NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 4030

EXPERIMENTAL INVESTIGATION OF CERMET TURBINE BLADES IN AN AXIAL-FLOW TURBOJET ENGINE

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SUMMARY

In 16 tests to evaluate cermet blades in an axial-flow engine, blade life of 150 hours at maximum turbine speed and exhaust temperature was obtained. Chipping of the blades in the tip region was a common characteristic in the tests. Only one test resulted in root failure.

Fourteen tests were made with six test blades in the turbine rotor; two tests were made with only two cermet blades in operation. Results indicate two probable causes of failure in cermet blades, impact and fatigue. Use of fuel with low carbon-forming tendencies improved blade life to some extent; another improvement was made by a change in test blade installation that removed an undesirable airflow condition that may have caused excessive vibration. It should be noted that this change included a reduction in the number of blades under simultaneous tests and thus decreased the probability of impact. Other modifications such as special surface finish, rounding of blade tips, increased thickness in trailing edges, and use of special nozzle guide vane assemblies made only minor changes in blade life.

From the frequency of airfoil chipping it is apparent that materials of greater impact resistance are required for successful cermet-blade application.

INTRODUCTION

Present turbine blade materials cannot withstand the extremely high operating temperatures desired for advanced aircraft engines. Among the several possible ways to overcome this limitation, is the use of turbine blades fabricated from cermets (compressed and sintered mixtures of ceramic and metal powders). Titanium-carbide based cermets are of special interest. Cermets of this type possess many properties such as thermal-shock resistance and stress-rupture and creep strength adequate for the requirements of turbine blades operating at several hundred degrees over present temperatures (refs. 1 to 3). Another advantage inherent to cermet blades is their low percentage of strategic material. However, prior research showed that the low short-time ductility of cermets creates problems in root-fastening design and that cermet turbine blades frequently fail by impact.

An experimental program to evaluate problems in the operation of cermet blades is being conducted at the Lewis laboratory. The results of this program given in references 4 to 6 describe the improvement in life that was obtained by improved blade root design. The present in- 5004
vestigation was undertaken to determine the endurance of K-152B cermet turbine blades in an engine for which blade-root stresses were low. In the engine selected for these tests, cermet blade-root stress attributed to centrifugal force was 13,000 psi as compared with 18,000 psi encountered in the previous research with a different type of engine (refs. 4 to 6).

During the course of this investigation, which included 16 endurance tests of the K-152B blades, changes were made in experimental variables. In some tests more than one variable was changed in an effort to obtain as much operating life as possible for the material, rather than to determine specific effects of individual changes.

The test conditions that were varied included the following:

(1) Two different types of test-blade installation were used. In these the relative spacing between test blades and standard metal blades was varied because it was suspected that this might be an important factor in vibration of the cermet blades.

(2) Two different fuels were used in the test operation in order to study the effect on impact damage that might result from different rates of carbon deposition in the combustion chambers. Pieces of deposited carbon break away from the combustion chamber walls and are carried through the turbine.

(3) Three different nozzle guide vane assemblies were used to vary the frequency of blade excitation from this source of vibration.

(4) Blade modifications were incorporated in some tests. These included rounding of the airfoil tips, increasing the thickness of the trailing edge, and imparting special surface finish to the airfoil.

The engine was operated at maximum conditions of turbine speed and exhaust temperature.

APPARATUS AND PROCEDURE

Blade Description

The cermet K-152B had the following nominal composition by weight: 62 percent titanium carbide; 8 percent solid solution of complex carbides (titanium, tantalum, and columbium carbides) and 30 percent nickel. Blades were made by the Kennametal Corporation from specifications supplied by the Lewis laboratory. Examination of the finished blades included radiography and surface inspection by the penetrant-oil method.

The root of the cermet blade (fig. 1) was skewed 9° relative to the turbine axis, as compared with $2\frac{1}{2}^{\circ}$ used in the standard blades for this turbine. This change was made to reduce bending stresses in the root (ref. 5). The airfoil length was 0.030 inch shorter than standard for most of the tests (3 to 16, inclusive). This was done to eliminate possible rubbing between blade tips and turbine shroud, in the event of shroud deformation.

In other respects, the cermet airfoil conformed to the design of the standard metal blades for this engine, with the exception of two modifications for several test operations. The trailing edges of the test blades were increased in thickness from 0.030 to 0.060 inch in tests 10 and 11. Another change in design consisted in providing 1/4-inch radii at the leading and trailing edge of the blade tips (test 15). Tests 12 and 13 combined these two modifications, together with a surface treatment intended to reduce surface stress concentration. The airfoils were polished with 45-micron diamond dust. The conditions of rounded blade tips and surface treatment were combined in test 14. (A summary of these modifications appears in table I, together with other test conditions.)

Blade Installation

All test blades were installed in the turbine rotor with a nickel-plated copper screen inserted between the cermet root and the matching rotor recess. The malleable screen allowed better distribution of centrifugal load. Presence of the screen proved to be of value in previous operation of cermet blades (refs. 4 to 6).

Turbine Rotors

Most of the tests were made with two turbine rotors modified to accept cermet blades in two groups of three blades each, mounted diametrically opposite. Each three-blade group occupied the space of four standard blades, as shown in figure 2. This arrangement was adopted in order to avoid high stress in the rim between the standard modified root serrations. The difference in the angle of skew in the two root serrations would have caused unfavorable stress in the rim if standard spacing had been employed. Spacing among individual test blades was the same as for standard blades.

The first rotor that was modified in the manner just described failed in the rim between adjacent cermet root serrations after a total time of 69 hours of test operation. Analysis of the failure showed that it was caused by the fact that the heat conductivity of the cermet blades was higher than that of the alloy blades and that recurrence could be prevented by augmenting the existing cooling air supplied to both sides of the rim. A second rotor was obtained for tests 7 through 14. In tests made with this rotor, air from the laboratory supply line was directed against the rim. The replacement rotor showed no evidence of serration cracking at the end of the test operation.

A third rotor used in this program was modified to provide for only two cermet test blades mounted diametrically opposite. The test blades were installed with the same spacing as the metal blades, as shown in figure 3. The purpose of this modification was to duplicate more closely the airflow conditions in a wheel with a full complement of cermet blades. An unfavorable rim-stress condition was introduced by the skewed root serration adjacent to the standard serration. However, additional cooling air was supplied to the rim, and the rim temperature was lowered to a safe level.

