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**CRADA Final Report
for
CRADA Number Y1293-0176**

**MICRO-TOUGHENED TITANIUM-BASED
INTERMETALLICS FOR HIGH-TEMPERATURE
SERVICE**

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Abstract

This Cooperative Research and Development Agreement (CRADA) report deals with the composition development, processing parameter development, microstructural evaluation, and mechanical properties development of the γ TiAl alloys. Two series of alloy compositions were identified. The first series consisted of four alloys, and the second series consisted of three alloys. In all cases, the alloy powder was prepared by the rotary atomization process at Pratt & Whitney (P&W). The powders were packed in titanium cans, evacuated, and sealed. The titanium cans were hot extruded at 1150, 1250, and 1400°C to an area reduction ratio of 16:1. The extruded bars were heat treated between 800 and 1320°C, and their microstructure characterized in the extended and heat-treated condition by optical, scanning, and transmission electron microscopy (TEM). The microstructural features such as colony size, width of colony boundary γ layer, interlamellar spacing, α_2 - α_2 spacing, γ lamellar width, and α_2 - γ layer ratio were quantified. Tensile bars were prepared from the extruded bars by electrodischarge machining followed by grinding. Tensile tests were conducted from room temperature to 1000°C. Three-point-bend tests were used to measure the fracture toughness at both room temperature and 800°C. The effect of long-term annealing at 800 and 1000°C on one of the alloys was measured at room temperature. Tensile properties of the alloys of this study were compared with the data reported in literature.

The two-phase γ TiAl alloys with refined lamellar structure, produced by hot extrusion of powders at 1400°C, produced the best combination of tensile properties at room and elevated temperatures and creep properties at elevated temperature. The fracture toughness of the alloys was between 22.3 to 22.6 MPa m^{1/2} at room temperature and increased to 40.1 to 41.4 MPa m^{1/2} at 800°C.

The excellent properties of the alloys studied in this CRADA stem from refined colony-size (<70 μ m) and fine α_2 to α_2 platelet spacing (<1 μ m). The tensile ductility increased with decreasing colony size and increasing interlamellar spacing. The yield strength increased with decreasing intermetallic spacing. The fine lamellar structure is stable for at least 200 days at 800°C. Powder metallurgy is a feasible way to produce two-phase γ TiAl alloys with outstanding mechanical properties.

The mechanical properties of the alloys developed in this CRADA are better than the results from the literature on alloys with lamellar microstructure.

CRADA Objectives

The subject CRADA has the following objectives:

1. Develop TiAl-based aluminide matrix alloys with improved mechanical properties and oxidation resistance.
2. Prepare TiAl alloy powders with desired powder sizes.
3. Develop titanium-aluminide matrix composites with improved low-temperature impact toughness and high-temperature creep resistance.
4. Develop industrial processing capability for manufacturing TiAl-matrix composites.
5. Generate an engineering data base and qualify TiAl-matrix composites for advanced military and commercial turbine-engine applications.

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The above objectives were somewhat modified during the course of this CRADA. First, the great success in improving the strength and toughness of TiAl-based alloy through composition and microstructure control eliminated the need for the development of the composites. The crada objectives also had to be modified because its duration was reduced from three to two years.

Completion of Objectives

All objectives of the CRADA were met within the constraints of the modified duration and funding. In fact, the CRADA resulted in γ TiAl alloy compositions with controlled microstructures that exceeded the strength and toughness and ductility properties of alloys reported in the literature.

CRADA Benefit to DOE

The Department of Energy (DOE) benefited significantly from this CRADA. It gave DOE the opportunity to successfully extend the knowledge base on nickel and iron aluminides to titanium aluminides. The program also benefited in that it gave DOE the use of γ TiAl compositions with high strength and toughness for automotive and energy-related programs requiring corrosion-resistant alloys. The CRADA also resulted in compositions, processing, and properties for the benefit of defense program-related applications. The CRADA has enhanced the DOE laboratory credibility with aerospace-related companies, which has happened with the work carried out during this CRADA.

