AFRL-RX-WP-TP-2011-4210

USE OF PRECIOUS METAL-MODIFIED NICKEL-BASE SUPERALLOYS FOR THIN GAGE APPLICATIONS (PREPRINT)

Donna Ballard

Metals Branch
Metals, Ceramics, and NDE Division

Ann Bolcavage and Randy Helmink

Rolls-Royce North America

APRIL 2011

Approved for public release; distribution unlimited.

See additional restrictions described on inside pages

STINFO COPY

AIR FORCE RESEARCH LABORATORY
MATERIALS AND MANUFACTURING DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7750
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
April 2011	Journal Article Preprint	01 April 2011 – 01 April 2011

4. TITLE AND SUBTITLE
USE OF PRECIOUS METAL-MODIFIED NICKEL-BASE SUPERALLOYS FOR THIN GAGE APPLICATIONS (PREPRINT)

5a. CONTRACT NUMBER In-house
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER 62102F

6. AUTHOR(S)
Donna Ballard (AFRL/RXLM)
Ann Bolcavage and Randy Helmink (Rolls-Royce North America)

5d. PROJECT NUMBER 4347
5e. TASK NUMBER 02
5f. WORK UNIT NUMBER 25100102

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Metals Branch (AFRL/RXLM)
Metals, Ceramics, and NDE Division
Air Force Research Laboratory
Materials and Manufacturing Directorate
Wright-Patterson Air Force Base, OH 45433-7750
Air Force Materiel Command
United States Air Force

Rolls-Royce North America
P.O. Box 420, Speed Code S-07
Indianapolis, IN 46206-0420

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-RX-WP-TP-2011-4210

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Materials and Manufacturing Directorate
Wright-Patterson Air Force Base, OH 45433-7750
Air Force Materiel Command
United States Air Force

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/RXLM

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-RX-WP-TP-2011-4210

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
PAO Case Number: 88ABW 2010-2299; Clearance Date: 04 May 2010.
Journal article submitted to the *Journal of the Minerals, Metals & Materials Society (JOM)*.

14. ABSTRACT
Precious metal-modified nickel-base superalloys are being investigated for use in thin gage applications, such as thermal protection systems or heat exchangers, due to their strength and inherent oxidation resistance at temperatures in excess of 1050 °C. This overview paper summarizes the Air Force Research Laboratory (AFRL) and Rolls-Royce North America interest in experimental two phase γ-Ni + γ'-Ni_3Al superalloys. AFRL is interested in alloys with a base composition of Ni-15Al-5Cr (atomic %) with C, B, and Zr additions for grain-boundary refinement and strengthening. The alloys currently being evaluated also have 4-5 atomic % total of platinum-group metals, in this case platinum and iridium. The feasibility of hot rolling these alloys to a final thickness of 175-250 μm and obtaining a nearly fully recrystallized microstructure was demonstrated. However, an anomalous grain-growth behavior was also observed at the surface in the intermediate and final rolled products. Future work will include evaluating alloys with a combination of rhenium and tantalum (up to 2 atomic % total) in place of the platinum and iridium.

15. SUBJECT TERMS
thermal protection systems, nickel, superalloy, thermomechanical processing

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
Unclassified	Unclassified	Unclassified	SAR	16	Donna L. Ballard
					19b. TELEPHONE NUMBER *(Include Area Code)* N/A

Use of Precious Metal-Modified Nickel-Base Superalloys for Thin Gage Applications

Donna Ballard[1*], Ann Bolcavage[2], and Randy Helmink[2]

[1]Materials and Manufacturing Directorate, Air Force Research Laboratory, Wright-Patterson Air Force Base, OH 45433, USA
[2]Rolls-Royce North America, ***