Modifications to Nozzle Guide-Vane Assemblies

Two modified nozzle guide-vane assemblies were used in the test program in addition to the standard assembly of 64 equally spaced vanes. The modifications were intended to change the excitation frequency of the gas stream impinging on the turbine blades. The modified assemblies were used in tests 8, 8a, 8b, 10, 11, and 12.

One special assembly had 57 vanes equally spaced (tests 8, 8a, and 8b). In the fabrication of the second modified assembly ("phased" assembly for tests 10, 11, and 12) a standard unit was cut apart on a diameter. An arc segment containing one vane adjacent to a cut face was removed, and the remainder of that half of the assembly was revolved through an arc equal to one-half standard vane space. With the two parts fixed in this relation, material was added to the inner and outer rings where required to complete the reassembly. Figure 4 shows the resulting vane spacing at the location of phase change. There was a similar discontinuity nearly diametrically opposite.

Engine Fuel

Two types of fuel were used, standard (JP-4) and gasoline. Gasoline was used whenever available during test operation to reduce carbon formation in the combustion chambers. Experience has shown that any excessive carbon deposits may become dislodged and pass through the turbine.

Engine Operation

The engine was mounted in a sea-level test stand, and instrumentation was the same as described for previous research (refs. 4 to 6). Acceleration was over a period of several minutes from idle condition to a turbine speed of 7950 rpm. Tailcone gas temperature was adjusted by means of a variable-area exhaust nozzle to 1260° F. These test conditions were maintained (with the exception of stops for inspection and routine repairs) until the test was ended by blade failure or by attainment of 150 hours at maximum operating conditions. A total of 16 tests were made, 14 tests with six blades, and 2 tests with two blades.

RESULTS AND DISCUSSION

Table I gives operating time, number of starts, test conditions, and brief description of failure. In most of the early tests the blades were damaged in the tip region (tests 1 to 4 and 7). Figure 5 shows a typical failure. There are two possible causes for these failures, impact and fatigue.

Damage may have been caused by the impact of carbon fragments passing through the turbine. For example, hard carbon deposits were found in the combustion chambers in amounts considered excessive. This was a condition peculiar to the individual test engine. Figure 6 shows a piece of carbon removed during inspection. The deposits were not homogeneous, varying from a soft and amorphous material to a silver-gray substance comparable to industrial limestone slag. Spectroscopic analysis did not indicate the presence of material other than carbon.

The substitution of gasoline for standard fuel made some improvement in maximum blade life. It was used in tests 5, 6, 9, 9a, 12, 13, and 14. Test operation of 43 hours and 57 minutes was obtained in test 14 before occurrence of failure. Periodic inspection showed that carbon formation was low. In tests where standard fuel was used, with the exception of tests 15 and 16 where test conditions were radically different, the maximum blade life was 19 hours and 27 minutes (test 8).

Fatigue was considered as the other possible cause of blade failure. Damage occurred principally as tip failure. Metal turbine blades fail in this area as a result of excessive vibration, and this lends credence to the possibility of fatigue damage to cermet blades.

Several changes were made on the assumption that vibration might be the cause of failure. The engine and blade modifications described in APPARATUS AND PROCEDURE are summarized as follows:

Engine modifications:

(a) Elimination of excessive space between cermet and adjacent standard blade; installation in tests 15 and 16 of a single cermet blade in same relative position as standard metal blades, as shown in figure 3

(b) Use of phased nozzle assembly to damp out excitation from the 64^{th} order of turbine speed

(c) Use of 57-vane nozzle assembly to bring excitation forces below the resonant frequency of a majority of blade complex vibration modes

Blade modifications:

(a) Honing the airfoil to remove surface stress concentrations

(b) Rounding the blade tips to 1/4-inch radii to lower vibratory stress in tip edges

(c) Increasing trailing-edge thickness from 0.030 to 0.060 inch to improve stiffness

The best performances of cermet blades were obtained in tests 15 and 16, using the rotor modified for two test blades in standard spacing. The blades in test 15 had 1/4-inch radii at the tips. This test was discontinued after 150 hours at a turbine speed of 7950 rpm and exhaust temperature of 1260° F. One blade from test 15 lost a small chip from the tip (leading edge) after 84 hours and 34 minutes; the other blade was chipped in the same location after 97 hours and 38 minutes. Chipping continued during the remainder of the test. The extent of damage at the end of 150 hours is shown in figure 7.

The two blades of test 16 were not modified. The test was ended after 150 hours and 30 minutes at the maximum conditions of operation. Initial chipping was observed in the leading edges of both blades and the trailing edge of one after 41 hours and 50 minutes. Damage was confined to the tip region. Figure 8 shows the total extent of damage at the end of the test.

It should be noted that there are three factors to consider in any comparison between test results obtained with the three-blade groups (tests 1 to 14, inclusive) and results from the single blade tests (15 and 16):

(a) Probability of impact damage was higher when six test blades were used rather than two.

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(b) Minor chipping in one blade might initiate progressively more severe damage in adjacent test blades.

(c) Vibration may have been more serious in the six-blade tests. The spacing between the outer blades of a cluster of three and the adjacent metal blades was not a normal condition (fig. 2). In the course of a concurrent program on light-weight metal blades one test blade was placed in the space normally occupied by two blades. This metal test blade failed because of fatigue in the tip after a short time; blade life was less than 2 percent of the time for similar test blades in standard spacing.

In order to determine the effect of the phased nozzle guide-vane assembly, tests 10, 11, and 12 may be compared with tests 3, 4, 5, and 7 made with the standard nozzle guide-vane assembly. The phased-assembly tests showed no improvement in blade life. Data obtained with the 57-vane assembly did not indicate that change in excitation frequency resulted in increased blade life.

The effect of the honed finish to the airfoil and the rounding of the blade tips was not demonstrated clearly because of limited data. Performance of blades with these modifications in tests 14 and 15 (rounded tips but not honed finish in test 15) have been discussed; the same type of blade with increased thickness in the trailing edges was operated for 21 hours and 48 minutes in test 13, and the failure was not similar to previous failures. Two blades of test 13 failed by lamellar fracture across the root as shown in figure 9. It is probable that insufficient clearance existed between the root and the rim serration and that this condition caused compressive root stress. The effect of increasing the trailing-edge thickness from 0.030 to 0.060 inch was not clearly demonstrated.

CONCLUDING REMARKS

At the conclusion of 16 tests made to evaluate and to improve the blade life of titanium carbide base cermet turbine blades in an axial-flow jet engine, blade lives of 150 hours at maximum turbine speed and exhaust temperature of the engine have been achieved in the two final tests with only minor chipping of the airfoil. Principles of root design resulting from previous research were applied with the result that root failures were encountered in only one of the 16 runs.

