Advanced high temperature turbine seals materials and designs

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INTRODUCTION

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 will be reduced.

Following results of R&D activities of a European project consortium will be presented:

- Development of design concepts for advanced turbine seals;
- Definition of criteria and requirements of the outer air seals;
- Study of the damage mechanisms of outer air seals used today;
- Assessments of the relevant properties of candidate materials and structures against the advanced design criteria and requirements;
- Lifetime prediction concepts.

Turbine outer air seals have two basic functions: to seal the cavity over the rotating blade and to hold the previous vane. Other functions are to reduce the cavity between vanes and blades and to provide a seal, which can rub in.

In order to define a first version of design criteria and requirements for materials and processes for advanced turbine seals which can be tested in the large scale integrated platform vehicles CLEAN (MTU – SNECMA concept), ANTLE (RR concept) or any other relevant aero engine or industrial gas turbine, the design, manufacturing and service requirements of outer air seals have been identified by MTU in co-operation with RR, Fiat and Alstom Power.

In general the outer air seal must be able to survive the hot gas environment and resist oxidation and corrosion. Above all, however, they must react in a safe manner when in contact with the rotating blade by easily giving way without damaging the blade tip.

CRITERIA FOR ADVANCED TURBINE SEALS DESIGN CONCEPTS

CRITERIA FOR ANTLE

The RR concept ANTLE (Affordable Near Term Low Emmissions) and its challenges are shown in figure 1.[1]

- Time to market reduction -30 %
- Cost of ownership reduction –20 %
- Life cycle cost reduction – 30 %
- Reliability improvement + 60 %
- CO_2 reduction – 12 %
- Nox reduction – 60 %

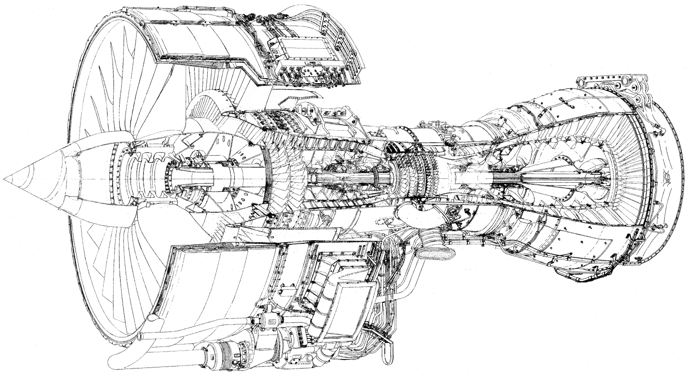


Fig. 1: Advanced aero engine concept: ANTLE, 3 shaft aero engine.

The relevant part for the ADSEALS project is the high and intermediate pressure turbine (figure 2). For this part outer air seals have to be developed which meet the advanced temperature and lifetime requirements.

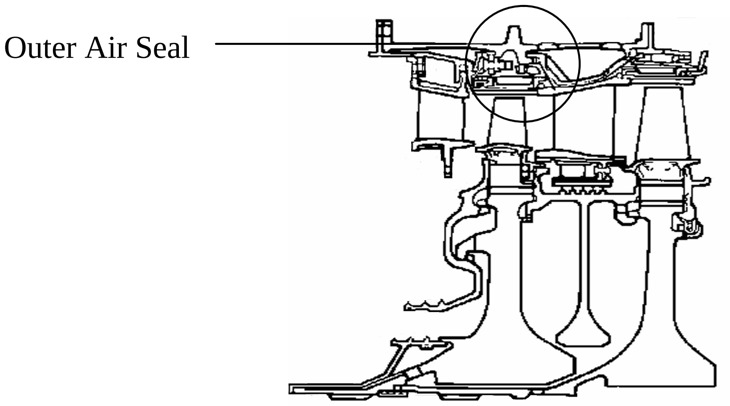


Fig. 2: High pressure turbine outer air seal (2 shaft, experimental engine).

In general based on 2D and 3D thermal and stress calculations the potential available candidate materials for high and intermediate pressure turbine outer air seals has to meet the following requirements:

- the peak temperature for the active seal part will be close to 1400 °C for the high pressure turbine and above 1200 °C for the intermediate pressure turbine.

