An investigation of high temperature oxidation found on jet engine turbine blades subjected to commercial airline service

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AN INVESTIGATION OF HIGH TEMPERATURE OXIDATION FOUND ON JET ENGINE TURBINE BLADES SUBJECTED TO COMMERCIAL AIRLINE SERVICE

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BY

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PREFACE

This thesis topic was chosen in order to obtain a more thorough understanding of high temperature oxidation and how it affects the turbine blades of a jet engine.

The author wishes to express his appreciation to Trans World Airlines for their support of this project.

CHAPTER I

INTRODUCTION

One of the major problem areas in jet engine operation today is turbine blade failures. This is especially true of engines used for commercial airline service, since they are subjected to longer operating periods between overhauls than military engines.

The object of this investigation is to study the high temperature oxidation process and specifically to (1) determine the type of oxidation damage found on jet engine turbine blades, (2) attempt to determine the effect oxidation has on a turbine blade property, such as ductility, (3) try to evaluate whether the 2,000-hour blade rework limitation imposed by the manufacturer is realistic, and (4) if possible to reach some conclusions as to what action can be taken to help alleviate the problem of turbine blade failure due to oxidation.

Importance of the Study

Data pertaining to the problems stated above are almost non-existent. The answers to these problems are of vital importance to the commercial airline industry, since a turbine blade failure is one of the most costly malfunctions that an operator can experience.

The turbojet engine manufacturers are constantly searching for better materials and better designs to allow longer operating periods between blade rework and to give a greater margin of safety with respect to blade failures. Consequently, if it could be determined that the 2,000-hour blade rework limitation imposed by one manufacturer could be increased to 2,200 hours, a considerable saving would be realized by the operating airline.

General Approach

The approach to the problems stated are: (1) a critical review of the pertinent literature on oxidation to give a general working knowledge of the subject; (2) a laboratory analysis of the blade microstructure to determine the types of oxidation on ductility; and (4) to use all accumulated data to evaluate the accuracy of the rework limitation and try to arrive at some conclusions which will be helpful in combating oxidation problems in the future.

Chapter II is presented to acquaint the reader with the necessary information pertaining to the theory of oxidation with emphasis on high temperature environments.

Chapter III gives the experimental procedure and analysis used to determine the type of oxidation present and the condition of the blade specimens examined.

In Chapter IV is given the theory and results of the experimental bend check to determine ductility loss due to oxidation.

Discussion pertaining to the feasibility of extending the turbine blade dehusk or rework limit is presented in Chapter V.

Finally, in Chapter VI, the conclusions and recommendations of the study are summarized.

CHAPTER II

THEORIES OF OXIDATION

The reaction between metals and their non-metallic environments constitute a subject called "corrosion". As discussed in Reference 1, the reaction can be metal-liquid or metal-gas. In the field of metal-gas reaction, the term commonly used is "oxidation". Specifically, this study deals with the oxidation of metals at elevated temperatures.

With the exception of gold, no pure metal or alloy is stable in air at room temperature. All metals react to form oxides, although in many cases the rate of reaction may be very slow, especially at low temperatures.

Even at ordinary temperatures, however, the initial stages of oxidation are very rapid, according to Reference 2, but soon slow down as the film begins to isolate the metal and air from each other. Oxidation at room temperature produces little change in appearance of most metals.

At higher temperatures the film quickly becomes thick enough to give interference tints, but the rate of thickening falls off as the film becomes thicker.

The Mechanism of Oxidation

As pointed out in Reference 3, the physical mechanism of oxidation occurs when a metallic surface which is free from oxygen and oxide is exposed to air or oxygen. Oxygen molecules will attach themselves by ordinary intermolecular or van der Waals forces to the surface. This physical adsorption takes place almost instantaneously, while the oxygen may enter more slowly into combination with the metallic base, because of the electron-transfer or electron-sharing between oxygen and metal atoms. Once this has occurred the oxygen becomes much more firmly attached than before. A metallic surface covered with chemically adsorbed oxygen can be regarded as a two-dimensional chemical compound. The next stage should be the formation of a three-dimensional oxide, but this will check its own growth, as previously noted, when still very thin unless the oxide film either

(1) contains definite pores, (2) can permit diffusion through the lattice, (3) intermittently develops cracks, or (4) is volatile and passes off into the gas phase, exposing fresh metal to attach, such as in the case of molybdenum and tungsten at high temperatures.

