Soft Magnetic Alloys for High Temperature Radial Magnetic Bearings

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Abstract
Magnetic bearings are a prime technology that will lead the next generation of gas turbines into the 21st century. Before magnetic bearings can be utilized, fundamental properties of the soft magnetic materials used to fabricate these components must be known at the intended operating temperatures and stress levels found in gas turbine applications. This paper present result of recent work carried out on the development of a radial magnetic bearing for a high speed, high temperature gas turbine application. Mechanical and magnetic data on candidate soft magnetic materials intended for use in a radial magnetic bearing were characterized at both room and operating temperature (550C). The effect which long-term exposure to high temperature has on these properties was also tested. The effect of heat treatment schedule and atmosphere were examined as to their effect on both the magnetic and mechanical properties of the materials for the short and long term exposure to this extreme environment. The use of the material data accumulated was utilized for the development of the radial bearing is explained along with a proposed design of a radial magnetic bearing.

Introduction
A magnetic suspension system relies on numerous components to be correctly matched in-order to function properly. At the operating conditions inside a gas turbine, both magnetic and mechanical properties of the materials must be known both at room and operating temperature. The soft magnetic materials chosen are alloys of iron-cobalt. The room temperature properties of the popular alloy Hiperco 50 are well known and documented (1) from its long-term use in high performance electro-mechanical devices. This material is usually chosen for the stator of the magnetic bearing. The development of a high strength version of this alloy, Hiperco 50-HS, was developed for use in high stress rotor designs. The properties of this alloy have been found to be very sensitive to heat treatment schedule and temperature (2). An alternative to Hiperco 50-HS is Rotelloy 5, which has properties similar to Hiperco 50-HS both in yield strength and magnetic properties but with a different set of elements added for manufacturing purposes (3,4). Table I list the basic properties of these soft magnetic materials. This paper describes the work carried out to characterize both magnetic and mechanical properties at room and elevated temperatures.

Material Tests
Magnetization curves (B-H plots) characterize magnetic properties of materials. A typical plot for a soft magnetic material is shown in Figure 1. Several important parameters are associated with this plot. One is the maximum value of the flux density (B), Bsat. Another is the value of magnetic field intensity (H) at which the flux density levels off. The area of the plot inside the top and bottom curves is a measure of loss in the material due to hysteresis. The relation of the flux density to the magnetic field intensity is written as:

$$B = \mu H$$

$$\mu = \mu_r * \mu_o$$

The value of H at which B levels off is important when a material is chosen in an electro-magnetic design. It is at this value where the relative permeability of the material (μ_r) changes and as more energy is added (H), little increase in flux density (B) is obtained. The ideal material would have a B-H plot that reaches its Bsat at a low H and has little to no hysteresis. Most materials need to be tested to determine their magnetic characteristics before a design can be analyzed.
Magnetic testing the samples at high temperatures requires the use of special wires and coatings. Ceramic-

coated copper wire, with high temperature potting materials, was utilized to meet this requirement. Figure 2 shows the sample developed for these temperatures (550C). The ring sample contains both primary and secondary windings, which are connected to a Walker Scientific AMH-20, used to perform the tests. Figure 3 shows the test sample sequence.

Mechanical properties of these alloys at room temperature are known, but the effects that long term exposure to high temperatures has on these properties is unknown. At this time, we are not able to test tensile specimens at the high temperatures. While this is a limitation, the stability of the material when exposed to high temperatures can be determined from testing samples before (Tp1) and after (Tp3) exposure. Figure 4 shows the tensile samples used to test the mechanical properties of these materials. The tensile samples were both laser cut and machined parallel and perpendicular to the roll direction. No samples were tested in the 45-degree direction. After the samples were fabricated, they were de-burred and all sharp corners and edges were removed to reduce the occurrence of stress risers in the transition zone. The samples were solvent cleaned and heat-treated. After heat treatment, a group of the tensile specimens were exposed to the schedule in figure 3. The tensile specimens, both exposed and the ones left at room temperature were pulled to failure on an Instron model 1125. The pull rate for all tests were .125 mm per minute for the first 1.25 mm of deflection and 1.25mm per minute afterwards.

