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RESEARCH MEMORANDUM

PRELIMINARY INVESTIGATION OF THE HEAT-SHOCK RESISTANT PROPERTIES OF MOLYBDENUM DISILICIDE BLADES UNDER CENTRIFUGAL LOAD

By Roger A. Long and John C. Freche

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
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SUMMARY

Two molybdenum disilicide turbine blades fabricated by hot-pressing techniques were used in an investigation to determine their heat-shock resistant properties under centrifugal loads imposed by turbine rotation.

Rotating heat-shock tests were conducted under blade centrifugal stresses of 927, 2080, 3710, and 5350 pounds per square inch. At these stress levels, hot-pressed molybdenum disilicide blades withstood heat-shock cycles in which the gas temperature was varied in specific time intervals from 500° to 1200° to 500° F and from 500° to 1800° to 500° F. The maximum rate of gas-temperature increase or decrease encountered in a scheduled heat-shock cycle was 32.5° F per second. The minimum rate of gas-temperature increase or decrease in a scheduled cycle was 7° F per second. The first blade failed during an involuntary decreasing-temperature heat shock in which the inlet-gas temperature was decreased from 1400° to 300° F in 3 seconds while the blade was subjected to a centrifugal stress of 3710 pounds per square inch. The second molybdenum disilicide blade failed between successive heat-shock cycles while under a centrifugal stress of 5350 pounds per square inch. A fatigue failure occurred which resulted from a small crack initiated either by heat shock during a previous heat-shock cycle, by impact with a foreign substance, or by vibration.

The limited data of this investigation indicated that additional development is necessary before the heat-shock resistant properties of molybdenum disilicide are satisfactory for turbine-blade application.

INTRODUCTION

High inlet-gas temperatures result in substantial increases in the power output of both turbojet and turbine-propeller power plants; however, turbine-inlet-gas temperatures are limited because of stress limitations in current high-temperature materials. Also, the large critical material content in current high-temperature turbine alloys makes the development of high-temperature materials of reduced critical material content suitable for turbine application desirable. A comprehensive program has been initiated by the NACA Lewis laboratory to develop high-temperature turbine materials with reduced critical material content.

Previous investigations were conducted to determine the feasibility of applying ceramic materials with promising high-temperature tensile strength properties, such as sillimanite and National Bureau of Standards Body 4811C, to rotating turbine blades (references 1 and 2). These investigations indicated the existence of a heat-shock problem and a blade-mounting problem due to the brittle nature of these materials.

More recent investigations (references 3 and 4) indicated that certain intermetallic compounds and ceramals afford much higher tensile strengths than current turbine alloys at temperatures above 2000° F. One of the most promising of these, hot-pressed molybdenum disilicide, possesses a tensile strength of approximately 42,000 pounds per square inch between 2000° and 2400° F (reference 5). The material appeared promising on the basis of availability as well. No data were available, however, as to the heat-shock resistant properties of an aerodynamic blade section fabricated from this material when subjected to centrifugal stress conditions. Such data are necessary to evaluate a material for high-temperature gas-turbine applications. Molybdenum disilicide is a brittle material and consequently presented a blade-mounting problem. This problem has been investigated (reference 6) and several methods of supporting blades fabricated from similarly brittle materials have been evolved. The blade-disk attachment method previously established (reference 1) and shown to be adequate for brittle ceramic materials was employed in this investigation.

Rotating heat-shock tests were made in a small-scale turbine rig by varying the inlet-gas temperature over definite ranges in varying time increments while the turbine rotor was motored at each of several tip speeds up to 632 feet per second (12,000 rpm). The maximum centrifugal stress imposed upon the molybdenum disilicide blades was 5350 pounds per square inch. This stress was calculated for the root of the aerodynamic section of the blade. The inlet-gas temperature was varied from 500° to 1200° to 500° F and from 500° to 1800° to 500° F. Each of these temperature ranges was covered in time increments of 5, 4, 3, and 2 minutes. The increments were chosen to impose varying thermal stresses upon the blades and to permit direct comparison with similar tests conducted with ceramic blades (reference 2).

APPARATUS

A description of the blade material, the turbine disks, the method of blade assembly, and the turbine installation is presented in the following paragraphs.

Blade material. - The blade material used in this investigation was molybdenum disilicide, hot pressed from finely divided powder to a solid body and ground to the finished blade shape. Molybdenum disilicide is an intermetallic compound consisting of molybdenum and silicon in the stoichiometric proportions of one part molybdenum to two parts silicon and having the chemical formula $MoSi_2$. A more complete chemical analysis of this material than is given in reference 5 is presented in the following table:

Material	Percent by weight
Molybdenum	63.44 ±0.30
Silicon	36.45 ±0.30
Carbon	0.20 to 0.36
Iron	0.50 to 1.00

Reference 5 describes the processing of this material and its properties. Similar processing procedures were employed in hot pressing the bodies from which the blades were ground. It can therefore be presumed that the properties of the blade material used in this investigation are equivalent to those reported in reference 5 for a body also made from fine nonuniform powder. Typical metallographic structure of the blades is shown in figure 1. No difficulty was experienced in grinding the blade contours except an occasional flaking at an edge where two surfaces joined. Surface grinding of this material was accomplished with soft bonded wheels and suitably bonded diamond wheels. Contour grinding on this material was accomplished with a diamond wheel which requires a minimum of dressing to retain its shape.

