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EFFECT OF CYCLIC CONDITIONS ON THE DYNAMIC OXIDATION OF GAS TURBINE SUPERALLOYS

by James R. Johnston and Richard L. Ashbrook

Lewis Research Center
Cleveland, Ohio 44135

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16. Abstract

The effects of operating parameters of a dynamic apparatus used to study oxidation and thermal fatigue of gas turbine materials were studied. IN-100, TD-NiCr, and WI-52 were tested at a maximum temperaure of 1090° C. Heating time per cycle was varied from 1/20 hr to 10 hr. Minimum temperatures between heating cycles were room temperature, 430°, and 650° C. Cooling-air velocities were zero, Mach 0.7, and Mach 1. Increasing the number of cycles for a given time at temperature increased weight loss. Thermal fatigue was related to number of cycles more than to time at temperature.

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SUMMARY

An investigation was conducted to determine the effects of operating parameters of a dynamic oxidation apparatus used to study oxidation and thermal fatigue of gas turbine materials. Three alloys, IN-100, TD-NiCr, and WI-52, were tested at a maximum temperature of 1090° C. The heating time per cycle varied from 1/20 hour to 10 hours; the minimum temperatures between heating cycles were room temperature, 430°, and 650° C; and the cooling air velocities used were zero, Mach 0.7, and Mach 1.

When the heating time per cycle was changed from 10 to 1/20 hours for a total heating time of 40 hours, the rate of weight loss of TD-NiCr, WI-52, and IN-100 increased by factors of 5, 6, and 22, respectively. Varying the heating time per cycle had little effect on thermal fatigue cracking. Cracking of IN-100, the alloy in this program most sensitive to thermal fatigue, occurred in the same number of cycles regardless of cycle length.

The effect of changing cooling air velocity on weight loss was unexpected. For instance, the highest cooling air velocity produced the lowest weight loss for all three materials. However, the differences in weight loss observed with different velocities were generally relatively small. The incidence of thermal fatigue cracking was greatly reduced when no forced cooling air was used, but little difference was noted when cooling air velocity was changed from Mach 0.7 to Mach 1.

The effect on weight loss of the minimum temperature between heating periods was not uniform for all the alloys. For WI-52 the weight loss increased as the minimum temperature was reduced. For IN-100 and TD-NiCr the highest weight loss occurred when these alloys were cooled to the intermediate temperature of 430° C. For all three alloys the lowest weight loss occurred when they were cooled to 650° C.

INTRODUCTION

The high metal temperatures that occur in advanced gas turbine engines make oxidation behavior an increasingly important consideration. Development and evaluation of turbine alloys and coatings for resistance to oxidation typically involve high-gas-velocity rig tests (refs. 1 and 2) as well as various forms of furnace tests. The comparative ranking of materials is strongly influenced by test parameters such as gas velocity and the severity of thermal cycling. Variations in such test parameters can drastically alter the kinetics of the oxidation process.

The dynamic oxidation tests used to evaluate gas-turbine materials differ from most furnace tests in two major respects. In dynamic tests heating occurs in a high-velocity gas stream, and the temperature of the specimens is cycled. High gas velocity can alter oxidation behavior by accelerating the evaporative loss of scales such as chromium oxide (Cr_2O_3). On the other hand, thermal cycling of samples can contribute to faster oxidation rates if scales are cracked or spalled by the resulting thermal stresses. When one considers thermal cycling it is apparent that there are several cycle variables that could strongly influence scale adherence and thereby affect observed oxidation resistance. Such variables are maximum and minimum temperatures of the cycle, heating and cooling rates, and length of time at maximum and minimum temperatures.

Recently, cycle frequency and exposure duration were found to be important variables in a study of furnace oxidation of coated and uncoated WI-52 (ref. 3) and uncoated IN-100 and WI-52 (ref. 4). In these investigations cycle frequency strongly influenced the rate of oxidation of the materials tested. In all cases increasing the cycle frequency (reducing the length and increasing the number of cyclic heating periods) resulted in higher rates of oxidation.

The purpose of the present investigation was to study the effect of cycle variables in a dynamic oxidation test in order to determine which are important in evaluating turbine engine materials. A burner rig using natural gas fuel provided hot combustion gases at a velocity of Mach 1. Maximum metal temperature was 1090° C. The heating time per cycle was varied from 1/20 to 10 hours. The minimum temperatures between cycles investigated were room temperature, 430°, and 650° C. The specimen cooling rate was varied by using cooling air velocities of zero, Mach 0.7, and Mach 1. Three uncoated alloys representative of three different classes of alloys were used to study these effects. The cast cobalt-base alloy WI-52 was selected as a typical engine vane material for which comparable cyclic furnace oxidation data were available. The cast nickel-base alloy IN-100 was selected as typical of γ' strengthened turbine blade material. The wrought alloy TD-NiCr was chosen as representative of a dispersion-strengthened high-temperature material having potential as a turbine vane material.

MATERIALS, APPARATUS, AND PROCEDURE

Materials

Conventionally cast alloys. - The materials tested were investment cast by commercial foundries. Inoculated molds were used to produce a fine grain size typical of that used for gas turbine blades and vanes. The compositions of the cast alloys are listed in table I. Two conventionally cast materials were tested: nickel-base IN-100 and cobalt-base WI-52.

Dispersion strengthened alloy. - The third alloy was a dispersion-strengthened nickel-base alloy, TD-NiCr, and its composition is also shown in table I. Specimens were machined from 6-millimeter-thick plate with the long dimension of the specimens parallel to the major rolling direction of this cross-rolled material.

Specimens

A drawing of the specimen used is shown in figure 1. It was 10.2 by 2.5 by 0.6 centimeter, tapered along one of the long edges with a 45° included angle and a 0.8-millimeter radius to simulate the contour of an airfoil leading or trailing edge.

High Gas-Velocity Cyclic Oxidation Apparatus

The burner installation is shown in figure 2. It is described in detail in reference 1. The schematic diagram shown in figure 2 shows the positions of the specimens with respect to the burner exit nozzle and the cooling air nozzle. The specimens were mounted on a rotating fixture that was moved vertically between heating and cooling positions by an air cylinder. Because the tapered edges of the specimens were outermost in the specimen holder and came closest to the burner nozzle as the the specimen holder rotated, they were called the leading edges.

The burner was designed to burn natural gas with compressed air at approximately 230 kilonewtons per square meter with exit gas temperatures as high as 1650° C. A double liner was used to permit the combustion air to efficiently cool the outer jacket as well as the flame tube. Water cooling was used only on the converging exit nozzle. Accordingly, heat losses were minimized, and the resulting fuel-air ratio was as lean as possible.

The temperature of the rotating specimens was monitored with a Chromel/Alumel thermocouple embedded in a dummy TD-NiCr specimen used in each run and by an optical pyrometer, sighted through the control room window. The specimen temperature was maintained within $\pm 8^{\circ}$ C of the nominal test temperature by a closed-loop

control system which used feedback from a radiation pyrometer sighted on the rotating specimens.

Test Conditions

The basic burner operating conditions used for this investigation are shown in table II. The specimens were alternately heated for a specified time at a test temperature of 1090° C and cooled to various lower temperatures. The burner chamber pressure was maintained at 230 kilonewtons per square meter to assure an exit velocity of Mach 1 at the nozzle throat. The following parameters were varied:

(1) Heating time per cycle

(2) Cooling air velocity

(3) Minimum cycle temperature.

