INTRODUCTION

Brunswick Corporation manufactures FELTMETAL® fiber metal products in its Deland, Florida plant. FELTMETAL® products are sheet structures made from randomly oriented fibers which are sintered to provide strength. A wide range of product properties are obtained by controlling product fiber diameter, porosity and sintering conditions. These products are used for abradable seals, acoustic media, filters, wicks, gaskets, and other applications. FELTMETAL® abradable seals are used for clearance control and improved efficiency in gas turbine engines and allow rotating engine components to cut close clearance paths in the seal material.

In February 1974, a FELTMETAL® seal product improvement program was started with two major objectives: (1) to determine the optimum density and tensile strength for each abradable seal application and, (2) to investigate, improve, and control the overall manufacturing process so that products could be offered to customers with greatly reduced tolerance in density and tensile strength. This report presents the results of a laboratory rub test program conducted to accomplish major objective #1.

A rub test program to evaluate improved FELTMETAL® seal material for both blade tip and knife edge applications was initiated. The program was started after discussions at Pratt and Whitney Aircraft and the Airline Maintenance Centers indicated a desire for a more uniform and more abradable FELTMETAL® seal that would permit tighter operating clearances. Advanced commercial and military engines will also be designed with closer clearances than the current designs. Therefore, a need exists for abradables that will sustain rubs through arcs greater than 60° to 80° being experienced with current designs. This is particularly true for inner knife edge seals where 360° rubs were desired to achieve higher operating efficiency and thrust/weight ratio. A 360° rub is a much more severe blade and knife edge wear situation than a partial rub because of the lack of tip cooling which occurs during the non-rub portion of a partial rub. To provide conservative specifications for current engines and suitable abradables for advanced engines, it was decided to conduct this program with 0.020 in. (0.5 mm) deep 360° rubs with both knife edges and blade tips. The rub speed selected was 800 ± 0 ft/sec (243 ± 3 m/s) which is typical for high compressor seal applications.

The FELTMETAL® seal product specifications define a minimum and maximum tensile strength and a minimum and maximum density. Together, these requirements establish four combinations of extreme density and tensile strength. The purpose of this program was to establish which of these four combinations or the possible intermediate combinations results in the seal material characteristics of optimum abradability and erosion resistance. It is known from particulate erosion rig tests that erosion resistance of fiber metal is directly proportional to product strength. Fiber metal tensile strength is directly proportional to an exponential function of density.
and to the severity of the sintering process. It follows that an ideal abradable seal (i.e., one which is simultaneously sufficiently abradable and sufficiently erosion resistant) is bounded by a window of tensile strength and density.

This report describes the rub test program that was conducted to form the basis of the product specification changes that were required to provide more uniform and more abradable FELTMETAL seal material. In June 1976, the FELTMETAL seal specifications for 19% dense material (FM-515B, FM-521B) and 21% dense (FM-509D) were revised to reflect tighter tolerances. FELTMETAL material made to the new specifications is being identified as FELTMETAL fiber metal III. An improvement in abradability was obtained with these specification changes by reducing maximum product strength. Minimum product strength remains unchanged to maintain present erosion resistance.

EQUIPMENT AND PROCEDURES

Test Equipment

The test apparatus consists of an air turbine which drives a disc containing the rotor element (knife edge or blade tip) to be tested. The abradable test specimen is mounted on a motorized table which moves it at a controlled rate and to a controlled depth of penetration into the rotor test element. The turbine can be operated up to 48,000 rpm which corresponds to a surface velocity of the rotor test element of 1000 ft/sec (305 m/s). The system is entirely enclosed by a burst shield while the turbine is running. The abradable position, the disc speed, and the axial force transmitted through the abradable are obtained with these specification changes by reducing maximum product strength. Minimum product strength remains unchanged to maintain present erosion resistance.

Test Procedure

The rub test abradable sample is weighed on an analytical balance and its volume is measured via length, width, and thickness measurements. From these, its density, relative to the 100% dense alloy from which it is made, is calculated. The tensile test specimens are divided into 8 in. long x 1/2 in. wide (203 x 12 mm) pieces and the weight density of these is determined as outlined above. The breaking strength of these specimens is measured on an Instron tester and tensile strength is calculated based on the actual cross sectional area of the specimen. The average of eight values is considered to be the tensile strength of the rub test specimen. Tensile strength is measured in the longitudinal direction. The rub test sample is epoxy bonded to a mounting plate and holes are drilled in the sample to provide air flow to minimize differential pressure forces generated in knife edge tests. This sample and backing plate composite is weighed on a Mettler balance and then attached to the motorized table of the rub rig. The recording transducers and the table motion are calibrated.

