CONCEPTS AND PROCESSES FOR ALTERNATE
SOLENOID COILS

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CONCEPTS AND PROCESSES FOR ALTERNATE SOLENOID COILS

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Prepared by H. F. Jordan

A solenoid coil concept with fire environment potential was proposed, fabricated, and evaluated with favorable results. A polyphenylmethylsiloxane polymer was used as a high temperature insulation coating for the bobbin coil assembly. Alternate concepts utilizing foil conductors and additional insulating materials were examined for follow-on development potential.

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CONTENTS

Section	Page
SUMMARY.	5
DISCUSSION	6
SCOPE AND PURPOSE.	6
ACTIVITY	6
<u>Bobbins.</u>	6
<u>Foil Conductors.</u>	7
<u>Insulating Materials</u>	10
<u>Coil Design Concepts</u>	13
ACCOMPLISHMENTS.	21
FUTURE WORK.	21
DISTRIBUTION	23

ILLUSTRATIONS

Figure		Page
1	Present Solenoid Coil Design	7
2	Metal Bobbins.	8
3	Foil Holder and Tension Fixture (Polaroid) . .	11
4	Expanding Mandrel (Polaroid)	12
5	Weight Loss Versus Temperature for LPP.	13
6	Outgassing of Cured Hydroxyl Resin	14
7	Weight Loss Versus Temperature for Hydroxyl Resin	15
8	Metal Bobbin Solenoid Coil	16
9	Hold Configuration for Metal Bobbin.	17
10	Foil Solenoid Coil	18
11	Terminating Strap.	19

SUMMARY

The 538°C fire environment and the restricted volume of the solenoid coil in a production part combine to restrict the design options available.

The following alternate materials and configurations were investigated.

- A coil using the polyimide insulated wire (AWG 31) in use in production now is wound on a metal bobbin. The metal bobbin and the wound assembly are dip coated with a hydroxyl resin, a high temperature insulation.
- Barrier anodized aluminum foil 0.559 mm thick is wound on an aluminum bobbin with an outer wrap of glass cloth and is dip coated with Resin.
- Copper foil insulated with Resin is wound on a copper bobbin, wrapped with glass cloth, and is dip coated with Resin.
- Parylene coated copper foil is wound on a copper bobbin, wrapped with glass cloth, and is dip coated with Resin.

Each approach uses an insulated metal bobbin and dip coated insulation to avoid failures related to conductor insulation defects and coil encapsulation.

Two solenoid coils, fabricated using a metal bobbin, and a polyimide wire approach gave acceptable test results. This approach was recommended for additional evaluation as a replacement for the existing solenoid coil.

Assemblies using foil were not fabricated because the additional equipment and processes required were not included in this endeavor. A long term study of these concepts was recommended. The anodized aluminum approach has the potential of almost eliminating carbonization and outgassing and it may in fact be functional over the entire temperature range.

The high temperature (538°C) characteristics of insulating materials considered in this report were examined in special tests.

Barrier anodization of thin foil was examined to determine if desired thicknesses were obtainable.

Thin foil was ultrasonically welded to confirm the validity of its use in attaching electrical terminations.

DISCUSSION

SCOPE AND PURPOSE

This project was undertaken to determine concepts with potential for improving the production yield rate of the existing design of a solenoid coil. Different materials and concepts were examined for their potential in this application. The use of a bobbin, of several insulating materials, and of foil as a conductor was examined in this project.

ACTIVITY

The basic causes of losses in the production coil must be understood so that these features can be avoided. The 538°C assembly fire-environment requirement limits the selection of materials that may be used and is a significant factor that restricts design options. Carbonizing of coil material and outgassing in this assembly at 538°C must not cause conduction between assembly switch contacts. The lack of volume available for electrical insulation between the coil conductor and the assembly housing is of similar significance. These factors combined eliminate the use of standard design concepts. The present design (Figure 1) provides that polyimide insulated wire be wound on a steel mandrel which forms part of an encapsulation mold (there is no coil bobbin). The mandrel is removed after encapsulation leaving the insulated wire to stand off the hi-pot voltage. The outer thin covering of encapsulation tends to have voids and cracks.

