Electromagnetic Devices for Operation in High Temperature Ambient of 1000°F (500°C)

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1.0 Introduction

There has recently been increased interest in motors and position sensors that can operate in ambient temperature environments of 1000°F (or approximately 500°C). This paper describes the material requirements and design impacts of electromagnetic devices for use in this type of temperature environment.

2.0 Materials

Most typical materials used to fabricate electromagnetic devices such as copper wire and permanent magnets cannot work at elevated temperatures anywhere near 1000°F. Each primary material presents its own challenges as discussed below.

2.1 Magnet Wire

Electromagnetic coils of most typical electromagnetic devices are wound from copper magnet wire. Copper magnet wire is available with many different types of insulation with the highest temperature insulation being a polyimide varnish rated for operation at a maximum temperature of 450°F (230°C). This wire is typically used in sizes that range from 20AWG down to 35AWG depending on the particular application.

The most readily available higher temperature alternative for copper magnet wires in this size range is stainless steel clad copper wire with ceramic fiber insulation. This particular type of wire was developed for use in high temperature sensors and thermocouples. It is available rated for maximum temperature operation of up to 1300°F (~700°C). This type of wire is not a drop in replacement for standard copper magnet wire, however. Due to the ceramic insulation, the minimum bend radius of this type of wire is quite large. Due to the stainless steel cladding, electrical connection of this type of wire must be done by welding, rather than traditional means such as soldering.

2.2 Magnetic Steel

The wire of an electromagnetic device is typically wrapped around some sort of magnetic steel structure. The magnetic steel creates the magnetic flux path that the device needs to operate properly. Common magnetic steels are made from silicon-iron, nickel-iron, and many other specialized configurations. These magnetic steels are typically formed into laminations, which are punched from 0.014” or 0.010” thick material. The laminations usually have some sort of insulation coating applied to their outer surfaces to electrically isolate each lamination.

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Magnetic steels actually perform better at higher temperatures. As temperature is increased the saturation flux density increases and the losses decrease. Most typical magnetic steels will work at temperatures well above 1000°F. The primary concern with using typical magnetic steels at elevated temperatures is the surface insulation. Some available insulation types are rated for operation at temperatures above 1000°F. There also are some magnetic steels available that are specifically tailored for high temperature operation.

2.3 Winding Insulation

The magnetic steel structure of an electromagnetic device is typically composed of a stack of magnetic steel laminations bonded or welded together. This structure is used to define the magnetic flux path and to hold the wound coils of the device. In order to provide electrical isolation between the magnetic steel structure and the coils, the magnetic steel structure is usually covered with an insulating material. Various powder coatings are typically used as well as tapes and films of kapton, nomex, etc. None of the typical insulation materials will work in an ambient temperature environment of 1000°F.

There are some powder coatings available that are rated for operation up to 1000°F. If the device generates no internal heat, these powder coatings will work. If heat is generated such that the temperature exceeds 1000°F, ceramic becomes a good choice to use for an insulation material. Since ceramic is not readily available as a coating or in thin films its application is quite different than traditional materials. Depending on the particular application, some sort of ceramic insert or bobbin must be fabricated that can be installed into the magnetic steel structure. Fabrication of ceramic inserts and bobbins by machining is both difficult and expensive.

Machined ceramics must be relatively thick to have good physical properties. Thicknesses on the order of 0.05" to 0.15" are common. When compared to traditional insulation material thicknesses of 0.005" to 0.010", the extra space required becomes significant. The extra required space will drive the size of the device to be larger, when compared to normal construction.

2.4 Permanent Magnets

The most commonly used permanent magnet materials have maximum temperature ratings that are much lower than 1000°F. The two most widely used permanent magnet materials are Neodymium-Iron-Boron, which has a typical maximum temperature of 300°F, and Samarium-Cobalt, which has a typical maximum temperature of 600°F. These temperature ratings prevent either of these two high-energy magnet materials to be used in high temperature applications.

