D HIGH TEMPERATURE MATERIALS

Stage Shot:	Color Print	Demonstration of Molydenum	No. Number
Stage Shot:		High Temperature Materials; Stress & Vibration	C-24154
Chart 1	Deutsch	Use of Critical Materials in Turbojet Engine	C-24190-A
Chart 2	Deutsch	Strength of Some Refractory Materials	C-24190-B

STRESS & VIBRATION

Stage Shot		See Left Side Of Photo	C-24154
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1949 INSPECTION OF THE NACA LEWIS LABORATORY

TALK ON HIGH-TEMPERATURE MATERIALS

Presented by Mr. G. C. Deutsch or Mr. G. M. Ault

Room CE-6,ERB

(See Stage Photo C-24154 and Color Photo)

The jet engine has components operating at much higher stress and temperature than does the reciprocating engine, consequently superior structural parts are required. Today this need is being met with the super-alloys. Unfortunately many of the elements finding common usage in the super-alloys are also those in the most strategically critical supply. An element is in critical supply when the quantity available for production of aircraft engines and for other essential uses is insufficient to meet the demands of a future emergency. Examples of elements which are critical are columbium, tungsten, cobalt, chromium, and nickel.

The seriousness of the problem is emphasized by the fact that if we were required to produce engines on a basis analagous to the peak production during the last war, we might be stopped in a very short time because of the lack of alloys. Thus, a particularly urgent problem for materials research is to reduce the use of critical materials.

Let us look at where these materials are used in jet engines. We have a diagrammatic engine (C-24190-A) for discussion, on which you can see the particular parts of the engine that we will discuss today and typical amounts of critical elements used in each part.

First, we see the turbine blades. They are to the jet engine what the piston is to the automobile engine, for they take the power from the gases and drive all moving parts. They make up only 2 percent of the total weight of the typical engine as shown on the chart, but contain 10 percent of the total strategic elements. This is a highly critical part in the engine since it may operate at temperatures above 1450° F, with stresses as high as 25,000 pounds per square inch at the hottest point.

Next is shown the support for the blades, the turbine disk. On the average, the disk contains about 15 percent of the total engine weight, but 20 percent of the weight of all critical elements used. A turbine disk operates at temperatures from 400° F at the hub to 1250° F at the rim and must withstand a complicated combination of centrifugal and thermal stresses.

The remaining 70 percent of the critical elements are distributed pretty well throughout the remaining 83 percent of the engine with the major portion being made up in the sheet metal parts such as combustion chambers and tail cone, and in the cast and forged supporting structural parts.

This diagram outlines where the critical elements are used and sets up areas that need study in an effort to reduce the use of these materials. Several general methods of attack to this problem exist.

One would be to reduce the temperatures in the engine and thus enable a less critical material to be used. A component temperature can be reduced by reducing the combustion temperature or by cooling. The reduction of gas temperature would be at a sacrifice of some of the engine efficiency which is so vital to the superior performance of our military aircraft. The latter method, that is by cooling, is being described elsewhere at this laboratory today.

Also, research can be directed toward studies that will give us a better understanding of the requirements for materials for particular parts of the engine. If we can learn the environment conditions of stress, temperature, and atmosphere imposed on particular parts, it may enable the manufacturer to respecify materials having less critical elements. Improvements have been made to date by the manufacturer and as engine studies continue, further strides will be made.

Another way to reduce the use of critical materials is to study and develop new materials containing more readily availableelements. As a part of the NACA research program on materials, we have been looking into the little considered field of ceramals and intermetallics in a search for new materials of low critical element content capable of withstanding the environment conditions of the gas turbine. Intermetallics are chemical compounds of metals and by the term ceramals we mean metal-bonded refractory chemical compounds.

My discussion and demonstrations will show our general method of attack and will indicate the promise of these materials for utility at high temperatures.

The strength property we use for screening these materials is the modulus of rupture. This property is a measure of the ultimate strength. On the chart (C-24190-B) are shown the modulus of rupture strengths of a few of these materials in pounds per square inch versus temperature in $^{\circ}F$. The materials are three ceramals: B_4C-Fe, TiC-Mo, and TiC-Co and the intermetallic compound: $MoSi_2$. (The B_4C-Fe ceramal and the intermetallic are being fabricated at this laboratory.) The TiC-Co combination has the most critical elements of those considered, but, if substituted for the current blade alloys, would still result in a saving of about 80 percent of the critical cobalt. It is of interest to note that B_4C-Fe, although relatively low in strength at temperatures below 2200° F, exhibits less decrease in strength with increasing temperature than the metal bonded TiC bodies. At temperatures above 2200° F, it thus has a considerable margin of superiority. Thus relative strength at low temperatures is not an indication of strengths at very high temperatures.