This project was directed at finding and examining concepts that consider this application's fire-environment and restricted volume with potential for a low production attrition rate. Several insulating materials and coil configurations were considered for use in this application. Configurations with two different bobbin designs and the use of foil and wire conductors were also considered. The bobbin avoids hi-pot failures that arise from wire insulation defects and provides conductor containment without encapsulation. Foil requires less conductor volume and does not require containment in the axial direction.

Bobbins

The nonconductive bobbin was considered desirable to reduce the possibility of hi-pot failures. An insulated metal bobbin appeared to be the best choice considering the strength and volume requirements. This was evident from calculations considering the forces resulting from the wire tension applied in the winding process. The accumulation of stress on the inner wall of a bobbin wound with 250 g of tension is computed to be approximately

Figure 1. Present Solenoid Coil Design

$$\text{Stress} = \frac{250 \times 1117}{3.81 \times 21.1}$$

$$= 3474 \text{ g/mm}^2$$

where

Number of turns is 1117,
Tension per wire is 250 g and
Wall cross section is 3.81 by 21.1 mm.

The insulation of a metal bobbin by a dip coating process, to be covered later, requires a configuration free of sharp corners. Bobbins such as those in Figure 2 appear reasonable. Even though the hole in the flanged bobbin has a relatively sharp edge it is far enough away from the assembly housing to provide the required 500 V breakdown strength. Bobbins without flanges were considered for use with foil conductors because of their inherent axial stability and because the physical separation between foil and housing, axially will prevent breakdown.

Foil Conductors

Winding volume can be reduced by the use of a wide foil of thin cross section, eliminating the unused volume existing between the round wire now in use. Foil usage also eliminates the layer-to-layer voltage build up of wire coils and it is more stable physically, in that it need not be constrained axially. The elimination of the wire-wound layer-to-layer voltage gradient,

The copper foil thickness required in this application was calculated considering the first wrap is wound on a bobbin diameter of 15.24 mm.

$$\begin{aligned}\text{Coil length } l &= \pi(\text{MCD}) \times 1117 \\ &= \pi(15.24 + 1117t)1117 \\ &= 53479 + 1247689t\end{aligned}$$

$$\text{Coil resistance } 28 = \frac{16.28 \times 10^{-6} (l)}{21.1t}$$

$$28 = \frac{16.28 \times 10^{-6} (53479 + 1247689t)}{21.1t}$$

$$590.8t = 0.87 + 20.31t$$

$$t = 1.525 \mu\text{m}$$

Where:

Resistivity = $16.28 \times 10^{-6} \Omega\text{mm}^2/\text{mm}$,

Total coil resistance = 28Ω ,

Foil width = 21.1 mm,

Number of turns = 1117,

Bobbin diameter = 15.24 mm,

t = foil thickness, and

The mean coil diameter (MCD) = $(15.24 + 117t)$.

Copper foil 0.001525 mm thick was unavailable commercially. The 0.0033 mm foil was made by a commercial vendor. Foil of this thickness and half the width (same cross-sectional area) can be used in a two-foil-coil construction. Both would be wrapped on a common bobbin with the inner wraps connected electrically and the coils wound in opposite directions (aiding magnetically).

Aluminum has a resistivity 1.64 times that of copper. Aluminum foil thickness required for a foil coil is 1.64 times that of copper or 0.0054 mm thick. It is commercially available in a thickness of 0.0055 mm because of its prevalent use in capacitors. Purchased material is available in widths of 0.794 mm increments.

Information concerning coil winding using foil shows that roller alignment is important to avoid wrinkling and to provide alignment of foil edges. A holder (Figure 3) was constructed to provide for tensioning and positioning of the foil as it was unrolled. An expanding mandrel was purchased and modified (Figure 4) to use with the bobbin. The mandrel stabilizes the inner diameter dimensionally and allows removal of the wound coil without scratching its inner surface.

