CRITICAL ANALYSIS OF THE Ti-Al PHASE DIAGRAMS

D. BATALU, GEORGETA COŞMELEAŢĂ, A. ALOMAN

In this paper the authors performed a critical thermodynamic and crystallochemical analysis of the most important binary phase diagram of Ti alloys, Ti-Al diagram. Different variants of the diagrams are critically analyzed and we suggest a schema and a flow diagram of Ti-Al diagram. The composition and structure of all intermediate phases of the Ti-Al equilibrium diagram are characterized.

Keywords: Ti-Al binary phase diagram, assessment

Introduction

Ti-Al binary phase diagram (BPD) is the most important phase diagram of Ti alloys. Aluminium is as essential for alloying titanium as carbon is for iron. Aluminium is the most abundant metal in the earth's crust (8.8 %), and it has found large applications due to its low density (2.71 g/cm³) and high corrosion resistance. Titanium is the seventh most abundant metal in the earth's crust (0.63 %) and the fourth most used material in the industry, after iron, aluminium and magnesium. Titanium is a very important metal, with large applications in aerospace industry, naval industry, automobile industry, medical engineering, fuel cells, chemical industry etc. There are many experimental and theoretical works on Ti-Al BPD, concerning the stable and metastable phases, the phase equilibria and the accuracy of the published papers.

In this paper we analyse the most cited Ti-Al BPD in order to point out the controversies between different authors and we propose a schema of Ti-Al built on mediation of existing data.

1. Critical analysis of some experimental and calculated Ti-Al BPD

The most controversial area of Ti-Al BPD ranges between 55 and 77 at. %
Al, and 900 to 1450 °C.

In Fig. 1 it is presented the Ti-Al BPD, published in 1990 [1]. With dashed lines are indicated the estimated transformation curves. There are four intermetallic compounds with variable composition (AlTi3, AlTi, Al3Ti, δ), and one with constant composition (Al3Ti).

![Graph showing Ti-Al phase diagram](image)

**Fig. 1.** The first variant of Ti-Al BPD [1].

At \( T \approx 1285 \degree C \) and \( x_{Al} \approx 49 \) at. % the peritectoid transformation \( (\beta_{Ti})_{0.43} + (AlTi)_{0.45} \leftrightarrow (\alpha_{Ti})_{0.49} \) occurs, but it was canceled in the latest works (they suggest the peritectic transformation \( L + \beta_{Ti} \leftrightarrow \alpha_{Ti} \)).

The liquidus and solidus curves of \( L \leftrightarrow \beta_{Ti} \) show a maximum that in other works doesn’t occur. The transformations of the intermetallic compounds are:

- peritectic transformations:
  \[
  \begin{align*}
  L_{0.53} + (\beta_{Ti})_{0.51} & \leftrightarrow 1480 \degree C (AlTi)_{0.475} \\
  L_{0.735} + (AlTi)_{0.695} & \leftrightarrow 1380 \degree C \delta_{0.715} \\
  L_{0.8} + \delta_{0.725} & \leftrightarrow 1350 \degree C (Al_{2}Ti)_{0.75}
  \end{align*}
  \]

- peritectoid transformation: \( (AlTi)_{0.65} + \delta_{0.725} \leftrightarrow 1240 \degree C (Al_{2}Ti)_{0.67} \)

- order-disorder transformation: \( (\alpha_{Ti})_{0.309} \leftrightarrow 1180 \degree C (AlTi)_{0.309} \)

In Fig. 2 it is presented an experimental Ti-Al BPD [2].