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There is only one commonly available type of permanent magnet material that can operate at a temperature of 1000°F. This particular material, Alnico, has a rated maximum temperature of approximately 1000°F. Compared to the high energy magnets listed above, Alnico is approximately 3-4 times less powerful, which means that the size of the electromagnetic device would have to grow significantly to maintain the same performance as a device using the high energy magnets mentioned above. Alnico is also more expensive.

Although Alnico can be used at temperatures up to approximately 1000°F, it will permanently demagnetize if this temperature is exceeded. So, if the ambient temperature is 1000°F, the device that uses Alnico magnets cannot generate any internal heat, or the magnets will demagnetize. A motor, for instance, will typically generate some internal heat, so careful consideration of the maximum expected temperatures should be given prior to using this permanent magnet material. If the application temperatures cannot be controlled to 1000°F maximum, then permanent magnet materials cannot be used. Other design schemes, such as switched or variable reluctance, should be pursued.

2.5 Adhesives

Epoxies and varnishes that are typically used in the construction of normal electromagnetic devices won't come close to working at a temperatures around 1000°F. Other means of bonding must be used. Alternatives to bonding such as welding of the magnetic steel laminations must be used. There are some ceramic adhesives and potting materials available that can be used well over 1500°F but their mechanical properties are not as good as typical materials.

3.0 <u>Device Size Considerations</u>

Changing typical materials used in electromagnetic devices to materials that can withstand high temperatures in the range of 1000°F or higher, generally causes an electromagnetic device to become larger in size.

The minimum bend radius of ceramic insulated wire increases device size because the coils cannot be as compactly wound as their standard copper magnet wire counterparts. The ceramic insulation thickness of the magnetic structure insulation makes the size even bigger. If Alnico permanent magnets are used instead of other higher energy types, the device size would need to increase even further to maintain similar performance.

For a simple solenoid type device, a diameter increase of 20% may be all that is needed to provide high temperature windings. A multipolar permanent magnet motor, on the other hand, might need a 100% or more increase in diameter to accommodate the high temperature coils and magnets. Device performance

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parameters that are sensitive to size and/or mass, such as inertia, will increase as well. Weights would increase proportionally to size.

4.0 Device Construction Considerations

High temperature materials impose a unique set of construction constraints. The ceramic insulated wire has a minimum bend radius. The ceramic insulation used to insulate the magnetic steel structure has a minimum thickness of approximately 0.05”. If magnets are used, they may require some sort of mechanical retention in combination with, or in place of high temperature adhesives.

Due to the minimum bend radius of the ceramic insulated wire, it cannot simply be wound around a tooth of the magnetic steel structure. A supporting structure such as a bobbin must be used to control the minimum bend radius of the wire. It could be possible to insulate the magnetic structure and then wind the coils in place, or it simply may be easier to wind individual bobbins and design the magnetic steel structure such that the bobbins can be inserted after they are wound. If the wire must be wound on bobbins, then the types of multipolar and multiphase windings that can be used becomes severely limited.

It is likely that mechanical retention of magnets to their supporting structure would be desired. Although some high temperature adhesives are available, mechanical retention would likely be needed at least as a backup to the adhesive. To mechanically retain alnico magnets, some sort of clamping mechanism would need to be employed. As mentioned previously, welding of the laminations of the magnetic steel structure would be the most likely alternative to bonding with adhesives.

5.0 Conclusion

Although the implementation is not trivial, electromagnetic devices can be manufactured that will work in ambient temperatures around 1000°F. Most typical materials used in electromagnetic device construction will not work in an ambient temperature of 1000°F. Alternative materials do exist, but do add additional design constraints and typically increase electromagnetic device size and weight.

6.0 About Firstmark

Firstmark Aerospace specializes in high performance electromagnetic devices for the aerospace industry. Our experience with electromagnetic device design and manufacture combined with high temperature materials gives us the unique ability to provide you with a product, which can operate at 1000°F. Our unique engineering expertise combined with years of product development experience give us the capability to handle your toughest electromagnetic device requirements. For more information, see our website, www.firstmarkaerospace.com, or contact us at the above address.