PROBLEMS IN HEAT-RESISTING MATERIALS FOR HIGH-SPEED FLIGHT AND PROPULSION

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The development of better light-weight and high-strength materials has always been a problem of great importance in aviation. With the advent of supersonic and hypersonic flights, temperature has been added to stress and weight. Now more than ever, lack of suitable materials presents a barrier to the achievement of the high performances that the aerodynamicist and the structural engineer are capable of introducing in their design. In that sense, it is appropriate to talk of a materials barrier.

The problem of materials can be discussed from two points of view; the first one is to consider the various types of solid materials on the basis of their atomic structure and discuss their fields of application and their ultimate limitations. I have used this approach in a recent study published in an AGARD monograph.[1] The second approach which I will consider here is to analyse the various sets of conditions imposed by different flight regimes and correlate the physical properties of materials with these flight requirements.

Perhaps the most important factor in this new era of very high-speed flight is the time during which the materials are subjected to extreme conditions of stress and temperature. In the classical subsonic flight regime, the time during which both airframe and engine had to perform without failure was relatively long. Equilibrium conditions were always achieved, except for temporary gust and maneuvering loads, and problems such as fatigue strength for airframe materials and creep strength for gas turbine components were of primary importance. As a result, a great deal of effort has been devoted to the problems of fatigue and creep, and it is fair to say that we now possess a good fundamental understanding of these two aspects of materials behavior. Now that the time may be extremely short, a new approach must be considered. Short time operation generally involves transient conditions resulting in the presence of temperature gradients giving rise to thermal stresses. Since these thermal stresses are dictated by the physical properties of the material, the choice of materials is of primary importance.

In the well-known "corridor of flight" graphical representation of Altitude vs. Speed, the boundary of the area referred to as "too hot", from the materials point of view, is located by assuming that the structure actually reaches a certain temperature below the stagnation temperature.

For each assumed temperature, there is a limiting curve based on the properties of presently available materials. It is important to realize that the "too hot" limit of the corridor is also a function of the time the structure has to withstand for a given flight regime.

In order to describe fully a problem of aerodynamic heating it is necessary to specify the heat flux as a function of time and the loading conditions, also as a function of time. From these two functions, the state of stress (mechanical and thermal) can be computed, at least in principle, at any point of the structure. Exact computations require that the physical and mechanical properties of the materials be known as functions of temperature. In order to carry out these computations, it is necessary to make an *a priori* choice of materials, and it is only at the end of lengthy studies that the choice of materials appears to be unsatisfactory. It is indeed very difficult for the materials engineer to suggest materials at the start of the study because it is not possible to state requirements in terms of the few properties that have been considered in the past, namely yield strength, elastic modulus, fatigue strength, creep strength, and density. The less conventional properties of materials which must now be considered for high temperature applications will be discussed now.

IMPORTANT PROPERTIES OF MATERIALS FOR HIGH-TEMPERATURE ENVIRONMENT

The most important mechanical properties for high-speed flight are related to high-temperature strength. For long life service, creep strength must be considered. Because of the importance of creep testing of materials used in gas turbines, this particular aspect of high-temperature materials testing has received great attention. For very high temperatures and relatively short time applications, creep strength is a parameter of secondary importance in materials evaluation. New concepts such as high rates of loading and high rates of heating must be considered. In order to solve this complex problem, very elaborate testing equipment has been devised for simulating conditions under which high rates of loading are superimposed on to high rates of heating. Such tests can only lead to empirical design criteria of dubious value. A long-range solution to this problem can be found only in systematic studies of the various properties of materials which are rate dependent.