The primary type of failure in this investigation was fracture of the blade airfoil. Analysis of the results indicates that there had been two probable causes of early failure of the blade airfoils, impact and fatigue. During the investigation changes and modifications were made in attempts to alleviate conditions believed to cause these types of damage. Use of a fuel with low carbon deposition in the combustors (to reduce the likelihood of blade impact damage) improved blade life to some extent. 5004

The best performance was obtained after a modification of test methods. The number of test blades in the turbine wheel was reduced from six to two, and the uneven spacing was eliminated between the test blades and adjacent standard metal blades. The reduction in the number of test blades decreased the probability of impact damage, and the elimination of uneven spacing removed an unfavorable airflow condition that may have caused excessive vibration. Other modifications such as different surface finish, rounding of the blade tips, increased thickness in the trailing edges, and special nozzle guide vane assemblies appeared to have only minor effects on test blade life.

From the frequency of airfoil chipping it is apparent that materials of greater impact resistance are required for successful application of cermets to blades or full-scale jet engines of the general type described herein.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, August 19, 1957

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TABLE I. - SUMMARY OF CERMET TURBINE BLADE TEST OPERATION

Test	Number of blades	Blade modification	Blade length	Type of nozzle guide vane assembly	Type of fuel	Number of starts	Operating time: Total, hr	Total, min	At max. speed, hr	At max. speed, min	Number of failed blades	Location of failures	Remarks
1	6	None	Standard	Standard	JP-4	3	1	57	1	25	All	Tip region	An apparent defect was observed in one airfoil. Exceptionally heavy carbon deposit was found in combustion liners.
2	6	None	Standard	Standard	JP-4	3	17	58	16	16	All	Midspan and tip region	Slight chipping in tip region had been observed for two of the test blades after 7 hr 30 min at maximum speed.
3	6	None	0.03-In. short	Standard	JP-4	2	6	23	5	53	All	Tip region	In this test, and in all subsequent tests, the airfoils were 0.03 in. shorter than standard. To avoid the possibility of damage from contact between the airfoil tip and the turbine shroud ring.
4	6	None	0.03-In. short	Standard	JP-4	1	5	47	5	31	All	Midspan and tip region	Four blades sustained damage in midspan or tip region. Two blades failed between center and base.
5	6	None	0.03-In. short	Standard	Gasoline and JP-4	16	32	55	27	22	All	Midspan and tip region	Three blades sustained damage in midspan or tip region. Remaining blades were chipped. This test was initiated with clean combustion liners in the engine; gasoline fuel was used. It was intended to attempt an evaluation of the effect of carbon on blade life. After 25 hr operation at max. speed, the fuel supply was changed to standard JP-4. No exceptional carbon deposit was observed in the combustion liners on subsequent inspection.
6	6	None	0.03-In. short	Standard	Gasoline	5	3	58	2	45	All	Midspan and tip region	Test operation was ended by failure in the turbine rotor rim between adjacent cermet test blades.
7	6	None	0.03-In. short	Standard	JP-4	17	22	53	18	35	All	Tip region	Relatively minor chipping was observed after 14 hr 11 min of operation at maximum speed. Extra cooling air was supplied to the rotor rim in this test and in all subsequent operation.
8	6	None	0.03-In. short	57-Vane assembly	JP-4	10	23	0	19	27	4	Tip region	Test operation was ended by a failure in the engine exhaust system. Four blades were badly chipped, but it was not possible to determine whether or not this was a result of test operation or the exhaust system failure. The two undamaged blades from this test were left in the turbine wheel, and operation was continued with four new blades (test no. 8a).
8a	6	None	0.03-In. short	57-Vane assembly	JP-4	1	9	38	9	7	1	Tip region	One of the replacement blades sustained tip failure. This was not discovered until after normal shutdown of the engine. The single failed blade was replaced with a new blade, and operation was continued (test no. 8b).
8b	6	None	0.03-In. short	57-Vane assembly	JP-4	4	6	22	6	22	All	Midspan or tip region	One blade was operated at maximum speed for 6 hr 22 min; three blades had a life of 15 hr 29 min for this operating condition; and two blades were not damaged until after 34 hr 56 min of maximum speed operation. This was the last test made with the 57-vane nozzle vane assembly.
9	6	None	0.03-In. short	Standard	Gasoline	13	28	22	23	7	1	Tip region	The failure apparently was caused by impact with a foreign object. This test was made with a standard nozzle guide vane assembly. The blade was replaced and operation resumed (test no. 9a).
9a	6	None	0.03-In. short	Standard	Gasoline	6	6	29	5	19	4	Midspan and tip region	Five of the blades had total maximum speed operation of 28 hr 26 min.
10	6	Thick trailing edge	0.03-In. short	Phased	JP-4	3	6	39	4	49	All	Midspan and tip region	The trailing edges were increased from 0.30 to 0.60 in. in thickness.
11	6	Thick trailing edge	0.03-In. short	Phased	JP-4	1	1	45	1	36	All	Midspan and tip region	This test was made under the same condition as test 10.
12	6	Thick trailing edge; $\frac{1}{4}$-in. radii tips; honed finish	0.03-In. short	Phased	Gasoline	7	12	49	7	35	All	Midspan or tip region	This test combined all blade modifications.
13	6	Thick trailing edge; $\frac{1}{4}$-in. radii tips; honed finish	0.03-In. short	Standard	Gasoline	6	24	18	21	48	All	Midspan tip, or root	Three blades sustained damage in center or tip region. One blade failed near the base. Two blades failed in the root, with a lamellar type of fracture.
14	6	$\frac{1}{4}$ - In. radii tips; honed finish	0.03-In. short	Standard	Gasoline	18	49	24	43	57	3	Tip region	One blade slightly chipped after 10 hr 35 min at maximum speed operation.
15	2	$\frac{1}{4}$ - In. radii tips	0.03-In. short	Standard	JP-4	19	161	21	150	0			Both blades sustained chipping damage in the tip region. One blade was chipped at the leading edge tip after 84 hr 34 min of operation at maximum turbine speed. After 97 hr 38 min both blades had been chipped. Chipping continued to occur during the remainder of the last operation. The blade tips were provided with 1/4-in. radius.
16	2	None	0.03-In. short	Standard	JP-4	21	158	33	150	30			On conclusion of this test both blades had sustained minor tip damage. Chipping of the blade tips was observed after 41 hr 50 min of operation at maximum turbine speed. Chipping continued to occur during the remainder of the test operation. The blades were operated as received, with no rounding of the tips or honing of the airfoils.

