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THE EFFECT OF HYDROGEN ON THE FRACTURE TOUGHNESS OF Ti-5Mo-5V-5Al-3Cr

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Abstract

Ti-5Mo-5V-5Al-3Cr (Ti-5553) is a deep-hardenable titanium alloy of commercial importance as a viable replacement for Ti-6Al-4V, Ti-10Al-2V-3Fe and some high strength steels in a variety of aerospace applications. Ti-5553 offers significantly improved thick section hardenability in a product capable of being extruded, rolled, forged, and/or cast. In addition, Ti-5553 can be heat treated in several ways to achieve high strength, high fracture toughness, high fatigue resistance, or a reasonable balance of properties. Production experience has indicated hydrogen content strongly influences the fracture toughness, a critical aerospace design parameter, at all levels below typical specification limits for titanium alloys. Positive identification of hydrogen as a prominent factor in fracture toughness control could have an impact in alloy specification limits, heat-treatment requirements, additional processing, and new alloy grades, all of which could lead to significant cost and/or value added for low hydrogen content material. Multiple characterization tools, including light microscopy, SEM fractography, and TEM, were employed to explore the effects of hydrogen on the microstructure of Ti-5553 and the resulting fracture toughness. Much reduced hydrogen content, within common material specification limits, appears have a strong effect on the fracture toughness of Ti-5553. While not unique to Ti-5553, it is an important dependence to understand in terms of property control. Changes in fracture toughness appear to correlate with the amount of boundary fracture, although the exact mechanism for how hydrogen modifies boundary fracture behavior is not understood, and merits additional study.

Introduction

Hydrogen has long been known to affect the toughness of titanium alloys, although the dependence upon hydrogen level is also dependent upon specific microstructure and base alloy chemistry [1-5]. The reported dependence has varied from positive to nil to negative. Though Hoeg et al noted little effect in this range [6], Chen and Coyn [7] observed a roughly 30% reduction in the toughness of Ti6Al4V as the hydrogen level was increased from 25 to 130 wppm. Meyn found a similar reduction [8]. These are plotted in Figure 1.

These reductions in toughness were reportedly not related to hydride formation, though hydrides are often implicated as the root cause of toughness reductions due to hydrogen. Kolachev [2] proposed a staged dependence in which the toughness reduction mechanism depends on hydrogen concentration, Figure 2. In the first stage, this is below about 50 wppm (for VT-6, or

Ti6Al4V), at the lowest levels, hydrogen is completely in solution and only modestly reduces toughness with increasing concentration. Beyond a critical value, C_1 in Kolachev's diagram, there is minimal dependence of toughness on hydrogen content until another critical level is reached, C_3, the level where titanium hydrides begin to form. At this point toughness is significantly lower, and continues to degrade until the hydrides form a continuous network.

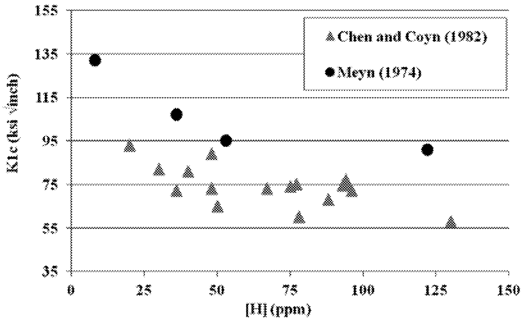


Figure 1. Toughness as a Function of Hydrogen Content for Mill-Annealed Ti6Al4V [7, 8].

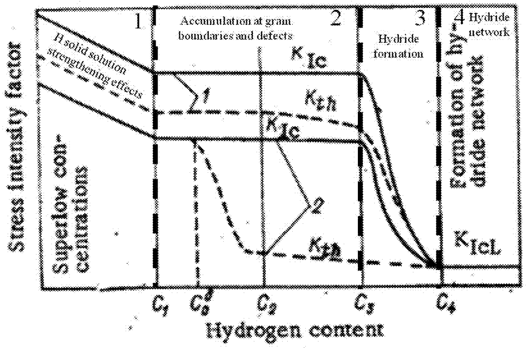


Figure 2. Qualitative Stress Intensity Factor Dependence on Hydrogen Content, from [2].

In the present evaluation with Ti-5553 titanium alloy, no hydrides were found, and it is assumed that all hydrogen was in solution for all conditions. However, an unexpected degree of scatter in fracture toughness was noted in early production material, and was traced to variations in hydrogen content, which occurred below the specification limit of 125 wppm maximum. The purpose of this effort was to quantify the degree of sensitivity of fracture toughness to hydrogen level for the Ti-5553 alloy, in two different heat treatment conditions.

