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STATEMENT OF PROBLEM

There is considerable design information available for the design of coils using conventional materials. There is little information available for the design of coils for the high temperature service. The problem is to establish allowances and limitations for these coils using ceramic encapsulation.

ABSTRACT:

Coils are used to convert electrical energy into magnetomotive force. This force, when coupled with various magnetic designs, forms the apparatus to detect, cause or prevent movement. These are the basic functions of position sensors, actuators, brakes and clutches.

A considerable amount of information is available for the manufacture of coils made from standard materials. This information is extended for ceramic insulated coils for high temperature applications. This report contains general design parameters and allowances to be used in the design of ceramic insulated and encapsulated coils, capable of operating up to 1100°F in a vacuum.
Introduction

Coils are used to convert electrical energy into magnetomotive force and magnetic energy. This magnetic energy and magnetomotive force when applied to a suitable magnetic material can produce motion, detect motion or prevent motion. These functions are designed into actuators, position sensors, clutches and brakes.

A considerable amount of information is available for the design and manufacture of coils from standard materials. This report records the design considerations necessary to design and manufacture ceramic insulated coils for high temperature operation, up to 1100°F, and in a vacuum. Factors of bobbin construction, winding allowances, terminations, encapsulant, coil surface, will be covered individually.

Bobbin Construction Material

Bobbins may be constructed of various materials and in various shapes. Bobbins may be metallic, such as Hiperco or stainless steel; or ceramic, such as alumina or lavite. Ceramic bobbins are desirable from the standpoint of their being insulation material but require thick walls to reduce breakage. Metallic bobbins are stronger than ceramic bobbins, but are difficult to insulate.

Ceramic Bobbins

Non-metallic or ceramic bobbins may be constructed. The ceramic bobbin itself is the primary insulation. The most satisfactory ceramic material to date is high purity alumina. This material has high strength, high insulation value and low or negligible moisture absorption. In the design of ceramic bobbins, the minimum suitable wall thickness is 0.050". Thicker and thinner walled bobbins are used but bobbins with wall thickness 0.040" and less normally are broken in the coil cure cycle. This breakage is caused by the expansion of the metallic coil wire pushing against the bobbin flanges. There is not a design configuration available that prevents this breakage.
The most important consideration in the design of ceramic bobbins is to maintain relative uniform wall sections through the bobbin. These uniform sections should be joined by generous radii. The walls should be blended into the core section with a radius of 0.125" but in no case should the radius be less than 0.060". All outer edges and edges from the flange to the core should be rounded to maintain a 0.040" external radius. Stress concentration grooves and machine marks must be avoided.

Due to the long delivery of alumina a substitute material is desired for prototype work. The most suitable substitute material is lavite fired at 2200°F for 1/2 hour with a 200°F/hr. rise and fall. This material during firing will grow about 1/2 of 1% in size. A coil developed on a lavite bobbin without breakage can be reproduced exactly on an alumina bobbin without breakage. The lavite bobbin will perform similar to the alumina bobbin, possessing a decrease in the desirable properties, especially strength and moisture absorption.

**Metallic Bobbins**

Metallic bobbins are relatively easy to construct and have high room temperature strength. It is necessary to isolate and insulate the lead wires and coil wires from the bobbins. This factor will be covered in detail later.

The most suitable metallic bobbin is of a non-magnetic material such as a 300 series stainless steel. A metallic bobbin must be carefully checked for adequate high temperature strength to withstand the stresses developed by the insulated coil. The most satisfactory wall thickness of a metallic bobbin of stainless steel is 0.060" although wall thickness of 0.030" to 0.125" are used.

Standard metal working practices may be used to manufacture the bobbin. All edges that may come into accidental contact with the conductor or lead wire should be radiused to no less than 0.015". Interior radius of the bobbin cavity should be 0.015" or less. Bobbins may be constructed from various pieces joined together by a suitable
braze or weld. All material must be selected for the application and temperature. Any flux used in welding or brazing must be removed to prevent contamination of the coil.

**Bobbin Shape**

Bobbins, both metallic and non-metallic, may be made in most shapes. It is desirable to have a coil of regular section and with a round core but coils are wound on various bobbin shapes, such as square or rectangular. If the core of the bobbin is of a shape other than round, it must have a generous corner radius to allow the winding wire to follow the contour of the corner. The easiest coil to wind is a simple right cylinder. The more the coil shape deviates from this, the more difficult it is to produce a satisfactory coil.