The tests in which these parameters were studied are summarized in table III and described in this section.

Heating time per cycle. - In tests to study the effect of heating time per cycle, four heating times were used: 10 hours, 1 hour, which has been the "standard" time in previous tests (ref. 1), 1/6 hour, and 1/20 hour. During these tests the cooling air velocity was held constant at Mach 1 (350 m/s), and the minimum temperature between heating periods was room temperature.

Cooling air velocity. - To evaluate the effect of cooling rate three cooling air velocities were used: the "standard" velocity of Mach 1 used in previous investigations, a velocity of Mach 0.7 (240 m/s), and zero velocity (free cooling of the rotating specimens without forced air). During these tests with various cooling air velocities, the heating time was 1 hour per cycle and the minimum temperature between heating periods was room temperature.

Minimum cycle temperature. - Three levels of minimum specimen temperature between heating periods were investigated. These temperatures were room temperature (the "standard" condition of ref. 1), 430°, and 650° C. Figure 3 shows heating and cooling curves for the three conditions. In the case of the room temperature test, the specimens were cooled for 3 minutes during each cycle. In order to cool the specimens to 430° and 650° C the respective cooling times were established experimentally. During these tests with various minimum cooling temperatures, the heating time per cycle was maintained at 1 hour and the cooling air velocity used was Mach 1.

Number of specimens tested. - The number of specimens in each test is listed in table III. The data for "standard" conditions were taken from reference 1. In those tests seven specimens of a single alloy were run at one time. However, when the test parameters were varied in this investigation, all three alloys were tested simultaneously in a single run. Because one position in the eight-position specimen holder was

used for a thermocoupled specimen, only seven positions were available. Therefore, usually not more than three specimens of a given alloy were run at one time (i.e., three of one alloy and two each of the other two alloys). In some instances because of a shortage of material only one specimen was run.

Inspection Procedure

Before testing, all specimens were degreased in trichlorethylene vapor and weighed on an analytical balance with a precision of 0.2 milligram. At intervals of 20 cycles, the specimens were removed from the apparatus, reweighed, photographed, and inspected for cracks with fluorescent dye penetrant and low power magnification. Before further testing, they were again degreased.

RESULTS AND DISCUSSION

Heating and Cooling Rates

The heating and cooling curves shown in figure 3 for the "standard" conditions are considered to be comparable to transient conditions that occur in low-pressure engines with relatively thick, uncooled airfoils. In such engines heat-up and cool-down times on the order of 1 minute are common (ref. 5). However, in more advanced, high-pressure engines using sophisticated cooling techniques involving thin wall airfoils, the heating and cooling times can be much shorter, on the order of 10 to 15 seconds (ref. 6). These shorter times result from the lower mass of the blades as well as from the higher heat-transfer coefficients caused by increased pressure. In terms of heat-transfer and temperature transients, the burner rig is somewhat less severe than high-pressure turbines but in terms of the levels of gas temperature and velocity that have been used, the burner conditions are probably more severe than most engines.

Weight Loss

Heating time per cycle. - The effect of varying the length of the heating time per cycle on the weight loss of IN-100, TD-NiCr, and WI-52 specimens is shown in figure 4. Where more than one specimen was tested, the curves shown were generated by averaging the results from several specimens. In cases where significant scatter occurred, the range of values is indicated by the vertical bars through the data points. The effect of changing heating time per cycle was pronounced for all three alloys: the weight loss sharply increased as the length of the heating period decreased, and at the

same time the number of cycles increased. To more clearly display the effect of heating time per cycle, the slopes of the curves of figure 4 were measured at a specific total heating time of 40 hours, and the resulting rates are plotted in figure 5. As the heating period was decreased from 10 to 1/20 hours per cycle, the relative weight loss rates at 40 hours total heating time increased 5, 6, and 22 times for TD-NiCr, WI-52, and IN-100, respectively. The increased weight loss rates associated with the shorter time per cycle and the associated greater number of cycles indicates the effect of the spalling that occurs during each cooling cycle. The great effect of heating time per cycle on the weight loss of IN-100 probably reflects the fact that IN-100 forms an aluminum oxide (Al_2O_3) bearing scale, which is very protective under isothermal conditions. It tended to keep the weight loss extremely low for tests with longer heating periods where only a few cycles occurred during the total test. As the frequency of heating and cooling increased, spalling of the protective scale occurred more frequently per hour of test time, and the rate of weight loss increased significantly.

As the frequency increases and the length of heating time during each cycle decreases, the rate of weight loss could be expected to approach a limit. This limit would occur when the thickness of scale formed in a single cycle was too thin to spall. The shape of the curves in figure 5 (concave upward) indicates that such a limit may occur, but except for TD-NiCr, the limiting heating time period would be much less than 1/20 hour. The TD-NiCr may appear to approach a limit partly because some weight loss occurs by sublimation of chromium oxide (Cr_2O_3) (ref. 1). Such loss would tend to be independent of the length of each heating period and depend only on total exposure time at test temperature.

Comparison of cyclic behavior of WI-52 in these burner rig tests with the static atmosphere cyclic furnace tests of reference 3 shows that exposure to burner conditions causes moderately greater weight loss than furnace tests. In figure 6 the results of the WI-52 burner rig tests are shown with those of furnace tests from the investigation of reference 3. This comparison indicates that, for a given weight loss and heating time per cycle, the furnace tests required total exposure times over two times that of the burner tests. This ratio appeared to be relatively constant over the range of heating times per cycle compared.

Cooling air velocity. - The effect of varying the cooling air velocity on the weight loss of the three alloys is shown in figure 7. The results of these tests appear somewhat anomalous since the highest cooling air velocity resulted in the lowest weight loss for all three alloys and the intermediate velocity resulted in the greatest loss for two of the three alloys. Except for the IN-100 results at times in excess of 60 hours (fig. 7(a)), the relative effect of changing cooling air velocity was small. For instance, after 40 hours exposure, WI-52 specimens had weight losses of 8800, 9400, and 11 200 milligrams for velocities of Mach 1.0, 0, and 0.7, respectively (fig. 7(c)). Differences of this magnitude are probably not significant since they could result from

differences between specimens and normal variation in test temperature. In the case of IN-100 specimens at the longer exposure times, it appears that some factor other than cooling air velocity was affecting the weight loss. Inspection of the IN-100 specimen subjected to Mach 0.7 cooling air indicated that the thermal fatigue cracks that were generated were considerably deeper than those of the specimens subjected to Mach 1 cooling air. Such cracks would increase the exposed surface area and create a somewhat higher apparent oxidation rate. This was not, of course, a factor in the case of specimens tested with no cooling air because no thermal fatigue cracks occurred.

