

Article

Influence of Yttrium on the Phase Composition of the Ti-Al System Obtained by the ‘Hydride Technology’

Natalia Karakchieva ^{1,*}, Alina Artemenko ¹, Olga Lepakova ², Victor Sachkov ¹ and Irina Kurzina ^{3,*}¹ Chemical Technology Laboratory, National Research Tomsk State University, 36 Lenin Avenue, 634050 Tomsk, Russia² Tomsk Scientific Center of the Siberian Branch of the Russian Academy of Sciences, 10/4 Akademicheskii Prospekt, 634055 Tomsk, Russia³ Smart Materials and Technologies Institute, National Research Tomsk State University, 36 Lenin Avenue, 634050 Tomsk, Russia

* Correspondence: karakchieva@mail.tsu.ru (N.K.); kurzina99@mail.ru (I.K.); Tel.: +7-3822-412-319 (I.K.)

Abstract: In this study, the influence of yttrium on the formation of the structural-phase state of the Ti-Al alloy, obtained by the “hydride technology” (GT) method, has been analyzed. Using transmission electron microscopy (TEM) and X-ray spectral microanalysis, the authors of the work have established the following phases formed in the sample volume and on the surface: Ti₃Al, TiAl, Al, α-Ti, Ti₃Al₅, Y₂Al, Y₅Al₃, YAl₃, YAl, and Y₆Ti₄Al₄₃. The lamellar structure has been formed in the alloy volume. The average width of the Al-rich lamellae was 0.36 μm and that of the Ti-rich lamellae was 0.21 μm. The formation of a triple Y₆Ti₄Al₄₃ phase, which is localized along the boundaries of the lamellar structure, has been recorded. The localization scheme of the formed phases of the TAY alloy has been proposed.

Keywords: hydride technology; yttrium; intermetallides; Ti-Al; Ti-Al-Y; Y₆Ti₄Al₄₃; lamellar structure

Citation: Karakchieva, N.; Artemenko, A.; Lepakova, O.; Sachkov, V.; Kurzina, I. Influence of Yttrium on the Phase Composition of the Ti-Al System Obtained by the ‘Hydride Technology’. *Metals* **2022**, *12*, 1481. <https://doi.org/10.3390/met12091481>

Academic Editors: Angelo Fernando Padilha and Koh-ichi Sugimoto

Received: 20 July 2022

Accepted: 31 August 2022

Published: 6 September 2022

Publisher’s Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The principal direction for improving the characteristics of heat-resistant aluminum alloys is through additives of transition and rare earth metals (REM) [1–5]. Small REM additives can control the structure of aluminum and aluminum-based alloys owing to the formation of secondary precipitates of intermetallic phases. The presence of heat-resistant dispersoids determines these alloys’ high level of strength [6–10].

REMs are of particular interest because of their ability to absorb a large amount of hydrogen. The maximum hydrogen content in hydrides corresponds to the LnH₃ formula. REMs interact with hydrogen slowly at room temperature and faster at a higher temperature (250–300 °C); yttrium interacts with hydrogen at 400 °C in vacuum. Studies show that the transformation of yttrium hydride from metallic YH₂ to semiconductor YH₃ is observed during continuous hydrogen absorption [11–14]. The yttrium additive has a positive effect on the structural stability of the alloys, reduces their liquation heterogeneity, and prevents the formation of harmful structural constituents. In this way, the aluminum alloy with a mass fraction of 1% of the alloying yttrium additive is related to an alloy having high mechanical properties at elevated temperatures [15].

When alloying with yttrium, because of a significant change in the structure and phase state, the mechanical properties are improved and the heat resistance of the alloys increases. The addition of up to 0.05 mass % of yttrium to all the studied media decreases the corrosion rate of alloys [16], increases the lattice distortion (the relative content of other dissolved atoms decreases, increasing the system energy), and promotes grain refining [17–19].

The oxidation characteristics of TiAl-based intermetallides at elevated temperatures are among the most important issues in terms of their application as potential high-temperature structural materials in the aerospace field [20]. Considering the growing need for increasing

the operating temperature of aircraft engines, resistance to oxidation above 800 °C is considered as a main obstacle to the practical application of these intermetallides [21]. Oxidation resistance can be improved by alloying and coating the surface with heat-resistant and wear-resistant phases [22,23]. In the case of alloying, such elements as Nb, Mo, W, Cr, C, and Si are considered useful because of their inherent resistance to oxidation [24–26]. However, the addition of some of these elements decreases the plasticity.

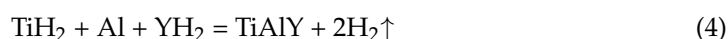
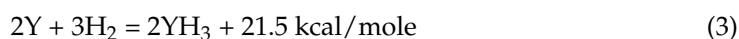
There are promising methods for improving the TiAl resistance to oxidation by Y-modification without deteriorating the mechanical properties [27,28]. However, the exact mechanism of the useful role of Y has not yet been clarified. The authors of [29] discussed how adding Y influenced the mechanical properties of TiAl alloys by reducing the grain size as well as the distance between the plates. In particular, the internal oxygen concentration in the TiAl alloys of elemental powder metallurgy (EPM) was reduced. The reason is the solid bond between the Y and O atoms [30], and the average oxygen concentration in experimental EPM alloys is 1500 weight parts per million, which is about ten times the solubility limit [31,32]. The supersaturated oxygen reacts with Y, followed by Y₂O₃ formation. When adding it, a barrier layer that prevents oxygen diffusion during thermal oxidation is created.

The early work of the authors [33] describes how a Ti-50Al (TA) sample (at.%) was obtained using the hydride technology. In the TA sample, TiAl is shown to dominate in the tetragonal and triclinic lattices. The Y additive slightly changes the AlTi₃ content but increases the effective energy of the TiAl lattice. In this work, the formation of the structure and phase composition in the volume and in the near-surface layer of the TA sample with the addition of 2 at.% yttrium has been studied in more detail.

2. Materials and Methods

2.1. Obtaining Alloy

The 49%Ti-49%Al-2%Y (at.%, hereinafter referred to as TAY) sample was obtained under hydrogenation-dehydrogenation conditions. The powder of titanium (TTEM-1; the particle size was 0.04–0.08 µm) or yttrium (characteristic) was poured into a quartz boat and placed in a reactor. Hydrogen was continuously fed through the reactor. The program stated that continuous heating was carried out up to a temperature of 420 °C. Then the resulting titanium hydride and yttrium hydride were thoroughly mixed with the aluminum powder (99%; the particle size was ~7 µm). Sample workpieces were molded from the resulting mixture (*d* = 0.13 cm, the bulk density was 3 g cm^{−3} (LabTools, St Petersburg, Russia, 2019)) at a pressure of 4 × 10⁶ Pa. Hydrogen can be removed from titanium at a high temperature in a vacuum. For this purpose, the sample workpieces were placed in the reactor, a vacuum of 0.01 Pa was created (at a residual pressure of oxygen, nitrogen, and carbon dioxide less than 1 × 10^{−3} Pa) and heated to 1200 °C. The workpieces were held at this temperature for 4 h and then cooled. The reaction equations of the process can be written as (1)–(4):



When writing the equation for obtaining yttrium hydride, the formula corresponds to YH₃, since according to the work by the authors of [34], yttrium under hydrogenation conditions at ~1 bar of hydrogen and 400 °C reacts to form YH₂. When the temperature is lowered to 200 °C, it forms YH₃.

