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Resistivity of $Fe_{.49}Co_{.49}Ta_{.01}$ High Strength Laminates from -73C to + 650 C

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TELCON HS 50 ALLOY IS A RECENTLY DEVELOPED IRON-COBALT SOFT MAGNETIC ALLOY (50.41% Fe, 48.75% Co, 0.45% Ta, 0.27% V, 0.08% Si, 0.04% Mn) INTENDED FOR COMMERCIAL APPLICATIONS REQUIRING HIGH STRENGTH. ITS PHYSICAL, ELECTRICAL AND MAGNETIC PROPERTIES HAVE NOT YET BEEN REPORTED OVER THE OPERATING TEMPERATURES OF INTEREST. THIS REPORT ADDRESSES THE RESISTIVITY TESTING OF THIS ALLOY IN .006" THICK STRIP PRODUCT FORM (DRY HYDROGEN ANNEALED) AND THE SUBSEQUENT CONCLUSIONS. WE TESTED THE MATERIAL IN A CRYOGENIC DEWAR FROM -73C TO 27C AND IN A FURNACE TO 650C. WE FOUND THAT AT LOW TEMPERATURES, THE RESISTIVITY OF THE MATERIAL INCREASED LINEARLY. THE COEFFICIENT OF RESISTIVITY IN THIS RANGE WAS $1.1X10^{-3}$ C^{-1}. AT HIGHER TEMPERATURES IT INCREASED FASTER THAN LINEAR. THE RESISTIVITY AVERAGED 12.18 MΩ-cm AT THE LOWEST TEMPERATURE, 13.42 MΩ-cm AT ROOM TEMPERATURE AND 45.86 MΩ-cm AT THE HIGHEST TEMPERATURE. ANALYTIC EXPRESSIONS FOR RESISTIVITY IN THE FULL TEMPERATURE RANGE OF MEASUREMENTS ARE PROVIDED. EDDY CURRENT LOSS AT ROOM TEMPERATURE IS EXPECTED TO BE 1918 W/lb FOR .006" SHEET AT 5000 Hz.

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ABSTRACT

Telcon HS 50 Alloy is a recently developed iron-cobalt soft magnetic alloy (50.41% Fe, 48.75% Co, 0.45% Ta, 0.27% V, 0.08% Si, 0.04% Mn) intended for commercial applications requiring high strength. Its physical, electrical and magnetic properties have not yet been reported over the operating temperatures of interest. This report addresses the resistivity testing of this alloy in .006″ thick strip product form (dry hydrogen annealed) and the subsequent conclusions. We tested the material in a cryogenic dewar from -73C to 27C and in a furnace to 650C. We found that at low temperatures, the resistivity of the material increased linearly. The coefficient of resistivity in this range was 1.1×10^{-3} C^{-1}. At higher temperatures it increased faster than linear. The resistivity averaged 12.18 μΩ-cm at the lowest temperature, 13.42 μΩ-cm at room temperature and 45.86 μΩ-cm at the highest temperature. Analytic expressions for resistivity in the full temperature range of measurements are provided. Eddy current loss at room temperature is expected to be 1918 W/lb for .006″ sheet at 5000 Hz.

INTRODUCTION

Silicon steels currently dominate the world of soft magnetic materials. These materials provide acceptable saturation magnetizations with relatively low hysteresis loss for their applications. They are also moderately priced. This is the main driver for their success. Fe Co soft materials are not so common however, their high cost being the main reason for their comparative rarity. The iron-cobalts provide the highest saturation (Bsat) of any soft magnetic material. They are currently available in 27% Co alloys, 36% Co alloys, and near 50-50 Fe Co alloys. Various elements can be added to boost resistivity, strength, and/or aid grain formation as necessary.

Telcon HS 50 is a near 50-50 Fe Co alloy boasting a flux density of 24.4 kGauss at 500 Oe. Telcon claims its resistivity is 10 micro-ohms-cm at room temperature.

