Advanced High Temperature Turbine Seals Materials and Designs

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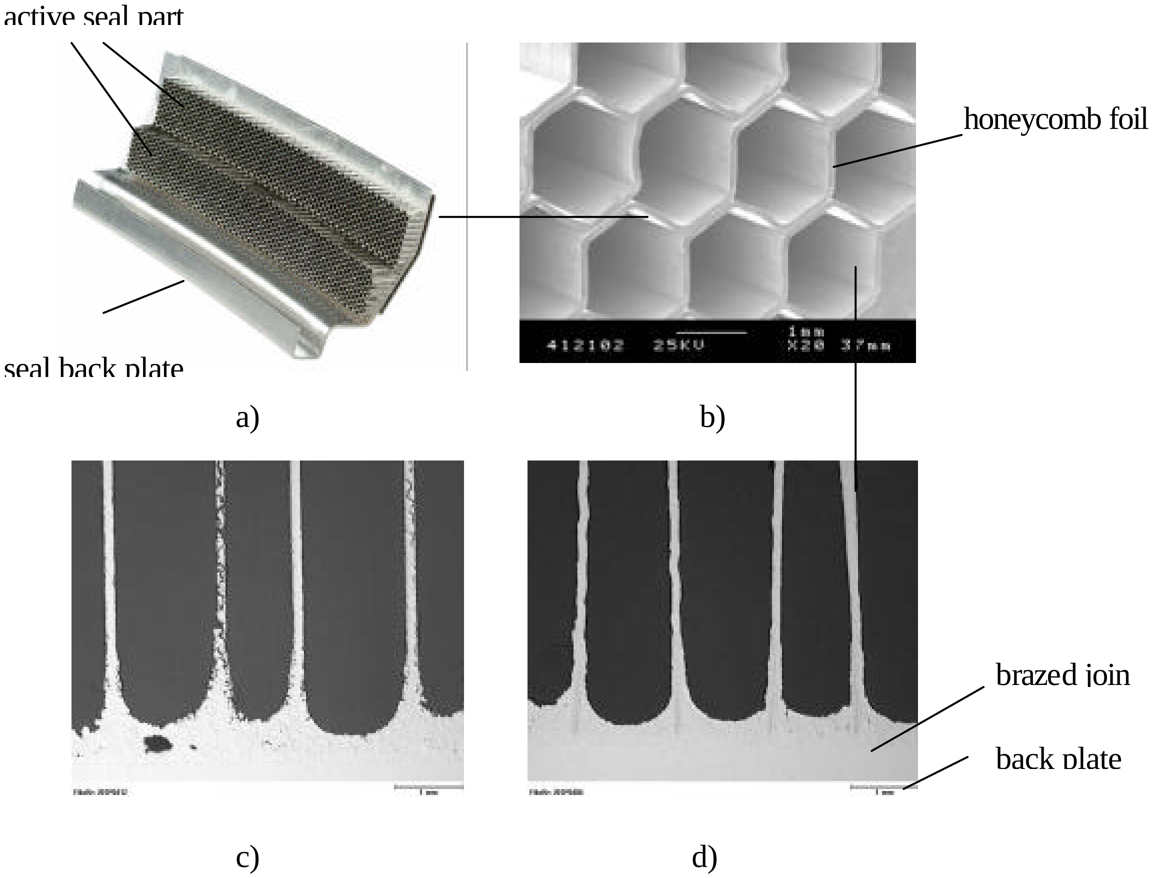
Abstract. Advanced turbine seal materials and designs are under development to achieve higher temperature capability, extended lifetime and reliability than the state of the art technology. Cooling air consumption, inspection cycles interval and repair costs of aero engines have to be reduced. In the following, results of a program funded by the European Community under the "Competitive and Sustainable Growth"-Program, project number GRD-1999-10608 (acronym: "ADSEALS") are presented. The relevant properties of advanced high temperature seal materials, especially FeCrAl-alloys and ceramic abradables, as well as advanced seal structures, like thin walled honeycombs, gradient fibre and hollow sphere structures as well as gradient porous coatings have been evaluated. The material and structure combinations which meet the advanced requirements were tested and validated in order to develop the most capable innovative technology for advanced gas turbine seals.