The knife edge insert is weighed on an analytical balance and installed into the test disc (shrink fit using liquid nitrogen bath). Height measurements are taken at five places around the circumference of the knife edge to be used in determining the amount of wear which occurs during a test.

Blade tip rub tests use a rotor configuration with blade tip inserts. The blade tip inserts are also weighed on an analytical balance and measured with a micrometer prior to testing. With the inserts installed, the test rotor is mounted on the drive spindle.

The motorized table is brought to a position leaving .010 in. (.25 mm) clearance between the abradable sample surface and the insert rub surface. The rotor speed is increased to the desired level of rotor element surface velocity and the motorized table is advanced at the desired rate to the desired depth of penetration. During this time - the rotor speed, table position, and the axially transmitted force are recorded on a Brush pen recorder.
The test measures the amount of insert wear and the depth of abradable penetration. The inserts and sample are weighed. Visual and metallographic inspections of the test results are conducted as required. The results are based on the test conditions used. Test conditions and test conditions used are listed at the bottom of the tables of results.

Table 1: Knife Edge Rub Test Data

Table 2: Knife Edge Rub Test Data

Table 3: Blade Tip Rub Test Data

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Table 1: Knife Edge Rub Test Data

Table 2: Knife Edge Rub Test Data

Table 3: Blade Tip Rub Test Data
Preliminary testing with the 360° knife edges showed poor reproducibility with both very poor (high rub energy and knife edge wear) and good rub characteristics. It was found that a low air pressure condition was created between the rotor and the abradable test sample as the clearance between the two approached zero. This low pressure created a force on the sample which was mounted in an axial anti-friction bearing (for force measuring purposes). The entire sample holding assembly is dead weight loaded to provide positive location of the assembly against a load cell. It was found that the pressure force in some cases exceeded the dead weight loading and, therefore, acted to pull the sample into the rotor, probably at a very high rate of penetration. Through-holes were introduced in the sample to vent the low pressure cavity to atmosphere and additional dead weight loading was added. These measures insured an adequate force margin and subsequent testing resulted in repeatable performance with identical test conditions.

The data summary for knife edge tests with Hastelloy X seal material is presented in Table 1. The data in Table 1 are arranged in the order of increasing tensile strength rather than chronological order to facilitate the evaluation of the results by the reader. In most cases, except for the highest strength samples, there was no knife edge wear; therefore, other parameters were used to evaluate the effect of density and tensile strength on abradability. These included rub energy, torque, discoloration and burnishing of the knife edge track in the abradable seal sample, and the length of the discolored portion of the knife edge.

Evaluation of all these results in Table 1 shows that the sample density per se is not an important factor in predicting abradability, whereas, there is a good correlation of the results with the tensile strength of the sample. Although there is considerable scatter in the normal force, torque, and rub energy data, there appears to be an exponential effect of fiber metal tensile strength on these results. This exponential effect for rub energy is shown in Figure 4 where the data suggests a linear relationship when plotted on semi-log paper.

Duplicated tests to show the effect of different knife edge materials were made with four abradable samples by rubbing both 302 SS and Waspaloy knife edges into the same sample. In each case, a somewhat more severe rub was experienced with the Waspaloy than with the Type 302 SS knife edge. This is surprising in light of the greater high temperature strength of Waspaloy. It is believed that this is the result of the Waspaloy alloy having a lower melting range than the Type 302 SS and that in transitional or heavy wear rub situations, the Waspaloy knife edge will reach its melting point quicker.

All rub tests are classified in Table 1 as "good rubs", "transitional rubs", and "moderate to heavy wear" depending upon knife edges. Photographs of the seal samples for typical good and bad rubs are shown in Figures 5 and 6. Based on the knife edge wear and appearance, the maximum allowable tensile strength for FM-515 has been reduced from 2650 psi (18.2 MPa) to 1800 psi (12.4 MPa) in the new FEMLMETAL® fiber metal III specification for FM-515B.

<table>
<thead>
<tr>
<th>ULTIMATE TENSILE STRENGTH, MPa</th>
<th>RUB ENERGY, FT-LB/IN²</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.4</td>
<td>0.000</td>
</tr>
<tr>
<td>6.9</td>
<td>165 (X)</td>
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<tr>
<td>10.3</td>
<td>3000</td>
</tr>
<tr>
<td>13.8</td>
<td>68000</td>
</tr>
<tr>
<td>17.3</td>
<td>173000</td>
</tr>
</tbody>
</table>

Figure 4 Effect of tensile strength on rub energy-knife edge rubs

Figure 5 Test #209 - Typical of good knife edge tests

Figure 6 Test #204 - Typical of bad knife edge tests
A minimum of 1000 psi (6.9 MPa) has been set based on engine field data concerning seal material erosion. Future plans include the development of an erosion test procedure to permit laboratory evaluation of the effect of tensile strength on erosion resistance.

