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Conventionally Cast and Forged Copper Alloy for High-Heat-Flux Thrust Chambers

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Scientific and Technical
Information Branch

Summary

The combustion chamber liner of the space shuttle main engine is made of NARloy-Z, a copper-silver-zirconium alloy. This alloy was produced by vacuum melting and vacuum centrifugally casting—a production method that is currently not available. Using conventional melting, casting, and forging methods, NASA has produced an alloy of the same composition called NASA-Z. This report compares the composition, microstructure, tensile properties, low-cycle fatigue life, and hot-firing life of these two materials. The results show that the materials have similar characteristics.

Introduction

To survive in the high-temperature, high-pressure environment of today's rocket engines, the combustion-chamber hot-gas wall must be fabricated from a high thermo-conductivity material and must be actively cooled. The space shuttle main engine (SSME) is typical of state-of-the-art liquid-propellant-cooled combustion chambers. The alloy used to fabricate the SSME combustion chamber is NARloy-Z, a proprietary copper-silver-zirconium alloy developed by the Rocketdyne division of North American Rockwell Corporation.

The SSME combustion chamber is a milled channel design in which coolant channels are machined into the outside surface of the chamber liner. Then these channels are closed out by electroforming to form coolant passages. This combustion chamber design and material combination is capable of withstanding a throat heat flux of the order of 163 MW/m^2 (100 Btu/in.^{2}-sec). The cyclic life of NARloy-Z is as good as or better than that of any other copper alloy tested to date.

NARloy-Z is made by vacuum melting oxygen-free, high-conductivity (OFHC) copper with additions of silver and zirconium. The melt is vacuum centrifugally cast into cylinders. The cylinders are hot spun forged to shape and rough machined before heat treating. They are then machined into thrust chamber liners.

Production of this material is a proprietary process and was not readily available because the original vendor who produced the billets had dismantled the entire melting and casting equipment. Reestablishment of this capability would be very expensive. The original production run produced only the cast cylinders, plus a few spares, that were required by the SSME program. As a result, NASA Lewis Research Center initiated a program to develop a high-conductivity copper alloy for its own use in fabricating thrust-chamber test hardware for research. Since the NARloy-Z material had good heat transfer and good low-cycle fatigue life, a decision was made to produce an alloy of typically the same composition as NARloy-Z, by using conventional casting methods. This report discusses the production of such an alloy, NASA-Z, which has nearly the same composition as NARloy-Z but is produced without the special vacuum melting and casting equipment. This report compares each material's mechanical and low-cycle fatigue properties, chemical content, and metallurgical structure. It also compares each material's cylindrical thrust chamber life obtained from hot-firing tests.

Background

Because of NASA's need for high-temperature, high-pressure, reusable thrust chambers for numerous advanced rocket engines, the Lewis Research Center undertook a program to find a suitable material for these chambers. Early analysis showed that high pressures resulted in extreme heat fluxes of the order of 114 to 163 MW/m^2 (70 to 100 Btu/in.^{2}-sec). To reduce chamber wall temperatures, chambers would have to be cooled regeneratively and be made from a high-conductivity material such as copper. In addition, the analyses showed that at these conditions the chamber wall, especially at its throat area, would have to resist very large thermal strains.

For similar reasons, Rocketdyne developed an alloy based on their early work on NARloy-A, a cast copper-silver alloy. This new chamber alloy, which was called NARloy-Z, contained (by weight) 96.5 percent copper, 3 percent silver, and 0.5 percent zirconium. This material was their choice for the SSME thrust chamber liner.

Lewis began its chamber materials program with a survey of high-conductivity alloys. It selected those that had the best known combination of tensile and fatigue properties as well as high thermal conductivity. The selected alloys were tested for their tensile and low-cycle fatigue (LCF) properties and were compared (refs. 1 to 3). During this time, several OFHC-copper contoured thrust chambers were designed and built for cyclic hot testing in the engine test facility to determine chamber wall temperature profiles, cyclic life, and failure mechanisms under actual high-heat-flux, high-pressure, and cryogenic-cooling engine conditions (refs. 4 and 5).