Aluminum foil 0.00635 mm thick was wound on a 2.54-mm-thick aluminum bobbin with approximately 57 g of tension at a rate of 150 revolutions per minute (using a machine shop lathe). One hundred layers were wound before a surface wrinkle developed because of an edge imperfection of the foil. A measurement of the wound diameter indicated a layer thickness of 0.0066 mm was obtained. The layer-to-layer alignment was estimated to be within 127 μ m. The wrinkle problem noted here could be eliminated by the use of edge flattening rollers in the foil coating process.

Insulating Materials

In addition to the polyimide and glass yarn insulations now in use, four other materials are considered to have potential in this device. These are a linear plastic polymer, polyparaxylylene; a thermal setting hydroxyl; barrier anodized aluminum; and 0.0762-mm-thick glass cloth. Glass cloth is considered for use as an impregnated wrap for insulation of the outer diameter of the coils in some concepts and it requires no evaluation of its basic fire environment properties.

Linear Plastic Polymer

The linear plastic polymer (LPP) is applied by a vacuum deposition process. It may be applied in pin hole-free thicknesses as thin as 25.4 μ m according to the manufacturer's literature. When adjacent coatings are free of coincident pinholes and a layer-to-layer voltage holdoff of 0.03 V is all that is required, thinner applications are possible. It is applied by the vendor in a continuous foil coating process for use in capacitors. The material has a dielectric strength of 7000 V per 0.0254 mm (7000 V per mil).

The use of LPP in this application would be as an insulator for copper foil. A special apparatus is required to unroll and reroll the foil inside the vacuum chamber during the deposition process. The design and construction of this equipment for the purpose of evaluations was not included in this project.

The polymer was tested for weight loss versus temperature (Figure 5). It exhibited a rapid weight loss above 450°C. The gases produced at elevated temperatures consisted of trace quantities of benzene

Figure 3. Foil Holder and Tension Fixture

and monome, dimer, and trimer molecules of LPP. These gases are considered nonconductive, although the gas pressure produced may cause some deposition of material in the next assembly which in turn could carbonize. Fire environment tests in a simulated assembly are necessary to confirm the material's value. Use of LPP as a 0.00076-mm-thick covering is envisioned. The small quantity of material used may contribute to its usefulness.

Hydroxyl Resin

This resin was recommended for this application and it was used in the conceptual evaluations. It is a thermal setting hydroxyl-containing polyphenylmethyilsiloxane polymer.

Figure 4. Expanding Mandrel

Outgassing of the cured resin (Figures 6 and 7) consists mainly of nonconductive benzene and biphenol molecules up to 300°C, and benzene and ethyl alcohol above 300°C. Ethyl alcohol is bipolar and may provide some measure of conductivity. The small amount of resin used in an assembly dip coat of 0.0127 mm in thickness in one concept, and a foil coating of 0.0076 mm thickness in another will limit the outgassing. Cured resin is 80 percent silicon-oxygen.

Resin will bond to aluminum, copper, stainless steel, glass, and polyimide insulation. Thin coatings (0.0127 mm) reportedly remain continuous when the metal is elongated by 10 percent. It has also been observed to be very flexible and remain intact on foil bent at sharp angles. Dip coat thicknesses have varied from 0.0005 to 0.0127 mm by using different ratios of solvent. The material is specified to have a dielectric strength of 3000 V per 0.0254 mm (3000 V per mil).

Barrier Anodization

In barrier anodization of aluminum, a nonporous aluminum oxide layer is formed. This layer is primarily amorphous oxide which is noncrystalline. The thickness of the anodization is dependent upon several variables with the anodizing voltage being predominant. Strips of foil were anodized using a potential of 20 V to produce

Figure 5. Weight Loss Versus Temperature for LPP

a thickness of approximately 0.0005 mm, confirming that thicknesses of interest can be obtained. In this application long strips of foil (30.5 m) are required and special equipment is necessary to maintain tension and to provide continuous unrolling and rerolling during anodization.

Coil Design Concepts

Four designs are detailed in the following paragraphs. Three of these utilize foil as the conductor and one uses the polyimide coated wire now in use in the production coil. All are insulated with the hydroxyl resin.

Wire Wrapped Bobbin

Two solenoid coils using stainless steel bobbins and AWG31 polyimide insulated copper wire (Figure 8) were fabricated and tested with satisfactory results. Details concerning their construction follows.

