Lewis

MATERIALS RESEARCH

Physics of Solids

Speakers: Robert A. Lad
George C. Fryburg

Jet engines first became practical when materials which could withstand the high temperatures of combustion gases were found. Ever since, the limit of engine performance has always been set by the temperature to which the turbine blades could be exposed. The main problem of the materials work at this laboratory is therefore how to raise this temperature by developing better materials. The situation has recently become more acute because of the shortage of alloying elements which are essential to even present-day materials.

We are attacking the problem in two general ways: First, by investigating materials which show promise to be superior to those in use, and second, by trying to find the basic factors which make a material strong at high temperatures. The first approach gives quicker but limited results; the second, although slower, will eventually provide the basis for major improvements.

I have mentioned our work on improving engine life by improving the materials. It is also possible to increase engine life by reducing stresses and by turbine blade cooling.

We will discuss research on reduction of stresses here. Turbine blade cooling is discussed at another stop in the inspection.

The lack of fundamental knowledge of what gives a material its strength and why it eventually fails is one of the important limitations on the search for better high-temperature materials. The physics of solids research at this laboratory is directed at increasing our understanding of this basic problem. Among the factors potentially important in determining the strength of a material are grain structure, cracks, the chemical nature of the surface, and irregularities in the arrangement of the atoms. We are studying the effect of each of these factors on strength and have chosen for discussion today the influence of the nature of the surface. To arrive at a fundamental understanding we must start with studies of the basic building blocks of the material; namely, the atoms; then arrangement, and the forces between them.

One can compute the tensile strength of an ideal solid from the forces of attraction between its atoms. The tensile strength of a specimen of the material is found by experiment always to be much lower than its computed strength. For some materials, the experimental value may be as low as 1/1000 of the theoretical. A major cause of this large discrepancy may be the presence of very minute cracks in the

surface, cracks so small that they are invisible even under the most powerful microscope. We are studying these cracks on the surfaces of single crystals of various materials to learn how and why they form.

To make these cracks visible, a layer of silver, 25 atoms thick, is deposited by vacuum evaporation on the face of a crystal and heated. The silver gathers into microscopic crystallites which arrange themselves along the cracks. Here is a microphotograph of the surface of a single crystal (fig. 1). Notice that the lines formed by crystallites of silver seem to appear at random angles. However, we have been able to show that these are not random angles, but that they can be related to the atomic structure. This model represents the surface layer of atoms in a crystal. The positively charged atoms are represented by the small spheres; the negatively charged atoms by the large spheres. You see that they are arranged alternately on a square grid. We now show straight lines which join these atoms. We present only those lines which contained a relatively large number of atoms per unit length of line. We then measure the angles which the lines of silver crystallites make on a crystal face from photographs such as this one. Those angles which occur most frequently are shown on this section of the model. They agree well with the angles of the lines drawn through the atoms. Hence, we may assume that these are not

random cracks, but are a result of the atomic structure -- that is, the cracks occur most often along the lines on which the atoms lie. These cracks may be the origin of the failure in materials under stress. In demonstrating that they exist and their nature, we have diagnosed to some extent the disease. We are extending our knowledge of the subject with the objective of finding the cure.

I will now discuss another aspect of the effect of the nature of the surface on strength. If a piece of metal is stressed beyond its elastic limit, it stretches or creeps until it finally breaks. In a turbine, for example, the blades creep under the action of the centrifugal force, and with excessive creep, may fail or rub against the turbine housing and be damaged. There is some evidence that the creep rate of metal is strongly affected by the chemical composition of the surface layers of atoms. However, no information was available on the relation between the creep rate and the composition of the surface. We have, therefore, undertaken a systematic study of this effect. The most difficult aspect of the problem is the fact that we are dealing with a surface layer one one-hundred-millionth of an inch thick. This quantity of material is too small for the usual chemical methods of analysis and we, therefore, use electron diffraction techniques for identification. An electron beam is projected on the surface under study and the reflected beam is photographed.

I will demonstrate in a motion picture the effect of altering the surface layer of a zinc single crystal. The tests were made on this apparatus. The crystal is held regidly at one end while a load is applied to the other end. The lucite chamber permits us to surround the crystal with reagents which change the composition of its surface. An oxide coated crystal is first surrounded by water. The load is applied and after a brief time, hydrochloric acid is introduced. The acid removes the oxide coating of the crystal. Here is a graph of the elongation with time of the zinc crystal under load (fig. 2). When surrounded by water, the rate of creep of the crystal is low. However, when the acid is added at this point, the creep rate increases sharply. This large increase in creep rate is due to the removal of the oxide layer on the surface of the crystal by the acid solution.

We will now show the movie of a typical experiment. The specimen has hooks soldered to the ends and is installed as shown. The crystal has an oxide layer which is not altered by the introduction of water. The experiment is now begun by loading the balance pan with the weight, and the crystal begins to creep. You can observe the slow extension of the crystal by watching the end hook. Now acid is added and very soon afterward the rate of extension increases many fold. The next sequence shows a second experiment.

These are but two examples of the fundamental studies in which we are engaged. Basic research of this type yields answers which will provide a sound basis for the search of better high-temperature materials of the future. In the meantime, problems are arising daily which require an immediate answer. The next speaker will describe our contributions to the solution of some of these problems.

MATERIALS RESEARCH

Strategic Materials

Speakers: George C. Deutsch
Charles Yaker
G. Mervin Ault

A large part of our work in high-temperature materials is on problems of shorter range interest. One such problem is that of the conservation of strategic materials in gas turbines. An analysis of the distribution of strategic material in the gas turbine has shown that the highest concentration is in the turbine blades. These blades are the components that operate under the most severe conditions of stress and temperature and consequently the reduction of strategic element content of the blades presents the most difficult problem. The materials which have met the severe blade requirements to date have been those containing large amounts of such scarce elements as cobalt and columbium.

