

Microstructure-Property Relationships in Cold Rollable, High-Strength α/β Alloys

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Abstract

For decades Ti-6Al-4V has been the workhorse alloy for aerospace sheet applications due to its good balance of properties and the known ability to hot roll it with relative ease. Sheet of Ti-6Al-4V is made by hot pack rolling, which is a costly and time consuming process, due to the alloy having insufficient room-temperature workability to support significant cold reduction or forming. Consequentially, Ti-6Al-4V is not typically offered in foil gauges, since the direct product of hot pack rolling contains an undesirable surface finish and insufficient gauge control. Hot pack rolling also limits the maximum sheet size and annual capacity.

As a world leader in advanced sheet alloys of titanium, nickel, cobalt, and specialty stainless steels, ATI is developing new titanium alloys with improved strength compared to Ti-6Al-4V that take advantage of a recent understanding of cold workability in high-strength alpha-beta titanium. These $\alpha+\beta$ alloys exceed Ti-6Al-4V strength while being highly cold formable. Cold rolling via coil processing also enables longer lengths of sheet with significantly improved gauge control and surface finish.

Results from pilot scale ingots will be presented upon, including final properties of these unique alloys and microstructure-property correlations developed through modelling.

Introduction

By volume, alpha-beta titanium alloys represent the largest segment of alloyed titanium used in the aerospace industry. This results from the lower alloy content and therefore price associated with these alloys over beta-titanium alloys, as well as the balance of properties they generally offer. Alpha-beta titanium alloys offer strengths comparable to nickel alloys and stainless steels while at 40% less density. These titanium alloys are generally weldable, superplastic formable, and can be diffusion bonded into complex components.

Ti-6Al-4V is commonly used in secondary structure sheet applications within the aerospace industry, such as clips, brackets, skins, skid plates, and other applications that demand corrosion resistance and or moderate

temperature excursions and penalize the mass of other material solutions [1]. Sheet in this alloy is typically made by hot pack rolling [2, 3]; a process that naturally lends to higher variability and smaller sizes than hot rolling sheets on strip mills and subsequent cold-rolling. Historically, titanium alloys that can be made in the latter process include lower strength alloys, CP titanium, and beta-titanium alloys, but not high-strength alpha-beta titanium alloys.

In addition to titanium alloys, ATI produces sheet in nickel, cobalt, and stainless steels using hot strip rolling and cold rolling processes. As a world leader in cold working advanced alloys of multiple systems, ATI has been refining and further developing the next generation of cold-workable titanium alloys with improved properties over Ti-6Al-4V. In addition to obvious performance goals, the use of cold rolling equipment enables greater gauge control, which can benefit design weight, and significantly increased manufacturing capacity over pack-rolling processes. For these reasons, ATI has continued to develop cold rollable, high strength titanium alloys; three of which will be described herein.

Materials and Experiments

Three alpha-beta titanium alloys with proprietary compositions were melted into 450lb ingots using a double-melted consumable-arc vacuum melting. Raw material ingredients for these alloys consisted of 100% virgin materials, and utilized both pure elemental additions and master alloys. The alloys herein shall be designated as Alloy A, Alloy B, and Alloy C. These alloys were processed from ingot to slab, slab to plate, and plate to sheet. Alloy C was subsequently also converted to foil from sheet. These steps were executed on production-scale equipment at ATI Specialty Alloys & Components using welded coil practices, though at larger scales continuous coil operations would be possible.

Mechanical testing of the alloys consisted of tensile testing in the as-worked material at slab, plate, and sheet conditions, as well as following several heat treatments in laboratory furnaces. In all cases, comparisons against Ti-6Al-4V were made, and the material was tested in a final annealed condition after alpha-beta thermomechanical work. Plate properties were measured in approximately 6.3mm thick sections, sheet in approximately 1.5mm thick sections, and foil in 0.55mm thick or less sections.

Sheet bend testing and tensile testing at room and elevated temperatures was conducted at an ATI laboratory following ASTM E290 (guided bending with no die) and E21 procedures, respectively. Bend tests were taken through a 120° angle, and inspected for cracks afterwards. High-cycle fatigue ($R = 0.1$, 9 Hz) in accordance with ASTM E-466 and fracture toughness testing in accordance with ASTM E-399 was conducted at NADCAP approved laboratories. In sheet, notched tensile tests were conducted using a K_t of 6.0 at a NADCAP approved laboratory. With the exception of room-temperature tensile testing of intermediate product forms, all other samples were tested following a mill anneal high within the $\alpha+\beta$ two-phase region.

Microscopy was performed using scanning electron microscopy using backscattered electron imaging. Samples were universally mounted in conductive phenolic compound, polished through colloidal silica, and imaged in an un-etched condition.

