NASA-TM-X-1341

NASA TM X-1341

TEST OF A CRACKED COMPRESSOR BLADE REPAIRED BY ELECTRON BEAM WELDING

by Roy D. Hager

Lewis Research Center

Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • FEBRUARY 1967

NASA TM X-1341

TEST OF A CRACKED COMPRESSOR BLADE REPAIRED BY ELECTRON BEAM WELDING

By Roy D. Hager

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – Price $1.00

TEST OF A CRACKED COMPRESSOR BLADE REPAIRED BY ELECTRON BEAM WELDING

by Roy D. Hager

Lewis Research Center

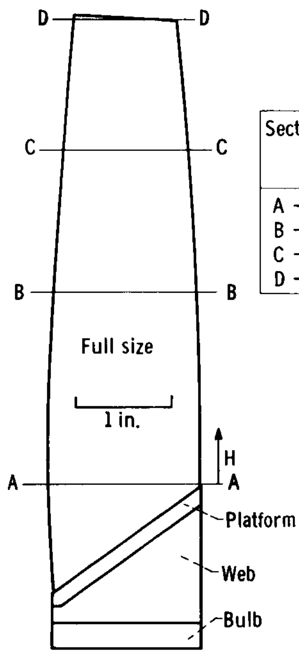
SUMMARY

Results are given for a fatigue test of a maraging steel blade that was repaired by electron beam welding. The repaired blade was initially cracked by a severe bending vibration while being run in a research compressor. Bending fatigue tests to determine the effectiveness of the repair method were performed to a stress level as high as ±61 000 psi before failure occurred. Since the failure did not occur at the weld, but 1/2 inch closer to the tip, electron beam welding can be considered a satisfactory repair method for this type of blade.

INTRODUCTION

Rotor blades used in turbomachinery in both research and commercial applications are often subjected to high cyclic stresses for short durations or to low cyclic stresses for long durations. These stresses may result in cracking of the blades. Because of the high cost of manufacture, it is not always feasible to have sufficient spare blades on hand to replace the cracked blades. If, however, a technique were available to repair cracked blades without inducing a distortion that could deteriorate rotor performance, considerable savings in time and cost could be realized.

In a research compressor being run at Lewis Research Center, several blades cracked as the result of severe bending vibration. In order to minimize the downtime, an attempt was made to repair the cracked blades by electron beam welding. To determine the acceptability of the procedure, one of the repaired blades was checked for distortion and was fatigue tested to failure on an electromagnetic shaker.



Section	0.0		0.500		1.00		1.500		1.837		θ	H
	Y_0	Y_L	Y_0	Y_L	Y_0	Y_L	Y_0	Y_L	Y_0	Y_L		
A - A	0.010	0.010	0.282	0.172	0.332	0.206	0.014	0.000	-----	-----	10°2'	0.0
B - B	.010	.010	.138	.063	.173	.082	.108	.047	-----	-----	33°40'	2.0
C - C	.010	.010	.090	.020	.105	.024	.071	.015	0.010	0.010	45°21'	3.5
D - D	.010	.010	.083	.022	.097	.026	.068	.016	.010	.010	53°19'	5.0

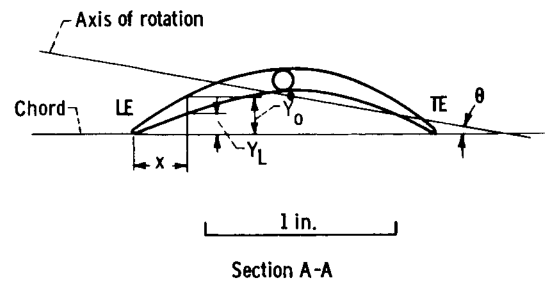


Figure 1. - Blade design and coordinates.

