MECHANICAL PROPERTIES OF Cu-Cr-Nb ALLOYS*

DAVID L. ELLIS

Case Western Reserve University / NASA Lewis Research Center
Cleveland, OH

Introduction

The Cu-Cr-Nb alloys were originally developed under the Earth-To-Orbit program for the Orbital Transfer Vehicle (OTV). The planned use was the combustion chamber of the regeneratively cooled rocket engine. The primary materials properties of interest were the elevated temperature tensile and creep strengths, low cycle fatigue (LCF) lives, and thermal conductivities. The currently used alloy NARloy-Z (Cu-3 wt.% Ag-0.5 wt.% Zr) was used as the standard for comparison for the new alloys.

The Cu-Cr-Nb alloys are strengthened by the high melting point intermetallic compound Cr_2Nb. The density of this phase is lower than Cu, so as the alloying levels are increased the density of the alloy decreases (Figure 7). At the higher alloying level tested, Cu-8 at.% Cr-4 at.% Nb (Cu-8 Cr-4 Nb) has a 4.1% lower density than NARloy-Z.

The objective of the current work is to expand the developmental work conducted previously to develop a database suitable for the initial design of a hypersonic vehicle heat exchanger. Experimental work was concentrated on the tensile strength, creep lives, LCF lives and thermal conductivities. The mechanical properties will be presented in this paper. Thermal conductivities have been previously reported (1).

Experimental Procedure

All Cu-Cr-Nb samples were made from conventionally Ar gas atomized powder produced by the Special Metals Corporation. The powder was canned in 5.08 cm (2") O.D. mild steel extrusion cans. The cans were extruded at 857°C (1575°F) using a round die with a 16:1 reduction in area.

Samples were machined from the extruded bars. For tensile and creep samples, a subsize design conforming to ASTM Standard E 8 (2) were used. The elevated temperature tensile tests were conducted in vacuum using a nominal strain rate of 1.1×10^{-4}/sec. Creep tests were conducted in vacuum using a constant load creep frame. Creep testing also was conducted on NARloy-Z samples for direct comparison to the Cu-Cr-Nb alloys.

Fully reversed, strain controlled LCF tests were conducted at room temperature, 538°C (1000°F) and 650°C (1200°F). A triangular waveform with a constant strain rate of 0.002/s was used. For the elevated temperature LCF tests, an inductively heated graphite susceptor was placed around the sample to provide heating. Oxidation was minimized by flowing Ar over the sample.

Results And Discussion

The chemical compositions of the alloys are listed in Figure 5. The alloying levels were near the values for stochiometric Cr_2Nb. A slight excess of Cr was chosen for increased hydrogen embrittlement resistance (3). The microstructures of all Cu-Cr-Nb alloys were very similar. Two typical transmission electron microscope (TEM) micrographs are presented in Figure 6. The images show the presence of large amounts of Cr_2Nb precipitates in a nearly pure Cu matrix. The interactions between dislocations and precipitates are currently under investigations, but as the images demonstrates, the extremely fine (<15 nm) Cr_2Nb are the primary strengtheners for the alloys.

---

* Work funded under NASA Grant NCC 3-463

The tensile strength of the alloys are presented in Figure 8. The values for NARloy-Z are the minimum design values reported by Rocketdyne (4). The average values are between 5% and 10% higher. Work is currently underway to tensile test NARloy-Z samples for direct comparisons. The results show clearly that the Cu-Cr-Nb alloys have a significant advantage in yield strength at all temperatures tested. In particular, the Cu-Cr-Nb alloys have approximately twice the elevated temperature strength of NARloy-Z above 400°C. An alternative way of looking at the results is the Cu-Cr-Nb alloys maintain their yield strengths to a much higher temperature than NARloy-Z. To a lesser extent, Cu-Cr-Nb alloys have a higher ultimate tensile strength (UTS) than NARloy-Z.

Three typical creep curves are presented in Figure 9. The stress for NARloy-Z had to be decreased to achieve comparable creep lives at the test temperatures. Figure 10 compares the creep lives for Cu-8 Cr-4 Nb and NARloy-Z. For simplicity, the lives of Cu-4 Cr-2 Nb are not shown, but they were approximately half that of Cu-8 Cr-4 Nb samples. In all cases, the Cu-Cr-Nb alloys have a much greater life and stress capability. It is particularly interesting to note that the creep life of Cu-8 Cr-4 Nb tested at 800°C is nearly identical to NARloy-Z at 650°C. This again indicates the possibility for increased operating temperatures and/or stresses with the Cu-Cr-Nb alloys.