**Coil Winding Conductor**

The coil winding conductor is an insulated wire generally composed of copper. Copper is a desirable conductor due to its low resistivity but other metallic materials may be used. The copper conductor may be protected by cladding such as stainless steel or by a plating of chrome or nickel. For high temperature operation nickel should be avoided as a protection material as it diffuses into the conductor, increasing the resistance of the wire.

The coil conductor must be insulated when wound into a coil. This insulation must be compatible with the wire, bobbin and encapsulant. Ceramic insulations have been used, but for high temperature coils the existing ceramic insulated wires are unsuited as the ceramic is applied over a layer of nickel. The most suitable insulation determined to date is a double layer of "E" glass serving. Wire manufacturers apply this glass with a binder to maintain its handling characteristics and coat the insulated wire with one of the insulating varnishes such as silicone. This insulating varnish is normal to the standard industrial practices for glass insulated wire. A more desirable glass insulation is Owens Corning "S" glass which is unavailable on wire at this time.
Prior to winding the conductor, the varnish must be removed from the glass insulation. This removal is necessitated as at high curing or operating temperatures the varnish will carbonize, forming a layer of carbon around each conductor through the encapsulant. The varnish may be removed by oxidation at high temperature (above 800°F) in an air atmosphere. A typical cycle suitable to remove silicone varnish from insulated wire consists of maintaining one pound of wire at 1000°F for one hour in a ventilated (air) oven.

**Bobbin Insulation**

Bobbin insulation is relatively simple with a ceramic bobbin as the bobbin itself forms the required insulation to ground. Special treatment may be required for the start and finish leads depending upon the lead configuration which will be covered later. Metallic bobbins require a barrier insulation between the coil and the walls of the bobbin. A suitable barrier material is pure muscovite mica pre-shaped to apply sufficient thickness to withstand the electrical potentials. Special attention must be given to the corners and any joints in the mica. A composite mica glass cloth may also be used. This composite material is very difficult to handle after the insulating silicone varnish is removed by heat cleaning. Composite material should be used only when muscovite mica is unobtainable. A satisfactory barrier insulation for low voltage coils on metallic bobbins is two thicknesses of 0.002" thick muscovite mica type NMF per HH-I-536 or type V-3 per ASTM D-351.

**Coil Winding**

Coil winding is accomplished on a winding machine and de-reeler set up to maintain control of the placement and tension of the wire during the winding process. The conductor wire insulation after the varnish is removed is very soft and fragile and care must be exercised to preserve this insulation. The de-reeler must be of the type that allows the wire spool to rotate, drawing the wire from the spool in a...
radial direction. Friction tension devices that slide on the wire must be avoided. Successful production has been obtained with a de-reeler having an automatic brake on the spool rotation axis and a release arm adjustable in tension incorporated in the first wire guide.

The coil winding machine must be equipped with wire guides to produce layer windings. The final wire guide must be below the coil and hold the wire below the surface of the encapsulant. Due to the properties of the encapsulant, this guide should be of stainless steel. Special attention must be paid to the guide support mounts and bearings to obtain the required alignment.

The coil must be wound slowly with each turn located as well as possible. Winding slowly will allow encapsulant to wet the coil conductor and to be carried into the coil. Excess encapsulant will be carried to the coil and occasional stops may be required to allow this excess to return to encapsulant storage. The helical winding lead should be adjusted to 0.0015" greater than the measured insulated wire diameter for an optimum winding. The insulated wire diameter should be established by measurement after the silicone varnish is removed by heat cleaning.

When the winding is completed with its lead arrangement, an outer layer of insulation should be placed on the coil. This may be a layer of sleeving, tape, or tie cord. This layer should be well filled with encapsulant to provide a uniform surface. Excess encapsulant on the outside will cause excessive cracking of this surface.

Coil Lead Wire

In a number of instances it is desirable in coil design to have a stronger wire for the leads, than the wire used to wind the coil. A stronger wire resists damage in coil connection and in handling, better than the winding wire. A coil lead wire should be of stranded construction which although larger in size, is more flexible and less subject to damage from bending than a solid wire. A coil lead wire developed for this application consists of seven strands of 30 AWG
oxalloy wire in rope lay. This wire is insulated with woven glass insulation of Owens Corning "S" glass.

This lead wire is attached to the coil winding by welding with a Cannon Percussive Arc Welder. In order to make a satisfactory joint a sleeve of copper is applied both to the winding wire and the lead wire.

The copper sleeve reduces the welding problem by making the weld section more uniform in size, supporting the wire mechanically for stiffness, excluding oxygen from the welded wires and supplying material to the weld interface. For mechanical strength a portion of the lead wire is wound into the coil body as a part of the coil. This prevents forces applied to the lead wires from being applied to the coil winding conductor.

