HIGH TEMPERATURE REFRACTORY METAL ALLOYS-ADVANCES AND CHALLENGES

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The operating temperatures of gas turbine engines are now reaching limits posed by the melting temperatures (T_m) of Ni base alloys and as indicated in figure 1 further improvements are limited. New materials, including alloys based on refractory metals with higher melting points, such as molybdenum (Mo) and niobium (Nb) alloys and refractory multiple principal element alloys (RMPEA) are now being seriously examined as alternatives. In order to be used in future gas turbine engines, the refractory metal alloys will have to match or surpass Ni alloys in performance as well as providing a high T_m. However, in a single component, single-phase form, these materials do not satisfy all the above requirements. One clear message from the evolutionary development of high temperature alloys is the importance of developing multicomponent alloys with multiphase microstructures and the capability to control phase fractions and morphologies to satisfy a number of mechanical property requirements. Besides the essential structural requirements, elevated temperatures also often involve aggressive environments that require a material to display an inherent oxidation protection. Some Mo and Nb alloys and RMPEA satisfy many of the structural requirements for engine applications. However, the alloy compositions with the most attractive structural performance do not offer acceptable oxidation resistance. Both Mo and Nb and many of their alloys have poor oxidation resistance which has limited their applications. The oxide layer that forms on Nb, Nb_2O_5, does not protect the metal from further oxidation, and Mo forms an oxide, MoO_3, that is volatile above about 700°C. For the Nb base alloys, the chemistry is complex and includes other transition metals, such as Cr, Ti and Hf. The oxidation behavior is also more complex with multiple oxide layers, but acceptable oxidation loss has been attained at 1200°C. The complex compositions of RMPEA also yields even more complex oxide structures and efforts to design alloys with oxidation resistance can lead to embrittlement. For Mo based alloys most attention has been on the multiphase microstructures that can be developed in the Mo-Si-B system involving the high melting temperature (>2100°C) ternary-based intermetallic Mo_5SiB_2 (T_2) with three phase alloys comprised of Mo(ss), T_2 and Mo_3Si that offer high temperature stability and robust microstructures, with performance exceeding Ni base alloys and new alloy designs are in development. During oxidation, after a transient period when the volatilization of MoO_3 enriches the surface in B and Si, a borosilicate surface layer develops that is protective. A significant enhancement of environmental resistance of refractory metal alloys and especially for RMPEA can be achieved by the use of coatings that are applied by pack cementation or thermal spray methods to promote resistance to CMAS, and water vapor attack as well as oxidation. These coatings can also serve as bond coats for TBCs. For refractory metal systems, the high strength and microstructural stability exhibited under extreme conditions of high temperature and stress creates challenges for conventional processing, such as forging. The challenge is to design processing methods that yield the desired final microstructure during initial alloy synthesis. Some progress has been made with solidification, but innovative powder metallurgy processing and additive manufacturing may be a more effective approach to achieve large-scale synthesis of uniform multiphase microstructures with controlled geometries. At present, it appears that the Nb base systems can serve in uncooled applications up to about 1200°C, and the Mo base systems can offer capability to above 1300°C. With a continued attention to advancing the fundamental understanding of alloy design, synthesis and processing further improvements in the performance of refractory metal alloys will be forthcoming.

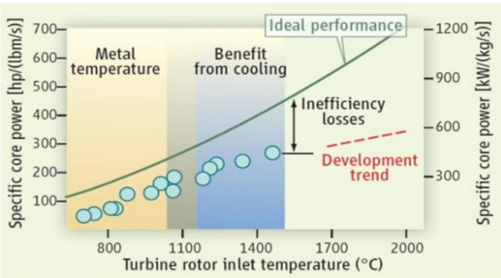

Figure 1 Development trend for Ni alloys in gas turbines indicating limitation for high temperature use.