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MEMO 4-7-59E

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ENGINE OPERATING CONDITIONS THAT CAUSE THERMAL-FATIGUE CRACKS IN TURBOJET-ENGINE BUCKETS

By James R. Johnston, John W. Weeton, and Robert A. Signorelli

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Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON

April 1959

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ENGINE OPERATING CONDITIONS THAT CAUSE THERMAL-FATIGUE CRACKS IN TURBOJET-ENGINE BUCKETS*

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SUMMARY

Five engine tests were conducted to definitely establish the failure mechanism of leading-edge cracking and to determine which conditions of engine operation cause the failures. Five groups of S-816 and M-252 buckets from master lots were run consecutively in the same J47-25 engine. The tests included a steady-state run at full-power conditions, rapid cycling between idle and rated speed, and three different start-stop tests. The first start-stop test consisted of cycles of start and stop with 5 minutes of idle speed before each stop; the second included cycles of start and stop but with 15 minutes of rated speed before each stop; the third consisted of cycles of gradual starts and normal stops with 5 minutes at idle speed before each stop.

The test results demonstrated that the primary cause of leading-edge cracking was thermal fatigue produced by repeated engine starts. The leading edge of the bucket experiences plastic flow in compression during starts and consequently is subjected to a tensile stress when the remainder of the bucket becomes heated and expands. Crack initiation was accelerated when rated-speed operation was added to each normal start-stop cycle. This acceleration of crack formation was attributed to localized creep damage and perhaps to embrittlement resulting from overaging. It was demonstrated that leading-edge cracking can be prevented simply by starting the engine gradually.

INTRODUCTION

In the study of turbojet-engine material problems, the turbine bucket is generally considered the most critical component because it is subjected to the most severe environment. The very high rotational speeds and high gas temperatures produce a stress and temperature condition in the buckets which alone or in combination with other environmental conditions can result in excessive creep or in failure. In addition to centrifugal stresses, vibratory stresses are also usually induced in the airfoils of the buckets. Such stresses are produced by pulsations of the hot gases as they flow from the combustion chambers through the nozzle vanes and on to the rotating buckets. Thus, vibratory stresses are superimposed as a bending or torsional stress upon the centrifugal stress applied by the rotation of the turbine. Finally, transient conditions of engine operation subject the buckets to rapid changes of gas temperature so that relatively high thermal stresses may be produced in the bucket airfoils.

In turbojet-engine studies conducted by the NASA (formerly the NACA) over the last several years, much has been learned about the stress rupture and fatigue mechanisms as they affect bucket life. Relatively little has been learned about the influence of thermal stresses on the life of turbojet buckets. The vast majority of work conducted by the NASA has been done with the aid of a turbojet engine which subjects the buckets to relatively high centrifugal stresses. Bucket failures that have occurred in this type of engine have been either conventional stress-rupture-type failures or have had the characteristics of mechanical-fatigue failures. In more recent investigations by the NASA, in which an engine that produces low centrifugal stresses in the buckets has been utilized for materials studies, a different situation has arisen. The buckets of this engine have exhibited a multiplicity of small cracks at the leading edges. Such a large number of cracks and their position in the airfoil suggested that they were thermally induced cracks. In the first preliminary tests, it was found that leading-edge cracks, of the nature mentioned, occurred in very short times and were so extensive that the test procedure was modified to record the type of cracks and the crack progression. A subsequent engine test was conducted, and frequent bucket inspections of the leading edges were made. All buckets were removed at intervals from the engine and inspected for minute edge cracking. The results from the first published report of these studies (ref. 1) indicated that the leading-edge cracks were caused by thermal fatigue. In the report it was reasoned that centrifugal stress and vibratory stresses were of secondary importance in causing the leading-edge cracks. This was also true of oxidation and residual stresses induced during fabrication. The fact that a multiplicity of cracks occurred at the leading edges in areas in which centrifugal stresses were not high tended to show that the cracks were not predominantly of the stress-rupture type. The fact that mechanical-fatigue cracks, when they have occurred in buckets in the past, have formed usually one or two major cracks and not a multiplicity of cracks suggested that mechanical fatigue was not the predominant mechanism. Similarly, the other failure mechanisms were eliminated as probable causes of the leading-edge cracks.

In another research project it had been shown that the J47 engine, the engine used for the present thermal-fatigue investigation, produced large temperature gradients in leading edges of the bucket airfoils during normal engine starts, accelerations, and decelerations (ref. 2). The most severe gradients occurred during starting when the temperature difference between the leading edge and the midchord was 600° F. Calculations based on additional (unpublished) transient temperature measurements (including bucket skin temperatures) have indicated that during engine starts thermal stresses are sufficiently high to cause yielding of the bucket material at the leading edge. The transient temperature studies and the skin temperature studies have tended to verify the initial conclusions that the leading-edge cracks were of a thermal-fatigue type. However, it should be cautioned that all these tests do not definitely prove that the failures resulted from thermal fatigue.

Still other engine tests have been conducted (results in preparation for publication) at higher temperatures. Again these tests have shown that leading-edge cracking was a severe problem, and, again, indirect evidence was obtained to indicate that the cracks were caused by thermal fatigue. In these studies, the engine test temperatures were higher than those of the references mentioned earlier, and the times for the formation of the cracks were lower. In these latter tests and in the previous engine tests, the cracking of the leading edges was not limited to a specific material or alloy type. Cracks were observed in both forged and cast materials and in nickel- and cobalt-base alloys. Materials tested in the above-mentioned investigations were: S-816, M-252, Udimet 500, the Inconel series - 550, 700, and 713, and several experimental alloys.

The purposes of the investigation reported herein are: (1) to prove that the leading-edge cracks which may be produced on the edges of the J47 buckets are thermal-fatigue cracks, (2) to determine the exact portion of the engine operating cycle primarily responsible for the initiation of the cracks, (3) to determine if other portions of the engine operating cycle may contribute to the crack formation or to the time of initiation, and (4) to suggest possible remedial measures to alleviate the cracking problem.

Buckets of M-252 and S-816 were tested in a J47-25 engine. The two materials were chosen because they were readily available in large lots and because they differed considerably in susceptibility to leading-edge cracking. The engine used was selected because it was a model in which cracking had occurred in relatively short periods of operation.

Five engine tests were performed during the investigation. These were conducted in the following manner. The first test consisted of a steady-state operation of a set of buckets at rated-speed or full-power conditions. The second consisted of rapid cycling of the engine between idle and full-power conditions. The third consisted of cycles of starting the engine, running it for 5 minutes at idle speed, and stopping.

The fourth consisted of cycles of starting the engine, running for 15 minutes at rated speed, and stopping; and the fifth consisted of cycles of starting the engine gradually, running for 5 minutes at idle speed, and stopping. Prior to each of the five tests, a new group of buckets was installed in the engine. All the buckets in the investigation came from the same master lots.

MATERIALS, APPARATUS, AND PROCEDURE

Turbine Buckets

The turbine buckets used in this investigation were standard J47-25 buckets forged from S-816 (AMS-5765A) and M-252 alloys having the following nominal compositions by weight percent:

Alloy	Cr	Ni	Co	Mo	W	Fe	Cb	Ti	Al	C
S-816	20	20	44.8 (Balance)	4	4	2.8	4.0	---	---	0.4
M-252	19	55.4 (Balance)	10	10	-	2	---	2.5	1.0	0.1

The buckets were obtained from two sources. The M-252 buckets were received in one lot from the fabricator. Although obtained directly from the manufacturer, the M-252 buckets were from production lots which would normally supply Air Force stock. The S-816 buckets were randomly selected from Air Force stock. The buckets had received the standard production heat treatments and were tested in the as-received condition.

The master lots of buckets were divided by random selection into five equal groups, one of which was used in each of the five engine tests. In each test there were 25 M-252 and 69 S-816 buckets.

Before installation into the test engine, the buckets were inspected for surface flaws using postemulsified zyglo. All buckets used in the tests were free of surface defects within the sensitivity of the inspection process. At appropriate intervals throughout each engine test the buckets were removed from the engine and reinspected to detect cracks which formed during engine operation. The inspection interval varied with the type of test as indicated later in the descriptions of of engine operation.