Abstract

Precious metal-modified nickel-base superalloys are being investigated for use in thin gage applications, such as thermal protection systems or heat exchangers, due to their strength and inherent oxidation resistance at temperatures in excess of 1050°C. This overview paper summarizes the Air Force Research Laboratory (AFRL) & Rolls-Royce North America interest in experimental two phase γ-Ni + γ'-Ni_3Al superalloys. AFRL is interested in alloys with a base composition of Ni-15Al-5Cr (atomic %) with C, B, and Zr additions for grain-boundary refinement and strengthening. The alloys currently being evaluated also have 4-5 atomic % total of platinum-group metals, in this case platinum and iridium. The feasibility of hot rolling these alloys to a final thickness of 175-250 μm and obtaining a nearly fully recrystallized microstructure was demonstrated. However, an anomalous grain-growth behavior was also observed at the surface in the intermediate and final rolled products. Future work will include evaluating alloys with a combination of rhenium and tantalum (up to 2 atomic % total) in place of the platinum and iridium.

Keywords: thermal protection systems, nickel, superalloy, thermomechanical processing

*Corresponding author. Address: Air Force Research Laboratory, Materials and Manufacturing Directorate, AFRL/RXLM, 2230 10th Street, Wright-Patterson Air Force Base, Ohio 45433-7817. Tel.: 937-255-4003; fax: 937-255-0445.

Nickel-base superalloys having densities exceeding 8 g/cm^2 may not initially be thought of as viable materials for acreage thermal protection systems (TPS) on hypersonic or space vehicles. Indeed, as the only reusable spacecraft currently in operation, the Space Shuttle utilizes many types of non-metallic TPS materials, in both tile and blanket form. In many cases, these nonmetallic materials are the only option under extreme environments (in terms of temperature, stress, etc.) which demand properties exceeding those of metallic thermal protection systems (MTPS) [1]. However, shuttle refurbishment between flights has been reported to require more than 17,000 labor hours[2] with a total inspection and refurbishment time exceeding 40,000 hours[3]. This level of maintenance is unacceptable for U.S. Air Force applications, where the turn-around time goal is hours to days rather than weeks to months. As a result, thin gage metallic sheet and foil may become an acreage option because the time for inspection can be significantly reduced, durability is improved, and replacement time is shortened because MTPS panels are mechanically attached rather than adhesively bonded. Historically, sandwich construction MTPS (outer surface-Alloy 617 nickel-base superalloy honeycomb core and face sheets; inner surface titanium alloy honeycomb core and face sheets) was evaluated (Figure 1) and was considered to be a leading candidate for a significant portion of the lower surface of the National Aeronautics and Space Administration (NASA) X-33 vehicle[2], a wedged-shaped subscale prototype of a reusable launch vehicle[4] designed by Lockheed Martin.

Weight is critical in vehicle design because total vehicle weight will impact performance[3]. In both current and proposed systems, the TPS is parasitic and not designed to carry significant structural load regardless of material selection[5]. Because of the increase in density of MTPS, materials under consideration must be very thin, 0.17 mm-0.25 mm for a typical face sheet and 0.05mm-0.10 mm for honeycomb core. One experimental class of alloys being evaluated for MTPS applications is platinum-group-metal (PGM)-modified nickel-base superalloys where one substitutes PGM, in this case platinum and iridium for nickel. Table 1 identifies a few of the alloys that have been evaluated at the Air Force Research Laboratory as well as a baseline platinum-modified nickel aluminide–β-NiAl(Pt) composition, e.g. Ni-50Al-15Pt used in the turbine-engine industry for airfoil coatings because of its oxidation resistance[6-9]. However, using β-NiAl(Pt) for a monolithic application is not practical because it is brittle and does not perform well across the entire service temperature range, particularly below 600°C.[10,11] Recent results on PGM-modified Ni + Ni_3Al ($\gamma + \gamma'$) compositions for bond coats[8,12-13] suggest that these γ–Ni + γ'–Ni_3Al compositions may be suitable thin gage candidates due to the formation of an adherent, protective α-alumina scale which provides increased environmental resistance over a larger service temperature range.[14] In addition, results reported in the late 1970's and early 1980's by Corti, et al [15-17] concluded that platinum had the best overall performance in both oxidizing and sulfidizing environments. Figure 2 compares the oxidation resistance of β-NiAl(Pt), candidate materials, and commercial alloys. Cyclic oxidation testing was performed at Iowa State University and the detailed test procedures are described in reference **. Although there is no added benefit to environmental resistance, iridium is added to the candidate alloys because it partitions almost equally to both γ and γ' – there is a slight preference for the γ phase – and reduces the lattice mismatch.[20,21]