The attachment of the lead wire to the coil winding wire produces a rough spot in the coil body. This roughness must be prevented from damaging adjacent turns of the coil by sleeving or a pad of insulation, preferably mica, between the lead joint and the coil body. The two lead joint welds must be the only joints within a coil body.

**Coil Lead Wire Insulation**

Coil lead wires must be insulated from the same types of destructive forces the coil winding wire may be subjected to. A glass sleeving or the woven glass insulation on the lead wire is normally sufficient for most applications. If either the start lead or the finish lead lies along the coil side or against the coil where the coil wires are normally at a different potential than the lead wire, full ground insulation must be applied between the lead and the coil. This insulation is not needed for the normal potential differences of the coil but for the high potentials, called inductive kicks, developed when an inductive circuit is opened.

**Coil Cleanliness**

A coil and its components must be clean during winding and kept clean through the life of the coil. Removal of varnishes in the
winding wire and composite mica, as included in the discussion of those items, will adequately clean off normal contaminations such as skin oil. Other contamination must be removed by cutting out the contaminated sections. After the varnish is removed the material must be kept clean in plastic bags or special cabinet storage.

All other components must be clean. This requires checking prior to winding. If there is any question as to the components being clean, they must be re-cleaned. Ceramic bobbins, sleeving, lead wire, tie cord and similar items may be re-cleaned by a high temperature air atmosphere bake similar to that used for varnish removal from winding wire. Metal bobbins and metal parts may be re-cleaned either by the process specified on the drawings, or by a wash in acetone and/or alcohol. To maintain cleanliness all cleaned parts must be stored only in special cabinets or sealed plastic bags.

Handling

Handling of components, wire and finished coils should be held to the minimum. Bending of the wire will cause detrimental effects that reduces the capabilities of the wire in that section. Handling of the coil before curing may damage the coil surface and coil tie, while handling after curing will loosen the lead wire insulation and may cause breakage or chipping of the coil surface. Contact between the coil and hands or contaminated equipment must be avoided by use of gloves and similar protection. The clean and dry coils must be stored in sealed plastic bags, special containers or cabinets.

Coil Curing

Coil curing is to be performed to the applicable specification for the encapsulant. This specification should include the following general conditions to insure the most satisfactory coil. When the encapsulant is an acid base material, a vacuum dry operation is desirable to remove excess acid prior to subjecting the winding wire to the temperature cure. This reduces the hot acid reaction on the wire. This vacuum drying is not as important on a highly inhibited encapsulant as one that is not inhibited.
Coil curing should be performed in a vacuum of $1 \times 10^{-4}$ torr pressure or less. Coil curing consists of increasing the temperature of the coil to 200°F above the maximum service temperature of the coil and holding the coil at this temperature for three hours. For relative low temperature ceramic coils, a cure temperature of 800°F minimum should be established. As the coil temperature increases through the 150° to 200°F range and again the 250° to 300°F range, a considerable outgassing load should be expected. When this occurs the rate of temperature increase must be reduced to maintain the required vacuum.

Curing at a temperature 200°F or more above the maximum service temperature, allows thermal cycle testing at 100°F above the maximum service temperature to remove infantile mortality failure from the coil. A satisfactory thermal cycle test for this purpose is to increase temperature to test temperature, hold for one hour minimum and reduce temperature to less than 400°F. The desirable rate of temperature rise and fall is 15°F per minute. Five of these thermal cycles have been adequate to check the quality of coils. The usual method of failure is an open coil at the maximum test temperature.

Coil Testing

Coils should be tested for conductor resistance and when coupled with a ground wall or built on a metal bobbin, the coils should be tested for insulation resistance. Conductor resistance should be taken and recorded after winding and curing, at the maximum and minimum temperatures on each thermal cycle and before delivery. The maximum deviation from calculated value should be less than 10%.

Insulation resistance should be taken at the same test conditions as outlined above. Insulation resistance should be measured at 50 volts or less when hot unless the coil is intended to carry higher voltages when hot. Any room temperature coil should be able to pass a 1000-volt test to ground.
Coil Design Limits

Coils designed in accordance with the above information are suitable for continuous operation at 1100°F and a pressure of $1 \times 10^{-4}$ torr or less. Under these conditions an operating voltage of 28 volts may be applied across the coil or between a coil lead and the case. The maximum allowable current density in the coil will depend upon the applied duty cycle. For duty cycles where the coil is energized for periods of time of a few seconds the allowable current density may be 2 or 3 times the allowable continuous current density. The continuous current density has been determined from limited testing at temperature to be 7,500 amperes per square inch of conductor cross section area.