A typical set of Cu-8 Cr-4 Nb LCF loops are presented in Figure 11. Cu-8 Cr-4 Nb exhibits some strain hardening, but not as much as many other alloys. The LCF lives of Cu-8 Cr-4 Nb and NARloy-Z are presented in Figure 12. At room temperature, Cu-8 Cr-4 Nb is equal to NARloy-Z at 2% total strain, the worst case, even though it has a lower ductility. At lower total strains, Cu-8 Cr-4 Nb lives were approximately 50% greater than NARloy-Z. The results for elevated temperature LCF testing showed that the Cu-8 Cr-4 Nb samples had lives 50% to 200% greater than NARloy-Z at 538°C. The results from testing at 650°C showed little difference from the 538°C tests. This again indicates the possibility of increased temperature capability over NARloy-Z.

Summary And Conclusions

The Cu-Cr-Nb alloys have significantly higher strengths than NARloy-Z at all temperatures tested. Usable strengths were retained up to approximately 700°C (1300°F). The creep properties of the Cu-Cr-Nb alloys were also greatly improved over NARloy-Z. The lives at a given stress were increased by up to 2-3 orders of magnitude with the largest increases occurring at the higher temperatures. Alternatively, the Cu-Cr-Nb alloys were capable of supporting a stress 10% to 50% greater than NARloy-Z for a given life. LCF testing showed Cu-8 Cr-4 Nb was equal to or better than NARloy-Z at room temperature. At elevated temperatures, the Cu-8 Cr-4 Nb was clearly superior to NARloy-Z and did not have any significant change in LCF between 538°C and 650°C.

Taken in total, the results indicate the possibility of trade-offs of temperature and stresses that could greatly increase the operating parameters of hypersonic vehicle heat exchangers.

Future Work

Future work will focus on completing the tensile testing of NARloy-Z to provide a direct comparison to the Cu-Cr-Nb data. In addition, research will examine the oxidation behavior of the Cu-Cr-Nb alloys in air and two potential engine environments. Since the fabrication of heat exchangers may require a sheet product, several tests will be conducted to determine a suitable rolling schedule and heat treatments.

Acknowledgment

The author would like to thank Michael Verrilli of the Structures and Acoustics Division of NASA Lewis Research Center for performing the LCF testing on the Cu-8 Cr-4 Nb alloy. The author would also like to acknowledge the help of Ron Phillips and Sharon Thomas of Gilcrest in conducting the tensile testing and Don Ulmer of Rocketdyne for providing the NARloy-Z.

References

(1) D.L. Ellis and G.M. Michal, "Mechanical and Thermal Properties of Two Cu-Cr-Nb Alloys and NARloy-Z," NASA CR-198529, NASA Lewis Research Center, Cleveland, OH (Oct. 1996)

(2) *1992 Annual Book of ASTM Standards, Vol. 03.01*, ASTM, Philadelphia, PA, (1992), pp. 130-149

(3) D.L. Ellis, A.K. Misra and R.L. Dreshfield, "Effect of Hydrogen on Cr2Nb and Cu-Cr-Nb Alloys," Hydrogen Effects On Materials Behavior, Proc. Of Fifth Intl. Conf., Moran, WY (Sept. 1994)

(4) Materials Properties Manual, 4th Ed., Rockwell International, Rocketdyne Div., (Oct. 30, 1987)

Background

- Originally developed for Orbital Transfer Vehicle (OTV) under Earth-To-Orbit (ETO) program
- Alloys designed to meet needs of combustion chamber liner
  - High elevated temperature strength and creep resistance
  - Long low cycle fatigue (LCF) life
  - High thermal conductivity
  - Properties that meet or exceed those of currently used NARloy-Z (Cu-3 Ag-0.5 Zr)

Fig. 1

Program Objectives

- Quantify tensile, creep and thermal conductivity at a level suitable for initial design work on hypersonic aircraft combustors and rocket combustion chamber liners

Fig. 2

Experimental Procedure

Production of Cu-Cr-Nb Alloys

- Conventionally atomized powders produced by Special Metals
- Extruded at 870°C (1575°F)
- 16:1 reduction in area
- Full consolidation achieved

Tensile Testing

- Subsized tensile specimens
- Vacuum testing
- Strain rate = 0.00011/sec

Fig. 3

Experimental Procedure (Cont.)