Corti, et al also documented[15-17] that platinum provided the best strength at temperatures in excess of 1000°C because it partitions to and strengthens the γ' precipitate phase.[18,19] A high volume fraction of the precipitate phase is desirable for reasonable high temperature strength and adequate creep resistance, which are important MTPS design considerations and may allow the use of thinner foils than is possible with conventional Ni-based superalloys. Figure 3 compares the tensile strength of commercial alloys to the PGM-modified candidates at room and elevated temperatures at comparable thicknesses.

Platinum prices fluctuate substantially[20] with a high in early-mid 2008 at over $2200/troy oz and an average price for the 1st quarter of 2010 at $1600/troy oz. Because some of the candidate compositions being evaluated at AFRL contain a Pt content of 2-3 atomic %, the material cost is not trivial. However, the inherent environmental resistance may justify this high cost if the alloy does not require additional environmental or thermal barrier coating (E/TBC) prior to service. Introduction of an E/TBC to either the face sheets or the core dramatically increases system complexity and expense. Also, these high cost alloys may not make up the entire sandwich structure, but instead used for the most demanding environmental applications. This assumes thin gage sheet and foil of a candidate alloy can be 1) produced by conventional hot working processes, 2) further manufactured into honeycomb core, and 3) subsequently joined to fabricate MTPS panels. However, processing of superalloys, let alone PGM-modified superalloys into the desired thin gages can be challenging. At present, most of the experience with PGM-modified Ni-base superalloys has been in the area of casting; relatively little has been reported on wrought processing.[21,22] Hypersonic heat exchanger applications will not be discussed in any detail but the processing, manufacturing and joining issues identified above are a consideration for this application as well. Research results to date include evaluating the hot working characteristics of and establishing the feasibility of near-conventional processes for producing sheet and foil products of an experimental PGM-modified Ni-base superalloy composition.[23]

ACKNOWLEDGMENTS

A portion of this work was conducted as part of the in-house research activities of the Metals Processing Group of the Air Force Research Laboratory's Materials and Manufacturing Directorate. The support and encouragement of the Laboratory management and the Air Force Office of Scientific Research (Dr. Ali Sayir, program manager) are gratefully acknowledged. The assistance of T. Brown, J. Brown, T. Goff, A Rosenberger and A. Pilchak in conducting the experimental work and data analysis is much appreciated. The invaluable mentoring and guidance provided by Lee Semiatin is acknowledged and always appreciated.

References :

1. Avallone, E.A., Baumeister III, T. & Sadegh A.M., eds., Standard Handbook for Mechanical Engineers, McGraw-Hill, New York, 2007, pp. 11--104-108.

2. Blosser, M.L., Development of metallic thermal protection systems for the reusable launch vehicle, NASA-TM-110296, 1996.

3. Myers, David E., Martin, Carl J., & Blosser, Max L., Parametric Weight Comparison of Current and Proposed Thermal Protections System (TPS) Concepts, AIAA Paper, 99-3459.

4. Reusable Launch Vehicle Program Fact Sheet NASA website, http://www.hq.nasa.gov/office/pao/History/x-33/rlv_facts.htm

5. Penmetsa, Ravi C., Grandhi, Ramana V. & Mark Haney, Topology Optimization for an Evolutionary Design of a Thermal Protection System, AIAA, 2006, 44 (No. 11), pp. 2663-2671.

