# Ductility Exhaustion Mechanisms in Thermally Exposed Thin Sheets of a Near-$\beta$ Titanium Alloy

F. SANSOZ, M. ALMESALLMY, and H. GHONEM

This study examines the effects of thermal exposure in air environment on the plastic elongation of thin sheets of Ti-15Mo-2.7Nb-3Al-0.2Si (Timetal-21S) alloy. Specimens with thicknesses of 0.12, 0.39, and 1.0 mm were exposed in air environment to temperatures ranging from 482 °C to 693 °C. Tensile tests conducted on these specimens at room temperature show a reduction of plastic elongation proportional to the thermal exposure parameters, time and temperature. Furthermore, a change in the failure mode into a quasi-brittle fracture was observed in the near-surface region. The depth of this region depends on both exposure time and temperature. The kinetics of embrittlement is studied through theoretical considerations of gas diffusion into metal. This approach shows that two distinct embrittlement mechanisms operate in this alloy. The characteristics of each of these mechanisms depend on the corresponding temperature range. At temperatures higher than 545 °C, the embrittlement activation energy is 41.2 kcal·mol$^{-1}$, indicating that the embrittlement process is governed by an enhanced diffusion of oxygen into Timetal-21S. Below this transitional temperature, the embrittlement activation energy approaches zero, a characteristic of slow kinetics transformation. The effects of solid-solution hardening, precipitation-hardening mechanisms, and alloying-element partitioning on ductility exhaustion processes are analyzed and discussed.

## I. INTRODUCTION

TIMETAL-21S (Ti-15Mo-2.7Nb-3Al-0.2Si, in weight percent) was originally developed to provide an oxidation-resistant foil product for use as a matrix in titanium metal matrix composites. This metastable $\beta$-titanium alloy can undergo relatively high operating temperatures while maintaining a good tensile strength and creep resistance. In addition, the good formability due to its bcc microstructure makes the alloy easy to roll into thin sheets (<1.0 mm). These considerations have made Timetal-21S a good candidate for many aerospace applications—in particular, hot-air ducting and plug and nozzle structures.[1] The latter application, which requires the use of thin sheets and foils to manufacture its honeycomb design, is located at the exit end of aero-engines and is exposed to turbine gases with temperatures reaching 621 °C. Considerable efforts were made to examine the viability of this alloy after it approached relatively high temperature levels. Schultz[2] pointed out that embrittlement due to diffused-in surface gas may limit the upper temperature in the practical use of Timetal-21S in temperatures of 550 °C to 600 °C. This is despite the knowledge that little metal wastage occurs *via* surface oxide formation up to 800 °C. Wallace *et al.*[3] estimated that the activation energy linked with the oxidation of Timetal-21S is in the temperature range of 600 °C to 800 °C. They showed that the kinetics of oxidation weight gain in this alloy was consistent with the gas uptake and oxygen diffusion in the metal during exposure rather than due to the growth of a surface oxide layer. Examinations of the contaminated subsurface microstructures revealed a significant increase in the amount of $\alpha$-Ti precipitation, as oxygen stabilizes this phase at elevated temperatures. Subsequently, it was found by Wallace *et al.*[14] that a small oxidation weight gain in sheets subjected to thermal exposure in air has a deleterious effect on the material plastic elongation. The extent of embrittlement was reported to coincide with the appearance of a brittle fracture band, which forms in the vicinity of the specimen edges as a result of surface diffusion. In this view, the higher the exposure temperature, the larger the depth of the brittle fracture band and the lower the residual ductility. Likewise, Wiedemann *et al.*,[5] who compared the effects of thermal exposure in both laboratory air and vacuum, stated that the surface diffusion of air elements had an aggressive effect on the ductility limit, and suggested that a surface coating would prevent sheet specimens from air embrittlement. Parris and Bania[6] reported a similar tendency toward reduction in the plastic elongation of exposed Timetal-21S sheets exposed to temperatures between 510 °C and 615 °C. They emphasized the role of a brittle $\alpha$ case being formed along the specimen surfaces. In addition, these authors investigated the role of oxygen on combined aging/bulk microstructure effects. They estimated that the oxygen concentration limit allowed in this alloy with no substantial effect on the material ductility, is 0.25 wt pct. This was calculated using measurements of the elongation after exposing $\beta$-annealed, non-aged specimens to temperatures ranging from 482 °C to 593 °C for periods of 4 to 24 hours. Huang *et al.*[7] investigated the embrittlement mechanisms occurring in relation to specific heat-treatment and aged conditions of Timetal-21S. At a low aging temperature of 400 °C/8 h, it was shown that in $\alpha/\beta$ systems embrittlement occurs due to the precipitation of the $\alpha$ phase along grain boundaries, particularly during the initial stage of aging.

The primary concern of this article is to provide a fundamental understanding of the ductility exhaustion mechanisms in $\beta$-Ti alloys following thermal exposure at temperatures lower than 700 °C in air environment. The temperatures of interest were 482 °C, 538 °C, 600 °C, 650 °C, and 693 °C.