Creep Testing

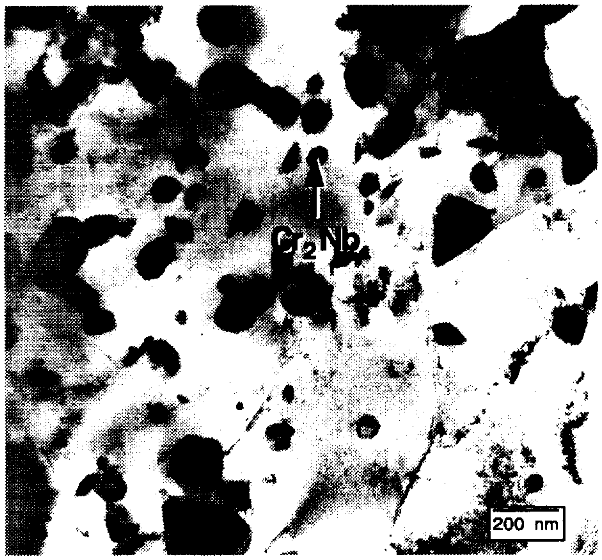
- Vacuum testing
- Constant load
- Displacement recorded by computer DAQ unit

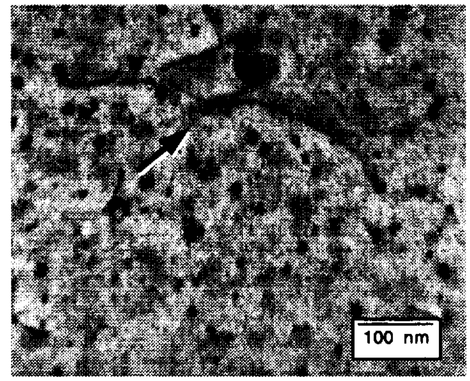
LCF Testing

- Only Cu-8 Cr-4 Nb alloy tested
- Strain controlled
- Fully reversed
- Triangular waveform
- Constant strain rate = 0.002/s

Fig. 4

Microstructure Of Cu-Cr-Nb Alloys





Arrow indicates two precipitates pinning dislocation

- Cr and Nb form a very high melting point intermetallic compound, Cr_2Nb
- Matrix is nearly pure Cu

Fig. 5

Alloy Chemistries

Alloy	Ag	Cr	Cu	Nb	O*	Zr	Cr:Nb
Cu-4 Cr-2 Nb - Powder†		3.27	Bal.	2.92	251		2.00
Cu-4 Cr-2 Nb		3.8	Bal.	3.6	N.A.		1.89
Cu-8 Cr-4 Nb - Powder†		6.45	Bal.	5.49	455		2.10
Cu-8 Cr-4 Nb		6.5	Bal.	5.5	640		2.11
NARloy-Z	3.0		Bal.		N.A.	0.5	

All chemistries in weight percent
*O is in ppm by weight
†Chemistry supplied by Special Metals
N.A. - Not available

- Alloy designations reflect amount of Cr and Nb in atomic percent
  - Cu-4 Cr-2 Nb = Cu-4 at.% Cr-2 at.% Nb