BLADE DESIGN

A scale drawing of a new compressor blade and a table with section locations, surface coordinates, and setting angles are presented in figure 1. The blades, which are constructed of maraging steel, were designed for use in a rotor with a 20-inch diameter, a 1200-foot-per-second tip speed, and a 0.4 hub-tip ratio. The blades have an aspect ratio of 3 and a measured first-bending-mode natural frequency of 160 cps. In operation at design speed, the calculated steady stress on the blade hub section is approximately 75 000 psi. The physical properties of the blade material are given in table I. Details of other properties of maraging steel and machining characteristics can be found in references 1 and 2. The blade material is an alloy of 18-percent nickel-cobalt-molybdenum age hardening steel that contains approximately 0.20 percent titanium, as shown in table I. This material has a yield strength of 200 000 psi and good toughness characteristics. A curve showing the variation of the maximum fiber stress as a function of the number of cycles for a smooth specimen with no steady load is presented in figure 2. This curve approaches the endurance limit after 10^6 cycles and thus indicates a practical limit for fatigue testing. The notched and smooth specimen lines of the Goodman diagram are shown in figure 3. The endurance limit for a fully reversed stress is plotted on the vertical axis, and the ultimate steady stress limit is plotted on the horizontal axis with a straight line connecting the two. The smooth-specimen fully reversed stress is

TABLE I. - PHYSICAL PROPERTIES OF COMPRESSOR BLADE MATERIAL

Composition, nominal percent	
Carbon	0.03 (maximum)
Nickel	18
Cobalt	7.5
Molybdenum	5
Titanium	0.20
Physical properties	
Density, lb/cu in.	0.29
Modulus of elasticity, psi	26.5 to 27.5×10^{6}
Coefficient of thermal expansion at 70° to 900° F, in./in./$^{\circ}$F	5.6×10^{-6}
Poisson's ratio	0.26
Rockwell C hardness	44 to 48
Strength and ductility at room temperature	
0.2 Percent offset yield strength, ksi	
Annealed[a]	95
Maraged[b]	200
Tensile strength, ksi	
Annealed[a]	135
Maraged[b]	210
Elongation, percent	
Annealed[a]	17
Maraged[b]	14
Reduction of area, percent	
Annealed[a]	75
Maraged[b]	60
Endurance, limit[c], 10^{8} cycles, ksi	
Smooth bar	
Annealed[a]	---
Maraged[b]	115
Notched bar	
Annealed[a]	---
Maraged[b]	46

[a]Annealed at 1500° F for 1 hour and air cooled.
[b]Annealed and then maraged at 900° F for 3 hours and air cooled.
[c]Vacuum melted.

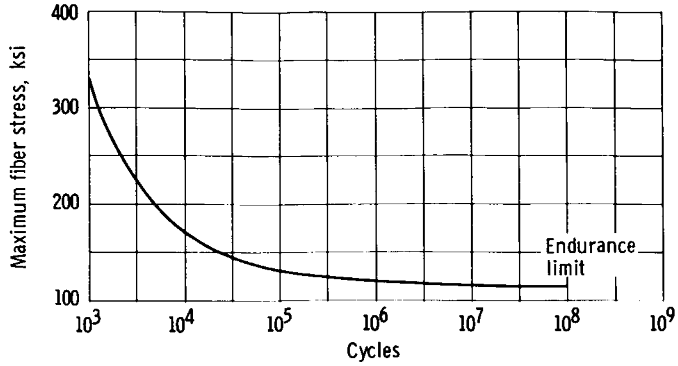


Figure 2. - Stress cycle diagram of 200 maraging steel. Smooth specimen of vacuum melt material at ambient temperature.

