Electropolishing Iron-Cobalt-Vanadium Laminate Stacks to Improve Performance of Electrical Machinery

by Dr. Andrew Kenny, * *Alan Palazzolo, Jason Preuss, Randall Tucker & Kevin Konno*

An electropolishing method was developed for electrical machinery laminated stacks of a 49% Fe, 49% Co, 2% V alloy. The method removed the metal most rapidly at the laminate interfaces. The glue between the laminates was washed away as the metal was removed. A mixture consisting of phosphoric and hydroxyacetic acids and ethylene glycol produced an unpitted polished surface. The electropolishing technique was especially effective at removing metal on the laminated stack surface that caused electrical shorting of the laminates.

Overview

Most electrical machinery that uses alternating current is fabricated from metal that is built up from thin laminates. This is done to prevent strong eddy currents which otherwise would be induced by the alternating magnetic field. Between the laminates are electrical insulating layers which are intended to prevent electrical resistance heating and power loss.

Two final manufacturing operations on parts made from laminate stacks can ruin the electrical insulation between the laminates. These two operations are grinding which smears the laminates together on the surface, and electro-discharge machining, which melts the laminates together on the surface. An electropolishing method was developed for laminates of an alloy of 49% Fe, 49% Co and 2% V. It removed only the very thin layer of surface metal that was responsible for the interlaminate shorting.

Evidence of interlaminate shorting

An experiment was conducted to verify that eddy currents were occurring in the laminated rotor. The experimental configuration consisted of a laminated rotor with a drive coil and a pickup coil wrapped around the rotor as shown in Fig. 1. The rotor outer diameter (OD) was ground but not electropolished. The theoretical voltage in the pickup coil was calculated from the following equation.

$$V = \frac{2\pi f \cdot N_p \cdot \mu_o \cdot A \cdot N_d \cdot I}{l_p} \qquad (1)$$

where

V = voltage in the pickup coil
N_F = number of turns in the pickup coil
f = frequency of the current in the driving coil
μ_o = the permeability constant
A = area of the flux path cross section
N_d = number of turns on the driving coil
I = current in the driving coils
I_f = effective path length which depends on the eddy currents

If there were large amounts of eddy currents produced in the rotor path, effectively the magnetic path length denoted by I_f in the equation would be increased because the path reluctance would be increased. Therefore the eddy currents

Nuts & Bolts: What This Paper Means to You

This work was partially funded by an AESF Research Small Grant. It deals with a rather practical application of electrochemical metal removal. An electropolishing method was developed for electrical machinery laminated stacks of a 49% Fe, 49% Co, 2% V alloy. The technique was especially effective at removing metal on the laminated stack surfaces that otherwise would lead to electrical shorting of the laminates.

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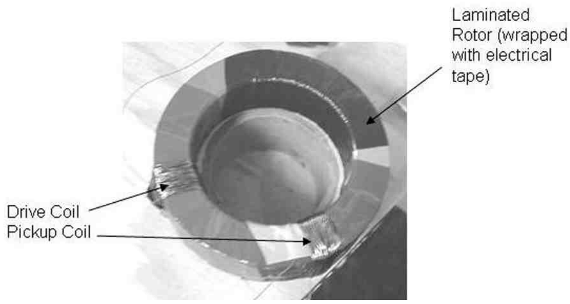

Figure 1—Experimental setup for measuring effects of eddy currents in a rotor.

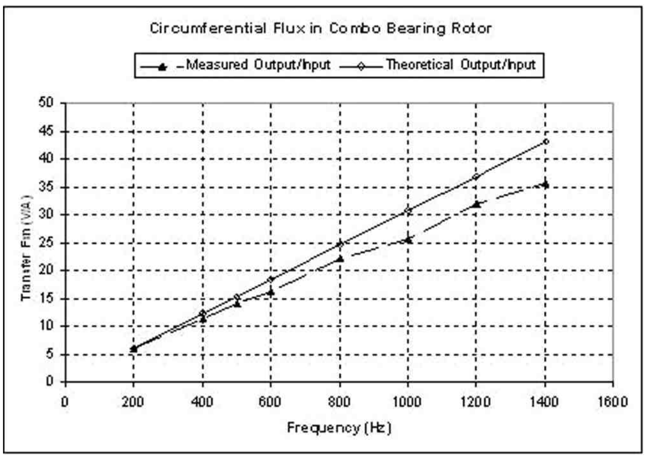

Figure 2—Frequency response from circumferential flux in an unelectropolished rotor.

would decrease the voltage output. This is what the experimental measurements in Fig. 2 show.