Three intermetallic compounds with variable composition (AlTi3, AlTi, Al3Ti) and two with constant composition (Al2Ti, Al5Ti2) can be identified.
The phase transformations are:
- melting:
  \[ L \leftarrow 1670^\circ C \rightarrow \beta_{\text{Ti}} \]
  \[ L \leftarrow 660.452^\circ C \rightarrow Al \]
- polymorphic transformation:
  \[ \beta_{\text{Ti}} \leftarrow 882^\circ C \rightarrow \alpha_{\text{Ti}} \]
- five peritectic transformations:
  \[ L_{0.494} + (\beta_{\text{Ti}})_{0.448} \leftarrow 1490^\circ C \rightarrow (\alpha_{\text{Ti}})_{0.473} \]
  \[ L_{0.551} + (\alpha_{\text{Ti}})_{0.514} \leftarrow 1462.8^\circ C \rightarrow (AlTi)_{0.55} \]
  \[ L_{0.725} + (AlTi)_{0.665} \leftarrow 1415.9^\circ C \rightarrow (Al_3Ti_2)_{0.714} \]
  \[ L_{0.791} + (Al_3Ti_2)_{0.714} \leftarrow 1392.9^\circ C \rightarrow (AlTi)_{0.75} \]
  \[ L_{0.999} + (Al_3Ti_2)_{0.75} \leftarrow 664.2^\circ C \rightarrow Al_{0.994} \]
- peritectoid transformation:
  \[(AlTi)_{0.645} + (Al_3Ti_2)_{0.714} \leftarrow 1199.4^\circ C \rightarrow (Al_2Ti)_{0.667} \]
- two eutectoid transformation:
  \[(\alpha_{\text{Ti}})_{0.396} \leftarrow 1118.5^\circ C \rightarrow (AlTi)_{0.382} + (AlTi)_{0.467} \]
  \[(Al_3Ti_2)_{0.714} \leftarrow 990^\circ C \rightarrow (Al_2Ti)_{0.667} + (Al_3Ti)_{0.742} \]
- order-disorder transformation:
  \[(\alpha_{\text{Ti}})_{0.309} \leftarrow 1164^\circ C \rightarrow (AlTi)_{0.309} \]

Fig. 2. The second variant of Ti-Al BPD [2].
In Fig. 3 the authors try to offer a new perspective of the most controversial area (indicated here as $\xi$ domain, and detailed in Fig. 4). With dashed lines are indicated the hypothetic transformation curves.

There is also a maximum of $L \leftrightarrow \beta_{Ti}$ transformation curves. The intermetallic compounds with variable composition are AlTi$_3$ ($\alpha_2$) and AlTi ($\gamma$), and the ones with constant composition are Al$_2$Ti and Al$_3$Ti. The Al$_2$Ti compound is considered stable up to 1216 °C, compared with 1199.4 °C, in other papers. Some experimental data that are also different from others are the peritectic transformations of Al$_3$Ti (1387 °C, versus 1392.5 °C in [2]) and AlTi (1460 °C, versus 1462.6 °C).

In Fig. 4 is presented the most controversial area of Ti-Al BPD.
The ξ domain is a particular point of view of the authors [3], but there are many mistakes in representing the transformations. The invariant transformations at 1214 °C and 1216 °C have only two points of intersection, and the ones at 1424 °C and 1445 °C have four points of intersection, instead of three, according with the thermodynamic rules. We consider that the metastable intermetallic compounds were introduced without a critical analyze.

The AlTi, Al_{1-x}Ti_{1-x}, Al_2Ti, Al_{11}Ti_5, Al_3Ti compounds are formed by peritectic transformations:

\[
L_{0.56} + (\alpha_{\text{Al}})_{0.515} \leftrightarrow \gamma_{0.525} \\
L_{0.665} + \gamma_{0.615} \leftrightarrow (Al_{1-x}Ti_{1-x})_{0.63} \\
L_{0.718} + (Al_{1-x}Ti_{1-x})_{0.645} \leftrightarrow (Al_2Ti)_{0.667} \\
L_{0.765} + (Al_2Ti)_{0.675} \leftrightarrow (Al_{11}Ti_5)_{0.691} \\
L_{0.791} + (Al_{11}Ti_5)_{0.72} \leftrightarrow (Al_3Ti)_{0.75}
\]

The Al_5Ti_2 compound is formed by a peritectoid reaction:

\[
(Al_{11}Ti_5)_{0.695} + (Al_3Ti)_{0.712} \leftrightarrow (Al_5Ti)_{0.712}
\]

In Fig. 5 is accepted the existence of Al_{23}Ti_9 intermetallic compound. It is represented with dashed line, suggesting an estimation of its boundaries. The intermetallic compounds are: AlTi_3, AlTi, Al_2Ti, Al_{11}Ti_5, Al_{23}Ti_9, Al_3Ti and α-Al_3Ti. All but Al_3Ti have variable composition (Fig. 5.a, b).

