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Summary

A hydrogen-oxygen subscale rocket combustion chamber was designed incorporating an advanced design concept to reduce strain and increase life. The design permits unrestrained thermal expansion in a circumferential direction and, thereby, provides structural compliance during the thermal cycling of hot-fire testing. The chamber was built and test fired at a chamber pressure of 4137 kN/m^2 (600 psia) and a hydrogen-oxygen mixture ratio of 6.0. Compared with a conventional milled-channel configuration, the new structurally compliant chamber had a 134 or 287 percent increase in fatigue life, depending on the life predicted for the conventional configuration.

Introduction

Conventional rocket combustors have historically been built by brazing bundles of alloy tubes into a combustion-chamber shape. The tubes are high-temperature, high-strength alloys that are cooled, during operation, by one of the propellants. Advanced space missions have packaging and configuration requirements that call for physically smaller systems. In the propulsion area, this is accomplished by increasing the combustion pressures, resulting in the same thrust being produced by progressively smaller and smaller engines. However, the heat flux also increases, and the cooling of the combustion-chamber walls becomes impossible with these alloy tubes. The thermal conductivity of the alloy tubes is too low and, as a result, enough heat cannot be conducted through the tubes into the coolant to keep the tubes from melting.

This problem has been solved by building the combustors out of high-conductivity copper alloys. The chambers are fabricated by milling channels on the outside diameter of a copper-alloy liner to form the cooling passages, and then the passages are closed-out by electroform bonding an outer covering of copper or nickel. The Space Shuttle main engine is built this way. Inherent to this type of construction is a limited fatigue life for the chamber. In the case of the Space Shuttle Main Engine, the predicted life is 55 cycles with a significant number of combustion-chamber-wall fatigue failures occurring before this. The fatigue failures that occur are not classical fatigue or even classic low cycle fatigue. They are, instead, creep-rupture failure caused by thermal strains beyond the elastic limit, experienced during both the start and shutdown transients on each cycle. Whereas the copper alloys used in these liners have an elastic limit in the range of 0.1 to 0.2 percent strain, the actual strains encountered are in the range of 2 to 5 percent, more than an order of magnitude higher. In spite of cracking that occurs as a result of these excessive strains, the Space Shuttle main engine operates successfully, primarily because any chamber cracks do not cause catastrophic mission failures, and, in fact, can hardly be detected. Nonetheless, alternative chamber designs should be considered for future engines.

Many separate efforts have been undertaken to solve the fatigue life problem of the milled-channel configuration. All attempts have concentrated on the improvement of material properties of candidate alloys and metal matrix composites. The potential for improving the situation by using improved materials is considered "second order," and, at best, deformation will still occur in this application.

The obvious answer is a new design of the combustion chamber. The new design should provide structural compliance to permit thermal expansion to occur and to substantially reduce the thermal strains. One such design is the design that was used for this effort.

This report describes a design, fabrication, and test program undertaken at the NASA Lewis Research Center to investigate the feasibility of structural compliance as a feature of combustion-chamber design to avoid or reduce thermal strains in these structures.

Apparatus

A broad base of fatigue data on copper and alloyed copper, milled-channel type of combustion chambers has been obtained on a low-cost subscale rocket engine test apparatus. The apparatus has been used to study chamber low-cycle fatigue, to screen candidate thrust chamber liner materials, and to evaluate advanced cooling concepts and fabrication techniques (refs. 1 to 3). This test apparatus is in the form of a cylindrical spool piece of 6.60 cm (2.6 in.) inside diameter and 15.24 cm (6 in.) length (see fig. 1). Inside the cylinder is a plug centerbody that causes an annular volume in the cylinder to be the combustion chamber. The contour of the plug constricts the flow of the combustion gases and causes a sonic throat condition to occur in the cylinder. It is at this sonic throat station that maximum heat flux is experienced, and this is the location that is studied for chamber fatigue life.