Stator Material Tests

Hiperco 50 was the only material tested for use as the stator material. The material was heat treated at 760C for two hours in a high vacuum environment. Figures 5 to 7 are the Tp1, Tp2 and Tp3 results. The testing showed its properties did not change during or after exposure to the high temperature environment. No mechanical tests were carried out at this heat treat condition.

Rotor Material Tests

Three alloys were examined for use as rotor material. The materials were Hiperco 50-HS, Rotelloy 5 and Hiperco 50. The Hiperco 50-HS samples were heat treated at two different temperatures in both high vacuum and hydrogen environment. The Hiperco 50 was heat treated at three different temperatures, different from the stator heat treatment schedule, all in a high vacuum environment. Rotelloy 5 was heat treated at one temperature in a high vacuum environment. The reason for these different heat treatments was to attempt to achieve the best mechanical properties with satisfactory magnetic properties.

Figures 8 to 10 and Figures 11 to 13 are B-H plots for Hiperco 50-HS, and Rotelloy 5 respectively. Both Hiperco 50-HS and Rotelloy 5 had changes to their magnetic properties at Tp2. This can be seen by examining the H required to raise the flux density in the material to 2 Tesla (20 kGauss). At Tp1, approximately 40 Oersted is required to raise both materials to 2 Tesla. At Tp2, approximately 100 Oersted is required to reach the same flux density. At Tp3, Rotelloy 5 recovers better than the Hiperco 50-HS to the original conditions, requiring 50 Oersted to reach 2 Tesla to 70 Oersted for Hiperco 50-HS.

Figure 14 is a typical stress-strain curve obtained from the tensile tests. Figures 15 and 16 are a summary of tensile tests for both parallel to and perpendicular to the roll direction. Heat treating the Hiperco 50 at 705C instead of the traditional 760C produced yield strengths greater than the initial strengths of Rotelloy 5 and Hiperco 50-HS heat-treated in vacuum. Hiperco 50-HS when heat-treated in hydrogen produced superior results than the vacuum heat treatment. While the yield strength of Hiperco 50-HS dropped slightly after exposure, the yield strength of Rotelloy 5 increased. This data has been reproduced with additional samples.

Radial Magnetic Bearing Modeling

The results from the mechanical and material testing are utilized for the design of a radial magnetic bearing actuator. Figure 17 shows a radial actuator intended for a gas turbine application. The desired force capacity of the bearing is 2,000 newtons at a speed of 35,000 rpm. Calculations for rotor growth due to centrifugal force and temperature were performed using Excel spreadsheets (3) based on work by Den Hartog (5) for both Hiperco 50-HS and Rotelloy 5 at room and operating temperature (550C). With a .05 mm radial interference between the support rotor outside diameter and the magnetic bearing rotor's inside diameter, the maximum stress is 290 mPa using Rotelloy 5 while using Hiperco 50-HS a stress of 275 mPa is calculated for room temperature operation. The stresses increase to 390 and 350 mPa respectively for an operating temperature of 550 C.

The mechanical data for the alloys in Table I is used to determine the change in the air gap between the stator poles and the rotor due to both temperature and speed changes. With a starting air gap of .38mm, the gap decreases to .34mm for the Hiperco 50-HS rotor at 35,000 rpm and to .35mm for the Rotelloy 5 rotor. The gaps will remain the same for either materials at room temperature or 550C operation at a given speed. The change in mechanical properties at the extreme temperatures has little change on the growth of the rotor outside diameter. Since the coefficient of thermal expansion of the two rotor materials are approximately equal to the material used in the stator, the gap change due to temperature changes will be negligible.

The magnetic data, along with the change in air gap, is use to determine the amount of NI required for each pole to reach the desired B level. The results obtained from the magnetic testing of the material were used in non-linear magnetic finite element runs. Figure 18 shows a plot of a model for the maximum force condition of the bearing shown in figure 17 using Hiperco 50 for the stator and

Hiperco 50-HS for the rotor with a gap of .38mm and a maximum flux density level of 1.5 Tesla. While the gap does not change at temperature for a given speed, the permeability of the material will change. This has only a minor effect since the air gap is the source for the highest resistance in the magnetic circuit. At room temperature, with Hiperco 50 for the stator and Hiperco 50-HS for the rotor, the NI reduces from 475 to 420 for a change of 0 to 35,000 rpm. Using Rotelloy 5 for the rotor, the NI changes from 455 to 425 for the same conditions. At a temperature of 550C, the NI is within 10 for the same speed from the room temperature value.