Therefore the most relevant property for the material choice is the oxidation resistance. According to the oxidation resistance, among the different classes of available materials, ceramic materials are the most suitable materials for the active seal part. For the abradability, a low strength relatively brittle material should be preferred. For the active seal part of high and intermediate pressure turbine outer air seal the structures has to meet the following structural requirements:

- suitable for rotor movements of radial depths up to 0,5 mm;
- smooth surface towards the gas path in order to minimise the disturbance of the laminar gas flow;
- dense structure to towards the backplate in order to minimise lateral leakage in the structure itself;
- mechanical stability to resist temperature and pressure gradients;
- abradability for unshrouded rotors: the blade tip should not being damaged when rubbing in.

The unit costs and costs of ownership of seal segments including the repair capability have to be reduced over the current technology (cost reductions of 20 – 30 % have to be achieved for the seal system compared with current technology by extending the life time of outer air seals.)

CRITERIA FOR CLEAN

The MTU-SNECMA concept CLEAN (Concept of Low Emissions and Noise) and its challenges is shown in figure 3. [2]

- Specific Fuel Consumption/ CO_2 - 30 - 40 %
- Weight: - 15 %
- Noise: ≤ -10 dB (-30 dB cumulative)
- NO_x-Emission < -85 % compared to ICAO 95

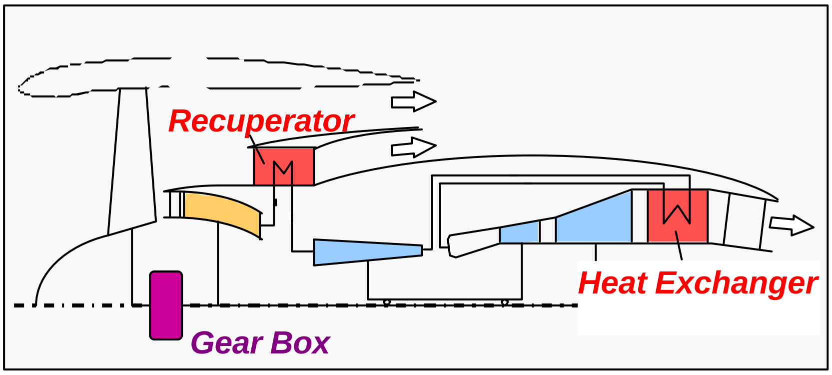


Fig. 3 MTU – SNECMA concept CLEAN.

The relevant part for the ADSEALS project is the high speed rotating low-pressure turbine (figure 4). For this part of the aero engine outer air seals have to be developed which meet the advanced temperature and lifetime requirements.

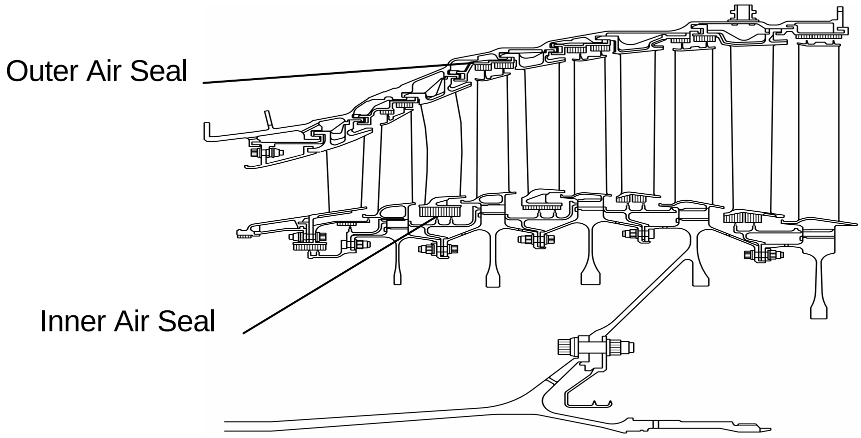


Fig. 4: Low-pressure turbine honeycomb seals.