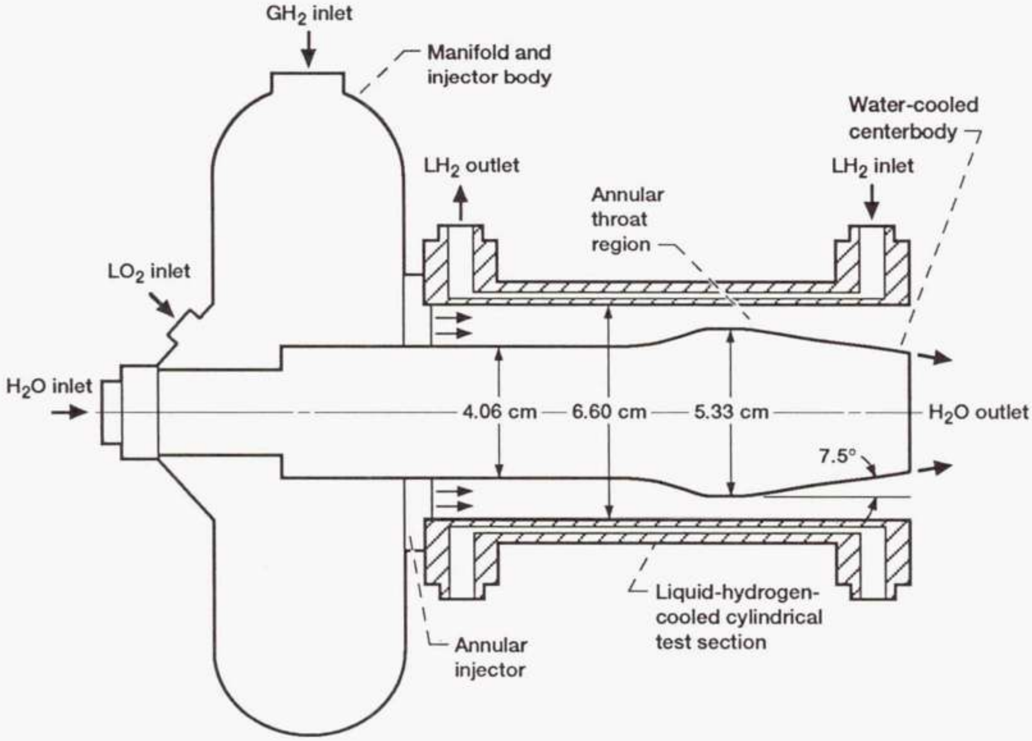


Figure 1.— Subscale rocket engine test apparatus.

The spool piece serves as a test section and the "standard" configuration has 72 rectangular milled cooling passages.

A variation of the standard configuration was used for the demonstration of the compliant chamber concept. The only difference between the standard configuration and the compliant configuration was a series of slots that were manufactured into the spool (see fig. 2). The purpose of these slots was to allow for the unrestrained thermal expansion of the wall material without imposing excessive thermal strains and, hence, cyclic plastic deformations in the wall. Since the compliant configuration was identical to the standard configuration except for the expansion slots, direct comparisons could be made to show the effects of structural compliance on fatigue life.

Figure 2.— Standard and compliant in liner comparison.

Design

Analysis of the thermal expansion expected at the throat location indicated that a slot of about 0.00127 cm (0.0005 in.) was needed between each of the 72 cooling passages. Furthermore, the slot width required in the combustion-chamber location (upstream of the sonic throat location) was even smaller. No method of cutting slots this small (0.00127 cm (0.0005 in.) wide by 0.216 cm (0.085 in.) deep by 15.24 cm (6.00 in.) long) was known. The method of fabrication that was selected to achieve these thin slots, was to machine individual U-shaped cooling passages, stack them onto a mandrel, and then bond them together on the outside diameter surface by a layer of electrodeposited copper. A series of shims placed between the channels, which would be removed after completion, would provide the slots. On attempting to arrange the shim procedure, there were concerns about designing the slot width to be just wide enough to close when the wall material was fully expanded and to not have any gaps available to hot-gas exposure. This ideal slot width varies because the axial variation in heat flux leads to an axial variation in circumferential thermal expansion; thus, the slot is widest at the sonic throat station and narrower upstream and downstream from there.

To avoid the difficult task of providing very thin, variable thickness shims, an alternative procedure was developed. This procedure called for the stack-up to be made with no shims and the resulting configuration to have the slots fully closed while fabricating at room temperature. After the first hot firing, however, the coolant channels would expand and plastically deform. After cooling, at shutdown they would contract and, thereby, expose slots of the precise dimensions needed for all the subsequent firings. These subsequent firings would then only close and open the slots with no further expected plastic deformation, and no further cyclic fatigue damage. This was the planned technique of allowing the slot width to design itself.

Fabrication

Several areas of difficulty were encountered in the fabrication of the slotted configuration described above. The primary cause of these difficulties was the original intent to produce a configuration identical to that used in obtaining the extensive data base on milled-copper liners tested in the past. For comparison purposes a chamber with 72 coolant passages of 0.168 cm (0.066 in.) wide and 0.127 cm (0.050 in.) high with a 0.089-cm (0.035-in.) wall thickness between coolant and combustion gases was needed. These dimensions defined the size of the individual U-shaped channel and resulted in the requirement of leak-tight electroform bonds onto a surface that was only 0.07 cm (0.027 in.) wide. In spite of the demanding leak-tight requirement of the electroform deposition, the chambers were successfully fabricated, and the bonds held throughout proof tests and all of the thermal strains of cyclic hot-fire testing.

A more viable candidate for future combustion chambers is given in references 4 and 5, which describe a method of producing copper or copper-alloy tube bundle chambers with structural compliance and with potential performance, reliability, and cost advantages over the copper-alloy, milled-liner configuration. Structural analysis performed in reference 6 shows the life advantages of this tubular configuration, while reference 7 shows the thermal advantages.