In this BPD the maximum of $\beta_{\text{Tl}} \leftrightarrow L$ transformation is more emphasized.
The phase transformations are:
- order-disorder transformation: \( \text{AlTi}_3 \leftarrow 1177^\circ C \rightarrow \text{Ti} \);
- polymorphic transformation: \( \text{Ti} \leftarrow 882^\circ C \rightarrow \text{Ti} \);
- four peritectic transformations:
  \[
  L + \text{Ti} \leftarrow 1457^\circ C \rightarrow \text{AlTi} ;
  L + \text{AlTi} \leftarrow 1445^\circ C \rightarrow \text{Al}_1\text{Ti}_3 ;
  L + \text{Al}_1\text{Ti}_3 \leftarrow 1395^\circ C \rightarrow \text{Al}_2\text{Ti} ;
  L + \text{Al}_2\text{Ti} \leftarrow 665^\circ C \rightarrow \varphi_{Al} ;
  \]
- two eutectoid transformation:
  \( \text{Al}_1\text{Ti}_3 \leftarrow 1148^\circ C \rightarrow \text{AlTi} + \text{AlTi} ;
  \)
  \( \text{Al}_2\text{Ti} \leftarrow 990^\circ C \rightarrow \text{Al}_2\text{Ti} + \text{Al}_2\text{Ti} ;
  \)
- two peritectoid transformations:
  \( \text{Al}_1\text{Ti}_3 + \text{AlTi} \leftarrow 1175^\circ C \rightarrow \text{Al}_2\text{Ti} ;
  \)
  \( \text{Al}_2\text{Ti} + \text{Al}_2\text{Ti} \leftarrow 777^\circ C \rightarrow \text{Al}_2\text{Ti} ;
  \)

In Fig. 6 a recent detail of the peritectic transformation \( L + (\text{Al}_2\text{Ti}) \leftarrow 665^\circ C \rightarrow (\text{Al}) \) is presented. Between Fig. 6 and Fig. 5.b there is a difference of 0.047 at. % Ti for the peritectic point.
Critical analysis of Ti-Al phase diagrams

83

Fig. 6. The peritectic transformation \( L \rightarrow (Al_3Ti) \leftarrow 665 \degree C \rightarrow (Al) \) [5].

In Fig. 7 a calculated Ti-Al BPD is represented. The sublattice model was used for the thermodynamic calculation. The BPD is similar with the one from Fig. 5, but the Al\(_{11}\)Ti\(_5\) compound is considered with constant composition and the Al\(_{23}\)Ti\(_0\) compound as being metastable, hence it was not included in the calculations. The results are very close to the experimental ones.

Fig. 7. The calculated Ti-Al BPD using the sublattice model.

2. Intermediate phases of Ti-Al BPD

The AlTi\(_3\) and AlTi intermetallic compounds are largely accepted as having variable composition, with a wide homogeneity domain. The Al\(_2\)Ti and Al\(_3\)Ti\(_2\) are accepted as having constant composition. The Al\(_3\)Ti is treated as an intermetallic
compound with variable composition in some papers, and with constant composition in other papers. There are twelve intermetallic compounds recognized in the literature [6]. The Al\textsubscript{1+x}Ti\textsubscript{1-x} (x=0.281) intermetallic compound can be assimilated with Al\textsubscript{16}Ti\textsubscript{9} ≅ Al\textsubscript{15}Ti\textsubscript{9}=Al\textsubscript{5}Ti\textsubscript{3}, compound that satisfies most of the experimental results. Other four compounds do not appear in any of the presented BPD, though they occur between 0 and 50 at. % Al, hence we consider them as metastable phases.

