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HIGH CYCLE FATIGUE PROPERTIES OF HAYNES 230 BEFORE AND AFTER EXPOSURE TO ELEVATED TEMPERATURES (PREPRINT)

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14. ABSTRACT
The objective of this work was to investigate the high cycle fatigue properties of a nickel based superalloy, Haynes 230, targeted for use in thermal protection system (TPS) applications. This study includes room temperature testing in longitudinal and transverse directions before and after exposure to elevated temperatures out to 107 cycles using a unique test system specifically developed for thin gage applications. Specimens with thicknesses of 0.127 mm were tested following exposure to a temperature of 982 C for 100 hours. The tensile properties exhibited by the as-received material were found to be independent of orientation, with extremely consistent results between the longitudinal and transverse specimens. In contrast, specimens exposed to elevated temperature showed a significant drop in yield stress, ultimate strength, and ductility. Similarly, fatigue properties of longitudinal and transverse as-received material vary only slightly, while exposure to elevated temperature causes a significant decrease in the fatigue strength of the material.

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HIGH CYCLE FATIGUE PROPERTIES OF HAYNES 230® BEFORE AND AFTER EXPOSURE TO ELEVATED TEMPERATURES

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ABSTRACT

The objective of this work was to investigate the high cycle fatigue properties of a nickel based superalloy, Haynes 230, targeted for use in thermal protection system (TPS) applications. This study includes room temperature testing in longitudinal and transverse directions before and after exposure to elevated temperatures out to 10^7 cycles using a unique test system specifically developed for thin gage applications. Specimens with thicknesses of 0.127 mm were tested following exposure to a temperature of 982 C for 100 hours. The tensile properties exhibited by the as-received material were found to be independent of orientation, with extremely consistent results between the longitudinal and transverse specimens. In contrast, specimens exposed to elevated temperature showed a significant drop in yield stress, ultimate strength, and ductility. Similarly, fatigue properties of longitudinal and transverse as-received material vary only slightly, while exposure to elevated temperature causes a significant decrease in the fatigue strength of the material.

KEYWORDS

High cycle fatigue, nickel superalloy, thin gage, elevated temperature

INTRODUCTION

In recent years, the emphasis on hypersonic vehicles and access to space has greatly increased. In addition, requirements for such vehicles include rapid turnaround time as well as increased reliability, durability, and sustainability. These unique requirements, along with expected system acreage surface temperatures between 500 and 1000 C, lead to the possible use of metallic materials for thermal protection system (TPS) panels over extended areas of the aircraft [1-2]. These metallic TPS panels will most likely be made of honeycomb sandwich panels with face sheet and core thicknesses minimized to decrease system weight. An example of a TPS system incorporating a metallic honeycomb structure is shown in Fig. 1. Typical material thicknesses for such a structure are on the order of 0.1 mm -0.25 mm. However, very little data exist concerning the mechanical properties of materials with thicknesses of less than 0.5 mm. In order for designers to optimize TPS for hypersonic applications, it is important to understand the material performance under appropriate conditions. Expected temperature profiles include excursions to very high temperatures for short time periods followed by extended periods of loading at lower temperatures. Exposure to low amplitude, high frequency acoustic loads along with a requirement for multiple missions may lead to fatigue lives in the very high cycle regime ($>10^6$ cycles).

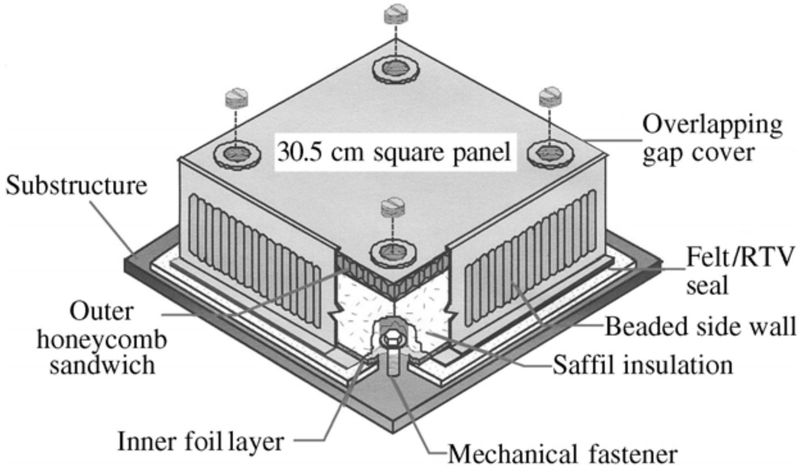

Fig. 1: TPS incorporating nickel superalloy honeycomb sandwich structure [1]

MATERIAL

The material chosen for this study was Haynes 230®, a solid solution strengthened Ni-base alloy. Haynes 230® is a commercial alloy with a very good combination of oxidation resistance, high temperature strength, and long-term thermal stability [3]. In addition to metallic TPS honeycomb applications, it is used for applications such as combustor liners, stator casings and various other turbine engine components.

