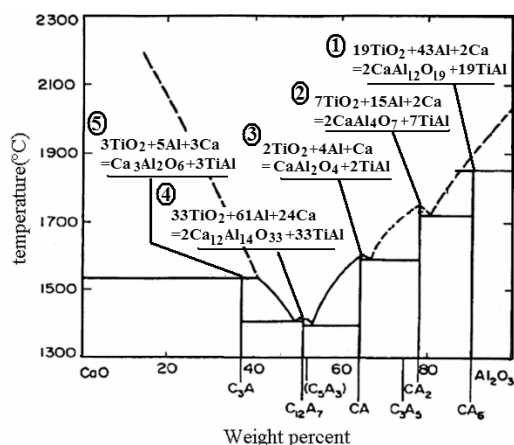


Fig. 5. Situation of different calcoaluminate products in CaO-Al₂O₃ phase diagram.

Enthalpy of different reactions in system of TiO₂-Al-Ca raw materials at 298K for production of 1 mole of TiAl as well as melting point of calcoaluminat slags versus M_{Ca}/M_{TiO₂} (M:mole) can be seen in Fig. 6.

According to Fig. 6, increasing of M_{Ca}/M_{TiO₂} ratio in raw materials leads to increasing of reaction heat and simultaneously decreasing of slag melting point. In M_{Ca}/M_{TiO₂} equal to 0.727, released heat is enough for partial fusion of slag and metallic product.

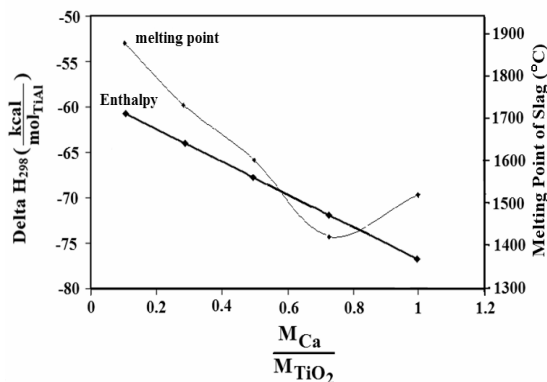


Fig. 6. Enthalpy of different reactions in TiO₂-Al-Ca system for production of 1 mole of TiAl as well as melting point of calcoaluminat slags versus M_{Ca}/M_{TiO₂} (M: mole).

Formation of $\text{Ca}_{12}\text{Al}_{14}\text{O}_{33}$ as a product is due to the partial fusion and therefore partial completion of reaction. But, more increasing of $M_{\text{Ca}}/M_{\text{TiO}_2}$ ratio led to production of powder products. This is due to the increasing of slag melting point in reaction 5 that prevent its fusion. Therefore holding of released heat and formation of metallic and non-metallic granulates is not possible.

3.3. Characterization of Products

After the reaction between TiO_2 , Al and Ca in all of the reactions in Table 3, the products included a mixture comprising of metallic and non-metallic granulates (Fig. 7). The X-ray diffraction pattern of different granulates indicated in Fig. 7 showed that granulate 1 included some non-metallic phases comprising of CaO , C_{12}A_7 ($\text{Ca}_{12}\text{Al}_{14}\text{O}_{33}$), Ti_2O_3 and TiO_2 (Fig. 8). Granulate 2 included Ti_3Al , Al and Ti phases (Fig. 9) whereas granulate 3 included Ti_3Al (Fig. 10) and granulate 4 included Ti, Al_5Ti_3 , Al_2Ti and TiSi phases (Fig. 11).

