Superior Oxidation Resistance Titanium Alloy ARCONIC-THOR™ for Aerospace Applications

Sesh Tamirisakandala, Ernie Crist, Fusheng Sun, Matthew Dahar

ARCONIC, 1000 Warren Avenue, Niles OH 44446, USA

Sesh.Tamirisakandala@Arconic.com

Abstract

Next generation fuel-efficient jet engines are running hotter presenting a structural challenge for the exhaust systems and structures adjacent to the engines. A conventional and affordable titanium alloy with superior oxidation resistance provides significant weight reductions and associated cost savings by eliminating the need for high density material systems such as nickel-base superalloys for service temperatures in between current titanium and nickel, enabling major technology advancement in high temperature aerospace applications. This paper presents an overview of Arconic's engineered material ARCONIC-THOR™ to address the needs of future aerospace systems.

1. Introduction

Major advances in materials and processes for gas turbine engines have led to higher operating temperatures that, in turn, have produced higher efficiency and reduced fuel burn [1]. Next generation fuel-efficient jet engines running hotter present a structural challenge for the adjacent airframe and exhaust systems. Higher-temperature operation is inevitable for components such as pylons, nacelles, heat shields, plugs, and nozzles. Materials for these structures must bridge the performance gap between the state-of-the-art high-temperature titanium alloys and high-density material systems (nickel superalloys, corrosion resistance steels, ceramic matrix composites CMCs), otherwise weight and cost penalties defeat the benefits offered by efficient engines.

As evidenced in the evolution of titanium alloys development for high temperature applications in the last 70 years shown in Figure 1, improvements in temperature capability have been incremental. Maximum temperature capability of titanium alloys saturated at 1100°F (593°C) since 1989. Traditional design and development of engineering titanium alloys are based on empirical formulations and trial-and-error approaches that are tedious, expensive, and time-consuming. Primary reason for this traditional alloy design approach is due to the complexities in titanium alloys. There are several competing and contradicting technical and economical attributes, shown in Figure 2, that must be addressed by superior oxidation resistance titanium alloy for high temperature aerospace applications. Balance of alloy formulation and processing to achieve desired combination of performance without compromising producibility aspects has been a major challenge. The high chemical affinity of titanium to oxygen and the high interstitial solid solubility of oxygen in α -titanium cause significant oxygen ingress during air exposure at high temperatures, resulting in the simultaneous formation of an oxide scale on the surface and an oxygen-rich, continuous, hard, and brittle layer underneath the scale (commonly referred to as α -case) as shown in Figure 3. Alpha case formed during service often limits the maximum service temperature of titanium alloys, since a significant amount of less ductile α -case results in the formation of surface cracks under tensile loading. The low local ductility and the large slip offsets at the surface can cause low overall ductility or early crack nucleation under cyclic loading conditions [2]. For long-term elevated-temperature applications, α -case depth and thermal stability are critically important in addition to creep resistance and strength. For short term elevated-temperature applications such as thermal protection systems and hot structures that include thin wall components, rapid degradation across the entire cross section could occur due to α -case formation.

Ti 6-4: Ti 6Al-4V Ti 8-1-1: Ti 8Al-1Mo-1V

Ti 6-2-4-6: Ti 6Al-2Sn-4Zr-6Mo Ti 17: Ti-5Al-2Sn-2Zr-4Cr-4Mo

Ti 6-2-4-2: Ti 6Al-2Sn-4Zr-2Mo-0.1Si

Ti 834: Ti 5.8Al-4Sn-3.5Zr-0.5Mo-0.7Nb-0.3Si Ti 1100: Ti 6Al-2.75Sn-4Zr-0.4Mo-0.45Si

Ti 21S: Ti 15Mo-3Nb-3Al-0.2Si

Figure 1- Evolution of high temperature titanium alloys in the last 70 years as depicted by their maximum service temperature and year of commercial introduction.

Figure 2- Superior oxidation resistance titanium alloy attributes.

Figure 3- Illustration of surface oxidation issue in high temperature titanium alloys.

The basic titanium alloy development approach has been: start with a known base alloy system; adjust/add alloying elements; utilize empirical experimentation approach / intuition to downselect a set of compositions; melt-process-heat treat-test; return to the base alloy and readjust chemistry and processing, if necessary; iterate alloy development to reach the target properties; scale-up and qualify a new alloy and process. This iterative approach generally resulted in new alloys with properties approaching those desired for new applications at a high cost and long development times (10-20 years), with some failures interspersed in success stories. Several questions that intrigued alloy developers are: Was a sufficient range of alloy compositions explored in the iterative process? Any critical element missed that might have provided better properties? Is the processing optimized for the best balance of properties? Is the final solution providing optimum balance of performance requirements and affordability for the intended application? Tweaks in chemistry and processing of existing alloys have not provided needed high temperature performance in the last 30 years. It's worth noting that oxidation resistance was not a primary driver in high temperature titanium alloys development (Figure 1) with the exception of Ti 21S. Current temperature needs are pushing beyond the available Ti alloys, forcing the only option of using high-density and expensive solutions for these applications, which increases the weight by approximately 25% and in most cases is an underutilization of their capability.

