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EFFECT OF HEATING METHOD ON STRESS-RUPTURE LIFE

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SUMMARY

Parts such as turbine blades as well as other high temperature machinery components are subjected to sustained loads at elevated temperatures. A laboratory stress-rupture test (time-to-rupture under fixed load at a constant elevated temperature) is often the principal means of determining the suitability of materials for such applications.

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Turbine blades are subjected to heating by a gas stream in actual usage while the laboratory tests generally use radiant (furnace) or resistance (electric current) heating. This experimental program was intended to determine the effect of various heating methods on both the stress-rupture life and the rupture reduction of area of superalloys. It was also intended to illustrate the importance of proper selection of heating method in simulating effectively a hardware application.

Using conventional radiant heating, resistance heating, or the combination of resistance and burner (hot gas stream) heating, the stress-rupture properties were determined for the nickel-base alloy Udimet 700 at three temperatures and the cobalt-base alloy Mar-M 509 at one temperature. In addition, the effect of burner heating was determined for Udimet 700 at one temperature. Specimens were always dead-weight loaded to result in conventional radiant heated stress-rupture lives of about 100-300 hours. Some non-rigorous tests (interrupted and without servo temperature control) using the combination of resistance and burner heating were conducted for the above two alloys as well as eight other alloys.

The stress-rupture lives determined by using resistance heating were about 20-30 percent of those obtained by using radiant heating for both alloys. No metallurgical features were found to explain the detrimental effect of resistance

heating as compared to radiant heating. It is recommended that a good experimental practice would be to avoid the use of resistance heating in stress-rupture testing and to use radiant furnace heating instead.

The stress-rupture life determined from the two burner heated tests also showed a reduction (about 50 percent) compared to the radiant heated results but part of this reduction was attributed to the burner temperature fluctuations. Results from the non-rigorous tests conducted with ten alloys tended to confirm that the effect of heating on stress-rupture life is not alloy dependent. It appears that use of conventional radiant heated stress-rupture data would result in a non-conservative life determination for an application that involves burner heating such as a turbine blade.

For Udimet 700 at all three test temperatures the rupture reduction of area obtained from the resistance heated tests was about 0.7-0.8 that obtained from the radiant heated tests. The life ratio was 0.20-0.25. This indicates that resistance heating gave a higher average creep rate than that obtained with radiant heating.

INTRODUCTION

Research programs to evaluate promising materials for space, aeronautical, or energy applications require a suitable means of simulating in a laboratory, test conditions which correspond to the intended operating conditions. These operating conditions are sometimes characterized by high rotational speeds or sustained loads at elevated temperatures in aggressive environments.

A stress-rupture test (time to rupture under fixed load at a constant elevated temperature) is a laboratory means of evaluating materials. Dead weight, or sometimes servo-controlled hydraulic loading is usually employed to simulate the sustained static loading or centrifugal loading of the component. Radiant heating (furnace) and sometimes resistance heating (electric current) are used to simulate the heating environment of the actual application. It is this effect of heating method on stress-rupture properties of superalloys which was studied in this investigation.

Other investigators have addressed some aspects of this subject. Comparisons of the effect on stress-rupture life of radiant and resistance heating are given in references 1 and 2. The investigation of reference 1 shows no effect on life for the short times (less than 17 minutes) that were studied. That of reference 2 shows that resistance heating had a destructive effect as compared to radiant heating for the longer time tests that were evaluated (radiant heat tests average about three hours). A series of Russian reports (references 3-9) give results for the effect of resistance heating with a superimposed high-speed cold air flow across fairly thin specimens as compared to test results obtained when radiant heating without a superimposed air flow was employed. These tests showed the results obtained with the former heating method to have much shorter lives than with the latter method. The radiant heated test times were less than fifteen hours.

This experimental investigation was performed to determine the effects of heating method on the intermediate time (100-300 hour) stress-rupture properties (life and reduction of area) of superalloys. In the laboratory determination of these properties we attempted to simulate such effects of aerodynamic heating under load as might be experienced by a hardware component such as a turbine blade. This study is also intended to illustrate the importance of proper selection of heating method to effectively simulate the hardware application.

Four types of heating methods were considered--radiant (furnace), resistance (electric current), burner (hot gas stream), and the combination of resistance and burner heating. Solid 6.35 mm (0.25 in.) diameter round bar specimens were dead weight loaded. Stress levels were selected to obtain about a 100-300 hour stress-rupture life using radiant heating. All heating methods with the exception of burner heating were evaluated for Udimet 700 at 927°C (1700°F), 982°C (1800°F), and 1038°C (1900°F) and for Mar-M 509 at 982°C (1800°F). The effect of burner heating on stress-rupture properties was studied only at 982°C (1800°F) for Udimet 700. Some non-rigorous (interrupted and without servo temperature control) tests using the combination of burner and resistance heating were performed for the above two alloys as well as eight other alloys. Lives from these tests were compared to the stress-rupture lives obtained from separate radiant heated tests conducted with the ten alloys. The rupture reduction of area was determined for all tests. A limited metallurgical examination was also performed.

This work was conducted using the customary U.S. system of units. Conversion to the International System of Units (SI) was made for reporting purposes only.

MATERIALS AND SPECIMENS

Materials

The two alloys which were extensively investigated in this program were the nickel-base alloy Udimet 700 and the cobalt-base alloy Mar-M 509. Table I gives the heat number and chemical analyses of the bar stock from which the Udimet 700 specimens were machined as well as those of the remelt stock used to cast the Mar-M 509 specimens. These analyses which were performed by an independent testing laboratory fall within the range specified by the manufacturer. Specimens were tested in the machined or as cast conditions with no heat treatment.

Some non-rigorous (interrupted and without servo temperature control) tests were performed on 10 superalloys using the combination of resistance and burner heating and the results compared to those obtained in radiant heated tests. The ten alloys were IN 162, WI 52, Mar-M 200, IN 713C, NX 188, Mar-M 302, directionally solidified IN 100, Udimet 700 cast, Udimet 700 wrought, and Mar-M 509. The remelt stock or bar stock of the alloys was obtained from commercial sources with the supplied chemical analyses showing all alloys to be within specification.

Specimens

The geometry of each type of specimen used in this investigation is shown in figure 1. Figure 1(a) shows the configuration used only for the radiant heated tests. Figure 1(b) shows the geometry used for all other tests. The two specimen designs differed only in the method used for holding them--the test sections being identical. The radiant heated specimens were gripped using the tapered portion while the other specimens were held by the threaded portion.

The wrought Udimet 700 specimens were machined to the dimensions given in figures 1(a) or 1(b). However, all other alloy specimens were cast to the dimensions given in figure 1(a). The cast specimens tested using other than radiant heating had a piece welded (conventional gas tungsten arc welding using INCO #82 filler metal) to each end into which threads were machined to obtain the figure 1(b) configuration. These specimens were held around the test section for alignment to locate centers used for holding while machining the threads.

FACILITIES AND TEST PROCEDURE

Radiant Heating

Figure 2 shows the facility that was used to perform stress-rupture tests using the radiant method of heating. A standard dead-weight lever-loaded creep frame was used for these conventional stress-rupture tests. The heating was supplied by a clamshell furnace which was mounted in the closed position around the specimen as shown in figure 2(a). The furnace is shown opened in figure 2(b). The specimen was dead-weight loaded using a 20 to 1 lever load frame. A universal joint was located in the load train both above and below the specimen. Specimen temperature was measured and servo controlled by chromel/alumel thermocouples which were mounted on the specimen as shown in figure 2(b).

Before the load was applied, the specimen was brought to the test temperature and stabilized for about two hours. As the weight pan was slowly lowered, to apply the constant load to the test specimen, a time meter was started. When the specimen separated into two pieces, the weight pan dropped, triggering a switch that stopped the time meter. The elapsed time was taken as the time to rupture.

Using radiant heating, duplicate tests of Udimet 700 alloy were run at 927°C (1700°F), 982°C (1800°F), and 1038°C (1900°F). In addition, duplicate tests of Mar-M 509 were run at 982°C (1800°F). Stress levels were selected to give lives ranging from about 100 to 300 hours for Udimet 700 and about 150 hours for Mar-M 509. The radiant heated duplicate tests of the other eight alloys were tested at 982°C (1800°F) with stress levels selected to give lives of approximately 100 hours.