Instrumentation

The instrumentation consisted primarily of chromel/constantan backside wall thermocouples. The backside wall thermocouples were located at four circumferential locations, 90° apart, at the throat plane. The liquid- hydrogen coolant-inlet temperature was measured by a platinum resistance bridge transducer inserted in the inlet manifold. The hydrogen outlet temperature was measured by a chromel/constantan thermocouple inserted into the outlet manifold. The combustion-chamber conditions were monitored as described in references 1 to 3. Namely, combustion-chamber pressure and propellant weight flows and coolant weight flows were monitored.

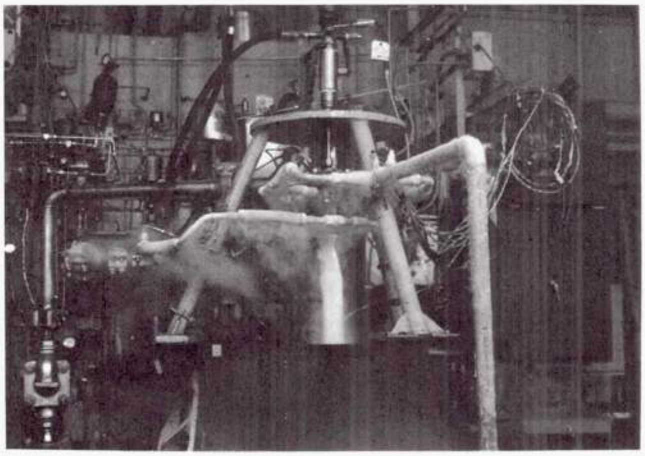


Figure 3.— Hot-test firing on test stand.

Procedure

The test procedure for the compliant chamber tests was identical to the test procedure used on the broad base of fatigue tests described in references 1 and 2. The coolant passages were cooled by a separate 4.07 kg/sec (1.85 lb/sec) liquid hydrogen flow. The chamber was fired for 1.7 sec to allow the chamber to reach steady-state hot conditions, and then shut down for 1.8 sec while the coolant continued to flow to achieve steady-state cold conditions. This 3.5-sec cycle was the standard cycle used in the tests of references 1 and 2, and was found to simulate actual conditions encountered in rocket engines of the milled-channel configuration. This cycle was repeated until the coolant supply was depleted (~50 cycles). While retanking the coolant, the combustion chamber was inspected and then subjected to another test series. This was repeated until a combustion-chamber failure was detected by sensing a coolant-passage leak.

Results and Discussions

Two chambers were fabricated into a structurally compliant design by the electroform deposition of copper onto the outside diameter of a mandrel of stacked, U-shaped copper channels. After fabrication, these chambers passed pressure proof tests and leak tests. However, one chamber was damaged in the process of installation and was scrapped. The second chamber was successfully test fired to a fatigue life of 178 cycles before a coolant leak on the combustion-side surface of a cooling passage.

Figure 3 is a photograph of a typical firing. Coolant water from the inside of the plug centerbody is jettisoned at the exit of the combustor and accounts for the white plume down the center of the exhaust. Occasional green colored exhaust was observed during the testing, indicating some burning of the

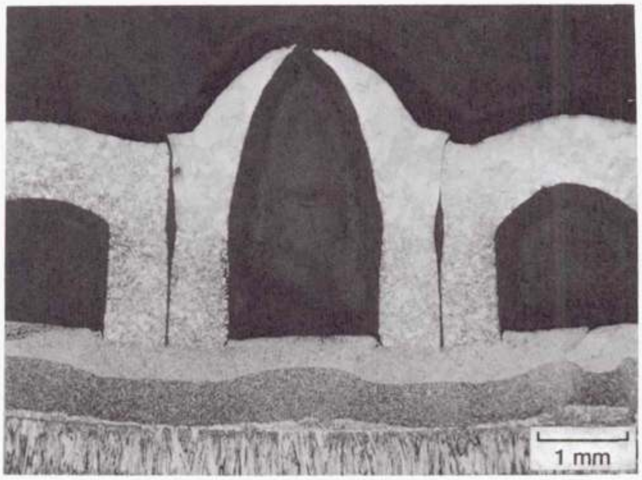


Figure 4.— Failure site.

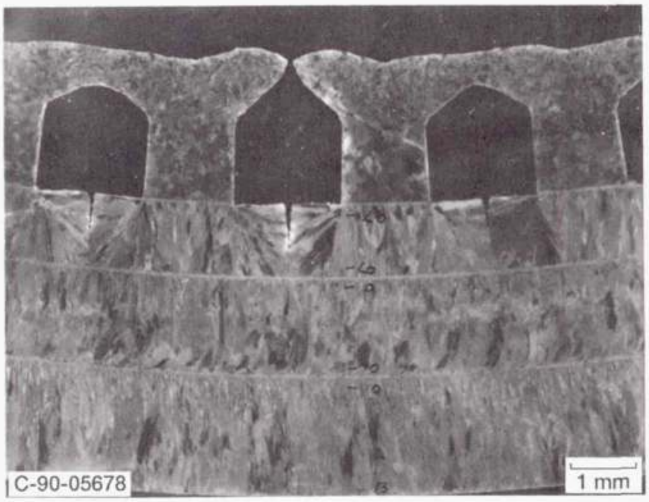


Figure 5.— Standard fatigue failure in OFHC copper liner.