Using this method, a TAY sample was obtained and the structural-phase state formation in the sample volume was investigated.

2.2. Research Methods

The X-ray structural and X-ray phase studies of the TAY system were carried out using the diffractometer DRON 4-07 (Bourestnik, Russia) device. Diffractograms were obtained by applying copper radiation (K α) according to the Bragg-Bretano scheme with a 0.02° step, exposure time at a point of 1 s, and in the angular range from 10 to 86°. The voltage on the X-ray tube was 30 kV; the beam current was 25 mA. The error in the measurement of the material grids is about ± 0.001 Å.

The electron microscopic studies of the samples' microstructure were performed by transmission electron microscopy (TEM) using the "JEM-2100F" (JEOL Ltd., Tokyo, Japan) device at an accelerating voltage of 200 kV with the attachment "JEOL" by means of energy-dispersion spectral (EDS) analysis. The images of the regions were photographed in the modes of bright-field (BF) and dark-field (DF) images. The microdiffraction patterns (MDP) were photographed from local areas in the sample volume and surficial region. The images of selected area electron diffraction (SAED) allow determining the lattice structure, as well as the presence of intergranular boundaries and/or point defects in the capture area. The foils were prepared by ion thinning.

The morphology and elemental composition of the sample surface were studied by means of scanning electron microscopy (SEM). A scanning electron microscope, QUANTA 200 3D (FEI Company, Hillsborough, OR, USA) was used. The following were the photographing parameters: the frequency was 50 Hz, the accelerating voltage was equal to 20 kV, and the surface resolution was 1–2 nm, including the energy spectrum resolution of ≈ 120 eV and the detection concentration limits of 0.1–0.5%. The results were presented in the form of energy-dispersive X-ray spectra (EDX).

Using a TM-3000 scanning electron microscope (Hitachi, Tokyo, Japan) with a QUANTA 70 attachment, used for elemental analysis on the surface of the TAY alloy sample, a change in the concentration of elements (Ti, Al, Y, and O) was observed. The photographing conditions included the accelerating voltage of 15 kV in the mode of charge removal from the sample (the electron gun was 5×10^2 Pa, the sample compartment was 30–50 Pa), the resolution of 30 nm, and the depth of field of 1 mm. The detector was represented by a four-segment solid-state detector of back-scattered electrons. The detector type was a Silicon Drift Detector (SDD); the detection element was B5~Am95. The modes were normal at 1~15 Pa with a low vacuum of 30~50 Pa.

The microhardness of the alloy samples was measured using a PMT-3M microhardness meter (LOMO, JSC, St. Petersburg, Russia). The microhardness was determined by the Vickers method. The load was 200 g.

3. Results

The Ti-Y system is referred to as binary systems with limited solubility that do not have intermetallic compounds. According to the state diagram, yttrium and titanium are completely mixed in the liquid state, and upon solidification they form an eutectic mixture of two limited solid solutions. In the solid state (below 875 °C), the material is represented by a mixture of two phases: α -Ti and α -Y. Due to the insignificant solubility of yttrium and titanium in the solid state, the constants of hexagonal crystal lattices α -Ti and α -Y vary little when one metal is alloyed with another [35].

According to the X-ray phase analysis (XPA) data (Figure 1), three basic phases were identified in the TAY sample after annealing in the vacuum medium. The first phase was Ti₃Al of the tetragonal syngony (P6₃/mmc) with parameters $a = b = 5.76$ Å, $c = 4.64$ Å, and with a CSR size of 134 ± 5 Å. The second phase was TiAl of the tetragonal syngony (P4/mmm space group) with lattice parameters $a = b = 2.75$ Å, $c = 5.34$ Å, and a SCR size of 40 ± 5 Å. Additionally, the third phase was Y₂O₃. Additional phases of Al (Fm-3m), α -Ti phase (P6₃/mmc), Ti₃Al₅ phase (P/mmm), and Y (P6₃/mmc) were also found in the TAY sample [33].

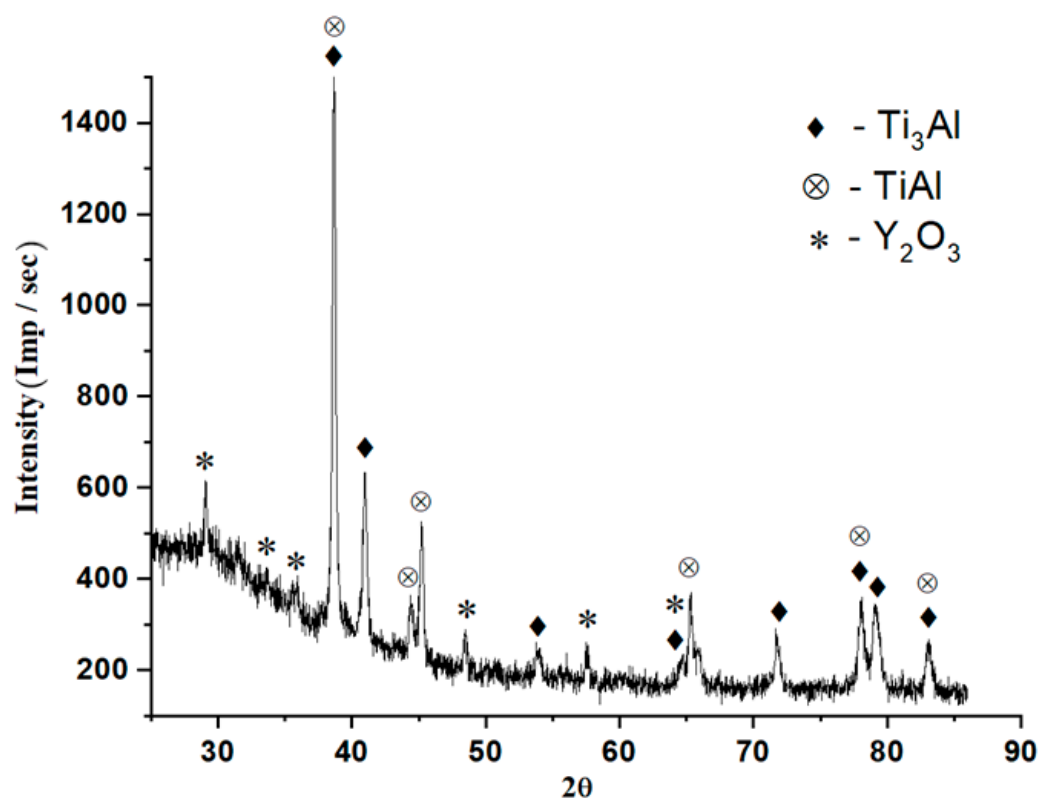


Figure 1. Diffraction patterns of the TAY alloy.

In the TAY sample, the alloy is represented by large gray particles (Figure 2a). According to the element distribution data, titanium and aluminum are uniformly distributed on the surface of the TAY sample (Figure 2b,c). Yttrium, being maximally distributed over the surface of the particles, is present in the alloy (Figure 2d). Such yttrium distribution hinders the development of diffusion processes on it. The energy-dispersive spectral analysis X-ray (EDX) spectrum of relevant regions is shown in Figure 2e.