Resistance or Combined Resistance and Small Burner Heating

Figure 3 shows the facility that was used for stress-rupture testing using either resistance or a combination of resistance and small burner heating. Figure 3(a) shows the loading frame with a 10 to 1 lever system to apply dead-weight load. Two universal joints both above and below the specimen were located in the load train. Resistance heating was accomplished by passing an electric current through the specimen. Flexible leads (fig. 3(b)) were connected to each end of the specimen to carry the current. These leads did not impose any mechanical load on the specimen. For tests where the specimen temperature was servo controlled, output from an infrared pyrometer was used for the feedback signal and the output was also recorded on a stripchart. Temperature was determined by an optical pyrometer. The latter was corrected for measuring through a glass window as well as for the emissivity of the specimens as detailed in the Load and Temperature Calibration section of this report.

Some tests were conducted using the combination of resistance and small burner heating. By varying the ratio of burner to resistance heating as well as by installing an insulator (firebrick) on the specimen opposite the side where the burner gas stream impingement occurred, the temperature across the test section could be maintained uniform. The firebrick reduced radiation losses. In these tests the A-1 fuel flow was varied to maintain a constant test temperature whereas the resistance heating was operated at a fixed current level. Two different nozzle shapes were used each having about the same cross-sectional area. One nozzle was round with a 1.6 cm (0.63 in.) diameter, and the other was elliptical with dimensions approximately 3 cm (1.2 in.) by 0.63 cm (0.25 in.).

For the tests using resistance or combined resistance and burner heating the weight was applied while the specimen was cold. The specimen was brought to temperature and stabilized within 3-5 minutes. Extreme care was taken not to overshoot the test temperature. After the specimen temperature had been stabilized, a time meter was started which stopped when the specimen failed. The elapsed time was taken as the time to rupture for the stress-rupture test.

Using the combination of resistance and elliptical nozzle burner heating or resistance heating alone, duplicate tests of Udimet 700 were conducted at 927°C (1700°F), 982°C (1800°F), and 1038°C (1900°F). In addition, at these three temperatures a single test of Udimet 700 using the combination of resistance and the round nozzle burner heating was conducted. For Mar-M 509 alloy, one resistance heated test and a duplicate test using the combination of resistance and elliptical nozzle burner heating were performed at 982°C (1800°F). Some interrupted tests using non servo-control of temperature with the combination of resistance and the elliptical nozzle burner heating were performed on ten alloys at 982°C (1800°F). These tests were interrupted by unloading at the end of an eight hour shift and reloaded the next workday.

Large Burner Heating

The facility for stress-rupture testing that used a large burner for heating is shown in figure 4. For these tests the dead weight was applied directly under the specimen with no lever system. A universal joint was located above and below the specimen as shown in figure 4(a). The large elliptical nozzle had a 8.23 cm (3.24 in.) major and 3.18 cm (1.25 in.) minor axis. The combination of the relatively small specimen diameter (0.635 cm (0.25 in.)) in relation to the burner stream size and the use of a radiation shield (in this case a pipe nipple suspended opposite the burner behind the specimen as shown in figure 4(b)) were sufficient to maintain a uniform temperature across the specimen test section. The specimen temperature was servo controlled by using the output from an infrared pyrometer as a feedback signal for adjusting the fuel flow. This output was also recorded on a stripchart to confirm the isothermal test condition. Other details of the test procedure for tests conducted with the natural gas burner were similar to those used for tests conducted with the combination of resistance and small burner heating. It is emphasized that no interruptions occurred between start of testing and failure of the specimen.

Because of the time and complexity involved in running tests in the large burner facility, only two stress-rupture tests were conducted using Udimet 700 at 982°C (1800°F). For comparison tests at 927°C (1700°F), the necessary loading would have required the addition of a lever loading system. At 1038°C (1900°F), the direct loading would have been possible but the projected continuous test time probably would have been about one week.

Load and Temperature Calibration

Application of both a constant load and temperature is necessary to perform a valid stress-rupture test. Calibrations were performed to insure that the exact applied load and temperature were known in each of the three facilities (figs. 2-4) used for this study. The radiant heating facility (fig. 2) is a conventional creep test frame which uses lever-loaded dead weight and standard thermocouple procedures to measure and control temperature. The load frame and temperature instrumentation are calibrated on a continuing basis as a standard operating procedure.

Load calibrations were performed in the burner facilities (figs. 3 and 4). Dead weight load was applied either with a lever system (fig. 3) or directly (fig. 4). For the lever system, the counterbalance was adjusted to level the beam with the specimen installed but without the lower pullrod assembly. After balancing, a load indicating gage was installed in place of the specimen to check the frame calibration. Standard 89 N (20 lb) weights were applied in five increments to 445 N (100 lb) and the gage readings noted. The calibration confirmed the load frame to have a magnification of ten to one within one percent. For the facility where the weight was applied directly (fig. 4), all weights including the weight pan, pullrod, and universal joint located below the specimen were weighed to determine the load applied to the specimen.

The temperature calibration method used for both burner heating facilities (figs. 3 and 4) were identical. Thermocouples tied to the exterior of a specimen would give false readings because of the influence of the burner stream. Therefore, optical pyrometers were used for the temperature standard. As no one could enter the facility during testing for safety reasons, the optical pyrometer was corrected for measuring through a glass window as well as for the emissivity of the specimens. The procedure to do this was as follows:

1. Two optical pyrometers were calibrated against a black body traceable to the National Bureau of Standards (NBS) between 900°C (1650°F) and 1120°C (2050°F).

2. An NBS lamp connected to a variable transformer for varying the filament temperature was mounted near the test specimen location. The two optical pyrometers were positioned, one near the lamp and the other outside the facility looking through the window. Measurements taken between 900°C (1650°F) and 1120°C (2050°F) indicated the decrease in optical reading required by the presence of the window. As shown in table III, the optical reading had to be lowered between 15°C (27°F) and 21°C (38°F).

3. As the optical pyrometer was calibrated against a black body which has a emissivity of 1.0, a correction was necessary to account for the lower emissivity (0.9) of the specimens. Reference 10 gives the necessary decrease in optical reading for this emissivity difference. As shown in table III, the optical reading had to be lowered between 6°C (11°F) and 8°C (15°F).

4. The corrections for reading through the glass and emissivity were summed to give an optical pyrometer reading to obtain the true specimen temperature. For example, table III shows that to obtain a 982°C (1800°F)

specimen temperature in the large burner, the optical reading outside the facility would be 954°C (1749°F).

5. A check of this temperature measurement method was performed to determine its accuracy. A Udimet 700 specimen (fig. 1(b)) was prepared with a through axial hole into which a chromel/alumel thermocouple was inserted with the ball attached at mid-length. The specimen was heated in the large burner with the thermocouple connected to a strip chart recorder. With a thermocouple output of 982°C (1800°F) two observers at two different times obtained the optical pyrometer reading of 954°C (1749°F) within plus or minus 2°C (3°F).

In order to insure that the temperature was uniform across the test section of the specimen in the burner facilities, photographs were taken of a specimen along the burner axis in the hot condition using infrared sensitive film. The density of the image on the film is proportional to the temperature. Processing the developed film through an optical densitometer showed the isotherms over the surface of the specimen to be uniform across the test section.

Reduction of Area and Pressure Measurements

The rupture reduction of area was determined for stress-rupture tests from the following expression:

$$\text{Rupture Reduction of Area} = \frac{(d_{i,1}+d_{i,2}+d_{i,3})^2-(d_{f,1}+d_{f,2}+d_{f,3})^2}{(d_{i,1}+d_{i,2}+d_{i,3})^2}$$

where d_i is the initial diameter and d_f is the final diameter. Three initial diameter measurements (120 degrees apart) were taken using a digital micrometer before test. Three final diameter measurements (also 120 degrees apart) were taken using a traveling microscope.