Introduction

Gas turbine air seals, have to reduce the cavities between vanes and blades in the gas path of the turbine and to provide an abradable seal with sufficient oxidation and wear lifetime. For the active seal part (Fig. 1a), potential materials and structure candidates have to meet the following requirements: (1) suitable for axial and radial rotor movements; (2) minimize leakage in the gap between the turbine blade tip or fin, (3) axial dense structure for minimizing leakage in the exhaust gas flow direction, (4) mechanical stability to resist temperature and pressure gradients and transients, (5) the blade tip (un shrouded rotor) or fin (shrouded rotor) should not being damaged when rubbing in the seal; (6) oxidation and rub in lifetime required up to several thousands of service hours in a hot exhaust gas atmosphere. State of the art design concepts for gas turbine sealing materials and structures need further development in order to meet the advanced requirements of future aero engines and industrial gas turbines.

Advanced Oxidation Resistant Metal Alloy Honeycomb Materials

Nickel based super alloys, such as Hastelloy X and Haynes 214 are used at present for honeycomb seals. The honeycomb seal (Fig. 1a) is made of thin metallic foils (70 to 130 µm thickness). (Fig. 1b) and is brazed on a seal back plate (Fig. 1a). The temperature capability of Hastelloy X, a chromium oxide former, is limited till 950°C due to evaporation of volatile Cr_2O_3. Haynes 214, an aluminum oxide former, can be used till 1200°C, but the seals lifetime is reduced due to internal oxidation and formation of fast growing aluminum oxides at lower temperatures. An improvement of the oxidation resistance can be achieved by the increase of the aluminum content by alloying or coating. But the high aluminum content in the alloy can deteriorate the mechanical properties, especially the ductility will decrease. Rolling of thin foils with brittle alloys is not feasible and chemical machining for producing foils from ingot material is expensive and environmentally not friendly. Moreover an additional coating of the seal with aluminum will increase the production costs for the seal. A more effective method to increase the oxidation resistance of the honeycomb materials would be to look for alternative foil materials, like FeAlCr–alloys. These alloys are aluminum oxide formers with increased oxidation resistance over nickel based super alloys, especially for cycling temperatures between 700 °C and 1200 °C. The oxidation resistance of aluminum oxide forming honeycomb alloys, like Haynes 214 and FeAlCr-alloys, like AlCrYHf, PM2000 and PM2Hf, relies upon the formation of a protecting stable, slow-growing, and stable α-aluminum oxide. At high temperatures, e.g. 1200 °C, the stable oxide forms on the honeycomb seal surface, but at lower temperatures and in the early stages of oxidation, the meta stable fast growing oxides γ-, δ- and θ-Al_2O_3 can form. For pre-oxidized honeycomb seals, the protecting α-Al_2O_3 scale is formed. But during service at temperatures lower than 1100°C, the protecting oxide layer could be worn off partially by rub in of the turbine blade tip or fin into the honeycomb. For Haynes 214, an unstable mixed oxide scale is formed on the honeycomb seal surface at the rub in position. The aluminum in the FeCrAl-alloys can diffuse faster than in nickel based super alloys. As the result, in a hot exhaust gas atmosphere, for the FeCrAl alloys, a self healing oxidation layer can be formed rapidly (Fig. 1d), whereas for the nickel based super alloys, internal oxidation can occur (Fig. 1c).

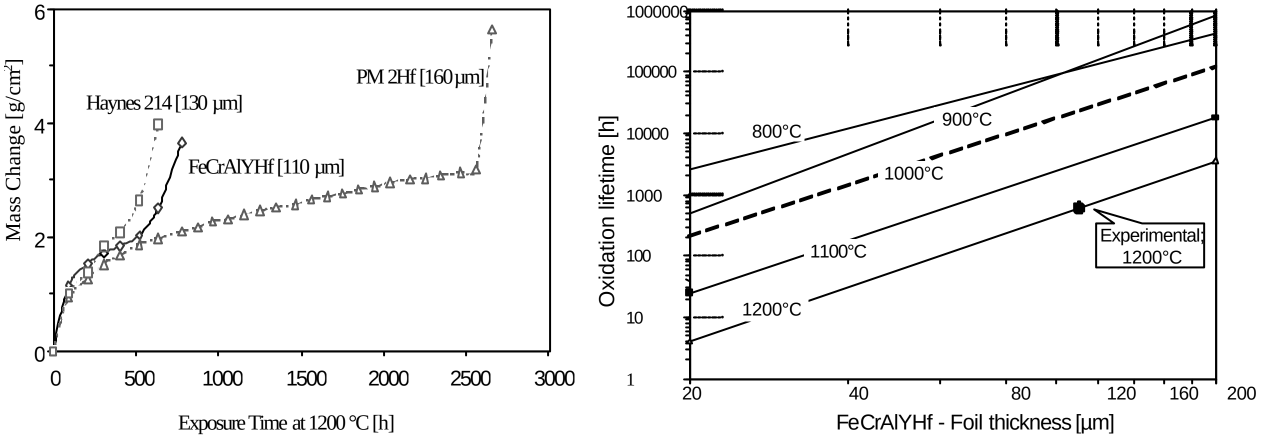


a) b)

c) d)