6. Sims, C.T., Stoloff, N.S. & Hagel, W.C., Superalloys II, John Wiley and Sons, New York, 1987, pp. 301-310.

7. Ibid., pp. 368-369.

8. Gleeson, B., et al., Effects of platinum on the interdiffusion and oxidation behavior of Ni-Al-based alloys, Mater. Sci. Forum, 2004, 461-464, pp. 213-222.

9. Hayashi, S., et al., α-NiPt(Al) and phase equilibria in the Ni-Al-Pt system at 1150 ^{o}C, Acta Mater., 2005, 53, pp. 3319-3328.

10. Pan, D., et al., Evolution of a diffusion aluminide bond coat for thermal barrier coatings during thermal cycling, Acta Mater., 2003, 51(issue 8), pp. 2205-2217.

11. Taylor, M.P., et al., Creep properties of a Pt-aluminide coating, Acta Mater., 2003, 51(issue 8), pp. 3241-3252.

12. Izumi, T. & Gleeson, B., Oxidation behavior of Pt+Hf-modified γ-Ni+γ'-Ni_3Al alloys, Mater. Sci. Forum, 2006, 522-523, pp. 221-228.

13. Hayashi, S., Narita, T. & Gleeson, B., Early-stage oxidation behavior of γ'- Ni_3Al-based alloys with and without Pt addition, Mater. Sci. Forum, 2006, 522-523, pp. 229-238.

14. Tatlock, G.J., Hurd, T.J. & Punni, J.S., High temperature degradation of nickel-based alloys, Platinum Metals Rev., 1987, 31, pp. 26-31.

15. Coupland, D. R., Corti, C.W. & Selman, G.L., The PGM concept: Enhanced corrosion resistant superalloys for industrial and aerospace applications, Proceedings of the Pettern Intl Conf. on the Behaviour of High Temperature Alloys in Aggressive Environments, 1979.

16. Corti, C.W., Coupland, D. R. & Selman, G.L., Platinum-enriched superalloys-Enhanced oxidation and corrosion resistance for industrial and aerospace applications, Platinum Metals Rev., 1980, 24, pp. 2-11.

17. Coupland, D.R., Hall, C.W. & McGill, I.R., Platinum-enriched superalloys-A developmental alloy for use in industrial and marine gas turbine environments, Platinum Metals Rev., 1982, 26, pp. 146-157.

18. Murakami, H., et al., Distribution of platinum group metals in Ni-base single-crystal superalloys, Superalloys, 2000, pp. 747-756.

19. Heidloff, A.J., et al., Structural stability of platinum-group-metal-modified $\gamma + \gamma$'Ni-base alloys, Metall. Mater. Trans. A, 2009, 40A, pp. 1529-1540.

20. Johnson Matthey website, http://www.platinum.matthey.com

21. Borodians'ka, H., et al., Fabrication of thin foils of binary Ni-Al γ/γ' two-phase alloys by cold rolling, Intermetallics, 2002, 10, pp. 255-262.

22. Chang, H. & Baker, I., Isothermal annealling of cold-rolled high-purity nickel, Mater. Sci. Eng. A, 2008, 476, pp. 46-59.

23. Ballard, D. L., et al., Hot Working of Platinum Group Metal-Modified Ni-Base Superalloys for Thermal Protection System Applications, J. European Ceramic Society, in review.