For the chamber materials testing program, Rocketdyne supplied samples of their material, NARloy-Z, to be included in the LCF properties comparisons. This testing was performed for NASA by Mar Test, Inc. (refs. 1 to 3). The comparisons showed that AMAX's Amzirc[1] (Cu, 0.15 percent Zr) and Rocketdyne's NARloy-Z had the overall best combination of properties and LCF lives at 538 °C (1000 °F) and that Amzirc had a slightly longer LCF life. However, Amzirc continually work softened as it was cycled, whereas NARloy-Z initially work hardened. Subsequently, these alloys and others which showed life potential were fabricated into subscale liquid-hydrogen-cooled cylindrical test chambers. The cylindrical chamber was selected for testing because it duplicated actual thrust chamber conditions at much reduced costs over the contoured test chamber reported in reference 4. This allowed repetitive tests for each liner alloy. These tests indicated that NARloy-Z had the longest and most uniform cycle life under the more realistic thrust chamber conditions. Consequently, Lewis desired to continue future thrust chamber R&D programs using the NARloy-Z alloy or an equivalent.

Apparatus and Procedure

Melting and Casting

The NASA-Z alloy was produced by AMAX at their base metals research facility. Approximately 1000 kg (2200 lb) of OFHC copper were placed in a machined graphite crucible and induction heated. The crucible was protected with an argon gas cover. When 1300 °C (2370 °F) was reached, silver shot was added to the crucible. At 1350 °C (2460 °F) zirconium chips made from sheet material were added. The melt was then immediately poured in an argon-protected tundish which emptied into a 20-cm- (8-in.-) diameter water-cooled die.

Forging Equipment

The castings were cut into 61-cm- (24-in.-) long billets. Then, the forger cut them in half and placed them in a natural gas-fired brick-lined furnace for heating to forging temperature. The cut billets were forged with a 1136-kg (2500-lb) steam-driven hammer.

Material Testing

To obtain tensile and fatigue properties of the material, a portion of the forgings were machined into hourglass-shaped specimens as shown in figure 1. A servo-controlled, hydraulically activated fatigue testing machine was used for all of the material tests. The machine had a programmer, a load cell, a diametrical strain extensometer, a linear variable displacement transducer, and an analog strain computer. References 1 to 3 contain more detailed descriptions of the test equipment and procedures.

[1]Alloy trade name of AMAX, Inc.

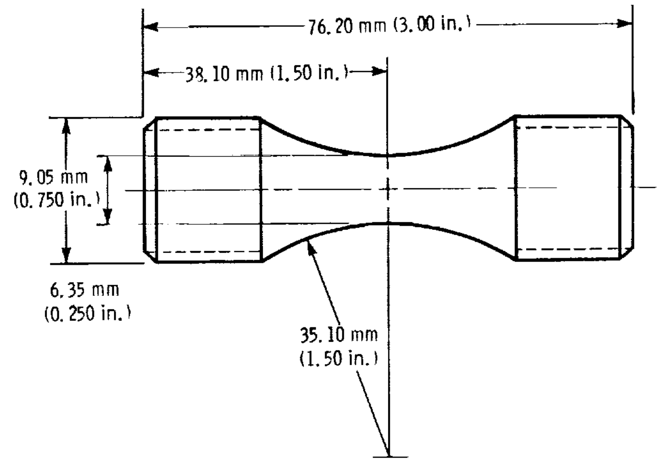


Figure 1.—Low-cycle-fatigue hourglass specimen design.

Rocket Test Facility

Lewis's rocket engine test facility was used for all the cylindrical chamber tests to obtain cyclic life data for the material under actual hot-fire conditions. This facility is a 222 410 N (50 000 lbf) sea-level test stand which has pressurized propellant storage tanks to supply the propellants to the thrust chamber. Reference 6 contains more detailed descriptions of the cylindrical thrust chamber design, test procedure, instrumentation, and facility used for the cyclic testing.

Cylindrical Thrust Chambers

Figure 2 shows a schematic of the cylindrical thrust chamber assembly used for cyclic hot-fire testing. Figure 3 is a photograph of a longitudinally cut section of the chamber mounted on its injector-manifold body. The propellants, gaseous hydrogen and liquid oxygen, are fed through the annular

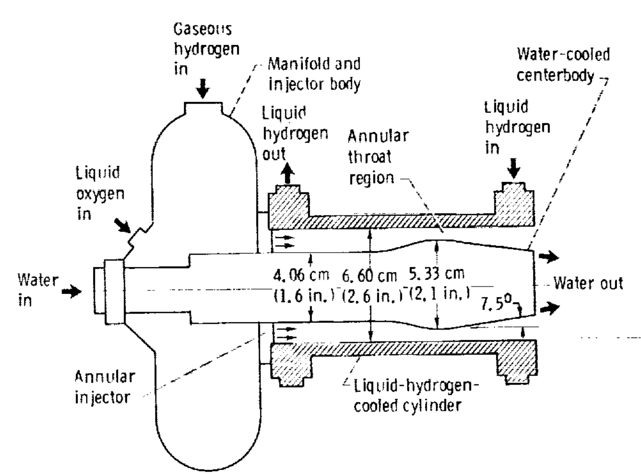


Figure 2.—Schematic of cylindrical thrust chamber assembly.