Stress and Temperature Distribution in Buckets

The centrifugal stress and temperature distributions in the bucket airfoil at rated engine conditions are shown in figure 1. The stress calculations were made using rotational speed, material density, and bucket geometry (ref. 3). The temperature distribution in the test engine was obtained with a spare turbine wheel prior to the installation of the test wheels. Six thermocouples were imbedded in the bucket airfoils to provide the spanwise temperature profile. By using the stress and temperature distribution in the bucket and stress-rupture data for the material, expected failure time can be computed for various sections along the airfoil span. The point with the lowest expected life is the critical zone; that is, the zone where fracture would occur if temperature and centrifugal stress were the only factors contributing to failure. The critical zone was given (for similar stress and temperature data) in reference 1 as centered at approximately 1.5 inches from the base of the airfoil. The expected life in the critical zone was greater than 10,000 hours.

The bucket material temperatures were not measured during the transient portions of the tests. It is believed, however, that the transient temperatures encountered were similar to those reported in reference 2.

Engine Operation

The five tests of this investigation were run consecutively in the same engine. The engine was not altered in any manner between tests except for modifications to the fuel controls as described later.

Engine speed was controlled during the idle and rated conditions at 3000 and 7950 rpm, respectively. Engine gas temperature was regulated by use of a variable-area exhaust nozzle. Turbine bucket temperatures were monitored by two thermocouples embedded in bucket airfoils. During the idle and rated-speed conditions, the bucket temperatures at the critical zone (1.5 in. from base) were controlled at 1000° F and 1440° F, respectively. These temperature levels correspond to allowable service conditions in military engines.

Steady-state test. - Before installation of the first group of test buckets, the engine was operated with a spare turbine wheel in order to detect any malfunctions that would cause premature shutdowns. In addition, the engine was equipped with an auxiliary oil supply to permit operation for times longer than normal.

The test engine was started as gently as possible with the standard fuel control in order to avoid excessive exhaust gas temperatures and was accelerated gradually to rated speed. This was done to minimize the effect of transient conditions on the buckets. The engine was operated continuously at rated speed until the inspection interval of 72 hours was reached or until an emergency shutdown was required. In most cases, the engine did not run the full 72 hours without a shutdown. Unplanned shutdowns resulted from malfunctioning of the engine accessories and thermocouple instrumentation and from the general deterioration of the tailcone and exhaust pipe sections, which required frequent repairs. However, a total test time of 360 hours was accumulated with only nine starts and stops for an average of 40 hours per start.

Rapid cycle test. - In this test a new group of buckets was installed in the engine and operated through cycles of rapid acceleration and deceleration between idle and rated speed. The total time of each complete cycle was $1\frac{1}{2}$ minutes: 15 seconds each for acceleration and deceleration and 30 seconds hold at each speed (idle and rated). In order to relieve the engine operators of the necessity of manually controlling the engine cycles, an automatic actuator was linked to the fuel regulator. However, the fuel regulator continued to govern the rate of acceleration in the normal manner.

It was desired to shut down the engine only at regular periods of 250 cycles ($6\frac{1}{4}$ hr) in order to inspect the buckets for cracks; however, several unplanned shutdowns were required for engine maintenance. During the test, the engine had been started gently and shut down a total of 14 times. The test was terminated after 1984 cycles.

Start-stop test. - A third group of new buckets was installed in the engine and subjected to repeated cycles of normal starts and shutdowns. The engine was held at idle speed for 5 minutes before each shutdown. Since the fuel control valve of the engine is manually governed during the starts, the maximum engine temperature attained depends upon the experience and skill of the operator. For these tests, the operator was required to hold the maximum exhaust gas temperature between 1400° and 1500° F. In military service this is considered a normal start for the engine. A cooling period was required between starts to allow the buckets to approach room temperature. To permit a reasonable number of start cycles each day, it was necessary to restart while the buckets were still warm, but in every case the buckets were cooled below 200° F.

The buckets were removed for inspection at intervals of approximately 40 cycles. The test was terminated after 425 cycles at which time 84 percent of the buckets of one alloy had developed leading-edge cracks.

Start - rated-speed - stop test. - The fourth group of buckets was subjected to cycles of starting and stopping with the addition of 15 minutes at rated speed before each shutdown. In this case the engine was accelerated and decelerated gradually between idle and rated speeds in order that no large thermal stresses would result from these transients.

The inspection period was shortened to intervals of 20 cycles because cracks were expected to form more readily in this type of operation. The test was completed after 200 cycles when 76 percent of the buckets of one alloy exhibited cracking.

Gradual-start - normal-stop test. - The final group of test buckets was operated through start-stop cycles as in the case of the third test, except that the severity of engine starts was greatly reduced. In order to start the engine more gradually than normal (i.e., to raise the temperature at a significantly lower rate), it was necessary to alter the fuel system.

In the standard-engine fuel system, duplex fuel nozzles in all eight combustors are supplied by two common manifolds. In the standard engine, fuel is supplied only to the small slots while starting in order to limit the fuel flow in each combustor. However, the fuel flow necessary to sustain combustion causes the engine temperature to rise very rapidly. To prevent this rapid temperature rise, a distributing valve was designed to supply fuel to each combustor nozzle in sequence. This permitted the engine to ignite on one combustor and the engine temperature to increase gradually as each succeeding nozzle was supplied with fuel. A comparison of the exhaust gas temperatures for the gradual start and a normal start is shown in figure 2.

The buckets were inspected at intervals of about 40 cycles up to 500 starts after which the period was increased to each 100 cycles. The test was terminated after 900 cycles failed to cause bucket cracking.

Metallographic Examination

Two buckets each of M-252 and S-816 from both the start-stop test and the start - rated-speed - stop test (eight buckets total) were sectioned for metallographic examination. Photomicrographs were taken to illustrate typical microstructures near the leading edge in cracked buckets. For comparison purposes, two unused buckets of each alloy were also sectioned to obtain typical microstructures of the as-recieved materials.

RESULTS

The results from the five engine tests are summarized in table I together with the time at rated speed and the number of starts for each test. Leading-edge cracks were observed in only two of the tests: the normal-start - stop test and the test in which rated-speed operation was added to each start-stop cycle. Since there was no indication of crack initiation in any of the other three tests, they were terminated after reasonably long test periods. In these cases, when no cracks were produced, the tests were continued until the total time at rated speed or the total number of cycles was about an order of magnitude greater than the values which were known to cause cracking in typical endurance tests (ref. 1).

Leading-Edge Cracking

During the normal-start - stop test, cracks were first observed in the M-252 buckets at 85 cycles and in the S-816 buckets at 295 cycles. At the end of the test (425 cycles), 84 percent of the M-252 buckets and about 9 percent of S-816 buckets were cracked. A series of photographs was taken (figs. 3(a), (b), and (c)) of a typical group of M-252 buckets to indicate the type of cracks observed and to show the extent of crack propagation. In general, the cracks in M-252 propagated gradually to an appreciable depth; the maximum depth of the deeper cracks was 1/8 inch. The cracks in S-816 were less severe, usually about 1/32 inch or less in depth. Many cracks propagated to their maximum depth relatively early in the test.

During the start - rated-speed - stop test (in which 15 min of rated-speed operation were added to each start-stop cycle), cracks were first noted in the M-252 buckets at 40 cycles and in the S-816 buckets at 63 cycles. At the end of the test (200 cycles and 50 hr at rated speed), cracks were observed in 76 percent and 32 percent of the M-252 and the S-816 buckets, respectively. Figure 4 shows the leading-edge cracking in typical M-252 and S-816 buckets during this test. The maximum depth of crack propagation was 3/8 inch in the M-252 and 1/2 inch in the S-816 buckets. These deep cracks were not typical of all the buckets. The average maximum crack depth for all the cracked buckets in this test was about 3/32 inch for M-252 and about 1/8 inch in S-816. None of the cracks propagated to complete fracture.

Microstructure of Cracked Buckets

Typical microstructures of untested buckets of S-816 and M-252 are shown in figure 5. The structures appear to be normal for the as-heat-treated condition of each alloy. The microstructures of both alloys run in the start-stop test (fig. 6(a)) exhibit agglomeration and spheroidization of grain boundary precipitates, but the hyphenation of grain boundaries is more pronounced in M-252. The S-816 bucket indicates a slight tendency to form precipitation along slip lines. Figure 6(b) shows the microstructure of cracked buckets after operation in the engine test in which 15 minutes of rated time were added to each start-stop cycle. In the case of M-252, the microstructure is not greatly different from that of the bucket from the start-stop test, but there appears to be slightly more matrix precipitation along residual grain boundaries. The microstructure of the S-816 bucket from the start - rated-speed - stop test contains definite evidence of overaging. In addition to the grain boundary hyphenation, there is considerable matrix precipitation, especially along slip lines.