In the heating mode up to 1200 °C in a vacuum environment, the material represents a lamellar structure based on titanium and aluminum. The internal microstructure was studied by the TEM method. Figure 3a,b show a thin lamellar structure.

A similar structure was observed in the Ti-Al-Sc sample, containing 2 at.% of scandium [32]. The data interpretation (Figure 3b) in the mode of bright-field (Figure 3(1,2)) and dark-field images (Figure 3(3–5)) showed that a $Y_6Ti_4Al_{43}$ triple compound with the P63/mcm space group and lattice parameters $a = b = 11.06$ Å and $c = 17.901$ Å was formed (Figure 3c). Moreover, as Figures 2 and 3 show, yttrium impurities are orderly arranged on the dislocations or on grain boundaries in the form of a compound and are not distributed randomly in the grain volume.

The $Y_6Ti_4Al_{43}$ compound is a Ternary Aluminide $A_6T_4Al_{43}$ with A: Y, Nd, Sm, Gd-Lu, Th, U, and T: Cr, Mo, and W [36] and belongs to the isotypic compounds of the $Ho_6Mo_4Al_{43}$ type structure (hexagonal, P63/mcm). The authors of [37] found that the absolute susceptibility values of the $Y_6Ti_4Al_{43}$ compound at room temperature were $11.2 (\pm 0.3) \times 10^{-9}$ m³/mol of the formula unit (f.u.). The authors believe that this may be associated with paramagnetic impurities or the sample surface state.

Figure 4a demonstrates bright-field (Figure 4, image 1) and dark-field images (Figure 4, images (2–5)) photographed in the TAY sample volume. The microdiffraction pattern was interpreted for a more detailed identification (Figure 4c). Dark-field images were photographed. According to the TEM data interpretation, the luminous regions correspond to the Ti_3Al phase.

The Ti_3Al phase is one of the constituents of the lamellar structure and belongs to an intermetallic compound with a wide homogeneity region. According to Figure 4a, this

phase appears to be a darker band (Ti-rich); the light bands correspond to the second phase of the lamellar structure (TiAl). The analysis of the width bands showed (Figure 5) that the Ti-rich fraction with a width up to 0.2 μm was 0.35; for the bands ranging from 0.4 to 0.5 μm , it was 0.21.

Al-rich bands are characterized by a large width range from 0 to 0.9 μm . Bands with a width of 0.5–0.6 μm make up the majority of the surface of the structure (the share is 0.25). There is an insignificant number (0.07 fraction) of bands with a width of 0.8–0.9 μm .

In the sample volume, the structure at the surface was represented by an oxide layer, a Ti_2Al phase, and randomly arranged particles, containing yttrium. The analysis of the quantitative composition distribution of aluminum, titanium, and yttrium in the sample showed that the lamellar structure was formed in the entire sample area and was represented by Ti_3Al , Ti_2Al , and TiAl phases (Figure 6a,b). Bands enriched in titanium (Ti-rich) and aluminum (Al-rich) alternated (Figure 6a–f). The EDS from the band section in the sample volume is presented in Figure 6 (spectrum 1–2). The aluminum content varied by the sample volume; Ti_3Al and TiAl phases were sequentially formed. In the sample volume, the Ti-rich and Al-rich bands were more homogeneous in composition.

The particles in the sample volume, located close to the near-surface layer, are compounds of yttrium and aluminum (Y_2Al , Y_5Al_3 , YAl_3 and YAl). The particles' composition is represented by phases of the Al–Y system, covered with an oxide layer. According to the spectral analysis (Figure 6, spectra (1–6)), an oxide layer is formed, represented by aluminum, titanium, and yttrium oxides (Table 1). Titanium can oxidize in air, so the titanium oxide formation is probably related to the fact that the sample was in contact with air. The layer formation occurs at the boundaries of Ti_3Al and TiAl. The concentration changes of the elements (Ti, Al, Y, and O) are shown in Figure 6g.

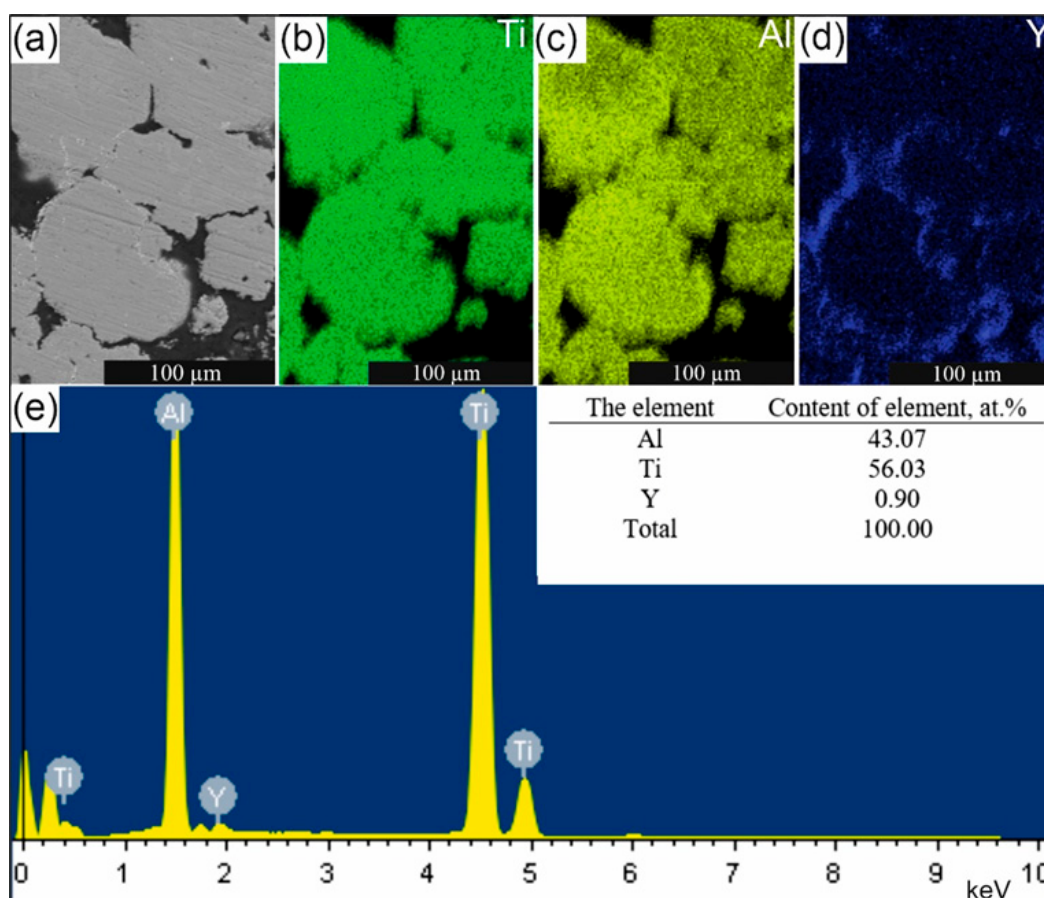


Figure 2. SEM images of the Ti–Al–Y alloy (a) with the super-spectral surface (b–d) and with the energy-dispersive spectral X-ray analysis (EDX) spectrum of relevant regions (e).