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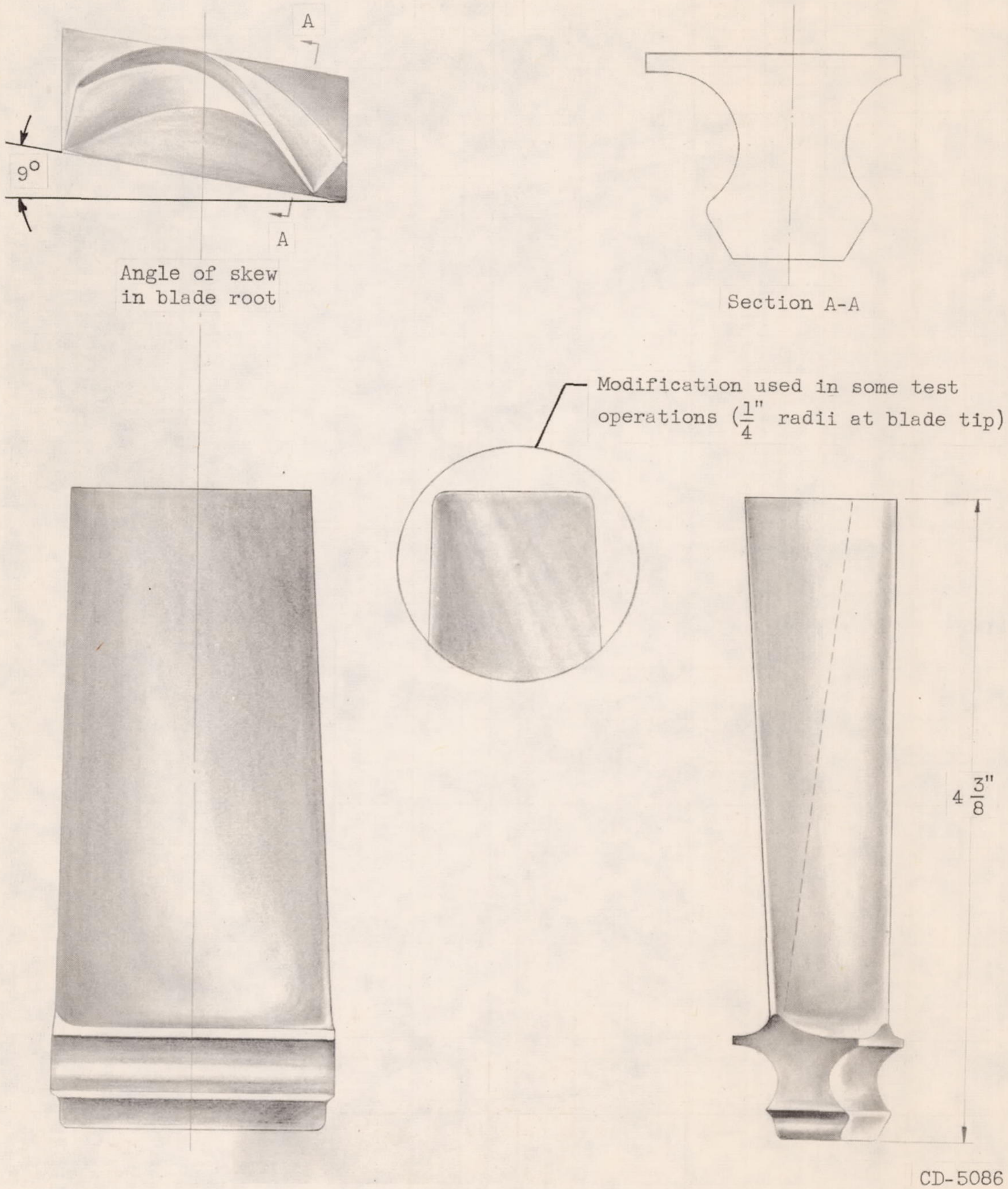

Figure 1. - Cermet turbine blade.