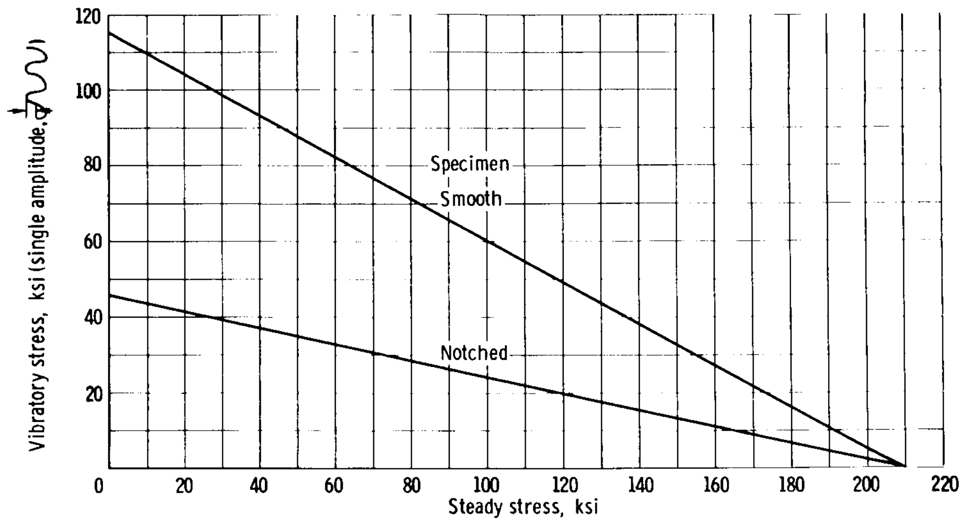


Figure 3. - Goodman diagram for 200 maraging steel at ambient temperature. Yield, 200 ksi; ultimate tensile strength, 210 ksi.

±115 000 psi for vacuum-melted maraging steel with ±46 000 psi reversed stress for the notched specimen stress limit. The notched value is determined by the stress concentration due to a deep machine mark or groove in the specimen. Based on the design steady-state stress of 75 000 psi, the Goodman diagram indicates up to ±30 000 psi vibratory stress for notched specimens and ±74 000 psi for smooth specimens.

INITIAL COMPRESSOR TEST AND BLADE FAILURE

During the research compressor test, several blades failed because of a severe bending vibration at 50-percent speed. The calculated steady stress at this speed is 18 800 psi which, according to the Goodman diagram, would allow a vibratory stress of ±104 000 psi for a smooth specimen or ±42 000 psi for a notched specimen. The estimated

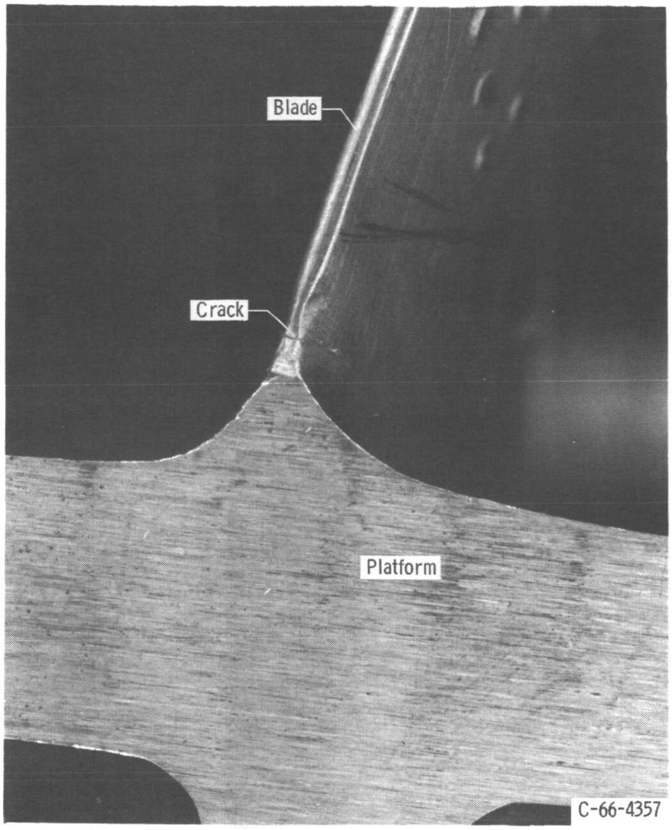


Figure 4. - Crack starting from blade trailing edge after initial compressor failure.