2. Innovation

Since the oxidation attack is limited to the outer region of components, whereas mechanical properties at elevated temperatures are determined by the bulk cross section, a promising approach would be to optimize both mechanical properties and oxidation resistance. Under internal R&D activity, using a model-centric approach combined with extensive alloy development experience and high throughput validation experiments, Arconic designed, developed, and demonstrated a superior oxidation resistance titanium alloy ARCONIC-THOR (Ti-6Al-4Sn-3Nb-0.5Mo-0.3Si) capable of service temperatures up to 1400°F (760°C) [3]. This conventional $\alpha+\beta$ titanium alloy exhibited significant reduction in weight gain due to oxidation compared to other commonly used high temperature Ti alloys such as Ti 21S and Ti 6-2-4-2, as shown in Figure 4. Presence of stable surface condition, absence of flaky scale, extremely high thermal stability even after long-term exposures, 5' reduction in weight gain compared to Ti-6-2-4-2, and dramatically reduced α -case depth at service temperatures were demonstrated. Improvement in post-thermal exposure residual fatigue life of ARCONIC-THOR compared to Ti 6-2-4-2 is demonstrated in Figure 5. All key attributes of superior oxidation

resistance titanium alloy identified in Figure 2 were satisfied by ARCONIC-THOR.

Figure 4- Oxidation resistance (weight gain as a function of time for thermal exposure at 1400°F) of ARCONIC-THOR compared with other Ti alloys and nickel IN 625.

Figure 5- Post-thermal exposure fatigue life of ARCONIC-THOR sheet compared to Ti-6-2-4-2.

3. Integrated Product Development

With an objective to fully develop and validate a production-ready superior oxidation resistant Ti alloy ARCONIC-THOR, an activity integrated project team (AIPT) comprising material and component producer (Arconic), airframe OEM (Boeing), and engine OEM (Honeywell) was formed to mature the technology by using an approach integrating design, materials, manufacturing, and modeling for rapid maturation and implementation. Building upon the detailed technical investigations conducted on sub-scale systems to optimize material and processing, full-scale components (Figure 6) were fabricated using production heat lots on production equipment. Manufacturability assessments and coupon/element testing were completed to demonstrate the product readiness from development to production floor. Statistically significant test data were generated and an aerospace material specification AMS6953ä [4] with minimum design properties (S-basis) for sheet product was created. Technology readiness level (TRL) and manufacturing readiness level (MRL) were matured from 3 to 6. An existing Integrated Computational Materials Engineering (ICME) workflow developed by Materials Resources LLC was extended to successfully model and predict oxidation behavior and post-thermal exposure life of ARCONIC-THOR (Figure 7). Business case and implementation roadmap for industrial insertion of the developed technology based on multiple implementation paths were developed. These successful demonstrations support the transition to selected current and developmental exhaust systems for Air Force engines and systems exposed to temperatures as much as 200°F above the current high temperature Ti alloy product capabilities with acceptable oxidation resistance. Benefits of this technology include significantly reduced weight and improved system performance with an estimated return on investment of 15:1 over a 10-year implementation period.

Figure 6- Focused maturation of ARCONIC-THOR material and processes via collaborative integrated product development.

Figure 7- ICME workflow of titanium alloy oxidation/life modeling.

4. Summary and Conclusions

ARCONIC-THOR is a ~50% lighter conventional titanium alternative to nickel superalloys for the next generation aerospace systems providing significant cost savings and fuel efficiency. Superior oxidation resistant properties enable ARCONIC-THOR to operate at service temperatures +200°F than the state-of-the-art Ti alloys. Arconic completed successful development projects with commercial aerospace and defense customers. AMS6953TM for sheet enables designers to incorporate ARCONIC-THOR into aerospace applications. ARCONIC-THOR can be produced as castings and wrought products such as sheet, plate, foil, billet, rolled rings, near-net forgings, and extrusions. The alloy is formable (cold, hot, and superplastic forming), heat treatable, weldable and is commercially available. Material datasheet of ARCONIC-THOR is included at the end of this paper.

5. Acknowledgements

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6. References

1. *Aerospace Materials and Applications*, B.N. Bhat, ed., <https://arc.aiaa.org/doi/book/10.2514/4.104893>, American Institute of Aeronautics and Astronautics, Inc. Reston VA (2018) 579-607.
2. G. Lutjering and J.C. Williams, *Titanium*, 2nd ed., Springer-Verlag, New York (2007) 50-52.
3. US Patent No. 9,957,836 Titanium alloy having good oxidation resistance and high strength at elevated temperatures.
4. Aerospace material specification AMS6953a Titanium alloy sheet 6Al-4Sn-3Nb-0.5Mo-0.3Si, Duplex annealed, SAE International (2018).