Buckets of both M-252 and S-816 from the start - rated-speed - stop test contained clusters of voids along the grain boundaries in areas close to the leading edge. Some of these voids are apparent in the photomicrographs of figure 6(b). There was no significant evidence of voids in either alloy operated in the start-stop engine test.

DISCUSSION

The results of this investigation showed that the leading-edge cracks in buckets result from thermal fatigue produced by repeated cycles of starts and stops. This is evidenced by the fact that cracks were produced in a test consisting only of cycles of starting, running the engine at idle for 5 minutes, and stopping. Since the centrifugal stress at idle speed is trivial (2000 against 13,000 psi at rated speed), it is logical to assume that any damage that occurred during the start-stop test was due primarily to cyclic thermal stresses. Also, the temperature of the buckets at idle speed is quite low, on the order of 1000° F, so that oxidation can be excluded as an important factor. In addition, it was shown that mechanical vibration did not contribute appreciably to the initiation of leading-edge cracks. This was demonstrated by the fact that cracks were not initiated by continuous operation at rated speed and temperature or by a great number of acceleration-deceleration cycles (between idle and full power). Also, the relatively long time of idle speed accumulated during the gradual-start - normal-stop test did not initiate cracks. These types of operation would have been most likely to induce vibration in the buckets.

It was also shown that engine starting alone was chiefly responsible for the crack formation. This was demonstrated by the gradual-start - normal-stop test in which 900 cycles failed to initiate any cracks, whereas only 85 normal-start - stop cycles were sufficient to cause crack formation. It follows from these results that normal stops alone cannot initiate cracks and, hence, that most of the damage occurs during the normal engine starts.

The one unique feature of engine starts is the very high temperature gradients which they induce into the bucket airfoil during the rapid heating almost immediately after ignition. It has been shown (ref. 2) that the temperature gradient across the chord during starts is appreciably more severe than those that occur during any other transient thermal condition which the engine experiences. The presence of these large temperature gradients and the resulting high thermal stresses during starting plainly indicates why engine starts can cause thermal-fatigue failure of the leading edge.

Since surface cracks of the type observed on the buckets are generally associated with tensile stresses, it may not be obvious how they are caused by a heating cycle (engine starts) where surface thermal stresses are compressive. The following discussion is believed to explain adequately the formation of tensile stresses in the leading edges of buckets upon heating. Upon engine starting, the sudden impingement of hot gases onto the leading edge of the bucket causes the temperature to rise in this region more rapidly than the bucket temperature as a whole. The leading-edge material tends to elongate as a consequence of this temperature rise but is partially restrained by the more massive relatively cool portions of the bucket. Consequently, a compressive stress will be induced into the outer fibers of the leading edge. If the heating conditions are very severe, the compressive stress will be sufficient to cause local plastic deformation at the leading edge. Then as the bulk of the airfoil becomes heated to a uniform temperature, the portion of the leading edge that experienced plastic flow in compression will be stretched by the thermal expansion of the interior portion of the airfoil. This will create a residual tensile stress at and near the surface of the leading edge. During stopping or cooling of the engine, additional stresses would be induced in the leading edge.

The results further showed that engine operation at rated speed and temperature accelerated the formation of leading-edge cracks. The addition of 15 minutes of rated-speed operation to each start-stop cycle reduced the number of cycles to cause cracks from 85 to 40 for M-252 and from 295 to 63 for S-816. The total rated-speed times in these instances were 10 hours and 15 hours for M-252 and S-816, respectively. Since these times are trivial in comparison with the expected rupture life of the bucket material under the full-power engine conditions (over 10,000 hr), it cannot be expected that the reduction in cycles to cause cracking was due to the attrition of the nominal stress-rupture strength of the alloys. It is more reasonable to conclude that the damage which occurred during engine operation at rated conditions resulted from the combination of the residual stresses caused by each start and the high temperature at rated speed. As discussed previously, it is believed that each engine start induces a residual tensile stress into the leading-edge portion of the bucket. When the engine is subsequently operated at high speed and temperature, this part of the bucket is subjected to a much higher tensile stress than the nominal stress in the major portion of the bucket airfoil. Of course, the time that the high residual stress is present may be very short since localized creep may relax the stresses at the leading edge. However, the damage will be cumulative because the next start will induce new residual stresses in the leading edge, and the process will be repeated.

The hypothesis of localized creep damage at the leading edge is supported by the appearance of voids in the grain boundaries (fig. 6(b)) of buckets run in the start - rated-speed - stop test. These voids are sometimes noted in rupture specimens (ref. 4) and are considered to be evidence of third-stage creep. Similar voids also have been noted in buckets which failed by a similar mechanism in other engine tests (ref. 5). Since the voids occur only in the areas close to the leading edge where the high thermal stresses are induced during starts, it seems reasonable to associate the creep damage with the stresses that arise as a result of engine starts.

There is some evidence that microstructural changes aside from creep damage may also have contributed to the earlier cracking of the buckets run in the start - rated-speed - stop test. As noted in the results, the photomicrographs in figure 6(b) indicate a more advanced state of aging than was evident in the buckets from the start-stop test (fig. 6(a). In the case of S-816, the structure appears definitely overaged. The evidence of overaging is not apparent in the M-252 structure, but it is possible that there were submicroscopic effects in M-252 involving precipitation of intermetallic compounds. It is possible that overaging caused some embrittlement of the bucket materials (run in the start - rated-speed - stop test) and reduced their resistance to failure by thermal fatigue.

Another significant result of the series of engine tests was the demonstration that leading-edge cracking was prevented by reducing the severity of the engine starts. It was shown, by incorporating a simple distributing valve into the fuel system and by permitting an additional 90 seconds for starting, that the engine could be started without a rapid rise in gas temperature (fig. 2). It appears that this reduction in the rate of gas temperature rise reduced the thermal stresses in the buckets sufficiently to preclude failure by thermal fatigue. The simplicity of this remedy suggests that it might be considered for use on jet engines in applications where the slight extra time could be tolerated. It should be possible to do this in commercial types of aircraft and in some military vehicles such as bombers and trainers.

CONCLUSIONS

A series of engine tests was conducted to definitely establish the failure mechanism of leading-edge cracking and to determine which conditions of engine operation cause the failures. Buckets of M-252 and S-816 were tested in a J47-25 engine. The test program yielded the following conclusions:

1. Thermal fatigue was definitely established as the failure mechanism responsible for the initiation of leading-edge cracks. It was shown that engine starts were chiefly responsible for the crack formation. The leading-edge material of the bucket experiences plastic flow in compression during engine starts as a result of the rapid increase in the temperature of the thin leading edge and consequently is subjected to a tensile stress when the remainder of the bucket becomes heated and expands.

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2. Leading-edge crack formation was accelerated when engine operation at rated speed and temperature was added to each stop-start cycle. The accelerated crack initiation was attributed to localized creep damage at the leading edge and possibly to embrittlement resulting from overaging.

3. It was possible to eliminate (or drastically reduce) thermal-fatigue cracking by the simple expedient of starting the jet engine slowly. It should be possible to do this in commercial types of aircraft and in some military vehicles such as bombers and trainers.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, January 13, 1959

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TABLE I. - ENGINE TEST RESULTS

Test number	Type of test	Total time at rated speed, hr	Total number of starts	Time to first crack				Percent buckets cracked at end of test	
				M-252		S-816			
				Number of starts	Hours rated speed	Number of starts	Hours rated speed	M-252	S-816
1	Steady-state	360	9	No cracks	No cracks	No cracks	No cracks	0	0
2	Rapid-cycle[a]	16	14	No cracks	No cracks	No cracks	No cracks	0	0
3	Start-stop	0	425	85	0	295	0	84	9
4	Start - rated-speed - stop	50	200	40	10	63	16	76	32
5	Gradual-start - stop	0	900	No cracks	No cracks	No cracks	No cracks	0	0

[a]1984 Cycles between idle and rated.