Technical Discussion

Introduction

The two-phase γ TiAl alloys are of great interest for applications in aircraft engines. For the F119 military engine, it will be used for the compressor variable vane inner shrouds. The TiAl-based alloys are also being developed to meet the longer term goals of increasing the thrust to weight of current engines by a factor of two for the integrated high-performance turbine engine technology (IHPTET). Implementation of γ TiAl is absolutely critical to the achievement of the IHPTET goals.

The γ TiAl-based alloys offer several advantages including:

1. Extremely low density (3.9 g/cm^3).
2. Good mechanical properties (especially density compensated) at elevated temperatures.
3. Adequate oxidation resistance at temperatures up to 800°C .
4. Thermal expansion coefficient that is significantly lower than the currently used nickel-based superalloys.

Besides their great advantages, the applications of γ TiAl alloys have limited use because of their limited tensile ductility and fracture resistance at ambient temperature and their limited processing window.

The joint cooperative research and development agreement (CRADA) between the Oak Ridge National Laboratory (ORNL) and Lawrence Livermore National Laboratory with Pratt & Whitney (P&W), a division of United Technologies, made significant progress toward addressing the disadvantages of γ TiAl alloys and brought them closer to their applications. The completion of the CRADA work resulted in the following major contributions towards the application of γ TiAl alloys:

1. Identified alloy compositions.
2. The two-phase γ TiAl alloys with refined lamellar structures ($d < 70 \mu\text{m}$) show both excellent tensile ductility and fracture toughness at ambient temperatures.
3. The γ TiAl alloys with controlled microstructures show outstanding strength and creep resistance at elevated temperatures.
4. Powder metallurgy (PM) is a feasible method for producing γ TiAl alloys with a combination of ambient temperature ductility and toughness and high-temperature strength.

The progress during the CRADA was transferred to P&W during quarterly review meetings. The purpose of this report is to provide a description of activities carried out during the course of this CRADA.

Alloy Compositions

Two series of alloy compositions were developed. The composition of each series in atomic percent is given in Table 1 below.

Table 1. Composition of two series of γ TiAl investigated

Alloy number	Alloy identification	Elements (at. %)								
		Ti	Al	Cr	Nb	Ta	Mo	B	W	Si
First series										
1	T2-73	<i>a</i>	47	2	2	--	--	--	--	--
2	T2-74	<i>a</i>	47	2	1	1	--	--	--	--
3	T2-76	<i>a</i>	47	3	2	--	0.6	--	--	--
4	T2-77	<i>a</i>	47	3	1	1	0.6	--	--	--
Second series										
5	T1-321	<i>a</i>	47	2	1	1	--	0.15	--	--
6	T1-322	<i>a</i>	47	2	1	0.8	--	0.15	0.2	--
7	T1-323	<i>a</i>	47	2	1	0.8	--	0.15	0.2	0.3

^aBalance.

Alloy Processing

The alloys from the first series of compositions were cold hearth-crucible induction melted in approximately 15-kg heats at P&W. Each of the compositions was atomized to rapidly solidified powder using the rotary atomization facility at P&W.

The series of alloy compositions were melted in approximately 100-kg heats at Duriron Company (Dayton, Ohio). Large heats were produced to have sufficient material for a broad-base microstructural characterization, properties data development, and fabrication of prototypic components. Each of the approximately 100-kg heats consisted of three heats weighing approximately 30 kg, which were cast into 100-mm-diam ingots. The ingots from each heat had a shiny appearance with no indication of oxidation (see Fig. 1).

Fig. 1. One-hundred-millimeter-diameter ingots of the second series of γ TiAl alloys melted and cast at Duriron Company (Dayton, Ohio). The shiny surface of the ingots indicates that they are extremely clean.