It is well known that the mechanical properties of solids are functions of the rate of strain, which in turn is a function of the rate of loading. Studies of the effect of rate of loading on the mechanical properties, how-ever, assume that no structural changes take place during the test. At room temperature, this is a sound assumption, and the effects of strain rate are real. A typical example can be found in ordinary mild steel, for which the yield stress is increased by as much as a factor of three for relatively small rates. At high temperatures, structural changes may take

place and the problem becomes more complex. It is important to empha-
size, however, that the only mechanism by which rapid heating may have
an effect on the behavior of materials is one involving changes in the
structure of the material itself. In other words the intrinsic properties of
a material are not influenced by the rate of heating but only by tempera-
ture. If the structure of the material can change with temperature,
however, the rate of heating will affect the structural changes, and hence
the physical properties. In order to illustrate this point let us consider a
part made of heat-treated steel tempered at a certain temperature. If
this steel is to be used for any length of time at high temperature, it is
obvious that the service temperature must remain lower than the tem-
pering temperature, or else the strength will progressively decrease with
time. If, however, the part is subjected to a very fast rate of heating and
will not stay at the maximum temperature more than a few seconds, it
is quite possible that the steel will retain its strength at temperatures
well above the tempering temperature. Because of the lack of recognition
of the structural changes taking place in a material at high temperature,
the problem of high rate of heating has not been clearly formulated. It
is often stated that we need more information on the properties of
materials subjected to high rates of heating. What is really needed is a
better understanding of the kinetics of solid state reactions in alloys.
The basic design problem is to know the exact temperature vs. time
history of a particular structural member. Knowing that, the metallurgist
should be able to predict whether or not the material will successfully
withstand the stress vs. time function the material will be subjected to.

Another important problem more or less connected with rate of
heating is the so-called resistance of materials to thermal shock. Re-
sistance to thermal shock is not a material property, but rather a material
behavior. The basic properties involved in this behavior are thermal
expansion, thermal conductivity modulus of elasticity, and strength. If
the variations of these four properties with temperature were known, the
resistance of a material to any suddenly applied heat flux should be pre-
dictable. At the present time, purely empirical heat shock tests are still
being used to evaluate materials subjected to high rates of heating. It is
hoped that a more scientific approach to the problem will be available
in the near future.

MATERIALS FOR LEADING EDGE AND NOSE CONE APPLICATION

One of the most severe high temperature materials problems is that
of a leading edge or a nose cone for hypersonic vehicles. The heat flux
involved in these cases is such that, under equilibrium conditions, any
known solid material would be completely destroyed. Fortunately, the
total time involved here is rather short and only transient conditions
prevail. The problem combines high rates of heating, high rates of

loading and extremely high temperatures localized on the surface exposed to the atmosphere. One approach to the problem is based on the heat sink principle. The part subjected to extremely high heat flux is made of a material which has enough heat conductivity and enough heat capacity. A large mass of this material must be provided in order to insure that, at the end of the flight through the atmosphere, the outside surface does not exceed a critical temperature beyond which the material would fail. Another interesting solution to this problem is to design the part so that the material is progressively removed during the flight. The term ablation is now generally accepted to describe this process. Resistance to ablation is not a property of a material, but describes its behavior. Many physical properties enter into the ablation process.

In addition to strength, properties not usually considered in materials engineering are of great importance. The melting point, specific heat, vaporization temperature enter into the problem. Depending on the material, evaporation or sublimation, viscosity of the molten phase, emissivity and absorptivity of the surface may control the ablation process. In some cases, combustion of the material may also play an important role. The subject of ablation offers a very strong argument for the need for a better cooperation between materials engineers and their colleagues in other fields. The ablation mechanism cannot be studied from the material side only. The processes involving removal of solid material are controlled in part by the conditions prevailing in the boundary layer, and a complete understanding of the problem cannot be gained until it is analyzed from both points of view of fluid mechanics and solid state physics.