Turbine disks. - The major principles of the disk design as described in reference 1 have been utilized, these being the method of supporting the blades by clamping between suitably contoured surfaces, and providing an overhanging mass of metal at the rim of each disk to resist spreading of the disks. The turbine rotor (fig. 2) consisted of two 9.82-inch-diameter disks, each machined integrally with a portion of the turbine shaft. The two rotor halves were held together by eight through bolts installed at a radius slightly less than the inner radius of the blade-ring assembly. Proper radial alinement between the two disks was obtained by piloting one disk upon a shoulder provided on the other disk.

In assembling the disks and the blades, the through bolts were tightened by applying a predetermined torque with a calibrated torque wrench. This procedure served to clamp the blade between the disks by compressing the asbestos-cloth cushion (fig. 2) around the blade and caused metal-to-metal contact between the matching disk surfaces. The bolts were then locked to the disks.

Blade assembly. - Each blade assembly consisted of one blade, one Inconel blade stub, and two aluminum spacers as shown in figure 3. Such an assembly was employed to conserve blades and to lessen the possibility of blade damage by flying chips from an adjacent blade breakage. The aerodynamic section of the blade had a $1\frac{1}{8}$-inch span and a 0.840-inch chord. A strip of asbestos cloth was fastened with a quick-drying cement around the base of the blade to reduce the possibility of damage from motion of the blade relative to the metal spacers. A 0.032-inch asbestos-cloth cushion was fastened around the sides and shoulders of the blade base in contact with the disk-clamping surfaces. A blade stub machined from Inconel to the same dimensions as the molybdenum disilicide blade base was employed in each assembly. The Inconel blade stub was clamped between the two disks directly opposite the molybdenum disilicide blade. Metal was removed from the Inconel stub when the rotor was balanced in order to simplify the rotor-balancing procedure. Two aluminum spacers contoured to match the rotor-clamping surfaces separated the molybdenum disilicide blade and the Inconel blade stub.

Turbine installation. - The turbine rig, the combustion-gas system, and the instrumentation were the same as those described in reference 1. The turbine rotor was motored by an electric dynamometer. An additional measurement of the inlet-gas temperature was obtained from a shielded thermocouple inserted into the gas stream approximately 8 inches upstream of the turbine. The indicated inlet-gas temperature measured at this location was recorded during the heat-shock cycles by means of a high-speed recording potentiometer.

PROCEDURE

A series of runs was made to determine the effect of superimposing thermal stresses on the centrifugal stresses induced in molybdenum disilicide blades during simulated turbine operating conditions. X-ray and dye-penetrant inspections were made of each blade prior to installation in the turbine to detect any existing cracks or porosity. The turbine was operated at constant speed to provide constant centrifugal blade loading during any particular heat-shock cycle. The inlet-gas temperature was increased from a minimum to a maximum value and then decreased to the original temperature during a specified period of time. Each period of time or cycle was divided as nearly as possible into equal increments. For example, in a 3-minute cycle, 1 minute was utilized to increase the gas temperature from the minimum to the maximum value. The temperature was held at this maximum value for 1 minute and 1 minute was utilized to decrease the temperature to the minimum value.

Typical gas-temperature variations with time are shown in figure 4. These cyclic temperature variations were arbitrarily chosen in reference 2. Similar cycles were run in this investigation to permit direct comparison with the heat-shock tests conducted with ceramic blades in reference 2. The gas temperature was varied by manual adjustments of the valve controlling the fuel supply to the burner. A constant rate of temperature increase or decrease was not always maintained, which explains the absence of parallelism in some of the curves.

Heat-shock cycles of 5, 4, 3, and 2 minutes during which the inlet-gas temperature varied from 500° to 1200° to 500° F for several tip speeds from 263 to 842 feet per second (5000 to 16,000 rpm, respectively) were scheduled. Heat-shock cycles of 5, 4, 3, and 2 minutes during which the inlet-gas temperature varied from 500° to 1800° to 500° F for several tip speeds from 263 to 842 feet per second were also scheduled.

Blade 1 was operated through single cycles of 5, 4, 3, and 2 minutes during which the inlet-gas temperature was varied from 500° to 1200° to 500° F at each of three tip speeds, 263, 394, and 526 feet per second (5000, 7500, and 10,000 rpm, respectively). The centrifugal blade stresses at the root of the aerodynamic section of the blade at these speeds are 927, 2080, and 3710 pounds per square inch, respectively. Similar single cycles were run during which the inlet-gas temperature was varied from 500° to 1800° to 500° F under imposed centrifugal blade stresses of 927 and 2080 pounds per square inch.

Blade 2 was operated through single cycles of 5, 4, 3, and 2 minutes at a tip speed of 632 feet per second (equivalent to 12,000 rpm or a centrifugal blade stress of 5350 lb/sq in.), during which the inlet-gas temperature was varied from 500° to 1200° to 500° F. Single time cycles of 5, 4, and 3 minutes were run during which the inlet-gas temperature was varied from 500° to 1800° to 500° F under an imposed blade stress of 3710 pounds per square inch. A 5-minute time cycle was also run over the same temperature range under an imposed blade stress of 5350 pounds per square inch.