ARCONIC-THOR™

ARCONIC
Innovation, engineered.

ARCONIC-THOR™ is an alpha-beta alloy with superior oxidation resistance up to 1382°F (750°C) for long term exposure, capable of being cold formed, hot formed, superplastic formed, welded & heat treated to different aerospace product forms. The physical properties, room and elevated temperature tensile properties of this alloy are similar to Ti-6242, but with superior oxidation resistance, improved creep resistance, and superior post-thermal exposure fatigue strength and post-thermal exposure tensile properties compared to Ti-6242. The Society of Automotive Engineers - Aerospace Material Specification Titanium and Refractory Metals Committee (SAE-AMS) has approved the standard Aerospace Material Specification (AMS) 6953 for ARCONIC-THOR™ sheet.

Chemistry (wt.%)

Material	Chemistry
Ti-6242	Ti-6Al-2Sn-4Zr-2Mo-0.1Si
ARCONIC-THOR™	Ti-6Al-4Sn-3Nb-0.5Mo-0.3Si
Beta 215	Ti-15Mo-3Nb-3Al-0.2Si
Inco 625	Ni-21.5Cr-9Mo-5Fe-0.5Mn-0.5Si-0.1C

Physical Properties

Alloys	Density g/cm ³	Electrical Resistivity, μΩ.m	Specific Heat Capacity, J/Kg.K	Thermal Conductivity, W/m.K	Thermal Expansion Coefficient 10 ⁻⁶ /°K
Ti-6242	4.54	1.85	460	7.00	7.7
ARCONIC-THOR™	4.48	1.80	519	6.29	9.2
Beta 21s	4.94	1.35	710	7.50	8.5
Inco 625	8.44	1.29	410	9.90	13.1
A286	7.94	0.91	420	15.1	16.5

Attributes:

- ✓ Superior oxidation resistance up to 1382°F (750°C)
- ✓ Room and elevated temperature tensile properties similar to Ti-6242
- ✓ Improved creep resistance compared to Ti-6242 at higher temperatures
- ✓ Superior post-thermal exposure fatigue strength than Ti-6242
- ✓ Good post-thermal exposure tensile property at RT & HT
- ✓ Producing, formable (cold, hot, SPF), heat treatable, & weldable
- ✓ Potential for lower fabrication costs

ARCONIC-THOR™ shows similar physical properties to Ti-6242

Beta21s has 9% higher density than ARCONIC-THOR™ Alloy

Inco 625 has 88.4% higher density than ARCONIC-THOR™ Alloy

ARCONIC-THOR™ Product Manufacturing

Billet GFM Forging (7" dia.)

Plate and Sheet Rolling

Forgings and Rings

Oxidation Resistance at 1202-1292°F (650-700°C) for 208 hours – ARCONIC-THOR™ Sheet

Arconic-THOR™ weight gain was <50% that of Ti-6242, and <30% that of Beta 21s, respectively

Oxidation Resistance Testing at 1292°F (700°C) for 208 hours – ARCONIC-THOR™ Sheet

ARCONIC-THOR™ Property Comparison Tables

ARCONIC-THOR™ (AMS6953) Minimum Mechanical Properties (Room Temperature)				
Nominal Thickness, inch (mm)	Specimen Orientation	UTS ksi (MPa)	0.2% YS ksi (MPa)	Elongation, % In 2" (50.8mm)
0.020 to 0.1874, incl (0.51-4.76mm)	L & T	135 (931)	125 (862)	8
ARCONIC-THOR™ (AMS6953) Minimum Mechanical Properties (900°F/482°C)				
Nominal Thickness, inch (mm)	Specimen Orientation	UTS ksi (MPa)	0.2% YS ksi (MPa)	Elongation, % In 2" (50.8mm)
0.020 to 0.1874, incl (0.51-4.76mm)	L & T	90 (621)	75 (517)	7
Ti-6242 (AMS4919) Minimum Mechanical Properties (Room Temperature)				
Nominal Thickness, inch (mm)	Specimen Orientation	UTS ksi (MPa)	0.2% YS ksi (MPa)	Elongation, % In 2" (50.8mm)
0.020 to 0.062, incl (0.51-1.57mm)	L & T	135 (931)	125 (862)	8
Over 0.062 – 0.1874 (1.57-4.76mm)	L & T	135 (931)	125 (862)	10
Ti-6242 (AMS4919) Minimum Mechanical Properties (900°F/482°C)				
Nominal Thickness, inch (mm)	Specimen Orientation	UTS ksi (MPa)	0.2% YS ksi (MPa)	Elongation, % In 2" (50.8mm)
0.020 to 0.062, incl (0.51-1.57mm)	L & T	95 (655)	75 (517)	7
Over 0.062 – 0.1874 (1.57-4.76mm)	L & T	95 (655)	75 (517)	10