IMMINENT CHANGES IN SOFT MAGNETIC DEVICES

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ABSTRACT

Ferromagnetic composite iron materials are starting to penetrate applications previously dominated by cold-rolled laminated steel (CRLS) structures. This is being driven by the potential for reduced costs, reduced parts per component, and increased design flexibility. As electromagnetic designers become more familiar with ferromagnetic composite iron materials, traditional components such as electric motors, power generators and inductors will be redesigned to take advantage of powdered metal technology in general and ferromagnetic composite iron attributes. CRLS based designs, which are limited to two-dimensional thermal and magnetic flux paths, are now starting to be designed in three dimensions, thus taking advantage of the isotropic nature of ferromagnetic composite iron materials. This promises to allow designs that are more compact, easier to fabricate and encourage new designs that would be impractical or impossible to manufacture in 2 dimensions. Current and potential applications will be discussed, as well as novel uses for ferromagnetic composite materials.

INTRODUCTION

Ferromagnetic composite iron technology is not a new concept. Its origins can be traced back to the time of Fritts[1] and Heviside[2] in the late 19th century in the form of dielectromagnetic powders. At the same time, laminated iron was also being investigated and due to its better magnetic performance and application needs, soon dominated the industry. Over the next 100 years, with technological improvements in both high purity iron manufacturing and insulating materials, dielectromagnetic powders, or ferromagnetic composite powders fitted various niches in radio engineering and telecommunications[3].

With the advent of water-atomized, high purity, high compressibility iron powders, ferromagnetic composite iron technology has come of age. This has been supported by improved polymeric insulating systems, and advances in the understanding of dielectromagnetics in general. The greatest challenge now is getting the magnetics designer to design components based upon ferromagnetic iron composite properties and attributes. This includes making the designers understand that they now have the flexibility to design components in three dimensions: magnetically, mechanically, and thermally. At the same time, designers have to be educated as to the advantages and limitations of ferromagnetic iron composite materials. There are natural limits directly related to the physical attributes of these materials: powder packing, insulation resistance and grain size. For example, in high frequency magnetic applications utilizing fine powders from either water-atomized iron or the more expensive carbonyl iron, it minimizes grain size effects. Another way to study the effect of grain size might be by using iron powders with different particle size distributions. Weglinski[4] has described a more complete review of material properties and processing.

CURRENT FERROMAGNETIC IRON COMPOSITES

Although there are many ways to produce ferromagnetic composite iron (FCI) materials, in order to compete with CRLS materials, only a few techniques are commercially viable. These systems involve taking a dielectric material, typically organic in nature, and using it to insulate a high purity water-atomized iron particle. This can be accomplished separately with either a discrete encapsulation or coating step performed prior to compaction, or in-situ, during a compaction and/or curing step. As with any process, the cost of processing has to be considered when weighing its benefits. In some cases, prior to insulation application or compaction, the iron particles are pretreated in such a manner as to put a very thin oxide coating on the surface. The coating thickness can range from a few nanometers to the micron range, depending upon the process and desired attributes. Commercially suitable organic materials can be lumped into two categories: thermoplastics and thermosets. Thermoplastics have a softening range that can sometimes be exploited during coating and compaction steps. Thermosets generally require a thermal treatment after the compaction step[5]. Depending upon the type of thermoplastic used and the mechanical load, component operation at elevated temperature might be limited because of the potential for creep. This has to be evaluated on a per-application basis. Thermoset systems, once cured, generally exhibit excellent elevated temperature stability, both magnetically and mechanically. There are other materials systems under development and testing, but the two systems referenced above are probably the most cost effective for large, commercial markets at this time.

PROCESS AND DESIGN CONSIDERATIONS

As with any advancements in a technology, education is of prime importance. In the case of FCI materials, education is not restricted to just the magnetic component designer. Both the powdered metal parts makers and the end users have to understand the advantages and limitations of FCI materials when compared to a CRLS material.

Probably most important to the powdered metal parts maker is understanding how to process the FCI material. Unlike conventional powdered metal materials where a lubricant is admixed, then burned out during sintering, lubricants in FCI materials will generally degrade both the magnetic and mechanical performance of the compact. While there may be some benefit from the lubricant during compaction and ejection, the lubricant usually lowers the effective density of the component, ultimately reducing the maximum possible magnetic induction. In order to get around this problem, the lubricant content should be minimized or eliminated. Alternatively, parts can be processed at elevated temperatures (higher densities are typically achieved by warm compaction) in order to move the lubricant to the die wall and aid in part ejection. For a thermoplastic FCI system, both the die and powder may be heated. For thermoset systems, typically, only the die is heated in order to avoid premature polymerization of the thermoset material. Alternatively, die wall lubrication techniques may also be employed for any FCI system (or powdered metal system). Otherwise, most FCI materials process as conventional powdered metal materials. After compaction, a curing step is sometimes required in order to develop the final component properties, but the post-curing is typically done between 160?C and 350?C in air. In some cases, temperatures as high as 500?C have been used[6]. For lower temperature curing (<250?C) with thermoset systems, shrinkages are minimal, thus allowing for tighter tolerances based upon the die set and spring-back effects.