I have here a blade made from the material which is currently most widely used on jet engines. If all engine production were predicated on this material, the production of engines even approaching the 18,000 engines per month state requested by Industrial Mobilization Board is impossible. Obviously, therefore, means must be found to overcome the strategic material problem in the turbine blades.

Within the last few years we have been directing much of our effort towards measures which would contribute to the solution of this problem. This effort is in conjunction with similar workbeing carried out by alloy and engine manufacturers and the military services.

Some of the approaches we are studying are described elsewhere today. Two others are indicated in the chart on the panel. Each approach is represented by a bar. The height of the bar is a weighted measure of the strategic content of the turbine blade representing the approach and we will discuss these approaches in order.

The first bar, which has been included for comparison purposes, represents the strategic element content of the currently most widely used blade alloy. The height of the second bar represents the strategic element content of newer alloys which preliminary tests have indicated to be very promising. The third bar represents the strategic element content of ceramal materials. These latter materials are mixtures of metals and ceramics. Both of these approaches hold promise of providing satisfactory turbine blades with a very large reduction in strategic element content. However, both involve developmental problems. It is these that I will discuss briefly.

I would like first to discuss the alloys represented by the second bar. Part of our work has been to investigate

how these materials can be fabricated into turbine blades while retaining the good properties indicated by laboratory test specimens. The strength of turbine blades made from these newer alloys is very sensitive to the forging or casting practice and heat treatment used in the fabrication process. Little information is available on the relation between these variables and the life of the turbine blades in an engine. It is therefore by systematic study and control of processing variables that we hope to compensate for the reduction of strategic elements and draw the maximum strength out of the materials.

To illustrate this procedure I will discuss a heat treatment study on a cast turbine blade. The use of cast alloys is especially attractive because it affords an easy way to achieve greatly expanded production. However, before cast alloys can be used to replace the current alloys, their reliability must be improved and their strength must be increased. We have found that reliability and strength are associated with microstructure, that is, the structure as viewed under microscope. In the next chart we see two typical microstructures (fig. 1). Here we have the structure of an "as-cast" blade. It is in this condition that the alloys has been used in the past. Here we have the heat-treated blade. It was placed in a furnace and the temperature controlled according to a preestablished schedule until this

structure was brought out. You will notice in the picture of the "as-cast" blade that the carbide precipitates are distributed at random throughtout the structure. In the heat-treated specimen you will notice that these original precipitates have largely disappeared and in their place is evident a lamellar or plate-like arrangement of precipitates. The heat-treated blade was found under test to be much stronger than the "as-cast" blade.

Some engine test results on a series of heat-treated and unheat-treated blades are shown in the next chart (fig.2). Here we have plotted the percentage of the blades that failed against the time of engine operation. The red curve represents the results for the heat-treated blades, the blue line the results for the unheat-treated blades. It can be seen that in the heat-treated sample the time for first failure was approximately three times that of the nonheat-treated sample. In general, heat treatment roughly doubled the life of the blades in the engine. This indicates the order of magnitude of grains that may be made through an understanding of the influence of processing variables.

Referring again to the original chart we see that a second apporach to the problem of strategic materials conservation is the use of ceramals. These are mixtures of metals and ceramics, which are designed to combine the properties of good strength at high temperature with good

resistance to thermal shock. In this chart (fig. 3) we show the potential relative life of ceramal blades compared to the life of the currently most-used alby blades. We see that even at current operating temperatures the ceramals have a potentially greater life than the current alloy. At the higher gas temperatures, which are extremely desirable from the standpoint of improving thrust, the comparison favors ceramals even more.

Ceramal blades are normally made by powder metallurgy methods. In one method, ceramic and metal powders are thoroughtly mixed, pressed in a die, and then heated. This process is known as cold pressing and sintering. Another process in which the pressing and sintering operation are combined is known as hot pressing, and can be illustrated schematically by this simple model. In this apparatus we have a die system such as the one I have in my hand. In it is a mixture of two types of disks. The opaque disks are the more refractory or temperature resistant of the two and for purposes of illustration will represent the ceramic material. The transparent disks represent the metal powder. This mixture has been heated to the hot pressing temperature. Just as in actual practice the mixture is heated to its hot pressing temperature. No pressure has as yet been applied to the mixture. The particles are, therefore, individual without any interconnecting bonds, and there are a considerable number of voids or empty spaces between them. By means

of a hydraulic jack, we now apply a pressure to the mixture. Colored fringes develop at the points of contact between the particles. These fringes are manifestations of contact stresses and are made evident by the use of polarized light. The stresses cause the softened particles to deform and to take shapes suitable to fill the voids. Thus after a period of time, a continuous body is obtained. In the actual sintering of ceramals, bonds between adjacent particles may be developed by any one or a combination of complex mechanisms, for example, by diffusion of the materials along grain boundaries. We are at present studying the complex mechanism of the actual sintering of ceramals which is demonstrated here only in a very qualitative manner.

An important problem associated with ceramals is the method of fastening them in the wheel. For metal blades that have a large degree of ductility the conventional fir-tree shown here is a very satisfactory method of retaining the blade in the wheel (fig. 4). Ceramals, however, are quite brittle and the sharp radii and rapid changes in cross section associated with the fir-tree type of mounting has resulted in premature blade failure. Considerable effort has, therefore, been directed toward the development of fastenings especially suitable for ceramals. In one of these which is shown here the pins retain the blade and provide some of the ductility that is lacking in the ceramals.