All three heats weighing 90 kg each were procured by ORNL and supplied to P&W for powder production. The -100 mesh powder from the 15- and 100-kg heats were canned in 75-mm-diam titanium cans. The cans were evacuated and sealed at P&W and sent to ORNL for consolidation. The sealed cans were coated with glass and heated for 2 h at the desired temperature and extruded through a 18-mm-diam die to produce a reduction ratio of

16:1. The extrusion temperatures of 1150, 1250, and 1400°C were used for the first series of alloys. The second series of alloys was only extruded at 1400°C. The extrusion temperatures of 1150 and 1250°C were used to produce the duplex microstructure and that at 1400°C (being above the α transus of 1320°C) was used to produce a refined lamellar structure. The target and check analysis for each ingot of the three 100-kg heats are shown in Table 2.

The extruded rods were heat treated between 800 to 1350°C to control their microstructure (grain size, interlamellar spacings, and α_2/γ platelet ratio). Alloy specimens were also aged at 800 and 1000°C up to 210 days (7 months) in vacuum for studying the effect of aging on microstructure and mechanical properties.

The hot-extruded and heat-treated bars were used to machine tensile specimens with 1.27 cm gage length and 0.32 cm diam. All of the specimens were prepared by electrodischarge machining followed by grinding. Tensile tests were performed on an Instron testing machine at temperatures up to 1000°C in air and at a cross-head speed of 0.25 cm. After heat treating, the specimens were polished to remove surface scratches using 0-grade emery papers. Prior to testing, the specimen was inductively heated inside a Pt susceptor, and the test temperature was controlled using a Pt-10% Rh thermocouple located at the specimen center. Tensile properties were determined from a strip chart recorded at a speed of 12.7 cm/min. Fracture toughness was measured at room temperature and 800°C in air by three point bend testing of Chevron-notched specimens with dimensions of 5 × 5 × 45 mm. The fracture toughness was calculated from the area of the measured load-displacement curves. Fracture surfaces were examined by scanning electron microscopy operated at 5 kV.

Microstructure features and phase compositions were studied by the use of both transmission electron microscopy (TEM) and electron microprobe analyses. Microstructural analysis was performed on Philips CM12 (120 kV) and CM30 (300 kV) microscopes. Phase transition was monitored by differential scanning calorimetric (DSC) analyses of alloy samples at a heating rate of 20°C/min in an argon atmosphere.

Results and Discussion

The canned alloy powder of alloys from Series 1 and 2 were successfully consolidated by extrusion at 1400°C ($>T_\alpha$) or 1150 and 1250°C ($<T_\alpha$). Wet chemical analyses indicate that rod of alloy T2-73 extruded at 1400°C contained 800 wt ppm O, 270 C, and 35 N. The DSC measurements showed that the T_α for T2-73 alloy was around 1320°C. The ($\gamma+\alpha$) field extends to 1220°C, which agrees well with that reported by Takeyama et al.¹

The microstructure of all the alloys extruded at 1400°C (in the α phase field) resulted in a fully lamellar structure with a colony size (or grain size) of 65 μm for T2-73. Hot extrusion at 1150 and 1250°C resulted in extremely a fine duplex structure. The as-extruded materials showed nearly theoretical density. There appears to be residual porosities in the materials, the amount of which decreases with increasing extrusion temperature, with the least porosity in material hot extruded at 1400°C.