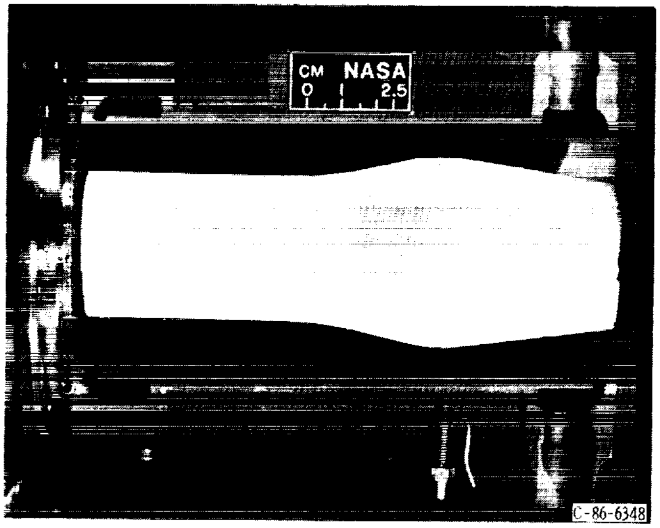
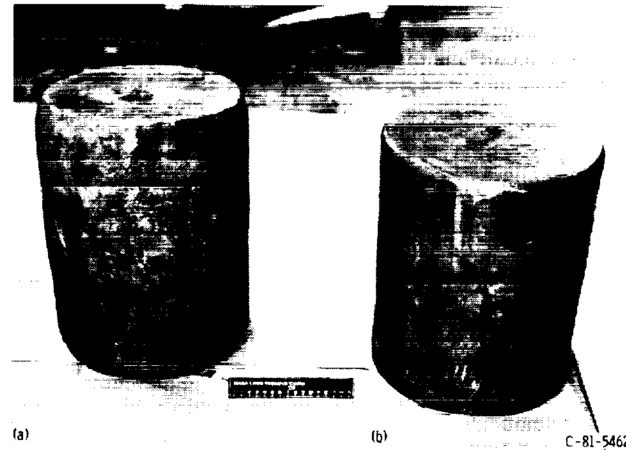


Figure 3.—Longitudinally cut cylindrical thrust chamber mounted on injector with centerbody.



(a) Temperature dropped below 760 °C during forging.
(b) Temperature maintained above 760 °C during forging.

Figure 4.—Properly and improperly forged billets.

injector. Inside the thrust chamber is the water-cooled centerbody that forms the annular thrust chamber throat. The cylindrical thrust chamber was separately cooled with liquid hydrogen.

Discussion of Results

Conventional Castings and Forging

AMAX was selected to produce NASA-Z using state-of-the-art fabrication methods. They had previously made special copper-base alloys for NASA and knew the importance of using oxygen-free clean material for the thrust chamber liners. Since this was a special order, AMAX produced NASA-Z in their research melting and castings facility. They melted OFHC copper, made the necessary additions of silver and zirconium, and cast the alloy in an argon atmosphere. The cast billets were rough machined to 20 cm (8 in.) diameter by 61 cm (24 in.) long and then shipped to Lewis for inspection and sampling.

The billets were then sent to another fabricator to be hot worked into fine-grained homogeneous forgings. The NASA-Z alloy forged very similarly to the copper-zirconium system alloys. The material was crack sensitive until the as-cast grain structure was broken up and refined. The forging temperature range was very critical. The billet shown in figure 4(a) was allowed to cool below 760 °C (1400 °F) while forging and, as seen, it cracked during the forging process. The billet in figure 4(b) was forged successfully by maintaining its temperature above 760 °C (1400 °F) while being worked. The billet was heated to 954 °C (1750 °F) and the material was lightly worked to begin the breakup of the as-cast structure. When the temperature reached 1450 °F the billet was reheated to 788 °C (1750 °F) before further hammering. The hammer load was progressively increased until the billet was heavily upset and worked throughout. After forging, the billet was given another 954 °C (1750 °F) heat cycle and allowed to air cool. At this point, the end of the billet was sliced off and inspected to ensure the proper grain structure had been achieved. Figure 5 shows a typical end slice that has a very fine structure that is uniform throughout with no significant flaws. The forged billet was then rough machined into the shape of a cylindrical thrust chamber and given the same heat treatment as NARloy-Z. This heat treatment consisted of a solution anneal at 954 ± 14 °C (1750 ± 25 °F) for 1 hr followed by a rapid water quench (maximum 30 sec from furnace removal to quench). The material was then aged at 510 ± 6 °C (950 ± 10 °F) for 2 hr and allowed to air-cool. The composition, structure, and properties of the two materials are compared and discussed in the following sections.