You will notice that the radii involved in the ceramal mounting are much larger than those in the fir-tree. Large radii mean lower concentration of stress, which is very important in the use of brittle blade materials.

To illustrate the significance of design on the strength of fastenings of blade materials, we have placed in this apparatus models of the two designs shown on the panel. The models are mounted in loading frames and pulled in tension by hydraulic jacks to simulate the tensile loading on the blade resulting from rotation. The loads on the two jacks are equal and will gradually be increased. You will notice that at the sharp corner in the fir-tree type of mount there develops a large number of colored fringes. This is an indication of high stress. Fewer fringes or color lines appear in the root intended for use with ceramals. As we increase the load, you will notice that the fir-tree type of fastening fails at an appreciably lower load than that of the improved design.

Fastening of this and other improved designs have been laboratory-tested and are now undergoing evaluation in full-scale engines. Here are some of the ceramal blades being tested in the engine. They look very much like the metallic blade used conventionally except for the root shape. With some of these, it has been possible to operate at full rated speed, gas temperature, and engine power output. Continued

research is directed at obtaining long life and increased temperature of operation.

I should now like to introduce our final speaker, who will discuss another phase of our research.

Lewis

MATERIALS RESEARCH

Vibration Studies

Speakers: Andre J. Meyer
William F. Brown

Another phase of our research is directed towards the understanding of design factors which contribute toward failure of materials in existing engines and to seek methods of increasing engine life. A typical example of this type of research is the study of compressor blade vibration which can cause actual failure of the blades and consequent destruction of the engine. Here we have a typical jet engine axial-flow compressor. During engine operation blades such as these are subject to various types of vibration. The problem is to discover the causes and the nature of these vibrations and to devise methods of reducing the vibration amplitude.

In this research the compressor blades are instrumented with strain gages and the engine is then operated over the entire normal speed range. Strain-gage signals are recorded and from these signals which indicate the vibration amplitude and from measurements of the blade natural frequency we are able to determine the nature of the vibration of current.

Our research of this type has indicated that it is possible to introduce enough damping in the compressor blade

mount to overcome aerodynamic excitation. One way in which this can be done is to introduce a film of solid lubricant in the blade mounting. The reason for the effectiveness of the film is shown in the next chart (fig. 1.). Here is a compressor blade, loosely mounted in the rotor. This arrow represents the centrifugal load due to the high speed of rotation. Normally this load is so high that the blade looks at the root and acts almost as if it were welded into the wheel. When a vibration esciting force is applied as indicated by this double arrow, the blade starts to vibrate or bend from this point up because the root itself acts as if it were part of the wheel. There is norubbing or friction in the mount and, therefore, all the vibration energy is absorbed in producing high tip amplitudes. In the blade at the right, a thin lubricant has been applied to the blade base. This lubricant prevents the looking action under the centrifugal force and when vibration is induced by an exciting force, some motion can occur in the mount. The friction accompanying this motion dissipates a large part of the vibration energy, thus minimizing the vibration amplitude. In the compressor, for example, the use of a thin film of molybdenum disulfide causes the blades to vibrate at about one-third the amplitude of the normal blade.

We can demonstrate the effectiveness of a lubricant film in the blade base by means of this apparatus. Here a blade is mounted on an electronic vibration excitor which

operates on the principle of a radio loud speaker. First, we observe the blade excited at its natural frequency. You will notice the large tip amplitude in the stroboscopic light. Now by turning this valve, lubricant is injected into the base mount. You will observe the immediate rapid drop in vibration amplitude and decrease in sound when the lubricant is added. This is due to the fact that the lubricant has permitted relative motion between the blade and its mount. Although for demonstration purposes we used a liquid lubricant in our tests, a solid film lubricant of MoS_2 proved most effective.

We have discussed research on methods of minimizing the effects of vibration. We will now discuss some research directed at eliminating the cause. It has also been found that a type of severe vibration excitation called "stalling flutter" can occur in axial-flow compressors. Stalling flutter is produced when an air stream strikes a blade at high velocity and at a high angle of attack. The amplitude of the flutter vibrations were found to be very sensitive to changes in the angle of attack. Thus, it is possible to drastically reduce stalling flutter by changing the angle of the stator vanes which direct the compressor air onto the blades.

Research on stalling flutter is carried out in a small wind tunnel of the type which you see in the panel. We will operate this tunnel to demonstrate the sensitivity of stalling

flutter vibrations to the angle of attack. Since the demonstration will make considerable noise I will discuss what we are to see prior to actually running the tunnel. Here is a series of blades which simulate those in an axial-flow compressor stage. Air will flow over these blades, and the angle with which the air strikes the blade will be determined by this set of adjustable guide vanes. These adjustable guide vanes simulate the stator vanes in the axial-flow compressor. This angle of attack as indicated by the pointer will be initially zero degrees. By operating this switch I will increase the angle, as indicated by a clockwise rotation of the pointer, to a value sufficiently high to induce flutter. We will view the flutter vibrations in stroboscopic light which effectively slows the motion so that it can be observed. The angle of attack will then be reduced and we will see a drastic reduction in the flutter vibrations. Since the tunnel noise will be severe, you may wish to cover your ears.