Minimum cycle temperature. - The effect of varying the minimum specimen temperature during cyclic oxidation is shown in figure 8 for the three alloys IN-100, TD-NiCr, and WI-52. As in the tests with different cooling air velocities, no consistent pattern was noted. The results for IN-100 and TD-NiCr (figs. 8(a) and (b)) were unexpected in that the intermediate minimum temperature (430° C) produced the greatest weight loss. More expectedly, the least weight loss for all three alloys occurred with the highest minimum specimen temperature (650° C). In the case of WI-52 (fig. 8(c)) reducing the minimum temperature resulted in increasing weight loss. The results of the three tests of TD-NiCr (fig. 8(b)) are not greatly different except for a somewhat flatter slope of the weight loss curve for the 650° C temperature. The results obtained with IN-100 specimens (fig. 8(a)) again were rather difficult to interpret with the specimens tested at the intermediate minimum temperature (430° C) having two to three times the weight loss of those tested at the other two temperatures. As in the case of specimens tested with varying cooling air velocities, those IN-100 specimens showing the greatest weight loss had deeper and more numerous thermal fatigue cracks. It is possible that the presence of these cracks contributed to the higher weight loss of the IN-100 alloy specimens tested with the intermediate minimum temperature. However, it is also likely that subtle variations in metal and scale properties with temperature contributed to these apparent inconsistencies. The very complex effect of temperature and exposure time on the composition of oxide scales of IN-100 and WI-52 has been demonstrated by the studies of isothermal oxidation described in reference 7.

Thermal Fatigue Cracking

Heating time per cycle. - The effects of heating time per cycle, cooling air velocity, and minimum temperature on the incidence of thermal fatigue cracking are shown in figures 9 to 11. It is apparent in figure 9 that the length of the heating time per cycle had little or no effect on thermal fatigue cracking. The number of cycles is the important variable. For example, IN-100 alloy specimens cracked in 20 cycles regardless of the heating time per cycle. The TD-NiCr and WI-52 specimens, which are less

sensitive to thermal fatigue, did, however, develop some cracks with heating periods of 1 and of 1/20 hour.

Cooling air velocity. - The absence of cooling air flow greatly reduced the incidence of thermal fatigue cracking of the three alloys tested (fig. 10), while, in general, little difference was observed between the tests with Mach 0.7 and Mach 1 cooling air. These results might be expected from the appearance of the cooling curves shown in figure 3(b). In that figure the cooling curve for Mach 0.7 velocity is only slightly less severe than that with Mach 1 velocity.

Minimum cycle temperature. - The effect of the minimum specimen temperature between cycles on the thermal fatigue behavior of the alloys is depicted in figure 11. It appears that the effect depends on the sensitivity of the alloy to thermal fatigue. For instance, IN-100 cracked extensively under all three conditions, while TD-NiCr and WI-52 cracked only in the most severe test where cooling was continued to room temperature. These results indicate that where determination of thermal fatigue resistance is desired, cooling should be continued to near room temperature.

GENERAL REMARKS

In a simulated or accelerated test compromises must be made between what an actual engine part will experience and what is feasible or possible in a simulation. In designing and planning the operation of the NASA burner rig we compromised on pressure and operated at atmospheric pressure rather than at the higher levels found in gas turbines. The burner rig gas velocity of Mach 1 is somewhat higher than the relative gas velocity in engines and therefore would be expected to be a more severe test condition. However, previous tests (ref. 1) comparing the effect of Mach 0.7 and Mach 1 conditions indicated that a velocity change over this range produced only a small effect in observed oxidation rates except for one alloy which formed volatile oxides. The specimen temperature can be adjusted to any level desired up to about 1200° C. Most of our testing has been at material temperatures between 1040° and 1100° C and thus represents an accelerated test since turbine material temperatures in current and near-future engines generally do not exceed 1000° C. The heating and cooling rates that occur with our "standard" cycle are comparable to those found in fairly heavy airfoils. The standard cycle of 1 hour at temperature followed by a 3-minute cooling period was originally selected as being a heating time long enough to approximate the flight of a supersonic transport. However, unpublished work by C. A. Barrett of Lewis shows that a cooling period of 3 minutes in furnace tests is too short for all the spalling to be completed. He has established 45 minutes as the minimum time to maintain the specimen at a low temperature between heating cycles. However, Barrett's work was done

without forced cooling air. With high-velocity cooling air spallation may be complete at times considerably short of 45 minutes.

The complexity of the process of cyclic oxidation and spallation is further evident from the results reported here. The results were not always what one would intuitively anticipate, nor did all three alloys respond in the same manner. For example, the cycle having the fastest cooling rate always resulted in the least weight loss in 100 hours. The intermediate cooling rate resulted in the greatest weight loss in two out of three alloys. On the other hand, the highest temperature (650° C) to which specimens were cooled between heating cycles resulted, as was expected, in the least weight loss in 100 hours for all three alloys But, surprisingly, cooling to the intermediate temperature of 430° C resulted in greater weight loss in two of the three alloys than did cooling to the lowest level (room temperature).

The cycle frequency had a strong effect on oxidation rates. For all three alloys the rate of weight loss for a given time at temperature was greatly accelerated by decreasing the heating time per cycle.

Although the cyclic oxidation process is extremely complex and not yet well understood, the burner rig is a valuable tool in evaluating alloys and alloy-coating systems. Also, by properly designed rig experiments it should be possible to gather information that would contribute to the understanding of the mechanism of cyclic oxidation.

SUMMARY OF RESULTS

An investigation was conducted to determine the effect of various operating parameters of an apparatus used to study dynamic oxidation and thermal fatigue of gas turbine materials. The major parameters studied were heating time per cycle, minimum temperature between heating periods, and cooling air velocity. Heating time per cycle was varied from 1/20 to 10 hours. The minimum temperatures were room temperature, 430°, and 650° C. The cooling air velocities used were zero, Mach 0.7, and Mach 1. Three materials, IN-100, TD-NiCr, and WI-52 were tested with a maximum cycle temperature of 1090° C. The most significant results follow:

1. The rate of weight loss was significantly affected by the length of the heating time per cycle. Decreasing the heating time per cycle from 10 to 1/20 hour increased the rate of weight loss of TD-NiCr, WI-52, and IN-100 by 5, 6, and 22 times, respectively.

2. Comparison of the cyclic behavior of WI-52 in the burner rig with cyclic furnace test results of another investigation indicated that the burner exposure was moderately more severe, requiring approximately one-half the time to produce similar amounts of weight loss. This ratio appeared to be relatively constant over a range of cycle frequencies.

3. The effect of varying the cooling air velocity from zero to Mach 1 on weight loss was somewhat anomalous. The highest velocity resulted in the lowest weight loss for all three alloys and the intermediate velocity resulted in the highest weight loss for two of the three alloys. However, the relative differences in weight loss observed were small except in the case of IN-100 where the incidence of thermal fatigue cracking may have affected the weight loss results.

4. The effect of the minimum temperature between heating cycles on weight loss was not uniform for all alloys. For two alloys, IN-100 and TD-NiCr, the highest weight loss occurred when they were cooled to the intermediate temperature (430^{o} C). The lowest weight loss occurred for all three alloys when cooled to the highest temperature (650^{o} C). In the case of WI-52, reducing the minimum temperature resulted in increasing weight loss.

5. The length of the heating time per cycle and total time at temperature had less effect than the number of cycles on the thermal fatigue cracking of the alloys. The alloy most sensitive to thermal fatigue cracking, IN-100, cracked in 20 cycles regardless of the heating time per cycle.