Fig. 6

Comparison Of Densities

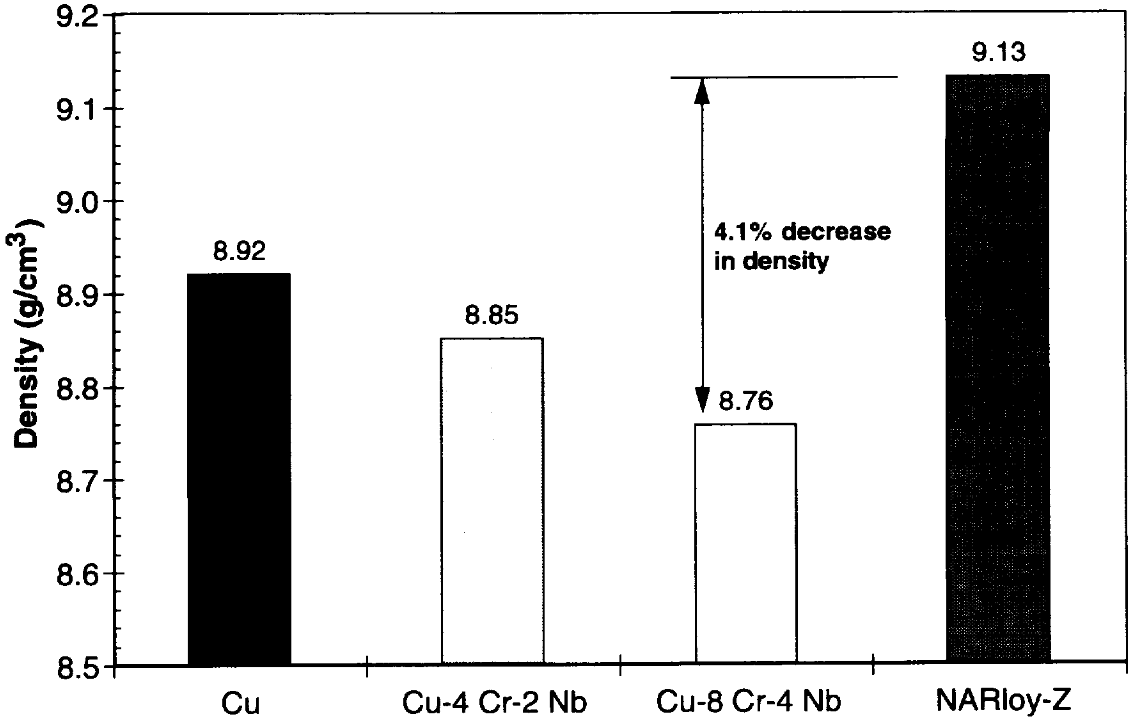
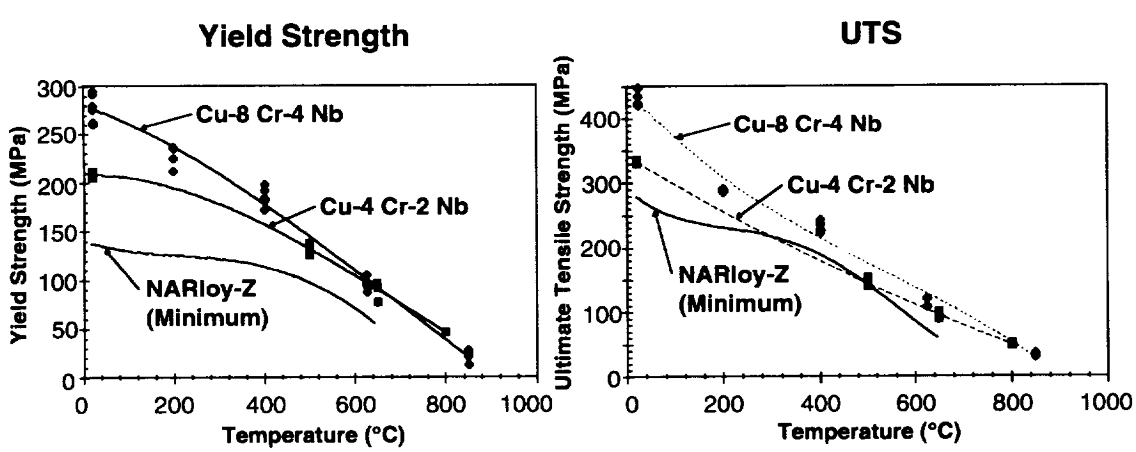


