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A SIMPLE INTRODUCTION TO THE STRUCTURAL MATERIALS USED IN AVIATION TURBINE ENGINES

by

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EDITED TRANSLATION

FTD-ID(RS)T-1560-80   4 June 1981

MICROFICHE NR: **FTD-C-81-00492**

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English pages: 11

Source: Hang K'ung Chih Shih, ~~Nr. 8,~~ 1979, pp. 18-19

Country of origin: China
Translated by: SCITRAN
F33657-78-D-0619
Requester: FTD/TQTA

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A SIMPLE INTRODUCTION TO THE STRUCTURAL MATERIALS USED IN AVIATION TURBINE ENGINES

Ding Wei-ming

Since the time when turbine jet technology was first used to propel aircraft, as capabilities of engines were increased, great changes occurred in the structural materials used in these engines. One of the important characteristics of the current generation of aviation turbine engines is a considerable increase in the thrust-to-weight ratio (that is, the ratio between the thrust of the engine and its weight), the pressure increase ratio (that is, the ratio between the pressure at the engine exhaust and the engine intake), and the pre-turbine temperature ratio. Moreover, all of these improvements were achieved very early. The changes in engine materials are closely related to these developments and, among them, the changes in materials for compressor and turbine components are the most striking.

CHANGES IN COMPRESSOR MATERIALS

If one looks for a second at the diagram of an engine, one can see that there are many blades. Toward the front of the engine, there are the compressor blades and, toward the back of the engine, there are the turbine blades. The arrangement between one set of static blades and one set of moving blades is called a level. When air flows through the blades of the compressor, the turning blades fan the air current. This does work against the flow of the current and this causes the pressure to go up. The temperature also follows the pressure up. Inside the first aviation turbine engines which were used, the work which was done by the compressor wheels on the air was obviously increased. Because of this, the blades which form the path through the compressor (both moving blades and static blades) obviously are exposed to increases in the temperature, force and moments of force as compared to the conditions which were found in the initial versions of the aviation engine. Concurrently, the materials which are used to manufacture compressors also experienced great changes.

The advent of titanium alloys. In the early aviation turbine engine, the compression ratios for the compressors were relatively low. Because of this fact, the temperature of the pathway was not high and the temperature of the compressor exhausts was approximately 200°C. The stress loading was not large either and the components were mainly made from stainless steel and high strength aluminum alloys. At present, however, the average temperatures of compressor exhausts are 300 and 400° celsius. The traditional aluminum alloys are unable to satisfy the operational requirements of turbine engine compressors. Moreover, stainless steel is too heavy and its capability of resisting sea water corrosion is inadequate; titanium alloys seem to be the coming thing.

The capability of materials to resist the actions of external forces can be expressed by using their strengths. The relative strength of titanium alloy is great (that is, the strength-to-weight ratio). Moreover, in the matter of resistance to corrosion, these alloys do not require a corrosion-resistant protective layer. Because of this fact, the appearance of these alloys immediately caused great attention in aviation circles and they spread rapidly into the design of aircraft and engines. Early on, in 1952, the United States first used titanium alloys to manufacture compressor blades and wheel discs. By the end of the 1960's, the fans, compressor blades and wheel discs of high thrust engines were mostly manufactured out of titanium alloys and the amount of titanium which was being used was increasing constantly. At the present time, in the engines of aircraft from outside China, all cold junction spare parts whose temperatures are lower than 450° C and all components in which the use of titanium alloys is conducive are seeing, in their constituent material, the replacement of aluminum alloys and stainless steel by titanium alloys.

Due to the fact that the specific gravity of titanium is small, its strength is high and its weight is obviously lighter than that of any of its competitor materials, it follows that the use of titanium in an engine will cause an effective increase in the thrust-to-weight ratio of that engine.

Practical application demonstrates that, in engines, after titanium is used to replace aluminum and steel one achieves results in the area of technological economy which are very obvious. For example, in the case of large thrust engines in the class of 20,000 kg of thrust, after titanium was used to replace aluminum and steel in the compressors of the engine, it was possible to reduce the weight of each engine by 454 kg. If one is considering the case of a large-scale jet passenger plane, which is equipped with four high thrust engines, then it is possible to cause a reduction in weight in the aircraft of 1816 kg and this means that one can increase the carrying capacity of the airplane by 20 or 30 passengers. These figures are only reached as reductions in weight occur in calcualtions made on the basis of net weight. In actual practical applications, for each kg of weight which can be taken off the weight of the moving parts of an engine, it is possible to reduce the weight of the component or assembly by five to 10 kg. If we use titanium to replace steel in the manufacture of the rotating blades of compressors, then, in such a case, the centrifugal force loading and the vibration loading which is exerted against the compressor wheels will be reduced by 40%. In this way, it is also possible to make use of lighter weight wheel discs and axles and the entire component or assembly is then greatly lightened. If the weight of large-scale engines can be reduced by 20%, then the correspondingly reduced weight of the aircraft as a whole will cause the engine to put out at three to seven times its normal output. The use which is being made of titanium alloys in engines is increasing constantly but it has still not reached the point where its use is satisfying the potential demand for it. In the engines produced by one U. S. aircraft company, before the 1960's the amount of titanium being used was not even enough to make up 10% of the total. By the end of the 1960's and the 1970's, the heaviest examples of titanium use had already reached the levels of 32%.