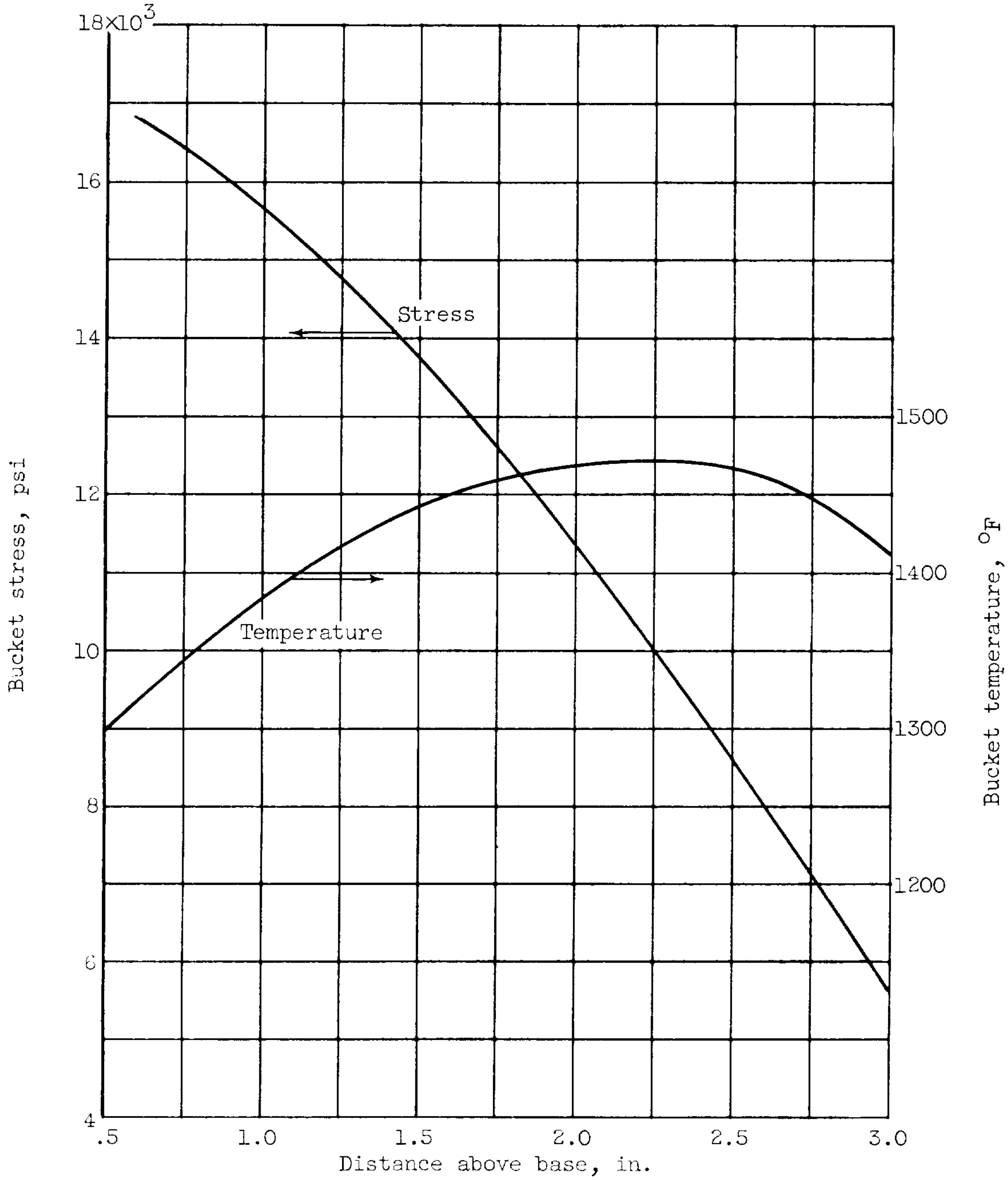


Figure 1. - Distribution of centrifugal stress and temperature in J47 turbine bucket at rated-speed conditions.

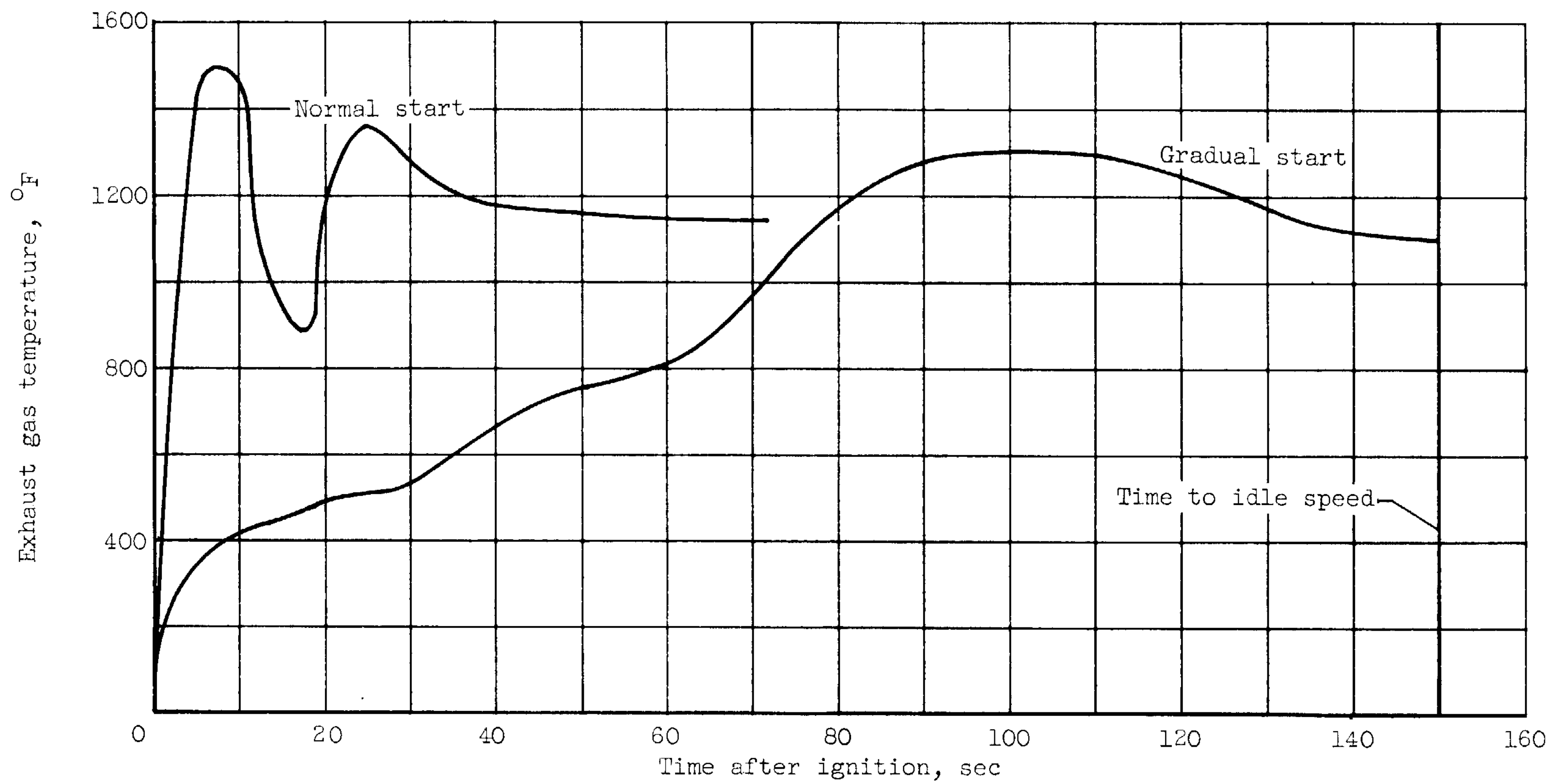
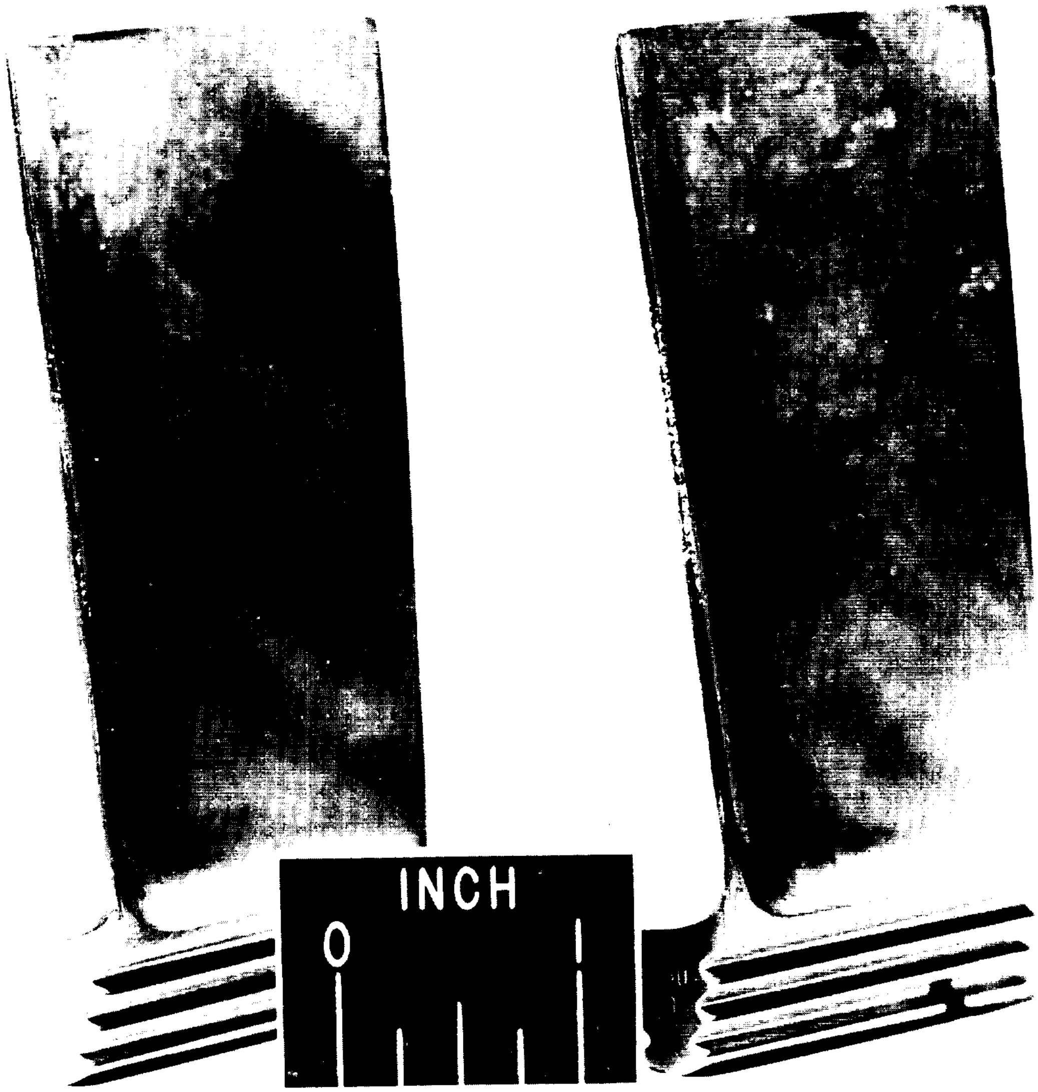