Figure 1 Advanced honeycomb seal material a) gas turbine outer air seal, b) honeycomb cellular structure, c) Haynes 214-honeycomb (130 µm) shows internal oxide formation, d) FeCrAl-honeycomb (110 µm), after exposure at 900°C, 200 h (1 cycle/1h) in hot exhaust gas atmosphere.

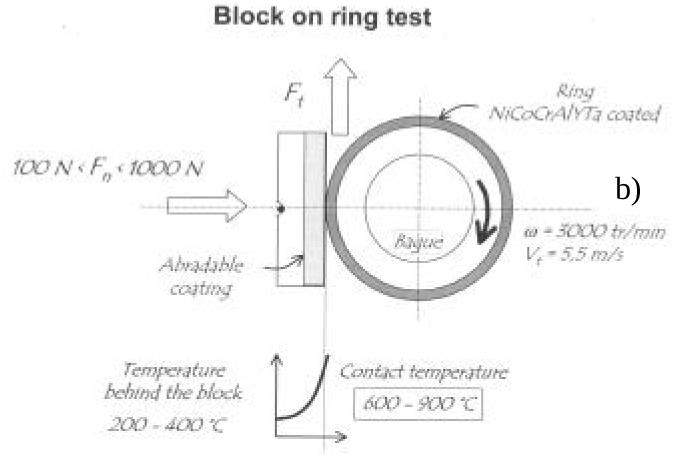
The lifetime of honeycomb seals is limited due to the decrease of the aluminum content in the foil material, the depletion of the protective oxide layer due to rub in of the blade and temperature as well as pressure transients. The oxidation lifetime of FeCrAl - alloys can be predicted using a model, which has been developed by KFA-Forschungszentrum Jülich [1]. This oxidation lifetime model is considering the foil thickness, the oxidation rate constant and exponent, the initial aluminum content of the alloy and the decreased aluminum content due to the depletion of the oxide layer. For nickel based super alloy honeycomb materials an oxidation lifetime model has not been developed due to lack of fundamental scientific knowledge. The evaluation of the oxidation rate constant and exponent in a hot exhaust gas atmosphere as well as estimations using the oxidation lifetime model show that FeCrAl-alloys are superior to nickel base honeycomb foil alloys for cycling temperatures of about 700 -1200°C (Fig. 2a and 2b) [1,4,5].



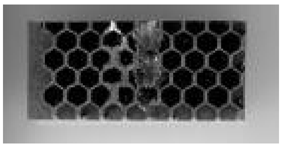
a) b)

Figure 2 Oxidation resistance of honeycomb nickel super alloy Haynes 214 and FeCrAl-alloy foil materials a) tested in simulated turbine hot exhaust gas, b) calculated oxidation lifetime till breakaway of the protecting oxide layer for a FeCrAl-alloy using a oxidation lifetime model [1].

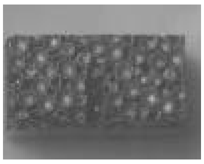
a)



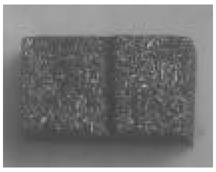
b)



honeycomb structure



hollow spheres structure



fibre structure

Figure 3 Test for evaluating abradability properties of different active seal structures materials and structures a) test parameters, b) tested FeCrAl alloy samples.

The abradability of honeycomb seal materials have been tested using hot rub in test rigs and block on ring test (Fig.3a). The dimensions and axial as well as radial rub in depths and incursion rate of the blade specimen or ring used for these tests, where according to the gas turbine requirements. The FeCrAl–alloys, perform equal to state of the art honeycomb alloys, e.g. Haynes 214, if the foil thickness is limited (Fig. 3b). FeCrAl–alloys dispersion strengthens by yttrium oxide particles show poor abradability properties. The blade tip or fin is worn off by the abrasive dispersed particles of alloys like PM2000 and PM2Hf.

