

Selecting Materials for Brazing a Honeycomb in Turbine Engines

Increasing aircraft turbine engine efficiency involves higher operating temperatures that introduce a number of engine manufacturing concerns

Labyrinth Seals

To reduce leakage flows in turbo machines, tight operational clearances between stator and rotor parts are desirable. With reduced clearances, the risk of rub contact increases. In such situations, the stator is fitted with an abradable structure or coating that minimizes damage to the rotor when such rub contact occurs.

A popular abradable structure is metallic honeycomb, which derives its abradability from a low structural density, typically in the range of 8 to 20% of the bulk alloy density. Honeycomb seal lands are always used as part of a

labyrinth seal, as schematically shown in Fig. 1. Seal fins on the rotor together with the stator wall form cavities. A gas flow is accelerated as it enters into the labyrinth from the high-pressure side through an annular gap (A). Subsequently, the flow area cross section increases dramatically as the flow enters the cavity (B) causing it to dissipate flow energy through a reduction of speed and pressure in a turbulent flow. A series of such events, creating a tortuous path for the gas flow, allows it to maintain a sizable pressure difference across the labyrinth seal, although a certain amount of leakage flow is inevitable.

The amount of leakage flow, however,

depends on the size of the clearance C. Small operational clearances can only be designed if the stator wall is lined with a structure that can easily be cut by the rotating seal teeth without damaging or overheating them — Fig. 2.

Engine Seal Locations

In a gas turbine engine, there is a large number of locations that require sealing against leakage flows. Honeycombs are used in both compressor sealing as well as turbine sealing applications.

However, air seals in low-pressure turbine (LPT) modules remain a domain of honeycomb as abradable seals. Typical five-stage, low-pressure aero engine turbine modules have ten gas path seal locations over shrouded blades and vanes, so

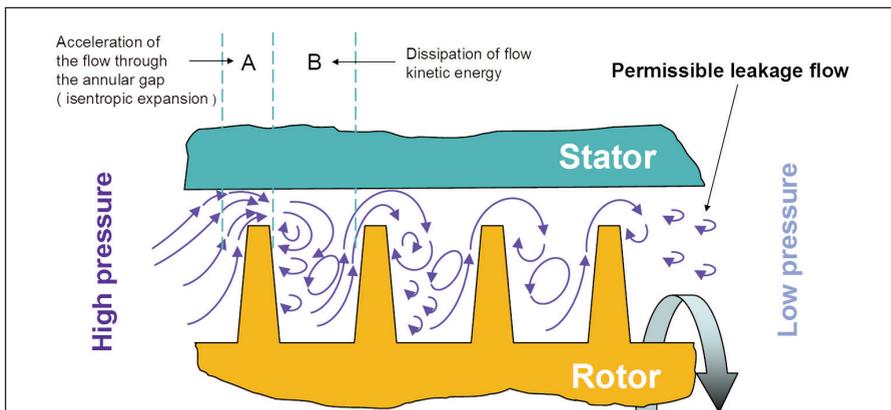


Fig. 1 — Labyrinth seal schematic.

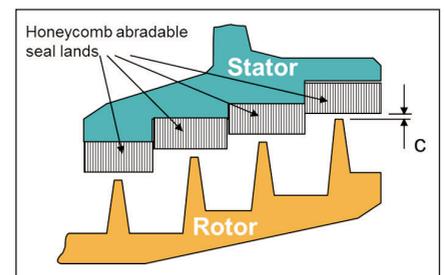


Fig. 2 — Stepped labyrinth seal with honeycomb seal lands.

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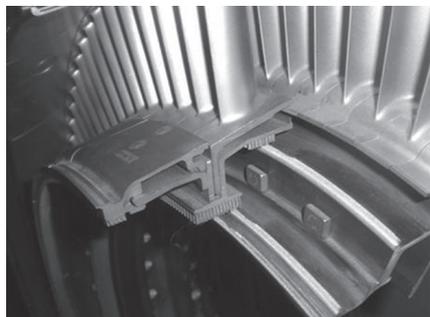


Fig. 3 — Honeycomb-lined interstage seals and abrasive-coated seal teeth.