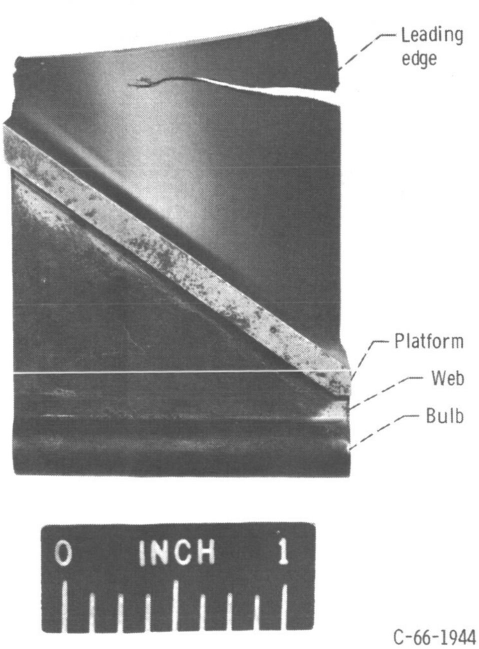


Figure 5. - Section of blade that failed in compressor test.

maximum vibratory stress level during the test (based on strain-gage location and measured stress levels) was ±110 000 psi. This estimated maximum stress is above the smooth limit and is considerably higher than that of the notched.

The high stresses resulted in hairline cracks in both the leading and trailing edges of the hub blade section. The majority of the blades had cracks originating in the leading edge, as that is the point that is farthest from the neutral axis and is therefore under the highest stress. In some blades, however, cracks started from the trailing edge, which can be attributed to a stress concentration in the root fillet between the outlet base and the blade surface. A crack of this type, which is shown in figure 4, starts from a thin point on the blade trailing edge in the region of the blade fillet. The blades that were repaired for use in the research compressor and the one blade that was repaired for fatigue testing had hairline cracks such as the one shown in figure 4. The length of the cracks, in some cases, totaled up to one-third of the blade chord.

One blade deformed when it failed in the research compressor. The lower portion of this blade with the open crack starting in the leading edge is shown in figure 5. This blade was not reworked but does show the appearance of the crack through the blade. The crack is angled from one blade surface to the other and is not straight from the leading edge to the maximum thickness.

REPAIR PROCEDURE

The blade welded for the shake test had long cracks in both the leading and trailing edges, representing the worst possible cracks that could occur without causing complete failure. These cracks should also represent the most difficult repair because of the remaining small cross-sectional area and the probability of inducing distortion.

In welding the cracked blades, the position and angle of the electron-beam welder had to be controlled in order to get proper penetration of the weld. Since the blade center is much thicker than the edge, a controlled weld intensity was necessary in order to fully penetrate the center and to prevent metal from being blown out of the thinner edge. Care had to be taken to remove completely any oil or dirt from the crack because any foreign material would cause porosity in the weld. After welding, the blades were hand polished around the welds and fillets to give an aerodynamically smooth surface and to eliminate any marks that might cause a stress concentration. X-rays were made to determine if the welds were fully penetrated and free of porosity.

The blades were annealed for 1 hour at 1500° F and then aged for 3 hours at 900° F. The fillets, blade edges, and surfaces were then shot peened with 0.0025- to 0.0035-inch-diameter glass beads to improve their fatigue characteristics. This process results in a residual compressive stress that reduces the total tensile stress caused by vibration and centrifugal force during operation. Inspection before and during repair has shown that distortion does not occur as a result of electron beam welding itself. During the annealing part of the heat treatment, however, the blade is heated to 1500° F which is sufficient to cause some distortion. In some cases, the bulb of the blade base swelled slightly while the blade-setting angle at the tip changed by approximately $\pm 1^{\circ}$.