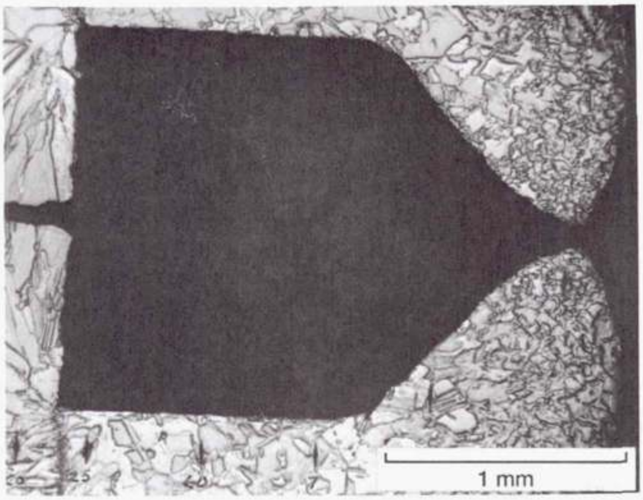


Figure 6.— Grain structure of standard fatigue failure.

copper wall material. This raised some suspicions that the wall was being run too hot, but because of the nature of construction, direct measurements of the wall temperature were not possible. All other test parameters (chamber pressure, mixture ratio, coolant flow, and coolant temperature) were within nominal limits. Posttest analysis has since shown that the wall was indeed run too hot. In order to obtain a better understanding of the behavior of the test configuration some posttest analyses was performed.

Posttest Destructive Analysis

After failure, the combustion chamber was subjected to posttest destructive analysis. The chamber was sectioned in the region of the failure and in other areas for comparison. Each specimen was polished and etched to show the metallurgical grain structure and was photographed at select magnifications to illustrate the findings.

The failure appears to be a pressure rupture caused by the insufficient strength of the OFHC (oxygen free, high conductivity) copper at excessively high temperatures. The absence of evidence of compressive cyclic yielding indicates that the failure was not of the type experienced on conventional milled-channel copper-alloy combustion chambers. It also indicates that the design feature of structural compliance provides significant improvement in chamber life. Figure 4 shows the failure site and the deformation in the two adjacent cooling passages. The failure occurred at the throat of the combustion chamber. Evident in figure 4 are two separate deformations. The first is the bulging of the cooling passage wall because of insufficient flexural strength. The second is the thinning, or necking down, of the rib tops because of insufficient tensile strength. Both of these deformations are caused by the cooling pressure force of 8224 kN/m^2 (1200 psia), and the yielding is caused by the reduced strength at the excessively high temperatures. The nature of the yield at the failure is clearly indicative of a purely tensile yielding with no evidence of any cyclically alternating tensile and compressive yielding.

Cyclically alternating compressive and tensile yielding, called thermal ratcheting, is the scenario of typical standard chamber fatigue failures, as shown in figures 5 and 6. Its absence in the current case indicates the effectiveness of the structural compliance present in this configuration. Notice the blunt shape of the standard failure in figure 5 and the thickening of the wall material near the ribs as a result of material movement during the compressive yielding part of the cycle. Also notice the fine grain structure near the failure in figure 6. This is also the result of the material movement in the compressive direction causing grain structure breakup and strain hardening similar to a worked material.

Figure 7 shows the failure of the compliant chamber at a slightly higher magnification. Notice the variation in the grain size from the bottom to the top of the channel. The fine grain structure at the bottom is what the entire channel was

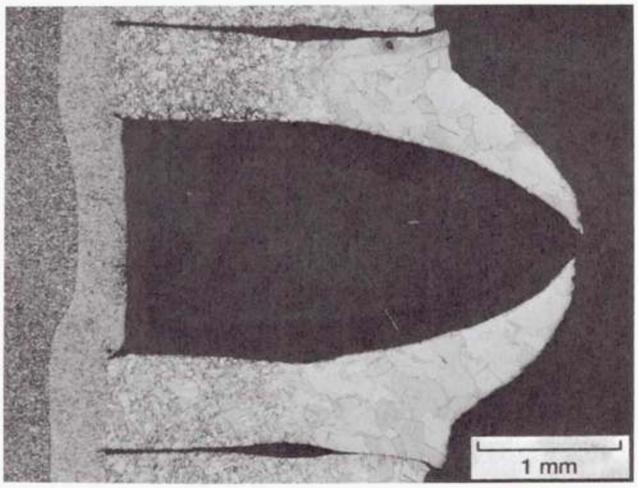


Figure 7.— Failure site.