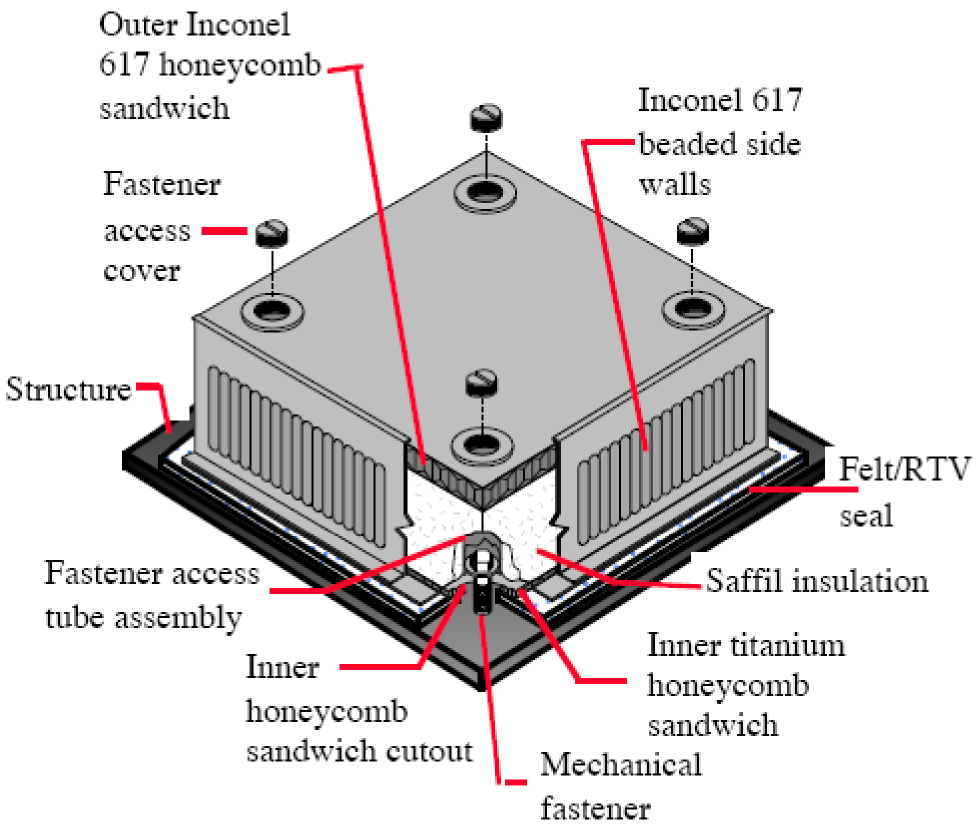
Outer Inconel
617 honeycomb
sandwich
Inconel 617
beaded side
walls
Fastener
access
cover
Structure
Felt/RTV
seal
Fastener access
tube assembly
Saffil insulation
Inner titanium
honeycomb
sandwich
Inner
honeycomb
sandwich cutout
Mechanical
fastener

Figure 1.

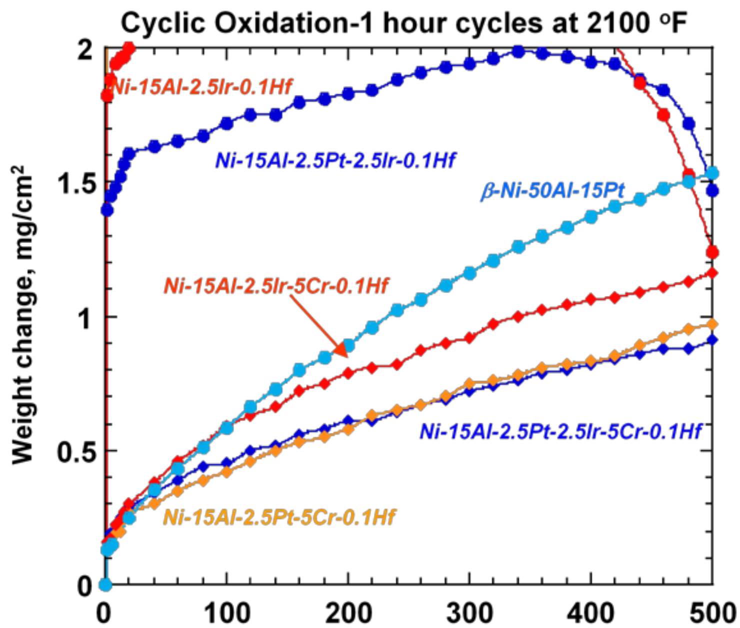

Figure 2. Oxidation performance of β-NiAl(Pt), PGM-modified Ni-base superalloys and commercial Ni-base superalloys. This is a representative figure. Candidate alloys and commercial alloys will be added to final figure.