The intermetallic $MoSi_2$ shows higher strength at all of these high temperatures. The two plotted curves for $MoSi_2$ show the increase in strength we have made by research that has enabled us to increase the density by 5 percent.

These materials have serious drawbacks because of their brittleness and very high hardness. This results in low mechanical shock resistance and difficulty in the fabrication of such complicated shapes as turbine blades. They cannot to date be made to shape by relatively simple casting or forging techniques, but must be made by powder metallurgy methods.

To demonstrate the desirable properties of one of the materials of low critical element content which we are making, we have chosen $MoSi_2$. Probably the best reason for this choice is its oxidation resistance. Most of the carbides are bad in this respect, whereas $MoSi_2$ is exceptionally good.

Molybdenum disilicide is made from two elements which, in their elemental form, are both very poor in resistance to oxidation. This may be demonstrated by heating a bar of pure molybdenum.

Demonstration. - We can see from this demonstration (Ref. color photo) that heating pure molybdenum to only 1500° F results in rapid oxidation and gives off a white cloud of smoke which is the oxide of molybdenum. However, when we combine Mo with silicon to form the $MoSi_2$ and make a body, it shows a remarkably clean surface after 150 hours at 2000° F. It has better oxidation resistance than any current high-temperature alloy. We have in these boxes a specimen of the new material and one of a representative high-temperature alloy. Both have been subjected to 2000° F for 150 hours. The differences in resistance to oxidation are apparent.

Demonstration - To demonstrate the relative strength of this material at high temperature, we have prepared a simple setup containing a test bar of the new material, and, for comparative purposes, a bar of one of the best known super-alloy blade materials which contains about 60 percent cobalt, which is a highly critical element. Each of the two test bars is supported upon two knife edges within an induction coil. Both are loaded at the center by a dead weight which gives a maximum stress of about 25,000 pounds per square inch in each specimen. They will both be heated to about 2000° F and we may observe the results. We see that the super-alloy fails by a very large deformation. Our non-critical material has survived the load and temperature without indication of failure. Its short-time strength at high temperatures is superior to that of the best known alloys of today. We have yet to evaluate the long-time strength of this new material.

Demonstration. - We have prepared a demonstration to illustrate how the new non-critical alloy, although brittle at room temperature, resists thermal shock. In this small furnace I have specimens of our $MoSi_2$ at a red heat. I will remove a specimen from the furnace and quench it in that beaker of ice water. The severity of quench is such that it will break a good ceramic. As you can see, the $MoSi_2$ has remained undamaged.

Another inherent advantage of the new material is its low density. The density of common high-temperature alloys runs around 585 pounds per cubic foot. The density of the new material is about 3/4 of these alloys. This results in two very desirable effects, first the use of the material would reduce the overall weight of the aircraft propulsion system. Secondly, for applications where the stress is determined by centrifugal force, for example turbine blades, the stress will be lower for the lighter materials. It is thus not necessary for the material to be able to withstand as high stresses, for its strength-weight ratio is high. Thus, an allied material, one of the TiC ceramals has, for example, operated for over 100 hours at moderately severe turbine conditions.

As mentioned previously, the superior properties of $MoSi_2$ and allied materials for engine use are offset by other properties such as high hardness and brittleness which are disadvantages in the handling and fabrication of difficult shapes like turbine blades. Considerable research on fabrication methods as well as on long-time properties will be required before $MoSi_2$ becomes a practical turbine-blade material that can make important savings in the use of critical materials.

In summarizing, it may be seen that an urgent problem for materials research today is the reduction of the use of scarce elements in the jet engine. Several approaches to the problem exist. We have presented our work along one of these approaches, that is, studies of new materials having reduced critical element content. We have shown the possibilities in this attack by demonstrating $MoSi_2$, a new material having good strength at temperature, good thermal shock resistance, extremely good oxidation resistance, and low density. Further immediate research is needed to develop this and other similar materials and to devise methods of fabricating these materials into complicated shapes so that they may be placed into the hands of the designer as a practical high-temperature material.

