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Magnet Wire Bonding

by
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After electrical coils are wound, they must be somehow secured in place, so as to avoid wire movement, thus damage. There are various wire securing methods in use today. This paper describes a method that does not require any additional material, and uses very low energy inputs.

Background

Normally, coil wires are held in place on bobbins, with tape, wax, or plastic hot melt. The coil is wound and held under tension while it is wrapped in tape, or wax is dripped on it. In combination with the walls of the bobbin, the tape or wax effectively holds the wire in place. For coils that are wound on bobbins, this is the most effective means for securing the wires.

Many free standing coils are wound, which do not use any type of bobbin form. Normally, the magnet wire is coated with an additional layer of heat and/or solvent activated adhesive (for certain high voltage coils, liquid adhesive is sprayed on the wire while winding, and then allowed to air or heat cure). This adhesive, which is usually a polyvinyl butyral, utilizes a low temperature thermoplastic resin. This means that the bonded adhesive can come apart after a certain minimum temperature is reached, or it again comes in contact with the solvent. Normally, this temperature is much lower than the base magnet wire insulation's thermal rating. A coil wound with this type of adhesive coated wire is usually designed for a relatively low heat rise, and non-rotating or non-moving components.

The adhesive is activated by either passing the wire through a solvent while winding, or heating the finished coil. Heating can be accomplished by passing current through the coil and using the coil's electrical resistance to create heat, by using external radiant heaters, or convection ovens.

When working with electric motor armatures and stators, two other methods are used to secure the wires in place. One is dipping the whole component into a varnish like material, and then baking off its solvent. The other is the trickle impregnation method, which uses heat to cure a catalyzed resin, such as polyester or epoxy, which is dripped onto the component. Tape or stringing is sometimes used to secure stator coils, sometimes also in combination with the varnish or the trickle method. Tape is normally hard to apply and handle. Therefore, its usage is decreasing. Stringing usually requires a lacing machine, which is expensive and not practical for two pole D.C. or universal motor stators.

Varnish dipping is an effective way of securing armature and coil wires, but it is a very messy system. After the components are dipped in the varnish, they continually drip until enough solvent is evaporated. This causes a build-up of varnish around the dip tanks and heating ovens, as well as the dipped coils. The fumes from the varnish's solvent must be viewed as a possible air pollutant, and therefore, controlled. Also, certain areas of the armature and stator that must be kept clean, will become coated with varnish, and therefore, must be cleaned in a separate operation.

Trickle impregnation is the most widely used anchoring method for D.C. or Universal Motor armatures and stators, today. It is a valid system, but with two major drawbacks; energy usage and complicated chemistry. The armature or stator coils are preheated, resin is dripped onto the coils and the coils are again heated to cure the resin. Two common methods of heating are now in use, external radiant heating and internal resistance heating. In the United States, radiant heating is the predominate method.

The chemistry of trickle impregnation is both complicated and messy. When working with epoxy, chemicals must be mixed. Polyester does not require mixing, and because of this, is normally used in the United States. However, uncatalyzed resin is highly flammable and can set in delivery nozzles or tubing and its noxious fumes must be controlled.

Radiant heating requires enormous amounts of input power per component. This is because the radiant heaters must be kept on, even when components are not being heated. A study was made in 1983 which showed that $0.038 (U.S. $) of electrical energy was used per medium size stator on a radiant heated trickle impregnation line. Resistance heating shows similar inefficiencies. As heating is slow, the entire component including iron, shafts, etc. must be raised to the preheat and cure temperatures.

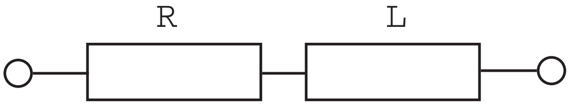
A clean, uncomplicated, and energy efficient method of anchoring has been searched for, for many years. In the last few years, magnet wire manufacturers have developed heat activated adhesive resins that are either high melting linear thermoplastic, thermo-set or hybrid material, which may contain multiple mechanisms for development of bond strength. We will not discuss the chemistry of the adhesive coating in this paper. We will, however, discuss how we use it.

Heating

The most efficient method of heating coils wound with heat activated adhesive, so as to bond them together, is by passing current through them very fast, so that only the coil reaches bonding temperature, not the entire component. A.C. or D.C. current can be used. However, we have found through experience that A.C. power delivers a better bond with these types of bondable wires. This is because the resin does not flow very well and all wires must touch one another, in order for a bond to take place. A.C. power will vibrate the coil wires and allow them to wipe together. In order to get a coil to bond as completely as possible, the wires must wipe against each other.