Pressure distributions were determined around a single specimen placed in the three different burner streams that were used in this investigation. Distributions were determined for the small burner using both the round and elliptical nozzles as well as for the large burner. The pressure measurement specimen was fabricated by drilling a hole longitudinally to the center of the test section to meet another hole which was drilled along a radius at the center of the test section. The end of the calibration specimen was fitted with a tube leading to a pressure gage and the specimen was mounted in the facility. The specimen was rotated to have the radial hole axis form different angles (nominally fifteen degree increments) with the burner stream. The burner were started and shut down after each repositioning of the pressure calibration specimen.

RESULTS AND DISCUSSION

Stress-Rupture Life

The times to failure for the stress-rupture tests of Udimet 700 and Mar-M 509 using the different heating methods are listed in table II and plotted in figure 5. Figure 5(a) shows the measured stress-rupture lives while figure 5(b) shows the lives obtained using the different heating methods normalized with respect to the radiant heated test results. As shown in figure 5, reproducibility as indicated by the duplicate tests was generally good.

Figure 5 shows that the radiant heating method always gave the longest stress-rupture life compared to the other investigated heating methods. Figure 5(b) also shows that resistance heating always gave about 20-30 percent of the life obtained using radiant heating. This was true for both alloys at the temperatures investigated. These results agree with the results of reference 2. The limited burner heating data for Udimet 700 showed about 50 percent of the stress-rupture life obtained using radiant heating. We believe a small part of the reduction in life due to burner heating can be attributed to slight fluctuations in temperature across the test section caused by the burner during the approximately 40-50 hours of continuous testing. These temperature fluctuations can induce small thermal stresses in the test specimen which could lead to earlier failure.

The stress-rupture lives obtained using the combination of resistance heating and the small burner must also be considered, noting that the specimen temperature varied more than would be expected with resistance heating alone. It is seen that the lives obtained using the combination of resistance and elliptical nozzle burner heating approach the lives that were determined using resistance heating alone. Lives obtained using resistance heating together with the round nozzle burner heating approximate the 50 percent reduction in lives obtained using large burner heating alone.

The difference in stress-rupture lives experienced using resistance heating only as compared to the combination of the small burner with the round or elliptical nozzles and resistance heating can be explained by referring to figure

6. This figure shows the pressure distribution around a specimen located in these three different burner gas streams. Pressure distributions were taken around the specimen to determine the nozzle characteristics and to insure an accurate measurement of the pressure at the stagnation point (0° angle between the burner stream and sensing hole axes). Note in figure 6 the similarity of the distributions for the small burner with the round nozzle and the large burner. Also, note that the design of the elliptical nozzle was such that the resultant stagnation pressure was only half that obtained with the round nozzle although the burner pressure in both cases was identical. The lower the stagnation pressure, the greater was the contribution of resistance heating in obtaining a given temperature (zero pressure would mean resistance heating alone). The higher the stagnation pressure, the greater was the contribution of the burner heating to obtain a given temperature. Since the combination of resistance heating with the elliptical nozzle burner resulted in a low stagnation pressure (and, hence, low gas stream velocities), it would be expected that the resistance heating contribution predominated and that the test lives would approach the very low lives obtained by resistance heating alone. This was indeed the case. For the combination of resistance heating with the round nozzle burner, the stagnation pressure was high. This gave high gas stream velocities suggesting that the resistance heating contribution was a secondary effect.

It should be noted that the side pressure loading on the specimens (fig. 6) caused by the gas pressure was negligible in comparison to the applied axial loading. The worst case occurred during tests with the large burner where a gas pressure less than 0.11 MN/m^2 (16 psi) was measured while the axial stress applied to the specimen was 34 MN/m^2 (5000 psi).

The 982°C (1800°F) interrupted and without servo temperature control tests using the combination of resistance and elliptical nozzle burner heating were not rigorously controlled tests. Therefore, only the ratio of the lives obtained in these tests to those obtained using radiant heating is given in table IV. The ten alloys studied which included Udimet 700 and Mar-M 509, gave life ratios between 19-30 percent. Specifically, both wrought Udimet 700 and Mar-M 509 had life ratios of 30 and 25 percent respectively. This compares to ratios of about 27 and 25 percent in the servo temperature rigorous controlled tests detailed in table II. The non-rigorous test results show that life reduction in these largely resistance heated tests compared to radiantly heated tests does not appear to be alloy dependent.

Reduction of Area

The rupture reduction of area for all stress-rupture tests using the different heating methods are listed in table II and plotted in figure 7. Figure 7(a) compares the actual measured rupture reduction of areas while figure 7(b) compares the rupture reduction of areas normalized with respect to the radiant heated tests. As shown in figure 7, the degree of reproducibility indicated by the duplicate tests was generally good.

Figure 7(b) shows that for Udimet 700 at the three temperatures investigated, radiant heating always gave the largest rupture reduction of area. In the case of Mar-M 509, however, radiant heating did not give the highest values of rupture reduction of area. For Udimet 700 at each of the temperatures investigated, the rupture reduction of area decreased in the same relative order as did the rupture lives for the various heating methods with two exceptions--resistance with round nozzle burner heating at both 927°C (1700°F) and 982°C (1800°F). In comparing the resistance and radiant heated tests, the lower rupture reduction of areas for the resistance heated tests confirms the results observed in reference 1 where lower rupture elongations were noted for resistance heating as compared to radiant heating.

Referring again to the Udimet 700 results at all three test temperatures (figure 7(b)) it is noted that the ratio of rupture reduction of areas of the resistance to radiant heated specimens was about 0.7-0.8 while figure 5(b) showed the stress-rupture life ratios were about 0.25-0.3. This indicated that resistance heating gave a higher average creep rate than that which was obtained with radiant heating. Similar results were obtained with burner heating.

Metallography

An examination was also performed to determine if metallurgical features could be found to further account for the differences in stress-rupture lives measured by the different heating methods. Three Udimet 700 specimens each tested to failure at 982°C (1800°F) using a different heating method--radiant, resistance, or large burner were examined. After failure but before sectioning, each specimen was electrodeposited with copper so that edges could be preserved in the sectioning process. Using conventional practice, the specimens were then mounted, sectioned, polished and etched before examination. The etchant used was 33 parts nitric acid, 33 parts acetic acid, 33 parts water, and 1 part hydrofluoric acid.

Figure 8 shows a photomacrograph and photomicrographs at 10X and 150X of each of the three Udimet 700 specimens. The resistance heated specimen had more voids along the specimen length than the other two because the temperature was maintained over a greater portion of the specimen. No local melting was observed on the fracture surface of the resistance heated specimen. Such melting might have been expected under conditions of resistance heating. No metallurgical features were found, however, to explain the detrimental effect of resistance as compared to radiant heating.

Other Investigators Findings

Results of other investigators pertinent to this investigation are given in references 1 thru 9. Some details of the research of these other investigators as well as how their results compare to those obtained in this study are examined in this section.

The investigation of reference 1 was directed toward providing specific data on certain launch vehicle materials that might be subjected to rapid heating while under sustained loading for relatively short periods of time. A comparison of radiant and resistance heating showed no effect on stress-rupture life of the Ti-5Al-5Zr-5Sn alloy between temperatures of 649°C (1200°F) and 871°C (1600°F). However, the test times were very short, in fact, only three radiant heated tests exceeded six minutes with the maximum time being 17 minutes. It is felt that because of these short test times, a fully realistic comparison of the effect of resistance and radiant heating on stress-rupture properties was not obtained. It is interesting to note that for the tests of reference 1, the resistance heated specimens always had elongations 80-85 percent of those that were radiant heated. This corresponds to the reduction of area findings noted in this study for Udimet 700.

The investigation of reference 2 was conducted to determine the effect of resistance heating versus radiant heating on the stress-rupture properties of coated columbium alloy C-103. The data revealed that the alloy tested under radiant heating had a stress-rupture life approximately six times greater than when tested using resistance heating at identical stress (962 MN/m^2 (9 ksi)) and temperature (1316°C (2400°F)) conditions. Resistance heated specimens had lives that averaged 29 minutes compared to an average of 175 minutes for radiant heated specimens. The authors of reference 2 speculate that the reduced life using resistance heating was most likely due to the internal temperature of the resistance heated specimens being higher than that of the radiant heated specimens. Only surface temperature measurements were performed in that study using an optical pyrometer. As was pointed out in step 5 of the Load and Temperature Calibration section of the present study, the internal specimen temperatures agree with surface temperatures within plus or minus 2°C (3°F). This suggests that the reduced life of the resistance heated specimens observed in reference 2 may not be due to higher temperatures.