Figure 5 shows in principle the gas temperature for one flight mission cycle.
The potential candidate materials for low pressure turbine outer air seals has to meet the following requirements:

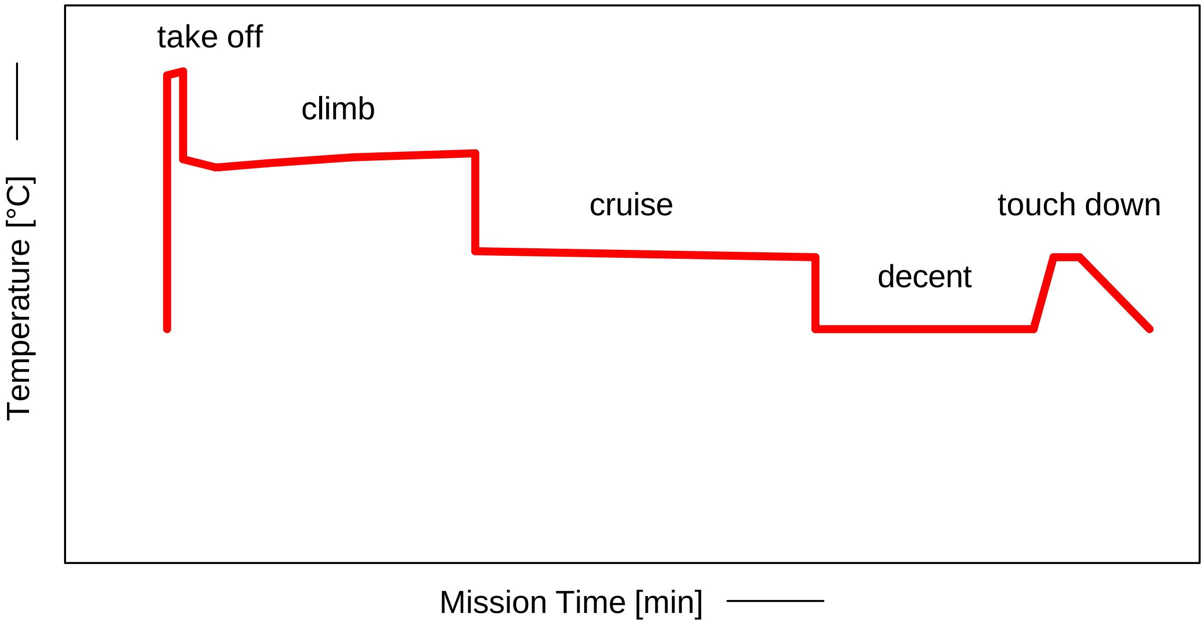


Fig. 5: Low-pressure turbine entrance temperature cycle.

For the active seal part of the low pressure turbine outer air seal, potential available structures has to meet the following requirements:

- suitable for rotor movements of axial width is about 10 – 15 mm;
- suitable for rotor movements of radial depths is about 3 – 5 mm;

- open cellular structure towards the gas path in order to minimise leakage in the gap between the blade tip fin and the active seal part by building up a resistance in the gas flow path (the exhaust gas pressure range from the entrance to the rear end of the low pressure turbine is about between 9 to 1,3 bar);
- dense structure to towards the backplate in order to minimise lateral leakage in the structure itself;
- mechanical stability to resist temperature and pressure gradients;
- abradability for shrouded rotors: the blade tip fin should not being damaged when rubbing in, with a velocity of 250 – 400 m/s at the blade tip;
- oxidation and rub in lifetime required to 20.000 hours.

As joining technology for honeycombs to the back plate brazing is the most effective process for joining the thin walled open structure reliable to a plate.

The concepts for joining the active seal part to the backplate, the following criteria have to be considered:

- the brazing foil or brazing powder material has to withstand improved temperature – lifetime conditions over the state of the art ;

- the brazing temperature has to be higher than the service temperature of the seal but not as high that the required properties of the active seal part and the back plate material will be degraded.

If the advanced seal material will meet the required life time, as an estimation for the required target costs for low pressure turbine outer air seals (considering a cost reduction target of 30 % over the state of the art and an extended life time of 100 % over current technology) a factor of 1,4 could be accepted.