TYPES OF MATERIALS OF INTEREST FOR HIGH-TEMPERATURE APPLICATIONS

With the development of the gas turbine jet engine in the post-war years, the field of high temperature materials was closely associated with the turbine blade problem. A tremendous amount of research lead to the rapid development of satisfactory alloys for service temperatures up to about 1600°F. Since most of these alloys contain elements of the iron group which have relatively low melting points, it is not surprising that further increase in temperature would pose a difficult problem. Attention was then given to the so-called refractory metals, namely molybdenum, tungsten, tantalum, and niobium. Molybdenum base alloys have been developed with sufficient strength for service up to about 2300°F. The other refractory metals are now receiving more attention. We all know what the main difficulty is with these metals, namely their very poor resistance to oxidation at high temperature. Two approaches to this problem are under investigation; protective coatings or alloying. The results are encouraging and there is some reason to believe that satisfactory solutions are in sight, at least for some specific applications.

Leaving the field of metals, we will now briefly review the potential applications of nonmetallic materials. Nonmetallic refractory materials may be divided into oxides and hard metals (carbides, nitrides, borides, etc.). All these materials are produced in powder form and are consolidated by pressing in a die and sintering at high temperature. In some cases, other techniques of forming may be used. as for example slip casting. The powder metallurgy methods of fabricating hard metals and pure oxides lends itself very well to the mixing of powders of various kinds including metal powders. The materials resulting from such a blend are called cermets and combine some of the properties of both ceramics and metals.

The physical properties of pure oxides and pure hard metals have not been extensively studied. Most of the effort has been devoted to materials containing a certain amount of metallic binder. By reducing the amount of metallic binder in a cermet the creep properties may be improved but the brittleness and thermal shock sensitivity become worse. In cermets as in any other solid material a compromise must be made between many different physical properties. The flexibility in the fabrication techniques used in the production of cermets, however, is a definite advantage in covering a wide range of properties.

One solid material, which is not a true metal and yet is not considered as a ceramic material in the classical sense, requires special consideration. Graphite, which is a crystalline form of carbon, has the highest melting temperature of all the elements, and hence offers an ultimate goal for high temperature materials applications. The effect of temperature on the mechanical properties of graphite is most unusual. It is the only solid material known whose modulus of elasticity and tensile strength increase with increasing temperature. It is brittle at room temperature, but around 2000°C it becomes ductile and its creep behavior is similar to that of metals. Of course, graphite is exceedingly sensitive to oxidation, and its use as an engineering high temperature material depends on a successful development of a satisfactory oxidation resistant coating.

CONCLUSIONS

Before closing this discussion of high-temperature materials problems, I would like to summarize the main concept leading to the inherent limitations of solid materials at high temperature and show how this concept leads to a graphic representation of a materials barrier.

Let us consider the heat flux, or the stagnation temperature, the material is subjected to and the time during which the material could perform without failure when exposed to such conditions. These two factors can be plotted on a graph with logarithmic scales, stagnation temperature in ordinate and time in abscissa. On such a graph, a material can be represented as covering an area limited by a curve such as curve 1 of the general form shown in Fig. 1. For high stagnation temperatures,
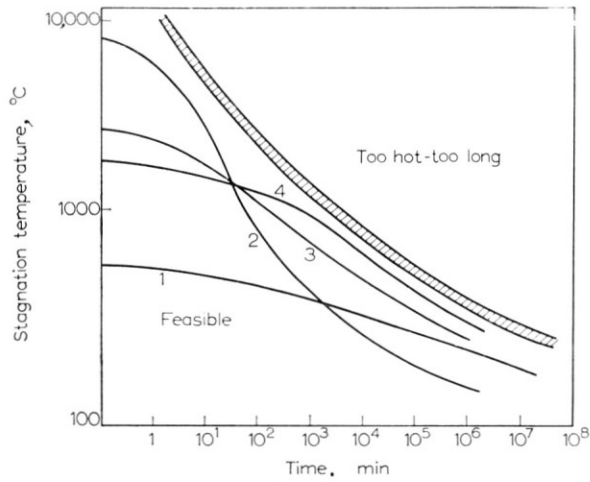
FIG. 1.