We will now present our research along still another approach to the problem of reducing the use of critical materials in engines. Mr Manson will discuss this topic.

GMA:mtd

1949 INSPECTION OF THE NACA LEWIS LABORATORY

TALK ON STRESS AND VIBRATION

Presented by Mr. S. S. Manson or Mr. W. F. Brown, Jr.

in

CE-6, ERB

(See stage photo C-24154 and color photo)

Another method of alleviating the strategic materials problem is to insure that each part of the engine is designed to incorporate a minimum amount of material necessary to perform its intended function. In this way, not only is strategic material conserved, but the weight of the engine is kept at a minimum which is also an important consideration.

TURBINE DISKS

Considerable attention has, for example, been directed to the turbine wheel. We have taken measurements of the temperatures of the various parts of typical turbine wheels and now know fairly well the conditions to which such wheels are subjected. We now can also be sure of the soundness of disk materials as a result of the excellent progress that has been made by the manufacturers in fabricating sound forgings. We have, therefore, devised a mathematical method of design which insures that each part of the disk is stressed to a uniform factor of safety at its operating temperature, thereby minimizing the material necessary to carry the total load.

Calculations based on this method indicate that considerable savings in turbine wheel weight can be effected. In some designs, the most obvious approach is by reduction in diameter as diameter is, by far, the most important single factor affecting wheel weight. In other engine types, for example this one, in which excellent progress is being made by the manufacturer in progressive redesign to reduce the weight, the most profitable approach is by reduction in disk thickness. For example, by removal of the metal represented by these aluminum sections, 50 pounds of strategic material can be saved. To evaluate this thinner design, we have machined a wheel to this contour and have given it a proof test in a spin pit at a speed slightly higher than that to which the production model of this heavier wheel is subjected before placing it in service. It was able to withstand this proof test without difficulty. We are now testing the wheel in a turbine and to date more than 50 hours of running time have been accumulated, approximately 20 percent of this time being at the full rated speed of the engine. So far, no problems have developed but we must give the wheel more running time to insure that problems do not develop. For example, one type of problem that might be anticipated is that of vibration - a problem that was encountered early in the development of steam turbines. We can, perhaps, best demonstrate the vibration problem by reference to this very thin disk. Of course, we don't expect to use such thin disks in an engine, but it is useful for demonstration purposes because of the large amplitude of vibration that can be induced. Corresponding serious vibration in disks of more reasonable thickness would be so small that they would have to be measured by very sensitive instruments.

The disk is mounted in an electronic exciter that produces impacts on it simulating those produced in the actual engine by the impingement of the hot gases. We have set the exciter frequency to correspond to one of the lower mode natural frequencies of the disk and we will now view the vibration in stroboscopic light.

DEMONSTRATION

This is one mode in which the amplitudes are high and can, therefore, be studied visually. In other modes, the amplitudes are small and the best approach is by the use of sand patterns. We sprinkle sand on to the disk and set the frequency of vibration to higher values corresponding to actual natural frequencies of the wheel. The sand naturally tends to pile up at points of minimum vibration and forms a pattern characteristics of the mode of vibration. We will now observe several of these modes.

DEMONSTRATION

A large number of vibration modes are possible, any one of which might be encountered in the engine. Hence, we must be very careful before recommending very thin disks arrived at purely on the basis of stress analysis.

HOLLOW TURBINE BLADES

Another component that readily lends itself to strategic material reduction by redesign is the turbine blade. For example, we could go to hollow blades which not only lend themselves to cooling as is being discussed elsewhere today, but are in themselves lighter and also require lighter wheels to carry them. However, hollow blades do have problems and one which we are particularly concerned with is the vibration problem. In a test comparing the vibration characteristics of this simple hollow blade to a solid blade of the same external contour, the hollow blade was found to have twice as many frequencies at which vibration could be excited within the operating range of the engine as the solid blade. One of the more serious of these vibration modes is the breathing mode in which the two halves of the blade move toward and away from each other producing high stress concentrations at the leading and trailing edge. Such vibrations have been the source of blade failures in engines incorporating this type of blade. We can, perhaps, best demonstrate by reference to this large scale model. The blade is mounted in an electronic exciter and I can set the frequency of vibration to correspond to one of the breathing modes.