In Table 1 there are summarized all the intermetallic compounds.

<table>
<thead>
<tr>
<th>No.</th>
<th>Formula</th>
<th>m/n</th>
<th>x\textsubscript{Al}</th>
<th>n\textsubscript{a}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Al\textsubscript{3}Ti\textsubscript{17}</td>
<td>0.176</td>
<td>0.150</td>
<td>20</td>
</tr>
<tr>
<td>2.</td>
<td>Al\textsubscript{6}Ti\textsubscript{19}</td>
<td>0.315</td>
<td>0.240</td>
<td>25</td>
</tr>
<tr>
<td>3.</td>
<td>AlTi\textsubscript{3}</td>
<td>0.333</td>
<td>0.250</td>
<td>4</td>
</tr>
<tr>
<td>4.</td>
<td>AlTi\textsubscript{2}</td>
<td>0.500</td>
<td>0.333</td>
<td>3</td>
</tr>
<tr>
<td>5.</td>
<td>Al\textsubscript{1}Ti\textsubscript{1}</td>
<td>0.666</td>
<td>0.400</td>
<td>5</td>
</tr>
<tr>
<td>6.</td>
<td>AlTi</td>
<td>1.000</td>
<td>0.500</td>
<td>2</td>
</tr>
<tr>
<td>7.</td>
<td>Al\textsubscript{1}Ti\textsubscript{1}</td>
<td>1.666</td>
<td>0.625</td>
<td>8</td>
</tr>
<tr>
<td>8.</td>
<td>Al\textsubscript{2}Ti</td>
<td>2.000</td>
<td>0.666</td>
<td>3</td>
</tr>
<tr>
<td>9.</td>
<td>Al\textsubscript{1/2}Ti\textsubscript{3/2}</td>
<td>2.200</td>
<td>0.687</td>
<td>16</td>
</tr>
<tr>
<td>10.</td>
<td>Al\textsubscript{1}Ti\textsubscript{2}</td>
<td>2.500</td>
<td>0.714</td>
<td>7</td>
</tr>
<tr>
<td>11.</td>
<td>Al\textsubscript{2}Ti\textsubscript{6}</td>
<td>2.555</td>
<td>0.718</td>
<td>32</td>
</tr>
<tr>
<td>12.</td>
<td>Al\textsubscript{1}Ti</td>
<td>3.000</td>
<td>0.750</td>
<td>4</td>
</tr>
</tbody>
</table>

The compositional characteristics of the Al\textsubscript{m}Ti\textsubscript{n} intermetallic compounds are presented in Table 2.