The quantitative microstructural data for T2-73 alloy are summarized in Table 3 which shows that the average interlamellar spacing is extremely fine, only 0.1 μm . The correspondence of α_2/γ lamellae is almost 1:1, with only the widest γ lamellae having γ/r twins inside. The heat treatment at 900°C for 2 h did not cause a significant change in the 1400°C extruded lamellar structure and may have only slightly thickened the γ layer at

Table 2. Comparison of target and actual vendor analyses (in atomic percent) of three alloys prepared by The Duriron Company, Inc. (Dayton, Ohio)

Element	Alloy 1				Alloy 2				Alloy 3			
	Target	Actual			Target	Actual			Target	Actual		
		454	455	459		456	457	460		461	462	463
Ti	48.85	49.16	49.45	49.06	48.85	49.53	49.40	49.29	48.55	49.23	49.05	49.23
Al	47.0	46.35	46.17	46.36	47.0	46.11	46.23	46.18	47.0	46.21	46.16	46.07
Cr	2.0	2.07	1.92	2.00	2.0	1.92	1.92	2.0	2.0	1.84	2.0	1.99
Nb	1.0	1.03	1.03	0.989	1.0	0.99	0.99	1.03	1.0	0.98	1.03	0.99
Ta	1.0	0.92	0.97	1.06	0.8	0.77	0.77	0.82	0.8	0.77	0.82	0.77
B	0.15	0.147	0.148	0.148	0.15	0.147	0.147	0.148	0.15	0.147	0.148	0.147
W	--	--	--	--	0.20	0.173	0.180	0.174	0.20	0.20	0.19	0.182
Si	--	--	--	--	--	--	--	--	0.30	0.269	0.27	0.28
C	--	0.033	0.033	0.033	--	0.033	0.033	0.033	--	0.066	0.033	0.033
O	--	0.149	0.150	0.200	--	0.149	0.174	0.120	--	0.174	0.175	0.174
H	--	0.067	0.063	0.079	--	0.107	0.087	0.059	--	0.059	0.067	0.075
N	--	0.030	0.038	0.033	--	0.025	0.042	0.043	--	0.024	0.025	0.025
Fe	--	0.040	0.036	0.036	--	0.057	0.036	0.029	--	0.028	0.028	0.028
Cu	--	--	--	--	--	--	--	--	--	--	--	--

Table 3. Quantitative microstructural data for PM Ti-47Al-2Cr-2Nb (at. %) (T2-73) in as-extruded and heat-treated conditions

Material preparation	Microstructural data
As-extruded at T_1	<p>Colony size: 65 μm</p> <p>Width of colony-boundary γ layer: 1 to 3 μm</p> <p>Interlamellar spacing: 0.1 μm</p> <p>α_2-α_2 spacing: 0.22 μm</p> <p>γ lamellar width: 0.1 to 0.5 μm</p> <p>α_2-γ layer ratio: $\sim 1:1$</p> <p>Very few γ/γ boundaries</p>
T_1 extrusion + 2 h/900°C	<p>Similar colony size: $\sim 65 \mu\text{m}$</p> <p>Slightly thicker γ layer at colony boundaries</p> <p>Few coarsened γ spots within colonies</p>
T_3 extrusion + 2 h/1325°C	<p>Colony size: $\sim 59 \mu\text{m}$</p> <p>Porosity size: 5 to 21 μm</p>

colony boundaries. This heat treatment also introduced a few small regions of coarsened lamellae inside the colonies. The fourth treatment at 1325°C of the extrusion at 1150°C resulted in the formation of a fine lamellar structure similar to that in the bar extruded at 1400°C with the exception of large cavities. The large cavities resulted from the coarsening of the porosity in the extrusion.