Fig. 7

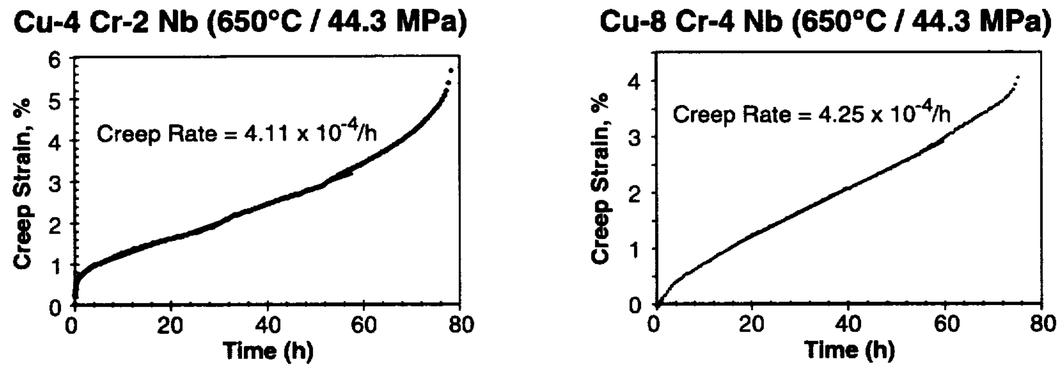
Elevated Temperature Tensile Strength

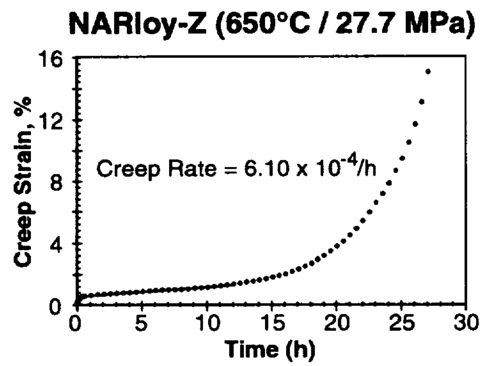


- Cu-Cr-Nb alloys have yield strengths approximately 1.5 - 2X higher than NARloy-Z
- Cu-8 Cr-4 Nb has a superior UTS compared to NARloy-Z
  - Cu-4 Cr-2 Nb has equal or better UTS than NARloy-Z

Fig. 8

Typical Creep Curves

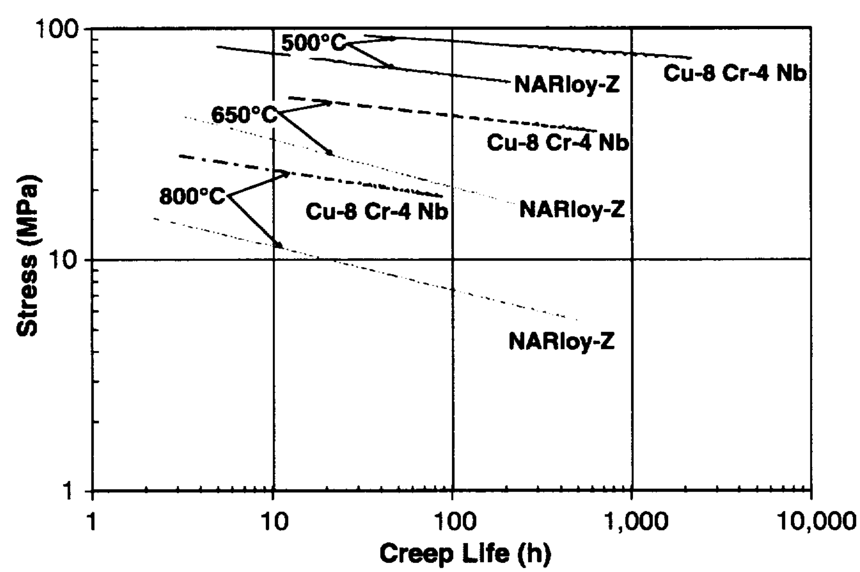




- Cu-Cr-Nb alloys spend the majority of their lives in Second Stage creep
- NARloy-Z can spend a significant portion of its life in Third Stage creep
- Cu-Cr-Nb creep elongations are generally lower than those of NARloy-Z

Fig. 9

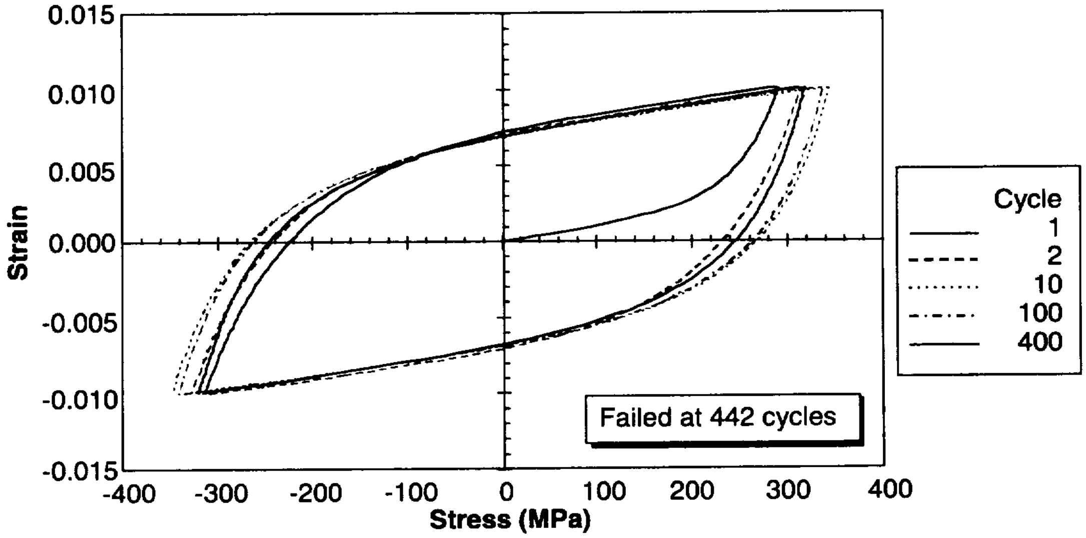
Comparison Of Cu-Cr-Nb And NARloy-Z Creep Lives