Results

Examples of the semi-finished slab is shown in Figure 1, and plate in Figure 2. Mill-annealed tensile properties for the alloys at various stages of semi-finished mill products is shown in Figure 3. Minimum bend radii are shown in Figure 5. Tensile properties of final heat treated sheet, including notched tensile tests, are shown in Figure 4. Properties of Ti-6Al-4V are shown as reference, and are based on [1] and [4]. Elevated temperature tensile strengths of sheet are shown in Figure 6.

Fatigue results for sheet were plagued by fatigue crack initiations at corners of the sheet cross-section, and the fatigue lives measured appeared to have greater variability than desired. Analysis of these indicated that crack initiation was taking place at surfaces associated with fine scratches or sharp corners. Despite these difficulties, the fatigue results of the Alloy C measured at ~0.55mm thick sheet are shown in Figure 8. Examples of the microstructures developed from the three alloys is shown in Figure 7.



Figure 1: Intermediate slab of Alloy A. The image is approximately 1 meter in width.



Figure 2: As hot-rolled plate condition of Alloy A. The image is approximately 0.45 meters in width.

Average mill-annealed properties (732-760C up to 1hr)				
		Slab	Plate	Sheet
Alloy A	YS	930	1006	985
	UTS	1006	1061	1096
	%EL		17%	11%
Alloy B	YS	944	923	944
	UTS	992	1040	1068
	%EL		17%	17%
Alloy C	YS		1034	1034
	UTS		1137	1130
	%EL		15%	18%
Ti-64 typ	YS	827	944*	
	UTS	965	1000*	
	%EL	16%	14%*	

Figure 3: Average properties of semi-finished, mill-annealed material. Strength units of megapascals. Ti-6Al-4V results based on [1] and internal work [4].

Average Properties						
Alloy A	YS	UTS	%El	%RA	Notched UTS	Ratio UTS _N /UTS
Long	1068	1220	9.5	27	1309	1.23
Trans	1220	1323	9.3	29	1426	1.17
Alloy B						
Long	992	1164	10.8	29	1288	1.30
Trans	1137	1233	15.3	36	1378	1.21
Alloy C						
Long	1034	1185	12.3	28	1357	1.31
Trans	1178	1309	17.8	37	1481	1.26
Typical Ti-6Al-4V Properties (hot pack cross rolled)						
L & T	944	1000	14%			

Figure 4: Average properties of final-annealed sheet from each alloy. Notched tensile data conducted with $k_t = 6$. Strength units measured in megapascals. Ti-6Al4V properties from [1] and internal work [4].

Alloy	Minimum bend radius
A	Long: 1.5T Trans: 2.5T
B	Long: 1.75T Trans: 2.5T
C	Long: 1.75T Trans: 3T

Figure 5: Minimum bending radius on 0.060" nominal sheet in a final annealed condition.

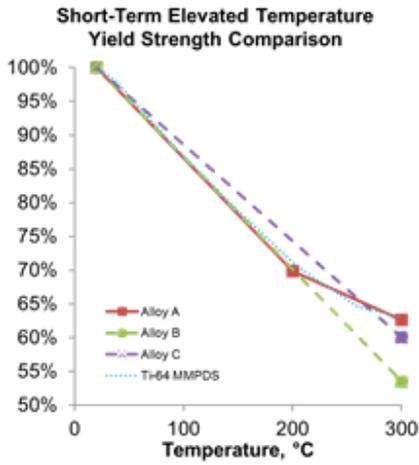


Figure 6: Elevated temperature tensile properties, normalized by alloy strength at room temperature. Alloys A, B, and C have very similar reduction in strength to Ti-6Al-4V [5].

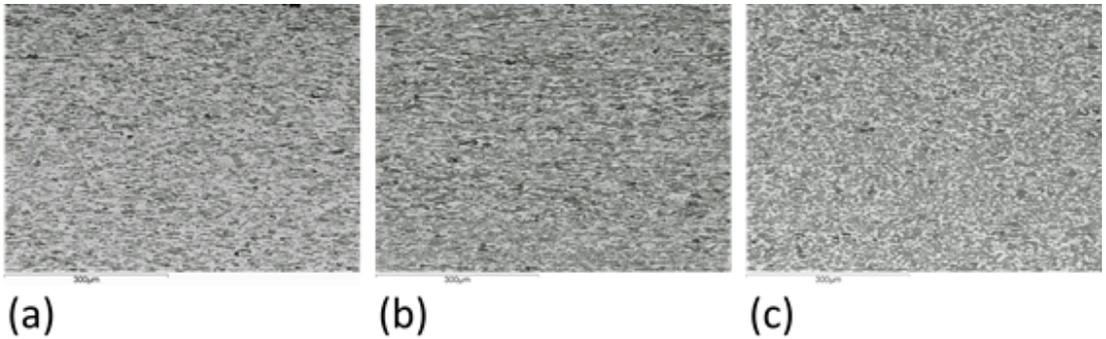


Figure 7: Longitudinal backscattered electron images of the final-annealed sheet. (a) Alloy A, (b) Alloy B, (c) Alloy C.