Room-temperature tensile properties of T2-73 alloy after extrusion at 1150, 1250, and 1400°C and various heat treatments are summarized in Table 4. The extrusions at 1250 and 1400°C after the heat treatment that resulted in the highest room-temperature ductility were tested at high temperatures. Tensile data as a function of temperature for the two extrusion temperatures are compared in Fig. 2. The 1400°C extrusion with 900°C heat treatment with refined lamellar structure showed only a slight decrease in strength at temperatures to 800°C and a substantial decrease above this temperature. The yield and ultimate tensile strengths of this material condition of alloy T2-73 are as high as 577 and 624 MPa, respectively, at 1000°C. The tensile ductility of this material showed a moderate increase with temperature and reaches a maximum of 7.5% at 800°C. The material (T2-73) extruded at 1250°C and heat treated at 950°C with fine duplex microstructure showed a moderate decrease in strength at $\leq 600^\circ\text{C}$ to a sharp decrease above 600°C. The material showed a yield and ultimate tensile strengths of 172 and 203 MPa, respectively, which are much lower than those obtained from the refined lamellar structure. This material showed a sharp ductile-to-brittle transition around 700°C, and the ductility increased to as high as 117.6% at 1000°C. The T2-73 material with the fine duplex structure showed a mixed fracture mode with cleavage fracture as the major fracture mode at room temperature. The material with the refined lamellar structure exhibited essentially translamellar fracture with individual lamellar-colony facet visible on fracture surfaces.

Table 4. Effect of heat treatment on room-temperature tensile properties of powder metallurgy Ti-47Al-2Cr-2Nb (at. %) (T2-73) hot extruded at T_1 , T_2 , or T_3

Heat treatment	Yield strength (MPa)	Fracture strength (MPa)	Plastic strain ^a (%)
1150°C Extrusion			
As extruded ^b	--	701	0
4 h/1000°C ^b	--	704	0
4 h/1070°C ^b	--	972	0
4 h/1200°C ^b	--	535	0
4 h/1325°C ^c	--	430	0
1250°C Extrusion			
As extruded ^b	997	1029	0.5
2 h/950°C ^b	945	949	0.6
2 h/1050°C ^b	878	878	0.4
2.5 h/1250°C ^b	--	398	0
2 h/1350°C ^c	--	540	0
1400°C Extrusion			
As extruded ^c	992	992	0.6
2 h/900°C ^c	971	1005	1.4
2 h/950°C ^c	977	1017	1.0
2 h/1000°C ^c	968	998	1.1

^aMeasured from strip chart.

^bFine duplex structure.

^cRefined lamellar structure.

The fracture toughness of 1400°C-extruded T2-73 material was 22.3 to 22.6 MPa m^{1/2} at room temperature that increased to 40.1 to 41.4 MPa m^{1/2} at 800°C. Comparatively, the 1250°C extruded material only showed a room-temperature toughness value of 9.3 to 9.7 MPa m^{1/2}.

The T2-73 extruded at 1400°C and heat treated at 900°C for 2 h showed the excellent strength at room and elevated temperatures. The properties of T2-73, lamellar structure are compared in Table 5 with PM Ti-48Al2Cr-2Nb prepared by HIPping², and the cast TiAl alloy (Ti-46.5Al-2.1Cr-3Nb-0.2W) prepared by thermomechanical treatment.³ All of the materials had refined lamellar structures. As shown in Table 5, the PM alloy of this CRADA investigation (T2-73) shows yield and ultimate tensile strengths that are more than 100% higher at all temperatures than the literature data. The TEM characterization showed that the superior strength of the extruded material of this study is due to the combination of its fine colony size (65 μm) and interlamellar spacings (0.1 μm) together with the unique ultrafine morphology of α₂ platelets, which are long and straight and quite regularly spaced between γ platelets. In fact, the extruded lamellar material can be considered as a microlaminate consisting of hard α₂ platelets and soft α platelets.

Fig. 2. Comparison of tensile properties of powder metallurgy Ti-47Al-2Cr-2Nb (T2-73) with refined lamellar and duplex microstructures.

The data presented in the previous section clearly demonstrated the benefits of hot extruding at 1400°C. The same extrusion conditions were used for the remaining alloy powders of both series of compositions listed in Table 1. Also, further treatments to improve the ductility of T2-73 alloy were investigated. The 2-h treatment at 1320°C of the 1400°C extruded bar of alloy T2-73 showed substantial improvement in room-temperature and elevated ductilities, with some reduction in strength (see Fig. 3). The decrease in strength corresponds to an increase in interlamellar spacing as shown in Fig. 4.