In starting, a low pressure drop (1.5 in. Hg) was set across the turbine nozzle and the burner was ignited using a fuel flow that gave an inlet-gas temperature of approximately 300° F. The turbine rotor was then motored to a tip speed corresponding to that at which a particular series of cycles was to be run. Next, the gas temperature was increased to 500° F, the base inlet-gas temperature from which all cycles were run. Necessary changes in the burner configuration since the investigation of reference 2 limited the base cycle temperature to 500° F in order to insure continuous combustion. The pressure drop across the turbine nozzle was then set according to values of inlet and outlet pressure computed to maintain zero angle of attack for an assumed constant value (90 percent) of nozzle efficiency for the combination of speed and maximum cycle temperature to be run. Fuel flow was adjusted to vary the inlet-gas temperatures over a definite range in equal increments in each of several time cycles.

RESULTS AND DISCUSSION

A summary of operating conditions and results is given in table I. Blades 1 and 2 were each considered part of one over-all evaluation; consequently, conditions of operation were not duplicated in either assembly.

Blade 1 was subjected to heat-shock cycles at three different centrifugal stress levels, 927, 2080, and 3710 pounds per square inch. The minimum change in inlet-gas temperature per unit time for a 500° to 1200° to 500° F cycle, which was imposed at all three stress levels, was a rate of inlet-gas temperature increase or decrease of approximately 7° F per second; the maximum change for this temperature cycle was 17.5° F per second. The minimum change in inlet-gas temperature per unit time for a scheduled 500° to 1800° to 500° F cycle was a rate of inlet-gas temperature increase or decrease of approximately 13° F per second; the maximum change for this temperature cycle was 32.5° F per second. The blade successfully withstood all the heat-shock cycles imposed prior to an unscheduled decreasing-temperature heat shock which occurred during the 5-minute cycle at a centrifugal blade stress of 3710 pounds per square inch. This failure resulted when loss of the fuel supply to the burner created a more drastic heat shock than intended at that time. The inlet-gas temperature decreased from 1400° to 300° F in approximately 3 seconds, a shock similar to but less severe than the decreasing-temperature heat-shock or blow-out cycle deliberately imposed upon the Body 4811C blades investigated in reference 2. It was intended that such a blow-out cycle should be imposed upon the molybdenum disilicide blades after the scheduled cycles had been completed. Examination of the blade fracture surface (fig. 5) indicates that no fatigue failure occurred. Apparently the blade failed either in tension or by heat shock. Since the tensile loadings imposed were well within the allowable tensile strength of the material, it is very likely that failure occurred because of heat shock.

Blade 2 successfully completed all the 500° to 1200° to 500° F cycles under an imposed centrifugal stress of 5350 pounds per square inch. Blade 2 also completed successfully all the 500° to 1800° to 500° F cycles in which the maximum and minimum rates of gas temperature increase or decrease were 21.7° and 13° F per second under an imposed centrifugal stress of 3710 pounds per square inch. Failure occurred between the 5- and 4-minute, 500° to 1800° to 500° F cycles while the blade was centrifugally stressed to 5350 pounds per square inch. The blade after failure is shown in figure 6. Fracture appears to have originated on the convex surface of the blade (fig. 6(a)). Examination of the origin of fracture indicates a fatigue-type failure (fig. 6(b)). Blade failure can be attributed in this case to one of three possibilities: (1) heat shock initiated a small crack which developed because of fatigue under continued turbine operation, finally resulting in blade failure; (2) impact by a foreign substance initiated a stress concentration and a fatigue failure resulted; or (3) failure resulted from fatigue caused by blade vibration and possibly originated from microdefects in the blade. The first of these possibilities is considered the most likely one. Blade failure due to impact by foreign materials is considered remote because fine mesh screens were employed in the air duct upstream of the turbine to filter out such substances. The blade design with its short length and thick section probably minimized blade vibrational tendencies.

Because of the small number of blades available, the investigation was limited and heat-shock resistant properties of molybdenum disilicide blades under turbine rotational loads were not determined conclusively. However, comparison can be made with results from a similar investigation (reference 2) made with beryllium oxide ceramic, Body 4811C. Assuming the second molybdenum disilicide blade also failed because of heat shock, neither blade was able to withstand heat-shock cycles as severe as those imposed upon Body 4811C blades, either from the standpoint of centrifugal load or rate of temperature change imposed.

The combined thermal and centrifugal stresses under which the hot-pressed molybdenum disilicide blades failed are considerably less than those encountered in normal turbine operation. The limited data obtained from this investigation indicate hot-pressed molybdenum disilicide, processed as described in reference 5, lacks satisfactory heat-shock resistant properties under centrifugal load and requires further development before satisfactory application to turbine blades is possible.

RESULTS AND CONCLUSIONS

The following results and conclusions were obtained from an investigation of the heat-shock resistant properties of molybdenum disilicide turbine blades under centrifugal loads:

1. One blade withstood heat-shock cycles in which the inlet-gas temperature was varied from 500° to 1200° to 500° F in various time increments while subjected to centrifugal stresses of 927, 2080, and 3710 pounds per square inch. The maximum and minimum rates of temperature increase or decrease were 17.5° and 7° F per second, respectively. This blade also withstood heat-shock cycles in which the inlet-gas temperature was varied from 500° to 1800° to 500° F in various time increments while subjected to centrifugal stresses of 927 and 2080 pounds per square inch. The maximum and minimum rates of temperature increase

or decrease were 32.5° and 13° F per second, respectively. The blade failed during an involuntary decreasing-temperature heat shock in which the inlet-gas temperature was decreased from 1400° to 300° F in 3 seconds under a centrifugal blade stress of 3710 pounds per square inch.