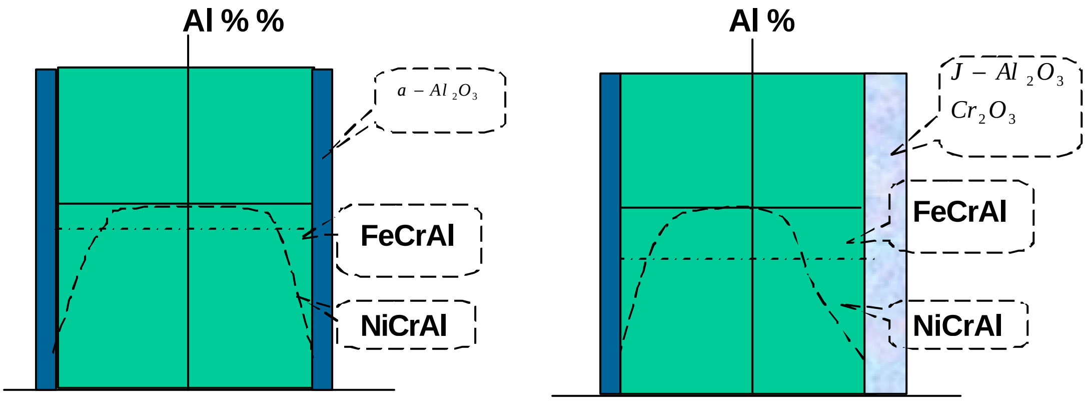
DESIGN CONCEPTS FOR ADVANCED LOW PRESSURE TURBINES

IMPROVED HONEYCOMB FOIL MATERIALS

Improved design concepts for turbine sealing systems with reduced air consumption for back-face cooling of the liner and back plate, with increased structural integrity of the abradable, bonding coat or braze alloy as well as shroud fin or blade tip needs further development. The materials for the honeycombs must be able to survive the hot gas environment and thermal cycling. Above all, however, they must react in a safe manner when in contact with the rotating blade by easily giving way without damaging the blade tip.The honeycomb is made of thin metallic foil typically 70-125 µm thick. The foil is corrugated into a half hexagon shape; the strips of foil are then laser welded to form the full hexagon shape and the honeycomb structure built up layer by layer.

Nickel based superalloys, [5] such as Haynes 214, Hastelloy X, are used at present for seal honeycomb. However, due to the continual development of the gas turbine engine the temperatures of the honeycomb segments have to withstand is constantly increasing.

The Hastelloy X is a chromia former. It can only used till 950°C due to evaporation of volatile Cr_2O_3. The Haynes 214 can be used till 1200°C, but the lifetime of these components is drastically reduced due to internal oxidation of the foil material, because Aluminium diffuse very slowly in the nickel-based alloy.



pre-oxidized **rub in and oxidized**

Fig. 6: Al concentration decrease in different alloys and for different damage mechanism.

A solution would be to increase the Al content in alloy matrix with aluminising to increase the oxidation limited life. But the high Al contents can deteriorate the mechanical properties of the alloy, especially ductility flexible as before.

Another way is filling with oxidation resistance materials to reduce the surface that increase the oxidation resistance. But its wear resistance will increase and as the result the abrasion of the turbine blade tip.

A more effective method to increase the oxidation resistance of the honeycombs would be to look for alternative foil materials, e.g. FeAlCr – alloys, like PM2000 [4], Aluchrom YHF [3], PM2Hf [4] and Kantahl AF. These alloys are aluminium oxide formers with increased oxidation resistance over nickel alloys for temperature up to 1200°C. The aluminium in the iron alloys diffuse faster than in nickel alloys. As the result for the iron alloys a self healing oxidation layer can be formed, whereas for the nickel-alloys, internal oxidation can occur (figure 6).

HOLLOW SPHERE STRUCTURES

Hollow sphere structures [7,8] are a new class of lightweight materials within the family of cellular materials. They can have a wide range of properties, which can be achieved by varying the base metal alloy, the sphere size and the structure. The honeycomb structures

are superior in structural weight and abradability over filled honeycombs, hollow sphere and fibre mat structures.
But honeycomb structures have less oxidation resistance compared to the other considered structures because of the larger open surface, which is in contact with hot exhaust gas. If the hollow sphere structure is cut in a way that an open half sphere structure appears towards exhaust gas channel of the turbine, than the abradability is like that of honeycomb structures.
The hollow sphere structure can be brazed on the back plate like honeycombs or potentially by sintering procedures.