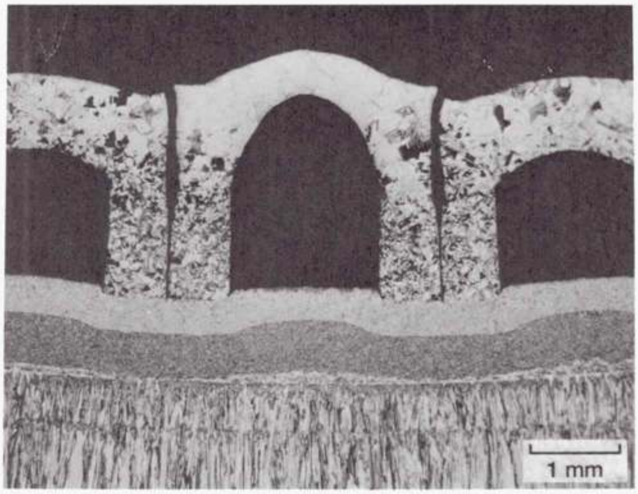


Figure 8.— 0.42 cm Upstream of failure site.

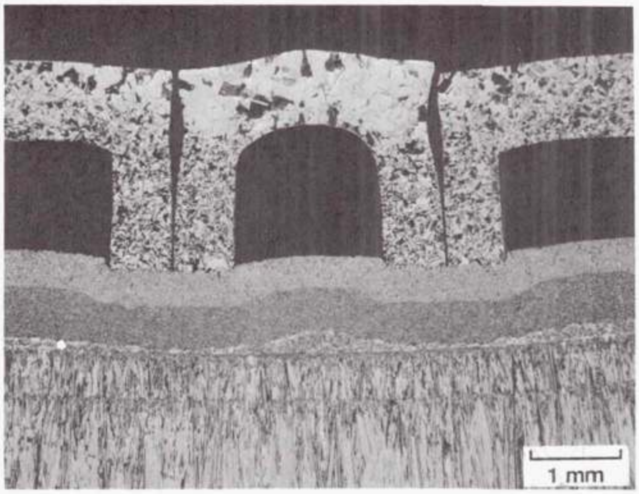


Figure 9.— 0.84 cm Upstream of failure site.

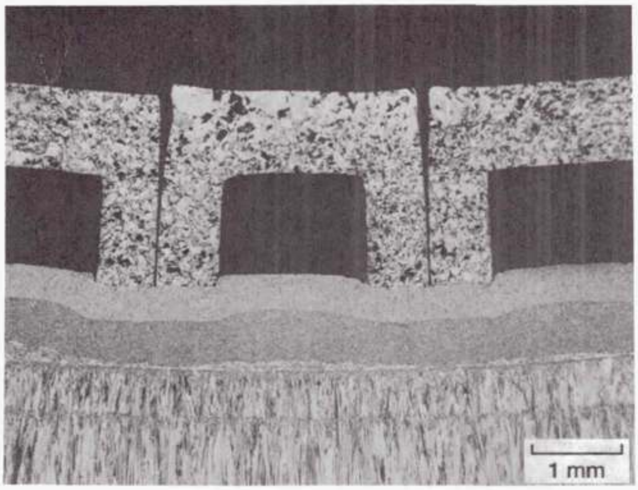


Figure 10.— 1.3 cm Upstream of failure site.

like before exposure to the hot-fire test environment. The larger grain size toward the top of the coolant channel is a result of grain growth caused by the excessive temperature during testing.

Figure 8 is a photomicrograph of an etched specimen taken 0.42 cm (0.16 in.) upstream of the throat (towards the injector). This is from the same channel that failed at the throat, but the specimen was taken from a location farther upstream in a slightly less severe heat environment. The condition of this specimen is also similar to what would have been expected at the failure site some time before the actual failure. As such, some insight can be gained as to the progression of the deformations towards failure. Notice the difference in grain size (growth) and structural deflection over the previous specimen. The heat-affected area is smaller, although the apparent annealing at the top of the coolant passage seems just as severe.

Another specimen was taken at 0.84 cm (0.33 in.) upstream of the failure site (throat). Figure 9 shows the etched specimen with the adjacent coolant channels. What is apparent is the lack of the severe distress evident in the previous specimens. This is what would be expected as the appearance of the throat specimen some time prior to the failure. Some plastic yield of a tensile nature is obvious, there is no evidence of any thermal ratcheting, and some evidence of grain growth is seen.

The next specimen (fig. 10), taken at a location 1.3 cm (0.5 in.) upstream of the throat location, shows only slight deflection and slight grain growth at the top of the coolant channel. Upward bulging as a result of the forces produced

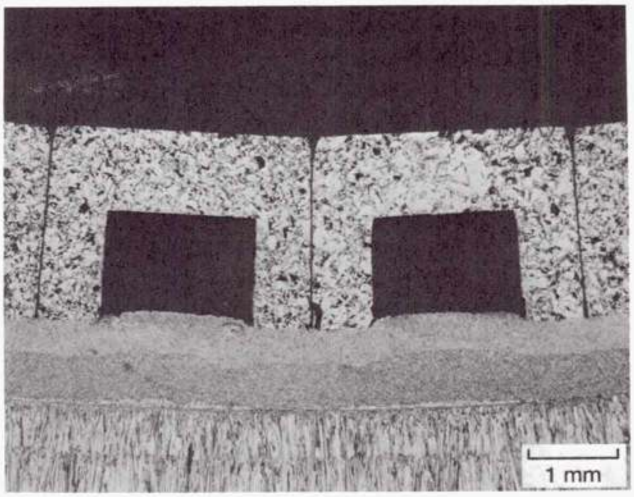


Figure 11.— 2.5 cm Upstream of failure site.