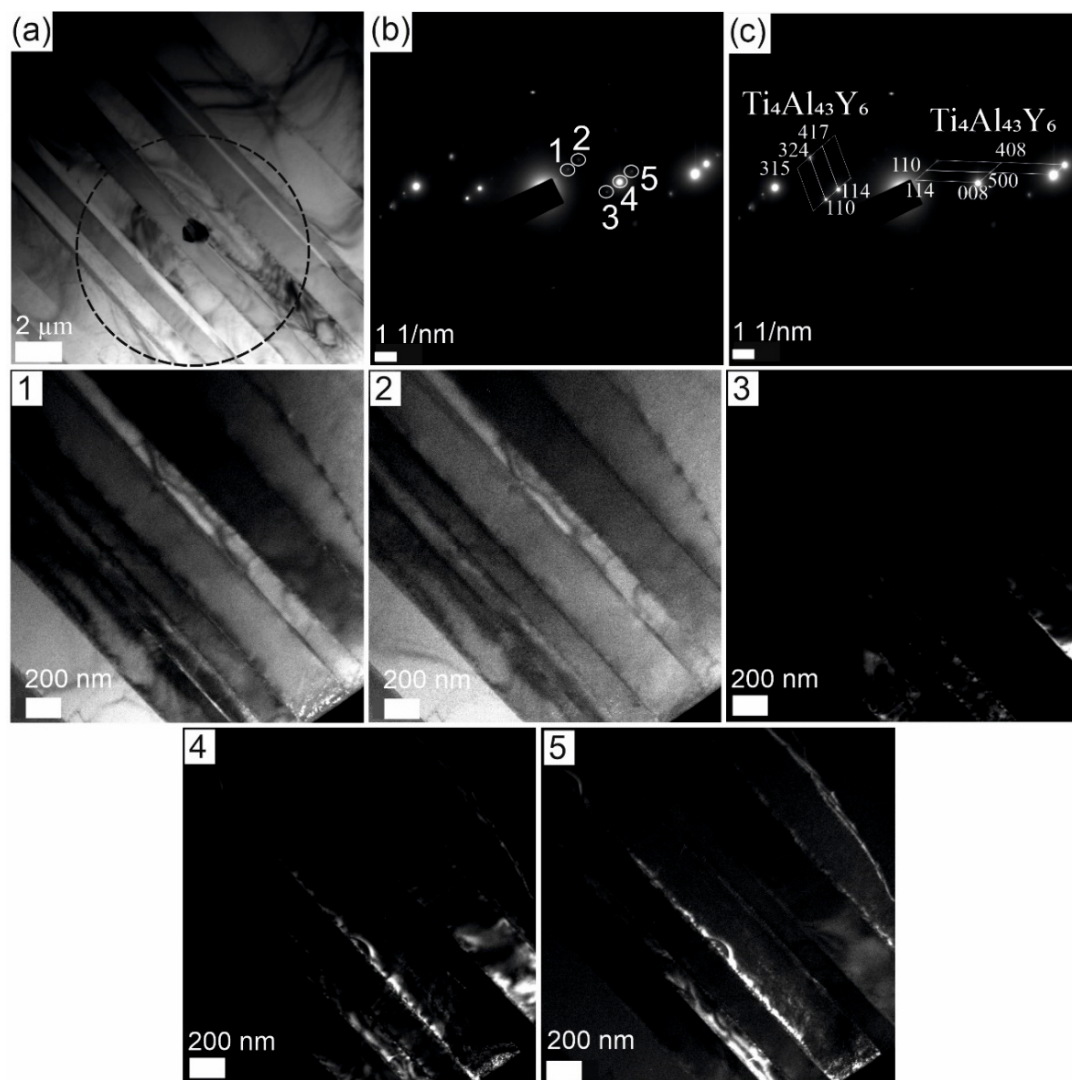


Figure 3. BF images of the Ti-Al-Y alloy (a), SAED pattern (b) of the Ti-Al-Y alloy with the bright image. SAED patterns of the Ti-Al-Y alloy in the relevant region (c). The dark-field images (1)–(5) correspond to reflexes (1)–(5) in the microdiffraction pattern (b).

Table 1. Summary table of the results of the EDS.

No. of Spectrum	at. %				Formula
	Ti	Al	Y	O	
1	75.12	24.09	-	0.78	Ti ₃ Al, TiAl
2	61.52	38.00	-	0.48	Ti ₂ Al
3	4.06	1.2	67.64	27.10	Y, Y ₂ O ₃ , TiO ₂ , Al ₂ O ₃
4	35.94	19.31	37.23	7.52	Ti ₂ Al, Al ₂ O ₃ , Y
5	10.12	4.61	72.11	13.17	Ti ₂ Al, Y, Al ₂ O ₃ ,
6	54.6	29.11	0.17	16.12	Ti ₂ Al, Al ₂ O ₃