<table>
<thead>
<tr>
<th>No.</th>
<th>Formula of the compound</th>
<th>Stoichiometric compositions</th>
<th>Range of the homogeneity domain</th>
<th>Width of the homogeneity domain, ( \Delta x_{\text{Al}} )</th>
<th>Degree of order, ( \eta )</th>
<th>Melting character</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Al\textsubscript{3}Ti\textsubscript{17}</td>
<td>0.150</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2.</td>
<td>Al\textsubscript{6}Ti\textsubscript{19}</td>
<td>0.240</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3.</td>
<td>AlTi\textsubscript{3}</td>
<td>0.250</td>
<td>0.2-0.382</td>
<td>0.182</td>
<td>0.818</td>
<td>-</td>
</tr>
<tr>
<td>4.</td>
<td>AlTi\textsubscript{2}</td>
<td>0.333</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5.</td>
<td>Al\textsubscript{1/2}Ti\textsubscript{3/2}</td>
<td>0.400</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6.</td>
<td>AlTi</td>
<td>0.500</td>
<td>0.467-0.62</td>
<td>0.153</td>
<td>0.847</td>
<td>Incongruent</td>
</tr>
<tr>
<td>7.</td>
<td>Al\textsubscript{1}Ti\textsubscript{1}</td>
<td>0.625</td>
<td>0.628-0.645</td>
<td>0.017</td>
<td>0.983</td>
<td>Incongruent</td>
</tr>
<tr>
<td>8.</td>
<td>Al\textsubscript{2}Ti</td>
<td>0.666</td>
<td>0.66-0.675</td>
<td>0.015</td>
<td>0.985</td>
<td>Incongruent</td>
</tr>
<tr>
<td>9.</td>
<td>Al\textsubscript{1/2}Ti\textsubscript{3/2}</td>
<td>0.687</td>
<td>0.685-0.72</td>
<td>0.035</td>
<td>0.965</td>
<td>Incongruent</td>
</tr>
<tr>
<td>10.</td>
<td>Al\textsubscript{1}Ti\textsubscript{2}</td>
<td>0.714</td>
<td>0.705-0.712</td>
<td>0.007</td>
<td>0.993</td>
<td>-</td>
</tr>
<tr>
<td>11.</td>
<td>Al\textsubscript{2}Ti\textsubscript{6}</td>
<td>0.718</td>
<td>0.73-0.76</td>
<td>0.03</td>
<td>0.97</td>
<td>-</td>
</tr>
<tr>
<td>12.</td>
<td>Al\textsubscript{1}Ti</td>
<td>0.750</td>
<td>0.742-0.755</td>
<td>0.013</td>
<td>0.987</td>
<td>Incongruent</td>
</tr>
</tbody>
</table>
Critical analysis of Ti-Al phase diagrams

The characterization of the crystalline structure is presented in Table 3.

### Table 3

<table>
<thead>
<tr>
<th>No.</th>
<th>Intermetallic compound</th>
<th>Strukturbericht Symbol</th>
<th>Prototype</th>
<th>Pearson Symbol</th>
<th>Space Group</th>
<th>Lattice Parameters [Å]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>α_{Ti}</td>
<td>A3</td>
<td>Mg</td>
<td>hP2</td>
<td>P6/mmm</td>
<td>-</td>
</tr>
<tr>
<td>2.</td>
<td>β_{Ti}</td>
<td>A2</td>
<td>W</td>
<td>c12</td>
<td>m3m</td>
<td>-</td>
</tr>
<tr>
<td>3.</td>
<td>Al_{3}Ti_{17}</td>
<td>Mg</td>
<td>hP2 (?)</td>
<td>P6/mmm</td>
<td>a=2.925; c=4.667</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>Al_{5}Ti_{19}</td>
<td>Mg</td>
<td>hP2 (?)</td>
<td>P6/mmm</td>
<td>a=2.900; c=4.645</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>AlTi_{12}</td>
<td>Ni_{3}Sn</td>
<td>hP8</td>
<td>P6/mmm</td>
<td>a=5.780; c=4.647</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>AlTi_{12}</td>
<td>Ni_{3}Sn</td>
<td>hP8 (?)</td>
<td>P6/mmm</td>
<td>a=5.775; c=4.638</td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td>Al_{2}Ti_{3}</td>
<td>Mg</td>
<td>hP2 (?)</td>
<td>P6/mmm</td>
<td>a=2.877; c=4.612</td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>AlTi</td>
<td>Au_{3}Cu</td>
<td>tP4</td>
<td>P4/mmm</td>
<td>a=4.001; c=4.071</td>
<td></td>
</tr>
<tr>
<td>9.</td>
<td>Al_{12}Ti_{3}</td>
<td>tP32</td>
<td>14/mbm</td>
<td>a=4.0262; b=2.9617; c=4.0262</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.</td>
<td>Al_{2}Ti</td>
<td>Ga_{3}Hf</td>
<td>tI4(24)</td>
<td>I4/amd</td>
<td>a=3.976; c=24.36</td>
<td></td>
</tr>
<tr>
<td>11.</td>
<td>Al_{3}Ti_{5}</td>
<td>Al_{3}Zr</td>
<td>tI16</td>
<td>I4/mmm</td>
<td>a=3.917; c=16.524</td>
<td></td>
</tr>
<tr>
<td>12.</td>
<td>Al_{5}Ti_{2}</td>
<td>Al_{3}Ti</td>
<td>tI28</td>
<td>-</td>
<td>a=3.9053; c=2.9196</td>
<td></td>
</tr>
<tr>
<td>13.</td>
<td>Al_{2}Ti_{9}</td>
<td>Al_{3}Ti</td>
<td>tI28</td>
<td>-</td>
<td>a=3.843; c=33.465</td>
<td></td>
</tr>
<tr>
<td>14.</td>
<td>Al_{3}Ti_{12}</td>
<td>Al_{2}Ti</td>
<td>tI8</td>
<td>I4/mmm</td>
<td>a=3.846; c=8.594</td>
<td></td>
</tr>
<tr>
<td>15.</td>
<td>ϕ_{Al}</td>
<td>Al</td>
<td>cF4</td>
<td>Fm3 m</td>
<td>a=4.0496</td>
<td></td>
</tr>
</tbody>
</table>