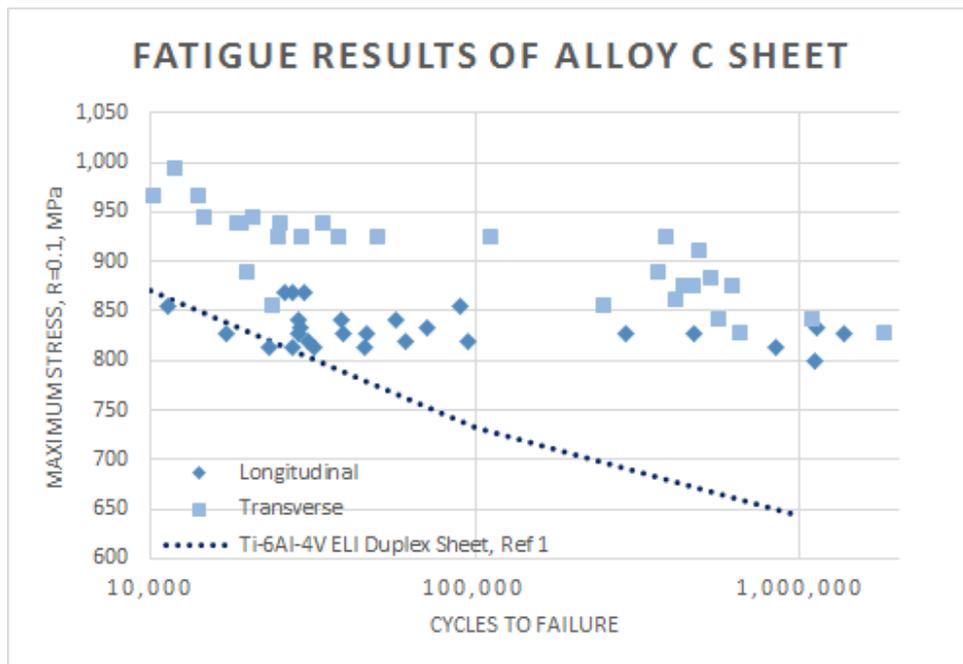


Figure 8: Fatigue results of 0.55mm thick Alloy C sheet. Load ratio of 0.1, 9 hertz loading frequency. Ti-6Al-4V ELI sheet fatigue data adapted from [1].

Discussion

As shown in Figure 3, Figure 4, and Figure 5 the balance of strength and ductility in these alloys is remarkable for an alpha-beta sheet alloy. Strengths exceed Ti-6Al-4V typical properties by approximately 7%, and the alloys are all capable of significant cold working as one would expect based on the bend testing. During production the alloys were welded successfully for processing, but more conclusive work is still needed to demonstrate acceptable welding capability for component assembly applications. Elevated temperature tensile properties are in-line with Ti-6Al-4V, so these alloys are likely amenable to moderate use-temperatures.

The experimental data for these alloys demonstrates they can be adjusted via heat treatment to produce a variety of tensile strengths. Cooling rate strongly affected formation of secondary alpha, and thus yield strength. Limited work on plate material (results presented at conference) demonstrate that the alloys can exceed 1500 MPa (215 ksi) ultimate tensile strengths in quenched and aged conditions.

The microstructures shown in Figure 7 for the alloys show that the material was heat treated at temperatures where approximately 50% alpha phase existed, and that upon cooling a fine distribution of secondary alpha precipitated in the regions between these prior beta grains. No evidence of microtexture is present based on a lack of orientation contrast from the backscattered electron images, though overall macrotexture was evident via the differences in properties between longitudinal and transverse directions.

The fatigue results of Alloy C sheet are as-expected: the alloy demonstrates a lifetime of 100,000 cycles to failure with a load ratio of 0.1 at a stress level of approximately 85% of yield strength in both the longitudinal and transverse directions. The difference between the stresses observed for the same equivalent lifetimes of longitudinal and transverse directions is approximately equal to the difference in yield strength of these alloys. Both of these fatigue curves are significantly higher than the Ti-6Al-4V ELI sheet curve provided in reference [1]. Additional work would be needed to understand the drop in lifetimes in the range of 1,000,000 cycles to failure in the transverse direction.

Cold working of the alloys was more than adequate for industrially viable processing. As discussed in the introduction, this enables weight savings in sheet alloys based on more precise gauge control. Likewise, coil processing of titanium sheet makes longer lengths and has greater annual capacities over sheets made by hot pack rolling [6]. These alloys do demonstrate a higher strength in the transverse direction, however, they also demonstrate equivalent or better elongations and work hardening in that direction. While this is not typical for titanium sheet produced by hot pack rolling, it is more common in aerospace aluminium alloys that are also produced on coils, rather than individual sheets.

Conclusions

Small-scale production testing of these new alloys demonstrates that a high-strength alpha-beta titanium alloys can exhibit cold workability. Scale-up is expected to result in continuous coil of the high-strength titanium alloys, which is a result of the excellent capability at ATI to manufacture cold rolled sheet and to execute careful alloy design.

References

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