Translations of a series of Russian reports (references 3-9) give results for stress-rupture life determined by two heating methods--conventional radiant heating and the combination of resistance heating with a superimposed high speed cold air flow. The Russian results showed that lives obtained using the combination of resistance heating with a high speed air flow (Mach 1.6) were 1/5 to 1/13 of the lives obtained using radiant heating. The Russian investigators attributed these reduced lives primarily to the corrosion-erosion effects due to the high speed air flow with secondary contributing effects due to vibrations of the thin (0.2 cm (0.08 in.)) sheet specimens used in their tests. The results of the present study indicate that resistance heating is the predominant cause for the lower stress-rupture life with standard size specimens. Because of the thin specimens used by the Russian investigators, corrosion-erosion and vibrations may indeed have played an important role in their tests.

CONCLUDING REMARKS

Results of this as well as other investigations (ref. 1-9) show that in selecting conditions to perform a laboratory test program or in using handbook data for certain applications, the effect of heating method on intermediate time stress-rupture properties should be considered. It cannot be conclusively stated why there is a detrimental effect on stress-rupture properties when resistance heating is used instead of radiant heating. However, it does appear that resistance heating introduces an undesirable variable into the testing procedure. It is recommended that a good experimental practice would be to avoid this wherever possible.

It should also be pointed out that use of stress-rupture data obtained by radiant heating for an application that involves burner heating is probably non-conservative. The burner fluctuations result in temperature variations across the specimen test section which would add thermal stresses that do not occur under the more uniform radiant heated conditions.

SUMMARY OF RESULTS

The effect of heating method on the stress-rupture properties of alloys was evaluated. The effects of radiant (furnace), resistance (electric current), and a combination of resistance and burner (hot gas stream) heating were studied at 927°C (1700°F), 982°C (1800°F), and 1038°C (1900°F) for Udimet 700 and at 982°C (1800°F) for Mar-M 509. Also at 982°C (1800°F), the effect of using burner heating only for Udimet 700 was evaluated. Some non-rigorous tests (interrupted and without servo temperature control) using the combination of resistance and burner heating for the above two alloys as well as eight other alloys were conducted. Using the stress-rupture properties determined from radiant heating as the baseline for comparison purposes, the major results are as follows:

1. Resistance heating resulted in only about 20-30 percent of the stress-rupture life that was observed in the baseline radiant heated tests for both Udimet 700 and Mar-M 509.

2. The limited burner heating data showed a 50 percent life reduction as compared to the radiant heated stress-rupture data. Part of this reduction is attributed to the burner temperature fluctuations as compared to the more uniform furnace temperature conditions.

3. The radiant heating method always gave the longest stress-rupture lives of all the heating methods investigated for both Udimet 700 and Mar-M 509. The non-rigorous tests (interrupted and without servo temperature control), with ten superalloys tend to confirm that the heating effects on stress-rupture life are not alloy dependent.

4. For Udimet 700 at all three temperatures the rupture reduction of area obtained from the resistance heated tests was about 0.7-0.8 that obtained from the radiant heated tests. The life ratio was 0.20-0.25. This indicates that resistance heating gave a higher average creep rate than that obtained with radiant heating.

5. No metallurgical features were found to explain the detrimental effect of resistance heating as compared to radiant heating.

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TABLE I. - COMPOSITION OF ALLOYS

Alloy	Heat number	Analyzed composition, wt. %															
		C	Mn	Si	Cr	Ni	Co	Fe	Mo	W	Ta	Ti	Al	B	Zr	S	Cu
Udimet 700 bar stock	8-1995	0.07	<0.1	<0.1	14.6	Bal	19.0	0.19	4.85	----	----	3.38	4.46	0.027	<0.05	0.003	<0.1
Mar-M 509 remelt stock	T-3008	0.62	<0.1	<0.1	23.4	10.0	Bal	<0.1	----	6.95	3.46	0.19	----	<0.01	0.54	-----	----

TABLE II. - COMPARISON OF STRESS-RUPTURE RESULTS OBTAINED BY VARIOUS HEATING METHODS

Alloy	Temperature		Heating method	Small burner nozzle shape	Specimen number	Stress-rupture						Reduction of area			
						Stress		Life				Percent	Percent of average radiant heat reduction of area	Average of duplicate tests	
										Average of duplicate tests					
	°C	°F				MN/m²	ksi	hr	Percent of average radiant heat life	hr	Percent of average radiant heat life			Percent	Percent of average radiant heat reduction of area
Udimet 700	927	1700	Radiant		U76	172	25	113.6	75.1	151.3	100.0	18.3	102.5	17.9	100.0
			Radiant		U725			188.9	124.9			17.4	97.5		
			Resistance heat		U732			48.6	32.1	44.2	29.2	15.4	86.3	15.4	86.3
			Resistance heat		U743			39.8	26.3			15.4	86.3		
			Small burner and resistance heat	Elliptical	U717			40.9	27.0	33.0	21.8	15.0	84.0	14.3	80.1
			Small burner and resistance heat	Elliptical	U720			25.0	16.5			13.6	76.2		
			Small burner and resistance heat	16 mm (0.63 in.) diam	U711			67.8	44.8			14.1	79.0		
Udimet 700	982	1800	Radiant		U78	97	14	99.4	108.2	91.9	100.0	20.1	92.8	21.7	100.0
			Radiant		U723			84.4	91.8			23.2	107.2		
			Resistance heat		U734			24.7	26.9	25.2	27.4	14.4	66.5	14.8	68.4
			Resistance heat		U736			25.7	28.0			15.2	70.2		
			Small burner and resistance heat	Elliptical	U718			28.1	30.6	24.5	26.7	13.6	62.8	12.6	58.2
			Small burner and resistance heat	Elliptical	U721			21.0	22.9			11.6	53.6		
			Small burner and resistance heat	16 mm (0.63 in.) diam	U712			47.8	52.0			15.6	72.1		
			Large burner		U741			40.8	44.4	44.6	48.5	20.0	92.4	19.7	91.0
					U744			48.3	52.6			19.4	89.6		
Udimet 700	1038	1900	Radiant		U710	34	5	309.7	95.2	325.2	100.0	38.7	105.3	36.8	100.0
			Radiant		U724			340.7	104.8			34.8	94.7		
			Resistance heat		U737			88.6	27.2	87.5	26.9	23.3	63.4	24.7	67.2
			Resistance heat		U738			86.4	26.6			26.1	71.0		
			Small burner and resistance heat	Elliptical	U719			66.5	20.4	70.1	21.6	23.0	62.6	21.6	58.8
			Small burner and resistance heat	Elliptical	U722			73.7	22.7			20.2	55.0		
			Small burner and resistance heat	16 mm (0.63 in.) diam	U713			160.3	49.3			28.6	77.8		
Mar-M 509	982	1800	Radiant		H50	103	15	132.2	93.8	141.4	100.0	23.7	107.0	22.2	100.0
			Radiant		G50			150.6	106.8			20.6	93.0		
			Resistance heat		X50			30.2	21.4			28.9	130.5		
			Small burner and resistance heat	Elliptical	Y50			30.3	21.5	35.4	25.1	22.3	100.7	24.0	108.1
			Small burner and resistance heat	Elliptical	Z50			40.5	28.7			25.6	115.6		