Oxidation Rate Equations

Many oxidation problems become that of determining the progress of a reaction with respect to time. A number of relationships have been discovered empirically, and are presented in Reference 4. These relationships give the weight increase Δm as a function of the time t. The equations are as follows:

(1) Linear $\Delta m = k_l t$

(2) Parabolic $(\Delta m)^2 = k_p t$, or the more general form $(\Delta m)^2 = k_p t + c$

(3) Cubic $(\Delta m)^3 = k_c t$

(4) Exponential $\Delta m = k_e \ln (at + 1)$

It is known that a metal may have three temperature ranges, as discussed in Reference 5, in each of which a different time relationship governs oxidation. In the intermediate temperature range the parabolic relationship is generally obeyed fairly accurately. At the higher temperatures a tendency toward linear oxidation is occasionally seen, and at low temperatures logarithmic oxidation is frequently observed.

Diffusion in the alloy surface plays an important part in surface oxidation. Actually, as shown in Reference 6, the diffusion rates of all the possible diffusing species in all layers should be known for a complete discussion of the oxidation mechanism and the evaluation of the rate-determining process. The numerical data, particularly for diffusion in compounds, are very hard to find and much experimental work remains to be done. No attempt was made to consider diffusion in this investigation.

Other Contributing Factors

Other factors affecting the oxidation rate, as stated in Reference 7, are permeability of the surface products, cracking of the surface layer, orientation of the base metal crystals, composition of the base metal, surface conditions, and environmental factors such as the rate of flow of the gas in contact with the metal, the gas temperature and the application of cyclic stresses, often called corrosion fatigue.

All of the foregoing information was presented to give an insight into the complexities of the problems involving high temperature oxidation. All of the above theories indicate that the turbine blading of a jet engine, operating in a high velocity, high temperature, corrosive environment, should be very prone to oxidation problems.

This is, in fact, very true. For example, engines subjected to commercial airline service operate approximately 250 hours per month with time between turbine blade refurbishing of 2,000 hours. During this time period, turbine blades are subjected to repeated cyclic loading, high and varying air temperatures and velocities, and corrosive combustion gases. As a result of these operating conditions, many failures have been experienced.

CHAPTER III

LABORATORY ANALYSIS OF BLADE OXIDATION

This chapter explains the experimental testing conducted in an effort to determine what type of oxidation existed on the blade specimens and the resultant damage incurred.

Procedure

Some first stage turbine blades which were scrapped for oxidation or had failed from secondary or resultant damage, and subsequently scrapped, were sectioned and polished in an effort to determine the degree of oxidation on the blades. The procedure used was that of cutting the blades into sections, mounting the sections in plastic and then hand-rubbing them on a series of decreasingly rough abrasive cloths. After the specimen had been smoothed to the roughness of the finest abrasive, it was polished on two rotating polishing wheels, each with a different degree of roughness, using water and polishing powder. This produced a mirror-like finish suitable for a cursory microscopic examination. If the surface of the specimen was of sufficient smoothness, it was etched with a Marbles reagent consisting of 25% nitric acid, 25% hydrochloric acid and 50% glycerol for approximately 30 seconds. Next the specimen was rinsed in water, dipped in acetone to remove the water and then blown dry with an air blast. The specimen was then ready for final microscopic examination and the photographing of areas of interest. The microscope used was a Baush and Lomb Metallograph having a magnification range of 70X to 2125X and incorporating a Poloroid camera for readily available photographic results.

The experimental work was accomplished as related above. The first specimen was a first stage turbine blade which had been removed at overhaul period and scrapped after oxidation removal had caused the blade chord length to be below the minimum limits. From past experience it is known that by the end of an engine overhaul period the leading and trailing edges of the blades will be deteriorated by thermal fatigue cracks and oxidation. This condition dictates that the leading and trailing edges be "dehusked" or ground off and reshaped with abrasive wheels. This generally means that at engine overhaul approximately .010 inches of material is removed from each edge to remove all oxidation and the blade is returned to service. This operation may be repeated a maximum of two times before the blade chord length is below the minimum limit allowed.