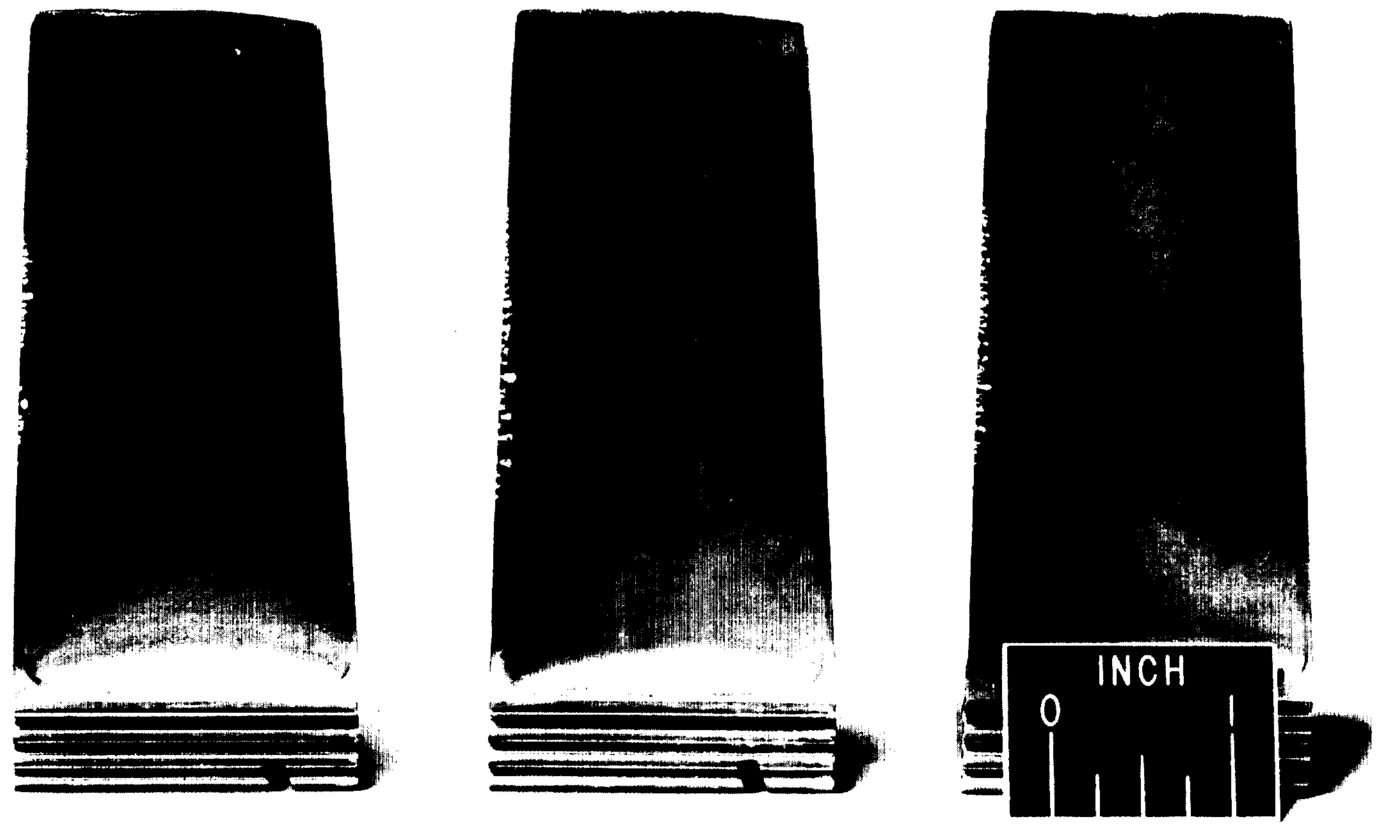
Figure 2. - Exhaust gas temperature during normal and gradual starts of J47 engine.



C-43052

(a) Inspection, 115 starts.