As we obtain better results with A.C. power, we must understand that we will also run into a serious problem by using it. Because we are working with stator or armature coils, we have to consider the effect of the component's iron core on the heating of the coil. If there was no iron, we would have very few problems when heating with A.C. If we use D.C. power, the iron would not play any real part in the control of the heating. However we must use A.C. power, and coils wound around iron cores, and therefore, must understand the problems.

If we assume that capacitance is negligible, any coil can be represented electrically by a series combination of resistance and inductance.



Where:
R = Resistance
L = Inductance

In heating the coil, an electrical current can be passed through the wire. As stated above, it is most effective to use alternating current. However, the inductance will restrict the current flow when using A.C. While this is not a problem, it should be remembered that the total “resistance” to current flow is higher than the actual D.C. resistance of the coil. This total resistance is known as impedance. For any coil, the impedance represented by the symbol Z. can be calculated as:

$$Z = \sqrt{R^2 + X_L^2}$$

Where:
R = Resistance
$X_L = 2\pi FL$
F = Frequency (50 or 60 Hertz)
L = Inductance

While it is important to know the impedance, it is equally important to know the quantity of heat required to raise a volume of copper or aluminum to a given temperature. Below we will illustrate mathematically how we raise copper to 200° C (392° F). We are using this temperature, as it is a midrange bonding temperature. We use 180° C (356° F) as the rise temperature, as it is the 200° C (392° F) bonding temperature, less a normal ambient temperature of 20° C (68° F).

$$Q = M \quad C \quad \Delta T$$

Where:
Q = Quantity of Heat
M = Mass of Material
C = Specific Heat of Material
ΔT = Temperature Difference From Start To Finish

When converted to electrical units of energy, we get 34,500 watt seconds per pound for copper and 73,205 watt seconds per pound for aluminum.

If we now want to know how much energy is required to heat the coil, we must find its weight with the following:

$$\left[\quad \left(\frac{R}{12}\right)^2 \right] (L)\ (\text{Density})$$

Where:
R = Wire Radius in Inches
L = Length of Wire in Feet
Density = For Copper: 554 Pounds Per Cubic Feet
For Aluminum: 168.5 Pounds Per Cubic Feet

The length of the wire used in the coil is usually determined by a resistance measurement taken with a wheatstone bridge and the following equation:

$$L = \frac{R x C_M}{R_S}$$

Where:
L = Length of Wire
CM = Circular Mils of the Wire
R = Resistance of Wire
Rs = For Copper: 10.37
For Aluminum: 17.0

From the above equations, it might seem obvious to simply calculate the energy required from the physical parameters and fix a time for applying that energy. In other words, a time-current level to reach a specific temperature. This time-current method is acceptable for heating a coil, in order to bond it. It is used in many production facilities, and has given excellent to fair results for simple coils that are wound on relatively slow and accurate winding machines. However, on a high speed production basis, there are wide variations in resistance, due to the way the winding machines lay the wire, manufacturing tolerances for the wire, and the physical geometry of the component. A potentially greater problem is line voltage variation. A 4%. line voltage change will give us a possible 16% change in coil temperature. If we use the same time and/or current to bond the same type stators or armatures, we will obtain different levels of heat, which will affect the bond’s strength. Therefore, a device to sense either the initial impedance and the final impedance, or the initial temperature and the final temperature, should be used. This device could act as a real time or closed loop quality control instrument. Devices to sense, monitor, and control impedance and temperature have been developed and are now being used to control the bonding cycle.

DC Bonding

There are times when the use of AC current is just not technically practical. This usually occurs where extremely large volumes of iron or steel are in very close proximity to the coil as it is being bonded. Using DC would then be more appropriate, so there does not have to be any attempt to control the coil's impedance.

If high voltages are required, very expensive rectifying devices will be required. These rectifiers, which are sometimes water cooled, are not required for AC bonding.

A typical use of DC bonding is when large free standing coils must be bonded directly on the coil winding machine's tooling. DC is used to eliminate impedance problems because of the winding machine's steel construction.

Thermal Control

A thermal monitor/controller was developed for commutator fusing. This patented device is used by many electric motor manufacturers to assure reliable connections to the commutator Later, other thermal monitor/controllers were developed for automatic brazing and thermal coil bonding.