Discussions and Future Plans

The test results of the magnetic materials when combined with finite element modeling produced some interesting results. While the change in permeability of magnetic material appears large, the overall affect it has on the magnetic circuit is small. The change in gap at the various speeds will change the required NI more than the change in temperature. This has an impact on the overall control system and power amplifier design that must take these changes into account for a suspension system to operate successfully. The differences in mechanical properties of the two rotor alloys have a much bigger impact on the design than the stator material. Rotelloy 5 when used as a rotor material, experiences higher hoop stresses than Hiperco 50-HS for the same conditions. The ratio of their individual calculated stresses to their measured yield stress is lower for Rotelloy 5 than Hiperco 50-HS. This should translate into a rotor design with a higher margin of safety when Rotelloy 5 is used.

One question that has not been answered is the long-term effect of combined stresses and temperature on the material properties. This work is presently being carried out. Additional work is under way to develop a facility at Draper Laboratory for the high temperature testing of materials on the Instron. Once these results have been obtained, they will be used to verify the future designs of high speed and high temperature magnetic bearing designs.

Nomenclature

B	Flux Density	Tesla
Bsat	Saturation Flux Density	Tesla
H	Magnetic field intensity	amp / meter
I	Current	amp
N	Number of turns	
μ	Permeability	henry / meter
μo	Permeability of free space $4\pi\ 10^{-7}$	henry / meter
μr	Relative Permeability	

1 Tesla	=	10,000 gauss (G)
1 Tesla	=	1 Wb / meter^2
1 henry	=	1 Wb / amp
1 amp / meter	=	.01257 Oersteds (O)

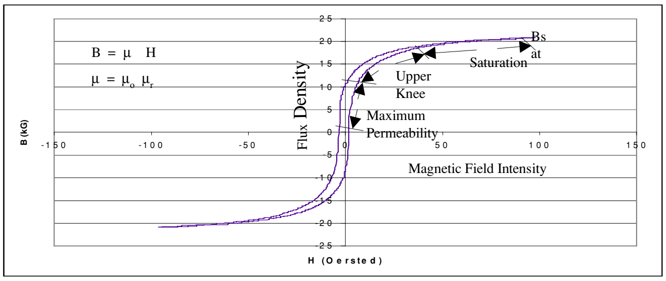
References

1. Bozorth, R. M., "*Ferromagnetism*," 8th Printing, D. Van Nostrand Company, 1951.
2. Kelleher, W. P. & Kondoleon, A. S.,"*A Magnetic Bearing Suspension System for High Temperature Gas Turbine Applications*," ASME Paper 97-GT-114, 1997
3. Stanley, J. K., "*Electrical and Magnetic Properties of Metals*," American Society for Metals, 1963
4. Tebble, R. S. & Craik, D. J., "*Magnetic Materials*," John Wiley & Sons Ltd., 1969
5. Den Hartog, J.P., "*Advanced Strength of Materials*," Dover Publishing, 1952

Table I Soft Magnetic Material Properties

	Rotelloy 5	Hiperco 50-HS	Hiperco 50
B_{sat} (Tesla)	2.24	2.29	2.44
Density (Kg / m^3)	8150	8120	8120
Coefficient of Thermal Expansion (10^{-6} /C) to 200C to 600C	9.5 10.4	9.5 10.5	9.5 10.5
Modulus of Elasticity (MPa 10^3) R.T. at 600C	250 210	207 155	207
Resistivity (micro ohm- m)	.26	.25	.25

Figure 1 Magnetization (B-H) Curve



B = Flux Density (Tesla)
H = Magnetic Field Intensity (Amp/meter)
μ = Permeability (henry/meter)
μ_o = Permeability of free space $4\pi 10^{-7}$ (henry/meter)
μ_r = Relative Permeability

Force ~ B^2
H = Current

	Hiperco 50	Rotelloy 3	Hiperco 50HS	Rotelloy 5
Bsat (T)	2.44	2.34	2.29	2.24
Permeability				
800 A/m (10 Oe)	2100	2100	1920	1740
4000 A/m (50 Oe)	460	455	435	430