6. The incidence of thermal fatigue cracking of the three alloys was greatly reduced when no forced-air cooling was used. Little difference was noted, however, when cooling air velocity was changed from Mach 0.7 to Mach 1.

7. The effect of the minimum specimen temperature between heating periods on thermal fatigue cracking depended on the sensitivity of the alloy to thermal fatigue. The IN-100 specimens cracked extensively under all three cooling conditions, while the TD-NiCr and WI-52 specimens cracked only in the most severe test where cooling was continued to room temperature.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 5, 1973,
501-21.

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TABLE I. - CHEMICAL COMPOSITION[a] OF TEST MATERIALS

Alloy	Composition, weight percent															
	Ni	Co	Cr	Mo	W	Cb	C	Ti	Al	Si	Mn	Fe	B	Zr	S	Other
IN-100	Bal	14.91	10.00	2.95	-----	----	0.15	4.34	5.45	0.11	<0.05	0.14	0.015	0.06	0.002	V, 0.90
TD-NiCr	Bal	-----	21.39	----	-----	----	.04	----	----	----	-----	----	-----	----	-----	ThO_2, 2.5
WI-52	0.53	Bal	21.02	----	11.07	1.89	.44	----	----	.29	.28	1.69	-----	----	.04	P, 0.006

[a]Vendors' analysis

TABLE II. - TYPICAL BURNER CONDITIONS

Maximum specimen temperature, ^{o}C	1090
Burner gas temperature, ^{o}C	1550
Gas velocity, Mach number	1
Burner pressure, kN/m^2	230
Specimen rotation speed, rpm	900
Burner air flow, kg/sec	0.45
Air-fuel ratio	25
Burner nozzle diameter, cm	5.1

TABLE III. - SUMMARY OF TESTS UNDER VARIOUS OPERATING CONDITIONS

Parameters investigated	Alloy			Constant parameters
	IN-100	TD-NiCr	WI-52	
	Number of specimens			
Heating time per cycle, hr:				Cooling air velocity, Mach 1; minimum cooling temperature, room temperature
10	2	3	2	
[a]1	7	7	7	
1/6	2	2	2	
1/20	2	2	2	
Cooling-air velocity, Mach number:				Heating time per cycle, 1 hour; minimum cooling temperature, room temperature
0	1	2	2	
.7	2	1	2	
[a]1.0	7	7	7	
Minimum cooling temperature, °C:				Heating time per cycle, 1 hour; cooling-air velocity, Mach 1
650	3	3	1	
430	2	2	2	
Room temperature[a]	7	7	7	

[a]Data from ref. 1.

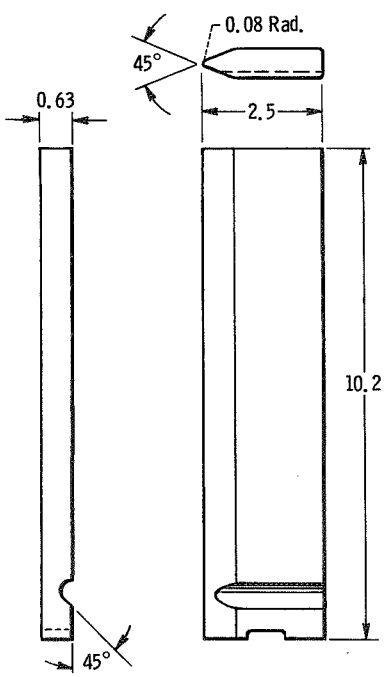
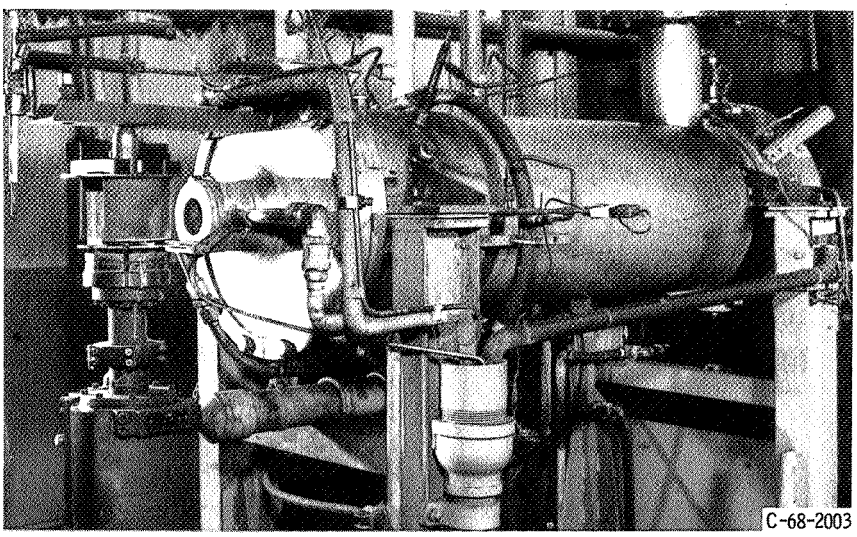


Figure 1. - High-velocity oxidation specimen. (Dimensions are in cm.)



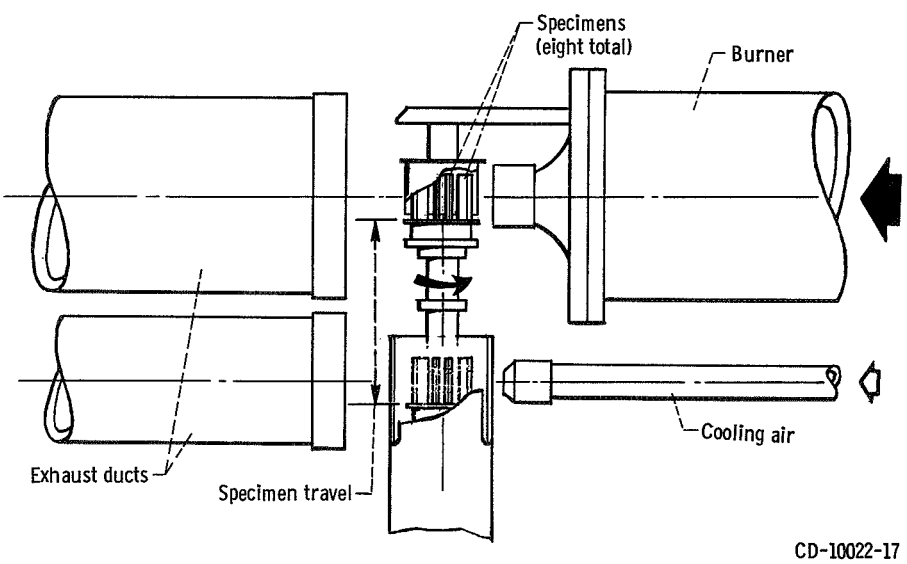


Figure 2. - High-gas-velocity oxidation apparatus.