3. The schema of Ti-Al BPD

The proposed schema (Fig. 8) is a synthesis of all analyzed Ti-Al BPD, and it is a qualitative one, its purpose being to evidentiate all the curves, invariant transformation, and important points. The authors consider all the intermetallic compounds having variable composition.

Ti-Al BPD has the following main characteristics:
- total solubility in liquid state;
- partial solubility in solid state;
- three intermetallic compounds with incogruent melting, formed by peritectic transformations (AlTi, Al_{11}Ti_{5}, Al_{3}Ti);
- one intermetallic compound formed by peritectoid transformation (Al_{2}Ti);
- one intermetallic compound formed by order-disorder transformation (AlTi_{3});

The phase transformations that take place in Ti-Al BPD are:
- five peritectic transformations:
The coordinates of the intersection points of the Ti-Al schema are presented in Table 4.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Significance</th>
<th>$X_{Al}$ [% at.]</th>
<th>$T_1$ [°C]</th>
<th>$T_2$ [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{dl}$</td>
<td>Melting temperature of Al</td>
<td>100</td>
<td>660.452</td>
<td>933.452</td>
</tr>
<tr>
<td>$p_{10}$</td>
<td>Transition point</td>
<td>99.90</td>
<td>665</td>
<td>938</td>
</tr>
<tr>
<td>$P_5$</td>
<td>Peritectic point</td>
<td>99.30</td>
<td>665</td>
<td>938</td>
</tr>
<tr>
<td>$p_8$</td>
<td>Transition point</td>
<td>77.46</td>
<td>1395</td>
<td>1668</td>
</tr>
<tr>
<td>$p_9$</td>
<td>Lyotectic point</td>
<td>75.00</td>
<td>665</td>
<td>938</td>
</tr>
<tr>
<td>$P_4$</td>
<td>Peritectic point</td>
<td>74.39</td>
<td>1395</td>
<td>1668</td>
</tr>
<tr>
<td>$p_7$</td>
<td>Lyotectic point</td>
<td>72.20</td>
<td>1395</td>
<td>1668</td>
</tr>
<tr>
<td>$p_6$</td>
<td>Transition point</td>
<td>67.80</td>
<td>1415</td>
<td>1688</td>
</tr>
<tr>
<td>$e_s$</td>
<td>Lyotectoid point</td>
<td>74.65</td>
<td>990</td>
<td>1263</td>
</tr>
<tr>
<td>$E_1$</td>
<td>Eutectoid point</td>
<td>69.76</td>
<td>990</td>
<td>1263</td>
</tr>
</tbody>
</table>
The curves and the horizontal lines of the invariant transformations of Ti-Al schema are (Fig. 8):