Metal Hollow Spheres Structures as Active Seal Parts

Hollow sphere structures are a new class of lightweight materials within the family of cellular materials (Fig. 4a) [2]. Optimised properties relevant for sealing systems can be achieved by varying the composition of the metal alloy, the sphere size and the sphere shell thickness as well as the porosity of the shell. FeCrAl–alloy hollow sphere structures with net structural porosities of about 85 %, comparable to those of honeycombs structures, have been developed and investigated. For the manufacturing of hollow sphere structures, FeCrAl-alloy powder was gas atomised by NANOVAL, Berlin, using an ingot produced by VDM Krupp, Verdohl. A FeCrAl powder-organic-binder-slurry was sprayed on styrofoam spheres. The coated styrofoam spheres were assembled to the required active seal part geometry. Heat treatment was applied for debindering and sintering in order to produce the FeCrAl–alloy hollow sphere seal. Cyclic oxidation tests show that the hollow sphere structures have an excellent oxidation resistance like FeCrAl-honeycomb seals, if the spheres shell density and the carbon content could be controlled as required [4,5]. According to rub in tests, hollow sphere seals show the required abradability (Fig. 3b), which can be optimized by limiting the sphere shell thickness and increasing the sphere diameter. In addition the hollow sphere structure will reduce the heat transfer and flow of the hot exhaust gas to the joint between the active seal part and the seal back plate, this will prevent oxidation attack of the joint and increase the lifetime of the air seal.

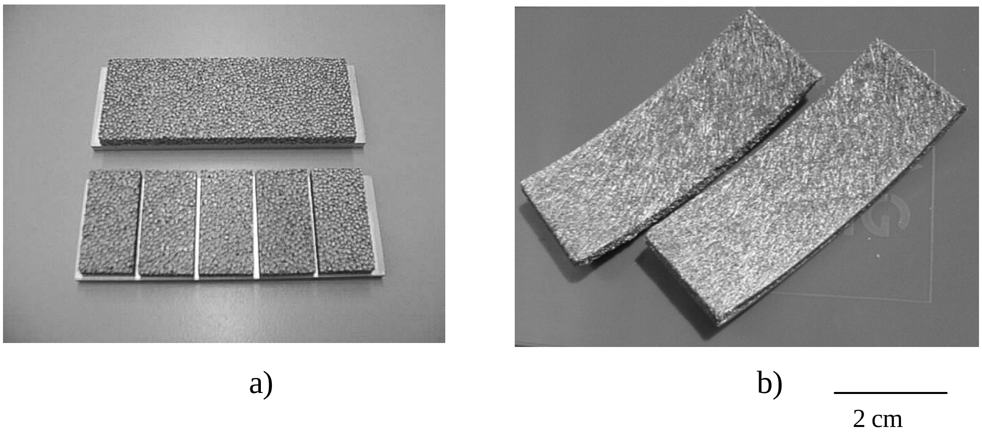


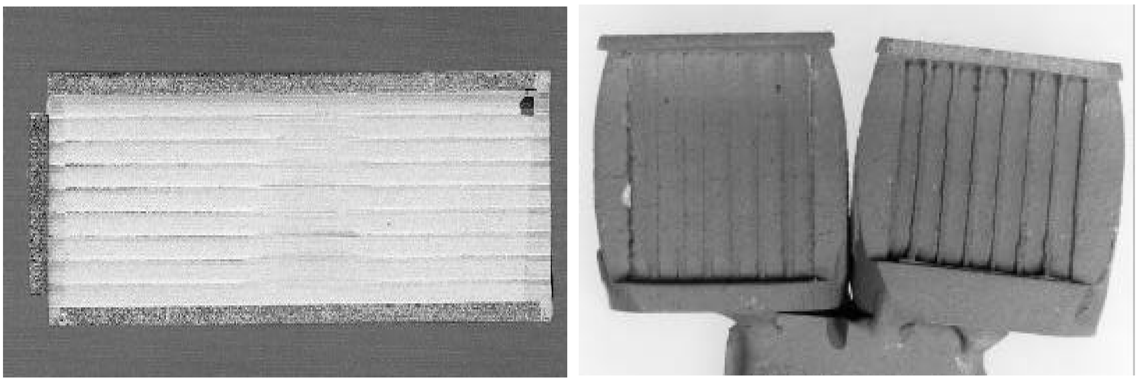
Figure 4 Innovative active seal part structures a) FeCrAl-alloy hollow sphere structures b) FeCrAl-alloy fibre structures [2, 3].