Fig. 4 — Stepped outer air seal segment with brazed on seal honeycomb of 1.59-mm (1/16-in.) cell size.

called outer and inner air seals, and three inter-stage seals, all using honeycomb lands to minimize clearances and leakage flows thereby improving module and overall engine efficiency.

Figure 3 shows the honeycomb lined interstage seals and knife edges coated with an abrasive, thermally sprayed alumina/titania, to further reduce the wear of the rotor parts during rub incursions.

To improve overall engine thermal efficiencies, there is an ongoing effort to push turbine entry temperatures to higher values. First and foremost, this af-

fects the high-pressure turbine (HPT) hardware, but with increased temperatures there, the LPT stages and their air seals see steadily increasing temperatures as well. Typically, the first LPT stages of modern engine designs today see temperatures of up to 1100°C (2010 °F) on take-off conditions. Later stages will see lower temperature loading, typically down to 600°C (1110°F). The seals must withstand these temperatures for extended periods of time and under highly cyclic loading conditions. Therefore, apart from good abrasability of the honeycomb seal lands, they must show adequate oxidation and hot gas corrosion resistance to survive the aggressive service environment.

Honeycomb and Seal Component Manufacture

Seal honeycomb is manufactured from thin metallic foil, typically 75 to 150 µm (0.003 to 0.006 in.) thick, which is corrugated and then laser spot welded in the nodes, to hold adjacent corrugated strip walls together, forming hexagonal cells. The welded honeycomb structure can be cut and shaped to fit backing members onto which the honeycomb is first tack welded and then joined by means of brazing. Welded honeycomb can also be formed into rings that are then brazed to turbine components to form integral ring seal faces such as interstage seals. To provide inner air seals, honeycomb segments are brazed to the shrouds of the nozzle guide vanes while outer air seals are often provided by brazing honeycomb lands to sheet metal segments that are then inserted into holder structures of the LPT casing. Such a brazed outer seal segment is shown in Fig. 4.

Honeycomb Materials

Seal honeycomb for application in engine compressors is frequently made from stainless steel foil. However, for the temperatures encountered in the turbine section, more heat- and oxidation-resistant materials have to be used. The materials are typically nickel-based alloys with high chromium alloying content.

For enhanced oxidation resistance, Haynes® 214, which is a material often used, shows a high alloying content of aluminum. The most popular alloys for turbine seal honeycomb applications are Hastelloy® X and Haynes® 214. Nimonic 86™ is used in some specialty applications. Two iron-based materials, having a high concentration of aluminum and additions of rare earth metal (Y, Hf, and Zr) or oxide (Y₂O₃), are generally referred to as FeCrAlYs. Of these iron-based materials, MI2100 composition is already in commercial use in gas turbine engine sealing applications, the yttria dispersion-strengthened FeCrAlY material, MI 2200, remains an experimental alloy.

Braze Filler Materials

To accommodate the high service temperatures, turbine side-seal honeycomb is typically brazed with nickel- or cobalt-based braze filler material (BFM) providing high initial as well as high remelt temperatures. Table 1 gives an overview of common braze filler compositions.

Requirements for Brazing Seal Honeycomb

The brazing of the honeycomb to a carrier structure does not only need to join these two elements together but also needs to reinforce the honeycomb structure itself. This is achieved by filling the gaps between adjacent honeycomb walls with braze filler material using capillary action and forming fillets at the base of the honeycomb. However, it is not desirable that the BFM travels up the entire honeycomb height. Typical specifications will limit the height of the fillet or how high the braze can climb up the faces of each cell. Filling of the nodes is typically also required to reach a certain minimum percentage of the honeycomb height, for

Table 1 — Chemical Composition and Liquidus Temperature of Braze Filler Metals

Braze	Ni	Cr	Si	B	Others	Liquidus
AMS 4777	Bal.	7	4.5	3.0	3 Fe	1000°C 1830°F
AMS 4778	Bal.		4.5	3.2		1040°C 1900°F
AMS 4779	Bal.		3.5	2.0		1065°C 1950°F

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example, 80% minimum or $d/e > 0.8$ (Fig. 5) to ensure proper seal integrity and avoid honeycomb degradation through aerodynamically induced fatigue.