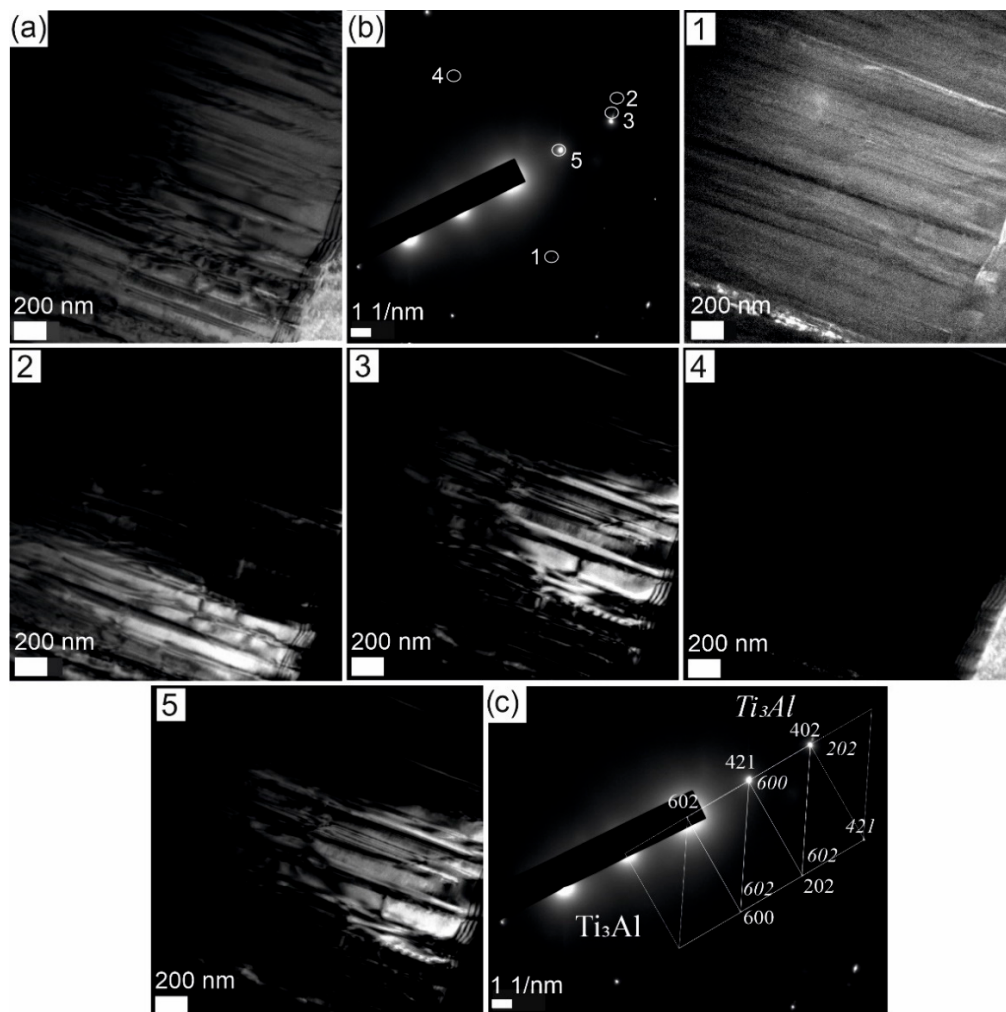


Figure 4. BF images of the Ti-Al-Y alloy (a) SAED pattern (b) of the Ti-Al-Y alloy with the bright-field image. SAED patterns of the Ti-Al-Y alloy in the relevant region (c). The dark-field image of Ti-Al-Y (1). The dark-field images (1)–(5) correspond to reflexes (1)–(5) in the microdiffraction pattern (b).

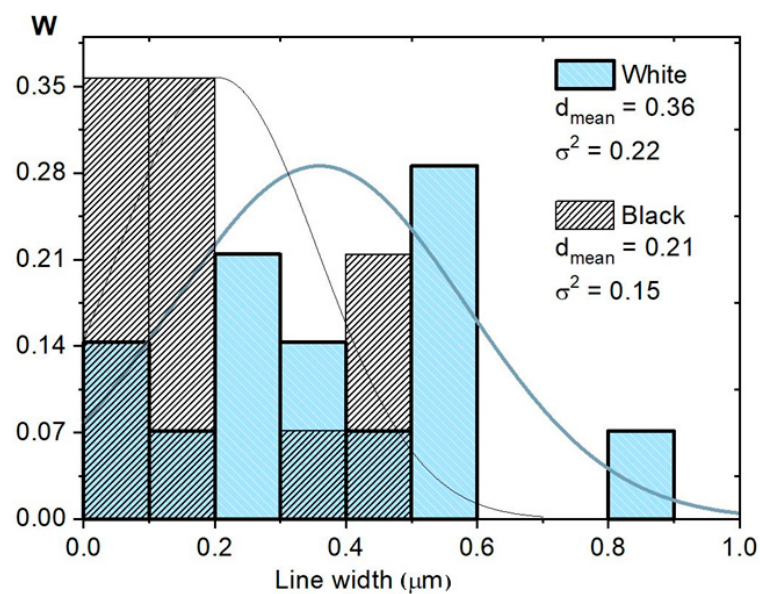


Figure 5. The width distribution of the lamellar in the Ti-Al-Y sample.

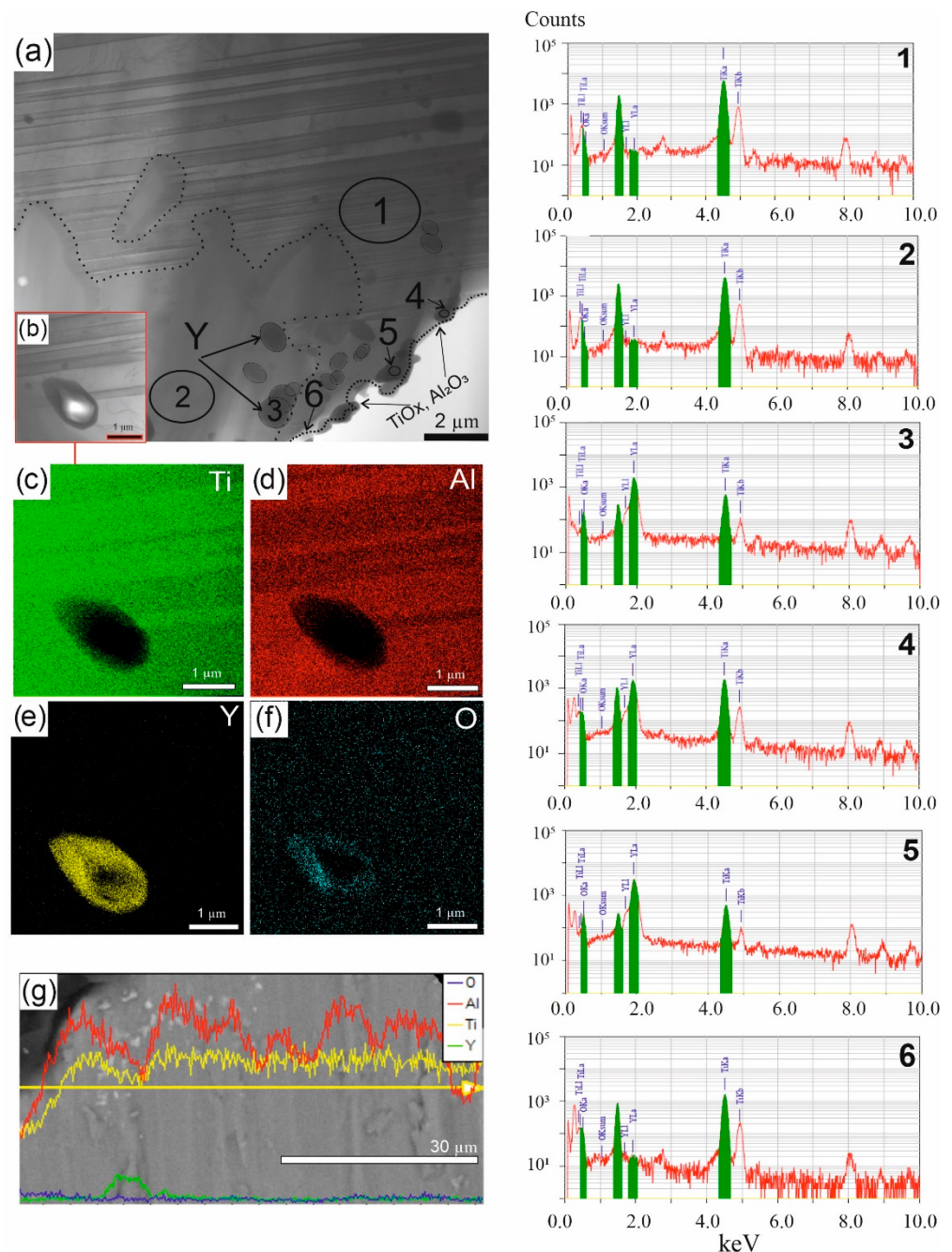


Figure 6. TEM images of the Ti-Al-Y alloy (a,b) with the super-spectral surface (c–f) and with the energy-dispersive spectral analysis (EDS) spectrum of relevant regions (1)–(6). SEM images of the concentration changes of the elements (Ti, Al, Y, and O) (g).

The work has shown that, when obtaining the TAY sample by the hydride technology, yttrium is distributed along the particle boundaries. A detailed study by the TEM method has shown that yttrium is present both in the form of individual particles and in combination with oxygen, aluminum, and titanium. The interaction with the latter leads to the formation of a triple compound. During the experiment, the authors discovered that yttrium has a heterogeneous distribution and concentration in some small areas in the interdendritic regions [38], and the oxide scale, which contains the Y_2O_3 phase, improves the high-temperature wear characteristics of Stellite 21, especially at temperatures above 500 °C.