Table 5. Comparison of tensile properties of TiAl alloys with (T2-73) refined lamellar structures prepared by casting or powder metallurgy

Alloy composition (at. %)	Material ^a preparation	Yield strength (MPa)	Ultimate tensile strength (Mpa)	Tensile elongation (%)
RM				
Ti-47Al-2Cr-2Nb	PM + HE + HT	971	1005	1.4
Ti-48Al-2Cr-2Nb	PM-HIP/HT	370	488	2.3
Ti-46.5Al-2.1Cr-3Nb-0.2W	MC + TMT	473	557	1.2
600°C				
Ti-47Al-2Cr-2Nb	PM + HE + HT	922	1091	3.0
Ti-48Al-2Cr-2Nb	PM-HIP/HT	317 ^b	527 ^b	5.0 ^b
Ti-46.5Al-2.1Cr-3Nb-0.2W	MC + TMT	408	525	1.7
800°C				
Ti-47Al-2Cr-2Nb	PM + HE + HT	841	1005	7.5
Ti-48Al-2Cr-2Nb	PM-HIP/HT	322 ^c	454 ^c	55.6 ^c
Ti-46.5Al-2.1Cr-3Nb-0.2W	MC + TMT	385	510	8.1
1000°C				
Ti-47Al-2Cr-2Nb	PM + HE + HT	577	624	5.3
Ti-48Al-2Cr-2Nb	PM-HIP/HT	--	--	--
Ti-46.5Al-2.1Cr-3Nb-0.2W	MC + TMT	278	284	--

^aPM = powder metallurgy, HE = hot extrusion at T₁, HT = heat treatment, HIP = hot isostatically pressed, MC = melting and casting, and TMT = thermomechanical treatment.

^bTested at 500°C.

^cTested at 850°C.

The tensile properties of the first series of alloys in the 1250°C and 1400°C extruded conditions are summarized in Tables 6 through 9. These tables confirm that the ductility of all the alloys extruded at 1400°C with fine lamellar structure are always higher than the duplex microstructure produced by 1250°C extrusion.

Fig. 3. The 2-h treatment at 1320°C substantially improves the ductility of 1400°C extruded T2-73 alloy with only a moderate decrease in strength.

Fig. 4. Correlation of yield of γ TiAl with interlamellar spacing by the Hall-Petch relationship.

Tensile properties of T1-322-2 alloy (one of the large heats from the second series of alloys) are compared with the best of the first series alloy T2-74 in Fig. 5. Data for the cast and thermomechanically treated³ alloy K5 are also included in Fig. 5 for comparison. This figure shows that the large heat of T-322-2 has the highest ductility of the three alloys and only slightly lower in strength than the best of the first series alloy T2-74-1. Furthermore, the alloy T1-322-2 is still significantly higher in strength than K5 alloy for the entire temperature range.

Effect of long-term annealing at 800 and 1000°C on the room-temperature tensile properties of the alloy T2-73 are presented in Tables 9 and 10. Data in Table 9 show that the long-term annealing (aging) at 800°C results in a slight decrease in yield strength and increase in ductility. In contrast, the long-term annealing at 1000°C results in substantial drop in strength and improvement in ductility. The annealing for three days at 1000°C provides the best tensile ductility with only slight reduction in strength.

Table 7. Tensile properties of powder metallurgy TiAl alloys^a
hot extruded at 1250°C, 16:1 ratio

Alloy no.	Test temperature (°C)	Yield strength (MPa)	Ultimate strength (MPa)	Plastic ^b elongation (%)
T2-73-3	Room	933	936	0.6
	300	781	878	2.2
	600	760	879	3.7
	800	--	--	--
	1000	170	201	117.6
T2-74-3	Room	843	857	1.2
	300	739	852	3.1
	600	690	787	2.8
	700	628	795	6.0
	800	585	673	63.7
	1000	192	224	128.6
T2-76-3	Room	753	777	1.4
	300	636	718	2.4
	600	611	734	3.5
	700	585	715	4.8
	800	522	593	63.9
	1000	194	222	68.6
T2-77-3	Room	847	864	0.9
	300	720	730	0.9
	600	707	783	2.1
	800	558	632	55.6
	1000	180	209	102.9

^aAnnealed 2 h at 950°C after extrusion fine duplex structure.