While in a liquid state, the BFM will not only wet the nodal walls and base but also penetrate the backing member and create a braze diffused zone that may contain undesirable phases such as chrome borides (Cr_xB_y) or silicides. Similarly, the liquid BFM may also alter the chemistry of the thin honeycomb cell walls by in-diffusion of elements from the braze filler into the honeycomb material or diluting the concentration of certain honeycomb material alloying elements by out-diffusion into the braze composition. By comparing the chemistries of the braze fillers and the honeycomb materials, it becomes evident that there is a high potential for diffusion processes based on the significant differences in chemical composition and large concentration gradients resulting from these.

Oxidation of Plain and Brazed Honeycomb

Oxidation Resistance of Plain Foil

To provide seals that can withstand higher temperatures, first and foremost, the honeycomb material itself needs to be resistant to high-temperature oxidation and corrosion. To determine a base metal's capability, a simple air oxidation test at 1100°C was carried out. The oxidation resistance was measured using the sample weight change per unit surface area after 24 h of exposure as a yardstick. Two performance classes were clearly revealed through the testing. The difference between the classes lies in the self-protection mechanism of the different materials. Nimonic 86™, Inconel® 617, and Hastelloy® X primarily form chromia (Cr_2O_3) surface oxide layers. However, these layers are not stable and therefore not protective at the selected test temperature. The MI 2100/2200 and Haynes® 214, all containing a high percentage of aluminum, tend to form Al_2O_3 surface oxide layers that are stable and protective even at 1100°C.

Weight change in the processed samples is a measure of the oxidation process

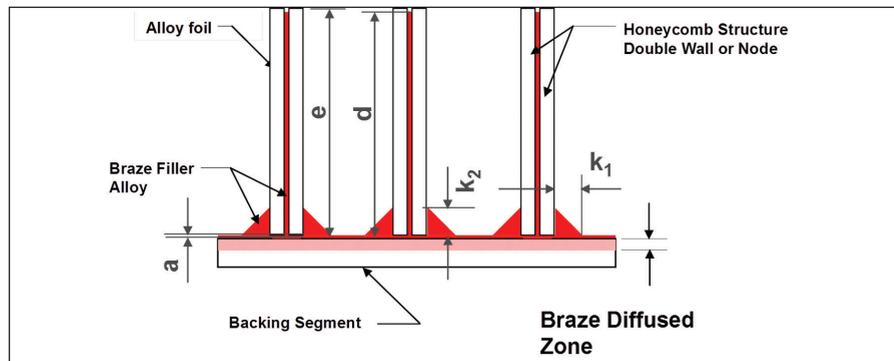


Fig. 5 — Designations of geometrical characteristics of brazed honeycomb. Section through nodal walls (schematic).

occurring to the engine components. Overall, the weight change is very small for the alumina formers compared to the results for the chromia formers in air oxidation at 1100°C.

The oxide layers on the FeCrAlY foil samples are thin and well adhered. The materials MI 2100 and MI 2200 tend to form fine-grained $\alpha-Al_2O_3$ layers and only partly Cr-rich oxide phases, while Haynes® 214 shows a higher degree of less desirable $NiCr_2O_4$ spinel oxides and coarse chromia embedded in the alumina (Refs. 1, 2). Apart from that, no significant internal oxidation of the foil materials was observed for the tests that were performed.

Thickness Effects

As the oxidation resistance of the honeycomb foil materials with high aluminum content relies on the formation of Al_2O_3 , with Cr_2O_3 being a lot less resistant at high temperature, the amount of available matrix aluminum plays an eminent role. The formation of protective alumina requires aluminum from the matrix and as the protective oxide grows in thickness or needs to be replaced after having spalled off, matrix aluminum will be consumed. Once the aluminum concentration in the matrix falls below a certain critical level, formation of Al_2O_3 at the surface is no longer guaranteed and