Five intermetallides can be formed in the TAY system: Al_3Y , Al_2Y , AlY , Al_2Y_3 , and AlY_2 . Intermetallides of the Al_2Y and Al_2Y_3 composition melt congruently at 1491 and 1104 °C, respectively. The remaining intermetallides are formed according to peritectic reactions: AlY at a temperature of 978 °C, AlY at 1129 °C, and AlY at 973 °C [39]. A detailed analysis of the composition and structure of the particles, formed during the obtaining of the sample by the hydride technology, was carried out by the TEM method (Figure 7). Y_2Al , Y_5Al_3 , YAl_3 , and YAl phases are detected in the TAY system and yttrium remains in the form of metal. The migration of aluminum ions probably takes place. A triple $\text{Y}_6\text{Ti}_4\text{Al}_{43}$ compound is also detected, which is presumably formed in the volume of the Ti_3Al and TiAl phases and the yttrium metal particle.

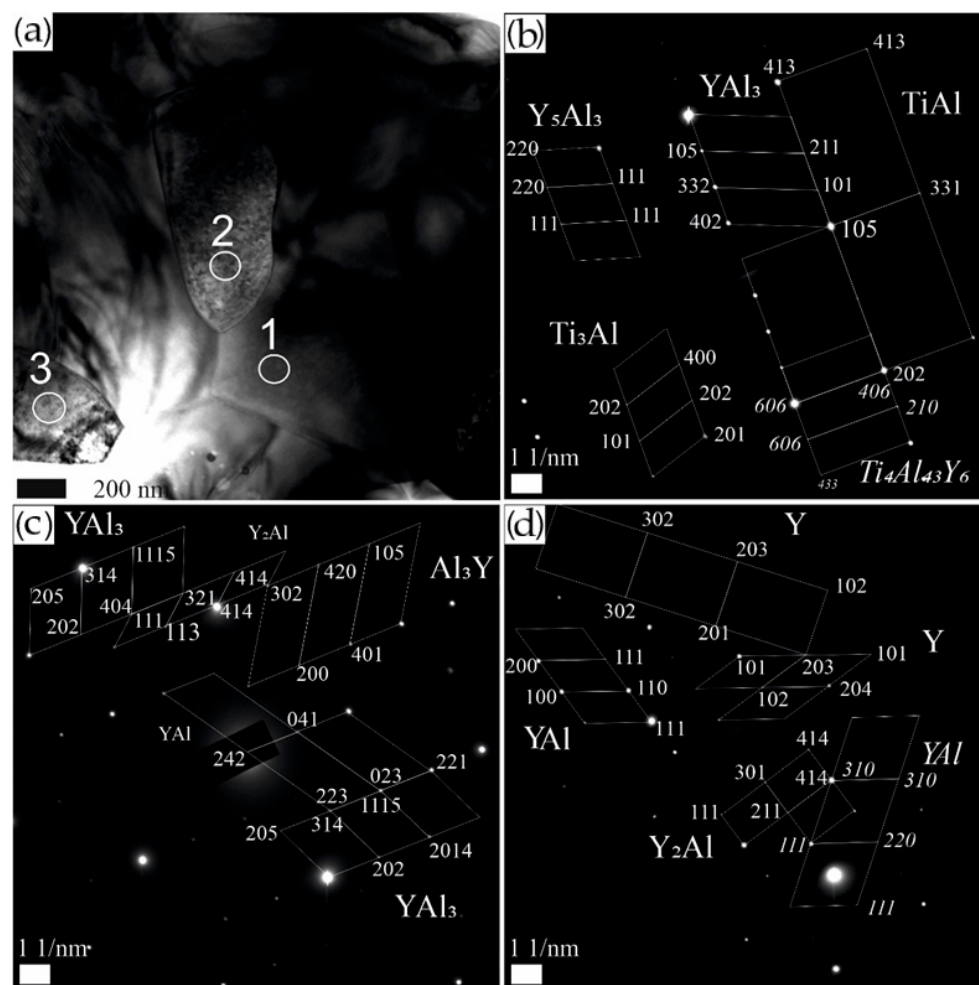


Figure 7. TEM image of the Ti-Al-Y alloy (a) SAED patterns of the Ti-Al-Y alloy in the relevant region (b–d).

4. Discussion

Figure 8 shows a scheme of the formed phases by the composition and their distribution by the volume of the samples' surface. The addition of yttrium leads to the formation of thermodynamically stable phases according to the state diagram [39]. When the yttrium concentration is up to 2 at.%, the formation of Ti_3Al (α_2), TiAl (γ), and Y_2Al is possible. In the triple system, titanium is used for the formation of oxide, aluminides, and partially the triple phase. Aluminum participates in the formation of titanium aluminides, oxide, Al-Y double phases, and a triple phase. Yttrium forms an oxide, double phases with aluminum, but it does not form double phases with titanium, and yttrium is part of the three-component phase.

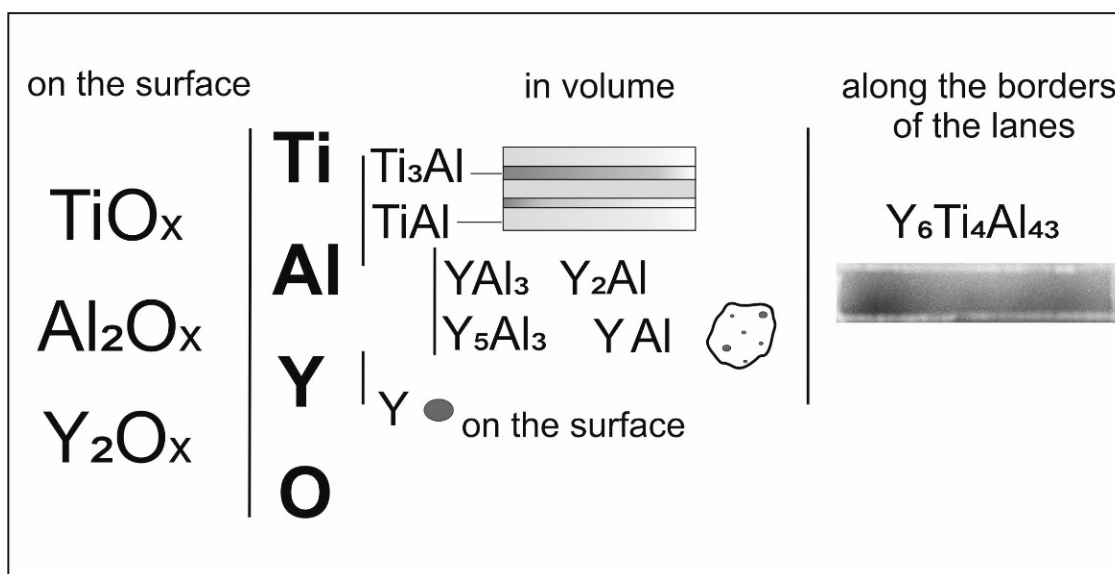


Figure 8. The localization scheme of the TAY alloy phases formed by the TAY hydride technology.