Figure 4 Tensile Tests Specimens

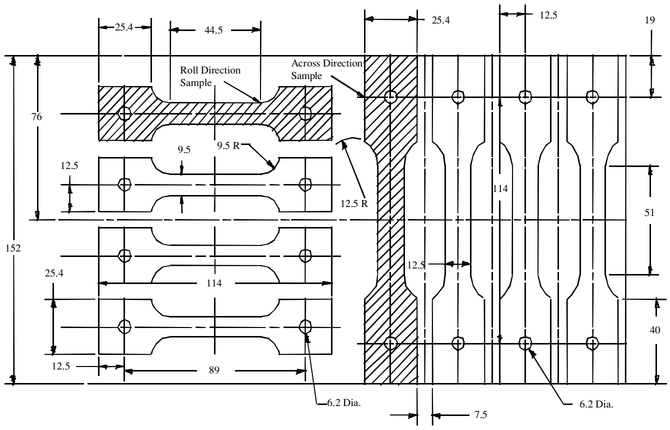


Figure 2 High Temperature B-H Test Sample

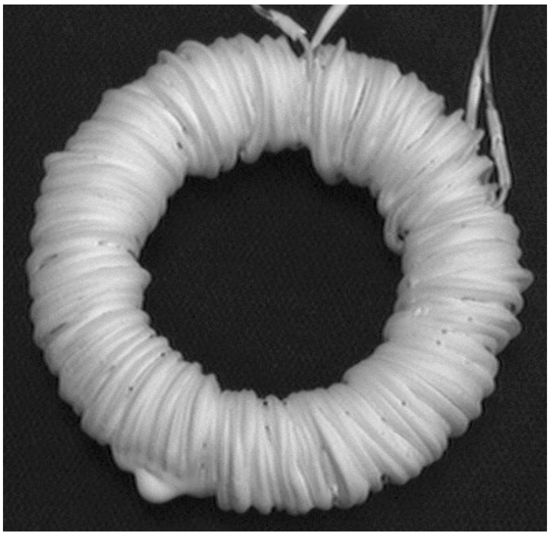


Figure 5 B-H Results Hiperco 50, Tp1

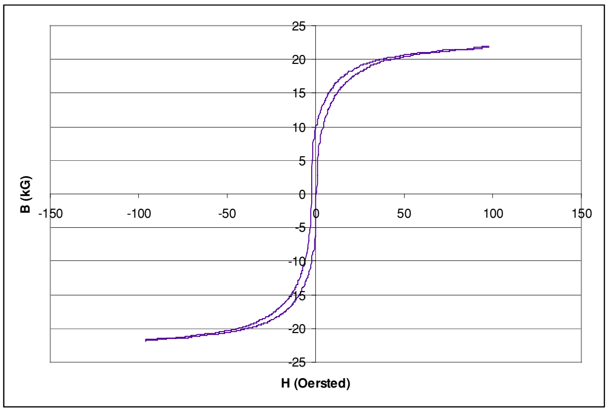


Figure 3 Material Test Profile

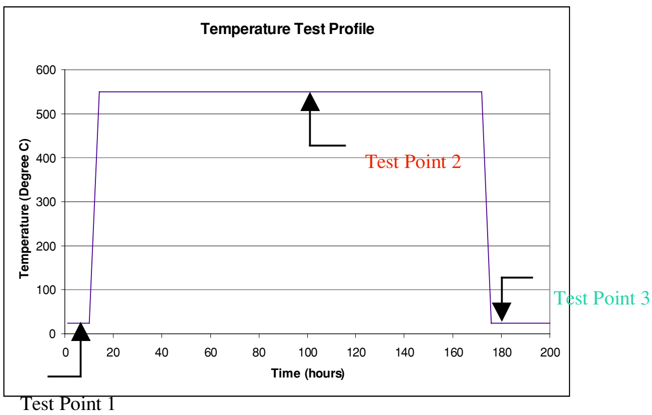


Figure 6 B-H Results Hiperco 50, Tp2