Designers have to be aware that components can now be designed in three dimensions. No longer are they restricted to the two dimensional lamination which limits properties mechanically, magnetically and thermally. They can also design structures with constant air-gaps because the materials can easily be formed into a simple circle of revolution, not previously possible with laminations. For a lamination, this can be envisioned by imagining a square lamination stack placed perpendicular to a diameter such that the width of each individual lamination is adjusted to fill the maximum area of the diameter. A very complex, step-wise lamination stack is then created in order to effectively fill the space. On the other hand, a FCI material could simply be pressed into the correct diameter, with a constant (instead of step-wise) air-gap between the soft magnetic material (FCI or lamination) and surrounding structure. Another potential attribute is that due to the composite nature of the FCI material and its associated isotropic properties. Stress management becomes simplified since there is no longer the danger of putting buckling stresses on laminations when the components are potted during subsequent assembly operations.

ECONOMIC CONSIDERATIONS

Lamination technology has dominated the electromagnetic industry for over 100 years. This makes it very difficult to compete with in terms of capitalizing costs and incorporating new technologies. Utilization of FCI materials requires that the cost of steel tooling be amortized throughout the production life of the component. Depending upon the complexity of the part, tooling can last many hundreds of thousands of strokes or less. Lamination tooling can have a life exceeding 100 million strokes, which makes the per–piece-cost very low. However, there is a much higher amount of scrap generated with a lamination, so FCI based components can potentially compete. Laminations sometimes require a separate coating step to develop the insulating layer. They also generally require an annealing step to remove residual stress from the punching step. FCI materials have the insulating layer built in, and stress reliving is either unnecessary or accomplished during the pressing or curing step. The case for FCI materials is further enhanced when one considers the systems cost. While a lamination design might require 50 strokes to produce enough laminations for one component, an FCI component is produced in one stroke. The 50 laminations also have to be assembled (stacked), which can sometimes involve deburring and weighing steps. Again, the FCI based materials can have considerable systems cost advantages.

Because lamination equipment is so predominant, there is little motivation to change. This is especially true when a designer familiar with conventional lamination attempts to design components with FCI materials. Generally, at frequencies below 60 Hz, FCI materials appear to be inferior in performance. However, when the design is modified to take advantage magnetically, thermally, and mechanically, FCI material can offer significant advantages. Probably the best known example of this is GM-Delphi's development of the ICE ignition core[7]. GM-Delphi took a conventional E-core lamination design and redesigned it for an FCI material. The result was a higher performance component in a smaller package, which costs less to make than a conventional lamination. It is this concept of redesigning to suit both the material properties and the processing attributes that will help vitalize FCI technology in the world.

Another important driver of FCI technology is the availability of both desktop computing and computer codes that can help the designer iterate changes virtually. New designs can be tried on the computer and tested against the design envelope. No longer does the designer have to go about producing expensive prototypes to see if the design will work. The majority of the testing can at least be initiated on the computer. The design can also be concurrently tested against the fabrication constraints dictated by the material. In the case of an FCI material, when the powdered metal parts fabricator requires a draft angle and beveled edge, the designer can quickly incorporate these requirements into the design and see what kind of effect it will have. In some cases, once the design is complete, actual machining templates can be created by the computer code to facilitate manufacturing of tooling to press the components. The use of computers can significantly reduce development time and costs, and give the designer new flexibility.

APPLICATIONS: PAST, PRESENT, AND FUTURE

Probably the oldest form of a FCI material is in a flyback transformer for high frequency applications. As mentioned previously, RF electronics applications have relied upon iron powder based FCI materials for many years due to its high saturation resistance. Variations on this include ferrites (iron oxide based), which can be used into the megahertz frequency range, but with much lower saturation resistance. There are many chokes and transformers made with iron based FCI materials. Some of these are used quite extensively in consumer lighting ballasts, computers, consumer electronics, and related applications. As mentioned above, GM-Delphi has successfully developed an ignition core for automotive applications. All of these applications have at least threatened the traditional lamination market, but have not gone any further due to resistance to change. However, new designs based upon FCI properties are starting to challenge the conventional attitudes. Moreover, with change, comes education. Simple one-to-one-substitution of an FCI material for a lamination is probably not going to work. The design has to consider the inherent properties of the FCI material and correctly substitute for the lamination properties. Battison et al[8] looked at the effect of changing one design parameter when substituting an FCI material for a 3% silicon steel in an automotive ignition core. A one-for-one replacement with the same air-gap as designed for the Si-steel lamination yielded an inferior result. By reducing the air-gap, the FCI material produced comparable performance, and reduced the parts count by a ratio of 25:1.