Thus, one remedy for this severe type of vibration is to simply change the stator blade angle. Investigations have shown that the vibration can be drastically reduced by changes in the angle of attack small enough so that the over-all engine efficiency is not appreciably affected. From studies of this type we hope to learn the basic relations between the aerodynamic and the design variables for the condition of stalling flutter. Such knowledge would permit

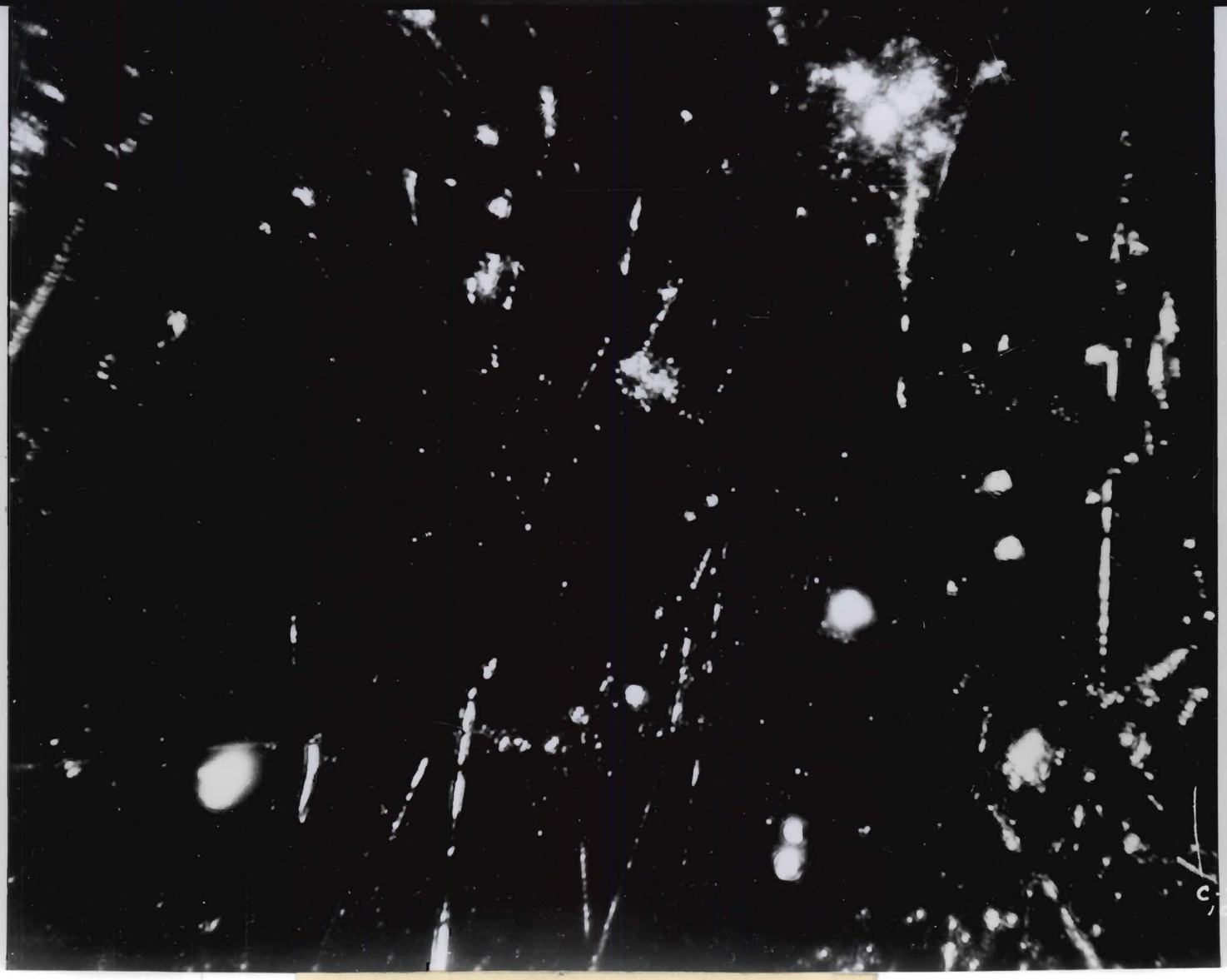
initial design of the compressor to avoid this type of vibration. We have already learned that the presence of the adjacent blades in a compressor drastically changes the condition for stalling flutter as compared with the conditions determined for single blades. Apparently the flutter theory developed for wings and propellers does not apply to stalling flutter in compressors and a new theory is required.

Gentlemen, this concludes our discussion of materials research. Thank you.

MATERIALS RESEARCH
EFFECT OF LUBRICANT FILM ON VIBRATION
CENTRIFUGAL FORCE
LUBRICANT FILM
STRATEGIC INDEX OF BLADE MATERIALS
RELATIVE STRATEGIC INDEX
CURRENT ALLOY
EXPERIMENTAL ALLOYS
CERAMICS
THOUSANDS
THOUSANDS
C-28524
10-17-51