DESION CONCEPTS FOR ADVANCED HIGH PRESSURE TURBINE SEALS

POROUS CERAMIC COATINGS

The abradable solutions for high pressure turbine seals are based on a series of parallel rails that are machined into the backing plate. The rails are to be filled or overfilled with a porous ceramic coating deposited via thermal spraying. During engine running the blade fin can then rub into the coated rails cutting a path to reduce over tip leakage in subsequent engine running.

This solution is shown in Figure 7:

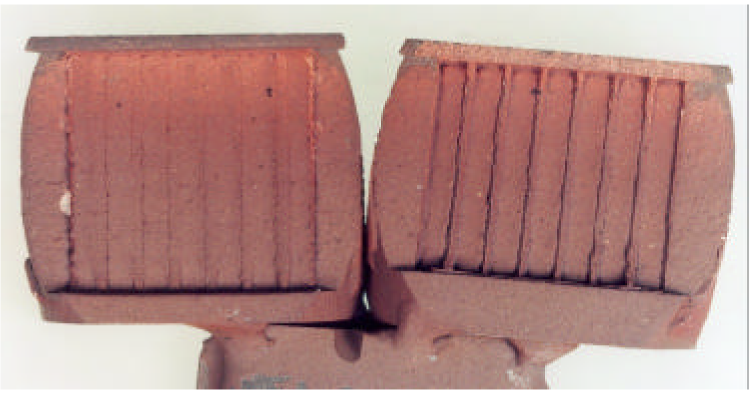


Fig. 7: Schematic of ceramic filled rails as advanced outer air seal concept.

The two principal choices for the ceramic coating were alumina and zirconia, both these materials are considered to be capable of operating at 1200°C in this type of application. It was decided to proceed with the manufacture of test specimens with rails filled with both alumina and zirconia as the different physical properties may result in a differing performance. Various solutions are under consideration for the more arduous application of abradable liner systems that will have the potential to act as part of an unshrouded sealing system. In such an application peak component temperatures are expected to be approximately 1400°C.

SUMEGRID

Sulzer Metco developed an innovative combination of investment casting and plasma spraying to produce turbine outer air seals. The grid structure and the back plate are an integrated part made by investment casting of a Ni/Co based alloy. A porous ceramic layer, e.g. zirconia oxide, is sprayed on the top of the grid walls in order to produce an abradable layer (figure 8).

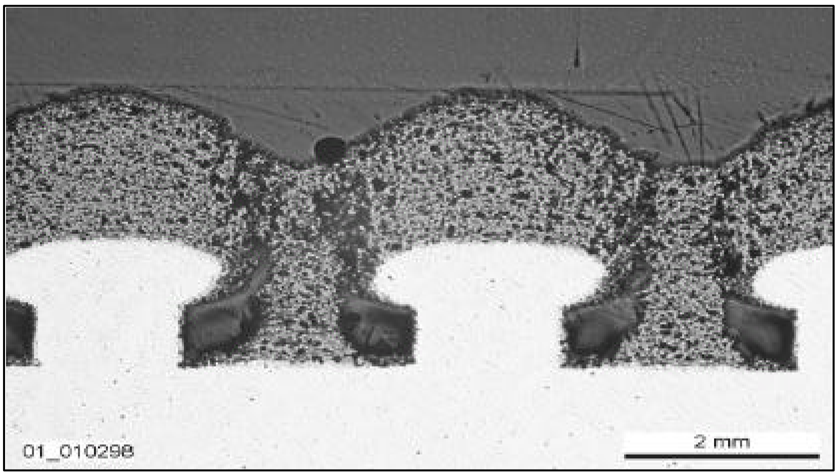


Fig. 8: Plasma sprayed ceramic on the top of the metallic grid.