DEMONSTRATION

A large number of vibrational modes are possible and the question arises as to the best means of preventing these vibrations. One method is by the use of stiffners such as those in this model. These stiffners also serve a very important purpose from the heat transfer point of view as is being discussed elsewhere today. From our viewpoint, they serve to tie the two halves of the blade together, thereby preventing them from moving relative to each other, and eliminating some of the modes of vibration. In a test in which we compare the vibrational characteristics of this thin blade with a solid and a hollow blade of the same external contour, the thin blade has essentially the same vibrational characteristics as the solid blade, thereby indicating that we did not expect to encounter any vibration problems with the thin blade that we have not already studied in connection with solid blades.

Another method is by the use of vibration dampners inserted into the hollow passage. Such methods we are also investigating.

A third method is to incorporate some damping in the mount. For example, one approach that has been suggested is the provision of clearance between the base of the blade and the mount into which it fits, so that the blade is loose. If the blade tends to vibrate, this looseness is supposed to allow some rubbing, thereby introducing damping which lessens the amplitude of vibration. All the data that we have been able to obtain along this line of investigation unfortunately indicates that regardless of any looseness that might be present in the mounting when the blade is inserted disappears as the blade tightens up due to the centrifugal forces resulting from the high speeds of rotation. Some results of our investigations are shown in the chart (C-24193).

Here we were actually studying compressor blades rather than turbine blades. You will notice the characteristic ball type of mounting used in axial flow compressor blades, but the implication to turbine blades are valid. Furthermore, compressor blades also represent components in which strategic materials can be conserved. At the present time, most axial-flow compressor blades are composed of a material containing 12 percent chromium. In part, this is used for corrosion resistance, but also because of the high internal damping capacity of this particular material. This damping capacity is relied upon to limit the amplitudes of vibration. If damping can be incorporated in other ways, then perhaps we can dispense with the need for strategic materials in this component. We are, therefore, studying blade looseness as a means of introducing this damping.

The test was run in a laboratory spin rig rather than in a compressor in order that we might be able to vary the exciting forces causing the vibrations. This exciting force we plotted along the horizontal axis. The rig was rotated at a speed of 15,000 rpm to produce the centrifugal forces encountered in the corresponding engine. The stress at the base of the blade developed as a result of the exciting forces were measured and these stresses we have plotted along the vertical axis. As you see, the stresses for both the loose blade, indicated by the circles, and the tight blade, indicated by the squares, were essentially the same. The relation is linear and builds up fairly rapidly to a stress at which we would expect the blade to fail after a short period of vibration. At the high centrifugal forces, the loose blade is, therefore, no more effective in producing damping than a tight blade.

Paradoxically enough, the best way to introduce useful friction was by the insertion of a lubricant between the disk and hollow blade. We used a solid high pressure lubricant and the results are shown in the lower half of the chart. At any exciting force, the stress that built up was lower than the corresponding stresses in either the loose or tight unlubricated blade and the stress leveled off at the high exciting forces so that at no reasonable exciting force would it ever reach the maximum allowable value. While we have not, as yet, substantiated these results in an actual compressor, we see no reason why they should not be applicable to compressors. For turbines, the problem is, perhaps, a little more difficult in that a lubricant must be found to withstand the high temperatures encountered in turbine rims. However, at least a method of approach is indicated.

LIQUID COOLED TURBINE BLADES

Another method of reducing the strategic material content of the jet engine is by the use of the liquid-cooled turbine blade. Here we have a model of the liquid-cooled turbine blade in which has many coolant passages for the purposes of demonstration; the thought being, of course, that coolant will pass through these holes and cool the outside surfaces of the blade and, therefore, make possible the use of a non-strategic material. These blades are being discussed elsewhere from a thermodynamic standpoint. However, I should like to point out some of their stress problems.