Experimental Procedures and Results

This paper reports on the results of interdependent studies at three different companies. While not all processing details are made available for publication, the consistency of the data lend credence to the results.

Certification fracture toughness tests, per valid ASTM E399, were carried out on 41 Ti-5553 airframe die forgings, in the Beta Annealed, Slow Cool and Aged (BASCA) condition and for multiple heat chemistries [9]. Subsequently, the hydrogen content was measured from material adjacent the fracture surface of the compact tension halves. The resulting dependence is plotted in Figure 3. These data highlight a negative dependence of toughness on hydrogen content in Ti-5553 in the BASCA condition, on the order of 1 ksi√in per 1 wppm.

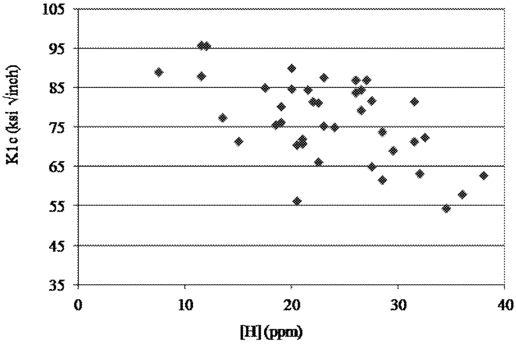


Figure 3. Fracture Toughness Dependence on Hydrogen Content in Ti-5553 Die Forgings.

Based on these observations, three additional laboratory studies were undertaken at Boeing to better elucidate this dependence over a broader range. In the first, 1.5-in gauge Ti-5553 plate in the annealed condition (1300 F / 4 hrs, 50 mins / air cool) was obtained to the chemistry shown in Table I. Plate blanks, roughly 6-in x 20-in were excised and beta-annealed in laboratory air furnaces to deliberately increase hydrogen content from the as-received level of 14 and 16 wppm, corresponding to near-surface and mid-plane locations. Time above the transus, at 1650 F, was 24 hours, followed by an air cool. A standard BASCA heat treatment was then applied to each of the plate blanks, consisting of 1650 F / 60 minutes, cooling at 2.5 F/min to 1125 F, and then aging at 1125 F for 8 hours. Blanks targeting elevated hydrogen levels were heat treated in air as above, while the lower hydrogen level blanks were heat treated in vacuum to avoid hydrogen pickup during heat treatment.

Table I. Ingot Chemistry for Ti-5553 Plate (Wt. %).

	Al	Mo	V	Cr	Fe	Zr	O	N	C	H
Ingot Top	5.30	4.96	5.20	2.75	0.31	0.002	0.170	0.01	0.011	0.0006
Ingot Bottom	5.37	4.97	5.23	2.79	0.31	0.005	0.172	0.01	0.011	0.0006

After heat treatment, tensile and compact tension coupons were excised from the exposed plates at the various hydrogen levels, and tested per ASTM E8 and E399 to determine tensile and toughness values as each level. Companion studies were carried out in similar fashion at VSMPO with Ti-5553 plate, and at ATI Aerospace utilizing 12-in billet rounds which were 3:1 upset forged into pancakes. The resulting toughness values as a function of hydrogen results for all three studies are co-plotted in Figure 4.

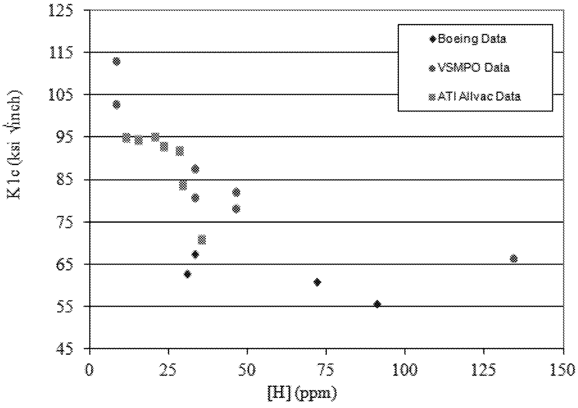
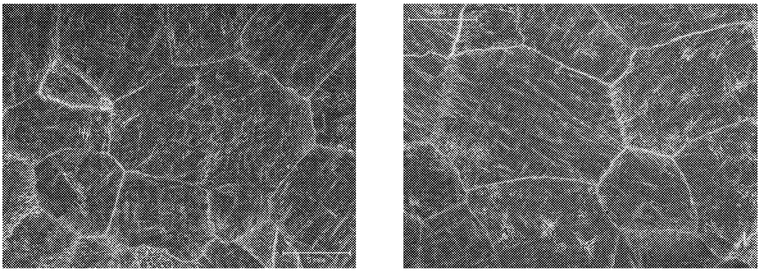