NACA

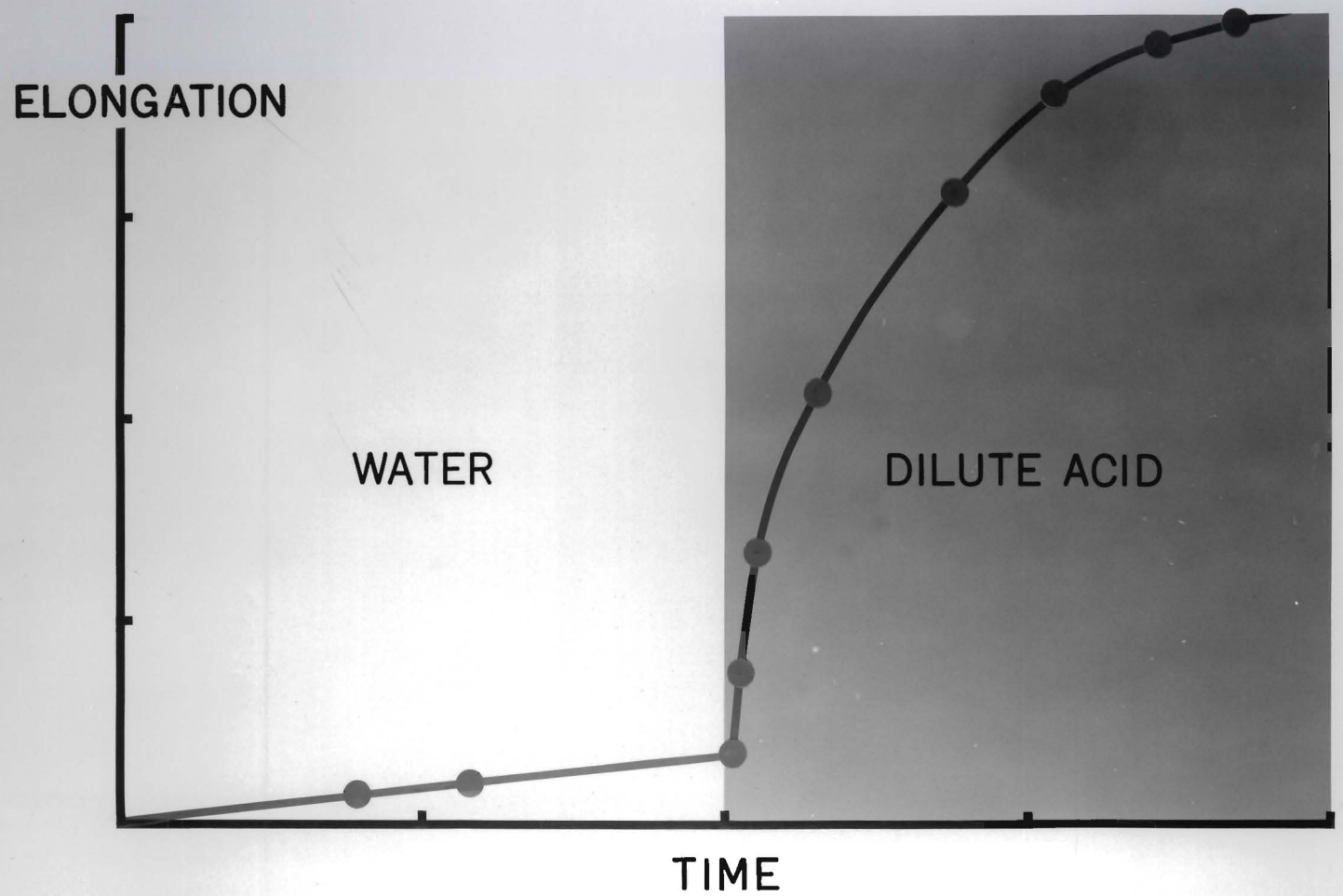
SURFACE CRACKS IN ROCK SALT



Materials Research - Figure 1

NACA

DILUTE ACID INCREASES ELONGATION RATE OF ZINC CRYSTAL



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Materials Research -- Figure 2

NACA

EFFECT OF HEAT TREATMENT ON MICROSTRUCTURES

AS CAST

HEAT TREATED

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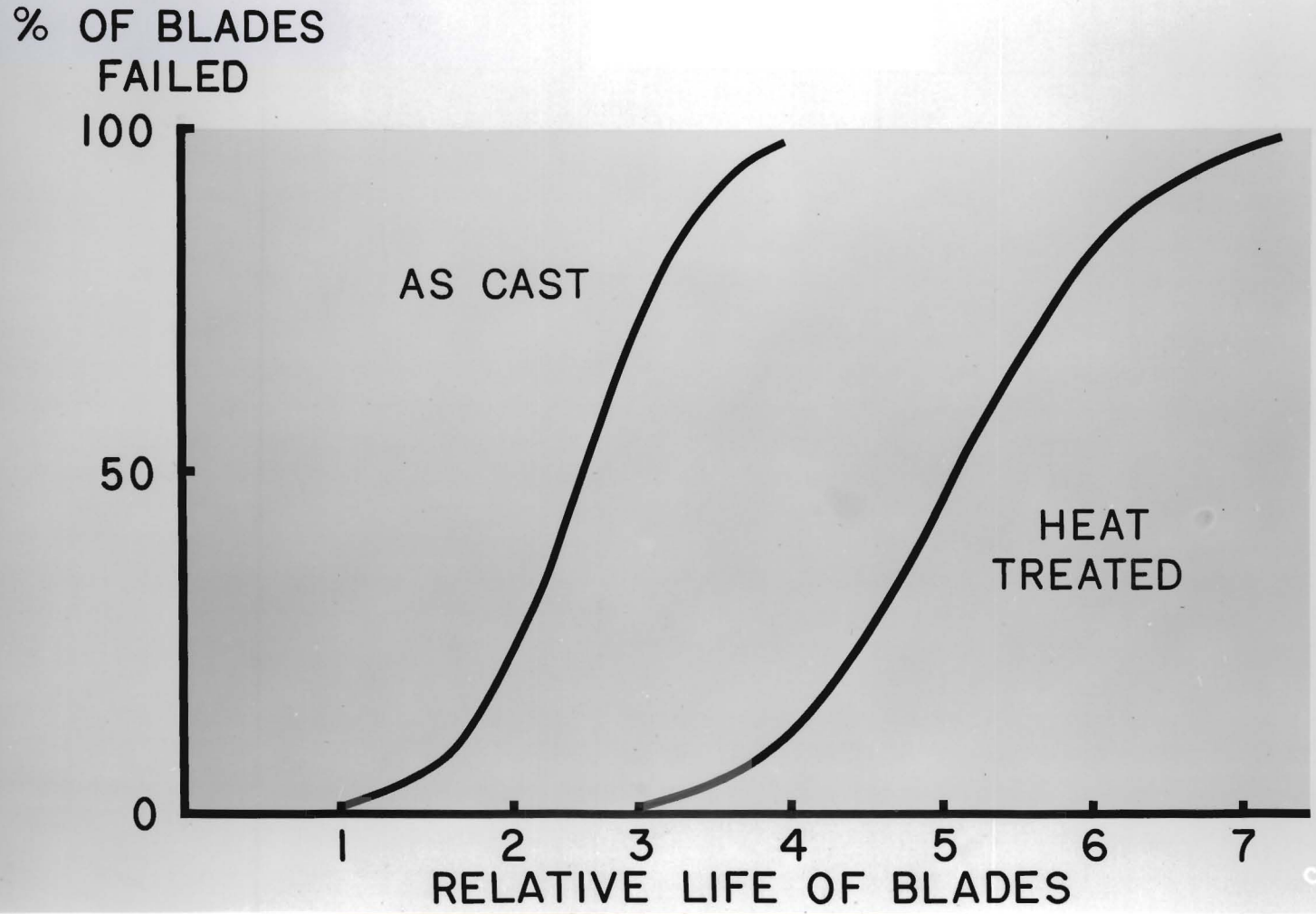
Materials Research -- Figure 3