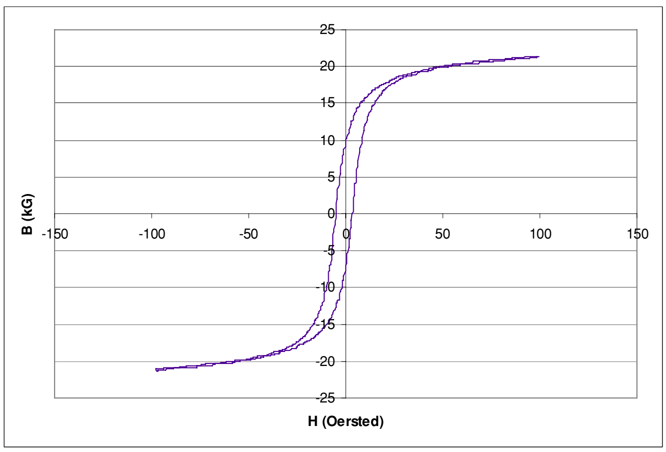


Figure 7 B-H Results Hiperco 50,Tp3

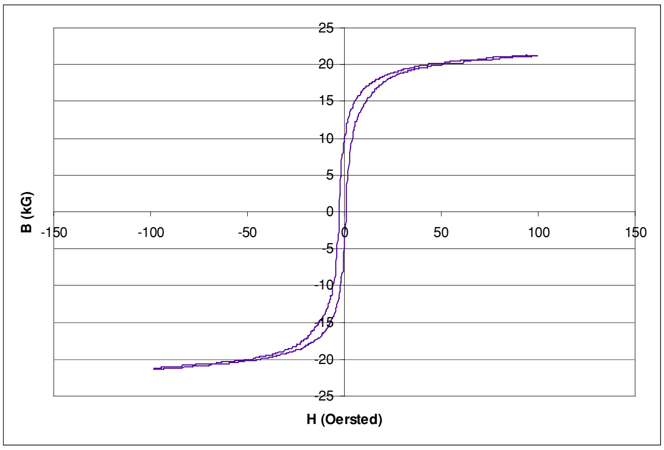


Figure 8 B-H Results Hiperco 50-HS, Tp1

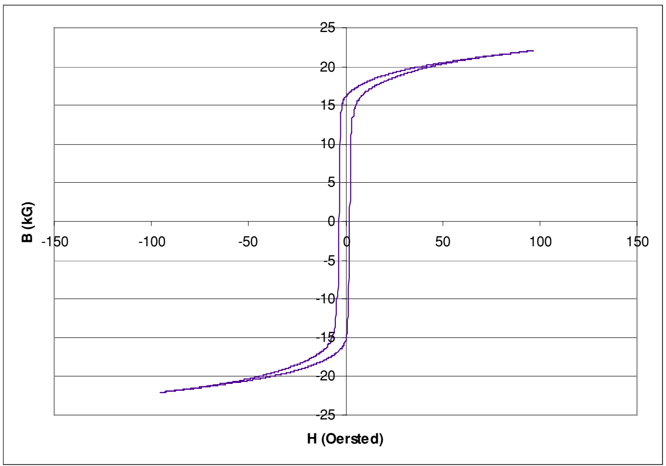


Figure 9 B-H Results Hiperco 50-HS, Tp2

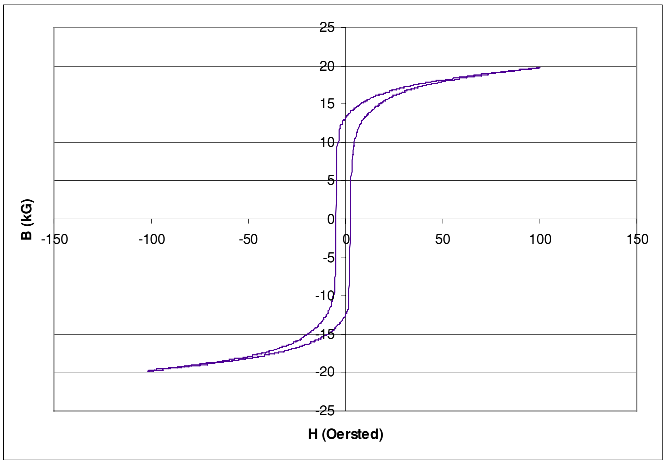


Figure 10 B-H Results Hiperco 50-HS, Tp3

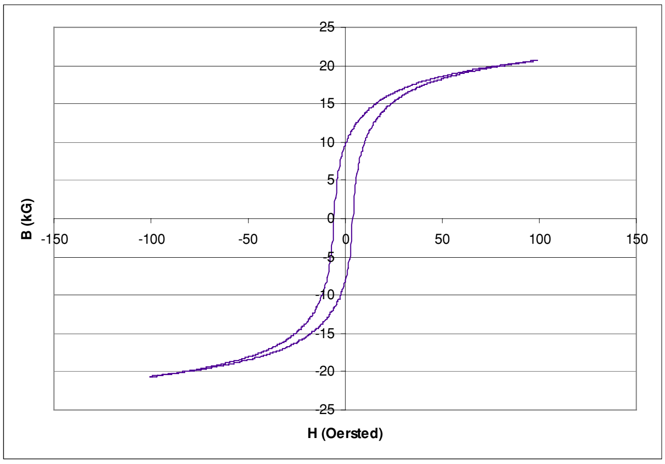


Figure 11 B-H Results Rotelloy 5, Tp1