the material will have a very limited life and at low stagnation tempera-
ture it could stand service indefinitely. Other materials will be repre-
sented by curves such as 2, 3, 4, etc., of Fig. 1. The envelope of all
these curves, represented by the heavy line on the figure divides the
field of stagnation temperature vs. time in two areas. On the left side
of the curve, materials could eventually be found to solve the problem.
On the right side of the curve is the "too hot, too long" area which is
beyond the materials barrier. This graphical representation of materials
behavior in thermal flight and propulsion systems should be considered
as a purely qualitative description of the problem and the scales shown
in Fig. 1 are not to be taken as a true picture of the present situation.
It is obvious that the stresses involved in each particular application will
displace the materials barrier curve of Fig. 1. The possibility of cooling
parts exposed to extreme heat fluxes will also shift the boundary. For
stationary installations, it is conceivable that the availability of practically
inexhaustible sources of coolant fluid may eradicate the materials barrier.
This is not the case for airborne systems. If the cooling fluid is expanded,
its initial weight will be limited and hence the barrier will be on the "too
long" side of the "too hot, too long" boundary. If the fluid is circulated,
the heat must be dumped out of the system by radiation. Since this solution
requires a radiator made of some kind of solid material, the "too hot, too
long" condition cannot be avoided.

It must therefore be concluded that, as far as materials are concerned,
there will not be the equivalent of a flight corridor, and the term Materials
Barrier is likely to have a much more realistic and more lasting meaning
than the once famous Sonic Barrier.

REFERENCE

1. P. Duwez, *High Temperature Effects in Aircraft Structures*, pp. 58–79, Pergamon
Press, 1958.

DISCUSSION

A. van der Neut*: I wonder whether the thermal compressive stresses which will occur in the outer layer would have some effect on the melting temperature. It is known that compression of ice reduces its melting temperature. By melting the ice reduces its volume and in this way it escapes to some extent volume-reduction by compression. With metals the specific volumes of the solid and the liquid state are just the opposite way. So it is likely that thermal compressive stresses would postpone the liquid state, which would be a favorable effect.

P. Duwez: Dr. Van der Neut is right in saying that compressive stresses would raise the melting temperature of most metals. From an engineering point of view, however, the effect is of little importance because the pressures involved are too low to produce any appreciable increase in melting temperature.

B. R. Noton: The stimulating lecture delivered by Professor Duwez has stressed the tremendous problems confronting the metallurgist in order to provide materials that can withstand the predicted kinetic heating temperatures and thus penetrate the "Materials' Barrier" referred to. This can partly be done be developing new materials and partly by improving the mechanical properties of the materials now generally being applied. However, the gains to be made here seem to the present speaker—who is not a metallurgist—to be uncertain and not likely to offer a sufficiently rapid solution to these problems. Research on these lines has, however, great long-term importance, as was evident in this lecture.

There is, nevertheless, a second principal method of attack on the "Materials' Barrier" and this is to create new design concepts, in which the existing "off-the-shelf" materials are used in various combinations as a team in single components such as panels. One well-known example of a design concept, is glass-fibre-reinforced plastic. Here, two materials are used that would be useless if used separately for structural components. Glass is too brittle to be used alone. One further indication of this design thinking is honeycomb sandwich construction, in which a core transmitting shear—which is weak when subjected to transverse or lateral compressive loads—separates dense covers reacting—the end or bending loads.

The speaker therefore feels that besides doing research on the development of new materials, we should also devote our research efforts to the creation of new design concepts in which the readily-available materials, such as aluminum alloys, 17–7PH stainless steel, titanium, Inconel X, ceramics and plastics, are considered in various combinations in single components. Considering glass-fibre reinforced plastics, for example, "Astrolite" has been tested with acetylene lamps, giving rise to a temperature of approximately 2500°F and the burn-through time was of the order of 5 min.

P. Duwez: I am in complete agreement with Dr. Noton in saying that the most promising approach to structural problems in high-temperature flight is the design of complete structures made of various materials. In combining these materials, however, it is necessary to achieve structural integrity and new methods of joining dissimilar materials such as metals and ceramics must be investigated. In order to solve this problem a close cooperation between the structural and the material engineer will be required.

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