by coolant pressure seem almost nonexistent. Notice the well-formed expansion gaps at the upper corners of the channels. These are the gaps that close on each cycle to form a smooth combustion side wall. It is evident that the self-design feature of these gaps was successful. The structural compliance feature seems also to be successful as there is no evidence of thermal ratcheting on any of the metallographic specimens.

The final specimen was taken at a location of 2.5 cm (1.0 in.) upstream of the original failure site. Figure 11 shows the etched specimen at this location. The only evidence that this specimen was fired exists in the expansion gap that plastically formed during the first fire cycle. The expansion gap is considerably smaller on this specimen because of the less severe environment at this location. Lower heat fluxes cause less thermal expansion, and the required expansion gaps are smaller as a result. The grain structure of the specimen appears completely unaffected, with the grain size at the top looking the same as the grains at the bottom. This grain structure appears similar to what would be expected at the throat after only one cycle.

Annealing Test Results

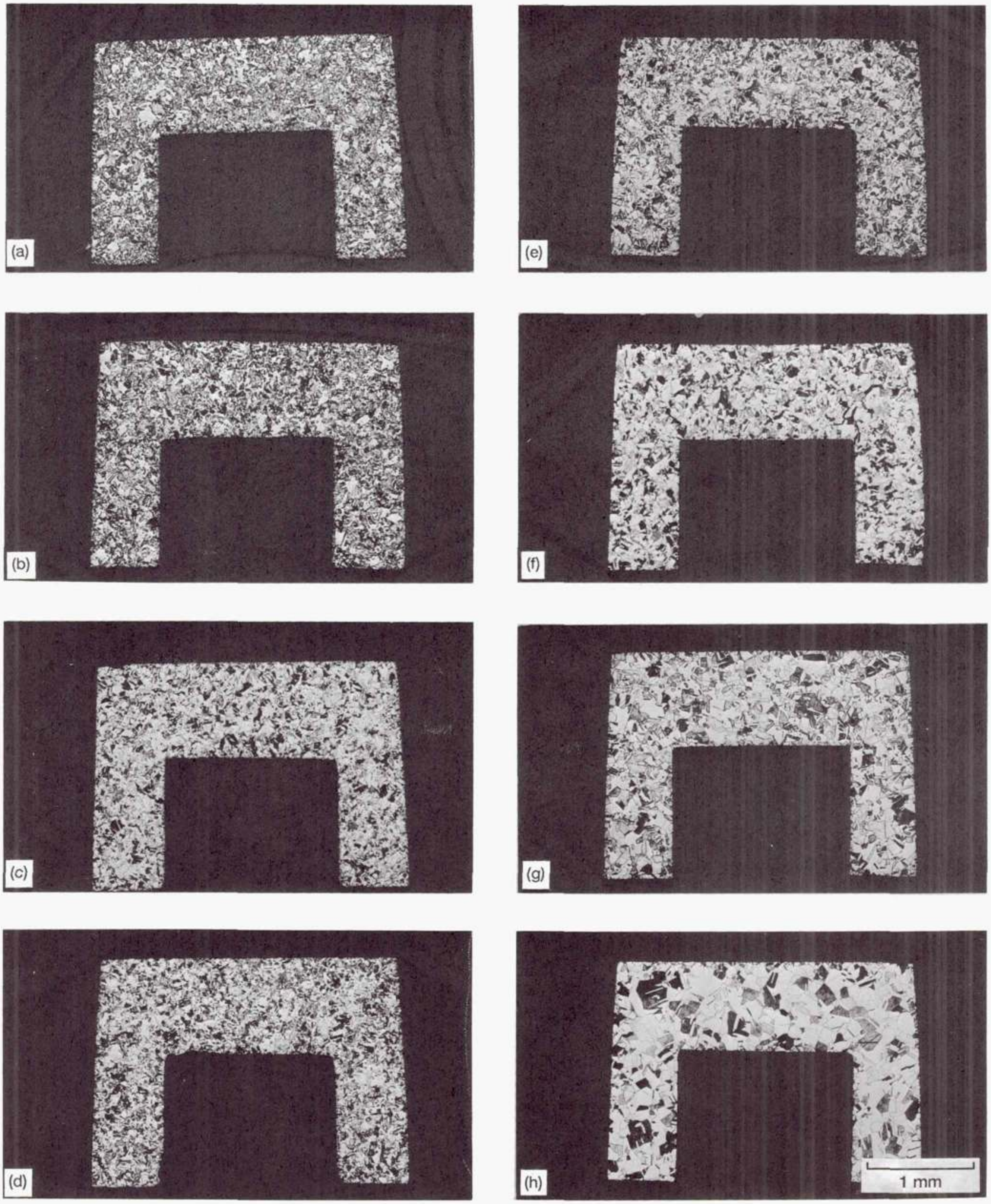
In order to obtain better definition of the thermal environment of the hot-fire tests, since direct temperature measurements could not be made, a series of annealing tests were devised to compare grain structures. During these tests coupons of the original OFHC copper channel material were exposed to various furnace annealing temperatures, polished, and etched. Photographs of the resulting microstructure allowed grain growth comparisons with the specimens extracted from the compliant combustion chamber.