BLADE VIBRATION TEST

The welded blade was mounted in a fixture for vibration tests (fig. 6) and bolted to the armature of an electromagnetic shaker (fig. 7). In figures 6 and 7, the holes near the blade tip are for damping wires to be used in future compressor tests. The vibration tests were conducted with strain gages mounted in the positions shown in figure 8. Section A-A is in the hub region where the failure occurred in the research compressor. For the initial vibration tests, six 120-ohm foil strain gages were used. Gages 1, 2, 4, and 6 were mounted to detect bending-mode vibrations, and gages 3 and 5 were mounted at 45° to detect the torsional mode. When the blade was tested at the higher stress levels

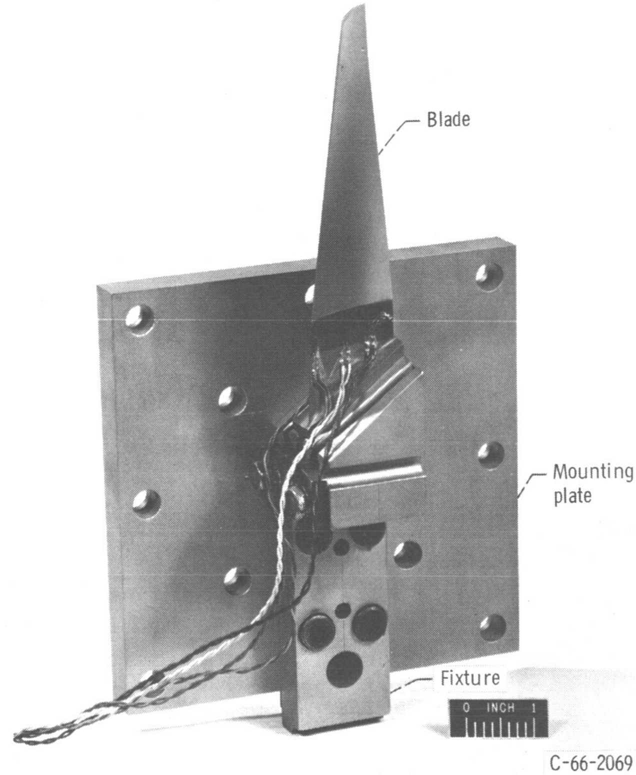


Figure 6. - Blade mounting fixture for vibration test.

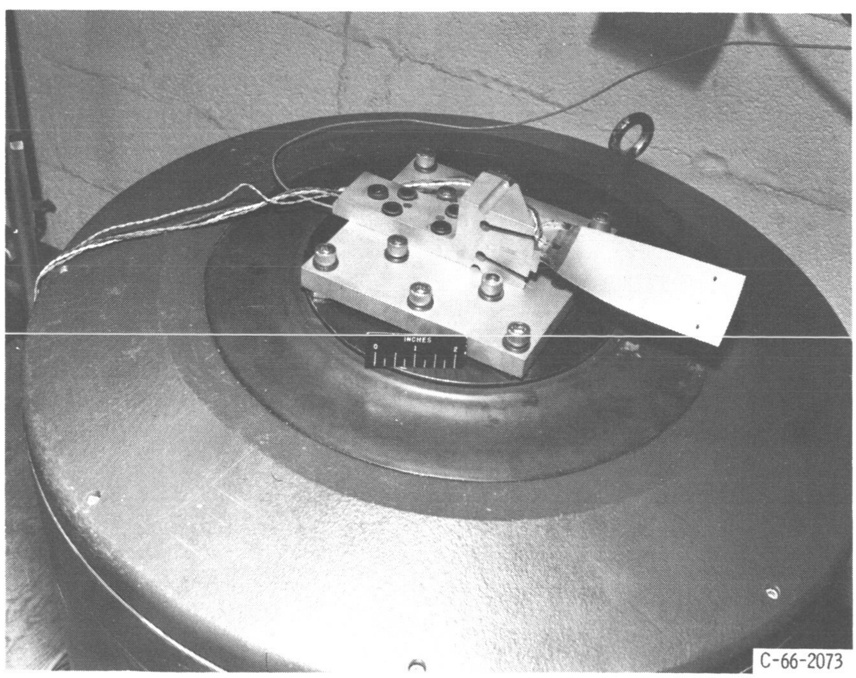


Figure 7. - Blade mounted on shaker.