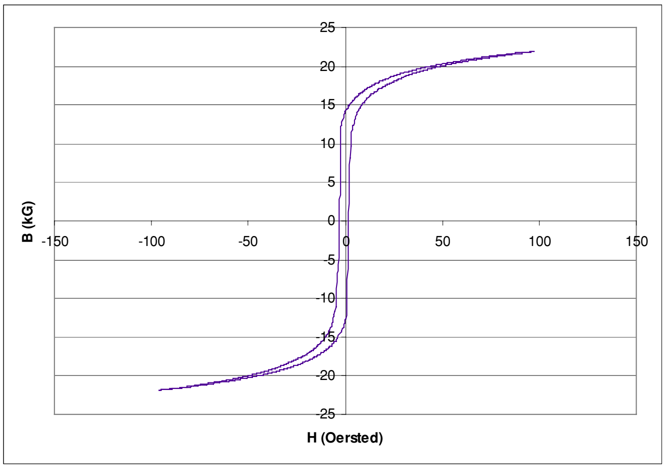


Figure 12 B-H Results Rotelloy 5, Tp2

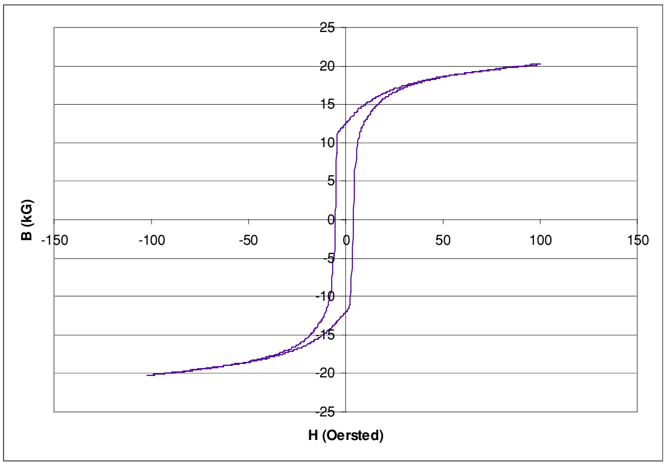


Figure 13 B-H Results Rotelloy 5, Tp3

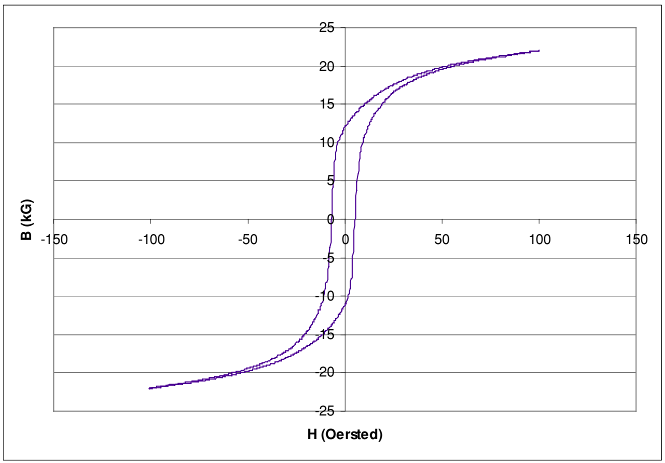


Figure 16 Tensile Test Results
Yield Strength, Roll Direction

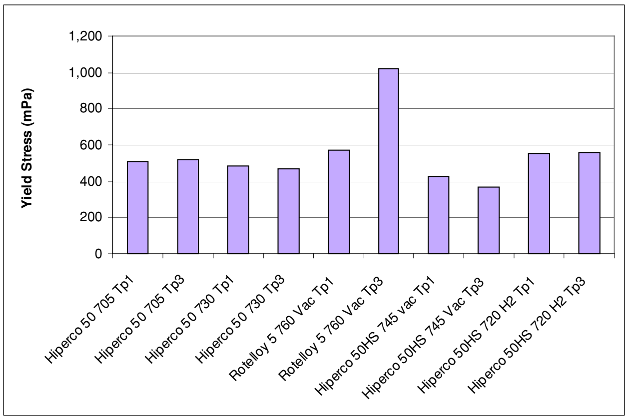


Figure 14 Typical Tensile Results, Hiperco 50-HS, Tp1