Another factor to be considered when selecting soft magnetic materials for use in a motor or generator, is the resistivity of the alloy. This specification is necessary for estimating the eddy current losses to be expected in the operation of the motor or generator. Eddy current losses occur when the flux applied to a conductor induces a current flow in the material. The induced current diminishes the useful energy in the system and generates heat. Eddy current loss in a stack of rotor laminates (see Figure (1)) is calculated for the low frequency case using the following equations[1,2]:

$$P_e = \frac{\pi^2 t^2 B^2 f^2}{6\rho}\left(W/_{m^3}\right) \quad (1)$$

$$P_e\left(W/_{lb}\right) = \frac{1}{(2.205)d} P_e\left(W/_{m^3}\right) \quad (2)$$

In these equations, t is the laminate thickness in meters, B is the induction in Tesla, f is the frequency in sec^{-1}, ρ is the resistivity in Ω-m and d is the density in kilograms per cubic meter. Flux penetration is complete in situations where

Equations (1) and (2) are used. Precisely what is a high frequency and a low frequency is defined in terms of a frequency dependent penetration depth given by:

$$\delta = \sqrt{\frac{\rho}{\left(\frac{\pi f}{2}\right)\mu_0 \mu}} (meters) \quad (3)$$

Here δ is the penetration depth in meters, μ_o is the permeability of free space ($4\pi \times 10^{-7}$ in SI or rationalized MKS units) and μ is the relative permeability. A representative value of μ was determined to be 2800 for this material by R. Strnat[3] using a toroidal solenoid with a core consisting of laminate ring stacks as per ASTM A927/A927M-94[4]. Using μ=2800, δ was calculated to be $0.00492573f^{-1/2}$ meters for this material. If 2δ is large compared to the laminate thickness, Equations (1) and (2) apply as the flux completely penetrates. This is not the case for the HS 50 alloy for frequencies of interest up to 5000 Hz as δ=.0027″ for this situation (2δ is 0.9 times the laminate thickness). The eddy current loss for the high frequency case is given by Equation (4).

$$P = \left(1.258x10^9\right)\frac{B^2\rho^2 f^{1/2}}{\mu^{3/2} t}\left(\frac{W}{m^3}\right) \quad (4)$$

All of the equations given are derived for the case of a constant permeability which does not correspond to the physical situation. Other simplifying assumptions were made in order to obtain analytical expressions. At a minimum they give useful approximate functional dependencies. For thicknesses comparable to the skin depth analytical expressions are not available. However, Hammond and Sykulski[5] point out that this intermediate behavior occurs over a very limited region in the thickness or frequency and that the gap between the high frequency and the low frequency expressions can be covered by interpolation.

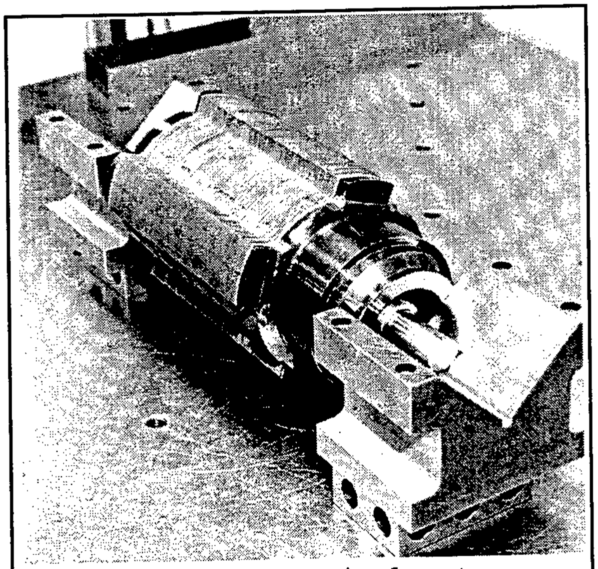

Figure 1. Typical rotor consisting of .006″ laminates oxide insulated from each other.