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MAC = 2005 ⇐ 1000 hrs. | Then ≈ 8-10%

EXTRACT FROM PROFESSOR HAMOUDA GHONEM ARTICLE

**Table II. Results of Tensile Testing on Specimens Subjected to Different Exposure Conditions**

| Thickness (mm) | Temperature (°Q | Time (h) | Yield Stress (MPa) | Plastic Elongatio (Pet) |
|---|---|---|---|---|
| 1.00 (450) | 538 | 40 | 1030 | 12.2 |
| | | 100 | 1030 | 11 |
| | | 163 | 1070 | 9.8 ← |
| | | 862 | 1015 | 8.5 |
| | 549 | 40 | 1030 | 11.1 |
| | | 80 | 1030 | 9.9 |
| | | 150 | 1030 | 8 |
| | | 700 | 1030 | 3 |
| | 650 | 40 | 1010 | 6.3 ← |
| | | 85.5 | 980 | 3.6 ← |
| | | 118 | 980 | 2.7 |
| | | 500 | 810 | 0 |
| | 693 | 40 | 920 | 1 |
| | | 80 | 910 | 0.3 |
| | | 186 | 610 (bby)* | 0 |
| 0.39 (450°) | 482 | 24 | 930 | 5.8 |
| | | 111.5 | 920 | 5.25 ← |
| | 538 | 20 | 1010 | 5.9 |
| | | 41.5 | 1010 | 5 |
| | | 116 | 1020 | 4.6 |
| | 650 | 5 | 950 | 4 ← |
| | | 20 | 950 | 2.8 |
| | | 80 | 950 | 2.2 |
| | 693 | 12 | 900 | 1.5 |
| 0.12 | 482 | 20 | 900 | 0.64 |
| | | 39 | 920 | 0.41 |
| | | 50 | 920 | 0.21 |
| | | 100 | 900 | 0.07 |
| | 538 | 5 | 900 | 1 |
| | | 25 | 915 | 0.44 |
| | | 52 | 900 | 0.21 |
| | | 100 | 900 | 0.11 |
| | 594 | 5 | 930 | 0.5 |
| | | 15 | 930 | 0.4 |
| | | 34 | 920 | 0.15 |
| | 650 | 2 | 920 | 0.8 |
| | | 5 | 940 | 0.4 |
| | | 10 | 925 | 0.11 |
| | | 20 | 790 (bby) | 0 |
| | 693 | 0.2 | 890 | 1.48 |
| | | 0.5 | 890 | 0.6 |
| | | 1 | 900 | 0.58 |
| | | 2 | 900 (bby) | 0.15 |
| | | 3 | 770 (bby) | 0 |

*bby: fractured before yielding.

Thembing 450° for 36 hrs
650 for 20 hrs
Company - 1000 hrs

A340 BETA21S. are Materials ↓
0.61mm
1.00mm
1.47mm
1.8mm

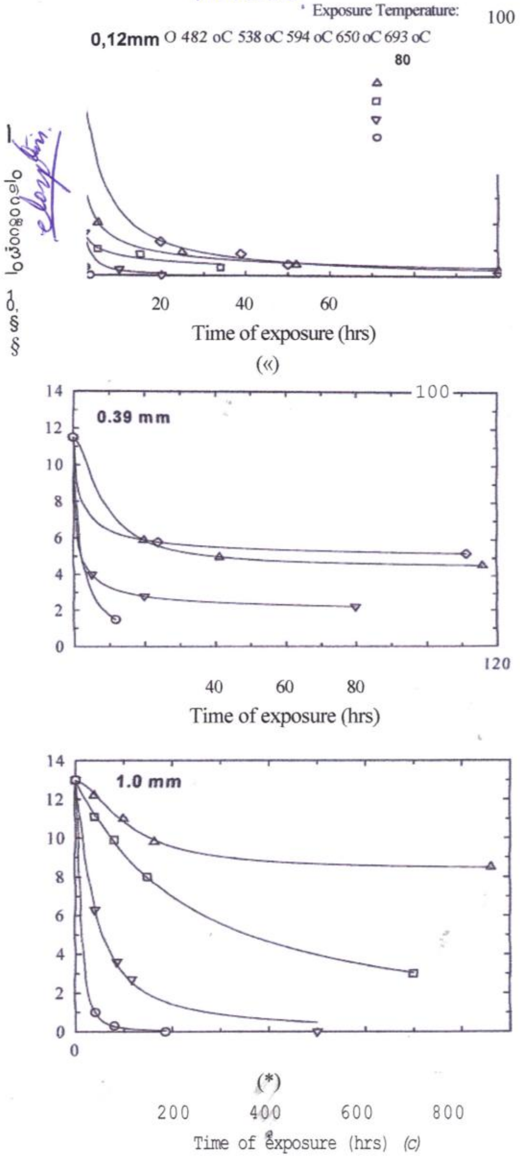

Fig. 6—Loss of tensile ductility *(d)* in Timetal 21S thin sheets exposed to air environment. Sheet thickness is (a) 0.12 mm, *(b)* 0.39 mm, and *(c)* 1.0 mm. All tensile tests are conducted at room temperature.

B. *Tensile Yield Stress and Ductility*

Monotonic tensile tests were conducted at room temperature to determine the residual ductility of the thermally exposed specimens. The procedure for these tensile tests was kept identical to that employed on the as-received microstructure. Table II lists the resulting yield stress and plastic elongation. The correlation of the ductility with exposure time, which is represented in Figure 6, shows that the ductility loss is proportional to both exposure time and temperature. Furthermore, the ductility loss was pronounced as the sheet thickness decreases. It can be noticed in Figure 6 that the initial ductility level is lower in thin samples, which may be explained by microstructure changes in these samples, as will be discussed in Section V. Table n also shows that the yield stress decreases moderately as the exposure time increases; in some cases, failure occurred before yielding was achieved. It could be seen, however, that for low-exposure temperatures (^538 °C), the yield stress increased slightly before decreasing after 50 hours of exposure. This could be interpreted in terms of a second-phase precipitation into

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