Figure 6. Outgassing of Cured Hydroxyl Resin

The volume required for a wire wound coil on a metal bobbin using the number of turns applied in production (1117) is computed as follows.

Given:

Turns	1117
Axial length of winding	21.13 mm
Wire diameter (nominal)	0.241 mm
Bobbin diameter	15.32
Turns for full layer	$21.13 / 0.241 = 87$
Turns for 11 layers	$87 \times 11 = 957$
Turns for 3 partial layers	$(1117 - 957) / 3 = 53$
Diameter of 14 layer coil	$15.32 + (0.866)(0.241)(2)(14) = 21.16 \text{ mm}$

Where 0.866 is the ratio of radial wire displacement to wire diameter.

Figure 7. Weight Loss Versus Temperature for Hydroxyl Resin

Dip coating the bobbin and the wound coil with resin will add approximately 0.05 mm providing a total diameter of 21.21 mm. This is well within the 22.22 mm diameter allowed. The 1-mm-radial gap provided in this concept is sufficient to stand off the 500 V breakdown voltage in itself on the outer diameter. The 0.0127-mm-coating of resin on the bobbin, inside and out, adds approximately 3000 V of insulation to the 600 V insulation of the wire.

The success of this approach depends on the adequacy of the bobbin's insulation, which in turn is a function of the processing as well as the bobbin design. It is necessary that sharp edges, where radii meet the flat surfaces, be eliminated because the resin will not coat sharp edges. An economical technique recommended for this task is tumble deburring. The parts should then be cleaned to remove grit deposited in the tumble process. The following cleaning process was recommended (and used on two parts fabricated for evaluation of overall concept).

1. Degrease with trichloroethylene.

NOTE:
DIP COAT BOBBIN IN 50 PERCENT SOLUTION
OF RESIN AND MEK AT RATE OF
50.8 mm/MIN

**NOTE: DIP COAT
WIRE WRAPPED BOBBIN COIL**

Figure 8. Metal Bobbin Solenoid Coil

2. Anodically clean in cleaning solution at 85 to 90°C for 2 to 5 min-utes. Water rinse.
3. Dip in 5:100 HCL (ionic) and DI water for 30 seconds. Water rinse.
4. Solvent rinse with isopropanol and blow dry.

The fabrication of two bobbins, in which the lead exit hole in the flange was radiused as shown in Figure 9A, proved difficult.

Figure 9. Hold Configuration for Metal Bobbin

Anticipating this was a production problem, the configuration recommended for further evaluation was as shown in Figure 9B, where edge C is left relatively sharp. Its separation (0.762 mm) from the assembly housing will provide protection against breakdown.

The cleaned bobbins were dipped into and removed from a 1:1 solution of resin and MEK at a rate of 50.8 mm/minute and subsequently cured at 149°C for 16 hours.

The wire was wound on the bobbin as eleven full layers and three partial layers, leaving room for the solder joints between the lead wire and the bobbin coil. Polyimide sheet insulation was placed below the solder joints and adhesive backed polyimide tape was placed over the solder joints. Glass yarn was then wound around the bobbin in the groove area with yarn on both sides of the joints to immobilize them. This final configuration was again dipped in a 1:1 solution of resin and MEK and then air dried for an hour before curing at 149°C. The only exposed metal, the solder joints, was covered below, above, and on the sides with insulating materials.

A cost analysis of this approach yielded 1.03937 standard hours and 0.60 material cost. This is 0.32376 less than that required for the present design.

Anodized Foil Coil

A complete solenoid coil as in Figure 10 was not fabricated using this approach because the development of the special equipment and processes necessary to anodize long strips (30.5 m) of foil was not included in this endeavor. The configuration envisioned, and examined piece meal, is as follows.

Barrier anodize foil with voltage adjusted to produce a specified resistance/foot of foil (prior development work would provide

Figure 10. Foil Solenoid Coil

this value). The unroll-anodize-reroll process would include edge flattening rollers at the beginning of the process.