2. Another blade withstood similar 500° to 1200° to 500° F heat-shock cycles under a centrifugal blade stress of 5350 pounds per square inch. This blade also withstood 500° to 1800° to 500° F heat-shock cycles in which the maximum and minimum rates of gas-temperature increase or decrease were 21.7° and 13° F per second while subjected to a centrifugal stress of 3710 pounds per square inch. Blade failure occurred at a stress level of 5350 pounds per square inch between successive 500° to 1800° to 500° F heat-shock cycles as a result of fatigue initiated either by heat shock, impact, or vibration.

3. It is concluded that the limited data of this investigation indicate that additional development is necessary before the heat-shock resistant properties of molybdenum disilicide are satisfactory for turbine-blade application.

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

REFERENCES

1. Freche, John C., and Sheflin, Bob W.: Investigation of a Gas Turbine with National Bureau of Standards Body 4811 Ceramic Rotor Blades. NACA RM E8G20, 1948.

2. Freche, John C.: Further Investigation of a Gas Turbine with National Bureau of Standards Body 4811C Ceramic Rotor Blades. NACA RM E9L07, 1950.

3. Maxwell, W. A.: Properties of Certain Intermetallics as Related to Elevated-Temperature Applications. I - Molybdenum Disilicide. NACA RM E9G01, 1949.

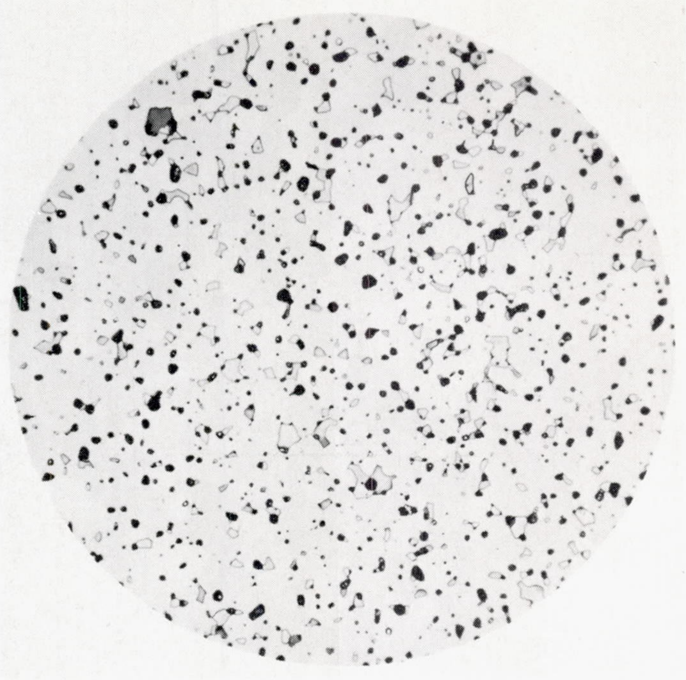
4. Deutsch, George C., Repko, Andrew J., and Lidman, William G.: Elevated-Temperature Properties of Several Titanium Carbide Base Ceramals. NACA TN 1915, 1949.

5. Long, Roger A.: Fabrication and Properties of Hot-Pressed Molybdenum Disilicide. NACA RM E50F22, 1950.

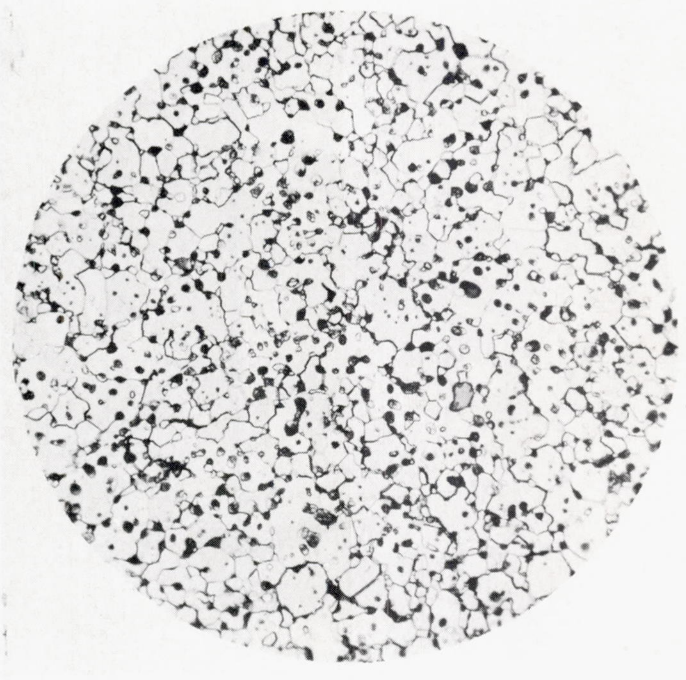
6. Hoffman, Charles A., Ault, G. Mervin, and Gangler, James J.: Initial Investigation of Carbide-Type Ceramal of 80-Percent Titanium Carbide Plus 20-Percent Cobalt for Use as Gas-Turbine-Blade Material. NACA TN 1836, 1949.