TABLE III. - CORRECTIONS TO OPTICAL PYROMETER READINGS

FOR TEMPERATURE MEASUREMENT

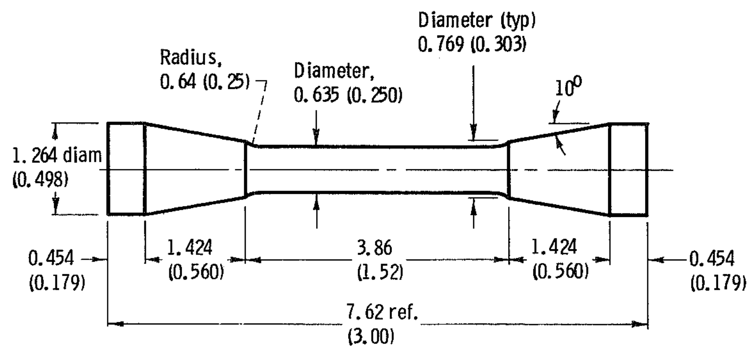
		Small burner			Large burner
Specimen temperature	°C	927	982	1038	982
	°F	1700	1800	1900	1800
Correction for reading through glass	°C	-15	-18	-21	-21
	°F	-27	-33	-38	-38
Correction for emissivity of 0.9 rather than 1.0	°C	-6	-7	-8	-7
	°F	-11	-13	-15	-13
Total of corrections for reading through glass and emissivity	°C	-21	-25	-29	-28
	°F	-38	-46	-53	-51
Optical reading to obtain the specimen temperature	°C	906	957	1009	954
	°F	1662	1754	1847	1749

TABLE IV. - STRESS-RUPTURE RESULTS FOR 982° C (1800° F)

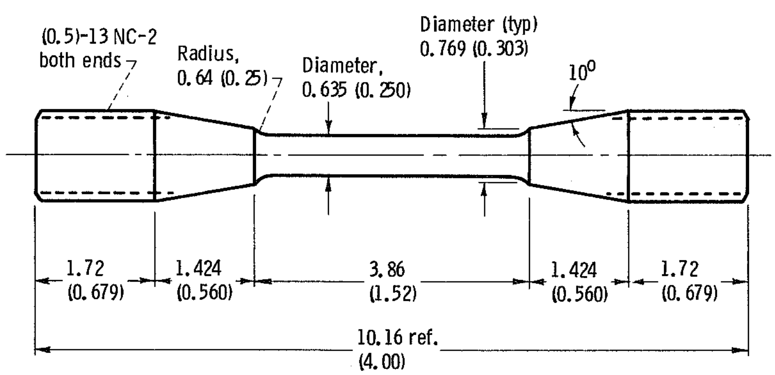
NONRIGOROUS TESTS

Average of duplicate tests except where noted.	
Alloy	Ratio of stress-rupture lives obtained by the combination of resistance and elliptical burner heating divided by that obtained by radiant heating
Udimet 700 wrought	0.30
Mar-M 302[a]	0.29
Mar-M 509	0.25
Udimet 700 cast	0.22
Mar-M 200	0.22
NX 188	0.21
WI 52	0.20
IN 713C[a]	0.20
IN 100 directionally solidified	0.19
IN 162	0.19

[a]Only one specimen tested using the combination of resistance and elliptical nozzle burner heating.

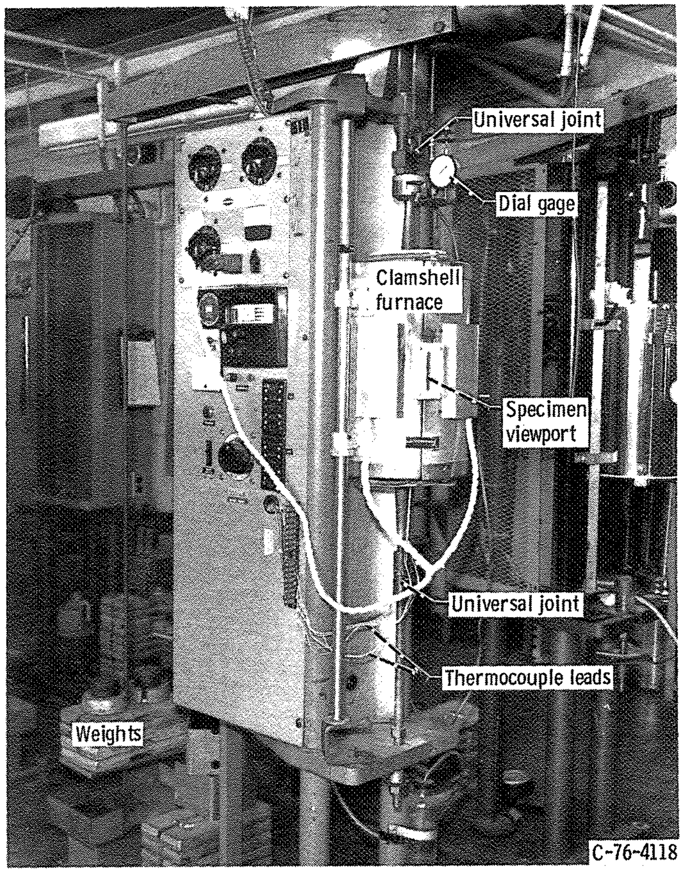


(a) Radiant heated specimens.



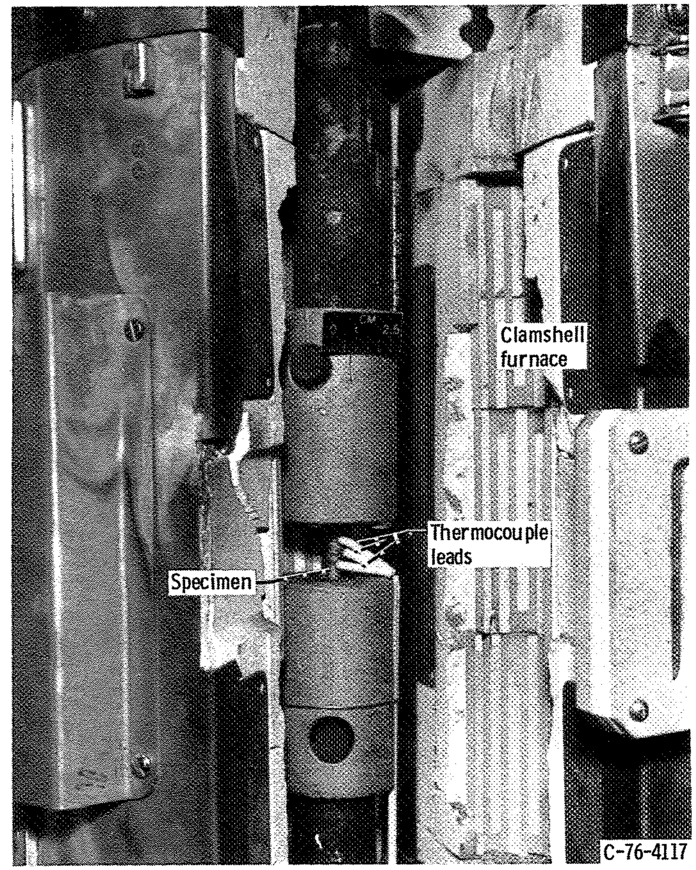
(b) Resistance and/or burner heated specimens.

Figure 1. - Geometry of test specimens. (All dimensions in cm (in.) unless indicated otherwise.)



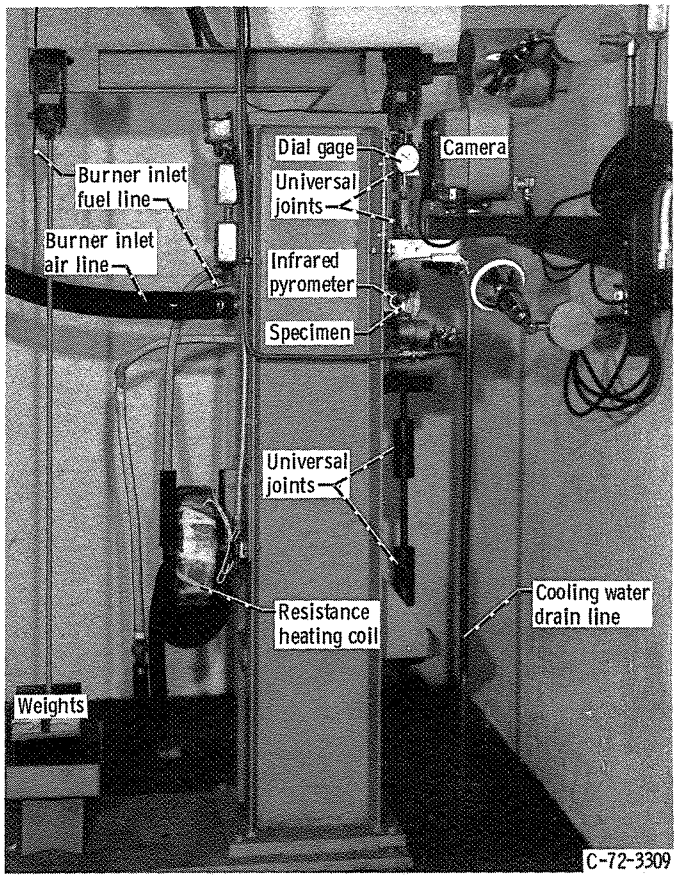
(a) General view of facility.