Microstructure Examination

Specimen number one was sectioned, mounted, polished and etched. A microscopic examination revealed very little oxidation present under 250X magnification. This is shown in Figure 1, and is indicative of what a lightly oxidized blade surface should look like. A view of the blade leading edge which was dehusked is shown in Figure 2, also at magnification 250X. This shows complete lack of oxidation.

Specimens two and three were taken from blades that had failed in service from resultant damage incurred in an engine which had suffered a turbine blade failure. These were not sections of the blade which was the primary failure. Specimen number two was mounted, polished and etched, and examined under a magnification of 250X. The results of this revealed a moderate layer of peripheral oxidation on all portions of the perimeter of the section, with very slight preferential oxidation or intergranular oxidation (IGO) starting to develop. This is sometimes also called intergranular attack (IGA) This specimen is shown by Figure 3.

Preferential Oxidation

Preferential oxidation is exemplified by a penetration into the surface by oxidation along the grain boundaries. In these cases the oxidation seems to occur more readily at the grain boundary rather than in the grain itself. Thus, this type of oxidation is called preferential oxidation. This type of oxidation is far more detrimental to the material than peripheral oxidation, and seems to follow peripheral oxidation in chronological order.

FIGURE 1. LIGHTLY OXIDIZED TURBINE BLADE SURFACE. MAGNIFIED 250X. ETCHED.

FIGURE 2. DEHUSKED TURBINE BLADE LEADING EDGE SURFACE SHOWING LACK OF OXIDATION. NOTE GRAIN BOUNDARIES EXTENDING TO SURFACE. MAGNIFIED 250 X. ETCHED.

FIGURE 3. PERIPHERAL OXIDATION WITH LIGHT PREFERENTIAL OXIDATION VISIBLE AT OXIDATION - BASE METAL INTERFACE. MAGNIFIED 250 X. ETCHED.

Specimen three is a very good example of preferential oxidation. This may be seen in Figure 4. This figure shows severe attack and deterioration of the metal along the grain boundaries. This is very deleterious to the material, both from a standpoint of fatigue from cyclic loading and from stresses induced by thermal gradients on starting and during normal power-setting variations.

Figure 4 shows that the corrosive operating atmosphere has broken through the layer of peripheral oxidation, leaving rough openings in this layer, and has attacked the base metal at the grain boundaries.

FIGURE 4. PREFERENTIAL OXIDATION. NOTE SEVERE ATTACK AND ERROSION OF GRAIN BOUNDARIES. MAGNIFIED 250X. ETCHED.

CHAPTER IV

EXPERIMENTAL ANALYSIS OF DUCTILITY LOSS

Based on the results of the microsctructure examination, it was thought that a correlation should exist between ductility and the amount and type of oxidation present. With this in mind, several turbine blades were cut with an abrasive cutting wheel, such that a section approximately 1.50 by .20 inches was removed, parallel to the blade leading edge. This section was subjected to a bending force near the middle of the section in such a way as to put the blade leading edge in tension. This is shown in Figure 5.

It was believed that the oxidized blade would be less ductile than the non-oxidized blade, and that this would be apparent from the magnitude of the angular bend that each blade would withstand before starting to crack. Therefore, the included angle of