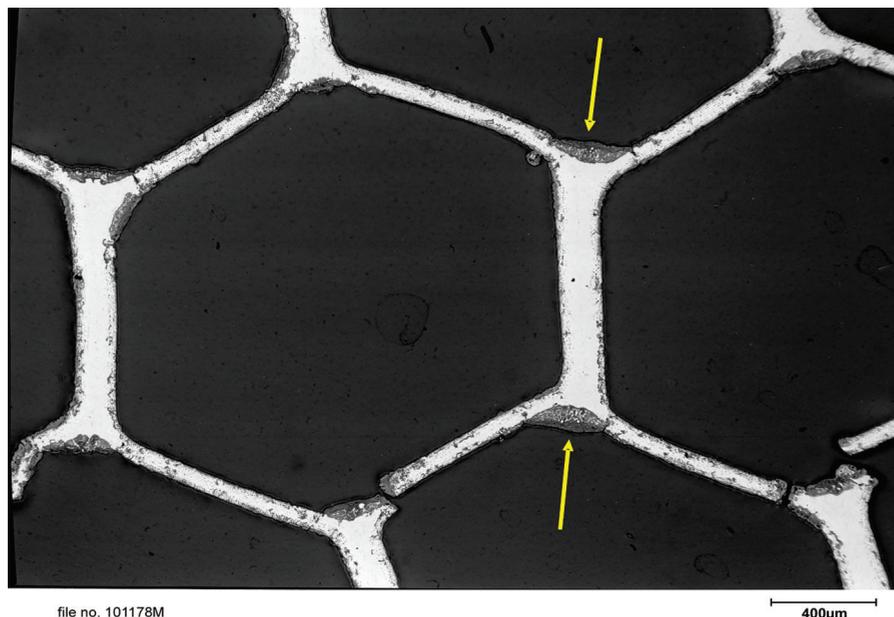


Fig. 6 — Condition of nickel-based seal honeycomb as returned from engine service. Cell size is 1.59 mm (1/16 in.).

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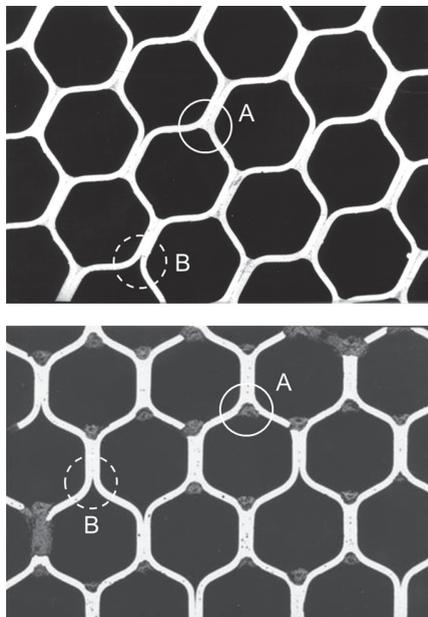


Fig. 7 — Appearance of FeCrAlY honeycomb with sized at 1.59-mm (1/16-in.) cells size . Top — As-brazed; bottom — after air oxidation at 1160°C (2120°F) over 65 hours.

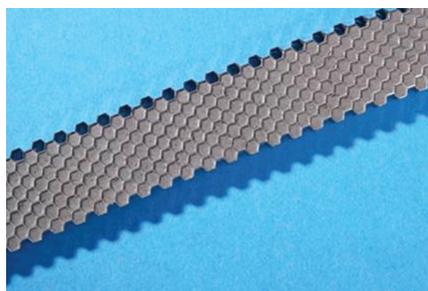


Fig. 8 — Honeycomb with preplaced braze filler material in the form of thin braze tape.

the oxidation mode changes drastically toward significantly higher oxidation rates, which, at high temperatures, can lead to accelerated or catastrophic oxidation failure, called break-away oxidation.

One solution for this type of failure is to increase the thickness of the honeycomb foil. The additional thickness will hold up to the depletion of aluminum for a longer period of time increasing the time to failure. Designers need to take these effects into consideration when designing honeycomb seals for use at extreme temperatures, even if the thicker foil material will increase the structural density of the honeycomb and compromise its abrasability.