Haynes 188 Seal Material. A complete set of test data for knife edge rub tests with Haynes 188 fiber metal is contained in Table 2 and a graphical presentation of the tensile strength and density combinations tested relative to the old and new specifications is shown in Figure 7. As with the Hastelloy X data, the normal force, torque, and rub energy required for the Haynes 188 knife edge rubs appear to be exponential functions of the tensile strength. This relationship for rub energy is shown in the semi-log plot in Figure 4 along with the Hastelloy X data. The data in Figure 4 and Table 2 indicate that the Haynes 188 fiber metal is a better abradable and that a lower energy is required at a given tensile strength with this material. From the data presented here, it is not clear whether this is the result of the alloy differences or a different fiber diameter and length with the Haynes 188 material.

![Graph of Density vs. Tensile Strength for Haynes 188 Seals](image)

Figure 7 Effect of density on tensile strength of Type A Haynes 188 FELTMETAL® seals

As with the Hastelloy X data, the Haynes 188 knife edge rubs are classified in Table 2 in the order of increasing tensile strengths. The severity of wear and appearance of the knife edge and seal sample increased with increasing tensile strength. Although the data indicate that a maximum tensile strength of 2100 psi (14.5 MPa) can be used before getting into a transitional or heavy wear situation for knife edge rubs, it has been decided to reduce the specified maximum tensile strength for FM-521 from 2650 to 1900 psi (18.2 to 13.1 MPa).

**Outer Air Seal (Blade Tip) Test Results**

**Hastelloy X Seal Material.** The initial test was conducted with an insert which simulated a blade tip rubbing surface 0.5 in. wide x 0.06 in. thick (12.7 x 1.5 mm). The turbine power was insufficient to drive the rotor reliably at the desired test speed. The insert was modified to 0.25 in. (6.3 mm) wide and six preliminary tests were conducted. These tests indicated rub results that were non-repeatable and grossly inconsistent with known engine performance data. It was concluded that the rigidity of the blade in the disc and the angle of the blade tip relative to the abradable were causes of the inconsistencies observed. Tests were evaluated with improved rub results with blade tip rub surface geometries in which a 70° relief angle was used, as in machine tool technology. From discussions of these test results with individuals involved in gas turbine engine gas path sealing at Pratt and Whitney Aircraft, it was decided that a reduction of the blade tip thickness from 0.06 in. to 0.02 in. (1.5 to 0.5 mm) and a change of material from Waspaloy to Incoloy 901 would result in a more representative blade tip model. It was also felt that the loose fit retention of the preliminary blade mounting in the disc which relied on centrifugal loading of the insert for stiffness did not present the blade tip rub surface to the abradable in a consistent manner. Consequently, the blade tip insert retention was redesigned and the insert material was changed to Incoloy 901.

The data summary for blade tip tests with Hastelloy X seal material is presented in Table 3. A graphical presentation of the tensile strength and density combinations is shown in Figure 8 relative to the old FM-509A and the new FELTMETAL® fiber metal specification, FM-509D for outer seal material for blade tip rubs.

![Graph of Density vs. Tensile Strength for Hastelloy X Seals](image)

Figure 8 Effect of density on tensile strength of Type A Hastelloy X FELTMETAL® seals

The Hastelloy X blade tip data shown in Table 3 are arranged in the order of increasing tensile strengths. These tests were classified according to "good," "transitional" and "heavy wear" rubs. The blade tip wear was light (less than 0.001 in., .025 MPa) or nonexistent until the tensile strength was increased to 2460 psi (17.0 MPa) in test No. 251 where the maximum blade wear observed was
only 0.0011 in. (.028 mm); so this was classified as a transitional rub. Only in test No. 242, with a fiber metal tensile strength of 2489 psi (17.2 MPa), was heavy wear observed. Because of the lack of wear, the "good" and "transitional" rubs were evaluated with the aid of the measured rub energy and the appearances of both the two blades and abradable specimens. Evaluation of these results presented in Table 3 leads to the same conclusion that was obtained from the knife edge results that the tensile strength and not the density of the abradable sample is the important criterion for predicting the abradability of fiber metal seals.

As with the knife edge results, the normal force, torque, and rub energy increase exponentially with tensile strength. The effect of tensile strength on rub energy is shown in Figure 9 where the data yield a straight line when plotted on semi-log paper. Comparing Figure 9 with Figure 4 shows that there is significantly less energy used (less heat generated/unit volume of abradable removed) for blade tip rubs than for knife edge rubs. Consequently, a higher strength fiber metal can be used for an outer blade tip seal (for more erosion resistance) before a poor rub situation occurs. It is believed that this is the result of more frictional heat being generated with knife edges.