The surfaces in contact with the coolant will be considerably cooler than the outside surfaces in contact with the hot gases and, therefore, the inside surfaces will want to expand less than the outside elements. This differential expansions gives rise to a system of thermal stresses across the blade section. These thermal stresses can be calculated by mathematical means, however, in order to obtain accurate results, the calculations become extremely time consuming and tedious. Therefore, in order to work more efficiently, we are supplementing the mathematical approach with the experimental attacks. One experimental method is based on an analogy first recognized by Biot. Here we make use of a plastic model of a liquid-cooled blade section. A slot is perpendicularly cut from the outside surface, passing through the blade to the inside surface of the cooling hole. Given a temperature gradient, then we can calculate mathematically just what displacements must be given to the sides of these slots to produce in the model a system of mechanical stresses equivalent to a system of thermal stresses which would have been produced by the selected temperature gradient. The mechanism by which we produce these relative motions is called a deformator, a model of which is shown here. By turning these micrometer screws, we are able to produce these motions of the sides of the slots. In the actual experiment, the model, with its deformator, is placed in a field of polarized light and photoelastic methods are used to determine the magnitudes of the stresses. We have prepared a Bakelite model of a liquid-cooled blade section. This model is mounted in a polaroscope and for the purposes of demonstration, it has been suspended from a simple type of deformator which merely forces apart and releases the sides of the slot. When I turn on the motor which actuates this mechanism, you will see that colored fringes pass across the blade section. The number of fringes passing a given point is related to the magnitude of the stress at that point.

DEMONSTRATION

Now, you will notice that at the center, the fringes converge and this is, therefore, a point of minimum stress. At the points adjacent to these surfaces, a large number of fringes pass and, therefore, these are regions of high stress. Calculations based on the mathematical approach and substantiated by experimental methods indicate that for a temperature difference of 500^{o} that stresses in the order of the yield point of most metals are produced. At the present time, we are not certain of the true significance of such thermal stresses, however, we are concentrating our efforts on determining their magnitude and correlating these with actual blade performance.

CONCLUDING REMARKS

Gentlemen, these are but a few of the problems which we encounter when we attempt to redesign jet-engine components on the basis of lower strategic material content and to reduce the engine weight. We have outlined some of the progress that has been made to date, however, considerable more research is necessary. This effort is justified by the goals to be achieved, namely, cheaper, lighter engines, using less strategic materials.


TRESS & VIBRATION
PERCENT OF ENGINE WEIGHT
PERCENT OF TOTAL CRITICAL ELEMENT
HIGH TEMPERATURE
MATERIALS


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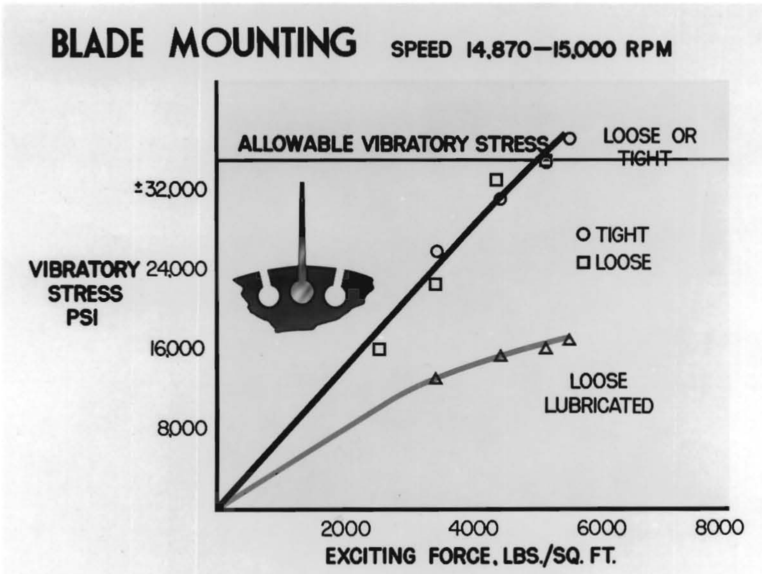