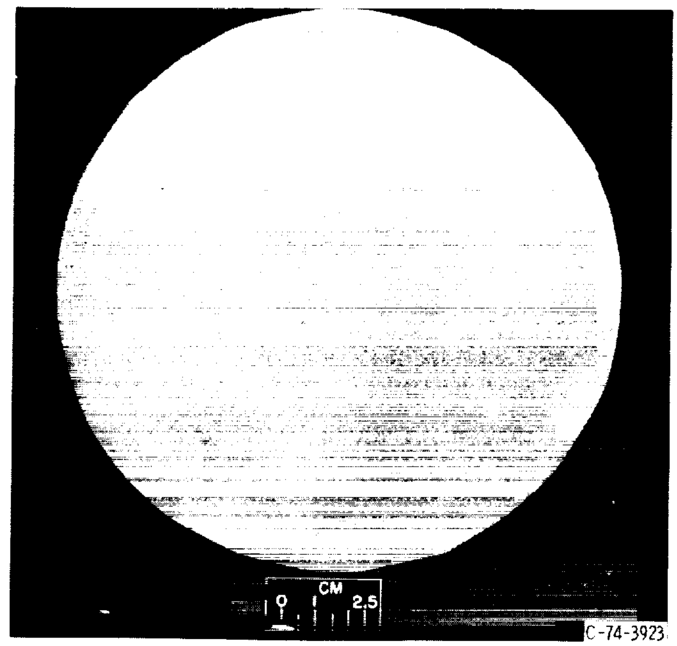


Figure 5.—Structure of billet after forging.

Composition Comparison

The compositions of NARloy-Z and NASA-Z reported by Rocketdyne and AMAX are shown in table I. The desired composition of the alloys is 96.5 wt % copper, 3 wt % silver, 0.5 wt % zirconium. As shown in table I, it appears that the NASA-Z alloy has a higher zirconium content than NARloy-Z. However, it should be noted that all the NARloy-Z analyses were conducted on samples that were taken from worked and heat-treated material while the NASA-Z analyses reported by AMAX were conducted on samples taken at the time the castings were produced. The NASA-Z as-cast materials appear to have been less homogenous than the worked and heat-treated NARloy-Z materials. Taking this into consideration with the fact that the materials had different production methods and periods, one can expect some composition variations. However, samples taken from the completed cylindrical thrust chamber which were subjected to spectrographic and gas fusion analyses showed that both materials are similar in alloy content and are low in interstitials or stray elements. The results of these analyses are also presented in table I.

TABLE I.—COMPARISON OF CHEMICAL CONTENT OF SAMPLES OF NARloy-Z AND NASA-Z

(a) Chemical analyses

Element	Composition, wt %	
	NARloy-Z[a]	NASA-Z[b]
Copper	96.79	96.68
Silver	2.80	2.72
Zirconium	.41	.60

[a]Rocketdyne alloy: 1976 chamber material analysis.
[b]NASA alloy: 1983 casting; AMAX analysis.

(b) Spectrographic and gas fusion analyses of samples taken from tested chambers

Element	Composition, wt %	
	NARloy-Z[a]	NASA-Z[b]
Copper	96.6	96.6
Silver	2.8	2.8
Zirconium	.4	.4
Carbon	[c]9	[c]44
Chromium	[c]10	[c]10
Iron	[c]110	[c]60
Manganese	[c]270	[c].1
Nitrogen	[c]2	[c]2
Oxygen	[c]7	[c]19

[a]Rocketdyne alloy: 1976 chamber material.
[b]NASA alloy: 1983 material.
[c]Trace element: composition, ppm.

Structure Comparison

For microstructural comparison, samples were taken from the walls of NARloy-Z and NASA-Z cylindrical thrust chambers. Photomicrographs of these areas at magnifications of ×50 and ×100 are shown in figure 6. Both materials have equiaxed recrystallized grains which contain annealing twins. Their grain sizes are calculated to ASTM 4. Also shown are evenly distributed particles which have been identified by microprobe analyses as silver-copper-zirconium precipitates. The structures of NASA-Z and NARloy-Z are considered to be identical.