In order to determine material properties applicable to hypersonic TPS, the Haynes 230® used for this study was cold rolled to a thickness of 0.127 mm. The grain structure is equiaxed with diameters approximately 25 μm. MC_6 carbides are arranged in stringers parallel to the rolling direction throughout the material, and have been shown to be fractured in the as-received condition (Fig. 2). In addition, much smaller $M_{23}C_6$ carbides can be found along grain boundaries.

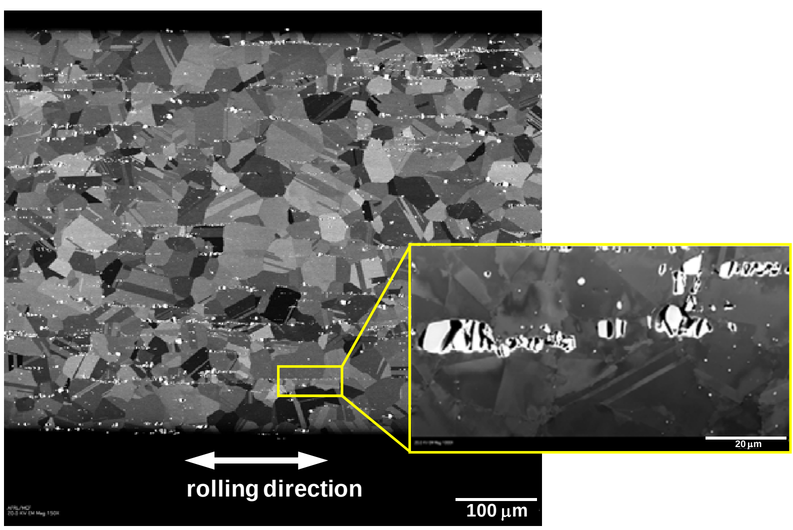

Fig. 2: Haynes 230 microstructure in as-received condition

EXPERIMENTAL PROCEDURE

A new test system was developed recently to test thin materials (0.075 mm – 0.2 mm) applicable to hypersonic TPS applications. It includes the capability to accurately measure displacements within the specimen gage section while testing at temperatures up to 1200 C [4,5]. Dogbone specimens of conventional length (152 mm) and gage section width (8.5 mm) were used for all testing, as shown in Fig. 3.

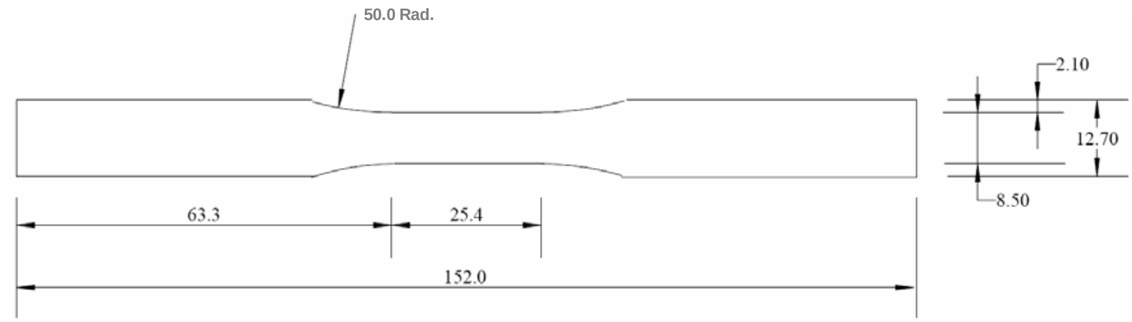

Fig 3: Specimen design (all dimensions in mm)

Three different material conditions were chosen for the experiments presented. The first two consisted of as-received material in the longitudinal (rolling) and transverse directions. The third condition was chosen to simulate a simplified loading condition based on expected temperature profiles during hypersonic flight. This includes excursions to a very high temperature for a limited time period followed by extended periods of vibratory loading at lower temperatures. In order to simulate a simplified version of this loading condition, one set of specimens, oriented in the rolling direction, was exposed to a temperature of 982 C (1800 F) for 100 hours before being tested at room temperature. Fig. 4 shows the edge of one specimen after the exposure. An oxide layer approximately 0.005 mm thick can be seen at the surface of the specimen. The oxide layer is not uniform, however, and the overall surface roughness has increased. Oxygen penetration into the subsurface of the material has also occurred preferentially along grain boundaries.