Figure 4. Fracture Toughness of Ti-5553 Plates in the BASCA Heat Treatment Condition as a Function of Hydrogen Content

Light optical microscopy (Figure 5) of the Boeing plates revealed little apparent difference due to hydrogen levels of 31-33 versus 72-90 wppm. Both conditions consisted of intragranular transformed beta lamellae with thin grain boundary alpha phase. An examination of the effect of hydrogen differences at lower levels, 11 wppm vs. 35 wppm in the ATI plates, did reveal slight differences, Figures 6 and 7. In the higher hydrogen level material, there appeared to be more light-etching alpha phase at the prior beta grain boundaries, although this is counter-intuitive, given that hydrogen is a known beta-phase stabilizer. This seems to correlate with slightly more intergranular fracture. However, both of these trends were quite subtle.

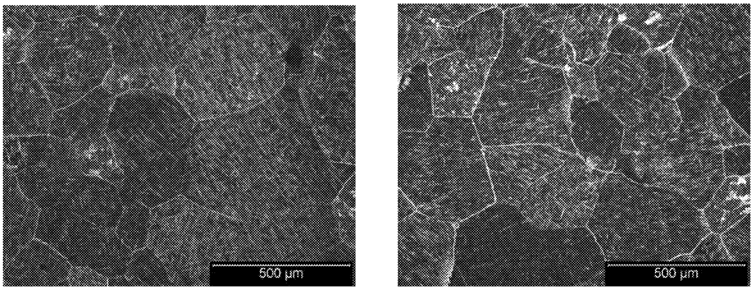


(a) [H] = 72, 90 wppm

(b) [H] = 31, 33 wppm

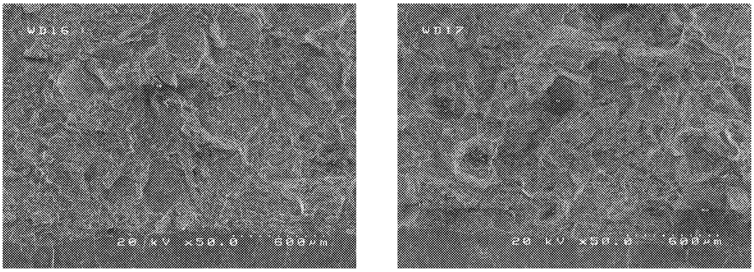
Figure 5. Light Optical Microstructures of Companion Boeing Ti-5553 Plates after BASCA Heat Treatment at Different Hydrogen Levels, Long. Transverse Sections, 200X. The microstructures are essentially identical for the two hydrogen levels.

It is worth noting that the changes in hydrogen level had little effect on tensile strength. In all cases for the Boeing study, the BASCA heat treatment produced an ultimate strength level of 160-163 ksi while the toughness ranged from 56-68 ksi√in.



(a) [H] = 11 wppm (b) [H] = 35 wppm

Figure 6. Light Optical Microstructures of Companion ATI Ti-5553 Plates after BASCA Heat Treatment at Different Hydrogen Levels, Long. Transverse Sections, 100X. In this case there appears to be slightly more grain boundary alpha at beta grain and subgrain boundaries for (b).



(a) [H] = 11 wppm (b) [H] = 35 wppm

Figure 7. Scanning Electron Fractographs of Companion ATI Ti-5553 Plates after BASCA Heat Treatment at Different Hydrogen Levels, Long. Transverse Sections, 100X. Slightly more intergranular fracture is visible for the higher hydrogen, lower toughness condition.

Summary

Hydrogen has been shown to have a significant effect on the fracture toughness of Ti-5553 in the BASCA condition. Between about 10 and 80 wppm, the fracture toughness can range approximately 40 ksi√in due to variations in hydrogen level, reaching values approaching 100 ksi√in for the lowest levels. Above about 80 wppm, the toughness is approximately constant and independent of hydrogen level, within the usual specification limit of 125 wppm. The mechanisms responsible for the large difference in toughness are unclear, but may be related to slight variations in boundary phase distributions, and interphase bond strength. It is suggested that more work is needed in this area to better understand mechanisms, and the potential of this effect in controlling the fracture toughness of titanium alloys.

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