- liquidus curve $T_{\text{Ti}}D_p2p_4p_6p_8p_{10}T_{\text{Al}}$, formed of 6 curves, corresponding to the six phases that separate from the liquid state:
  - the liquidus of $\beta_{\text{Ti}}$, $T_{\text{Ti}}D_p2$;
  - the liquidus of $\alpha_{\text{Ti}}$, $p_2p_4$;
  - the liquidus of $\text{AlTi}$, $p_4p_6$;
  - the liquidus of $\text{Al}_{11}\text{Ti}_5$, $p_4p_8$;
  - the liquidus of $\text{Al}_3\text{Ti}$, $p_6p_{10}$;
  - the liquidus of $(\text{AlTi})$, $p_{10}T_{\text{Al}}$;
- solidus curve $T_{\text{Ti}}D_p1p_3p_5p_7p_9p_{10}T_{\text{Al}}$;

- solvus curves:
  - $e'_1f_3$, normal solvus (AlTi phase precipitates);
  - $e'_2f_4$, normal solvus (AlTi$_3$ phase precipitates);
  - $p_1p'_1$, normal solvus (Al$_{11}$Ti$_5$ phase precipitates);
  - $p_1f_3$, normal solvus (Al$_3$Ti phase precipitates);
  - $P'e'_3$, retrograde solvus (AlTi phase is dissolved);
  - $P'f'_3$, retrograde solvus (Al$_{11}$Ti$_5$ phase is dissolved);
- $e_3f_3$, normal solvus (Al$_3$Ti phase precipitates);
- $p_3p'_3$, retrograde solvus (AlTi phase is dissolved);
- $p_4E_4$, normal solvus (Al$_3$Ti phase precipitates);
- $e_4f_4$, normal solvus (Al$_2$Ti phase precipitates);
- $p_5f_5$, normal solvus ((Al) phase precipitates);
- $p_4f_4$, normal solvus (Al$_3$Ti phase precipitates);
- $d_2e_2$, retrograde solvus ($\alpha_Ti$ phase is dissolved);
- two polymorphic curves $T_{p_1}P_{p_1}$ and $T_{p_1}P_{p_1}$, corresponding to the beginning and the ending of the Ti polymorphic transformation ($\alpha_Ti \leftrightarrow \beta_Ti$);
- ordinus curves:
  - $f_1D'E_1'$, superior ordinus;
  - $f_2D'e_1'$, inferior ordinus;
- horizontal lines:
  - the horizontal lines of peritectic transformation: $p_1P_1p_2$, $p_3P_3p_4$, $p_5p_5p_6$, $p_7p_7p_8$, $p_9p_9p_{10}$;
  - the horizontal lines of eutectoid transformations: $e_1'e_1'e_1'$, $e_4'e_4'e_4'$;
  - the horizontal line of peritectoid transformation: $p_1p_1p_2$.

Fig. 8. The schema of Ti-Al BPD.
3. The flow diagram of Ti-Al BPD

The flow diagram of Ti-Al BPD was built based on the Ti-Al schema and according with Gibbs phase rule. The flow diagram has 8 rectangles that represent the triphasic equilibria, connected by lines that represent the biphasic equilibria.

Fig. 9. The flow diagram of Ti-Al BPD.
Conclusions

1. Ti-Al BPD is the most important phase diagram of Ti alloys, and new assessments are necessary to be done, especially based on new and more accurate experimental works.
2. Though the Ti-Al BPD has been intensively studied we can not consider any of the published diagrams fully reliable. The published Ti-Ni BPDs should be critically analyzed, before using them for any practical or theoretical applications.
3. By our critical analysis of some Ti-Al BPD we suggest a general schema, considering all the intermetallic compounds with variable composition.
4. A synthesis of all important points and curves from the Al-Ni BPD was realized in our work, indicating also their coordinates (Table 4).
5. Based on our suggested Ti-Al schema we built the flow diagram (Fig. 9), that allows to establish the correct succession of biphasic and triphasic equilibria.
6. Ti-Al is also an essential part of the Ti-Ni-Al ternary phase diagram, and it shall be used for the ternary phase diagram assessment.
7. Through our assessment we pointed out that many published works regarding the Ti-Al BPD have many controversial results and even some unacceptable mistakes.

REFERENCES