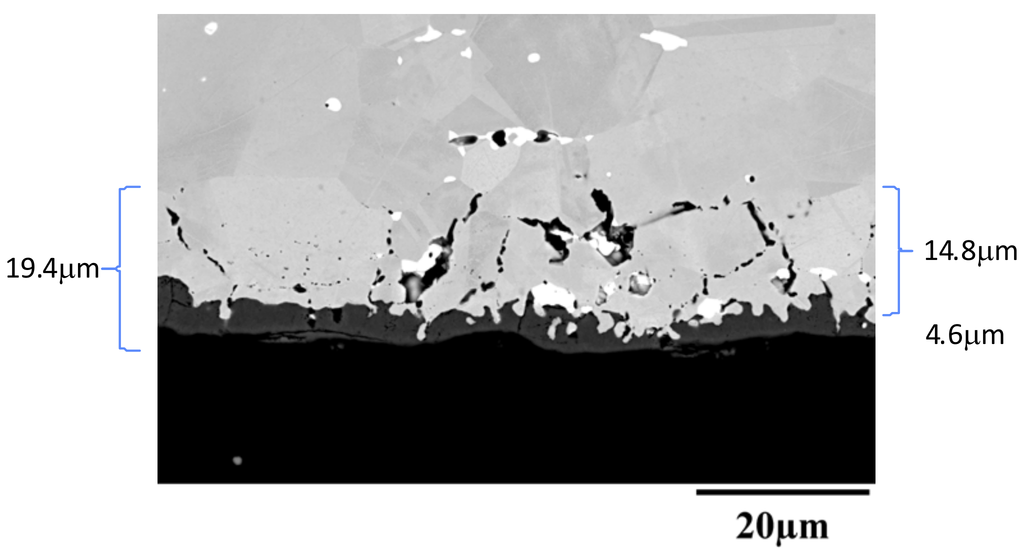

Fig. 4: Surface condition after exposure to 982 C for 100 hours.

RESULTS

Tensile Behavior

Fig. 5 shows the results of one tensile test for all three material conditions considered, with the inset figure showing a closer view of the yield portion of the curves. Additional tests were run at each condition and showed very good consistency, but were removed from the figure to make it easier to discern the differences in the curves. The longitudinal tensile tests were performed at a loading rate of 0.030 mm/s, and the transverse tests at 0.054 mm/s. However, previous testing has shown that there is no rate effect at these loading rates [6]. The as-received material shows very consistent behavior in the longitudinal and transverse orientations, with the two curves almost on top of each other. The carbides oriented preferentially in the rolling direction appear to have no effect on the large strain behavior of the material. The material exposed to elevated temperature shows a different behavior. From the inset figure, it is clear that the material exposed to elevated temperature before testing yields at a much lower stress than the as-received material. However, after the initial yielding a second region of linear behavior occurs. The modulus is much lower during this second linear portion of the curve, and remains constant until more than 1% total strain has been accumulated. At this point a second "yield" point occurs, but it is not until the stress has increased beyond what is seen in the as-received material at the same strain value. After the second inflection of the curve, the material softens considerably and shows less overall hardening than the as-received material, resulting in a lower ultimate tensile strength. In addition, the exposed material shows a drop in overall ductility of approximately 40% when compared with the failure strain of the as-received material. The overall drop in initial yield strength, ultimate strength, and ductility are most likely due to the oxide layer that has formed on the surface of the material. The reasons for the second linear region following the initial yielding are presently unknown.