Figure 2. - Facility for stress rupture testing using radiant heating.



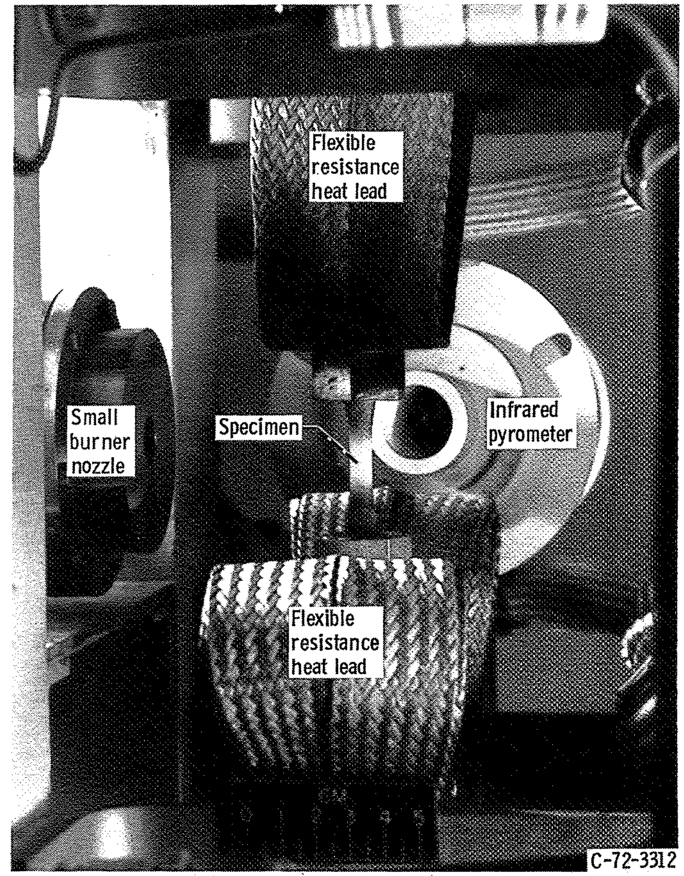
(b) Close-up showing specimen with furnace opened.

Figure 2. - Concluded.



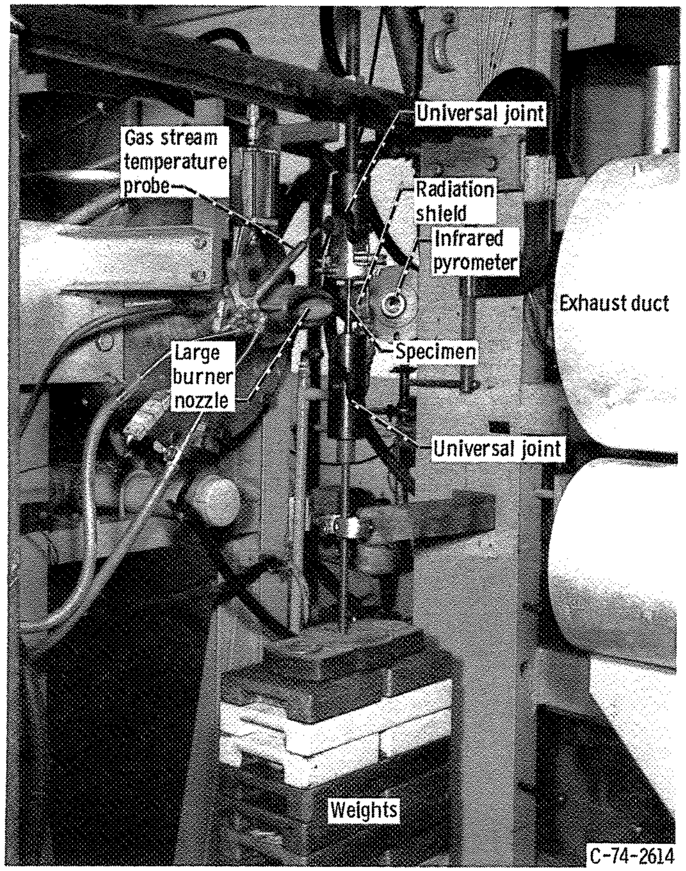
(a) General view of facility.

Figure 3. - Facility for stress rupture testing using either resistance heating or resistance with small burner heating. Specimen is shown undergoing a resistance heating test.



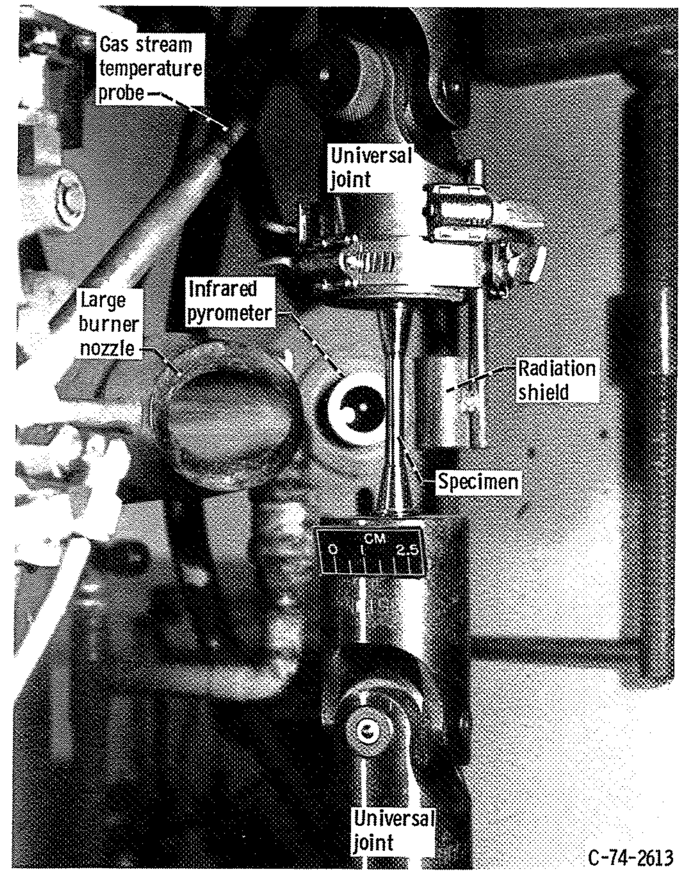
(b) Close-up showing the small 16 mm (0.63 in.) diameter burner nozzle.

Figure 3. - Concluded.