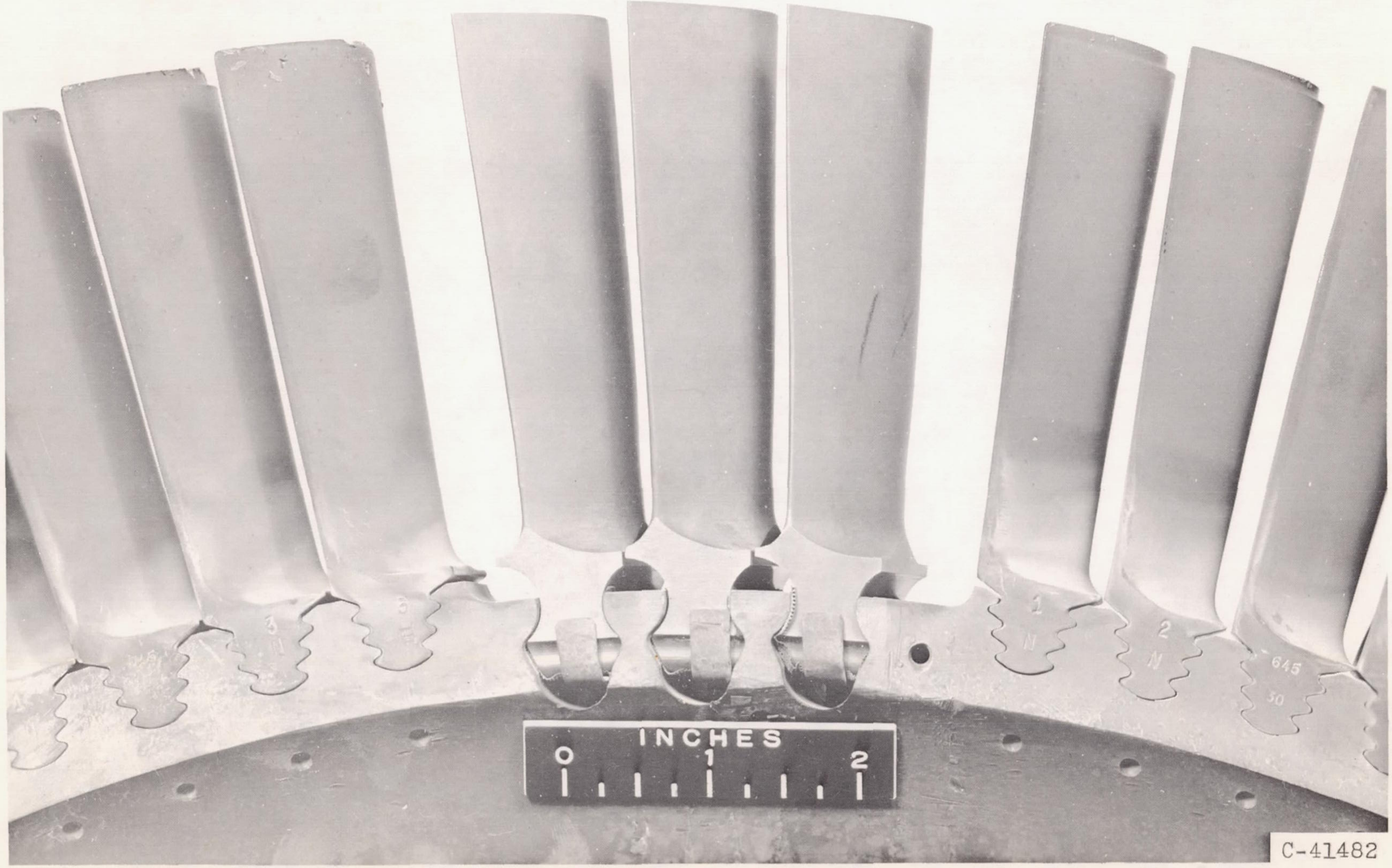

Figure 2. - Three cermet turbine blades mounted in space normally provided for four standard metal blades.

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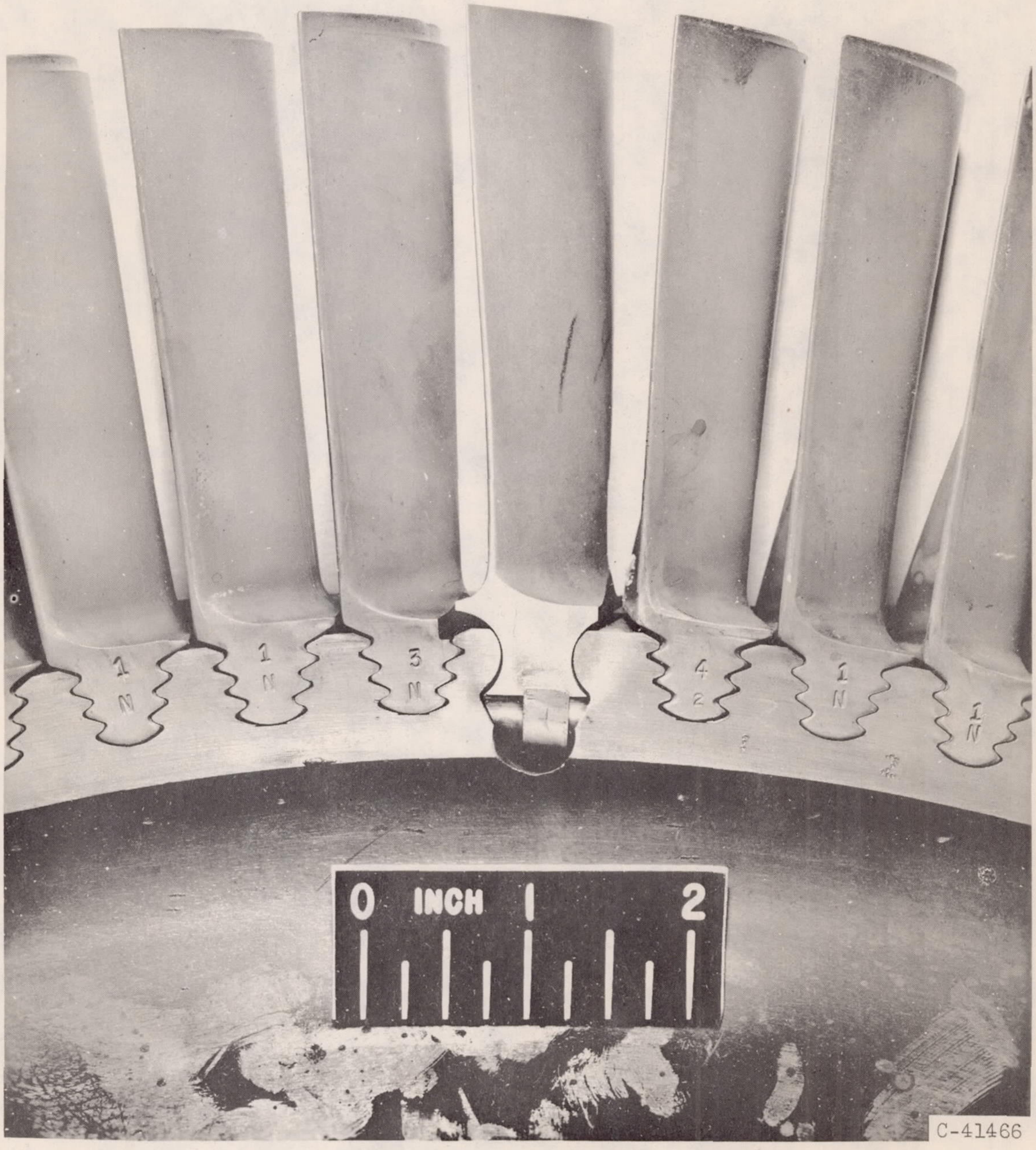

Figure 3. - Cermet turbine blade installed in standard spacing.