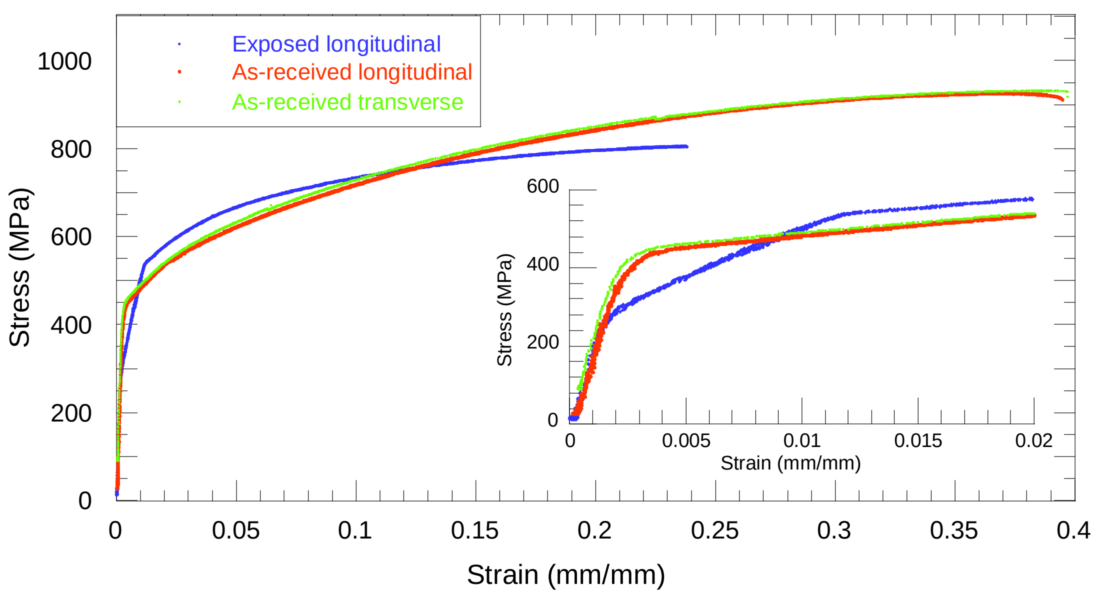

Fig. 5: Room temperature tensile test results for as-received longitudinal, as-received transverse and exposed longitudinal specimens

Fatigue Behavior

The S-N plot in Fig. 6 shows the results of fatigue tests performed on the three conditions of Haynes 230® material discussed previously. All of the fatigue tests were performed at room temperature, with a stress ratio (R) of 0.1 and a frequency of 30 Hz. The most tests were performed on the as-received longitudinal material to determine a baseline behavior for Haynes 230®. It was anticipated that the longitudinal direction would exhibit the greatest fatigue strength, since the larger MC_6 carbides are oriented parallel to the loading direction. Fatigue tests were run at stresses ranging from 525 MPa to 700 MPa and showed typical behavior. The scatter in fatigue life was fairly small at the higher stresses and much larger near the fatigue limit stress. Although only four tests have been run at the minimum stress, the scatter is clearly more than an order of magnitude, with fatigue lives ranging from 400,000 cycles to runouts of over 15,000,000 cycles (shown with arrows at 10^7 cycles).

For the as-received transverse specimens, the carbides are oriented perpendicular to the loading direction and across the width of the gage section. It was anticipated that these carbides, which were already fractured in the as-received condition, may decrease the fatigue strength by initiating cracks within the material matrix and allowing the cracks an easy path to grow. However, this was not observed in the limited tests that have been performed. At the highest stress of 700 MPa, the fatigue life appears to be slightly lower than for the longitudinal specimens, but at the lower stresses this trend does not continue. At 600 MPa the lives are essentially the same, and at the lowest stress of 525 MPa the data falls within the scatter of the longitudinal data. Although the reasons for the similar behavior are unclear, it may be due to the large strains that occur during the first cycle of the fatigue tests. By looking at the tensile test results in Fig. 5, it becomes apparent that even near the fatigue limit stress of 525 MPa, strains of up to 2% can be expected in the gage section during the initial cycle. At 600 MPa, the strains may approach 5%. Based on the large number of cycles to failure, it seems clear that the cycling will quickly shake down to become essentially elastic. However, the initial strain may help to redistribute any large stresses that would naturally occur around the carbides, minimizing their potentially detrimental impact on the fatigue life.