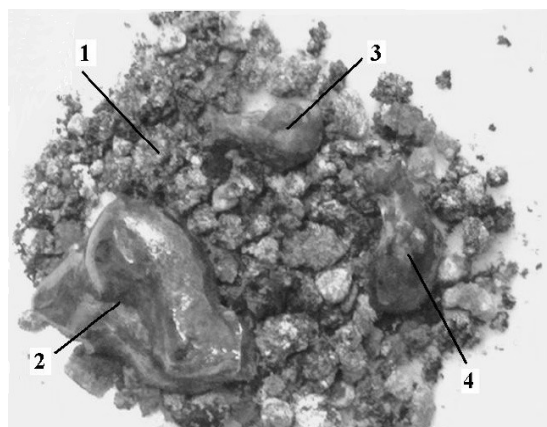


Fig. 7. Products resulted by smelting of $\text{TiO}_2 - \text{Al} - \text{Ca}$

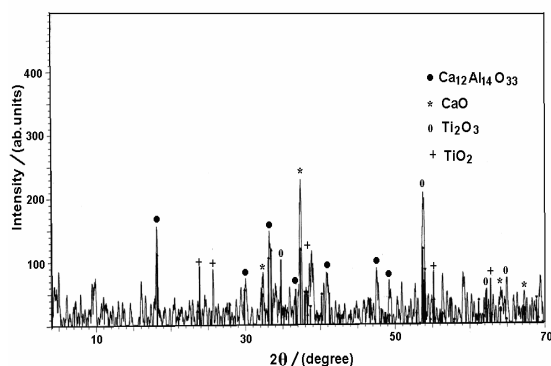


Fig. 8. XRD analysis from granulate 1 of Fig. 7.

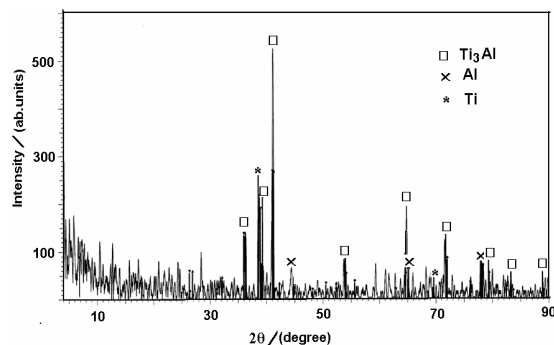


Fig. 9. XRD analysis from granulate 2 of Fig. 7.

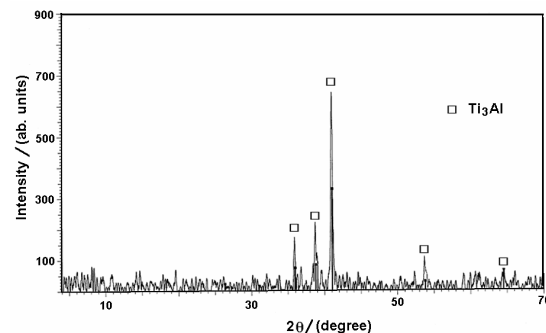


Fig. 10. XRD analysis from granulate 3 of Fig. 7.

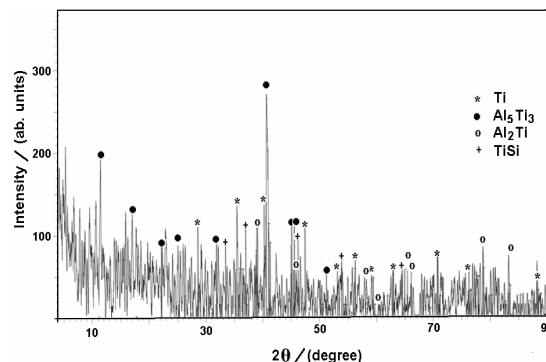


Fig. 11. XRD analysis from granulate 4 of Fig. 7.

3.3.1. Microscopic study of a metallic granulate

Granulate 2 in Fig. 7 is a metallic multi-phases material. Figs. 12 and 13 are the optical and scanning electron microscope microstructure of this granulate, respectively. From the optical microstructure (Fig. 12), it is seen that product contained high amount of porosities. In order to analyse the microstructure, SEM examination was used. The SEM microstructure showed three different regions (Fig. 13). According to EDX analysis, the matrix phase was Ti_3Al . The white precipitation was Ti and the dark precipitation was Al. On the basis of the theoretical reactions (Table 1), it is expected that TiAl be presented in

the final product. Lack of TiAl in final product could be due to the fact that during the reactions, the temperature was not high enough and therefore reaction was not completed. The uncompleted reactions result in production of metallic and non-metallic granulates.