After chemically stripping the end of the foil, it is then wound into two coils around the aluminum bobbin at a tension of approximately 100 g and a rate on the order of 100 rpm. The final wrap of each coil would be ultrasonically welded to 0.005-mm-thick aluminum strips (Figure 11) coated with B staged resin. The aluminum strips are wrapped around the coils and cured at 149°C. Subsequently, 0.076-mm-thick glass cloth is wrapped around the foil and the assembly is dip coated with resin and cured at 149°C. Sleeves of aluminum could be heat shrunk over the coils as an alternate to the use of the aluminum strips.

Bobbin thickness (0.508 mm), foil thickness (6.529 mm), terminating wrap (0.203 mm), outer glass wrap (0.305 mm), and resin dip coat (0.0254 mm), indicate a total diameter of 22.149 mm which is within the allowed 22.225 mm specification maximum. Minor perturbations in the preceeding thickness may result in an oversize part. In this event, the foil thickness can be reduced by adjusting the tension in the foil anodization process or the number of wraps can be reduced since the minimum resistance permitted is 2 Ω less than the targeted 28 Ω .

Figure 11. Terminating Strap

The advantage of this approach lies in the thermal stability of the materials used. Outgassing and carbonization at 538°C are obviously minimal. Additionally, the use of a bobbin represents an advantage over the production part.

The cost of manufacturing foil coil solenoids is estimated to be similar to that of the present design.

Resin Insulated Copper Foil Coil

A copper foil coil as described here was not fabricated because the special equipment and process development necessary to form the foil insulation was outside the scope of this endeavor. The construction envisioned is as follows.

Copper foil of 0.0033 mm thickness is coated in a continuous immersion and tunnel furnace cure process with equipment providing for the unrolling and rerolling at a controlled tension to avoid surface irregularities. Thickness is controlled by the ratio of solvent to resin used with a total thickness of foil and resin of 0.005 mm or less anticipated.

The remaining processes are similar to those described for the aluminum foil coil.

The use of glass resin in place of polyimide insulation is considered potentially better from a carbonization point of view. Polyimide insulation is approximately 70 percent carbon whereas glass resin, after cure, is approximately 80 percent silicon and oxygen.

LPP Insulated Copper Foil

A foil coil using LPP for foil insulation was not constructed because the special equipment and process development necessary was beyond the scope of this endeavor. Construction details are anticipated to conform to those recommended for the preceding foil coils except for those dealing with coating the foil prior to use in the coil.

Coating LPP is a vapor deposition process used for coating capacitor foil, etc. In this thickness, foil would be exposed to vapor deposition of LPP for approximately 30 seconds during the unroll and reroll processing. The proven ability of this material to provide a thin and even coat is the driving force behind its consideration.

ACCOMPLISHMENTS

A solenoid coil concept was proposed, fabricated, and evaluated with potential for eliminating the high voltage breakdowns and the encapsulation defects of the present production coil. Additional concepts of similar potential but requiring further process development were formulated.

The following materials and processes used in the proposed concepts were evaluated in areas within the scope of this endeavor.

- Barrier Anodization. Foil was anodized at 20 V achieving the film thickness needed for this application.
- Foil Winding. Thin foil (0.006 mm) wound on a bobbin gave results indicating that acceptable layer-to-layer spacing and registration are reasonable process expectations.
- Thin Foil Welding. Thin foil (0.006 mm aluminum) was ultrasonically welded to 0.076-mm foil (for use in electrical termination of foil).
- Resin Insulation. Thicknesses in the range of interest for foil coating (0.00076 mm) and bobbin coating (0.0127 mm) were achieved by varying the solvent ratio. High temperature test results indicated that the resin has potential for this application. The resin coated polyimide type insulation as well as metal and glass.
- LPP. This material's fire environment characteristics were analyzed.

FUTURE WORK

Additional assemblies similar to the two fabricated for this endeavor should be manufactured and tested to determine the potential of this approach statistically. Assemblies of this concept should be subjected to assembly fire environment testing and all other assembly test requirements. Process development activity is needed to examine:

- Continuous strip barrier anodization of foil,
- Continuous strip resin coating of foil,
- Continuous strip LPP coating of foil,
- Foil winding of solenoid coils,

- Termination techniques applicable to foil coils, and
- Assembly fire environment results of coils using resin and LPP insulations.

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