TABLE I - SUMMARY OF OPERATING CONDITIONS AND RESULTS OF MOLYBDENUM DISILICIDE BLADE INVESTIGATION

Blade	Inlet-gas temperature range (°F)	Cycle time (min)	Approximate rate of gas temperature increase or decrease (°F/sec)	Turbine tip speed (ft/sec)	Turbine speed (rpm)	Centrifugal blade stress (psi)	Operating results
1	500-1200-500	5	7	263;394;526	5000;7500;10,000	927;2080;3710	Completed
		4	8.75	263;394;526	5000;7500;10,000	927;2080;3710	Completed
		3	11.66	263;394;526	5000;7500;10,000	927;2080;3710	Completed
		2	17.5	263;394;526	5000;7500;10,000	927;2080;3710	Completed
	500-1800-500	5	13	263;394	5000;7500	927;2080	Completed
		4	16.25	263;394	5000;7500	927;2080	Completed
		3	21.7	263;394	5000;7500	927;2080	Completed
		2	32.5	263;394	5000;7500	927;2080	Completed
		5	13	526	10,000	3710	Blade failed before cycle was completed when fuel supply was shut off
2	500-1200-500	5	7	632	12,000	5350	Completed
		4	8.75	632	12,000	5350	Completed
		3	11.66	632	12,000	5350	Completed
		2	17.5	632	12,000	5350	Completed
	500-1800-500	5	13	526	10,000	3710	Completed
		4	16.25	526	10,000	3710	Completed
		3	21.7	526	10,000	3710	Completed
		5	13	632	12,000	5350	Completed
		4	16.25	632	12,000	5350	Blade failed immediately prior to begining this cycle



(a) Unetched; X500.



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(b) Etched; X500.

Figure 1. - Typical metallographic structure of molybdenum disilicide blades.

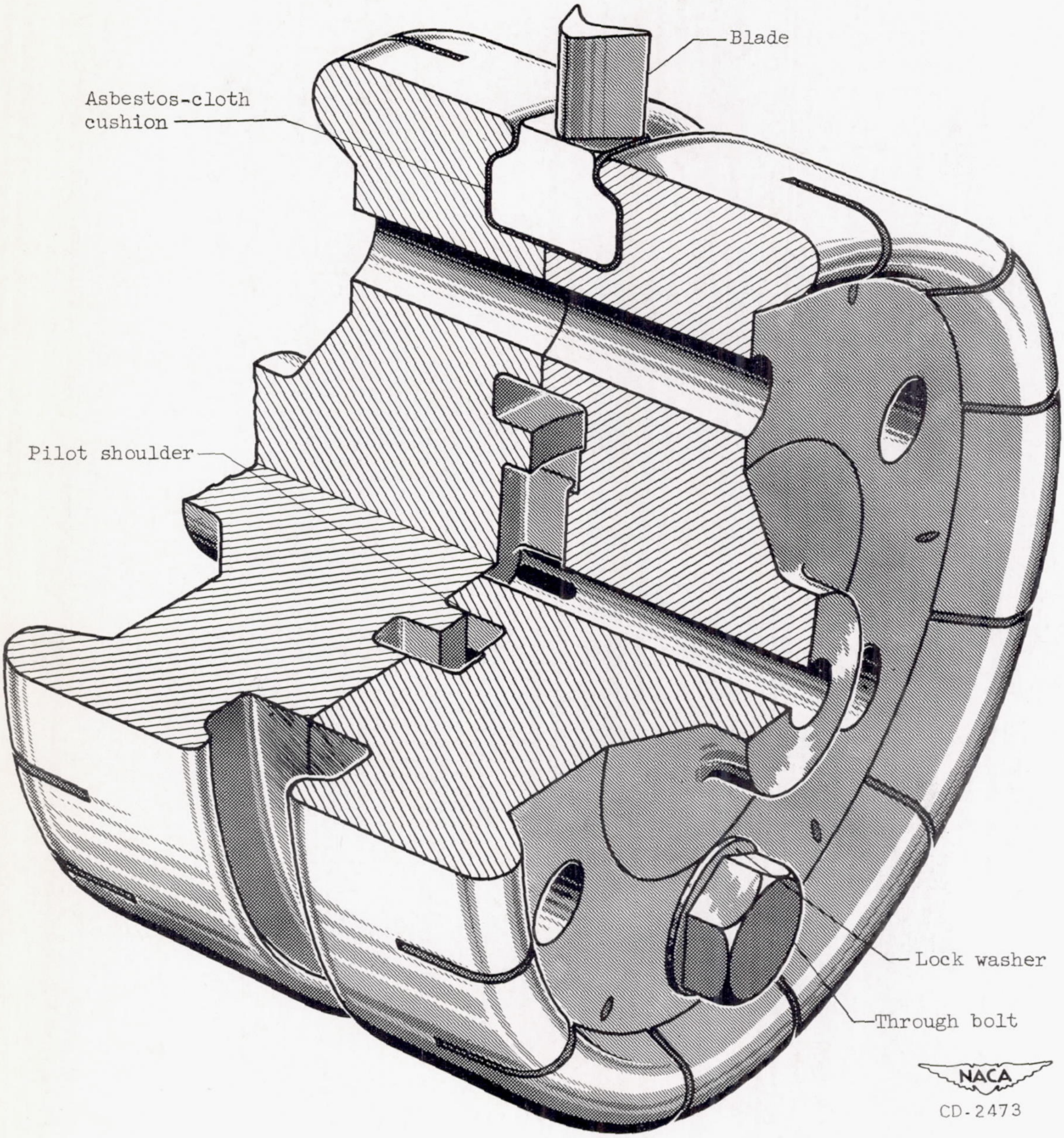


Figure 2. - Cross section of turbine rotor.