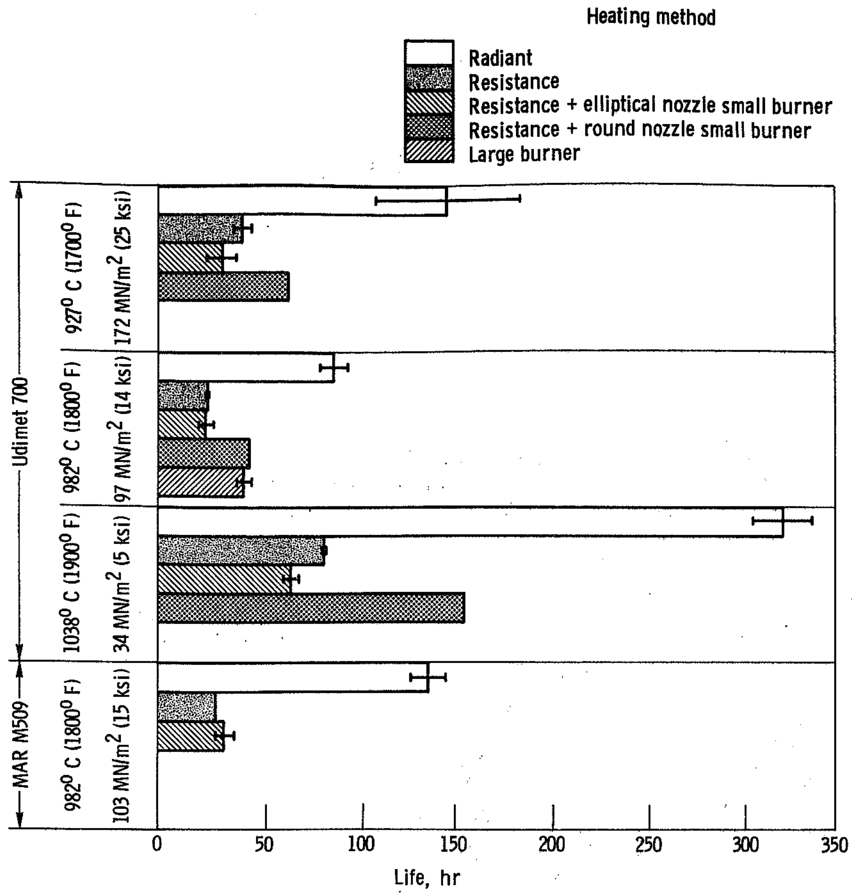
(a) General view showing direct loading on the specimen.

Figure 4. - Facility for stress rupture testing using the large burner for heating.

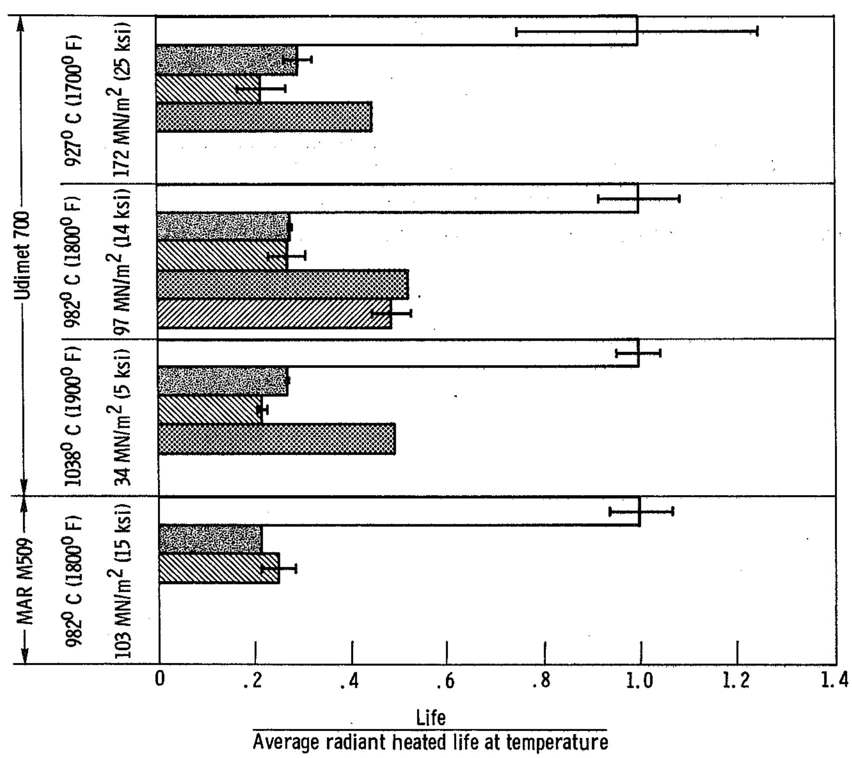


(b) Close-up showing radiation shield behind the specimen.

Figure 4. - Concluded.



(a) Measured stress rupture lives.



(b) Stress rupture lives normalized with respect to the radiant heated tests.

Figure 5. - Stress rupture lives of Udimet 700 and MAR M509 as determined by using different heating methods.

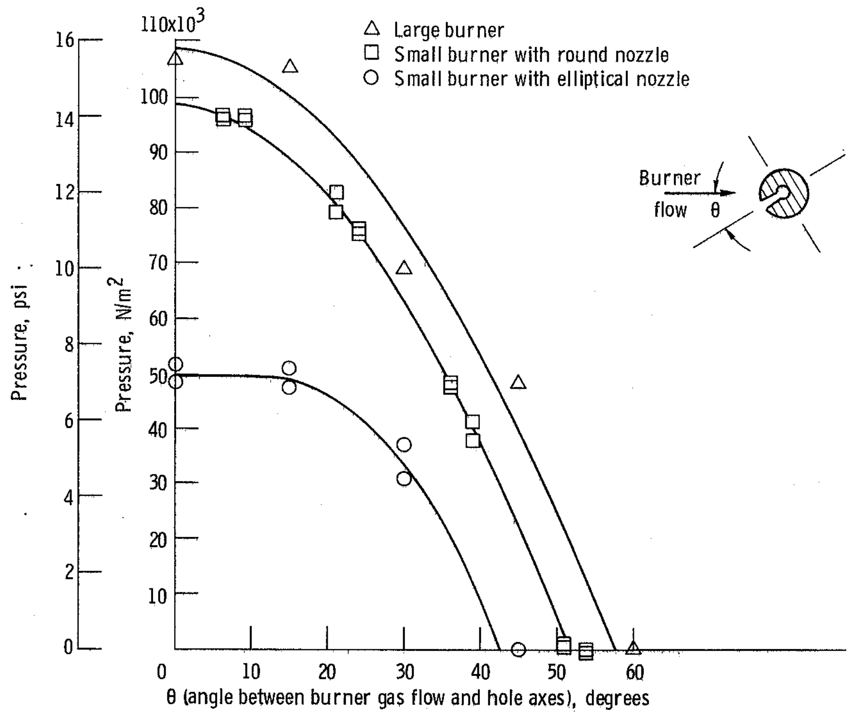
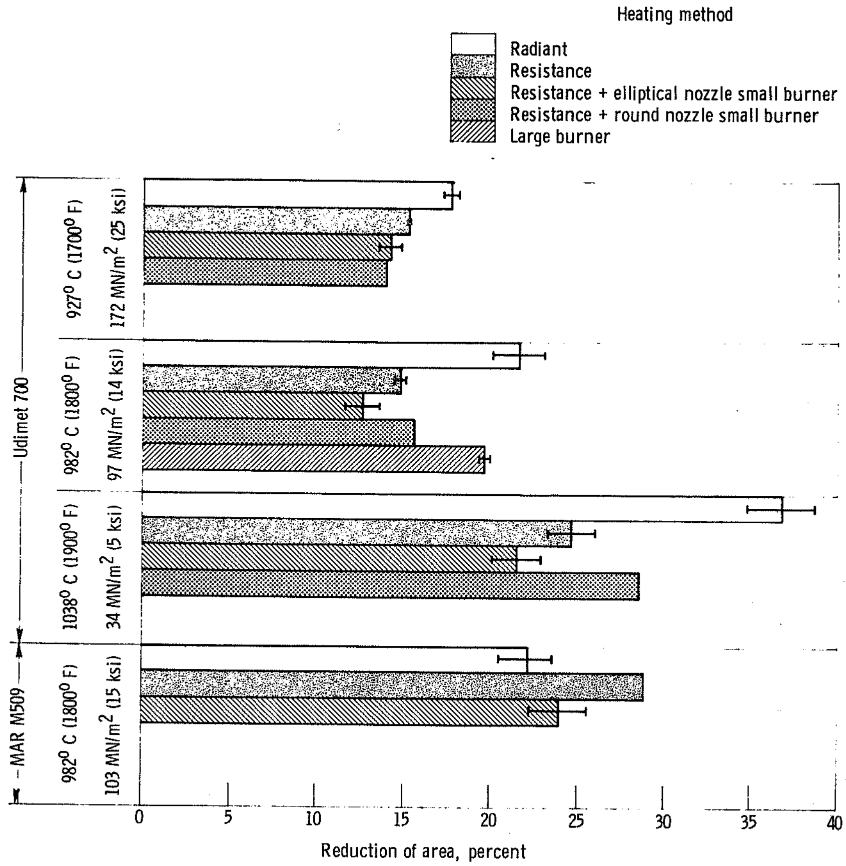
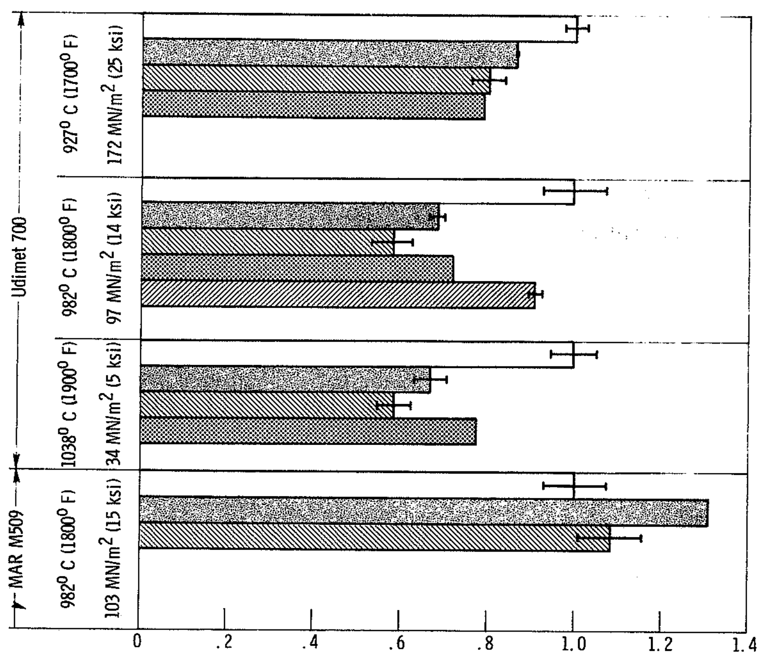