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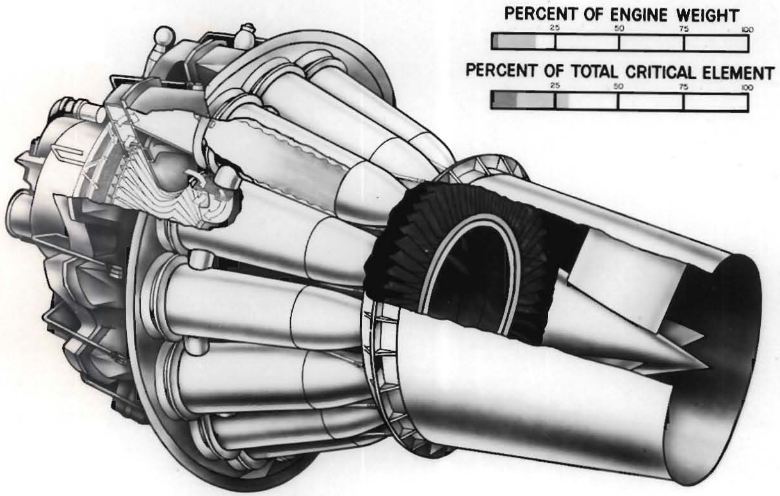
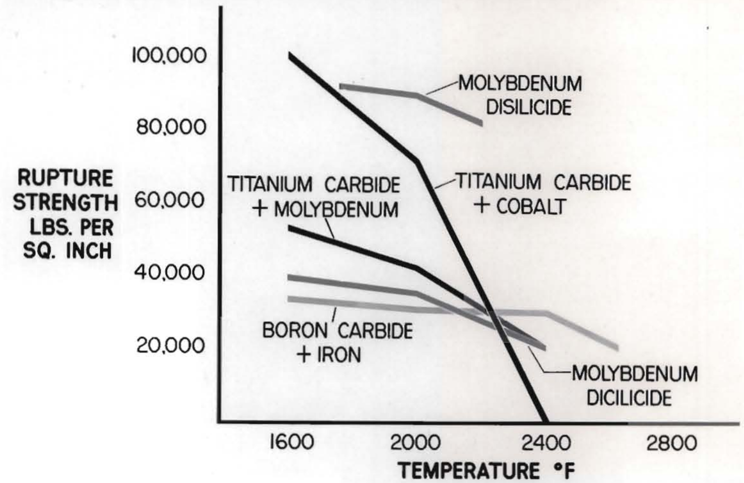


STRENGTH OF SOME REFRACTORY MATERIALS



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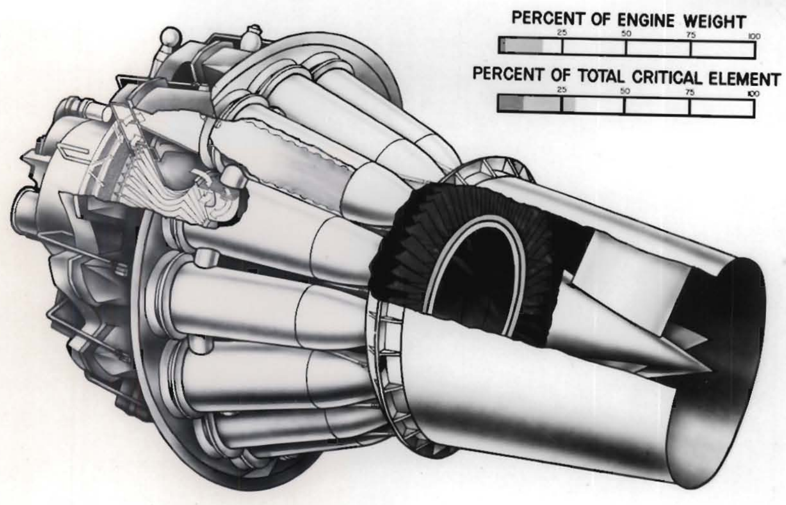

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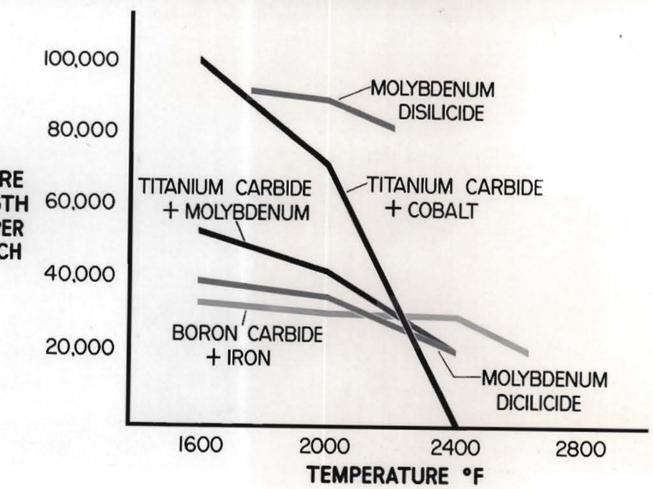

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