NACA

HEAT TREATED CAST BLADES LAST LONGER



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Materials Research -- Figure 4

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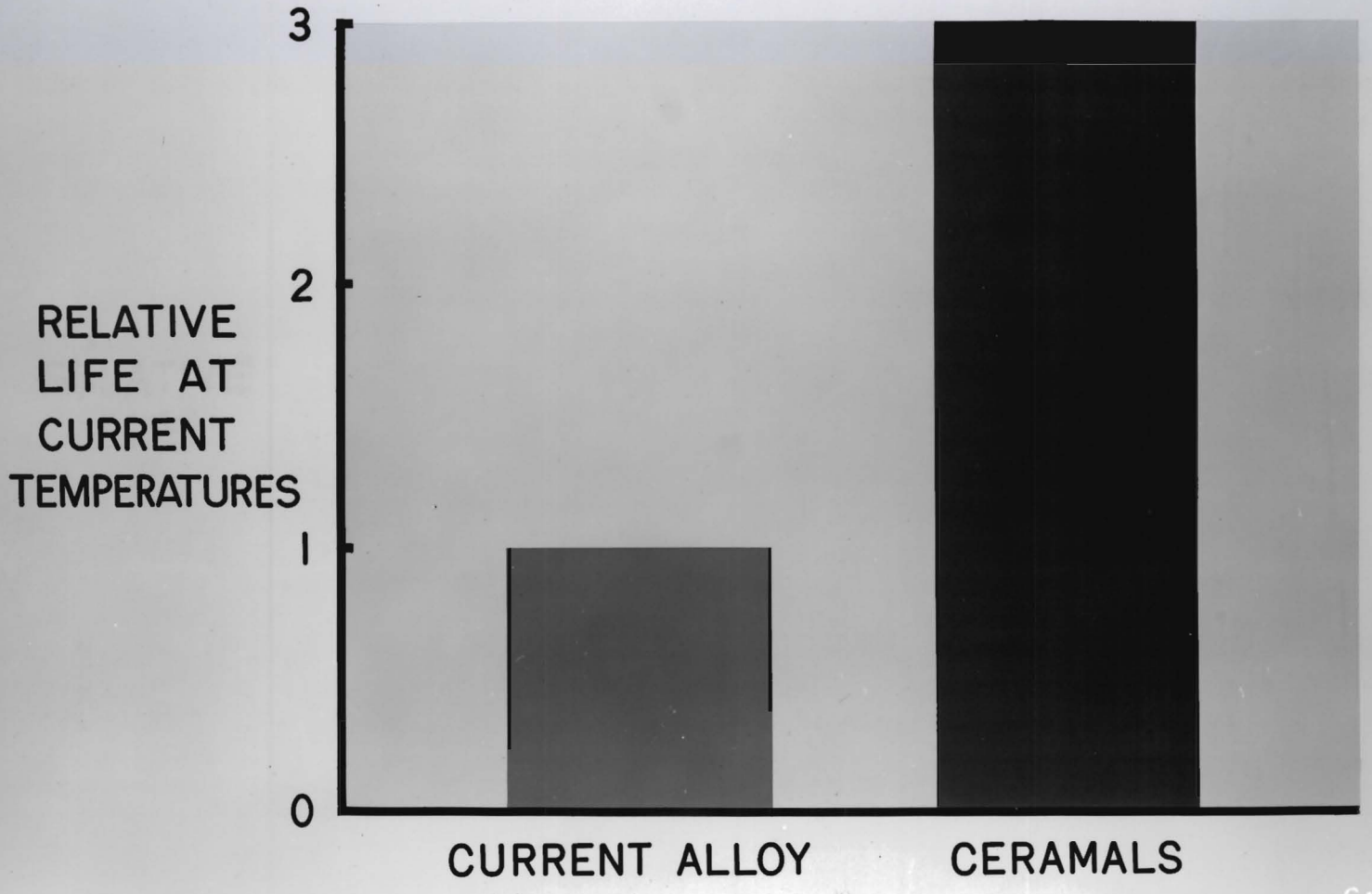
POTENTIAL LIFE OF CERAMAL BLADES



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Materials Research -- Figure 5