Tensile and Low-Cycle Fatigue Properties

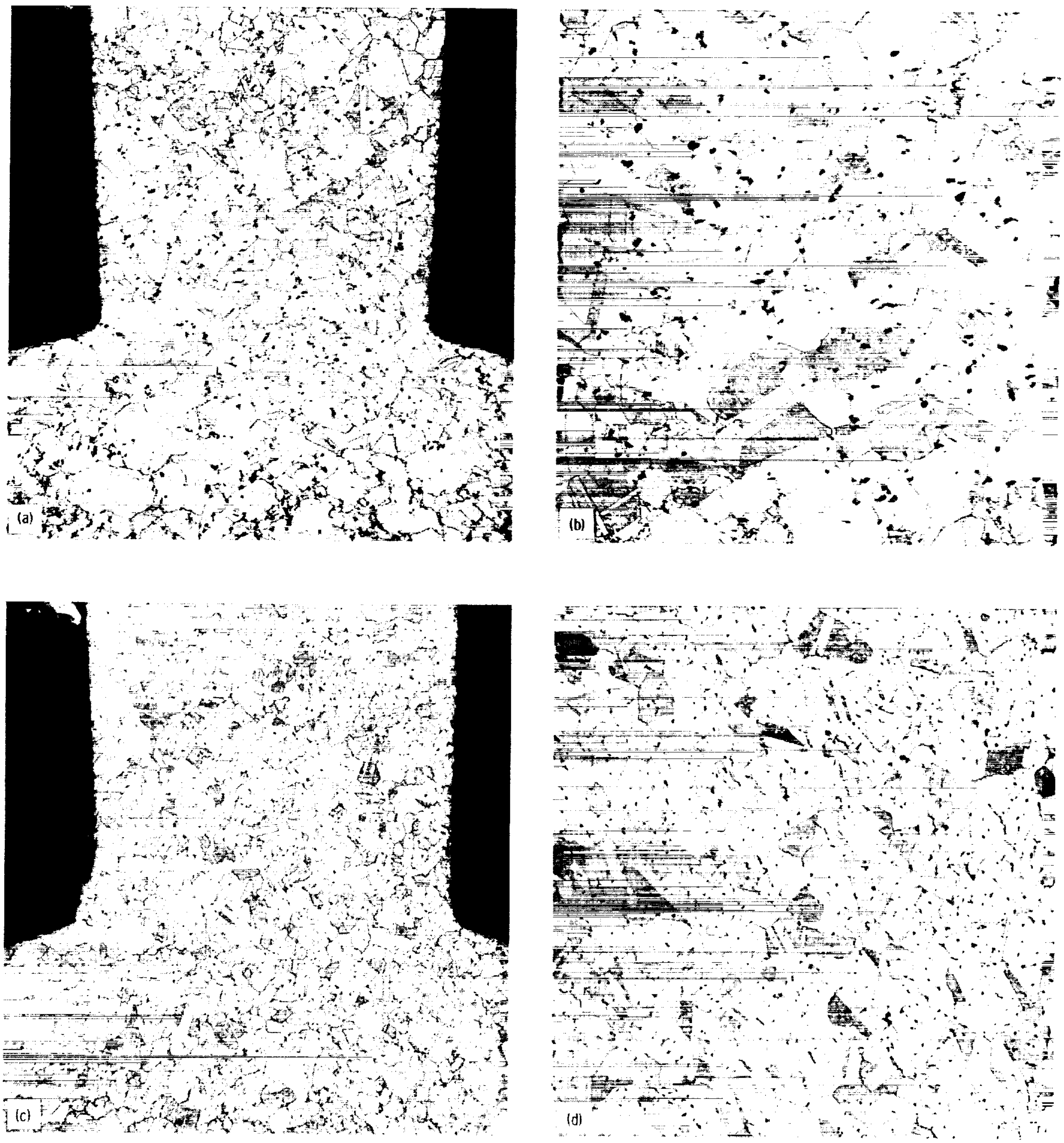
After successful casting, forging, heat treating, and comparison of the alloy's content and microstructure, the NASA-Z material was tested for its tensile properties, LCF, and cylindrical thrust chamber cyclic life. These data were to be compared directly with those for identically tested NARloy-Z. To avoid the possibility of introducing a test procedure bias on the results, the NASA-Z material was sent to Mar Test, Inc. (who had previously tested NARloy-Z and other high-conductivity copper base alloys (refs. 1 to 3)), to perform identical tensile and LCF testing. The tensile properties at room temperature and 538 °C (1000 °F) are shown in table II. The NARloy-Z data are also presented, and the data show that the NASA-Z material is slightly higher in tensile strength and slightly lower in yield strength than the NARloy-Z material. However, when the percentage differences are calculated for each property, they are within ±5 percent. This is within the normal variation from heat-to-heat for heat treatable alloys.