The transfer function between the current input in the drive coil and the voltage output in the pickup coil as determined by measurement is plotted versus frequency in Fig. 2. On the Y-axis is the ratio of the voltage in the pickup coil to the current in the driving coils. At 800 Hz the measured voltage in the pickup coil was 9.7% less than the theoretically predicted value and at 1400 Hz it was 17.1% less.

The nonconducting material between the laminations is meant to decrease the eddy currents produced by the alternating current in the input coil. But the experimental evidence indicates that there is some electrical contact between the laminates and some eddy currents do flow.

Electrical contact between the laminates occurs on the surface after grinding or electrodischarge machining. To remove the surface metal connecting the laminates, an electropolishing technique was developed.

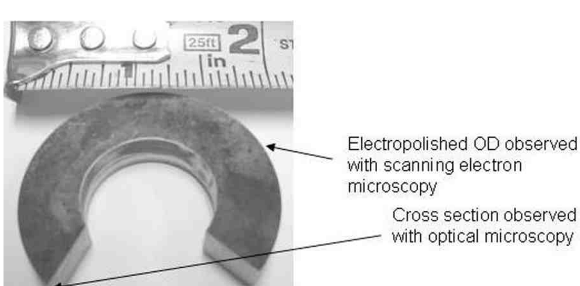

Figure 3—Electropolished rotor laminate stack.

Background on electropolishing

Electropolishing is especially effective at uniformly removing a surface layer because electric charges accumulate at protuberances on the surface.[1] This concentrates the metal removal at the roughest ridges, quickly polishing them down until the surface is flat.

The element atoms with the lower electrochemical potential are removed from the surface most readily by electropolishing. In particular, the electrochemical potentials of the two major elements in the alloy are:

Iron	0.441V
Cobalt	0.290V

Cobalt has the lower potential. Electropolishing leaves the surface layer iron-rich, but that is acceptable in this case since the magnetic saturation level of the alloy increases up to 73% iron.[2]

The electrolyte formulation affects the quality of the electropolished surface. Inhibitors of acid corrosion such as ethylene glycol and surfactants help improve the electropolished surface quality when added to the mixture.[3] The ASM Handbook recommends a solution of 90% acetic acid and 10% perchloric acid for electropolishing iron-cobalt alloys.[4] However, this is for the preparation of metallographic samples for microscopy. Different compositions are used by commercial electroplaters, who have to consider environmental and cost concerns when choosing all chemicals.

Electropolishing procedure

The electropolishing for this project was performed in two trials, both on the same laminated rotor made from 0.1 mm (0.004 in.) thick sheets of 49% Fe, 49% Co, 2% V alloy. In the initial attempt, the process utilized an electrolyte composed of phosphoric and sulfuric acid. With this mixture, the material removal was insufficient and nonuniform, and the surface was pitted. The second electrolyte was composed of phosphoric acid, ethylene glycol and hydroxyacetic acid. With this mixture electropolishing produced an excellent smooth surface.

In order to determine the effectiveness of electropolishing, both optical and scanning electron microscopy were used. The electropolished OD surface was examined directly with the scanning electron microscope. A section was cut out of the laminated rotor as shown in Fig. 3 and studied under the optical microscope. The area of the cross section near the rotor OD was of particular interest since a view of that cross section showed a cross section of the electropolished surface itself.

Discussion of results

The optical micrographs in Fig. 4 show cross sections through the rotor OD after electropolishing with the second electrolyte mixture which included ethylene glycol and hydroxyacetic acid. In Fig. 4(a), a single laminate separated by thin layers of adhesive is visible. Figure 4(b) is a magnified view at the OD surface where the two laminates meet. The microstructure of the alloy studied consists of a bulk phase in which a fine strengthening precipitate is dispersed.[5] The bulk alpha phase and the precipitated phase are both visible.

These micrographs show there is no smeared metal left from the grinding operation on the OD after electropolishing. The laminates are distinctly separated on at the surface. Where the laminates meet, there is a small dip on the electropolished surface because the electropolishing technique removed the metal at the sandwich interface at a faster rate.