Metal Alloy Fibre Structures as Active Seal Part

Fibre structures offer the potential for optimisation of their abradability and oxidation resistance by variation of the fibre alloy composition, fibre thickness and structural density as well as texture of the fibre distribution. For the manufacturing of sintered fibre structures (Fig. 4b), a special process called crucible melt extraction for making the required fibre was developed by the Fraunhofer Institut IFAM, Dresden [3]. Instead of drawing or machining, the metal fibres were generated by extracting directly out of a melt pool by means of a water cooled rotating extraction device. In order to receive discontinuous short fibres, the outer rim of the extraction wheel is divided into evenly spaced segments by a number of notches. Thus, the mean length of the fibres can be chose between 3 and 25 mm. The fibres were processed with suitable deposition methods and sintered in order to produce the active seal part. Cyclic oxidation tests with FeCrAl-alloy fibre structures show poor oxidation resistance due to the large open surface exposed to the hot exhaust gas [4]. The fibre thickness, alloy composition and density of the structure have to be improved in order to achieve the oxidation resistance as required. According to rub in test results, fibre structure seals show excellent abradability properties (Fig. 3b) superior to alternative sealing structures for shrouded rotors.

Ceramic Abradables as Active Seal Parts

Ceramic abradables exhibit the potential of excellent oxidation resistance superior to metal alloys [4].In addition the ceramic layer also acts as a thermal barrier coating to keep the seal temperatures below the materials temperature limits.Turbine air seals with ceramic abradables as active seal part are based on a series of parallel rails that are machined into the seal backing plate. The rails are filled or overfilled with a porous ceramic coating deposited via thermal spraying (Fig. 5a). Sulzer Metco developed an innovative combination of investment casting and plasma spraying to produce turbine outer air seals [4]. The grid structure and the back plate are an integrated part made by investment casting of a nickel or cobalt super alloy. A porous ceramic layer, e.g. zirconium oxide, is sprayed on the top of the grid walls in order to produce an abradable layer. During engine running the blade fin can then rub into the coated rails or cast grid, cutting a path to reduce leakage. The two principal material choices for the ceramic coatings were aluminum and zirconium oxides, both these materials are capable of operating at 1200°C, what has been validated by cycling oxidation tests in a hot exhaust gas atmosphere (Fig. 5b). According to rub in test results, porous ceramic coatings show poor abradability properties. For peak component temperatures of approximately 1400°C, a second ceramic layer with improved abradability has to be sprayed on top in order to avoid damage of the turbine blade tip when rubbing in, especially for un shrouded rotors.



a) b)

Figure 5 Ceramic abradables as active seal part, a) railed seal backing plate with porous zirconium oxide coating, b) tested at 1200°C, 25 h (100 cycles x 15 minutes) in hot exhaust gas atmosphere.

Conclusions and Future Prospective

The final assessment of the relevant properties of the different materials & structures is summarized in Table 1. Overall FeCrAl-alloy honeycomb structures show the required oxidation resistance and abradability considering a limited foil thickness. But honeycombs are joined to the seal back plate by a brazing process which uses nickel or cobalt base brazing materials. The alloying elements of the brazing material diffuse into the honeycomb alloy, what decreases the aluminum content and as the result the oxidation resistance locally.

Key Property for Turbine Active Air Seal Part	Advanced Honeycomb Alloys	Metal Alloy Hollow Sphere Structures	Metal Alloy Fibre Structures	Ceramic Abradables
Cyclic Oxidation Resistance in Hot Gas Atmosphere	- FeCrAl-alloys show fair oxidation resi- stance between 700 and 1100 °C - Improved brazing material has to be developed	- Fair oxidation resistance - Sphere shell thickness, shell porosity, alloy composition and impurities need optimization	- Poor cyclic oxidation resistance of open structure. - Sealing by coating or filling of the fibre structure necessary	- Excellent oxidation resistance up to 1200 °C of oxide ceramics - Oxidation resistant coating and cooling of seal back plate necessary
Abradability for Rub In of Turbine Blade Tip (un shrouded rotor) or Fin (shrouded rotor)	- Fair performance for FeCrAl-alloys with limited foil thickness for shrouded rotors - Foil thickness limitations decreases oxidation resistance	- Good perfor- mance for shrouded rotor - Potential optimization by variation of shell thickness and alloy composition	- Excellent performance for shrouded rotor - Effect of necessary filler and sealing coatings have to be investigated	- Not feasible for un shrouded rotor and poor performance for shrouded rotor - Improvement of an abradable top coat necessary

Table 1 Summary of relevant properties for different gas turbine air seal materials and structures.

Testing of FeCrAl-alloy based honeycombs, hollow sphere and ceramic seals in real aero engines and industrial gas turbines environment is planned. The fibre structure concept required improvement of the oxidation resistance before commitment could be made to a gas turbine test run.

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