However, in compressors, the large scale use of titanium alloys ran into the problem of catching fire. When the operational configuration of an engine is suddenly changed, the way in which the engine plates and blades are receiving heat is also changed as a response. If the heat expansion is not uniform, or if some factor such as engine vibration comes into play, then, as a result of these factors, the tips of the titanium alloy blades and the inside walls of the engine plates may collide with each other. In such a circumstance, these two types of components, both of which are made out of titanium alloys, can be made to catch fire due to high speed friction between them, and this will cause the engine to be damaged. This problem of titanium alloys catching fire has actually materialized in several engines. For example, on the basis of 1977 statistics, for a certain large scale turbofan engine, during one million hours of flight, there was an average incidence of seven accidents due to fire. In order to resolve the problem of titanium alloys catching fire, it is necessary to take several titanium alloy engine plates and change them into plates made from alloy steel which has a relatively larger specific gravity or to add a covering rubber separation layer to the surface of the interior walls of the engine plates which correspond to the operational blades in question. This prevents the titanium alloy blades from colliding with other titanium alloy engine plates.

THE USE OF HIGH TEMPERATURE ALLOYS TO REPLACE TITANIUM ALLOYS IN COMPONENTS

In high pressure ratio, large thrust engines, the operational temperatures of the exhausts of compressors are as high as 500 or 600° Celsius. The highest operational temperatures which titanium alloys can sustain are around 450° Celsius. Obviously, the operational tempeatures at the back levels of the compressors exceed the temperaturs which titanium alloys can normally take. It is necessary to make use of high temperature titanium alloys. However, high temperature titanium alloys are still in the stage of experimental proeuction. Moreover, stainless steel, in this kind of high temperature application, has unsatisfactory characteristics as far as resistance to corrosion is concerned, so this sort of material is also incapable of satisfying the requirements. Because of all these reasons, we must select for use some other form of high temperature alloy.

At present, in high performance aviation turbine engines, the use which is made of high temperature alloys in the construction of the compressors is increasing. The use of high temperature alloys in the functioning of compressors is a great change as far as the selection of materials for the construction of compressors is concerned. Moreover, the necessity for the development of this kind of alloy is caused by the development of high performance aviation turbine engines.

Experimentation with ~~complex~~ composite materials. A material which is mechanically ~~compounded of a mixture of~~ mixed or formed from two or more materials is called a ~~complex or compound ma~~ composite material.. In every day life people see many types of ~~compound of complex~~ composite materials, for example, reinforced concrete is a typical example of a ~~compound~~ composite material. The compound materials to which this article refers are new types of structural materials which have been developed for aircraft ane engines. There are mainly two types of compound materials which have been developed for aviation turbine engines.

One type is carbon fiber compound material. There are compound materials which are basically formed from polyethelene which has added to it, as a strenthening material, longitudinal carbon fibers.

The other type is boron fiber compound or composite material. This is composite material which is formed from a basic material of aluminum or polyethylene and polyamide with boron fibers (these are made from boron which is deposited on a tungsten wire) added as a strengthening material.

These new types of composite materials possess exceptionally good capabilities. These materials have very strong capabilities for resisting destruction and deformation during the application of external boundary loading, that is to say, these materials possess very high strength and rigidity. Carbon fiber composite materials have a tensile strength which is almost the same as that of steel material and its weight is one-fifth that of steel or one-third that of titanium. It is, to put it simply, both light and strong.

Besides this, composite materials, will not fracture under ~~under conditions of reflex loading action,~~ the effects of repeated loading ~~do not break and split~~. They have excellent ~~tensile strenght~~ fatigue properties... Because these materials are ~~formed out~~ composed of ~~several~~ many fibers, the breaking of any given one of the fibers in the materials will not cause the entire component to break. Moreover, even if an entire component did break, it still would not pose a threat to any of the other components around it. After a blade had been broken up or smashed, it would just form a powder of broken up fibers and these would not impact against other blades behind the broken one, thus preventing secondary destruction. Besides this advantage, composite materials also have characteristics of a high resistance to vibration and this means that the fan blades of compressors, if made from this type of composite material, need not be made with vibration reducing bases. These are all prime characteristics which are required in structural materials which are to be used in the construction of aircraft and engines. Because of this fact, these materials have received extremely large amounts of attention from aviation circles in all the various countries of the world.

Even so, however, in the rise of these sorts of materials, people have run into some problems. For example, concerning the fan blades for a large scale British turbofan engine, in the past these blades were made from the sort of carbon fiber composite material which we have been discussing but, due to the fact that the characteristics of this material in the area of resistance to shock were inadequate, the company switched to the use of titanium alloys for the manufacture of the blades. Because of this type of experience, even up to the present day, composite materials are only used in low temperature components of small scale aviation turbine engines.