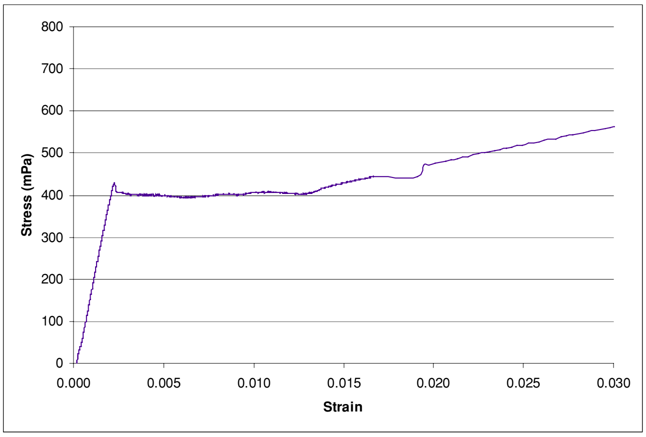


Figure 17 Radial Magnetic Actuator for a High Temperature Gas Turbine Application

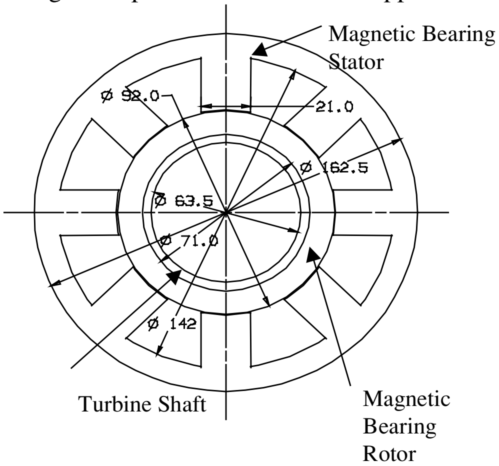


Figure 15 Tensile Test Results
Yield Strength, Perpendicular Direction

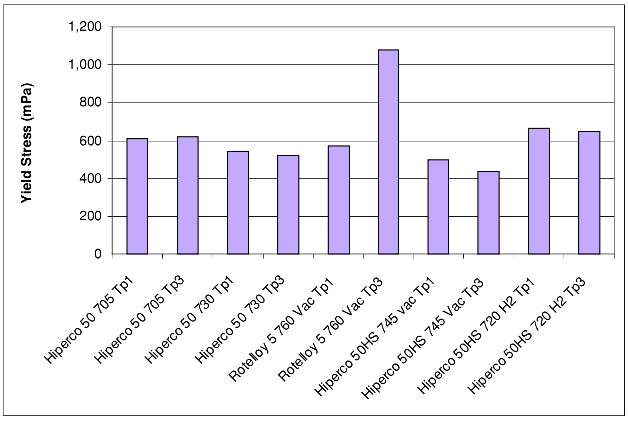


Figure 18 Non-linear FE Magnetic Model
Material, Hiperco 50 Stator
Hiperco 50-HS Rotor