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Development and evaluation of TiAl sheet structures for hypersonic applications

S.L. Draper [a,*], D. Krause [a], B. Lerch [a], I.E. Locci [a], B. Doehnert [b], R. Nigam [b], G. Das [c], P. Sickles [d], B. Tabernig [e], N. Reger [e], K. Rissbacher [e]

[a] NASA—Glenn Research Center, Cleveland, OH, United States
[b] Pratt & Whitney, West Palm Beach, FL, United States
[c] Pratt & Whitney, East Hartford, CT, United States
[d] Engineering Evaluation and Design, Florence, KY, United States
[e] Plansee AG, Reutte, Austria

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Abstract

A cooperative program between the National Aeronautics and Space Administration (NASA), the Austrian Space Agency (ASA), Pratt & Whitney, Engineering Evaluation and Design, and Plansee AG was undertaken to determine the feasibility of achieving significant weight reduction of hypersonic propulsion system structures through the utilization of TiAl. A trade study defined the weight reduction potential of TiAl technologies as 25–35% compared to the baseline Ni-base superalloy for a stiffener structure in an inlet, combustor, and nozzle section of a hypersonic scramjet engine. A scramjet engine inlet cowl flap was designed, along with a representative subelement, using design practices unique to TiAl. A subelement was fabricated and tested to assess fabricability and structural performance and validate the design system. The TiAl alloy selected was PLANSEE's third generation alloy Gamma Met PX,[1] a high temperature, high-strength γ-TiAl alloy with high Nb content. Characterization of Gamma Met PX sheet, including tensile, creep, and fatigue testing was performed. Additionally, design-specific coupons were fabricated and tested in order to improve subelement test predictions. Based on the sheet characterization and results of the coupon tests, the subelement failure location and failure load were accurately predicted.

Keywords: Titanium aluminide; Sheet; Mechanical properties; Fabrication

1. Introduction

Gamma TiAl is an attractive candidate for structural aerospace applications due to its high-strength, low density, and good oxidation resistance [1,2]. Hypersonic vehicles have aggressive thrust/weight targets and high operating temperatures. Significant weight benefits could be realized by utilizing γ-TiAl for large, static structures in a hypersonic engine. However, design methodology, manufacturing techniques, finite element analysis, and material characterization need to be further developed before TiAl can be implemented into structural components. This program aimed to further the technology readiness of Gamma TiAl for structural applications. Gamma Met PX (GMPX), a high-strength TiAl based on the TNB alloys developed by GKSS Research Center, was selected due to its excellent mechanical properties [3,4]. The microstructure and mechanical properties of several GMPX sheets were characterized. A scramjet inlet flap subelement was designed and fabricated from GMPX sheet and plate. Coupons, designed to enable the accurate prediction of subelement behavior, were also fabricated and tested. Using the mechanical property database generated and the results of the configuration-specific coupon tests, the subelement failure location and load were accurately predicted using ANSYS.

2. Materials and procedures

2.1. Sheet characterization

Five of Plansee's Gamma Met PX (GMPX) sheets were microstructurally examined by optical, scanning (SEM), and

[1] Gamma Met PX is a trademark of PLANSEE AG, Austria.

* Corresponding author. Tel.: +1 216 433 3257; fax: +1 216 433 3680.
E-mail address: Susan.L.Draper@nasa.gov (S.L. Draper).

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transmission electron microscopy (TEM). Four of the sheets were 1 mm thick and one was 1.5 mm thick. All sheets were characterized in the as-received condition. An inductively coupled plasma (ICP) was used to analyze the chemical composition of the sheets.