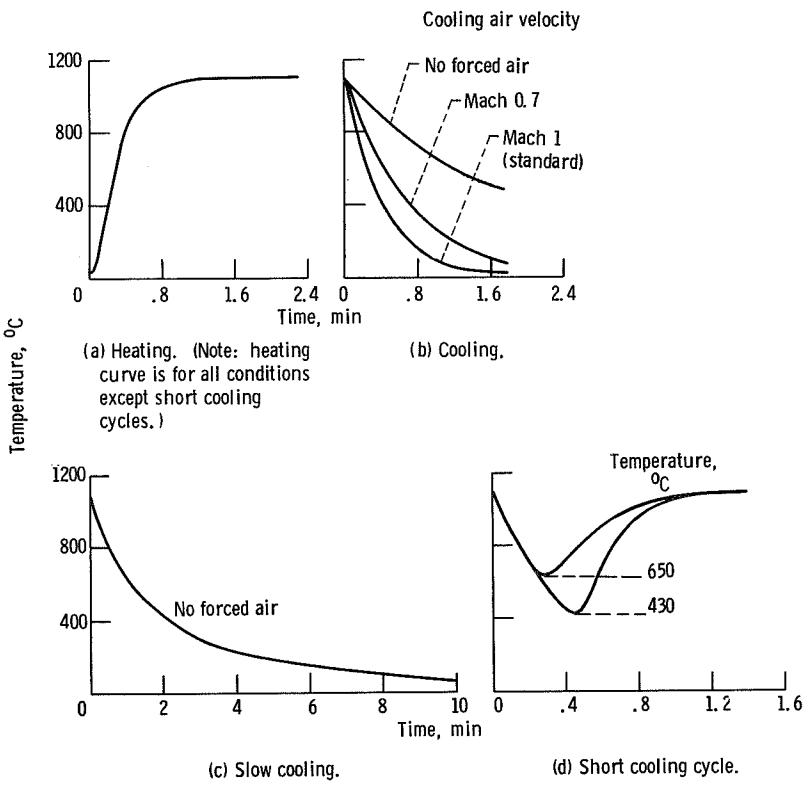


Figure 3. - Typical heating and cooling curves during various test cycles.

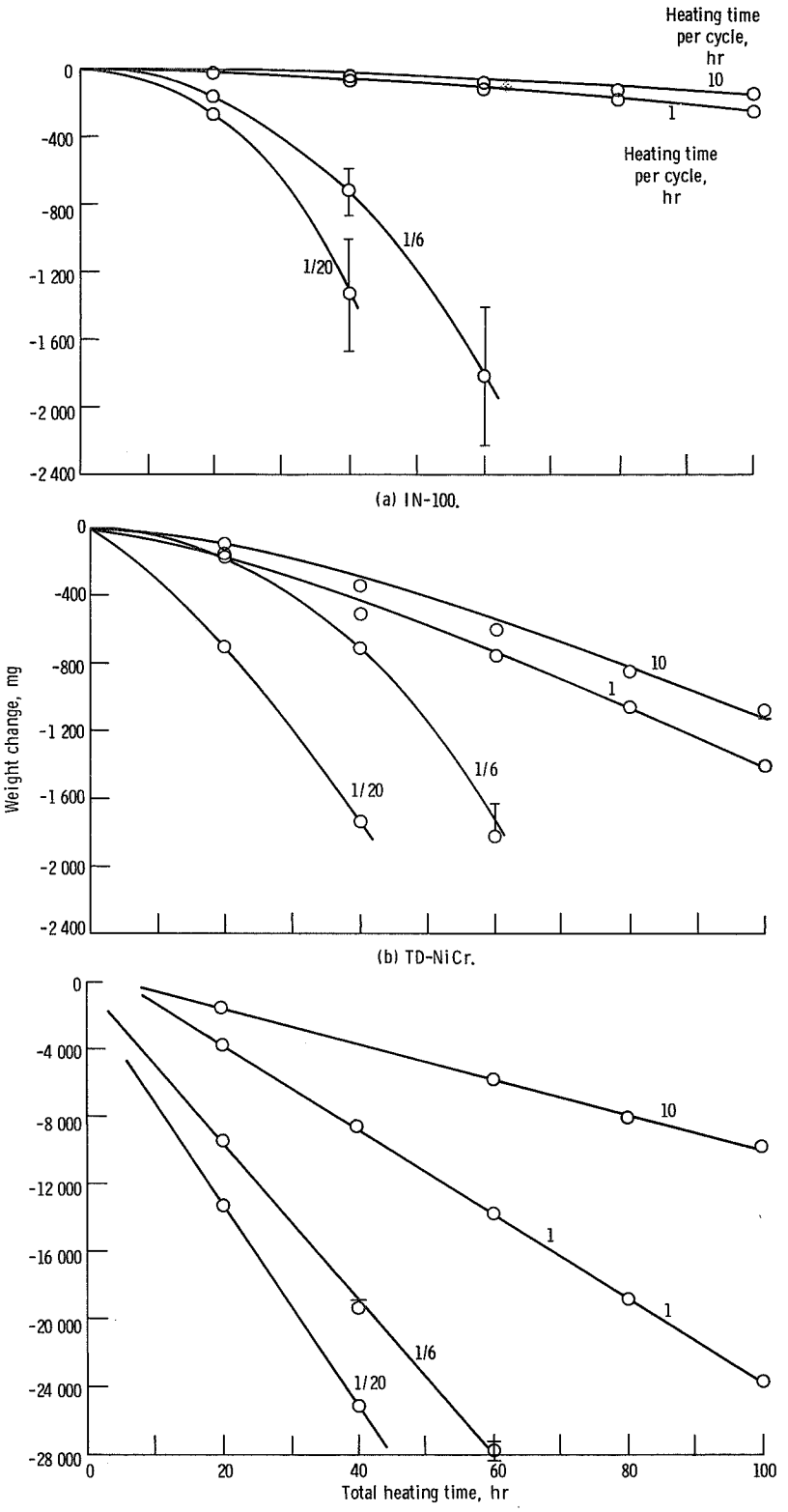


Figure 4. - Effect of heating time per cycle on weight change of IN-100, TD-NiCr, and WI-52 in a high-velocity oxidation apparatus. Maximum cycle temperature, 1090° C; minimum cycle temperature, room; cooling-air velocity, Mach 1 (350 m/s).

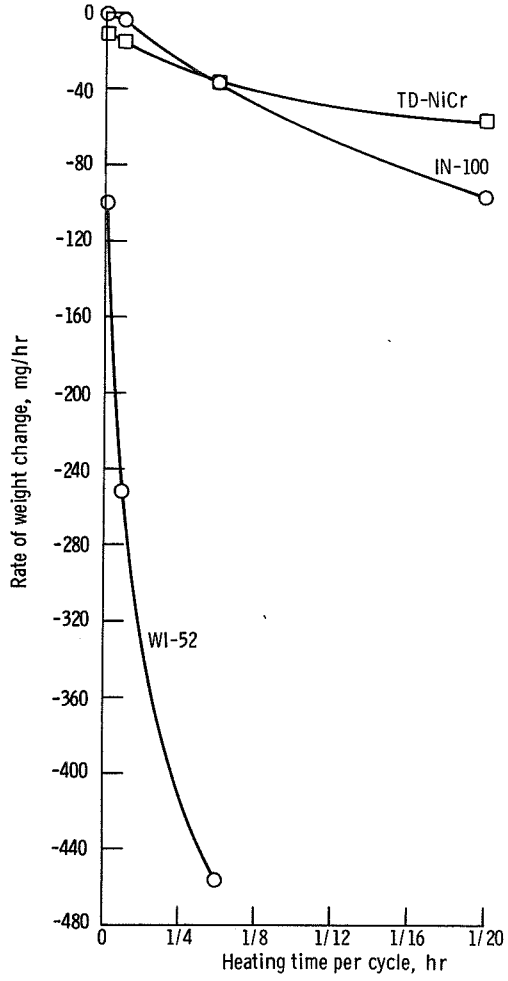


Figure 5. - Effect of heating time per cycle on rate of weight change of IN-100, TD-NiCr, and WI-52 after 40 hours exposure in high-velocity oxidation apparatus. Maximum cycle temperature, 1090° C; minimum cycle temperature, room; cooling air velocity, Mach 1 (350 m/s).