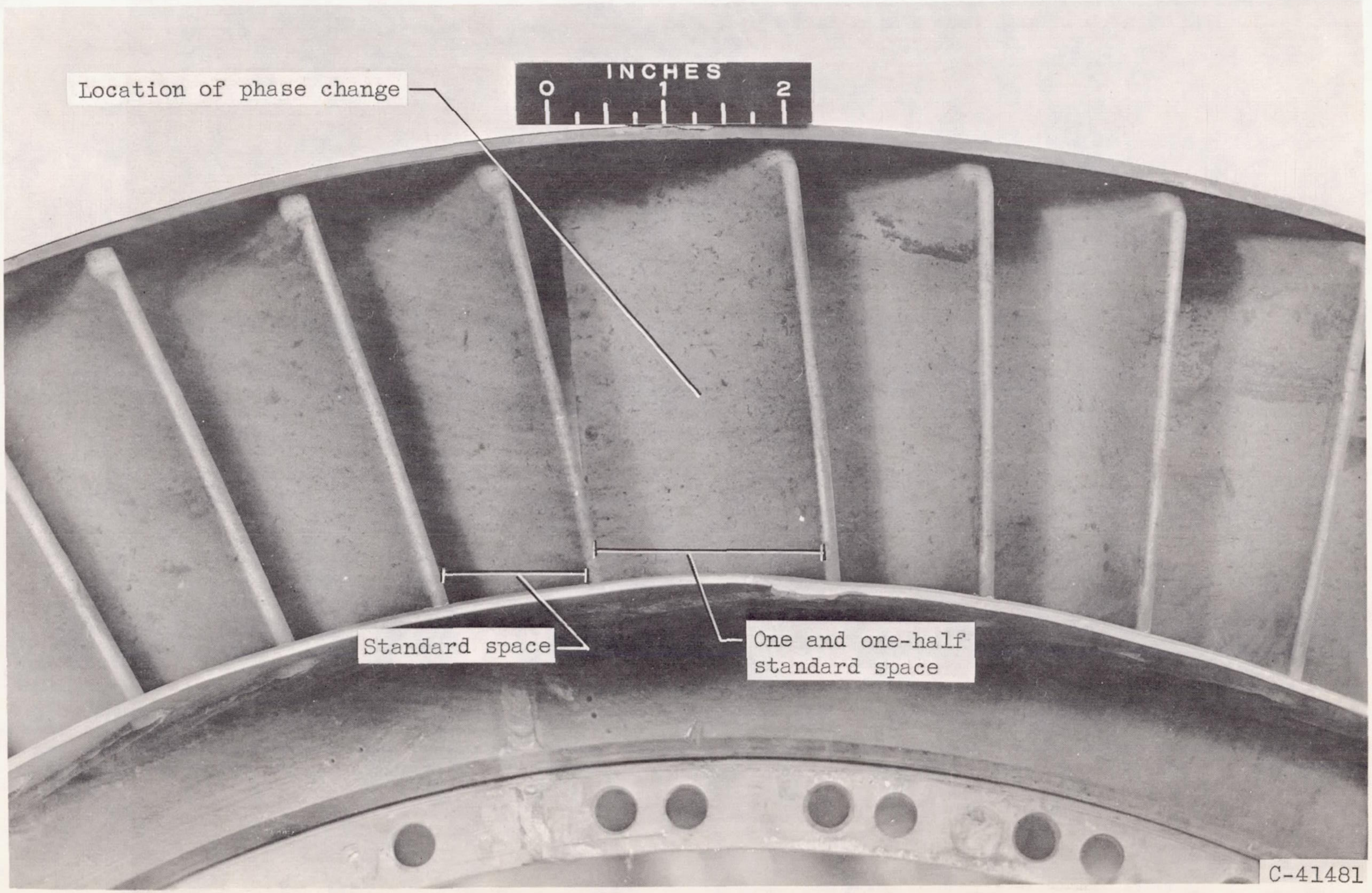

Figure 4. - Phased nozzle diaphragm, showing location of phase change; 61 standard spaces; 2 phase-change spaces.

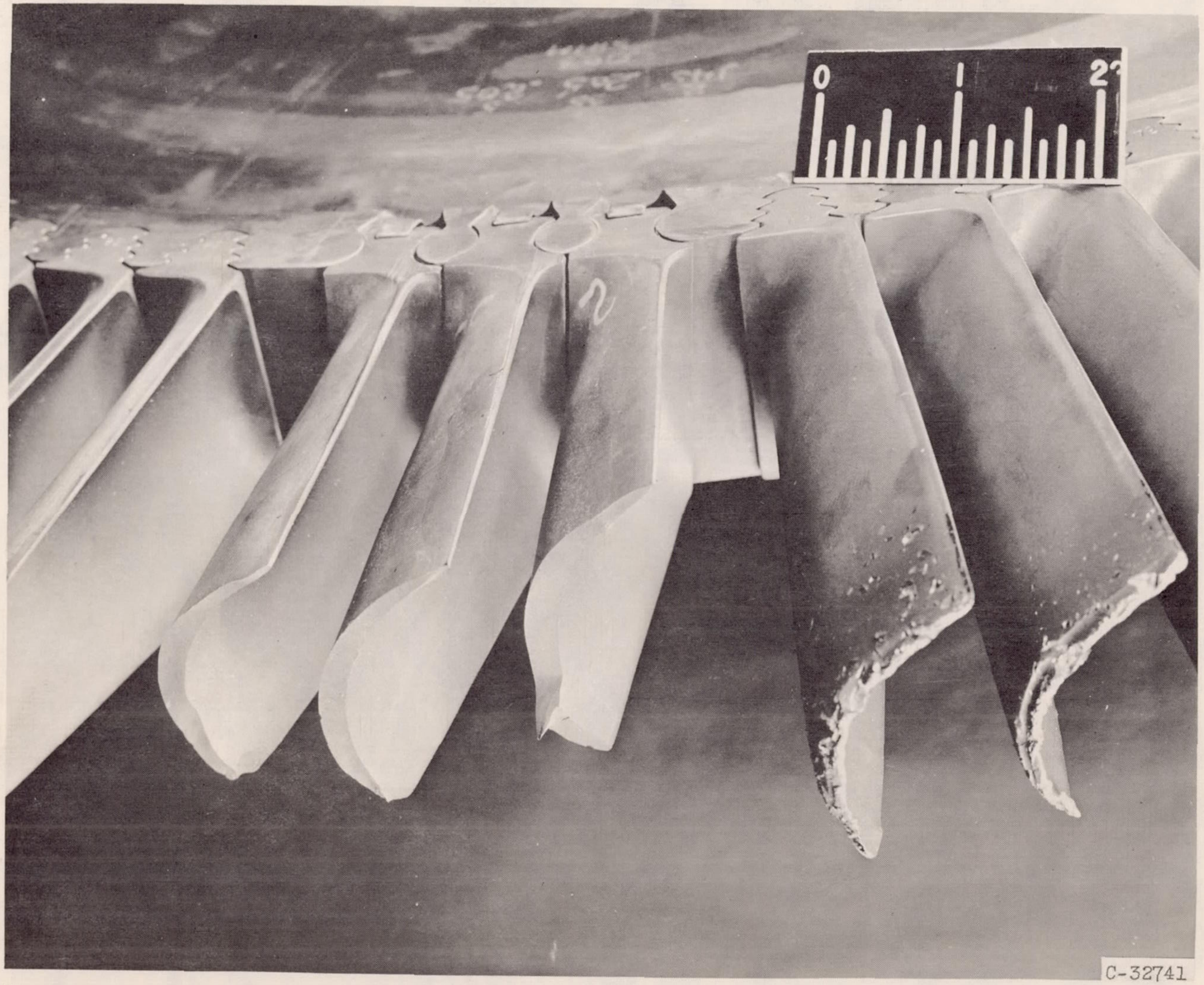

Figure 5. - Blade failures in test 1 after 1 hour and 25 minutes at maximum turbine speed, typical of runs 1 to 4 and 7.