The direct application of Equation (4) for μ=2800 gives a value of 4.5X lower than Equation (1) at 5000 Hz for a temperature of 22C. Splicing the high and low regions together would require a value of only 1008 for μ. Going back to Equation (3), one finds that 2δ for μ=1008 would be 1.5 times the laminate thickness, a case of full penetration. Therefore, guided by Hammond and Sykulski's observation concerning interpolation, Equation (1) has been used for all subsequent loss calculations as the resistivity and thickness of the materials being considered indicate that an intermediate situation exists.

From Equation (1) we see that eddy current loss relates directly to resistivity. The eddy current loss varies inversely with resistivity. One must remember, however, that eddy current loss is only a part of the total loss the material will experience. In any given situation its significance depends on whether it is larger or smaller than another primary source of loss, hysteresis loss.

According to Telcon's data sheet[6], the alloy's resistivity is 10 micro-ohms-cm at room temperature. However, for the application we are considering, we need to know the resistivity from -73C to 450C. This range encompasses the low cold start temperature in Alaska (-54C) and the hot engine temperatures. No information was available on the resistivity throughout this range. The goal of this testing was to determine the resistivity throughout the range and calculate a coefficient of resistivity.

METHODS, ASSUMPTIONS, AND PROCEDURES

The specimens used in this testing were .600 inches long, .100 inches wide and .006 inches thick. They were electric-discharge machined in the longitudinal, transverse and 45 degree orientations with respect to the rolling direction. We then divided the specimens randomly and annealed them at three different temperatures: 1300°F, 1328°F and 1350°F in dry hydrogen for one hour. This annealing procedure is one which produces high tensile strength material in the 110 ksi range as per the Telcon data sheet. This strength results from the small grain size in the annealed material as shown in the scanning electron microscope (SEM) photo in Figure (2) for material annealed at 1350F for two hours. The average grain size is nominally one micron. Strength scales roughly as (grain size)$^{-1/2}$ per Petch's law. The specimens were designated: 1300F/90°, 1328F/0°, 1328F/45°, 1328F/90°, and 1350F/90° (anneal temp/orientation). A specimen of each anneal and orientation type was randomly selected for testing.

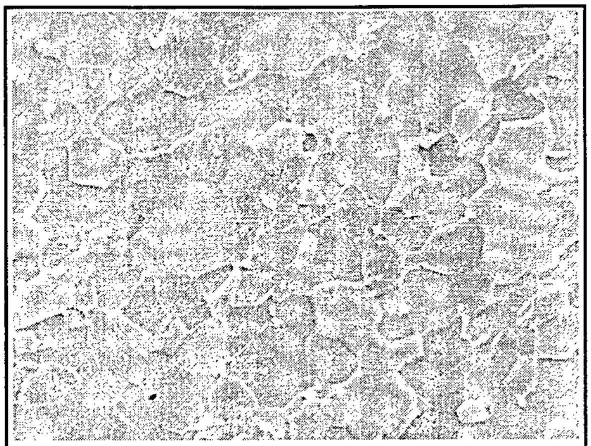

Figure 2. SEM photo of Telcon HS 50 grains, 1350F annealed for 2 hours.

The samples had a thin coat of magnesium-oxide that was sanded off with 240 grit paper. The sanding also provided a rough surface for affixing contacts. In the low temperature portion of the testing, silver paint was used to attach gold wires to the samples. In the high temperature testing, gold was sputtered onto the strips to make contacts. Next, we welded gold wires onto the contacts to make electrical connections with the specimens.

We mounted the specimens on a high accuracy test head and placed them into a cryogenic dewar cooled to -73°C with liquid nitrogen and helium. We measured each sample's resistivity in the forward and reversed directions while incrementally increasing the temperature to 27°C. Also, we performed two data runs with each sample. The first run was with no applied magnetic field. The second was with a 1.5 Tesla magnetic field applied perpendicular to the sample's plane. We had previously determined that the direction of the field did not affect the measured data. Resistance was measured using