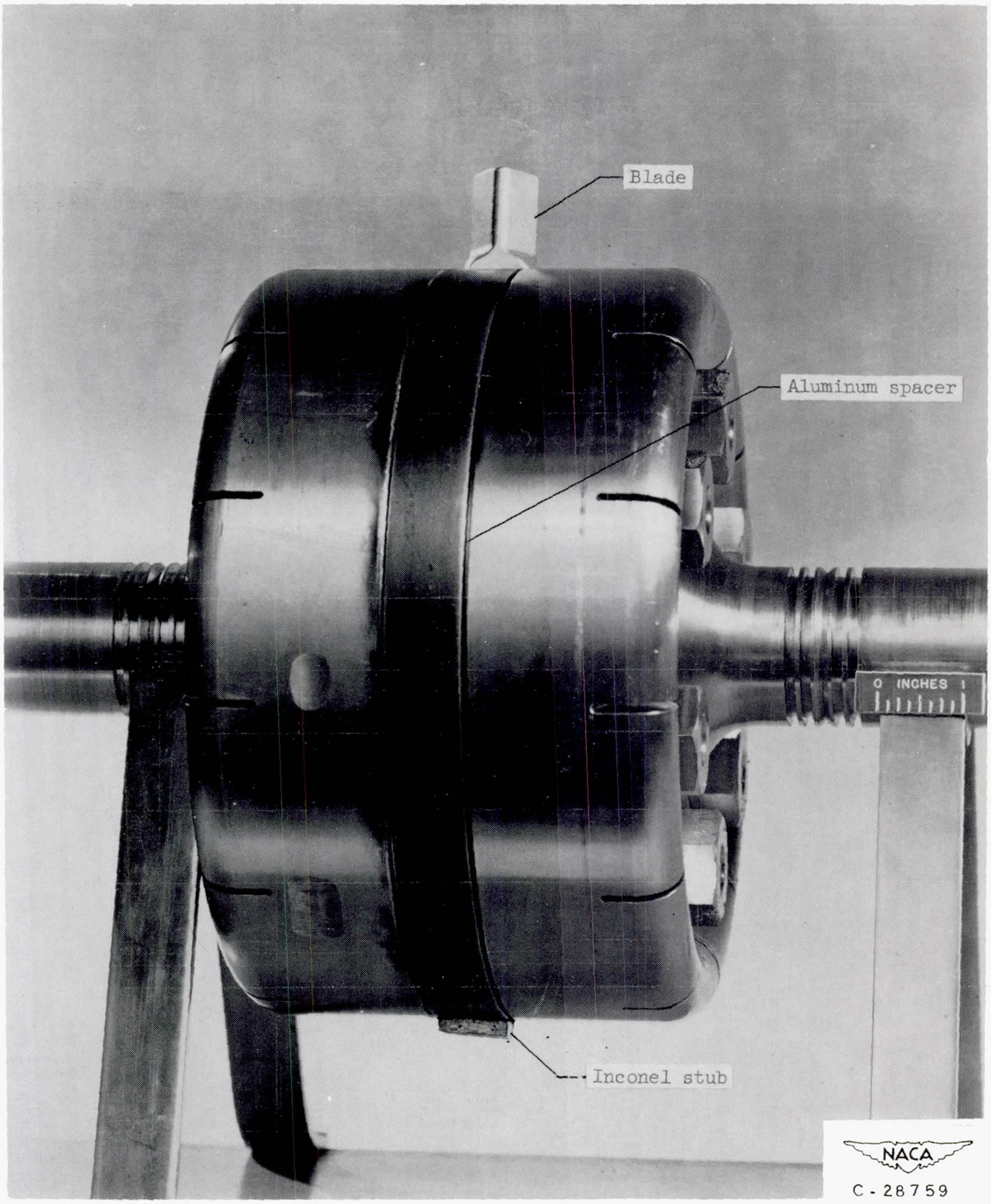


Figure 3. - Rotor assembly with one molybdenum disilicide blade, an Inconel blade stub, and two aluminum spacers.