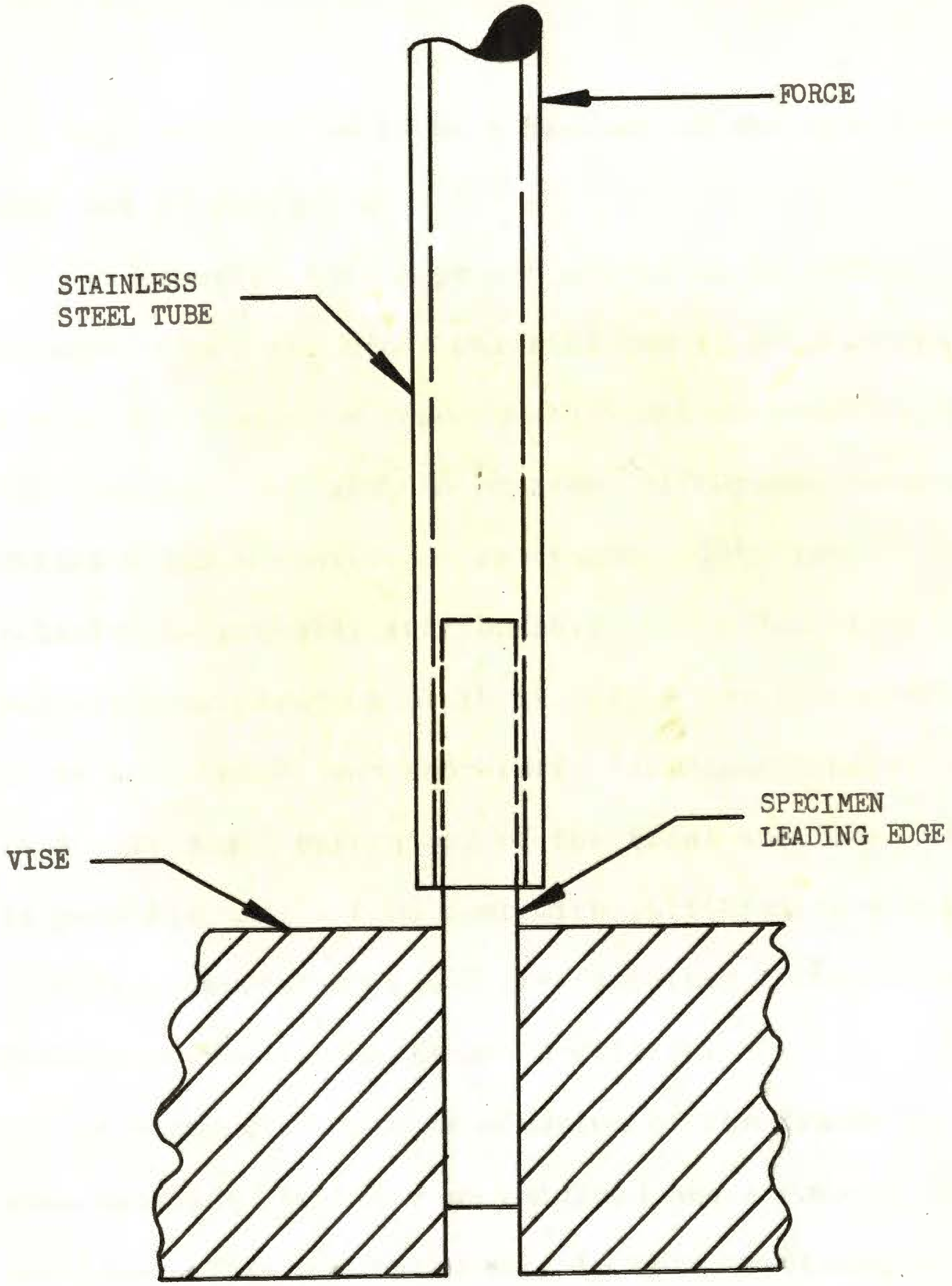

FIGURE 5. SKETCH OF TEST SET-UP USED TO BEND TURBINE BLADE LEADING EDGE SPECIMENS FOR DUCTILITY INVESTIGATION.

the bent specimen would be a measure of the ductility loss due to oxidation.

In practice this approach proved to be inconclusive, since the blade material was so brittle that a very small angular bend caused complete fracture of the specimen, and with no apparent difference between oxidized and non-oxidized specimens. This lack of correlation is probably attributable to the fact that the oxidation penetration depth is only a few thousandths of an inch thick, and therefore, the damaged material is a very small percentage of the total specimen. It is possible that a bend test with sufficiently sensitive instrumentation would give a better correlation between oxidation damage and ductility.

A microsctructure examination of the fractured area was made, both for an oxidized and a non-oxidized specimen. This indicated that in both specimens the cracks originated along grain boundaries, as would be expected. Each specimen had some small cracks near the point of fracture which show the crack following a boundary. This is displayed by Figure 6 for the non-oxidized section and by Figure 7 for the oxidized specimen. This failure along the grain boundaries indicates that damage by intergranular attack, as in preferential oxidation, would make the material very susceptible to failure by cyclic stresses.

FIGURE 6. NON-OXIDIZED SPECIMEN SHOWING TENSION FAILURE CRACKS FOLLOWING GRAIN BOUNDARIES. MAGNIFIED 250X. ETCHED.

FIGURE 7. OXIDIZED SPECIMEN SHOWING TENSION FAILURE CRACKS PROCEEDING ALONG GRAIN BOUNDARIES. MAGNIFIED 250X. ETCHED.