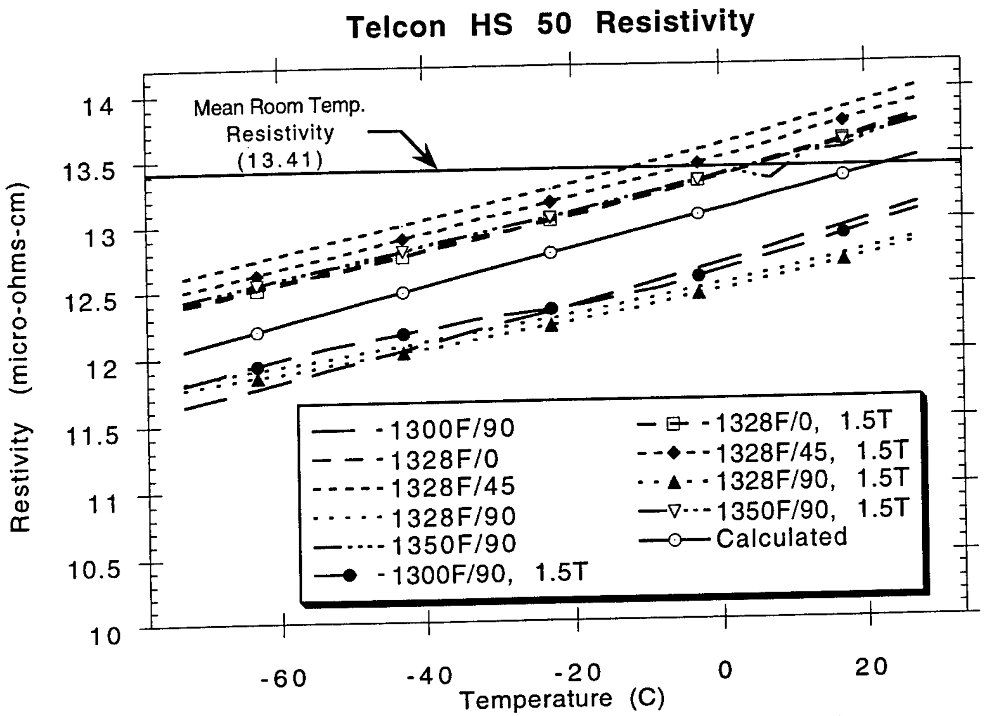

Figure 3. Resistivity of Telcon HS 50 Alloy anneals, with and without 1.5 T field applied (-73°C to 27°C temperature range).

similar methods to the four point method described in ASTM standard A712-75[7]. We took voltage measurements at five degree increments using a 50 mA current in the forward and reversed directions.

A Keithley 220 provided the current source while a Keithley 180 nanovoltmeter and 195A digital multimeter respectively measured the resistance voltage and checked the input current. A Hewlett Packard 3455A digital voltmeter measured the voltage from a platinum thermometer. A Danfysik magnet power supply applied the 1.5 Tesla field and National Instruments' Labview controlled the experiments.

We performed the high temperature portion of the testing in a dewar designed for use up to 700°C. The samples were heated in a nitrogen atmosphere by a silicon carbide heater. A Keithley 220 current source applied a 100 mA current in the forward and reverse directions. Since magnetic fields did not affect the data appreciably in the low temperature testing, none were applied in the high temperature portion. A Keithley 619 multimeter measured the voltage at three degree increments as the temperature increased to 650°C. Additional readings were taken as the sample cooled to room temperature.

RESULTS AND DISCUSSION

For the most part the results reinforced the available data on the alloy. The average resistivity with no field was 12.18 micro-ohms-cm at -73°C, 13.42 μΩ-cm at room temperature (22°C), and 45.86 μΩ-cm at 650°C. The room temperature value was slightly higher than the nominal data sheet value of 10 μΩ-