This concept has the advantage of superior oxidation resistance of the zirconia oxide and the superior abradability of the porous ceramic layer on the top of a honeycomb structure. The ceramic layer also acts as a thermal barrier coating. In addition the metallic back plate and grid could be cooled by air to keep the component temperatures below the materials temperature limits.

MODEL FOR THE OXIDATION AND RUB IN LIFE OF TURBINE OUTER AIR SEALS

The analysis of damages in real aero engines show that oxidation makes the seals honeycomb brittle, so that its life is limited by the oxidation[11]. The reason for this effect is the scale-forming element, Al, in the alloy matrix is consumed. If the remaining Al% is decreased beneath a critical concentration, a breakaway oxidation occurs. Alumina-forming alloys are excellent oxidation–resistant materials at high temperatures. Their resistance relies upon establishment of a stable, slow-growing, and adherent α-alumina. But at lower temperatures and/or in the early stages of oxidation, the metastable oxides γ-, δ- and θ-Al_2O_3 grow. Once the aluminium content in bulk alloy is too low to reform external oxide, an internal oxidation occurs.

A rapid depletion of aluminium accompanies this internal oxidation process, exacerbating the onset of breakaway corrosion. For pre-oxidation segments, a stable and adherent α-

Al_2O_3 scale has been formed over the whole honeycomb after 1 h at 1090°C in air. This scale protects the base alloy from being oxidised.

But during the services, some 0,5%-1% surface scale would be repetitively worn off by rotor tip rub-in (figures 9/ 10). Once a given protective oxide layer worn off, a fresh alloy would start to oxidise, then an unstable mixed oxide scale would be formed at this position. Based on above analyse the lifetime of OAS segment can be limited by oxidation. Growth and wearing off of the protective alumina scales after long service times to a depletion of aluminium in the alloys, eventually resulting in breakaway oxidation.

This lifetime limited can be predicted using a model, which has been developed by KFA Forschungszentrum Jülich. [6]