TABLE II.—SHORT-TERM TENSILE PROPERTIES OF NASA-Z AND NARloy-Z

[Diametral strain measurement and control; strain rate, $\dot{\epsilon}$, 2×10^{-3}/sec.]

Material	Test temperature,[a] °C	0.2 percent offset yield strength, MN/m^2	Ultimate tensile strength, MN/m^2	Reduction in area, percent
NASA-Z	Room temperature	187.0	327.3	47.6
	Room temperature	184.2	323.6	48.2
	538	127.0	160.0	54.8
	538	126.8	160.0	53.2
NARloy-Z	Room temperature	196.5	316.5	51
	Room temperature	200	315.8	51
	538	131	153	41
	538	129	152.4	42

[a]Room temperature in ambient air, 538 °C in argon.



(a) NARloy-Z; magnification, ×50. (b) NARloy-Z; magnification, ×100.
(c) NASA-Z; magnification, ×50. (d) NASA-Z; magnification, ×100.

Figure 6.—Photomicrographs of NARloy-Z and NASA-Z showing grain structure and precipitants. Samples taken from cylindrical thrust chambers in coolant channel area.

TABLE III.—LOW-CYCLE FATIGUE TEST RESULTS OBTAINED IN ARGON

[Temperature, 538 °C; strain rate, $\dot{\epsilon}$, 2×10^{-3}/sec; axial strain control, ratio of infinity; and E, 98.6×10^{3} MN/m^2.]

Material	Poisson's ratio	Total strain range, percent	Frequency, cpm	Stress range at start		Cycles to failure, N_f
				MN/m^2,	ksi	
NARloy-Z	0.345	1.0	6	272	39.4	1169
	.335	2.0	3	300	43.5	331
	.335	1.2	5	283	41.0	1126
	.34	.7	8.57	265	38.4	3601
	.34	3.5	1.714	307	44.5	99
	.34	2.5	2.4	300	43.5	253
	.34	.85	7.06	269	39.0	2469
NASA-Z	0.346	3.50	1.71	306.6	44.47	173
	.325	3.50	1.71	275.4	39.94	147
	.318	3.00	2.00	303.8	44.06	207
	.329	1.00	6.00	284.2	41.22	1582
	.310	3.00	2.00	315.7	45.79	248
	.319	1.00	6.00	275.4	39.94	2168
	.340	2.50	2.40	297.5	43.15	357
	.341	1.50	4.00	294.0	42.64	718
	.337	2.50	2.40	314.3	45.58	250
	.340	1.50	4.00	285.6	41.42	490
	.348	2.00	3.00	294.7	42.74	252
	.348	2.00	3.00	310.8	45.08	338

The LCF test data for the two materials are tabulated in table III and plotted in figure 7. The type of sample, test equipment, conditions, and variations of testing are all detailed in the referenced reports (refs. 1 to 3). The LCF test data show very close agreement in the fatigue lives especially at the lower total strain ranges (1 percent or less) and only a small divergence at the higher total strain ranges. This is considered to be normal behavior because LCF test data for similar materials showed even greater data variation at these high strains. At these strain levels, there is considerable metal movement and instability per cycle resulting in considerable differences in cyclic life.

Typical LCF test data for NARloy-Z and NASA-Z are shown in figures 8(a) and (b). These are plots of the stress range versus cycles at a total strain close to 1 percent. It should be noted that early in the testing, both materials exhibited a slight amount of strain hardening before strain softening began. This again shows the materials behave similarly.