CHANGES IN THE MATERIALS USED IN COMPONENTS FOR TURBINE

The pre-turbine temperatures which are found in aviation turbine engines have undergone a drastic increase. In the last more than two decades, these temperatures have gone from approximatelky 800° Celsius to 1300° Celsius. Because of this fact, the structural materials used in turbine components have undergone very large changes and most of these changes have appeared in the few areas indicated below.

Cast high temperature alloys replace high temperature alloys which deform. There are many metals which, under ordinary temperature conditions, have excellent mechanical characteristics. These metals are not easily damaged or deformed during the actions of forces and moments of force. However, under high temperature conditions, they not only deform and turn soft, they even reach the point where they melt. Because of these facts, the high temperature parts of aviation turbine engines all make use of temperature resistant alloys based on nickel, cobalt and iron for their manufacture. Because of the fact that the temperatures of the pre-turbine combustion gases in turbine engines are going up, in order to make high temperature alloys capable of dealing with even higher temperatures, the addition of strengthening additives to the alloys becomes ever more common. Because of this fact, the difficulties attendant on working with these materials in manufacturing processes have become ever greater in number and severity and there have been obvious changes in the characteristics of the materials used in turbine blades and turbine wheels or discs. The deforming high temperature alloys which were formed by forging processes and were in common use before are no longer appropriate for the current applications. There has been a requirement for the development of high temperature alloys which are manufactured by the use of casting processes and, if one considers the type of materials which are selected for use in engines, then high temperature alloys are made by the use of casting processes are going to take the place of high temperature alloys which deform.

<u>The development of new forms of high temperature alloys.</u> The melting points of high temperature alloys based on nickel already approach the preturbine temperatures in modern aviation turbine engines and these alloys are not suitable for the requirements of the operational temperatures of these engines. At present, new forms of high temperature alloys are in the midst of test production for use with the new generation of turbine blades and these alloys are based on niobium. The characteristics of these alloys under high temperature conditions are excellent when compared to those of alloys based on nickel. However, the problem of high temperature oxidation has still not been solved and these new alloys have still not been put into use.

<u>The development of high temperature composite materials.</u> High temperature composite materials are formed by the addition to nickel-based alloys of certain high melting point metallic wires such as tungsten wire, molybdenum wire, niobium wire or even ceramic filaments, and so on, or by the addition of high melting metals which may be required for their formation. Because of the fact that the high temperature strength of high temperature composite materials is much greater than the high temperature strength of nickel-based alloys, these high temperature materials have a real future and several countries are conducting active preliminary research into these materials.

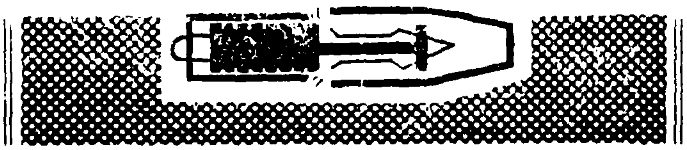
Among those high temperature composite materials which are presently in the midst of being researched, the developmental progress seems to be larger for those composite materials which are made by taking high melting point metal wires and using these to strengthen the base material. Research production has already been made of several high temperature composite materials which have excellent characteristics in extended operation in heats of from 1100° Celsius to 1200° Celsius. However, the technology involved in these materials is relatively complicated. Moreover, the research into high temperature composite materials which are strengthened by the use of monocrystalline porcelain filaments has still not reached fruition and the technology involved with this type of material is still very complicated. The two types of high temperature composite materials which we have talked about above both have one common drawback and that is the fact that the strengthening filaments and the basic metals involved must function together before the structure in which the two exist together can be reliable. If they act independently relative to each other, then the structure is not reliable.

As far as eutectic alloys that are composed of directional crystals are concerned, the mechanical arrangements of their structures are neater or more orderly, if you prefer, than those of the two types of composite materials which we have talked about above. Moreover, with this type of crystalline alloy, there is no mutual interaciton between the strengthening materials and the basic metals involved. The drawbacks which existed for the two types of composite materials which we discussed above do not exist for this type of crystalline alloy. Moreover, the technology involved with this type of alloy is relatively simple. Because of these facts, this type of high temperature composite material is recognized as having potential for development. At present, there are already turbine blades for several engines which have been manufactured from this new type of material.

<u>The development of high temperature ceramic materials</u>. On the basis of theoretical estimates, the pre-turbine

temperatures in aircraft are capable of reaching 2000° Celsius. and more. The high temperature alloys and high temperature composite materials which we have discussed above will also not be able to satisfy the developmental requirements for such temperatures. Because of this fact, several countries are currently in the midst of large scale research into high temperature ceramic materials. The United States has already made use of carbonized silicon ceramics for the manufacture of turbine blades and guide vanes and these have been isntalled in engines for the purpose of carrying out tests of these components. The results of these tests have been excellent. This type of carbonized silicon ceramic blade possesses outstanding temperature characteristics. Moreover, it is light in weight and has the capability of being used in the high performance aviation turbine engines of the future.

航空涡轮发动机结构材料简介



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