The structure and localization of the formed phases vary in the depth of the sample. When obtaining a sample of the TAY composition by the hydride technology under hydrogenation-dehydrogenation conditions, an oxide layer (oxides of titanium, aluminum, and yttrium) is formed on the surface. A different phase structure is formed in the sample volume. Depending on the conditions of obtaining them, the localization of stable phases may vary. When using the hydride technology to obtain a new alloy, a lamellar structure with layers containing Ti_3Al and TiAl is formed in the volume. The areas, enriched with the γ -phase, have a width twice as large as the α_2 phase. Yttrium, according to the state diagram, forms phases only with aluminum of a variable composition, localized by individual grains in the regions that are close to the surface of the alloy particles. In addition, the $\text{Y}_6\text{Ti}_4\text{Al}_{43}$ triple phase formation was registered, which is localized along the boundaries of the lamellar structure. Most of the yttrium concentration was fixed on the surface of the particles in the form of an oxide phase or in the form of individual particles that had not interacted with other metals.

In this way, this work has discussed the formation of a unique alloy, representing gradient changes in the number and composition of the phases throughout the surface and containing a lamellar structure in the volume. It is assumed that the resulting material will be characterized by improved physical and mechanical properties and may be promising for practical application.

The microhardness value has been 1.75 GPa for the TAY alloy obtained by HT.

5. Conclusions

Based on the results of the work done, the following conclusions can be drawn:

1. Layered compositions, based on intermetallic phases and the alloying additive of 49Ti–49Al–2Y (at.%) yttrium, have been obtained using the “hydride technology”. This technology allows, under hydrogenation-dehydrogenation conditions, to alloy the Ti–Al system with up to 2 at.% yttrium;
2. The following phase compositions have been formed in the sample: Ti_3Al , TiAl , Y_2O_3 , Al, α -Ti, Ti_3Al_5 , Y_2Al , Y_5Al_3 , YAl_3 , YAl , $\text{Y}_6\text{Ti}_4\text{Al}_{43}$. A lamellar structure has been formed (Ti_3Al and TiAl);
3. Yttrium is distributed in the matrix of intermetallic phases with a simultaneous increase (two times) in the thickness of the layers and/or separate phases are formed: Y_2Al , Y_5Al_3 , YAl_3 , and YAl . As the alloy particle moves away from the surface into the volume, there is a gradient of changes in the concentration of yttrium and oxygen

and, accordingly, a change in the qualitative and quantitative phase composition of yttrium-containing phases;

4. The $Y_6Ti_4Al_{43}$ (P63/mcm) phase forms at the grain boundaries and/or in the grain volume;
5. An oxide layer (Y_2O_3 , TiO_2 , and Al_2O_3) is formed at the surface boundary which prevents the sample oxidation.

Author Contributions: Methodology, visualization, and writing—original draft preparation, N.K.; investigation, O.L. and A.A.; conceptualization and data curation, V.S.; reviewing and editing, I.K. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by the Tomsk State University Development Program (Priority-2030).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The analyses (SEM research) were carried out with the equipment of Tomsk Regional Core Shared Research Facilities Center of National Research Tomsk State University (Grant of the Ministry of Science and Higher Education of the Russian Federation no. 075-15-2021-693 (no. 13.RFC.21.0012)).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Li, Z.; Jiang, H.; Wang, Y.; Zhang, D.; Yan, D.; Rong, L. Effect of minor Sc addition on microstructure and stress corrosion cracking behavior of medium strength Al–Zn–Mg alloy. *J. Mater. Sci. Technol.* **2018**, *34*, 1172–1179. [\[CrossRef\]](#)
2. Zhang, J.; Wang, H.; Yi, D.; Wang, B.; Wang, H. Comparative study of Sc and Er addition on microstructure, mechanical properties, and electrical conductivity of Al-0.2 Zr-based alloy cables. *Mater. Charact.* **2018**, *145*, 126–134. [\[CrossRef\]](#)
3. Wu, S.H.; Zhang, P.; Shao, D.; Cheng, P.M.; Kuang, J.; Wu, K.; Zhang, J.Y.; Liu, G.; Sun, J. Grain size-dependent Sc microalloying effect on the yield strength-pitting corrosion correlation in Al–Cu alloys. *Mat. Sci. Eng. A Struct.* **2018**, *721*, 200–214. [\[CrossRef\]](#)
4. Belov, N.; Naumova, E.; Akopyan, T. Effect of 0.3% Sc on microstructure, phase composition and hardening of Al–Ca–Si eutectic alloys. *Trans. Nonferrous Met. Soc. China* **2017**, *27*, 741–746. [\[CrossRef\]](#)
5. Erdeniz, D.; Nasim, W.; Malik, J.; Yost, A.R.; Park, S.; De Luca, A.; Vo, N.Q.; Karaman, I.; Mansoor, B.; Seidman, D.N.; et al. Effect of vanadium micro-alloying on the microstructural evolution and creep behavior of Al–Er–Sc–Zr–Si alloys. *Acta Mater.* **2017**, *124*, 501–512. [\[CrossRef\]](#)
6. Li, J.H.; Wiessner, M.; Albu, M.; Wurster, S.; Sartory, B.; Hofer, F.; Schumacher, P. Correlative characterization of primary $Al_3(Sc, Zr)$ phase in an Al–Zn–Mg based alloy. *Mater. Charact.* **2015**, *102*, 62–70. [\[CrossRef\]](#)
7. Saumitra, S.; Todorova, T.Z.; Zwanziger, J.W. Temperature dependent lattice misfit and coherency of Al_3X ($X = Sc, Zr, Ti$ and Nb) particles in an Al matrix. *Acta Mater.* **2015**, *89*, 109–115.
8. Dorin, T.; Ramajayam, M.; Lamb, J.; Langan, T. Effect of Sc and Zr additions on the microstructure/strength of Al–Cu binary alloys. *Mater. Sci. Eng.* **2017**, *707*, 58–64. [\[CrossRef\]](#)
9. Hallem, H.; Lefebvre, W.; Forbord, B.; Danoix, F.; Marthinsen, K. The formation of $Al_3(Sc_xZr_yHf_{1-x-y})$ -dispersoids in aluminium alloys. *Mater. Sci. Eng.* **2006**, *421*, 154–160. [\[CrossRef\]](#)
10. Hallem, H.; Forbord, B.; Marthinsen, K. An investigation of dilute Al–Hf and Al–Hf–Si alloys. *Mater. Sci. Eng.* **2004**, *387–389*, 940–943. [\[CrossRef\]](#)
11. Seijirau, S.; Fukai, Y. Metal-Hydrogen Systems: Fundamentals and Applications. In Proceedings of the International Symposium on Research Involving Palladium and Other Platinum Group Metals, Conference Centre, Tokyo, Japan, 1 November 1994.
12. Daou, J.N.; Vajda, P. Hydrogen ordering and metal-semiconductor transitions in the system YH_{2+x} . *Phys. Rev. B Condens. Matter.* **1992**, *45*, 10907–10913. [\[CrossRef\]](#) [\[PubMed\]](#)
13. Van Gogh, A.T.M.; van der Molen, S.J.; Kerssemakers, J.W.J.; Koeman, N.J.; Griessen, R. Performance enhancement of metal-hydride switchable mirrors using Pd/ AlO_x composite cap layers. *Appl. Phys. Lett.* **2000**, *6*, 815–817. [\[CrossRef\]](#)
14. Weaver, J.H.; Peterson, D.T.; Benbow, R.L. Electronic structure of metal hydrides. *Phys. Rev. B* **1979**, *20*, 5301. [\[CrossRef\]](#)
15. Snitovsky, Y.P. Phase composition and concentration of yttrium in films during the deposition of aluminum and aluminum alloys from the gas phase. *Bull. Yurga State Univ.* **2021**, *4*, 16–31. [\[CrossRef\]](#)
16. Yu, L.; Tang, J.; Qiao, J.; Wang, H.; Wang, Y.; Apreutesei, M.; Chamas, M.; Duan, M. Effect of yttrium addition on corrosion resistance of Zr-based bulk metallic glasses in NaCl solution. *Int. J. Electrochem. Sci.* **2017**, *12*, 6506–6519. [\[CrossRef\]](#)
17. Peterman, D.J.; Harmon, B.N.; Marchiando, J.; Weaver, J.H. Band theory of ScH_2 and YH_2 . *Phys. Rev. B* **1979**, *19*, 4867. [\[CrossRef\]](#)
18. Wei, Q.; Zhang, Z.Y.; Wang, X.L.; Wang, Y.; Zhao, Y.T. Effect erbium, yttrium on properties and microstructure of 6082 alloy. *Mater. Sci.* **2016**, *34*, 529.