^bMeasured from a strip chart.

Table 8. Tensile properties of powder metallurgy TiAl alloys
hot extruded at 1400°C, 16:1 ratio

Alloy no.	Test temperature (°C)	Yield strength (MPa)	Ultimate strength (MPa)	Plastic ^b elongation (%)
T2-73-3	Room	958	992	1.4
	300	940	1011	1.8
	600	910	1076	3.0
	800	830	992	7.5
	1000	569	615	5.3
T2-74-3	Room	931	996	1.9
	300	845	993	3.3
	600	854	1027	3.7
	800	789	937	10.0
	900	711	792	8.6
	1000	568	617	6.6
T2-76-3	Room	781	889	2.8
	300	732	864	2.8
	600	719	942	5.2
	800	646	830	15.1
	1000	411	474	19.0
T2-77-3	Room	815	923	2.5
	300	700	905	4.6
	600	688	906	5.0
	800	648	806	24.8
	1000	392	444	14.0

^aMeasured from a strip chart.

^aAnnealed 2 h at 900°C after hot extrusion.

^cAnnealed 2 h at 1050°C after extrusion.

Table 9. Effect of long-term annealing at 800°C in vacuum on room-temperature tensile properties of powder metallurgy Ti-47Al-2Cr-2Nb hot extruded at T_1 ($>T\alpha$)

Annealing time (d)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Total elongation (%)
0 ^a	945	1000	1.5
30	857	959	1.6
90	830 ^b	966 ^b	2.5 ^b
171	755	898	1.8

^aAnnealed for two days at 900°C after hot extrusion.

^bData from an alloy with the composition slightly different from Ti-47Al-2Cr-2Nb.

Fig. 5. Comparison of tensile properties of the alloys T2-74-1 and T1-322-2 of this study with the K5 alloy from the literature.

Table 10. Effect of long-term annealing at 1000°C in vacuum on room-temperature tensile properties of PM Ti-47Al-2Cr-2Nb hot extruded at T_1 ($>T_\alpha$)

Annealing time (d)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Total elongation (%)
0 ^a	945	1000	1.5
3	707	884	4.8
10	600	728	2.7
90	486	583	2.2

^aAnnealed for two days at 900°C after hot extrusion.

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Report of Inventions

There were no inventions developed under this agreement.

Commercialization Possibilities

This is possible, however without commercial source for material needs to be developed, even the best aluminide will not find applications.

Plans for Future Collaboration

No plans have been made for future collaboration.

Conclusions

The extensive work on the composition development, processing parameter development, microstructural evaluation, and mechanical properties development of the γ TiAl alloys under this CRADA have resulted in the following conclusions:

1. Two-phase TiAl alloys with refined fully lamellar structures, produced by hot extrusion of powders above T_a (specifically at 1400°C), have excellent tensile and creep properties at room and elevated temperatures and creep properties at elevated temperature.
2. The excellent properties stemmed from refined colony size (<70 μm) and fine α_2 to α_2 platelet spacing (<1 μm).
3. The tensile ductility increases with decreasing colony size and increasing interlamellar spacing.
4. The yield strength increases with decreasing interlamellar spacing.
5. The fine lamellar structure is stable for at least 200 days at 800°C.
6. Powder metallurgy is a feasible way to produce two-phase TiAl alloys with outstanding mechanical properties.
7. The mechanical properties of the alloys developed in this CRADA are better than the results from the literature on alloys with lamellar microstructure.

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