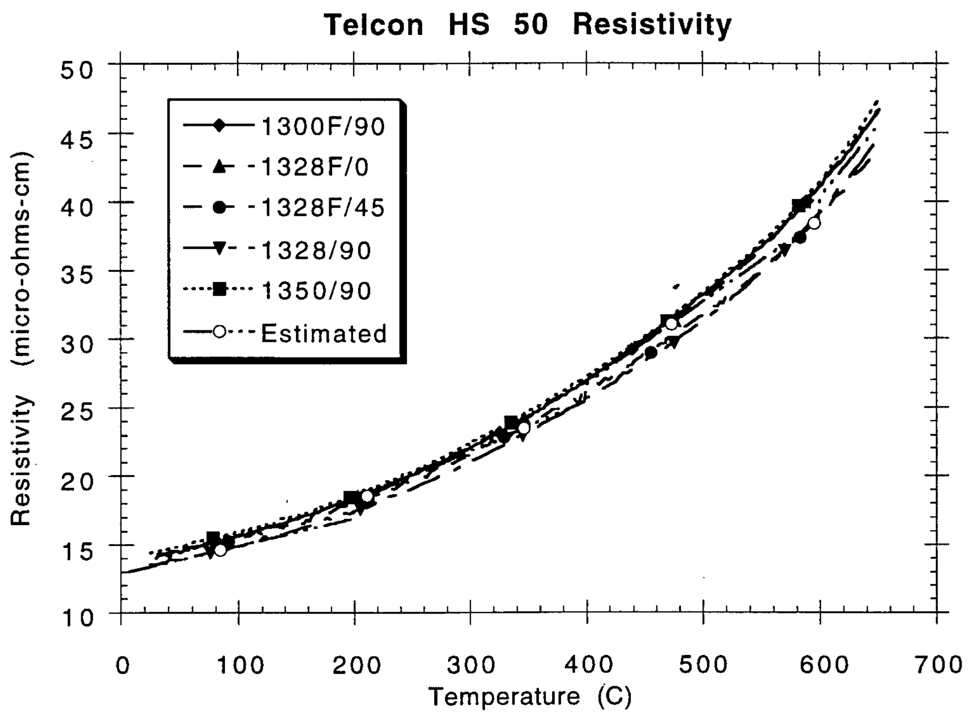

Figure 4. Resistivity of Telcon HS 50 Alloy anneals with no fields applied (7°C to 650°C temperature range).

cm. With the magnetic field applied, the average room temperature resistivity dropped slightly to 13.39. Our overall average room temperature resistivity was 13.41 +/-5% micro-ohms-cm and the coefficient of resistivity was .0011 C^{-1}. Table 1 shows the resistivities for each sample, with and without the 1.5T field. Figure (3) graphically displays the resistivity of each sample throughout the low temperature range.

Note that the resistivity in this range increases quite linearly. Therefore, in this area one can calculate the resistivity within +/-5% using[8]:

$$R_2 = R_1\left\{1+\alpha_1\left(t_2-t_1\right)\right\}(\mu\Omega-cm) \quad \text{(5a)}$$

(for t<27°C)

$$R = 13.41\{1+.0011(t-22)\}(\mu\Omega-cm) \quad \text{(5b)}$$

Table 1

	Resistivity μΩ-cm		
Sample	-73°C	22°C	650°C
1300F/90°	11.64	13.03	46.49
1328F/0°	12.40	13.69	46.67
1328F/45°	12.61	13.93	44.10
1328F/90°	11.81	12.79	44.78
1350F/90°	12.43	13.67	47.25
1.5 T field			
1300F/90°	11.80	12.91	-
1328F/0°	12.39	13.71	-
1328F/45°	12.50	13.83	-
1328F/90°	11.76	12.75	-
1350F/90°	12.43	13.67	-

Resistivity of Fe Co samples with respect to anneal temperature and rolling direction

In Figure (4) the resistivity vs. temperature over the high temperature range of interest is plotted using Equations (5b) and (6). Figure (3) shows a plot of the measured resistivities and the resistivity calculated using the average room temperature resistance as R_1 and room temperature, 22°C, as t_1. We calculated the average coefficient of resistivity (α) to be $1.1\text{x}10^{-3}$ C^{-1}.

