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the potentialities of the ceramic could not be determined definitely.

Blades of similar design were fabricated from National Bureau of Standards 4811 material. The results (9) indicate that the material is suitable for operation at least at speeds of 14,000 rpm and gas temperatures of 1800 F. A severe thermal shock set up by failure of the air supply caused fracture of the blades.

Blades of another design were fabricated by the Kennametal Corporation from 20 per cent cobalt-titanium carbide in such manner as to be interchangeable with metal blades in a turbine. Three ceramal blades and 139 blades of alloy A were successfully operated (10) at gas temperatures up to 2000 F and speeds up to 15,000 rpm. Almost simultaneously with increase of speed to 17,500 rpm all ceramal blades failed at the root where material temperatures are very low. The probable cause of the failures was resonant vibration at the particular operating speed, although a contributing cause probably was damage done to the blade roots when the wheel metal was peened against the blade roots for retaining purposes.

Another installation of three blades of 20 per cent cobalt-titanium carbide ceramal was made, this time without peening the wheel metal against the blades. In addition, the blade roots were plated with copper in order to reduce possible localized stresses produced by bearing against the wheel. Twelve new control blades of metal (alloy A) and the three ceramal blades were operated at varying conditions including $2^1/_4$ hr at a gas-inlet temperature of 2200 F and a wheel speed of 15,000 rpm. Up to this point 50 per cent of the metal control blades had failed. During an overhaul for replacement of a failed metal blade, one ceramal blade was inadvertently fractured by being struck. Operation was resumed at 2200 F gas temperature and 15,000 rpm. After $3^1/_2$ more hours of operation at this condition, during which 2 more control blades failed, a piece of the wheel rim holding one ceramal blade pulled apart from the wheel proper. The direct cause of the failure is believed to be the high temperature at this point on the wheel caused by the high thermal conductivity of the carbide-type ceramal. Excessive creep of the rim had been noticed in previous runs, but replacement of the wheel had not been made for fear of damaging the ceramal blades. The third ceramal blade failed simultaneously with the wheel failure in what may have been a normal failure. It is difficult to state that any of the ceramal blade failures was normal, because of the events surrounding their destruction. All that can be concluded is that one ceramal blade outlasted 50 per cent of the metal blades, and one ceramal blade outlasted 67 per cent of the metal blades prior to failures that were not caused by failure of the blade material. The third ceramal blade outlasted 67 per cent of the metal blades when it failed, perhaps normally, simultaneously with a minor wheel failure.

It is apparent that carbide-type ceramals present wheel-cooling problems because the heat transfer from the combustion gas to the wheel rim is large. This problem probably can be solved by the use of better wheel materials or by added wheel cooling.

Conclusion

A number of ceramics and ceramals have demonstrated their excellent tensile properties at elevated temperature. Carbide-base materials possess good thermal shock resistance and operate cooler than most high-temperature alloys or oxide-base materials, although they may present oxidation problems and difficulties with wheel cooling. Both ceramics and ceramals have operated as blades in gas turbines at temperatures above those in service use with alloy blades, although speeds were lower. Lives of ceramic and ceramal materials are still short, primarily because of mechanical design problems which cannot be anticipated prior to research evaluation. Additional research is required on such factors as elevated-temperature fatigue properties before ceramics and ceramals may be considered competitive with heat-resistant alloys except for short-time operation.

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Discussion

J. W. Freeman.[3] The author is to be complimented on a thorough and complete coverage of a new and interesting development in structural materials. He is indeed fortunate to have the opportunity to be in a position to work with these new materials which show so much promise for extreme temperature service.

The presentation was so thorough that it is difficult to discuss the paper without simply raising questions which the workers in the field have not yet had time to solve. There are three questions, answers to which would be of interest:

1 What was the type of wheel failures with the ceramal blades?

2 Ceramics and ceramals present problems of mechanical design for the utilization of brittle materials. Is the testing of ceramic and ceramal-type blades in an engine designed for metals satisfactory for these brittle materials?

3 The data infer that ceramics and ceramals have properties superior to metals at the more elevated temperatures. Is it therefore not surprising that the metal blades performed so well at the extreme temperatures in comparison to the TiC-20 per cent Co ceramal blades?

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It is difficult to specify unequivocally the nature of the single-wheel failure that has taken place. The ceramal blade funneled more heat to its root than did the alloy blades to their roots, consequently overheating the failure zone. Deformation had previously been noted in this region also. It may be presumed that the failure was of a stress-rupture type because no signs of fatigue nor excessive corrosion were displayed by the fractured surface.

In answer to Dr. Freeman's second question, the author thinks that each ceramal should be considered as a separate case for design especially at the root fastening. In general, however, the ceramals do not possess as high strength at the roots as the alloys because the root operates cooler than the airfoil section and the ceramals are chiefly advantageous at the higher temperatures. On the other hand, the lower densities of most ceramals reduce the centrifugal stress proportionately. The net result is that the root size may have to be increased for the heavier ceramals or remain unchanged for the lighter. Special precautions should be taken not to injure the blade root in mounting it in the wheel. The root may have to be protected by a thin coat of a soft buffer metal from compressive fracture if the wheel is forced against the blade because of thermal expansion.

The results presented on ceramal turbine blades are first results. Of all ceramal blades evaluated, only one can be considered as a possible normal failure. For these reasons, it is preferable to await additional evaluations before commenting on whether the potentialities of the carbide ceramals have been assessed to their fullest.

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