19. Emamy, M.; Nodooshan, H.R.J.; Malekan, A. The microstructure, hardness and tensile properties of Al-15%Mg2Si in situ composite with yttrium addition. *Mater. Des.* **2011**, *8–9*, 4559–4566. [\[CrossRef\]](#)
20. Kim, Y.W. Ordered intermetallic alloys, part III: Gamma titanium aluminides. *JOM* **1994**, *46*, 30–39. [\[CrossRef\]](#)
21. Becker, S.; Rahmel, A.; Schorr, M.; Schutze, M. Mechanism of isothermal oxidation of the intermetallic TiAl and of TiAl alloys. *Oxid. Met.* **1992**, *38*, 425–464. [\[CrossRef\]](#)
22. Heo, S.H.; Kim, I.B.; Han, J.W.; Hwang, W.S.; You, B.D.; Kim, M.S. Comparisons of high temperature oxidation behavior between reactive-sintered and melted Ti-45at.%Al-1.6at.%Mn. *Met. Mater. Int.* **2000**, *6*, 449–453. [\[CrossRef\]](#)
23. Tang, Z.; Niewolak, L.; Shemet, V.; Singheiser, L.; Quadackers, W.J.; Wang, F.; Wu, W.; Gil, A. First-principles investigation of site. Preference and bonding properties of alloying element in TiAl with O impurity. *Mater. Sci. Eng.* **2002**, *328*, 297. [\[CrossRef\]](#)
24. Yoshihara, M.; Miura, K. Effects of Nb addition on oxidation behavior of TiAl. *Intermetallics* **1995**, *3*, 357–363. [\[CrossRef\]](#)
25. Anada, H.; Shida, Y. The effect of various ternary additives on the oxidation behavior of TiAl in high-temperature air. *Oxid. Met.* **1996**, *45*, 197–219.
26. Brady, M.P.; Smialek, J.L.; Humphrey, D.L.; Smith, J. The role of Cr in promoting protective alumina scale formation by γ -based TiAlCr. Alloys. *Acta. Mater.* **1997**, *45*, 2371–2382. [\[CrossRef\]](#)
27. Maki, K.; Shioda, M.; Sayashi, M. Effect of silicon and niobium on oxidation resistance of titanium aluminide (TiAl) intermetallics. *Mater. Sci. Eng.* **1992**, *153*, 591. [\[CrossRef\]](#)
28. Wu, Y.; Hwang, S.K. High-temperature oxidation of elemental powder metallurgy processed TiAl-Mn-Mo-C alloys with yttrium addition. *Acta. Mater.* **2004**, *45*, 1272–1281. [\[CrossRef\]](#)
29. Park, H.S.; Hwang, S.K.; Lee, C.M.; Yoo, Y.C.; Nam, S.W.; Kim, N.J. Microstructural refinement and mechanical properties improvement of elemental powder metallurgy processed Ti-46.6Al-1.4Mn-2Mo alloy by carbon addition. *Metall. Mater. Trans. B* **2001**, *32*, 251. [\[CrossRef\]](#)
30. Kobayashi, Y.; Tsukihashi, F. Thermodynamics of yttrium and oxygen in molten zirconium. *Metall. Mater. Trans. B* **1998**, *30*, 352–354. [\[CrossRef\]](#)
31. Menand, A.; Huguet, A.; Nerac-Partaix, A. Interstitial solubility in γ and α_2 phases of TiAl-based alloys. *Acta. Mater.* **1996**, *44*, 4729–4737. [\[CrossRef\]](#)
32. Karakchieva, N.; Lepakova, O.; Abzaev, Y.; Sachkov, V.; Kurzina, I. The Influence of Scandium on the Composition and Structure of the Ti-Al Alloy Obtained by “Hydride Technology”. *Nanomaterials* **2021**, *11*, 918. [\[CrossRef\]](#)
33. Belgibayeva, A.; Abzaev, Y.; Karakchieva, N.; Erkasov, R.; Sachkov, V.; Kurzina, I. The Structural and Phase State of the TiAl System Alloyed with Rare-Earth Metals of the Controlled Composition Synthesized by the “Hydride Technology”. *Metals* **2020**, *10*, 859. [\[CrossRef\]](#)
34. Soroka, O.; Sturm, J.M.; van de Kruijs, R.W.E.; Lee, C.J.; Bijkerk, F. Control of YH_3 formation and stability via hydrogen surface adsorption and desorption. *Appl. Surf. Sci.* **2018**, *455*, 70–74. [\[CrossRef\]](#)
35. Gromov, V.E.; Sosnin, K.V.; Ivanov, Y.F.; Zenina, E.V.; Rubannikova, Y.A. Formation of structure and phase composition of Ti-Y surface layer by electro explosion and electron-beam treatment. *Russ. Univ. Rep. Math.* **2016**, *21*, 850–852. [\[CrossRef\]](#)
36. Niemann, S.; Jeitschko, W. Ternary Aluminides $\text{A}_6\text{T}_4\text{Al}_{43}$ (A = Y, Nd, Sm, Gd-Lu, and U.; T = Ti, V, Nb, and Ta) with $\text{Ho}_6\text{Mo}_4\text{Al}_{43}$ Type Structure. *J. Solid State Chem.* **1995**, *116*, 131–135. [\[CrossRef\]](#)
37. Wolff, M.W.; Niemann, S.; Ebel, T.; Jeitschko, W. Magnetic properties of rare-earth transition metal aluminides $\text{R}_6\text{T}_4\text{Al}_{43}$ with $\text{Ho}_6\text{Mo}_4\text{Al}_{43}$ -type structure. *J. Magn. Magn. Mater.* **2001**, *223*, 1–15. [\[CrossRef\]](#)
38. Radu, I.; Li, D.Y.; Llewellyn, R. Tribological behavior of Stellite 21 modified with yttrium. *Wear* **2004**, *257*, 1154–1166. [\[CrossRef\]](#)
39. Raghavan, V. Al-Ti-Y (Aluminum-Titanium-Yttrium). *J. Phase Equilib. Diffus.* **2005**, *26*, 191. [\[CrossRef\]](#)