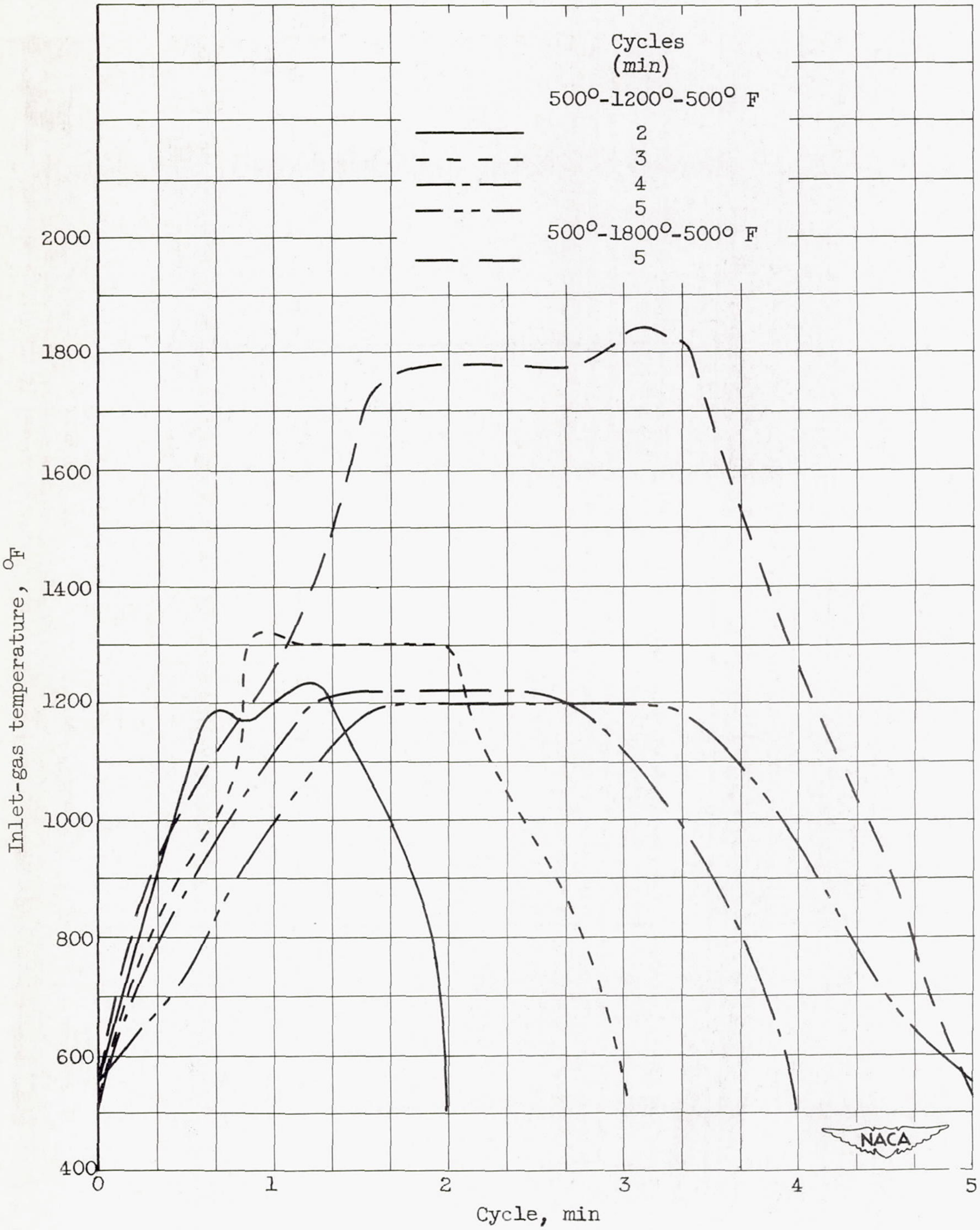
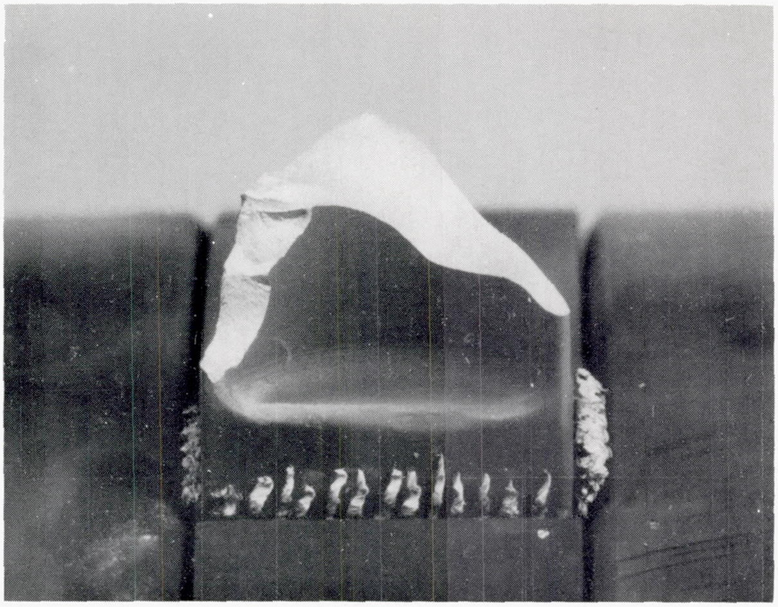


Figure 4. - Typical rotating heat-shock cycles obtained with blade 2 showing variation of inlet-gas temperature with time. Centrifugal blade stress maintained at 5350 pounds per square inch.