Scanning electron micrographs of the rotor OD surface are shown in Fig. 5. Figure 5(a) shows the surface immediately after

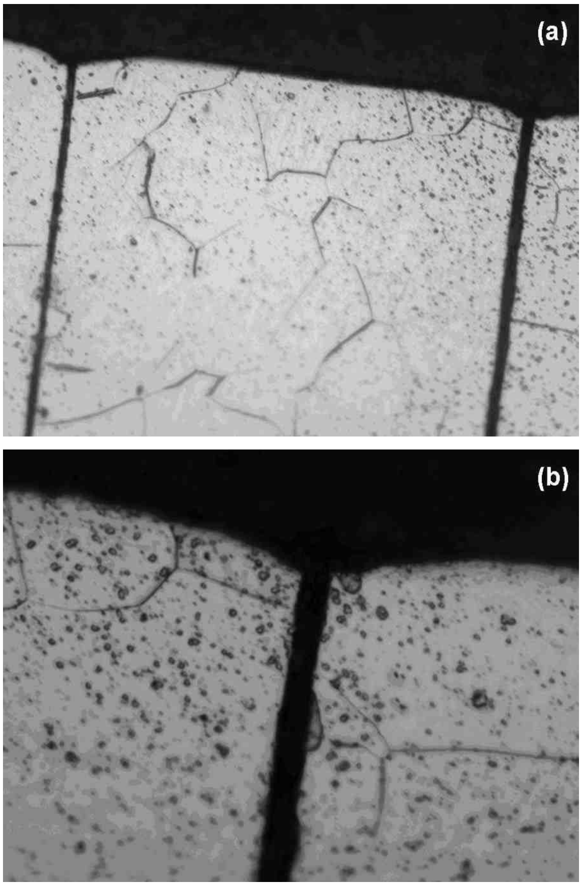

Figure 4—(a) OD surface electropolished - Cross section 400X; (b) OD surface electropolished - Cross section 1000X.

it was ground. Grinding smeared the laminate surfaces together so that no individual laminate could be distinguished. The micrograph in Fig. 5(b) shows the surface after electropolishing with the first electrolyte mixture of phosphoric and sulfuric acids. The thin adhesive layers between the metal laminates are visible. Insufficient metal was removed to remove the interconnecting metal on the surface completely, but the laminates were visible. Figure 5(c) shows the rotor OD surface after it was electropolished again but this time with the mixture of phosphoric and hydroxyacetic acids and ethylene glycol. The laminates were completely separated with no smeared metal remaining. The rough material in the grooves is the epoxy glue between the laminates. A trough is observed at the grooves between the distinctly separated laminates.

The edge effect of charge accumulation probably helped, by causing the material near the laminate edges to be removed at a faster rate. This effect is illustrated in Fig. 6. The corner edges had a higher voltage due to charge accumulation. This caused more anodic dissolution exactly where it was most needed to remove smeared metal between the laminate edges.

A very highly magnified SEM micrograph of this electropolished surface is shown in Fig. 7. The surface is very smooth. The pitting shown is not typical. The smooth surface around the pit is more typical.

Evidence of prevention of interlaminate shorting

Electropolishing the laminate stack prevented interlaminate shorting. Evidence of this is shown in Fig. 8. An experiment identical to that shown in Fig. 1 was conducted on an electropolished stack. The voltage on the output coil dropped by about 6% at 1400 Hz compared to what would be theoretically expected with no interlaminate smearing. By comparison to the test on the unpolished sample, (Fig. 2), a 17% loss in performance occurred. In other words, electropolishing cut the effect of eddy currents roughly in half.

Conclusions

Electropolishing removed the thin layer of ground metal on the surface of the rotor laminate stack. Both optical and electron microscopy clearly showed the laminates were distinct with no metal between them after electropolishing. Induction testing showed that there was a clear improvement in performance with electropolishing.