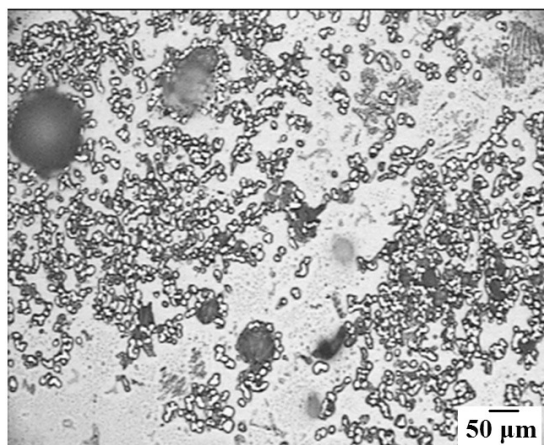
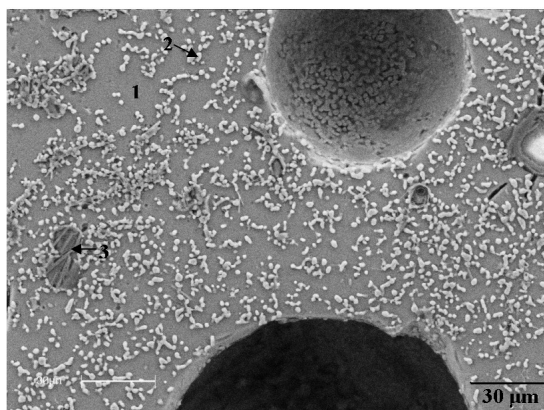


Fig. 12. Optical microstructure of metallic granulate 2 of Fig. 7.



| Region analysed | Ti(wt%) | Al(wt%) |
|-----------------|---------|---------|
| 1 | 77.23 | 22.14 |
| 2 | 95.73 | 3.13 |
| 3 | - | 99.36 |

Fig. 13. SEM microstructure of metallic granulate 2 in Fig. 7 and EDX analysis of indicated area. 1= Ti₃Al, 2=Ti, 3=Al

3.4. Remelting of Metallic Granulates

Alumino-calciothermic reduction of TiO₂ according to reaction numbered 4 (Table 1) led to production of metallic and non-metallic granulates. The metallic granulates can be separated easily. 25 g of separated metallic granulates remelted in an arc remelting furnace under high purity argon. Chemical analysis of obtained ingot is shown in table 4. This

composition can be related to TiAl region in phase diagram indicated in figure 1. On the other hand x-ray diffraction pattern of product reveals the formation of TiAl, Ti₃Al and TiAl₃ phases.

Production of Ti₃Al and TiAl₃ phases as well as TiAl can be described on the basis of Ti-Al phase diagram. According to figure 1, TiAl is a stable phase in following chemical composition domain:

$$\text{Ti}_x\text{Al}_{1-x} \quad x=44-52 \text{ (atomic percent)}$$

Therefore, if chemical composition of a group of atoms with lattice structure of TiAl changes from Ti₅₀Al₅₀ to Ti₅₂Al₄₈, it is possible to formation of two unites with lattice structure of TiAl₃ for keeping of elemental equilibrium. On the other hand, if chemical composition of a group of atoms with lattice structure of TiAl changes from Ti₅₀Al₅₀ to Ti₄₈Al₅₂, it is possible to formation of two unites with lattice structure of Ti₃Al.

Table 4. Chemical analysis of remelted ingot

| Element | Ti | Al | Ca | Others |
|----------------|-------|-------|------|--------|
| Weight Percent | 48.59 | 51.14 | 0.12 | 0.15 |

4. CONCLUSIONS

A non-completed reaction between TiO₂, Al and Ca, according to considered reaction of $33\text{TiO}_2 + 61\text{Al} + 24\text{Ca} = 2\text{Ca}_{12}\text{Al}_{14}\text{O}_{33} + 33\text{TiAl}$ resulted in the formation of a mixture of metallic granulates consisting of Ti₃Al, Ti, Al₅Ti₃, Al₂Ti and non-metallic granulates consisting of CaO, C₁₂A₇ (Ca₁₂Al₁₄O₃₃), Ti₂O₃ and TiO₂. The metallic granulate contained high amount of porosities. Remelting of the metallic granulates led to obtain an ingot consisting of TiAl, Ti₃Al and TiAl₃ phases.

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