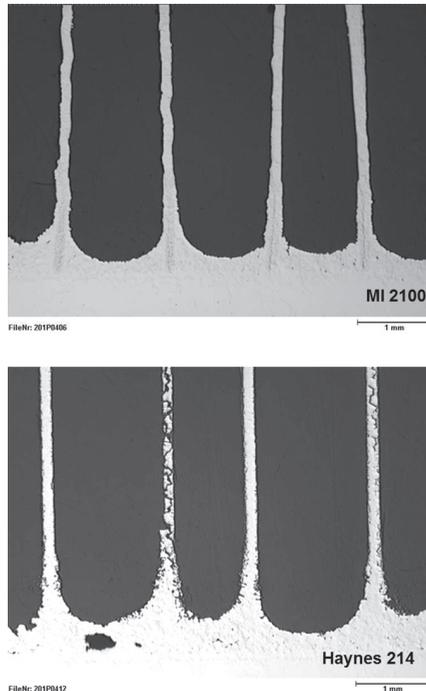


Fig. 9 — MI 2100 and Haynes® 214 honeycomb brazed with AMS 4783 powder braze filler material and subsequently subjected to cyclic oxidation at 900°C (1650°F) in burner gas.

Oxidation of Brazed Honeycomb

Figure 6 shows an enlarged top view onto a honeycomb seal face as it is returned from engine service. A preferred oxidation attack is observed at the nodal walls as indicated with arrows. In the as-brazed condition, this would have been a free surface entirely composed of braze filler material, created by the BFM climbing up the nodal joints during the brazing operation. The oxidation of the BFM penetrates the nodal joint to a certain degree, thereby reducing the wall thickness of the neighboring single foil wall. With the reduced thickness, the cell wall has little chance of surviving further oxidation and/or mechanical loading and will ultimately fail by cracking, as is seen in the lower right-hand corner of Fig. 6.

It is difficult to say whether the ultimate failure of the honeycomb is caused by mechanical/aerodynamic loading of the weakened structure or further oxidation. However, what becomes apparent

from Fig. 6 is the fact that the failure mechanism is induced by preferred oxidation of excess braze filler metal.

Compared to the single foil walls of the honeycomb structure in Fig. 6, the double walls look relatively healthy with less internal oxidation compared to the thinner sections. This may be due to the thickness effect discussed above. In any case, it leads to the nodal walls surviving the service exposure much better than the single walls, which can ultimately lead to the nodal walls being the only part of the seal structure to remain intact, an effect that is called “tombstoning.”

The strong oxidation of the BFM at the nodal joints is quite easily repeated in laboratory air oxidation experiments, as can be seen in Fig. 7. In the case shown there, it is clear that the failure of isolated single walls was caused by oxidation only, as there was no mechanical loading of the honeycomb in the 65-h accelerated isothermal oxidation test at 1160°C (2120°F). Note that the structure shown in Fig. 7 has nodal areas that are well filled with braze (node side Type A), while in some places there is little to no excess braze (node Type B). The Type B nodes survive the fairly heavy oxidation treatment very well, while the overfilled Type A sides of the nodes all show significant oxidation attack, obviously originating from free surfaces of the BFM. Therefore, precise metering of the amount of braze filler metal added in the joining process becomes important in avoiding excessive BFM in the brazed structure, which promotes oxidation attack. The fact that there is preferred oxidation starting at the free braze filler surfaces at high temperatures does not come as a surprise as the chemical compositions of the standard braze fillers (Table 1) are optimized for melting characteristics and not necessarily for high-temperature oxidation resistance.

Even when the amount of excess braze at the nodal joints is limited to a minimum, detrimental effects from the braze filler can still be observed, especially for Fe-CrAlY-type honeycomb. By preplacing thin braze filler metal in the form of amorphous foil inside the nodal walls of honeycomb, a brazed structure can be produced showing little excess BFM at the nodes. In the oxidation testing of a honeycomb structure similar to MI2200 brazed with

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BNi-5a amorphous foil, it becomes apparent that the oxidation resistance of the nodes suffers from the preplaced braze foil. The impression is that the BFM poisoned the composition by in-diffusion of undesirable elements or by diluting the aluminum concentration locally.

With the need for more precise metering of the BFM, methods other than filling the honeycomb with braze powder need to be applied. One such method is the use of braze tape. Braze tape containing the common BFMs is available in a variety of thicknesses and therefore braze filler amounts can be controlled per unit surface area and is preplaced in the honeycomb structure, as shown in Fig. 8. Another method of predetermining the amount of braze filler more precisely is the use of all-metallic braze foil, which can also be preplaced in the honeycomb structure (Brazcor™ honeycomb) as discussed above. However, using metallic braze foil significantly adds to cost and the complexity of manufacture so that the use of braze tape becomes the preferred method and increasingly popular.