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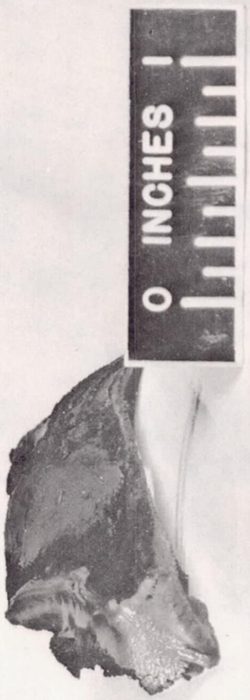

Figure 6. - Carbon deposit removed from combustion chamber.

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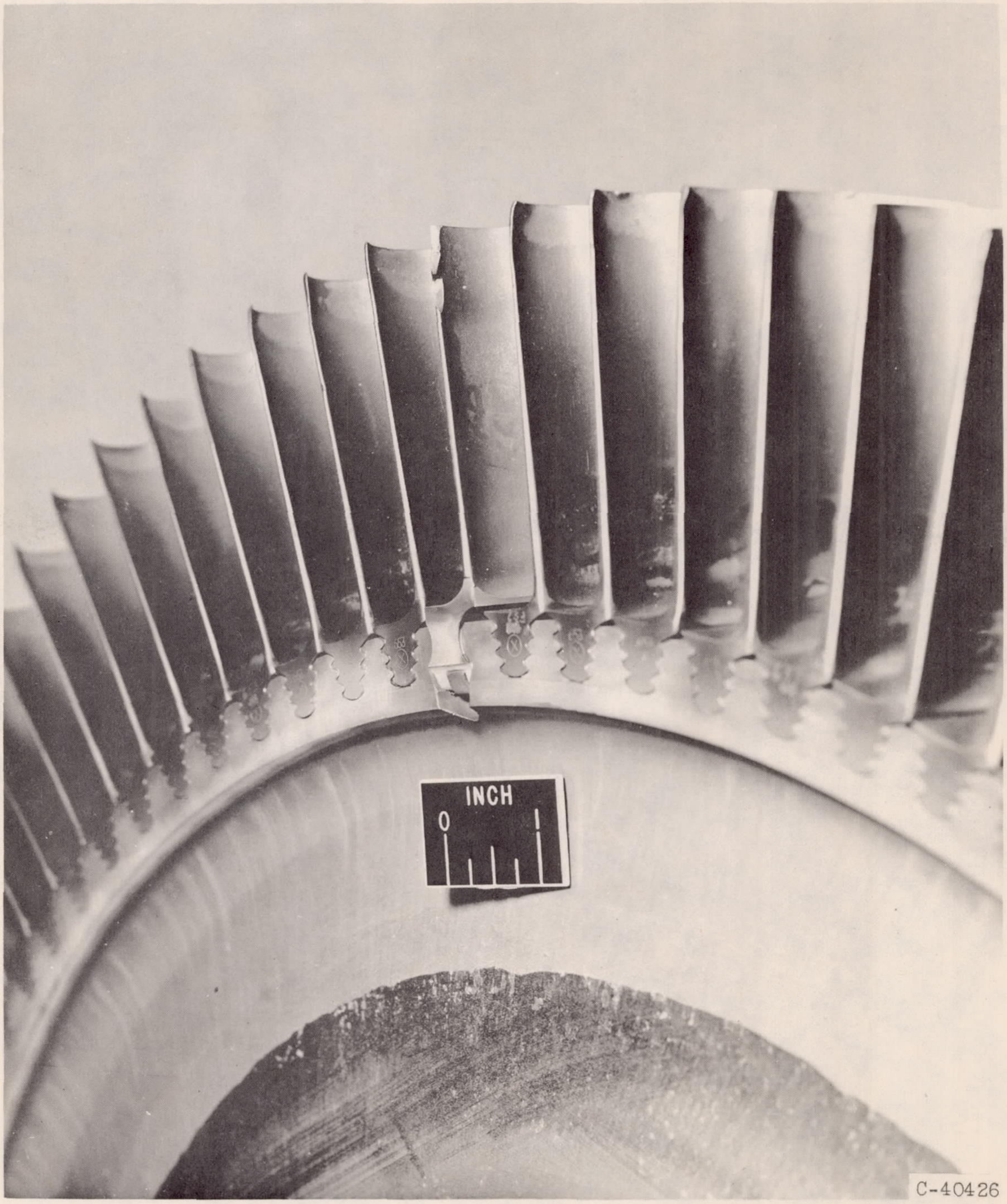

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Figure 7. - Cermet blades from test 15 after 150 hours at maximum turbine speed.