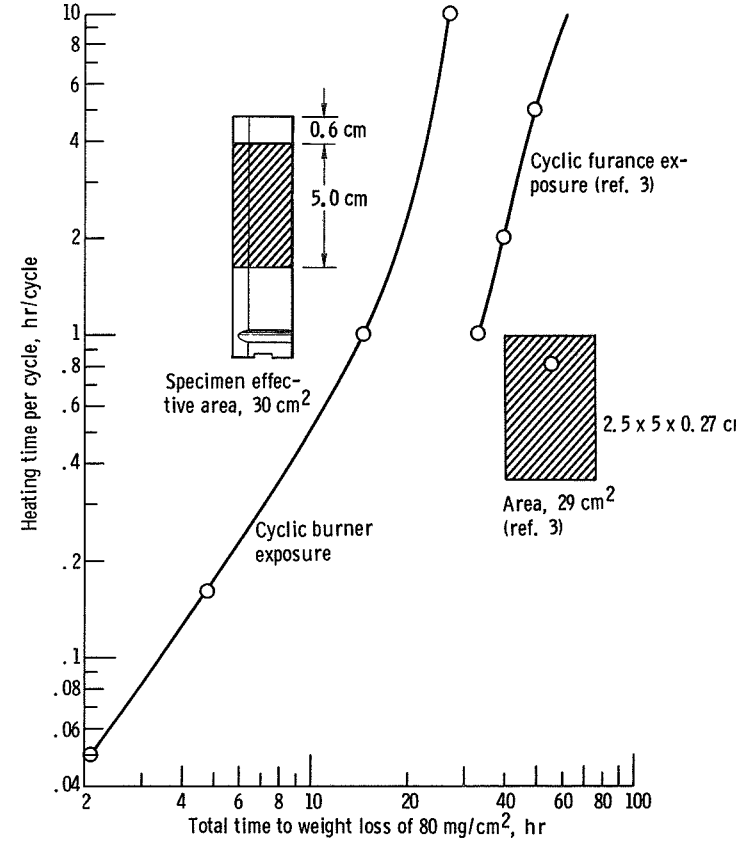
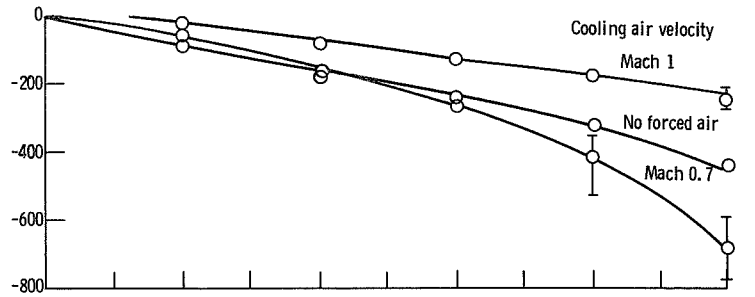
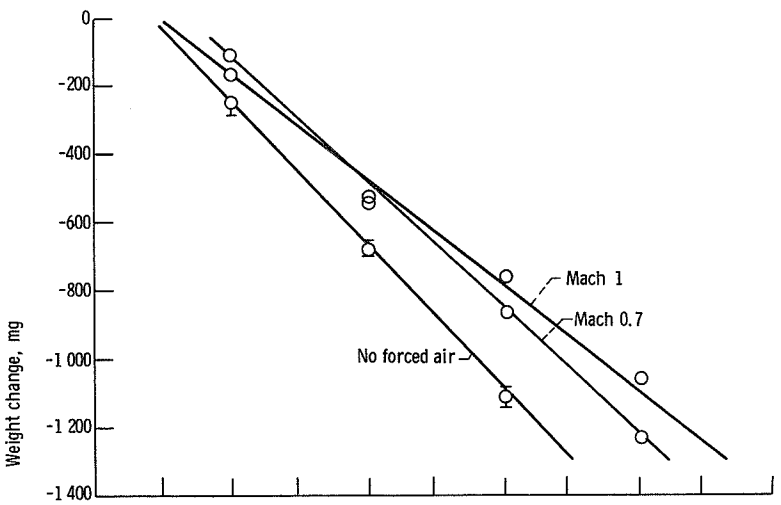


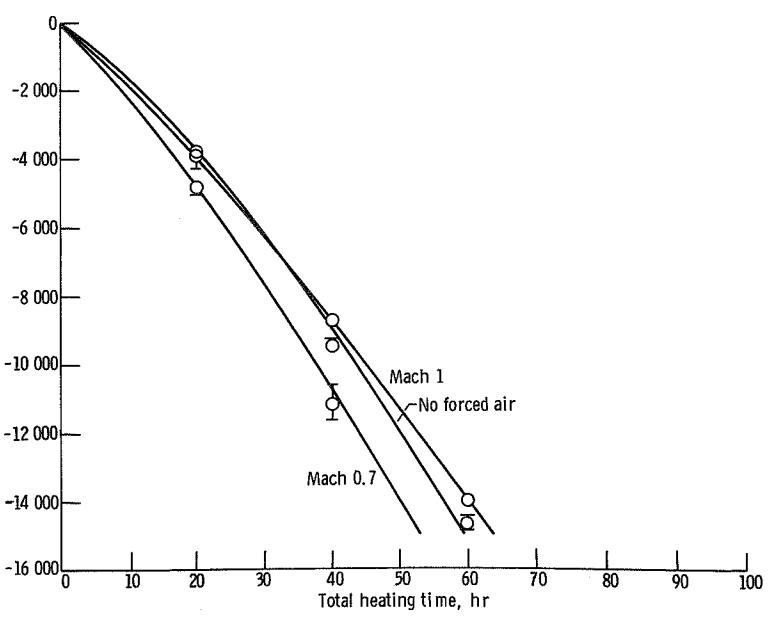
Figure 6. - Effect of heating time per cycle on total time to cause weight loss of 80 milligrams per square centimeter for WI-52 in high-velocity oxidation apparatus.



(a) IN-100.

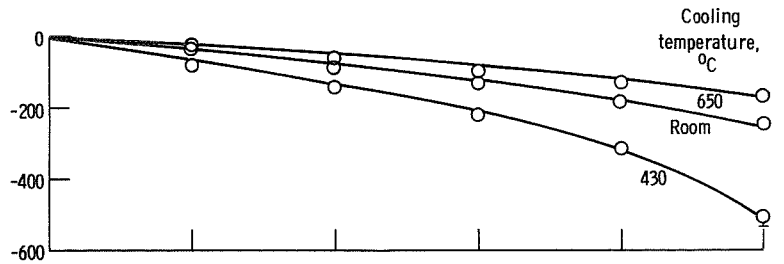


(b) TD-NiCr.