Cylindrical Thrust Chamber Tests

Although LCF specimen testing is a good screening tool for determining relative fatigue properties, it does not accurately simulate geometry or the conditions of a rocket engine firing. Therefore, the NASA-Z material was cyclically tested in cylindrical thrust chambers until failure under test conditions identical to those reported in reference 6 for NARloy-Z and other copper-base alloy chambers. For this program, four cylindrical thrust chambers were fabricated from the NASA-Z billets produced by AMAX Corporation. These cylinders were cyclically tested to simulate the startup and shutdown thermal cycle of a typical rocket thrust chamber. Thermocouples were imbedded in the cooling channel ribs at several circumferential locations, as shown in figure 9, to allow the hot-gas wall temperature to be calculated. The cyclic test sequence consisted of a 1.65-sec hot firing followed by a 1.85-sec off period, during which the liquid hydrogen coolant flowed continuously. This allowed the hot-gas wall temperature at the throat to cycle

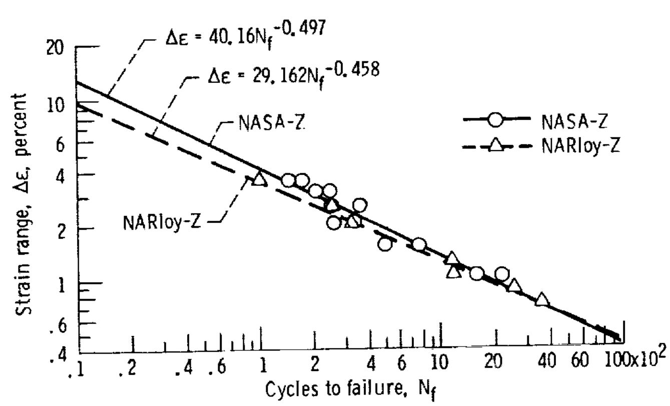
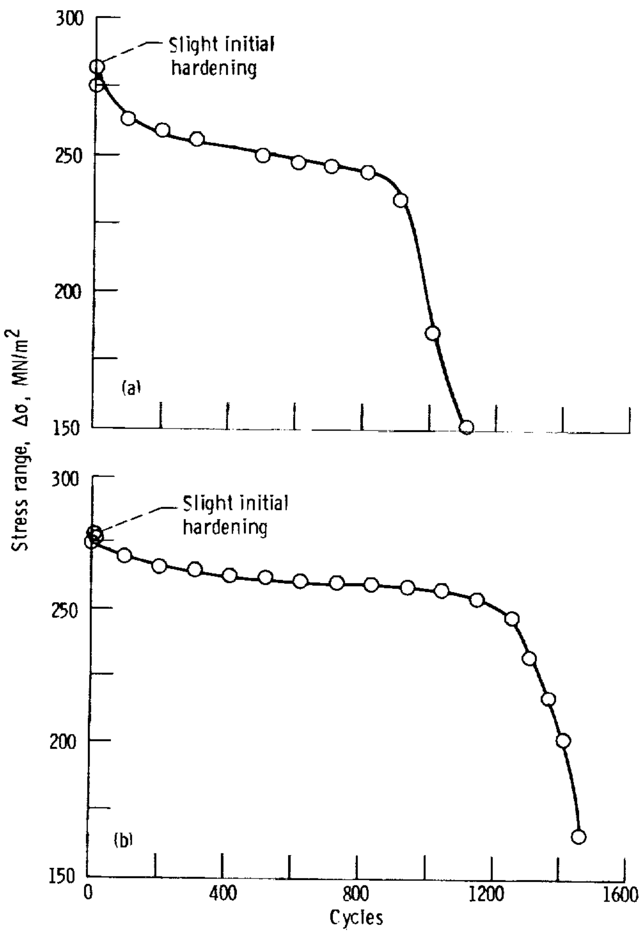


Figure 7.—Low-cycle fatigue for NASA-Z and NARloy-Z. Strain rate, $\dot{\epsilon}$, 2×10^{-3}/sec; temperature, 538 °C; atmosphere, argon.



(a) Example of cyclic strain softening in NARloy-Z alloy tested in argon at 538 °C using strain rate of 2×10^{-3}/sec. Total strain range, $\Delta\epsilon_t$, 1.2 percent; low-cycle fatigue life, N_f, 1126 cycles.
(b) Example of cyclic strain softening in NASA-Z alloy tested in argon at 538 °C using a strain rate of 2×10^{-3}/sec. Strain range, $\Delta\epsilon$, 1.0 percent; low-cycle fatigue life, N_f, 1582 cycles.

Figure 8.—Examples of cyclic strain softening.