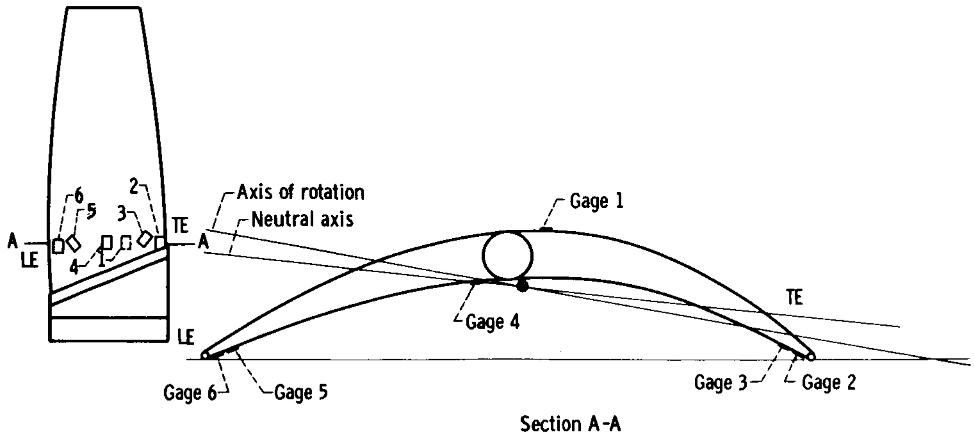


Figure 8. - Strain gage locations for vibration tests.

(above 40 000 psi), the foil gages failed in fatigue. After the 120-ohm gages were replaced once with more foil gages and again failed in fatigue, they were replaced by 350-ohm wire gages that are more suitable for use in fatigue vibration tests. Because of the larger size of the wire gages, only four were mounted in positions 1, 2, 4, and 6; these were used only to measure bending. The strain-gage outputs were run through a selector switch and a strain-gage bridge and were displayed on an oscilloscope. Tip deflection data were approximated by a machinist's scale during the tests.

An electromagnetic shaker was used to excite the blade in the first bending mode and to achieve the desired oscillating stress levels that were used to evaluate the welded blade. Each test was to be run at 160 cps for 5 hours at each vibratory stress level, which would produce 2.88×10^6 cycles in fatigue. After each test, the blade was visually inspected before the stress level was raised and the test repeated.

TEST RESULTS

The stress levels and approximate tip deflections as measured are shown in table II. In the last test, the stress level was ±61 000 psi at the leading-edge strain gage and was 50 minutes before the blade failed. During the last 5 minutes, the resonance frequency changed slowly from 158 to 138 cps at which point the blade broke (fig. 9). Throughout the test series, no cracks were found in the blade until failure occurred at the stress level of 61 000 psi. The test blade accumulated a total of 17.6×10^6 cycles to the time of failure from the initial stress level of ±18 600 psi to the breaking stress of ±61 000 psi.

Since the last three tests were at vibratory stress levels above the notch limit on the Goodman diagram (±46 000 psi) and the location of the break was 1/2 inch above the weld, it would appear that electron beam welding is a satisfactory method of blade repair.

TABLE II. - EXPERIMENTAL RESULTS OF VIBRATION TEST

[Resonancy frequency, approx. 158 cps.]

Run	Approximate tip deflection, in.	Run time, hr	Gage					
			1	2	3	4	5	6
			Oscillatory stress on gage, psi					
1	7/32	5	±11 500	±3 500	±8 200	±4 500	±4500	±18 600
2	10/32	5	±17 500	±5 000	±11 500	±6 700	±6700	±28 000
3	12/32	5	±23 750	±6 750	±15 000	±7 000	±9000	±37 500
[a]4	14/32	5	-------	±12 000	±20 000	±8 500	-----	±42 000
5	15/32	5	-------	-------	-------	±10 750	-----	±47 000
[b]6	19/32	5	±39 000	±23 000	(c)	±18 000	(c)	±56 500
7	21/32	50 min	-------	------	(c)	±20 500	(c)	±61 000

[a]120-Ohm gages replaced because of gage failure.

[b]Gages replaced with 350-ohm wire gages.

[c]Not installed because of space limitations.