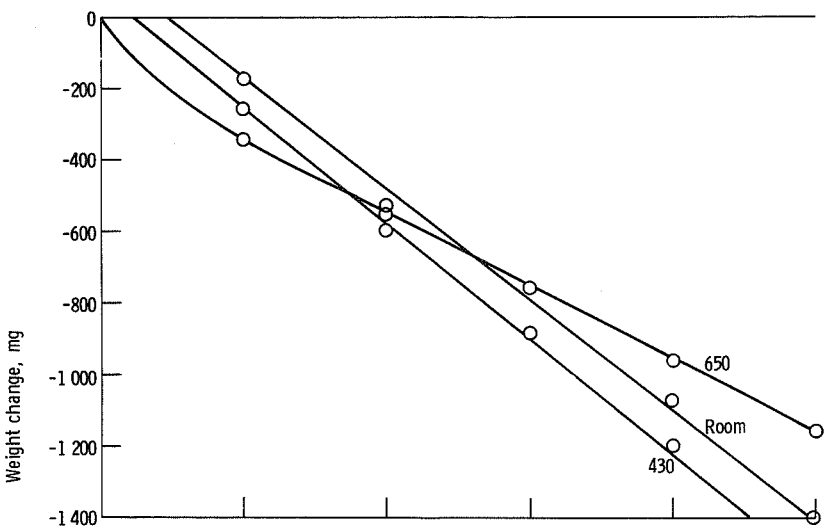


(c) WI-52.

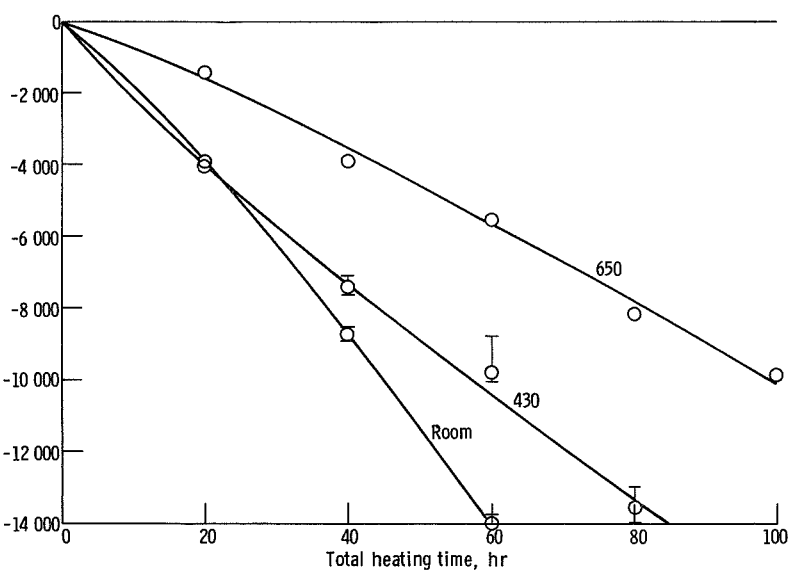
Figure 7. - Effect of cooling air velocity on weight change of IN-100, TD-NiCr, and WI-52 in high-velocity oxidation apparatus. Maximum cycle temperature, 1090° C; minimum cycle temperature, room; heating time per cycle, 1 hour.



(a) IN-100.



(b) TD-NiCr.



(c) WI-52.

Figure 8. - Effect of minimum cooling temperature on weight change of IN-100, TD-NiCr, and WI-52 in high-velocity oxidation apparatus. Maximum cycle temperature, 1090° C; cooling air velocity, Mach 1; heating time per cycle, 1 hour.

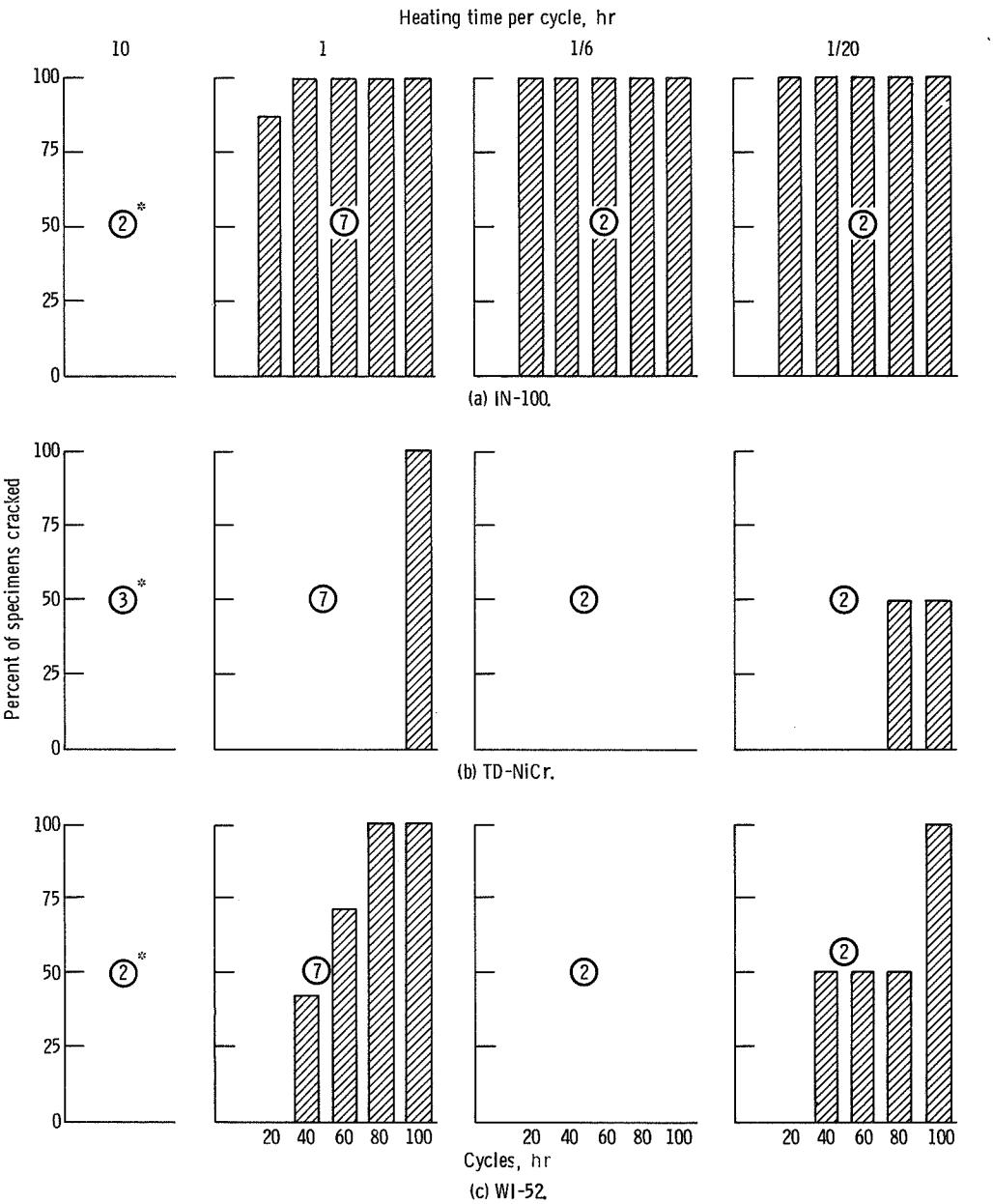


Figure 9. - Effect of heating time per cycle on thermal fatigue cracking. Maximum test temperature, 1090° C; minimum cycle temperature, room; cooling air velocity, Mach 1. Circled numbers are the number of specimens tested. Asterisks denote test run only 10 cycles.