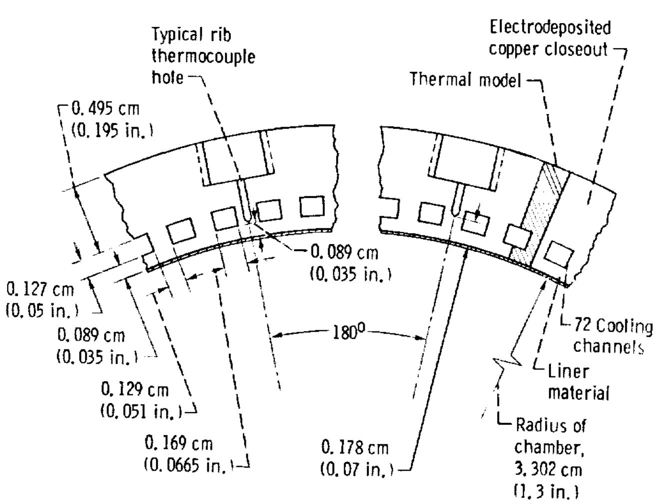


Figure 9.—Cylinder-wall cross section showing instrumentation locations and dimensions.

from approximately 28 to 780 K (50 to 1400 °R). Each test sequence consisted of 50 to 70 thermal cycles. The cyclic fatigue life of each of the four chambers was determined by subjecting the thrust chamber to these cyclic tests until a through crack developed allowing the liquid hydrogen coolant to escape into the combustion chamber. The test results are presented in figure 10. All the cyclic test results of reference 6 are also included in figure 10 so that they can be compared directly with previous chamber cyclic test results, including those of NARloy-Z. Of the four NASA-Z chamber tests, three had cyclic lives almost identical to those of the two NARloy-Z chambers. Figure 10 also shows that one NASA-Z chamber had a lower life, which could have been caused by either a hot spot on the chamber wall undetected by the thermocouples or unknown material/manufacturing flaws that were not detected prior to testing. The former is the likely answer since posttest examinations showed no prior problem areas in the material.

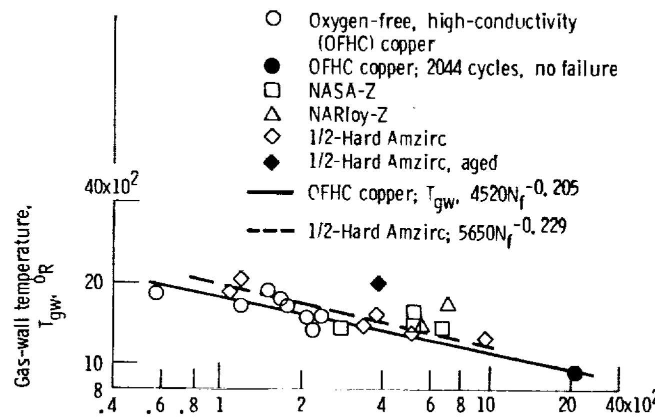


Figure 10.—Steady-state hot-gas side wall temperature versus cycles to failure for cylindrical thrust chambers. (Gas-wall temperature T_{gw} calculated from thermocouples in chamber wall.)

Concluding Remarks

This report compared two copper alloys, NARloy-Z and NASA-Z. Every item compared—composition, microstructure, tensile properties, low-cycle fatigue life, and hot-firing life—showed that these materials have similar characteristics. Therefore, NASA-Z can be substituted for NARloy-Z in thrust chamber liners.

Summary of Results

A program was undertaken to develop a material that would be readily available and which would be suitable for liners in advanced thrust chambers. The material selected was

NASA-Z, which had a composition similar to that of the space shuttle main engine thrust chamber material NARloy-Z. Both materials were analyzed, tested, and compared. The following results were obtained:

1. The compositions of NASA-Z and NARloy-Z were analyzed using chemical, spectrographic, and gas fusion analyses. These analyses showed good agreement of the alloys' contents and that both materials were low in interstitials or stray elements.

2. The microstructures of the materials were compared from samples taken from cylindrical thrust chamber liners. The grain sizes were similar, and in each the silver-copper-zirconium precipitates were well dispersed.

3. The materials were tested for their room temperature and 538 °C (1000 °F) tensile properties. There were slight variations of the properties, but the differences were so small that a prediction cannot be made on any effect that they would have on the chamber fatigue life.

4. Low-cycle fatigue tests were performed and compared. The data show very close agreement in the fatigue life, especially in the lower total strain region, and only a small divergence in the higher total strains. From these data, the materials can be considered to have the same LCF characteristics.

5. The two alloys were used to make cylindrical thrust chambers. These chambers were hot fired to determine their cycles to failure under rocket engine test conditions. The cycles to failure versus wall temperature data were compared. The NASA-Z test results compare favorably with the NARloy-Z test results.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, December 2, 1986

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15. Supplementary Notes

16. Abstract

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