Fatigue Cracking

Another degradation mechanism observed for brazed honeycomb is fatigue cracking in situations where mechanical loading and oxidation are superimposed such as in cyclic oxidation or burner rig testing. Figure 9 shows Haynes® 214 and MI 2100 honeycomb after cyclic oxidation at 900°C (1650°F) over 200 h. Both honeycombs were brazed with AMS 4783 BFM, which was selected for its high melting temperature to produce a high-temperature seal. While the combination MI 2100/AMS 4783 seemed to survive the cyclic oxidation well, the combination Haynes® 214/AMS 4783 showed significant deterioration in the structure and formation of cracks in the honeycomb wall metal. At higher magnification of the Haynes® 214 honeycomb, several features became apparent — Fig. 10. First of all, a thick surface oxide layer could be observed in parallel with a fair amount of internal oxidation along cracks that had formed and obviously propagated along grain boundaries of the coarsened structure of the honeycomb material.

Secondly, a high number of spherical

and needle-shaped precipitates were seen. It is worth noting that similar features were not observed for the unbrazed material in air or burner gas oxidation, which leads to the assumption that their occurrence is linked to the brazing of the structure.

Clearly, the above example shows combining a material that reflects good high-temperature oxidation resistance (Haynes® 214) with a braze material of sufficiently high melting temperature (AMS 4783) does not automatically produce a well-performing high-temperature seal. The pairing MI 2100 and AMS 4783 resulted in a much more stable seal configuration that shows good performance at up to 1100°C and only starts to deteriorate at 1200°C (2190 °F) by a mechanism initiated by diffusion of silicon from the braze filler into the honeycomb material (Ref. 3).

Summary

The performance of honeycomb structures made from alumina-forming, high-temperature-resistant NiCrAl, and FeCrAlY materials is significantly impacted by the presence of less oxidation-resistant braze filler materials necessary to join the abradable honeycomb to a supporting structure. Several failure mechanisms are observed that can be summarized as BFM-induced oxidation and/or braze filler oxidation-induced fatigue of seal honeycomb. Therefore, the need exists to develop braze filler materials with much improved oxidation resistance to provide honeycomb seal lands for use in turbine labyrinth seals at operating peak temperatures above 1100°C.

Conclusions

To improve the thermal efficiency of jet engines, there is a trend toward higher turbine entry temperatures while reducing the cooling effort. This leads to ever-increasing temperatures that honeycomb seals in the low-pressure turbine module of modern engines will have to withstand. While metallic foil alloy materials that can withstand a turbine hot gas environment at temperatures in excess of 1100°C are available, suitable braze filler materials to join seal-type honeycomb fabricated from these high-temperature-re-

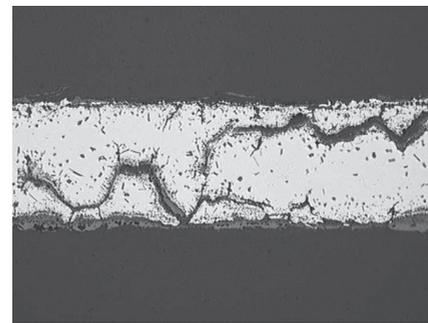


Fig. 10 — Haynes® 214 honeycomb at higher magnification showing cracks and significant deterioration in the structure.

sisting materials are not. Various degradation mechanisms of brazed seals at high temperature, all directly or indirectly linked to the presence of braze fillers with fairly limited high-temperature oxidation and hot gas corrosion resistance, can be detected. These can be summarized as braze filler metal-induced oxidation failure or braze filler oxidation-induced fatigue failure. Clearly, there is a need for more oxidation-resistant brazes for joining ultrahigh-temperature seal honeycomb.

When designing honeycomb seals for use at extreme temperatures, the influences of honeycomb wall thickness on the seal lifetime as well as compatibility of braze filler and honeycomb material need to be taken into consideration. Minimizing the amount of excess braze filler covering the seal structure must also be achieved to provide sufficient durability of the seals in high-temperature service. ♦

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