Tensile, fatigue, and creep specimens were machined in both the longitudinal and transverse direction from sheets using elecrodischarge machining (EDM). Since TiAl is susceptible to EDM damage, the cut surfaces had to be polished by hand or low stress ground in order to remove any pitting. Electrolysis free EDM resulted in the least amount of EDM pitting and was used for the tensile and some of the fatigue samples. Initial tensile samples were polished by hand to 600 grit; however, sufficient material was not removed to eliminate failures occurring at residual EDM damage. Only data from samples which failed in the gage section is reported and all error bands represent 95% confidence intervals. Subsequent tensile tests used the fatigue specimen design which had a large transition radius to minimize stress concentrations and enable automated grinding of the edges. Tensile samples were tested from 23 to 800 °C using a strain-rate control of $1 \times 10^{-4}\ \mathrm{s}^{-1}$. Fatigue tests were run in load-control with a tension–tension ($R\sigma = 0.05$) cycle. Tests were conducted at various temperatures from 23 to 800 °C at a frequency of 0.5 Hz. The fatigue tests were conducted at a beginning stress level and cycled to approximately 10^6 cycles. If the specimen had not failed, the maximum stress was increased by approximately 14 MPa and cycling continued for another 10^6 cycles. This process was repeated until the specimen failed. This "step testing" has been shown to reliably provide failure data on Gamma TiAl samples [5]. Of the 13 load-controlled tests, 10 samples failed on the first load block and therefore were not step tests. For the three specimens receiving steps, the fatigue life was taken as the number of cycles in the last step only and the previous steps were deemed inconsequential to the life. A few samples were tested in strain-control under fully reversed loading, using anti-buckling guides, to give some idea of their response under this test mode. At room temperature, a smaller sample size was used and tested without buckling guides in an unconstrained fashion. All fully reversed tests were conducted at a constant strain range and at a strain rate of $1 \times 10^{-4}\ \mathrm{s}^{-1}$. Creep testing was performed on 114 mm long, reduced gage samples at 760 °C. Creep strain was determined as a function of time via an extensometer that was pinned to the shoulders of the specimen, above and below the gage section. All the relative motion of the extensometer was assumed to have occurred in the gage section.

2.2. Configuration-specific coupon testing

Brazing was selected as the joining technique for the subelement primarily due to schedule constraints. Consequently, all of the configuration specific test coupons were joined by brazing. The brazing technique is proprietary to Plansee such that the details cannot be given, however, it was performed above 1000 °C in a high vacuum furnace with a slow heat up and cool down. During the fabrication method development, Plansee appraised the strength of brazed round test bars by brazing two round bars together, end-to-end, and tensile testing across the braze. The braze strength of a Ti-Ni braze alloy was approximately 330–450 MPa at both 23 and 700 °C. While this was comparable to the braze strength obtained in a previous program on Gamma Met 100 [6], it is considerably lower than the raw material capability of 750–1050 MPa. The Ti-Ni braze was selected based on obtaining the best balance of tensile strength and oxidation resistance of brazed material. Sheet tensile samples were put through a braze thermal cycle and subsequently tensile tested to determine the effects of the braze thermal cycle on material tensile properties. While the strength of the as-received and exposed samples were equivalent, the plastic strain to failure decreased by 50% due to the braze thermal exposure. GMPX has been shown to embrittle due to oxygen penetration during high temperature exposures [7]. While the braze was performed under high vacuum, it is possible that sufficient oxygen was present to diffuse into the near-surface microstructure and decrease the ductility of the alloy.

To better understand the subelement performance when loaded, four configuration-specific coupons were defined, fabricated, and structurally tested. The specimens were designed to assess key configuration features. The results were used to define the capabilities of the material and structure, especially at stress concentration locations such as steps, bolts, and brazed joints and were incorporated in the pretest and post-test subelement strength predictions. Gamma Met PX sheet and plate were brazed together using a Ti-Ni braze alloy to fabricate the four types of coupons (braze shear, stepped tensile, bolted clevis, and braze peel samples) shown in Fig. 1.

A braze shear test method, developed under a previous program [6], was utilized to test the Gamma TiAl braze joint. The test sample consisted of two pieces of material brazed together as shown in Fig. 1a. The braze shear samples were tested at 23, 371, and 649 °C using a constant crosshead speed of 2.54×10^{-4} cm/s. Stepped tensile specimens were used to determine the stress concentration in the subelement where two sheets were brazed together and one of the sheets is discontinued, creating a step, Fig. 1b. The stepped tensile specimens were fabricated by brazing either a 1 mm sheet or a 6.4 mm plate on both ends of a 1 mm thick sheet which was 140 mm long, Fig. 1b. The stepped tensile specimens were tested at 23 and 600 °C. Only the samples fabricated with the 6.4 mm thick plate were tested at elevated temperature, with thermocouples placed at the center and at 6 mm intervals. Bolted clevis samples determined the stress concentration at the subelement bolt holes and were fabricated by brazing three TiAl sheets, one on top of the other, Fig. 1c. The three sheets included two 1 mm sheet and a 6.4 mm thick plate. A test fixture was designed and machined to test the bolted clevis samples in an in-plane biaxial load frame. The bolted clevis samples were tested at room temperature using stroke control with a linear displacement ramp of 2.5×10^{-4} cm/s. Brazed peel samples, with a configuration shown in Fig. 1d, were processed in a one-step brazing cycle with the long aspect laying flat and the short dimension undergoing a vertical braze. The braze peel samples were tested at either 23 or 760 °C with a constant crosshead speed of 2.54×10^{-4} cm/s.