Figure 12 shows various annealed grain sizes for each of several temperatures. Figure 12(a) shows the as-received channel grain structure. (A magnification of 25× was used for all the annealing test specimens.) The annealing test was performed by heating the as-received channel material at temperatures varying from 315.5 to 760.0 °C (600 to 1400 °F) for 10 min. The annealing time was selected as equivalent to the exposure time of the chamber channels during the hot-fire tests. Figures 12(b) to (h), photomicrographs of the annealed test specimens after polishing and etching, show the changes in grain structures. The specimens in parts (b) to (e) were annealed at 315.5 to 593.3 °C (600 to 1100 °F) and show only slight, if any, grain growth. Parts (f) to (h), however, for specimens annealed at 648.9 to 760.0 °C (1200 to 1400 °F), show a progressive increase in grain size. These figures were used to compare the grain size with that of the channel specimens taken from the fired chamber. This comparison shows that figure 7, which is at the failure site (throat area), has a larger grain size at the top of the channel than the figure12(h) (760.0 °C anneal) grains. This indicates that the temperature at the top of the fired specimen was greater than 760.0 °C (1400 °F). Figure 11, at a location of 0.42 cm (0.16 in.) upstream of the failure site, also shows a larger grain size at the top of the channel than does figure 12(h), again, indicating a temperature greater than 760.0 °C (1400 °F). Only at 0.84 cm (0.33 in.) upstream of the failure site (fig. 9) do grain sizes approximate those shown in figure 12(h), indicating a region in the chamber where the wall temperature was about 760.0 °C (1400 °F).

In addition to metallography, several of the chamber specimens were analyzed using the scanning electron microscope (SEM). The SEM's (fig. 13) show that the hot-gas-side surfaces have considerable porosity and some recast copper. The porosity and recast copper indicate that temperatures in these areas were above 1083 °C (1981 °F), the melting point of copper. These findings are similar to those reported in reference 8, thus providing further evidence that severe blanching of the channels had occurred. This reference is a study of blanching of copper combustion chambers. It includes data of gas-side wall temperature versus hot-gas-side wall roughness (in microinches), as well as porosity and surface melting of severely blanched copper.

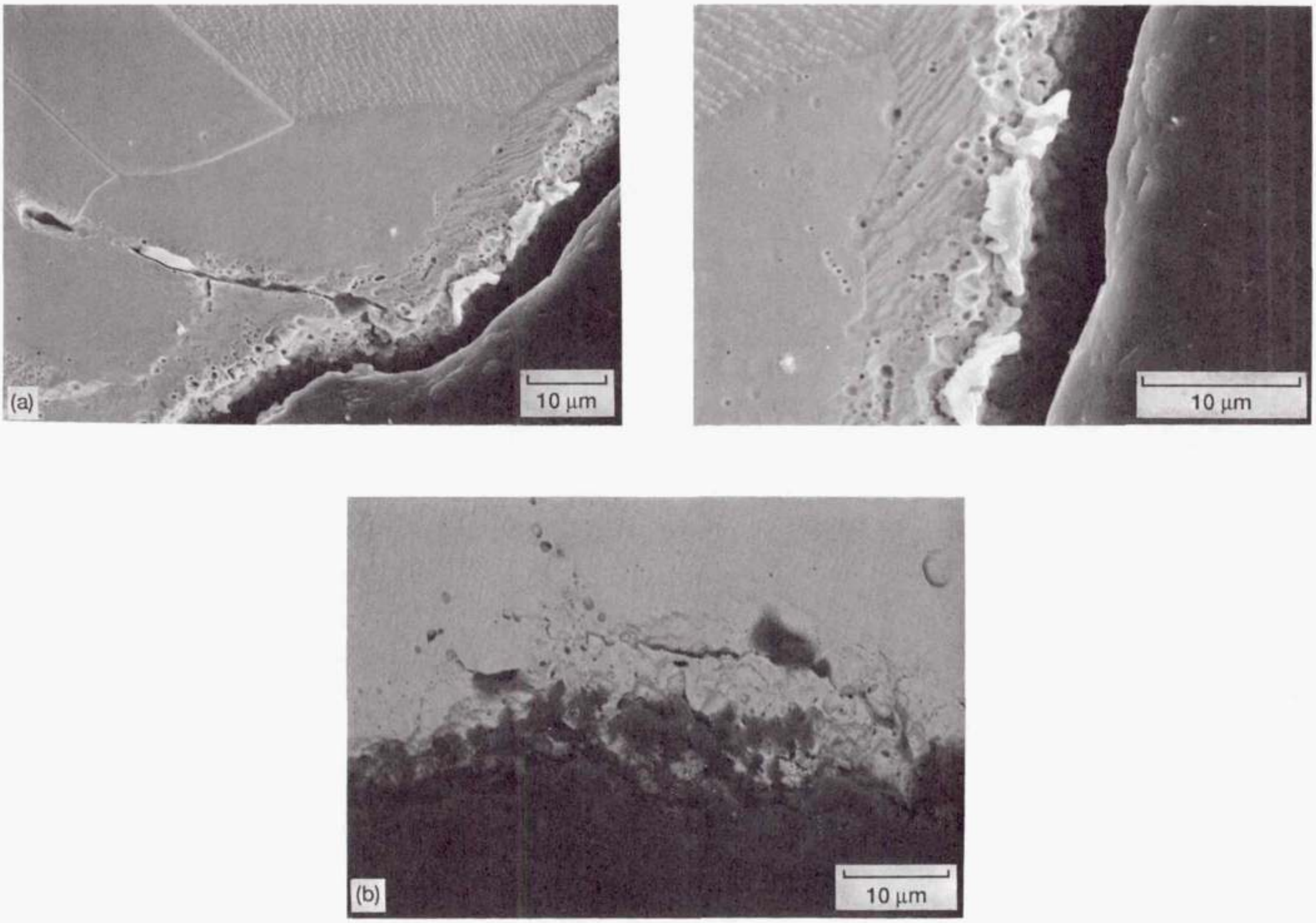
The surface roughness of an as-received channel was measured to have a 32-μin., or less, finish. Then the roughness of fired chamber throat area channels was measured. The average roughness was 380 μin., with a range 175 to 590 μin. Reference 8 shows that at a surface roughness of 400 μin. the hot-gas-side wall temperature is be predicted to be 871.1 °C (1600 °F).