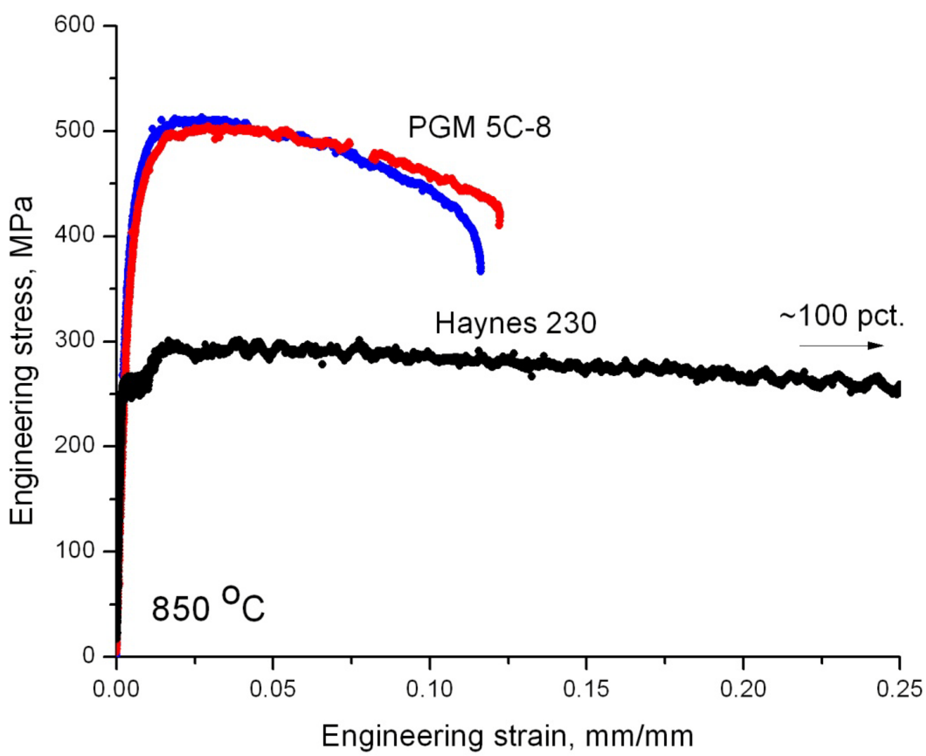

Figure 3. Tensile property comparison at 850 °C of candidate materials to commercial Ni-base superalloys. These are representative curves. Will add commercial alloys to final figure.

Table 1. Atomic Percent

Heat Number	Ni	Cr	Al	Hf	C	B	Zr	Pt	Ir
Pt-modified β	35.0		50.0					15.0	
5A	79.4	5.0	15.0	0.30	0.25	0.04	0.04		
5B	74.4	5.0	15.0	0.30	0.25	0.04	0.04	5.0	
5C	74.4	5.0	15.0	0.30	0.25	0.04	0.04	3.0	2.0
8A	75.6	5.0	15.0	0.15	0.12	0.08	0.03	2.0	2.0
10A	75.6	5.0	15.0	0.15	0.12	0.08	0.03	2.0	2.0
10B	79.6	5.0	15.0	0.15	0.12	0.08	0.03		
10C	74.4	5.0	15.0	0.30	0.25	0.04	0.04	3.0	2.0
10D	79.4	5.0	15.0	0.30	0.25	0.04	0.04		
10E	75.6	5.0	15.0	0.10	0.12	0.08	0.03	2.0	2.0