At high temperatures, the resistivity does not vary linearly throughout the entire temperature range[9]. A discussion of this phenomenon is not attempted in this report. However, the data may be fitted directly using a polynomial to get a useful analytical expression.

$$R = 13.290 + .00425t + .00006014t^2 (\mu\Omega - cm)$$

(6) (for t>27°C)

Or, following the approach of others, the temperature range can be subdivided into zones where a linear fit can be applied. Knowing the resistivity at the baseline temperature of each of these zones, one can calculate the resistivity with Equation (5a). These zones range from -73°C to 27°C, 27°C to 200°C, 200°C to 400°C, 400°C to 600°C and 600°C to 800°C. We calculated the coefficient of resistivity within each of these linear zones.

The baseline resistivities were obtained from experimental data. Although the results of this type of calculation will not yield precise figures, the result will be useful for approximating resistivities throughout a large temperature range. The expressions we provide in this work should prove to be useful in modeling eddy current losses in advanced motor/generator designs. Equation (1) for the case of ρ=13.41 $\mu\Omega$-cm, d=8150 kg/m^3, f=5000 Hz and B=2.2 Tesla, a typical value for this material, gives an eddy current loss of 1918 W/lb. The predicted eddy current loss vs. temperature,

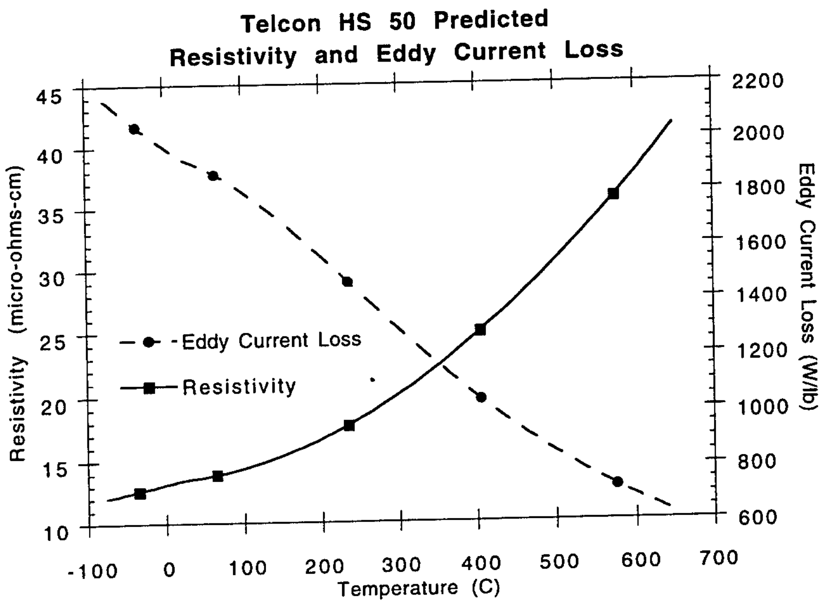

Figure 5. Predicted resistivity and eddy current loss at 5000 Hz of Telcon HS 50 Alloy from -75°C to 650°C.

Table 2

Temperature range (°C)	Coefficient of resistivity $(\alpha, C^{-1}, 10^{-3})$	Baseline resistivity $(\mu\Omega\text{-cm})$
-73 - 27	1.1	12.18
27 - 200	1.5	13.42
200 - 400	2.0	18.17
400 - 600	2.3	26.63
600 - 800	2.6	40.24

Mean coefficients of resistivity with respective resistivities

from our resistivity vs. temperature data, is shown in Figure (5). Note that it is nearly a factor of two lower than room temperature at the engine operating temperature. The chosen frequency is characteristic of advanced airborne generator frequencies.

CONCLUSIONS

The resistivity of the samples was found to be independent of the anneal temperature and orientation. Although grain sizes for the anneals varied from one to two microns, resistivity was found to be independent of grain size. Table (1) depicts this fact. While it is possible that the range of anneal temperatures used for this experiment was not large enough to display a clear trend in the variation of the resistivities, what we see in this sampling is probably just a statistical distribution of the resistivities of about +/- 5%.

Using the information derived from this work, the resistivity can be estimated with a reasonable margin of error. Given the number of uncertainties in the design of magnetic devices, at least the resistivity can be better approximated using the expressions given in this work, leading to better eddy current loss estimates.

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