The posttest analysis indicated that the channel chamber had metal temperatures greater than 760.0 °C (1400 °F). Further, the severe blanching of the channels from the onset of testing suggests that initial temperatures could have been as high as 732.2 to 760.0 °C (1350 to 1400 °F).



(a) As received.
(b) Annealing temperature, 315.5 °C (600 °F).
(c) Annealing temperature, 426.7 °C (800 °F).
(d) Annealing temperature, 537.8 °C (1000 °F).
(e) Annealing temperature, 592.3 °C (1100 °F).
(f) Annealing temperature, 648.9 °C (1200 °F).
(g) Annealing temperature, 704.4 °C (1300 °F).
(h) Annealing temperature, 760.0 °C (1400 °F).

Figure 12.— Channel grain structures after 10-min anneal.



(a) Secondary electron image showing molten area and porosity.
(b) Backscatter image showing surface melting at failure site.

Figure 13.— Scanning electron microscope photographs.

Conclusions

A design, fabrication, and fatigue test program was undertaken to investigate the feasibility of designing a structurally compliant rocket thrust chamber that would avoid or reduce the damaging thermal strains that limit the fatigue life of present rocket combustion chambers. The configuration was designed to allow unrestrained thermal expansion in the circumferential direction without plastic yielding. This was accomplished by providing axial slots between each coolant passage that close when the wall material expands and that open when the material contracts at shutdown. A procedure was developed where the slot width dimension designed itself.

The chamber was hot-fire tested until it failed at 178 thermal cycles. The failure was a simple pressure rupture caused by the insufficient strength of the OFHC copper at excessively high temperatures. Surface conditions indicated that the chamber had been run too hot. Blanching was observed in the throat area with an average measured roughness of 380 μin. This roughness corresponds to a metal temperature of 871.1 °C (1600 °F). In spite of the severe environment, the feature of structural compliance appears to have increased the fatigue life of the chamber significantly. The predicted fatigue life for a smooth-wall milled-channel configuration at these temperatures (871.1 °C (1600 °F)), is 46 cycles. An increase of 287 percent fatigue life because of the structural compliance is thereby demonstrated.

The posttest metallographic analysis showed the simple pressure rupture failure, with no signs of the typical alternating tensile and compressive yields (thermal ratcheting) of a conventional fatigue failure.

Grain growth analysis indicates metal temperatures in excess of 760.0 °C (1400 °F). The predicted fatigue life for a smooth-wall milled-channel configuration at 760.0 °C (1400 °F) is 76 cycles. With this life as a comparison, the increase in fatigue life because of the structural compliance is 134 percent.

The electroform deposition of copper as a means of fabrication has proven itself a viable method of constructing compliant structures used in severe environments. The leak-tight integrity of the narrow electroform bonds was not compromised in spite of the thermal strains encountered.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, May 1, 1992

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13. ABSTRACT ***(Maximum 200 words)***

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