- Cu-4 Cr-2 Nb lives are approximately half that of Cu-8 Cr-4 Nb
- For a given life, Cu-8 Cr-4 Nb can support 20%+ higher stresses
- For a given stress, Cu-8 Cr-4 Nb alloy has lives 2 to 3 orders of magnitude longer than NARloy-Z

Fig. 10

Typical Cu-8 Cr-4 Nb LCF Loops

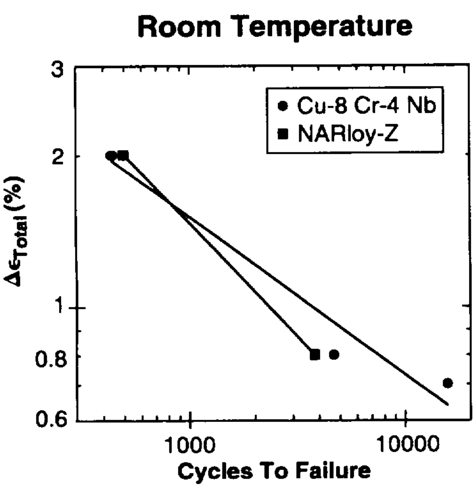


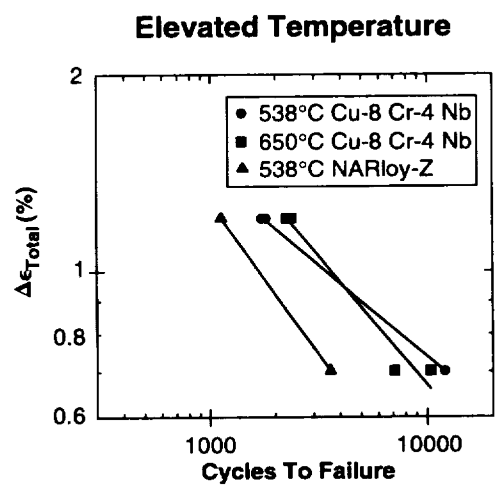
Room Temperature (Sample 1-1)

- Some strain hardening of Cu-8 Cr-4 Nb occurs
  - Not as much as Cu
- Consistent behavior up to failure

Fig. 11

Low Cycle Fatigue Lives





- Cu-8 Cr-4 Nb at least as good as NARloy-Z at room temperature
- Cu-8 Cr-4 Nb has 50% to 200% greater LCF life at 538°C (1000°F) than NARloy-Z
  - No significant difference between 538°C and 650°C (1202°F) Cu-8 Cr-4 Nb LCF lives

Fig. 12

Summary

- Cu-Cr-Nb alloys have much higher yield strengths than NARloy-Z
- Cu-Cr-Nb alloys have greatly increased creep capabilities
  - 20% or greater increase in stress for a given life
  - 2 to 3 order-of-magnitude increase in life for a given stress
- Cu-Cr-Nb alloys have better LCF capabilities
  - Elevated temperature LCF properties are significantly better than NARloy-Z
- Thermal conductivity data set available in NASA CR-198529

Fig. 13

Conclusions

- Cu-Cr-Nb alloys are attractive replacements for NARloy-Z in elevated temperature, high flux applications
- Cu-Cr-Nb alloys offer considerable potential for hypersonic aircraft heat exchangers

Fig. 14

Future Work

- Complete NARloy-Z tensile testing
- Perform microscopy on LCF samples
- Determine strengthening mechanism(s) by further TEM analysis
- Examine oxidation resistance of Cu-Cr-Nb alloys
  - Air
  - Water saturated air
  - Possible mixed $O_2/H_2/H_2O/CO/CO_2$ environment representative of hydrocarbon fueled engine
- Determine suitable rolling schedule and heat treatments to produce Cu-Cr-Nb sheet

Fig. 15