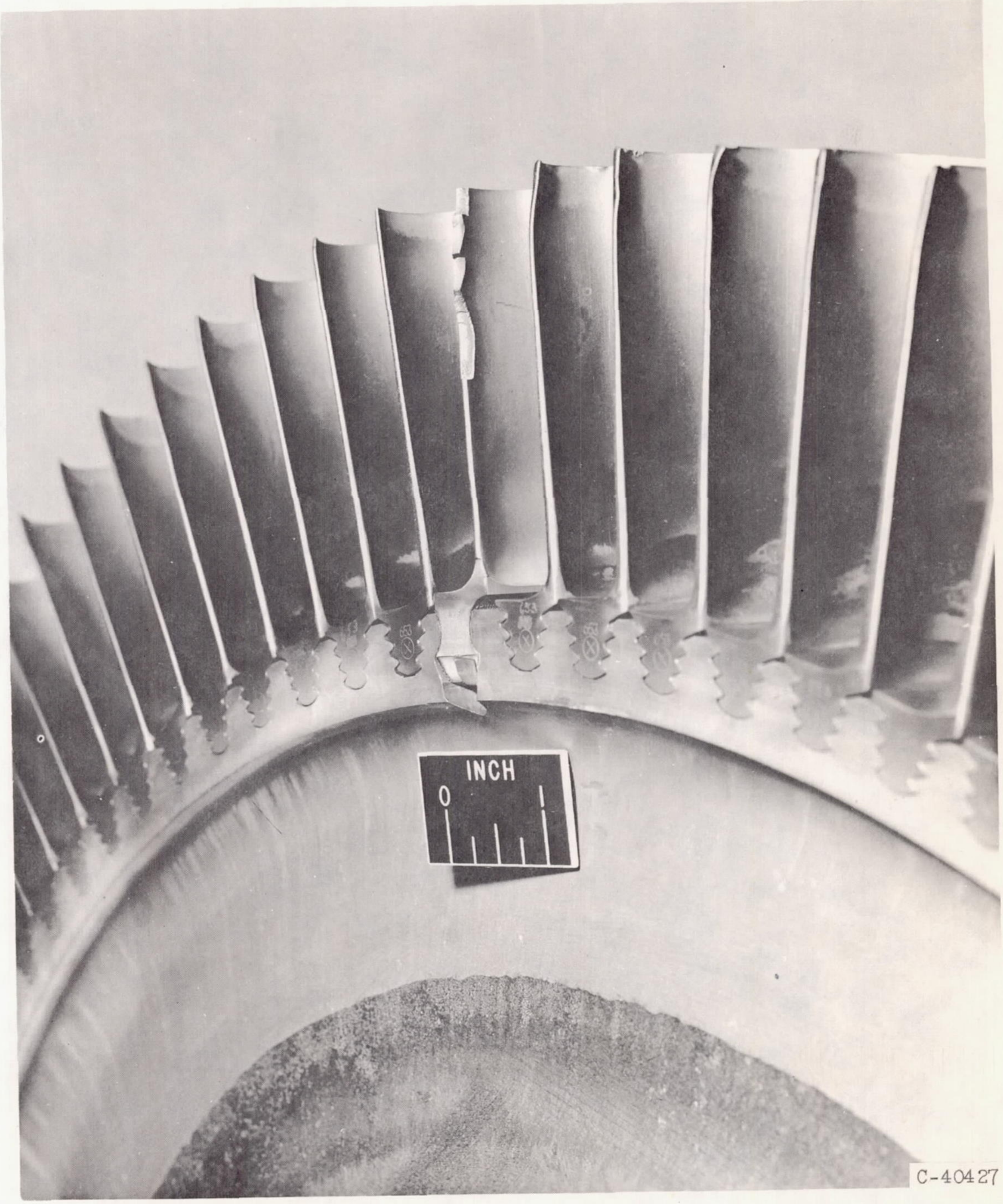

Figure 7. - Concluded. Cermet blades from test 15 after 150 hours at maximum turbine speed.

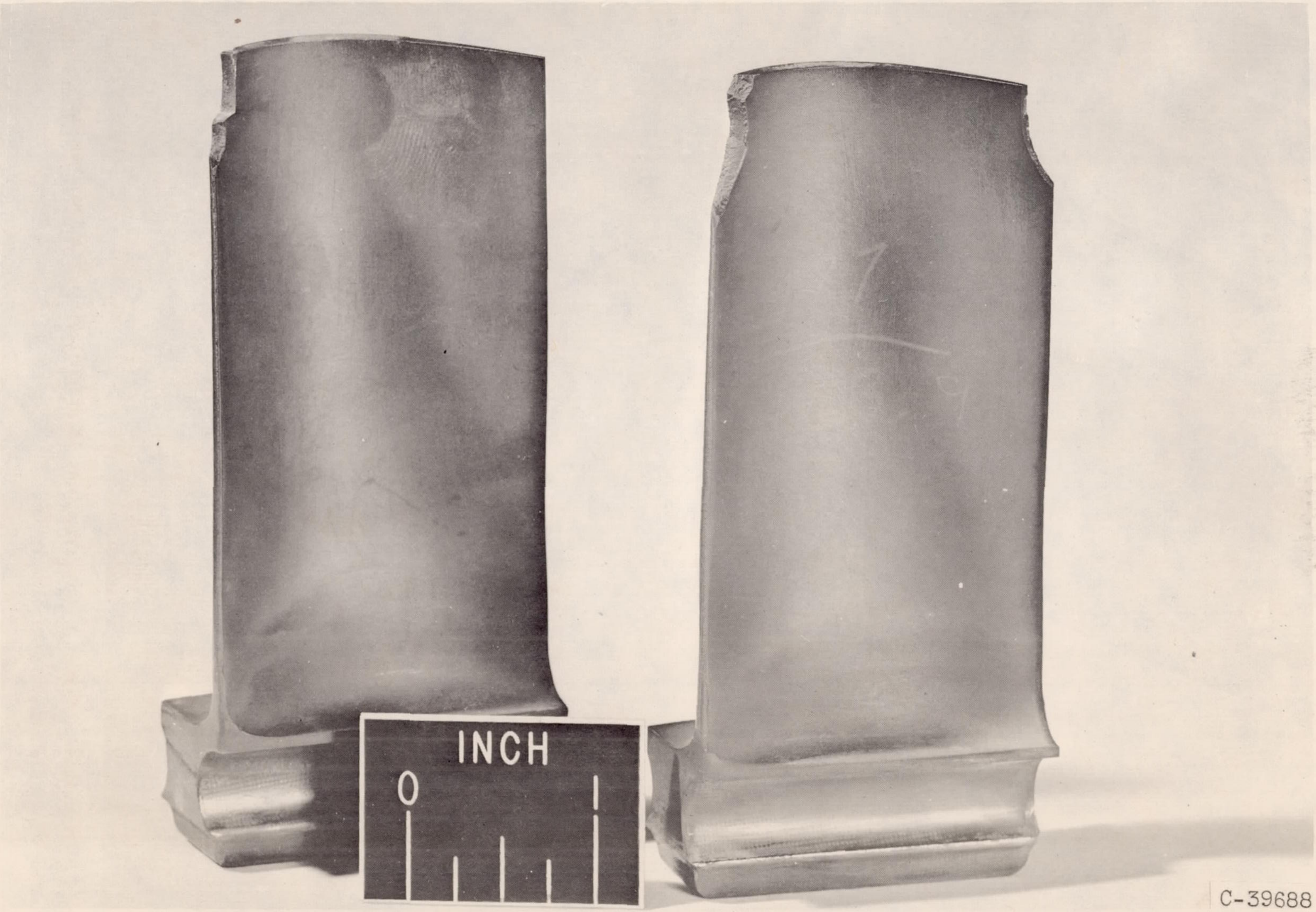

Figure 8. - Cermet blades from test 16 after 150 hours 30 minutes at maximum turbine speed.

Figure 9. - Lamellar fracture in blade root observed in test 13 after 21 hours and 48 minutes at maximum turbine speed.

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