![Photographs of the seal samples for typical good and bad rubs are shown in Figures 10 and 11.](image)

**Figure 10** Test #247, typical of good blade tip test

**Figure 11** Test #242, typical bad blade tip test

Photographs of the seal samples for typical good and bad rubs are shown in Figures 10 and 11.

The maximum recommended tensile strength of 2200 psi (15.2 MPa) was established for FM-509D for blade tip rub applications based on the increase in blade tip wear and on the appearance of the rub groove of higher tensile strength samples.

![Ultimate Tensile Strength, MPa](image)

**Figure 9** Effect of tensile strength on rub energy-blade tip rubs

<table>
<thead>
<tr>
<th>ULTIMATE TENSILE STRENGTH, MPa</th>
<th>10.3</th>
<th>13.8</th>
<th>17.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>SYMBOLES</td>
<td>□</td>
<td>×</td>
<td></td>
</tr>
<tr>
<td>HASTELLO X SEALS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HAYNES 188 SEALS</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 3**

The effect of tensile strength on rub energy requirements for Haynes 188 seals was equivalent to the Hastelloy X data for blade tip rubs. Here again, an exponential relationship is indicated by the straight line relationship on semi-log paper in Figure 9.

Based primarily on the blade wear data shown in Table 3 and a comparison of the Haynes 188 blade tip data relative to the Hastelloy X blade tip rubs, a maximum tensile strength of 2400 psi (16.5 MPa) is recommended for a new FM-522A specification for blade tip applications where more erosion resistance is required than is provided by the lower density (19% nominal) FM-521B. Currently, Haynes 188 products are being used where a little higher oxidation resistance (50°F more) is required than is provided by the Hastelloy X FELTMETAL® seals.

**CONCLUSIONS AND RECOMMENDATIONS**

1. Tensile strength rather than density is the predominant parameter in determining the abradability of FELTMETAL® seal material.
2. There is a threshold tensile strength for knife edge seals beyond which knife edge wear increases rapidly for 360° rubs. This threshold strength is 1800 psi (12.4 MPa) for Hastelloy X seal material and 2100 psi (14.5 MPa) for Haynes 188 material.

3. The similar threshold tensile strengths for blade tip seals for 360° rubs are 2200 psi (15.2 MPa) for Hastelloy X and 2400 psi (16.5 MPa) for Haynes 188 material. This threshold strength for blade tip applications is much less distinct than the one for knife edge applications and exhibits itself as a gradual change from good abradability to poor abradability.

4. Slightly improved abradability was observed using Type 302 SS relative to Waspaloy knife edges. This may be related to the melting points of the two alloys.

5. Improved abradability of Haynes 188 fiber metal relative to Hastelloy X fiber metal was obtained for both knife edge and blade tip rubs. It is not known whether this is the result of alloy differences or differences in fiber diameter and length.

6. The measured strength limitations are considered conservative for most engines since they do not rub at any one time through a 360° arc. However, they should be considered for upper strength limitations for advanced engines that may be designed so tight that 0.020" (0.5 mm) deep 360° rubs will be experienced.

Product specifications were revised to incorporate the strength limits for good abradability defined in this program. Concurrent processing improvements were also introduced to allow the FELTMETAL seal products to be produced to the tighter specifications. Current product specifications are:

<table>
<thead>
<tr>
<th>PRODUCT</th>
<th>ALLOY</th>
<th>APPLICATION</th>
<th>DENSITY</th>
<th>UTS RANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>FM-5158</td>
<td>HAST, X</td>
<td>KNIFE EDGE SEAL</td>
<td>18 - 20</td>
<td>1800 - 1900 (12.4 - 13.1)</td>
</tr>
<tr>
<td>FM-5213</td>
<td>HAYNES 188</td>
<td>KNIFE EDGE SEAL</td>
<td>18 - 20</td>
<td>1100 - 1900 (7.6 - 13.1)</td>
</tr>
<tr>
<td>FM-5090</td>
<td>HAST, X</td>
<td>BLADE TIP SEAL</td>
<td>20 - 22</td>
<td>1500 - 2200 (10.4 - 15.2)</td>
</tr>
<tr>
<td>FM-522A</td>
<td>HAYNES 188</td>
<td>BLADE TIP SEAL</td>
<td>20 - 22</td>
<td>1400 - 2400 (9.7 - 16.5)</td>
</tr>
</tbody>
</table>

Future work in this program includes modification of the rub rig to provide constant speed operation and direct torque measurement to facilitate analytical comparison of materials in good rub situations. An erosion test program should be conducted to better define the lower strength limits for the various seal products. Also, additional work on the effects of fiber morphology on abradability is recommended.