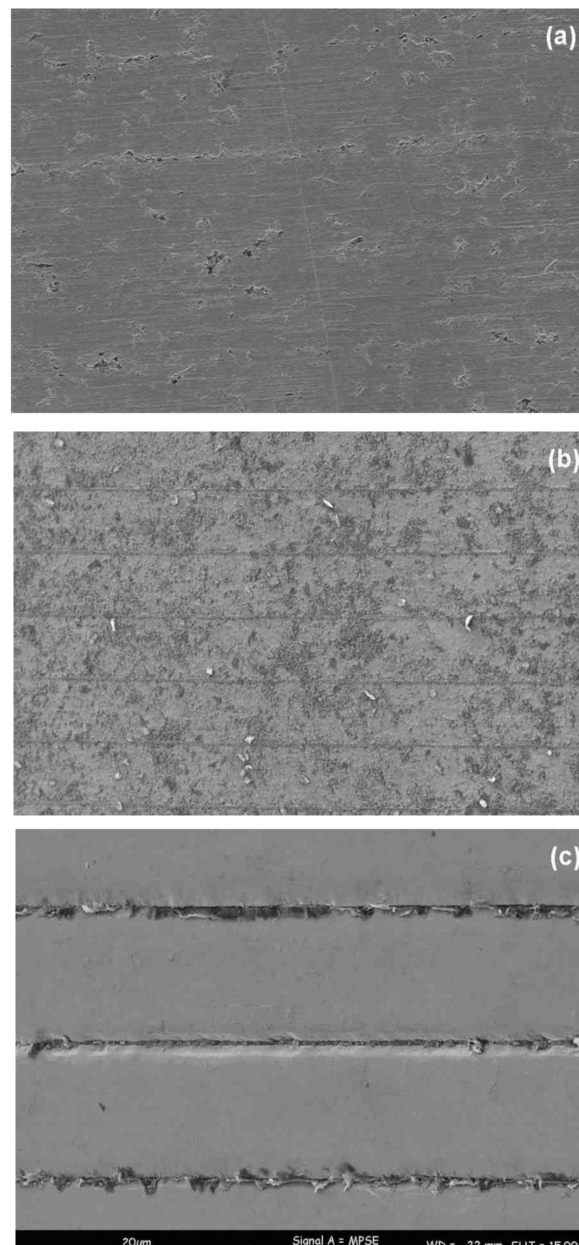

Figure 5—Scanning electron micrographs of the rotor OD: (a) The rotor lamination OD after grinding; (b) After polishing with electrolyte containing sulfuric acid; (c) After polishing with electrolyte containing ethylene glycol and hydroxyacetic acid.

Figure 6—High charge at laminate corners.

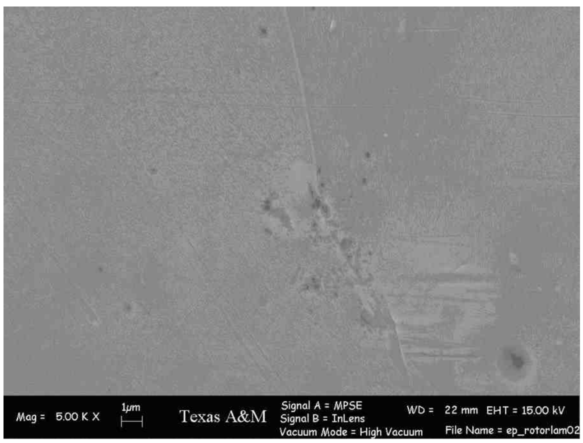

Figure 7—A 5000X view of the final electropolished surface.

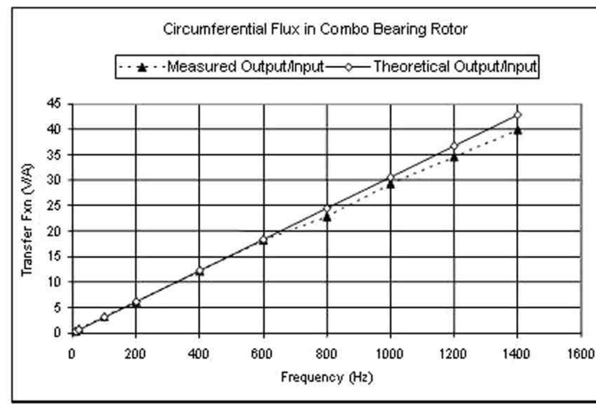

Figure 8—Frequency response from circumferential flux in an electropolished rotor.

The scanning electron microscope showed the electropolished surface to be very smooth, despite the fact that the microstructure contained two phases with different concentrations of iron and cobalt. Precisely controlled removal of a very thin layer of metal was achieved.

The glue between the alloy laminates was washed away as the metal was removed. The combination of polishing more of the metal away at the corners and washing away the glue left very shallow troughs between the laminates.

Acknowledgements

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