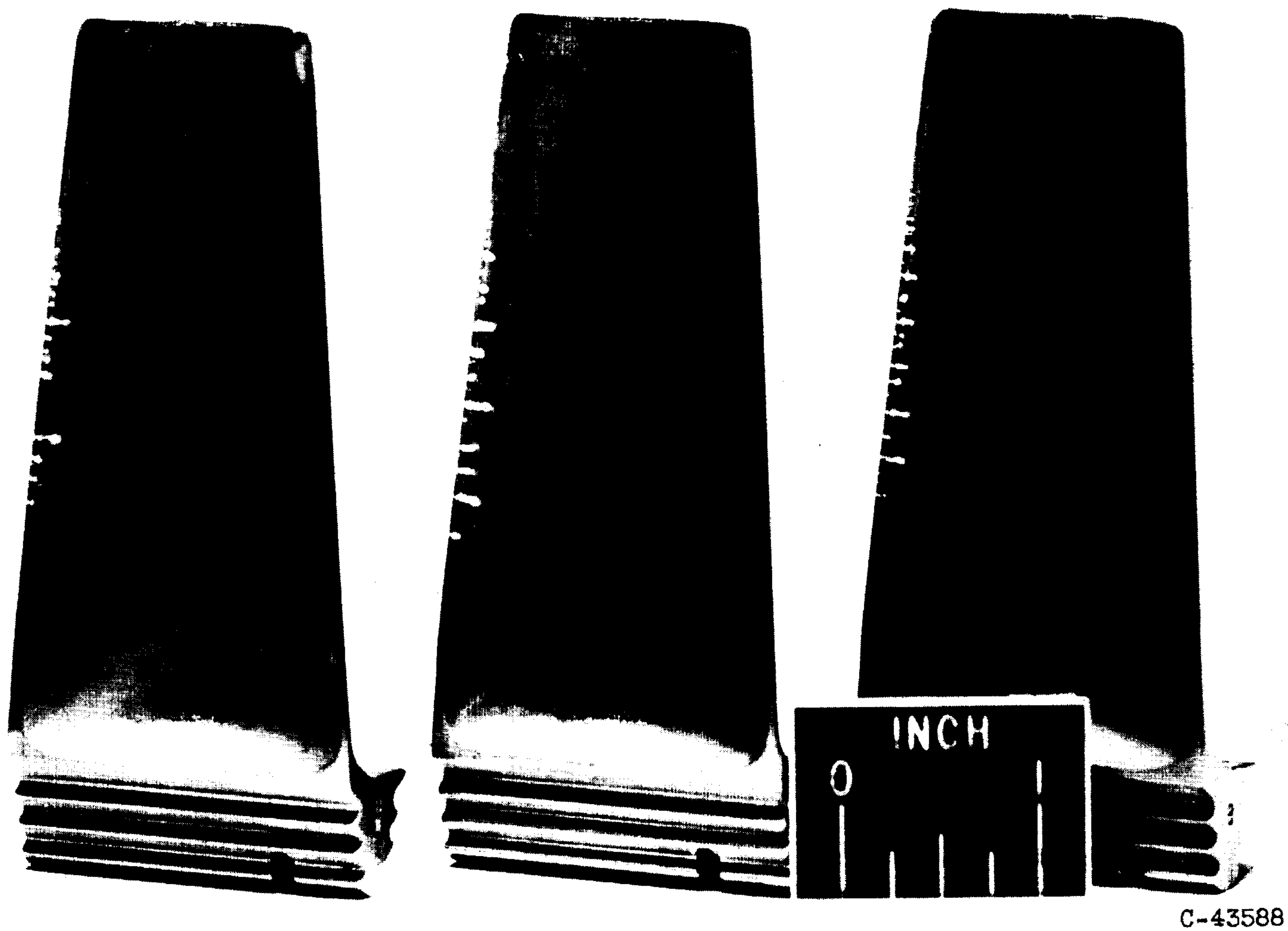
Figure 3. - Progression of cracks in M-252 buckets during start-stop test.



C-43142

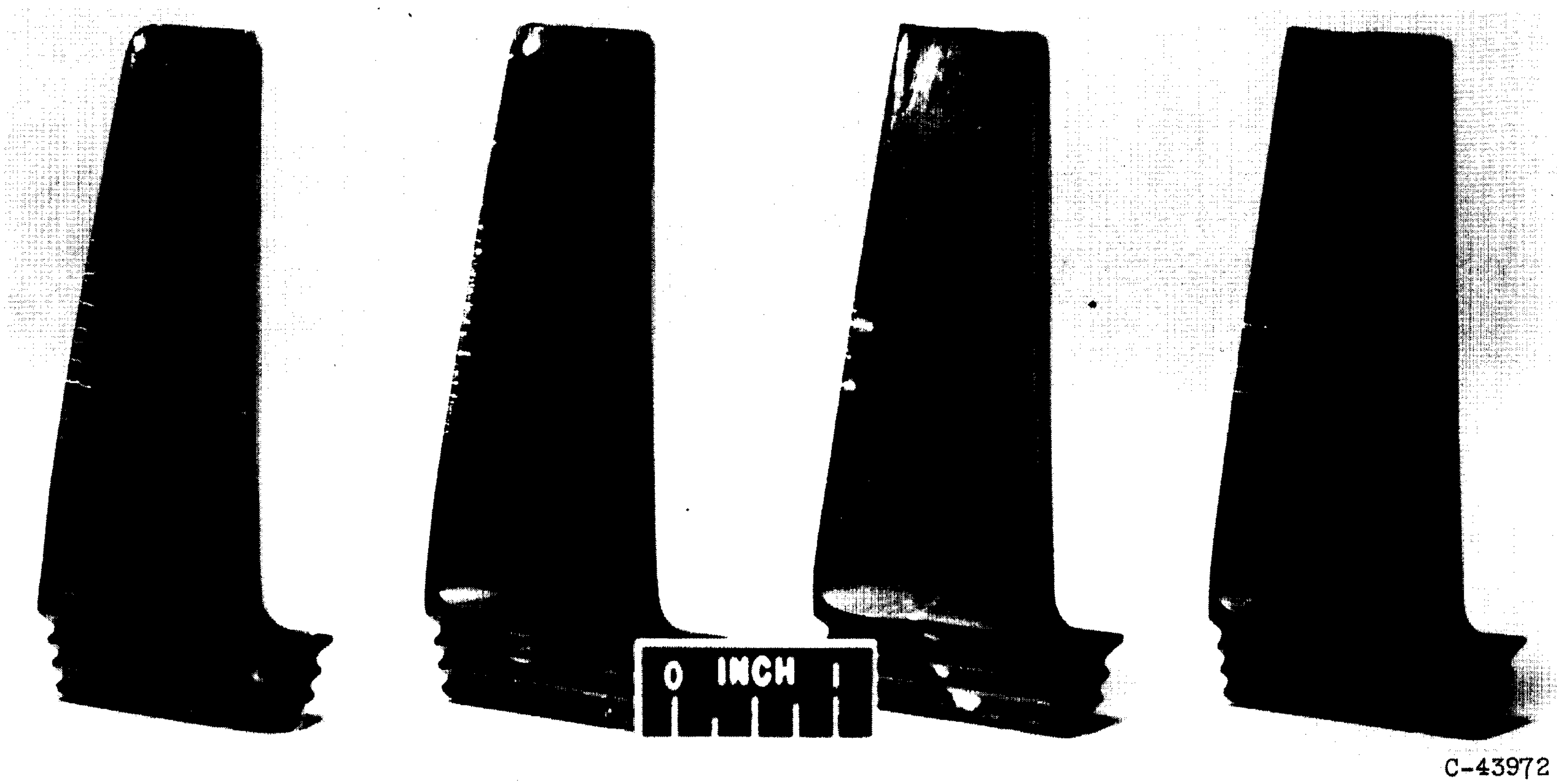
(b) Inspection, 205 starts.

Figure 3. - Continued. Progression of cracks in M-252 buckets during start-stop test.



(c) Inspection, 425 starts.

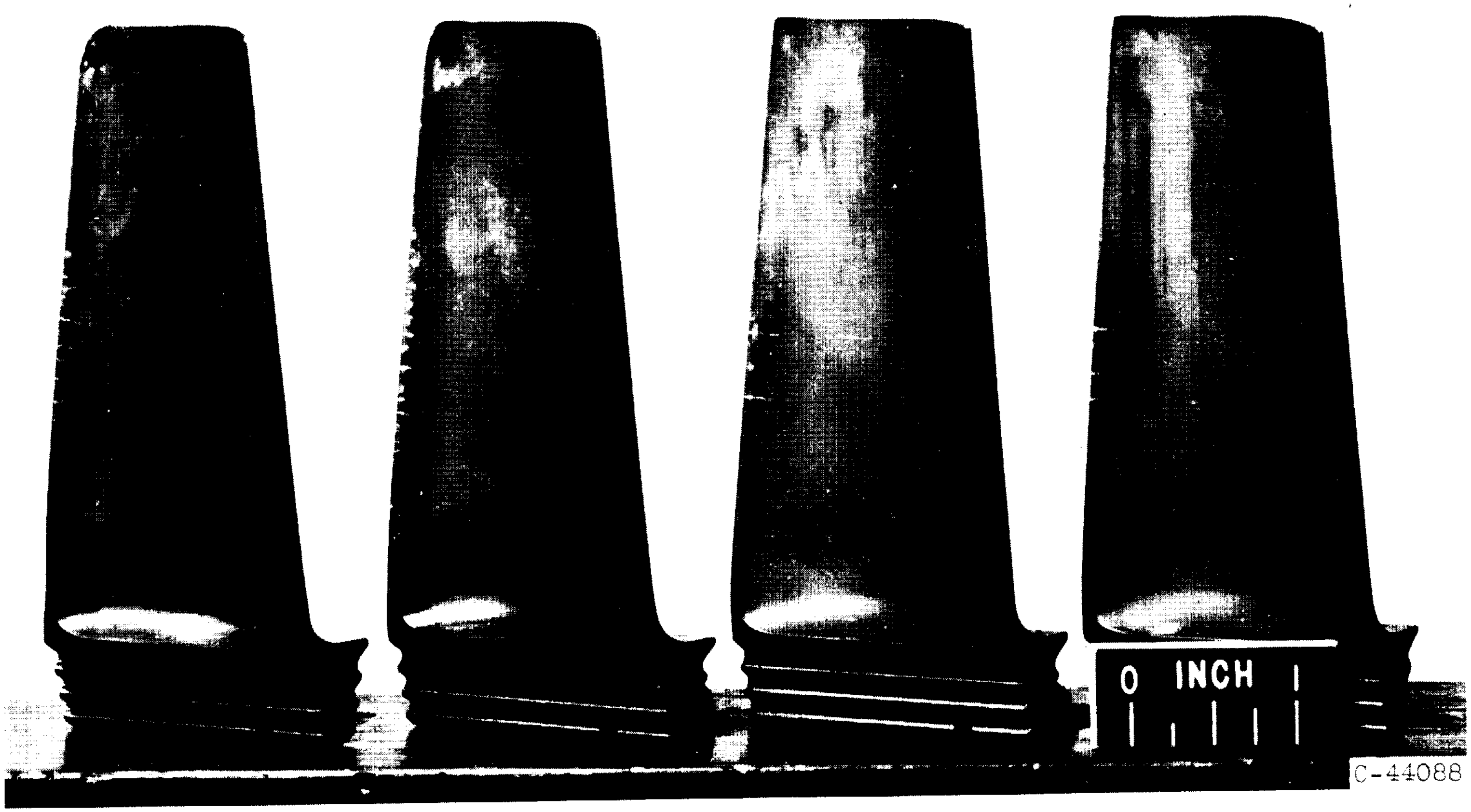
Figure 3. - Concluded. Progression of cracks in M-252 buckets during start-stop test.