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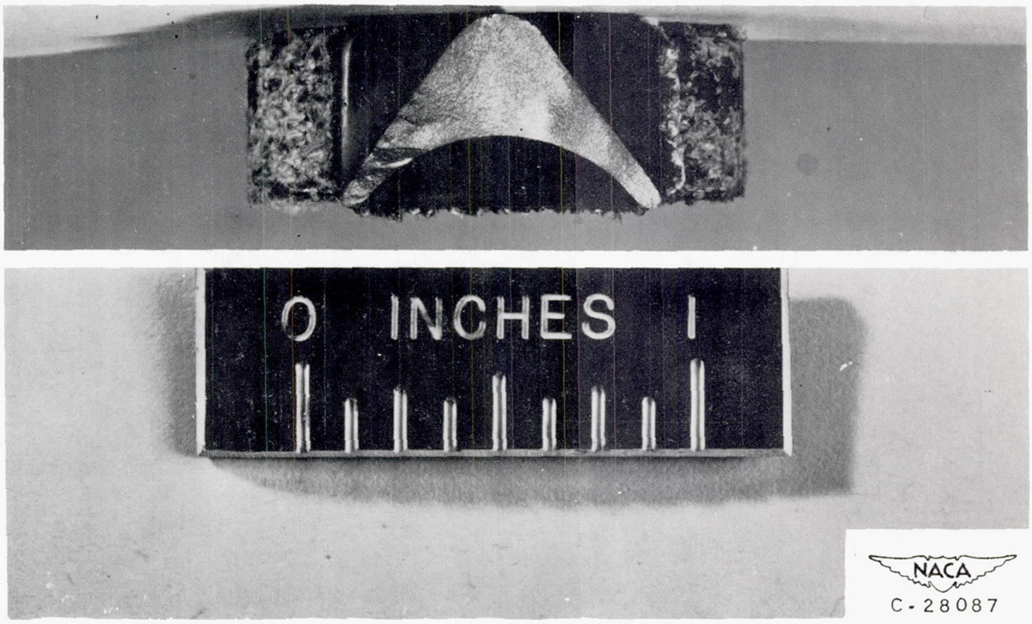
(a) Blade fracture surface. Blade in rotor.



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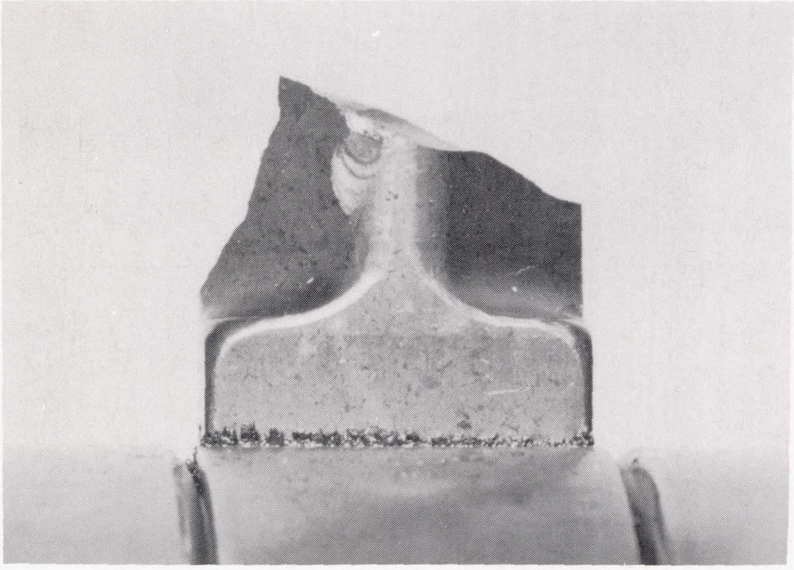
(b) Blade fracture surface. Blade removed from rotor.

Figure 5. - Molybdenum disilicide blade 1 after failure.



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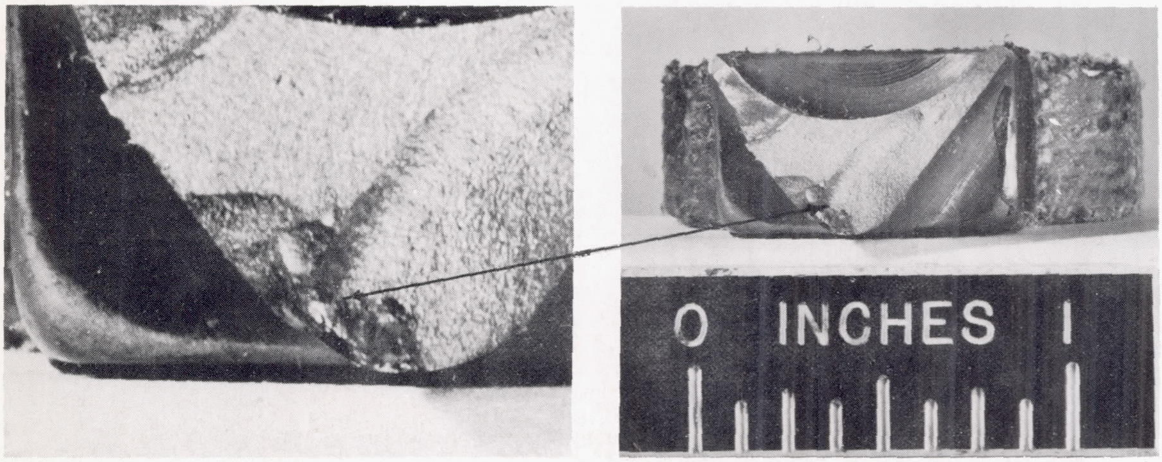
(a) Blade in rotor showing possible impact fracture area.



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(b) Fracture surface showing possible initial fracture area. Blade removed from rotor.

Figure 6. - Molybdenum disilicide blade 2 after failure.

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