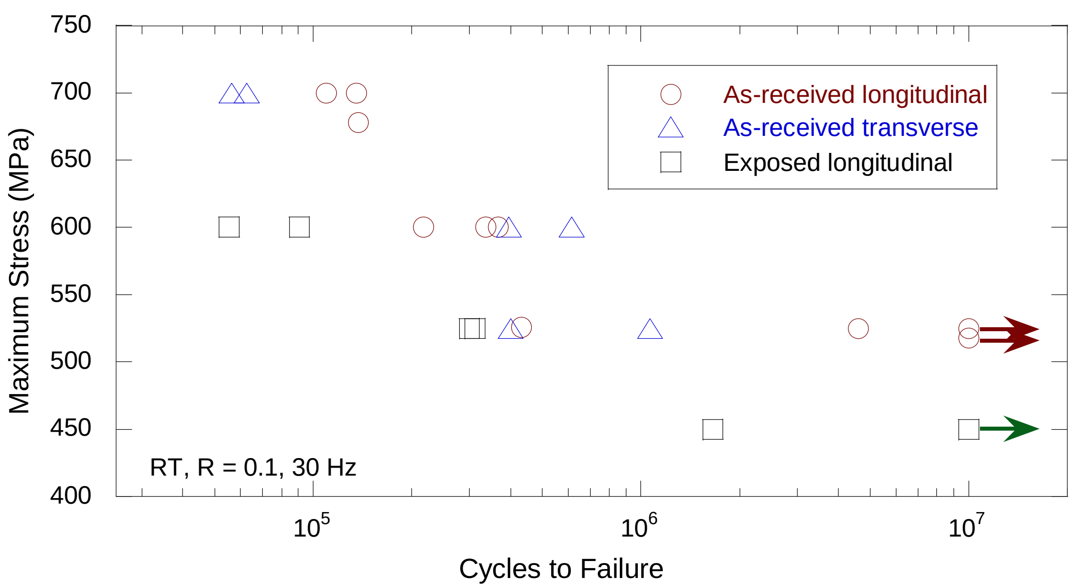

Fig. 6: Room temperature fatigue results for Haynes 230® (R = 0.1, *f* = 30 Hz.)

While there appears to be little difference between the fatigue strength of the as-received longitudinal and transverse material, the same is not true for the longitudinal material exposed to elevated temperatures. Fig. 6 clearly illustrates the detrimental effect that exposing specimens to a temperature of 982 C for 100 hours has on the fatigue strength. At 600 MPa, the highest stress tested with the exposed material, the fatigue life is approximately 1/5 of the as-received material. Surprisingly, the difference is much less at 525 MPa. Failure is seen at stresses even as low at 450 MPa in the exposed material. However, instead of comparing the fatigue lives at a given stress, it may be more appropriate to compare the stresses associated with certain lives. For instance, it appears that the stresses at which failure will occur at any specific fatigue life are approximately 75 MPa less for the exposed material than for the as-received material. Detailed analysis of the fracture surfaces have not been completed, but it seems likely that the oxidation layer on the surface, as well as the oxygen penetration along grain boundaries into the material act as fatigue crack initiation points leading to early failure. It is not known if the loss in strength and ductility would decrease if the exposure time was lessened, or if the same property degradation would occur as soon as a significant oxide layer is formed.

CONCLUSIONS

Room temperature tensile and fatigue tests were performed on a solid solution strengthened alloy in the as-received (longitudinal and transverse) condition and after exposure to an elevated temperature of 982 C for 100 hours.

- The tensile properties exhibited by the as-received material seem to be independent of orientation, with extremely consistent results between the longitudinal and transverse specimens.
- The specimens exposed to elevated temperature showed a significant drop in yield stress, ultimate strength, and ductility. In addition, the stress-strain response of the exposed specimens exhibited a second linear region with decreased modulus immediately following the initial yield point.
- The fatigue properties of longitudinal and transverse as-received material vary only slightly, and any perceived differences could be due to the lack of a statistically significant number of data points.
- Exposure to elevated temperature causes a significant decrease in the fatigue strength of the material, most likely caused by brittle oxide layer formed on the surface as well as the oxygen penetration along the grain boundaries.

REFERENCES

[1] Poteet, C.C.; Blosser, M.L.: Improving Metallic Thermal Protection System Hypervelocity Impact Resistance Through Numerical Simulations
Journal of Spacecraft and Rockets, Vol. 41, No. 2 2004, pp. 221-231

[2] El-Soudani , S.M.: High Performance RX2™ Ti 6242S Titanium for Re-useable Launch Vehicles Metallic Thermal Protection Systems
American Institute of Aeronautics & Astronautics, AIAA-2000-5147, 2000

[3] Haynes International, Inc., Haynes 230® Alloy Information Brochure, No. H-3000, 2007

[4] Morrissey, R.J.; John, R.; Ruddell, M.J.; Blosser, P.E.; Buchanan, D.J.:
Test System for Elevated Temperature Characterization of Thin Metallic Sheets
Submitted to ASTM Journal of Testing and Evaluation, 2010

[5] Porter, W.J.; Li, K.; Morrissey, R.; and John, R.:
Microstructural Characterization of Foil-gage Haynes® 230®, submitted for publication

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