M-252 M-252 S-816 S-816

(a) Inspection, 100 starts, 25 hours.

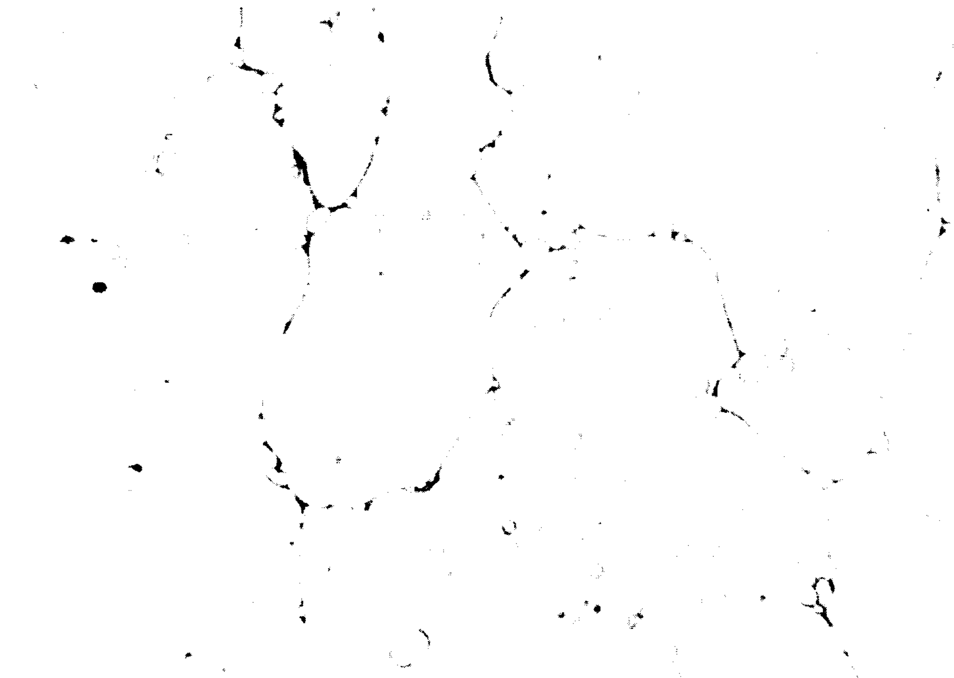
Figure 4. - Progression of cracks in M-252 and S-816 buckets during start - rated-speed - stop test.



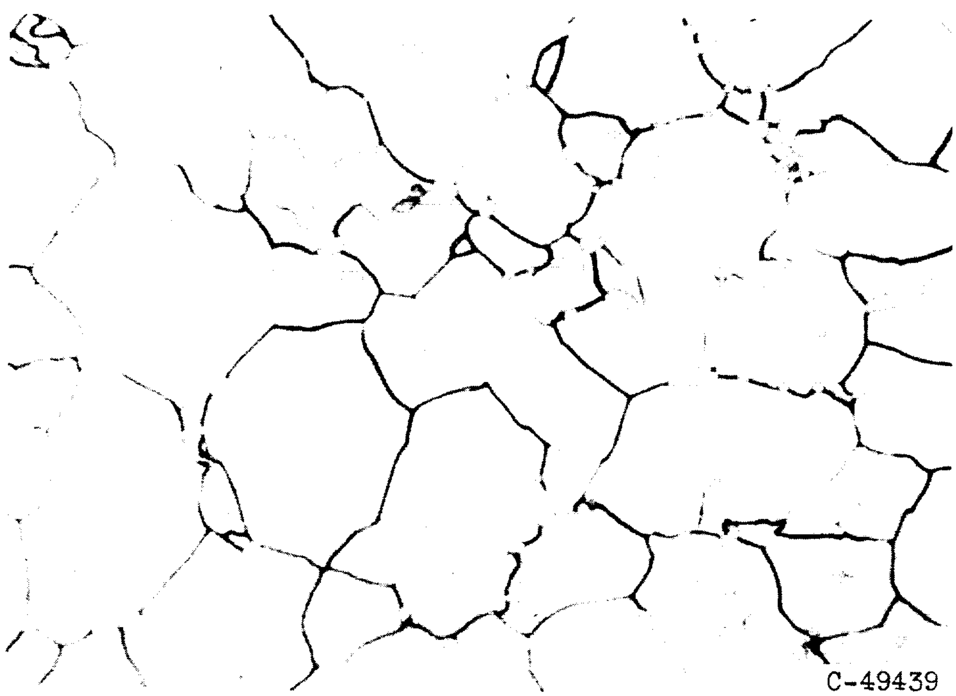
M-252 M-252 S-816 S-816

(b) Inspection, 200 starts, 50 hours.

Figure 4. - Concluded. Progression of cracks in M-252 and S-816 buckets during start - rated-speed - stop test.

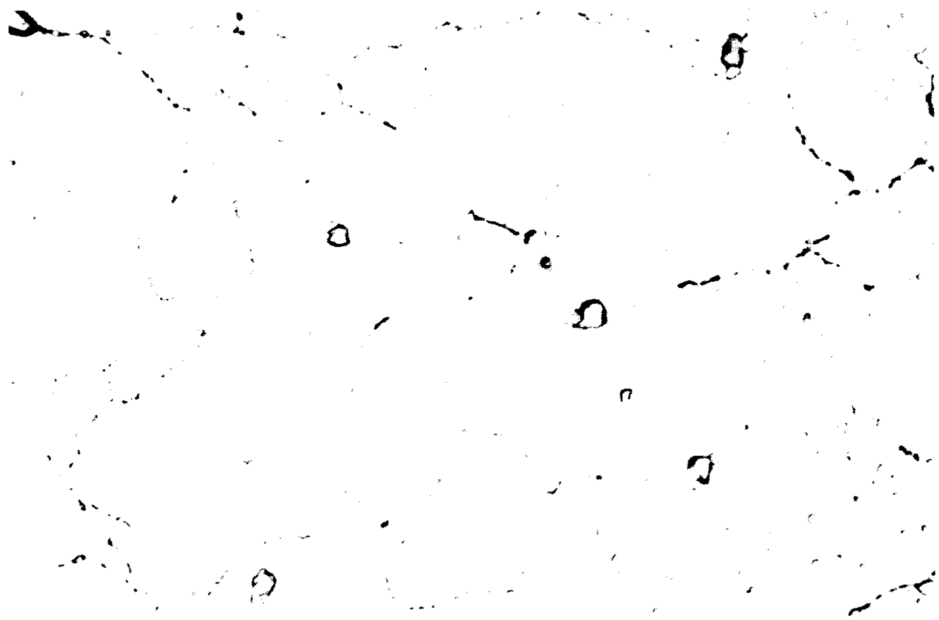


(a) M-252. Etchant, 92 percent HCl - 5 percent H_2SO_4 - 3 percent HNO_3.