CHAPTER V

EVALUATION OF TURBINE BLADE REWORK TIME LIMITS

The problem of establishing a time limit for rework of turbine blades to remove oxidation had several aspects. First, the time between blade dehusking should be as long as practicable, since approximately .010 inches of metal is removed from both the leading edge and the trailing edge of the blade. This dictates that the number of times this rework may be accomplished must be limited to two, since the blade chord length would be out of overhaul specification limits after the third rework operation.

Secondly, the blade rework limit must provide a reasonable margin of safety with respect to blade failures, since, although a turbine blade failure is generally not considered to be serious, it definitely is a very costly failure to repair.

One should consider the turbine blade failures that have been experienced by engine operators. This past history or failure rate is often indicative of whether the time between blade rework should be raised or lowered; however, a poor blade design or other related problems could be reflected and thus give an erroneous indication.

From the above discussion we see that the optimum blade rework time limit is the one that gives the engine operator the least total cost per flying hour, and is arrived at by a series of compromises and in some cases by trial and error.

One jet engine manufacturer is presently doing an intensive laboratory analysis in an attempt to determine the feasibility of extending the blade dehusk or rework limit from 2,000 hours to 2,200 hours. Based on the experimental analysis of Chapters III and IV and the recent very good turbine blade failure rate of the airline operator in question, the author would recommend adopting a 2,200-hour blade dehusk period.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Based upon the experimental metallurgical analysis of Chapter III, it is concluded that the high temperature oxidation found on jet engine turbine blades is chiefly of two types. The first type found was peripheral. This covers the perimeter of the blade chord, or surface of the blade, with a coat of oxide which tends to slow further oxidation. However, as the blade is continued in operation, the peripheral oxidation gives way to preferential oxidation, sometimes called intergranular attack. This is more harmful than peripheral oxidation and is the type of oxidation which is most conducive to blade failure.

Secondly, it was not conclusively proven by the experimental testing of Chapter IV that oxidation reduces the material ductility. This was probably due largely to the lack of sensitive measuring equipment. It is recommended that further testing in this area be pursued with suitable strain gages and a better means of force application, such as an hydraulic press.

Some of the problems related to the establishment of a practical turbine blade rework time limit were discussed in Chapter V. Based on the facts presented there, it is the conclusion of this study that the time limit be raised to 2,200 hours between overhaul and blade dehusking.

Oxidation will be reduced by lowering the starting temperature, such as by decreasing the starting fuel flow. This could present a problem of hard starting due to the lower fuel-air ratio, unless a fuel nozzle could be designed to give a satisfactory starting fuel distribution for the lower flow.

Another means of reducing turbine blade failures would be to use a material which would be less susceptible to oxidation. Still another way would be to use a new turbine blade design which would lower operating stresses and hence reduce oxidation rates and lengthen blade life.

It is recommended that the above areas be explored further as a possible solution to the costly problem of high temperature oxidation and resultant failure of jet engine turbine blades.

REFERENCES

1. Kubaschewski, O. and Hopkins, B.E., Oxidation of Metals and Alloys. (New York: Academic Press, Inc., 1953) p. 1.
2. Evans, Ulick R., An Introduction to Metallic Corrosion, (London: Edward Arnold and Co., 1948) p. 11.
3. Evans, Ulick R., Metallic Corrosion Passivity and Protection, (London: Edward Arnold and Co., 1946) p. 100.
4. Kubaschewski, Op. Cit., pp. 37-38.
5. Ibid, p. 161
6. Ibid, p. 20
7. Miley, H. A., "Fundamentals of Oxidation and Tarnish" The Corrosion Handbook by Herbert H. Uhlig (New York: John Wiley and Sons, 1948) pp. 11-17.

BIBLIOGRAPHY

1. Evans, Ulick R., *An Introduction to Metallic Corrosion*. (London: Edward Arnold and Company, 1948).

2. Evans, Ulick R., *Metallic Corrosion Passivity and Production*. (London: Edward Arnold and Company, 1946).

3. Kubaschewski, O. and Hopkins, B. E., *Oxidation of Metals and Alloys*. (New York: Academic Press, Inc., 1953).

4. Miley, H. A., "Fundamentals of Oxidation and Tarnish," *The Corrosion Handbook* by Herbert H. Uhlig (New York: John Wiley and Sons, 1948).