Figure 6. - Pressure distribution around a specimen located in different burner streams.

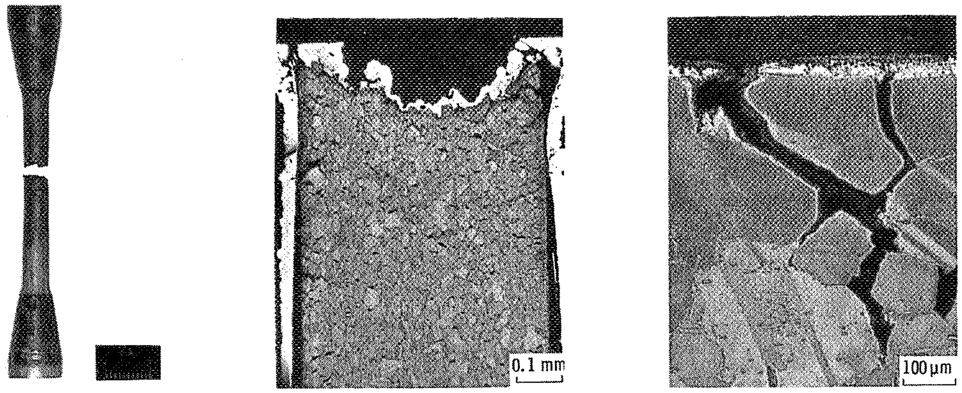


(a) Measured rupture reduction of areas.

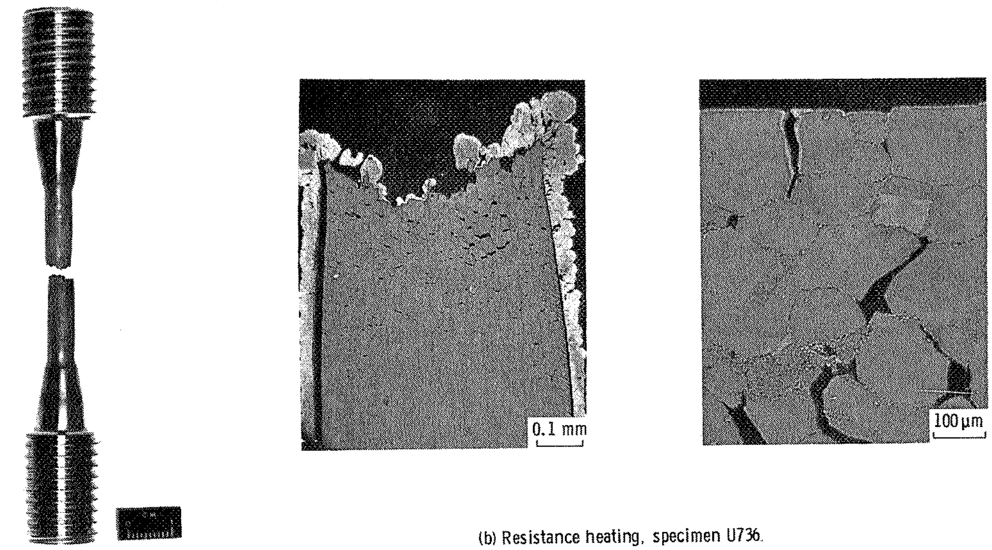


(b) Rupture reduction of areas normalized with respect to the radiant heated tests.

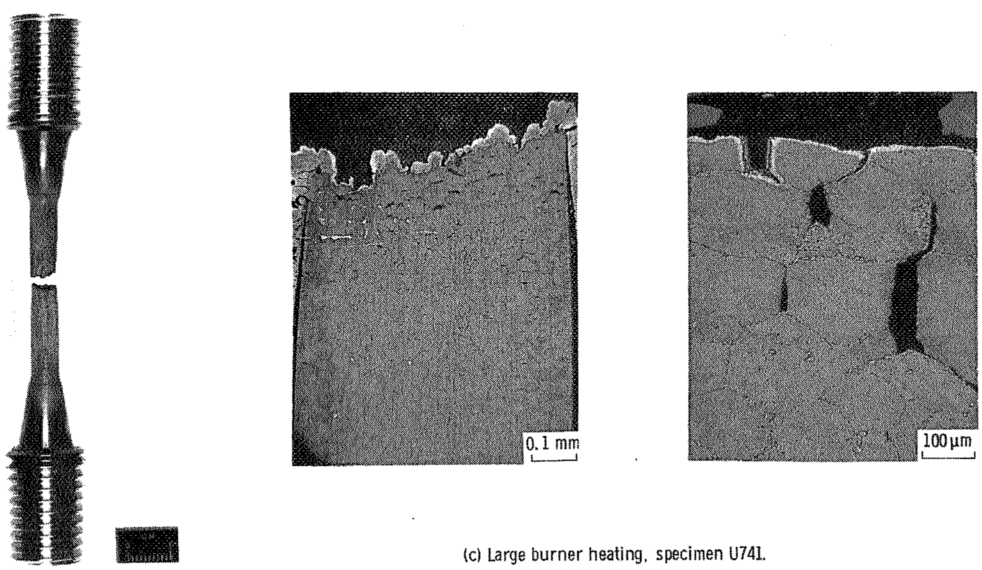
Figure 7. - Rupture reduction of areas of Udimet 700 and MAR M509 as determined by using different heating methods.



(a) Radiant heating specimen U78.



(b) Resistance heating, specimen U736.



(c) Large burner heating, specimen U741.

Figure 8. - Stress rupture failures of Udimet 700 at 982° C (1800° F) as determined by using three different heating methods.

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15. Supplementary Notes

16. Abstract

The effect of radiant (furnace), resistance (electric current), burner (hot gas stream), and a combination of resistance and burner heating on intermediate time (100 to 300 hr) stress-rupture life and reduction of area was evaluated. All heating methods were studied using Udimet 700 while all but burner heating were evaluated with Mar-M 509. Limited test results of eight other superalloys were also included in this study. Resistance heated specimens had about 20 to 30 percent of the stress-rupture life of radiant heated specimens. The limited burner heating data showed about a 50 percent life reduction as compared to the radiant heated tests. A metallurgical examination gave no explanation for these reductions.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Creep rupture strength; Radiant heating; Resistance heating; Udimet alloys; Nickel alloys; Cobalt alloys; Creep tests; Thermal resistance; High temperature air; High temperature tests; Mechanical properties; Metals; Heating	Unclassified - unlimited STAR Category 26

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