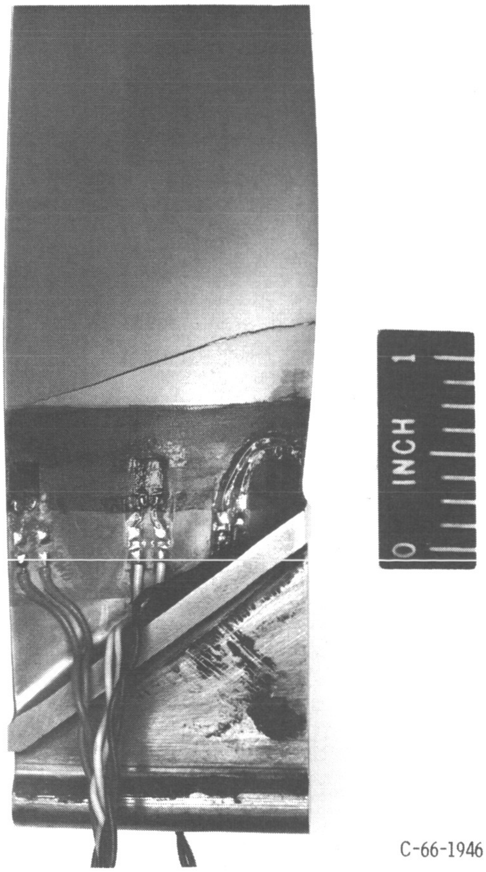


Figure 9. - Blade failure during fatigue test.

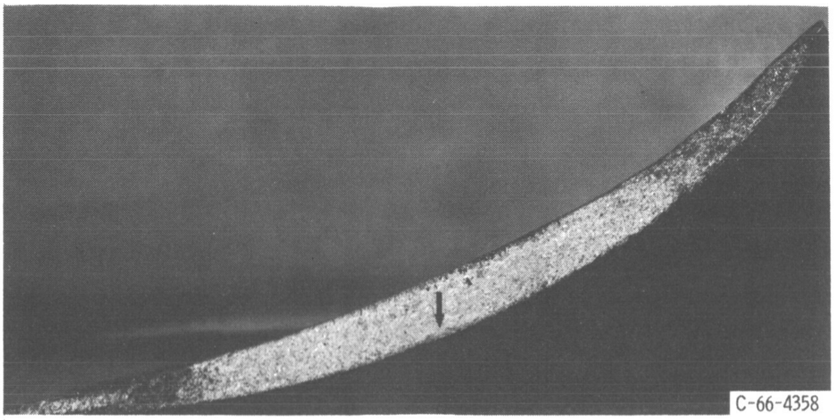


Figure 10. - End view of fatigue crack.

A metallurgical examination of the crack (fig. 10) indicated that the crack starts at the point marked with the arrow and proceeds outward in both directions. The lighter portion of the surface indicates the region of a pure fatigue crack and the darker ends show where the blade was broken in bending.

CONCLUDING REMARKS

Test results indicated that electron beam welding is a promising repair method for cracked compressor blades. Although the notch fatigue limit of maraging steel is ±46 000 psi, failure occurred at a vibratory stress level of ±61 000 psi. When failure did occur, it was not at the weld but was 1/2 inch above the repaired section.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 17, 1966,
720-03-01-48-22.

REFERENCES

1. Anon.: New Breed: The Maraging Steels. Welding Des. Fabrication, vol. 39, no. 1, Jan. 1966, pp. 35-37.
2. Anon.: Maraging Steels - Processing and Fabrication. Welding Des. Fabrication, vol. 39, no. 1, Jan. 1966, pp. 37-38.

NASA-Langley, 1967 E-3600

03410
160 cop
23-3-67

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—National Aeronautics and Space Act of 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Technical information generated in connection with a NASA contract or grant and released under NASA auspices.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

TECHNICAL REPRINTS: Information derived from NASA activities and initially published in the form of journal articles.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities but not necessarily reporting the results of individual NASA-programmed scientific efforts. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546