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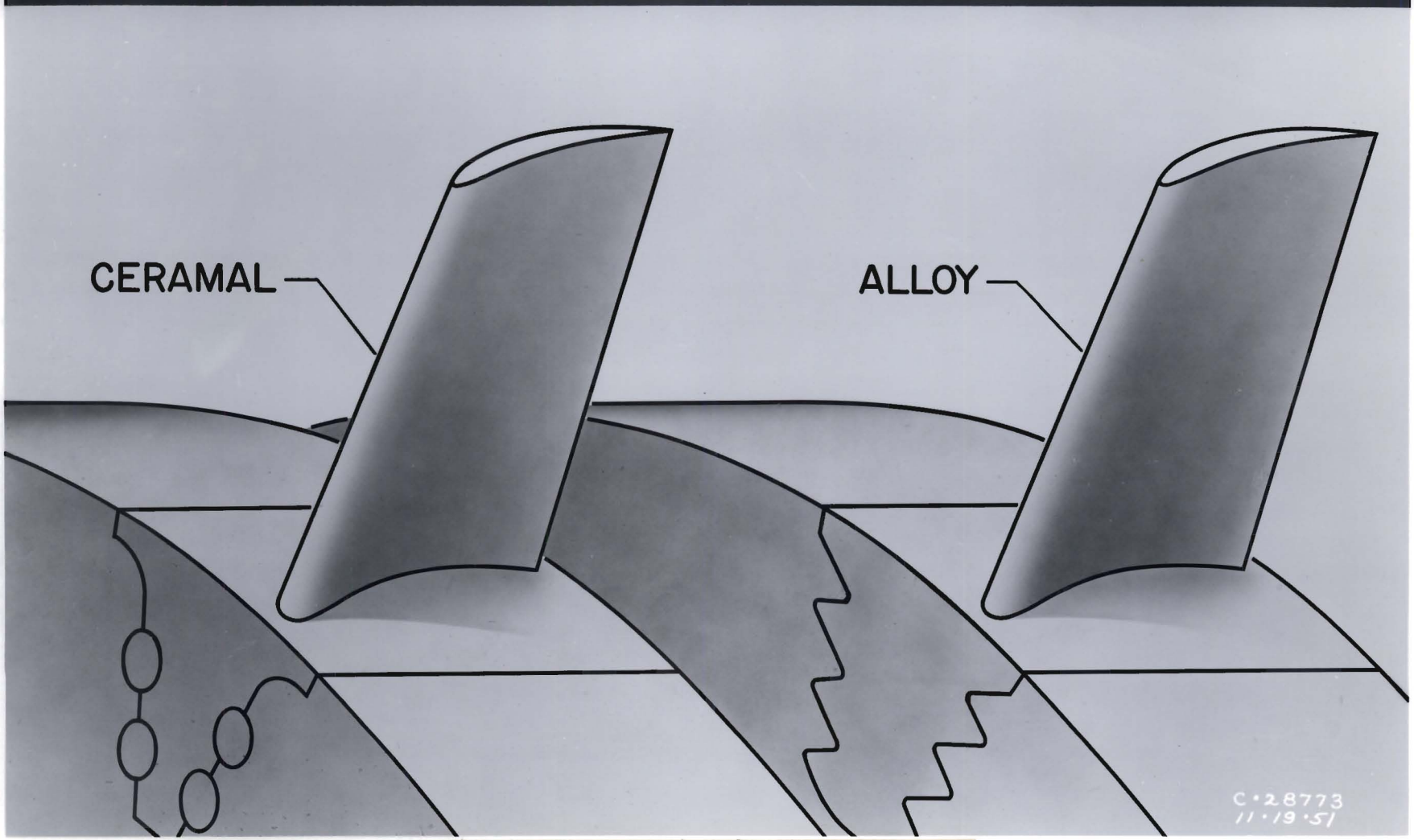
BLADE FASTENINGS