The Thermal Coil Bonding Monitor/Controller uses a fiber optic assembly to direct energy from the coils being bonded, to a thermal detector. When a preset temperature is sensed by the detector, the current being applied to the coil is interrupted. All physical matter above absolute zero emits infrared radiation that is directly proportional to its temperature, in accordance with certain physical laws. As a result of this phenomenon, opto-electronic systems using infrared detectors can rapidly and accurately monitor the heat producing or heat conducting characteristics of an object or process without contact.

The use of fiber optics as a sheltered optical path, and window, enables the temperature of the part to be monitored and controlled, while the part is inaccessible. Temperature measurement, accuracy, and long term stability can be assured by remotely locating the detector and signal processing electronics away from environmental hostilities; thereby eliminating process related problems (i.e., R.F. or electrical noise, thermal drift, atmospheric attenuation, etc.), as well as overcoming the physical mounting of the thermal detector.

Infrared radiation emitted from the target area is collected and transmitted through a coated fiber optic by a process of multiple internal reflections, to a photon detector located in the electronic processing unit. The collected radiant energy is modulated before it reaches the detector. This modulation is performed in order to insure optimum performance from the photon detector, and to keep background temperature variations from adversely effecting the accuracy of the measurement. The photon detector converts the received radiant energy to a proportional A.C. signal. This signal is then processed with digital circuitry.

The side of the fiber optic not attached to the electronic processing unit can be in contact with the coils being bonded, or can be in a lens housing. When in a lens housing, there can be a distance between the lens and the surface of the coil. Without the lens, the fiber optic can actually touch the surface of the coil or be a predetermined distance from it. Normally, it is never more than 0.15 inches (3.8 mm) from the coil's surface. The determination as to which method of applying the fiber optic to the coil depends upon the coil's geometry. A physical contact or small gap fiber optic would be built into the machine's tooling when bonding stators. A lens system might be used, say, when bonding armatures.

A predetermined peak temperature is digitally entered into the electronic processing unit. The accuracy of the system is ±1% of the scale setting in degrees Fahrenheit. The response time of the system is 5 milliseconds.

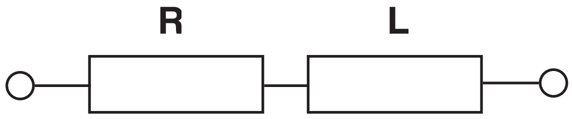
The thermal coil bonding monitor/ controller is an accurate and easy to use system. No calculations are required. However, the thermal monitor requires separate contactors which are normally thyristors, and separate protection against coil shorts. If there is an open in the coil, the thermal controller could be looking for peak temperature forever. An override system is, therefore, built into the controller, to indicate a problem, if the peak temperature is not reached in a given predetermined period of time.

One of the problems with using a thermal coil bonding monitor/controller, is determining where the temperature is to be read. Until recently, the temperature was read at the surface of the magnet wire's insulation. This was not acceptable, as the heat dissipated from the wire took too long to get through the insulation. However, recently, new photon detectors, fiber optics and techniques have been developed that allow the reading of the temperature on the surface of the wire, through the magnet wire's insulation. This technique treats the insulation as not even existing. Therefore, the thermal monitor/controller can terminate the bonding power, as soon as the actual wire in the coil reaches the predetermined bonding temperature.

Impedance Control

An Impedance Controller includes its own thrysistors and circuitry to sense coil shorts. It requires complicated mathematical inputs that are derived from the equations outlined below. Because of this, a powerful microprocessor must be used in the controller.

If we go back to our original statement that the coil be represented as:



and the impedance

$$Z = \sqrt{R^2 + X_L^{\,2}}$$

As electrical energy in the form of an alternating current is applied to the coil, the only heat developed is in the resistive portion of the circuit. As the wire heats, the resistance increases and the current will, of course, decrease. The wire heats uniformly and quickly. The resistance follows the equation:

$$R = R_0(1 + \alpha T)$$

Where:
R = Resistance at Elevated Temperature
R_0 = Original Resistance (at ambient temperature)
α = For Copper: 0.00393
For Aluminum: 0.0039

It can be seen from the above that the initial current is a function of the initial impedances if the impedance is high, the current is low; if the impedance is low, the current is high. On most coils, the time that is required to heat the coil to a given temperature is inversely proportional to its initial impedance, thus a circuit can be developed to set the point at which the current to the coil is turned off. If the initial current is higher than the nominal (impedance is lower) the coil will take longer to heat, and hence, longer to get to its peak bonding temperature. If, on the other hand, the initial current is lower than the nominal (impedance is higher) the coil will take a shorter period of time to heat, and hence, a shorter time to reach its peak bonding temperature. From the above, it can be seen that an Impedance Controller can be developed to control the temperature of the coil.