There are also many attempts at incorporating FCI materials into power generation device. One reason for failure has been due to the lack of mechanical strength when designed to directly replace a lamination. FCI materials currently do not have as great a strength as a lamination because the material only contains mechanical and polymeric bonds. Laminations, being fully dense, and originating from cast-wrought material, are metallurgically bonded, thus having considerably more strength. Because these devices are traditionally multi phase, they require a very complex winding pattern. This winding operation imparts considerable stress on the ferrous core and can on occasion, break a laminated core. Sometimes when FCI materials are directly substituted for a CRLS design, they are not capable of withstanding the rigors of conventional winding. However, when the component is redesigned to use a simpler winding and account for FCI attributes, significant performance improvements can be realized.

In one example of this, low speed performance and cost reduction were the main factors in considering an FCI material. A company had a requirement for both a minimum and maximum output for an alternator. Design requirements dictated that the FCI based component fit into the same volume and utilize the same drive system as the original lamination design. A prototype meeting the design requirements was built from FCI material supplied by QMP[5]. When equipped with rare earth magnets, the device produced 40% more power at the minimum speed and 30% more power at the maximum speed compared to the OEM design (3% silicon steel lamination). The designer also took the opportunity to redesign the winding pattern, which not only simplified the winding (minimizing stress and complexity); it also reduced the amount of copper wire, which translated into additional cost savings. The designer is now modifying the original FCI based design to use less expensive magnets in order to further reduce costs while meeting the low speed output requirements. With a 40% margin at the low end, and 30% at the top speed, chances are very good that the FCI based design will be brought to market with lower cost magnets.

In another study, researchers at Laval University looked at replacing an electric automotive fan motor with FCI materials. After performing a computer optimized design study, they developed two brushless-motor prototypes, which were both processable with conventional powdered metal techniques and fit the existing component envelope. Prototype stators were produced by wire EDM cutting solid blocks of a FCI material supplied by QMP[5]. The second iteration of the prototype further improved the torque response of the device. For both prototypes, concentrated windings, rather than distributed windings were utilized, which simplified the winding pattern and significantly reduced the amount of copper. The original motor contained 109 g of copper with the final prototype containing 76.5 g of copper. Results of this study will be released in a pending IEEE publication.

Another project under development is looking at an FCI material specifically designed for higher frequency applications, but with high current densities. The device is essentially an ignition source for an electric arc, and falls into the classification of a pulse transformer. GM-Delphi has already exploited FCI materials for low frequency pulse transformers, so this is essentially a high frequency variation. The design calls for a minimum of 25kV at 900 amperes, with a pulse width of about 300 nanoseconds. The designer currently uses ferrites, which cost anywhere from $6.00 to $9.00 per pound for the raw material. A FCI material produced 29kV under the same test conditions, with the cost estimated to be well under $2.00 per pound for the raw material. Further work is being done to optimize the design versus the fabricability of the material.

Future designs are only limited by the designer's imagination and the physical limitations imposed by powdered metal fabrication techniques. Where lamination technology essentially plateaued with a 2-dimensional structure, the inherent isotropic properties of FCI materials can stretch the envelope. For example, small, low frequency transformers are potentially the next frontier for FCI materials. There are literally millions of transformers designed to operate at 50-60 Hz. Current FCI materials with proper design can potentially penetrate a portion of this market. However, it will also require improved design philosophies and education of the end users. At face values, FCI materials will always appear to be lossier than laminations. However, low frequency transformers are typically inefficient, so by redesigning the transformer around FCI magnetic and fabrication constraints, a FCI based transformer with similar efficiencies can theoretically be produced at a lower cost than a lamination-based design.

In the area of electric motors, FCI materials can make a significant impact. Disk motors are currently under development, which require the placement of laminations perpendicular to the axis of the disk[9]. This design is extremely difficult to build with laminations. Incorporation of FCI materials would make it far easier to fabricate because of the isotropic properties of the material. Small brushless and switched reluctance motors are also possible. With the advent of inexpensive electronic control systems, these motors when made from FCI materials, can compete with more conventional lamination based designs and offer more features, such as variable speed and stepping functions at a fraction of the cost.

As the world moves towards more environmentally friendly modes of transportation, there will be an increased demand for electric motors and power generating devices. The car of the future could be entirely electric or utilize hybrid systems consisting of hydrocarbon or hydrogen powered generators driving electric powertrains. Electric drive systems for bicycles, scooters and light vehicles are already on the drawing boards[10]. The technology is here and like many other imminent technologies, needs to find the critical application that will propel it into the future.

CONCLUSION

Ferromagnetic Composite Iron materials are breaking new ground in the area of soft magnetic applications. While in the past the technology has been limited by raw materials input and a general prejudice from the lamination side of soft magnetics, new advances in insulating materials and design methodologies (computer code and its availability) are making FCI materials more commercially viable. As FCI materials gain acceptance by designers, they will at least be tried in specific applications. It is in the trying of these materials that they will gain acceptance, since from a technological standpoint, FCI materials are reaching maturity. And as the global demand for lower cost goods increases, the soft magnetics industry will be forced to utilize materials better, and more efficiently. Powdered metal fabrication techniques when combined with FCI materials make this a very attractive technology.

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