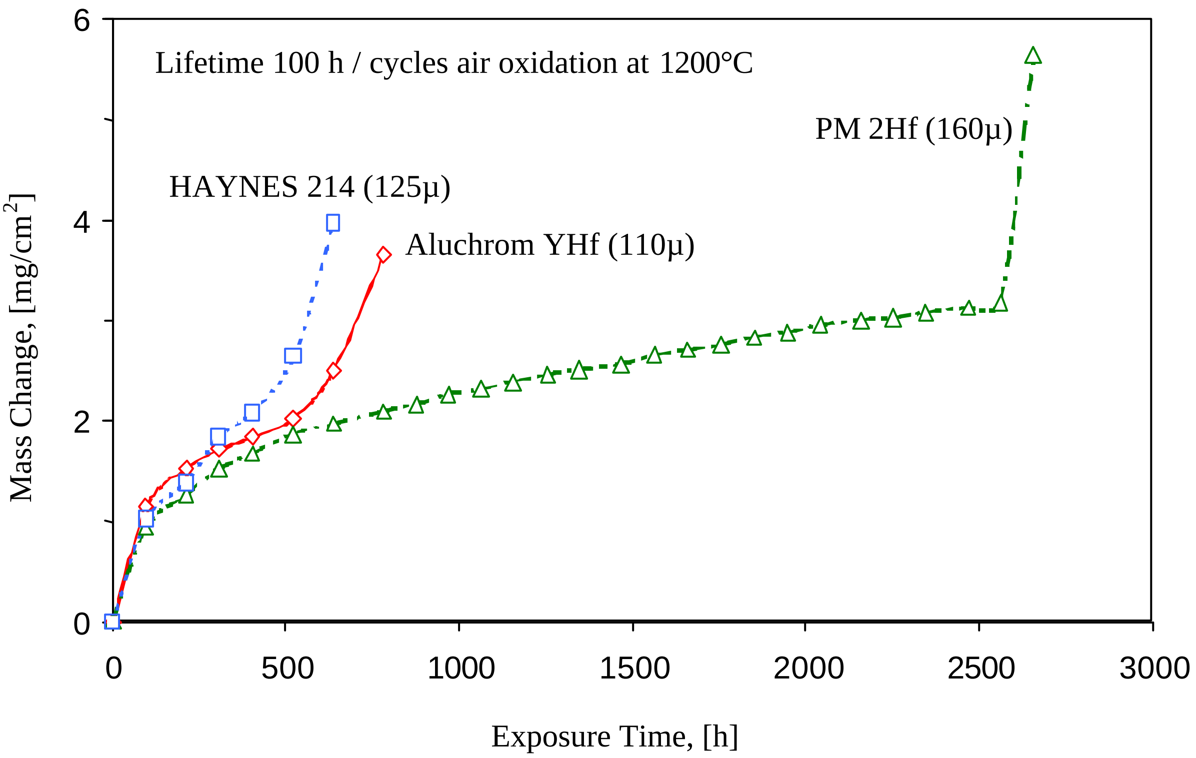


Fig. 9: Comparing the oxidation curves for nickel and FeCrAl –alloys.

The calculation shows that the mechanical damage of a small part of the oxide scale has a great influence on the lifetime of alumina-forming alloys. The FeCrAl - alloy Aluchrom VHF has much better re-healing ability than Ni-based alloy Haynes 214 and, if rubbing-in of tip destroys the oxidation layer (figure 9).

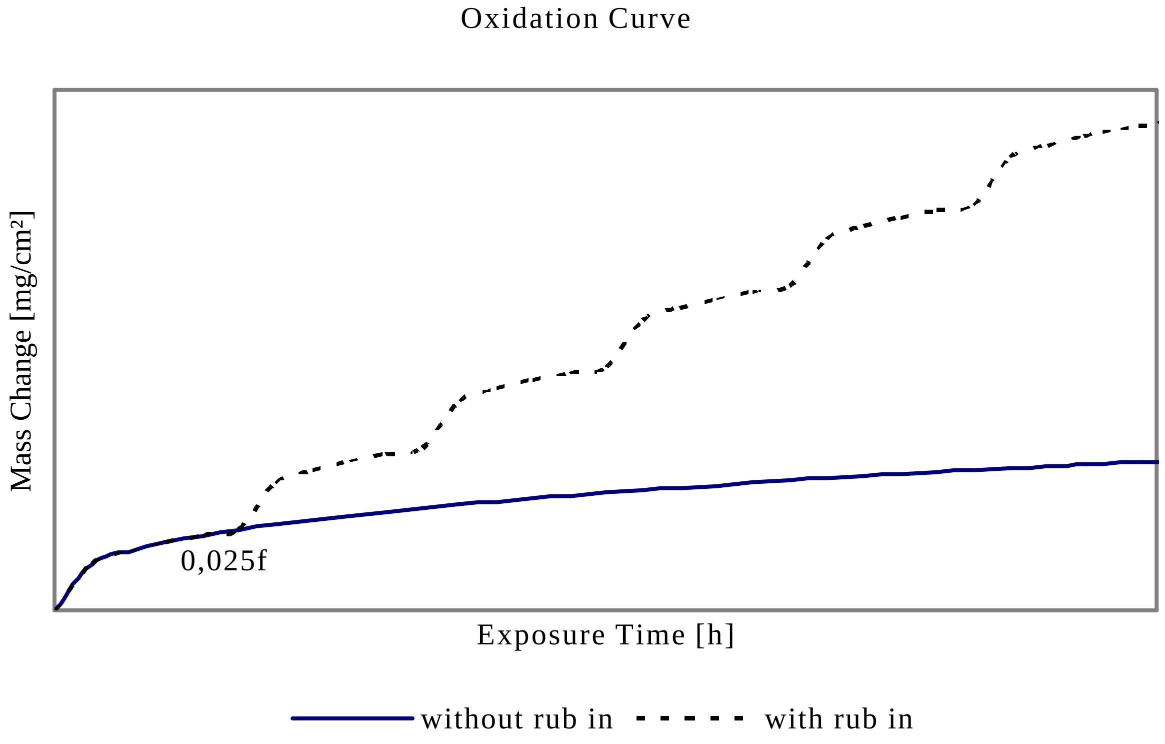


Fig. 10: Al concentration decrease in FeCrAl- and Ni alloys.

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