The impedance controller can control bonding temperature. However, the Thermal Monitor/Controller will control the coil's actual temperature more efficiently and more accurately.

Stator Bonding

When bonding D.C. or universal motor two pole stators, both coils are normally bonded simultaneously. The coil end turns are clamped under pressure, so that all the wires touch each other; thus there is assurance of all the wires being bonded. Two types of clamping pressure are used. One only compresses the coil, so that it follows the shape as produced by the winding machine, The other actually forms the end turns to a new shape.

Forming tools are made of molded rubber, as well as plastics, ceramic, and metals. Molded rubber and plastic tooling are an economic, versatile, and safe medium. However, if actual forming is required, rubber and plastic tooling might not be strong enough. When tooling is made of a harder material, it must be faithfully maintained, or it can damage the coil's insulation.

Various machines are available for bonding stators, from simple one station units to fully automatic systems. Contact between the stator coils being bonded and the bonding power supply can be made to stranded wires attached to the coils, directly through the actual magnet wire insulation, or to terminals set into the stator. The type of contact also determines the type of machine to be used. Stator bonding has been used for years by almost every type of motor manufacturer, even for power hand tools.

Armature Bonding

Normally; all of the armature's coils are bonded at the same time. It is also possible to bond one or two coils at a time, but this is not always practical. Contact is made by electrodes that apply a predetermined pressure on the commutator's brush track. The armature, when bonding one or two coils at a time, is indexed from one commutator segment to another. The machine dwells between each index step, so that bonding current can be passed to the specific coils. When bonding all the coils at one time, the armature is not rotated.

It is not easy, in production, to properly clamp the end turns of an armature during bonding. In order to avoid any loose wires, a few drops of a polyester resin, thickened with powdered mica, can be placed on the end turns. This resin/mica mixture only coats the surface of the end turns, so that any loose wires are tied down. It is not intended for the resin to seep into the coils, as in trickle impregnation. The coils themselves are bonded with the magnet wire's heat activated adhesive overcoat material. The resin/mica mixture will be cured by the temperature of the bonding cycle. Heat shrinkable tape can also be used to hold any loose end turn wires. However, it is difficult, in production, to apply this tape.

Production Speed and Reliability

Under normal conditions, the bonding cycle takes 0.75 to -1.75 seconds per bonded coil or group of coils. The levels of energy required to bond at these speeds are at about the limits of the wire. If the wire is within the wire manufacturer's tolerance, and not stretched or damaged, no problem should occur. However, more than reasonable damage, or out of tolerance wire could cause the coil to blow apart. We have found that wire tolerance problems just do not normally occur. Other problems do.

Minimal problems occur because of mechanical damage to the wire during winding. Stretching and scraping of the insulation are the most common. These can be controlled and easily identified. Scraping of the insulation can sometimes be detected as a massive short by the protection circuitry built into the bonding power supply.

The most serious problems occur at the connection to the coil. If there is a high resistance joint at the termination, the coil can be destroyed. If a low resistance connection is made, but the wire is mechanically damaged at the termination, (i.e. by stretching, nicking, etc.) the coil could also be destroyed. The solution is tight control over the termination process.

It is best to run a high-pot test before applying bonding current. This eliminates coils with possible shorts, damaging the machine's tooling. It is also possible, but not recommended, to high-pot test the coils after bonding. Bonding machines are available that incorporate automatic high-pot testing.

Economic Factors

Magnet wire with a heat activated adhesive overcoat costs more than the same class of non-bondable magnet wire. However, less than two seconds of electrical power is required to bond the heat activated adhesive coated wire. With trickle impregnation, minutes are required to create a valid bond. It has been shown over and over again that the higher wire cost is more than offset by the savings in energy.

On the average, bonding machinery costs about half as much as trickle impregnation machinery. On the lowest production end, there is a four to one savings. In the long run, the return on investment should be even greater, as less maintenance is required and the machinery should have a longer life, as it is simpler.

The thermal controllers are accurate and extremely reliable. The time/current method has a tolerance of about ±20°. This means that if we are attempting to heat a coil to 200° centigrade (392°F), we would actually heat within a range of 160° Centigrade (320°F) to 240° centigrade (464°F), which is not always acceptable. The time/current method eliminates the need for calculations or optical maintenance. However, using a thermal monitor/controller almost guarantees perfect results. It should be considered for any high production system.

Conclusion

With the heat activated adhesive magnet wire available, a valid and economic alternative is available for armature and stator bonding. It has been proven in production as a reliable and simple method. Eventually, this bonding system will he the predominate one throughout the world.