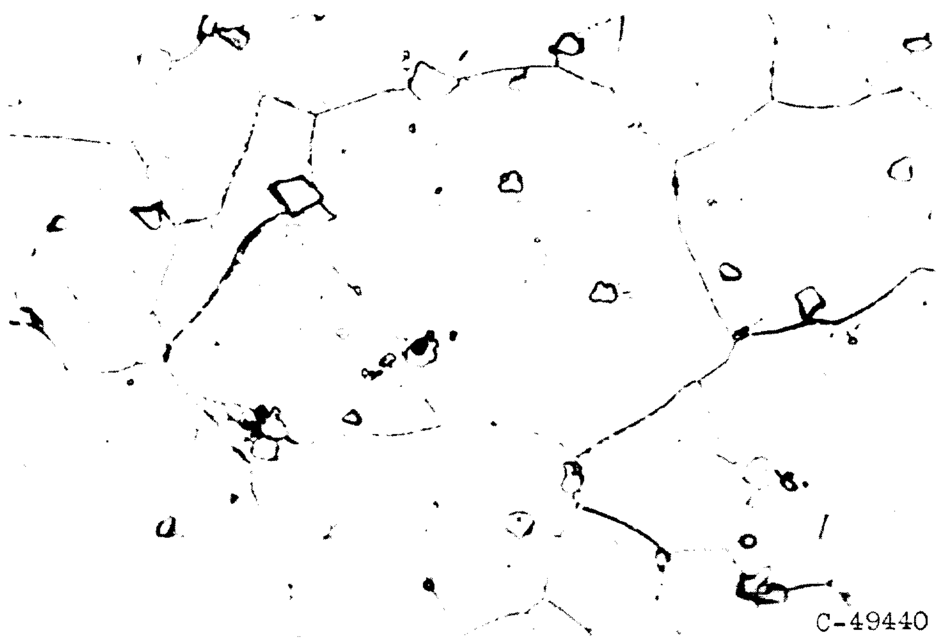


(b) S-816. Etchant, aqua regia plus glycerol.

Figure 5. - Microstructures of as-received buckets. X750.



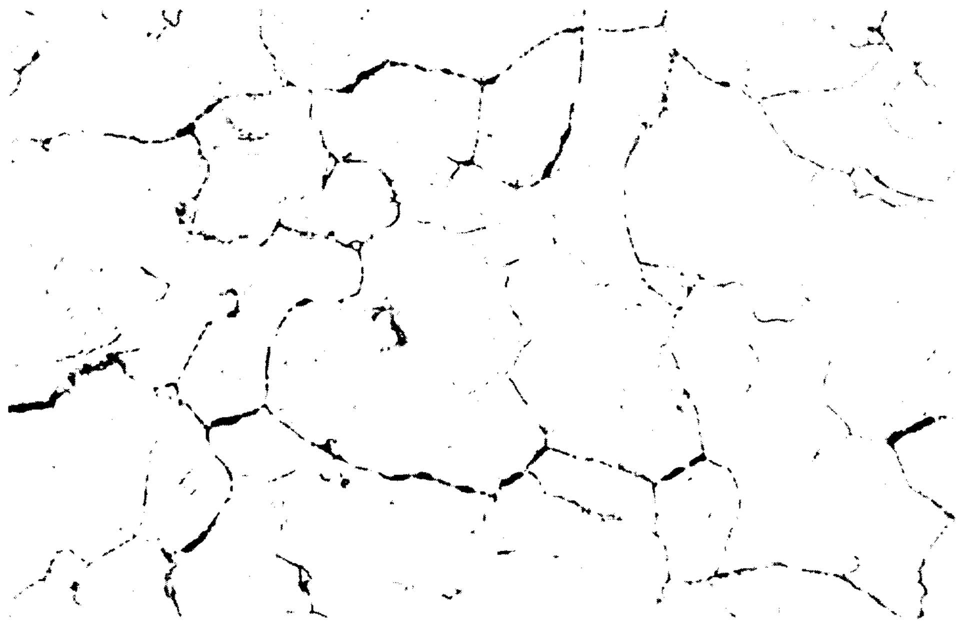
M-252. Etchant, 92 percent HCl - 5 percent H_2SO_4 - 3 percent HNO_3.



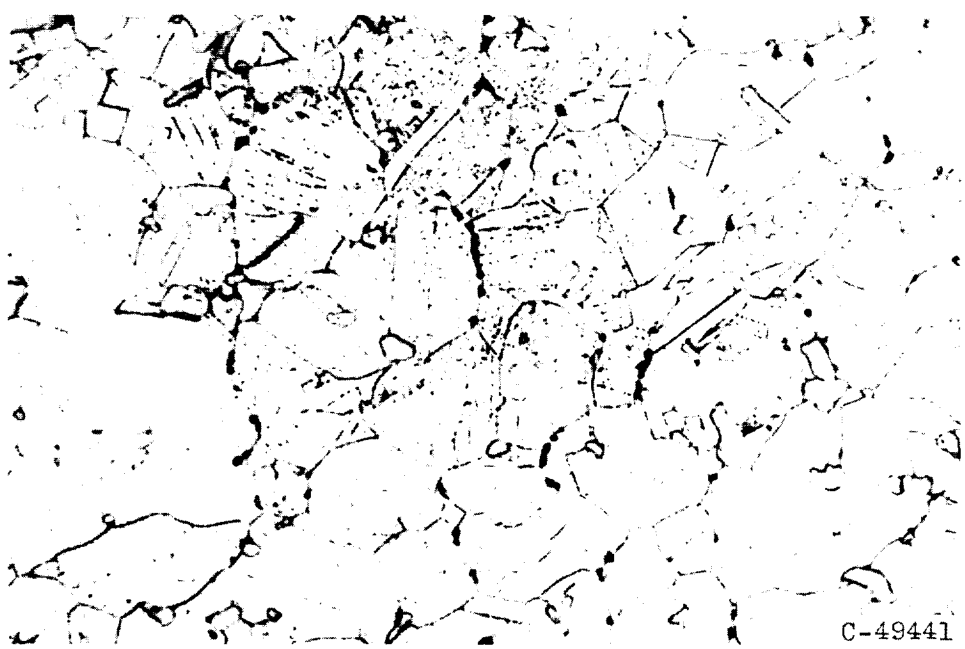
S-816. Etchant, aqua regia plus glycerol.

(a) Cycle: start, 5 minutes at idle, and stop.

Figure 6. - Microstructures of buckets after engine testing. X750.



M-252. Etchant, 92 percent HCl - 5 percent H_2SO_4 - 3 percent HNO_3.



S-816. Etchant, aqua regia plus glycerol.

(b) Cycle: start, 15 minutes at rated speed, and stop.

Figure 6. - Concluded. Microstructures of buckets after engine testing. X750.

NASA - Langley Field, Va. E-281

NASA MEMO 4-7-59E
National Aeronautics and Space Administration.
ENGINE OPERATING CONDITIONS THAT CAUSE THERMAL-FATIGUE CRACKS IN TURBOJET-ENGINE BUCKETS. James R. Johnston, John W. Weeton, and Robert A. Signorelli. April 1959. 24p. diagrs., photos., tab. (NASA MEMORANDUM 4-7-59E)

A series of engine tests was conducted to definitely establish the failure mechanism of leading-edge cracking and to determine which portions of engine operation cause the failures. The types of operation in the respective tests included steady-state operation, rapid cycles of acceleration and deceleration, and cycles of starting and stopping. The results indicated that the cracks were initiated by thermal fatigue and were caused chiefly by engine starts. Crack initiation was accelerated by engine operation at rated speed and temperature and prevented by starting the engine gradually.

Copies obtainable from NASA, Washington

1. Engines, Turbojet (3.1.3)
2. Engines, Control - Turbojet (3.2.2)
3. Alloys, Heat-Resisting (5.1.4)
4. Materials, Properties - Thermal (5.2.11)
5. Materials, Propulsion System - Operating Stresses (5.3.2)
6. Operating Problems, General (7.10)

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