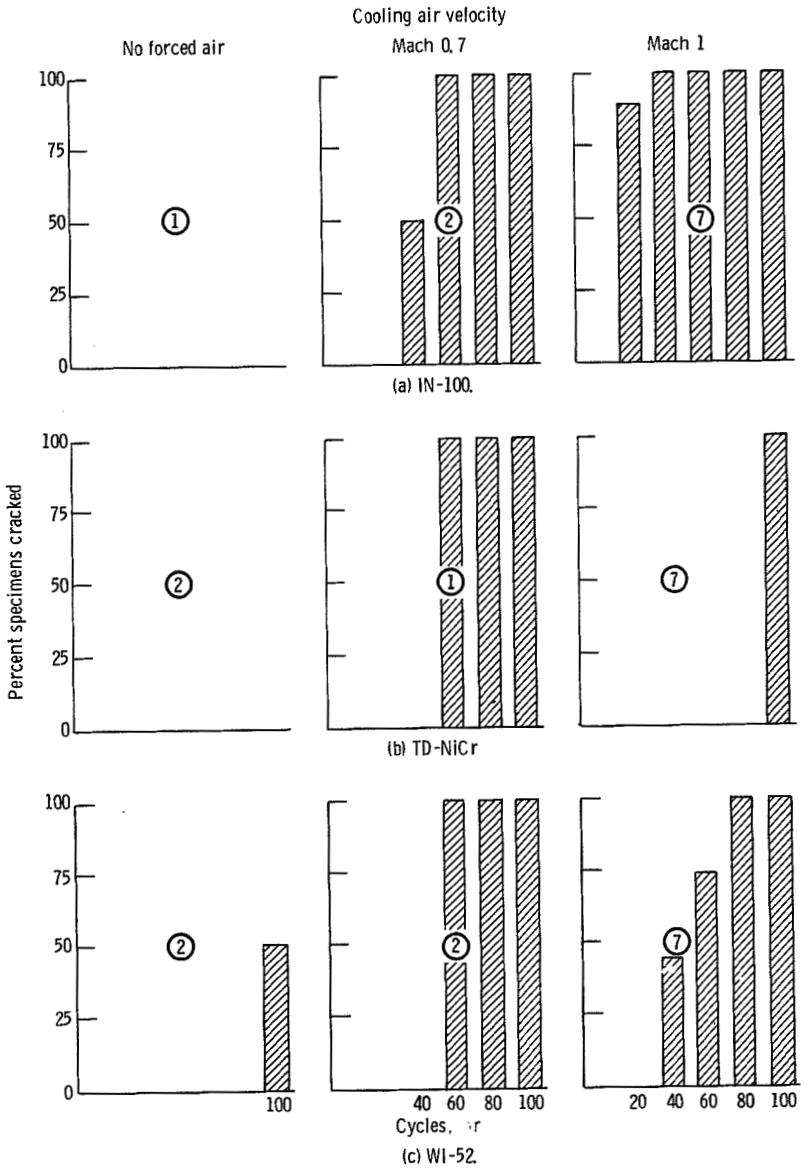


Figure 10. - Effect of cooling air velocity on thermal fatigue cracking. Maximum cycle temperature, 1090° C; minimum cycle temperature, room; heating time per cycle, 1 hour. Circled numbers are the number of specimens tested.

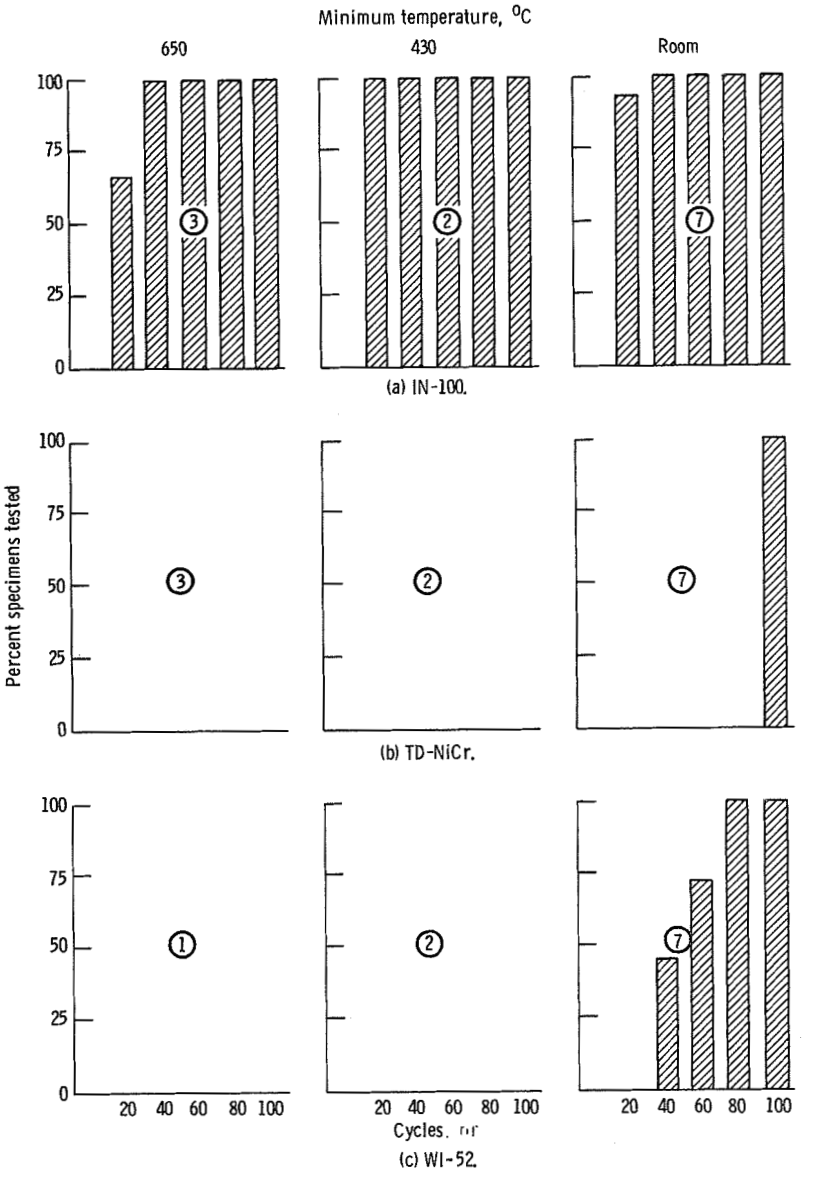


Figure 11. - Effect of minimum cooling temperature on thermal fatigue cracking. Maximum cycle temperature, 1090° C; cooling air velocity, Mach 1; heating time per cycle, 1 hour. Circled numbers are the number of specimens tested.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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