Materials Research -- Figure 6

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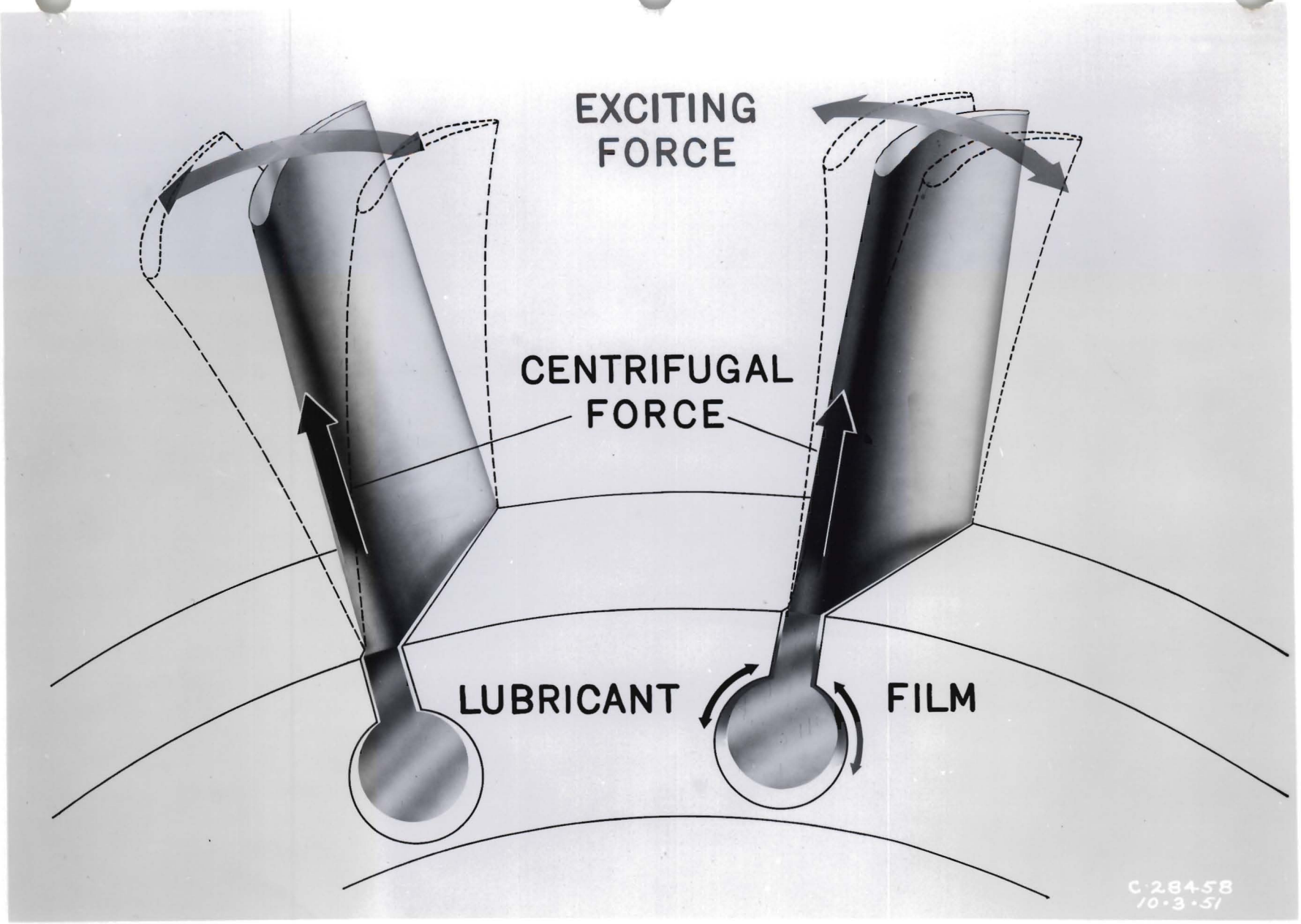
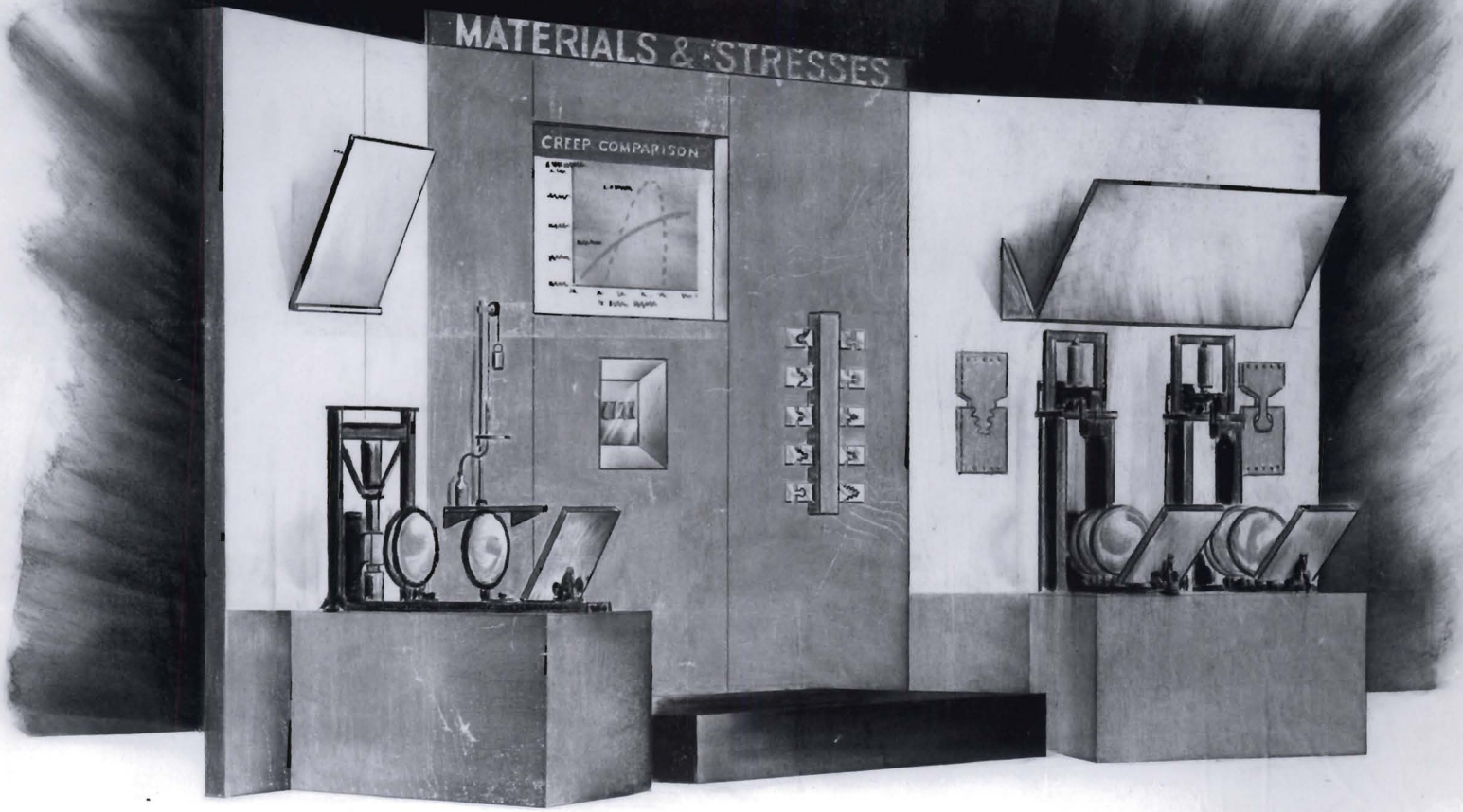


Materials Research -- Figure 7



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