THE NEED FOR 3D PRINTING OF AIRPLANE ELECTRIC MACHINES

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***Abstract* – As only provided with an "active" rotor assembly of the symmetric circuit and control architecture of SYNCHRO-SYM as the exception,[1] all electric machine systems for electric airplane propulsion are actually the same century old asymmetric electric machine circuit and control architectures with a "passive" rotor assembly of permanent magnets, DC field windings, slip-induction windings, or reluctance saliencies that only achieve distinguishable performance enhancement by introducing a refined selection of available (or futuristic) high performing material, winding, packaging, manufacturing, thermal management or electronic control techniques. Since its conception (circa 1950s), amorphous metal ribbon (or its nanocrystalline counterpart) has significantly better electromagnetic properties for electric machine cores than any available electrical steel but has never been successfully applied in an electric machine system, although attempted several times, because of extreme tool wear or worse, irreversible damage to its delicate magnetic properties with traditional methods of manufacturing the core slots and the precision flat air-gap surfaces. Although 3D Printing has been proposed as a manufacturing solution, such as by ARPA-e,[2] empirical studies orchestrated by Best Electric Machine show that MOTORPRINTER is the only practical 3D Printer concept in development for the additive manufacture of amorphous or nanocrystalline electric machine cores with integral frame and bearing assembly.**

***Index Terms*—brushless, real-time, sensor-less, synchronous, wound-rotor, doubly-fed, electronic power transformer**

I. INTRODUCTION

As only provided with an "active" rotor assembly of the symmetric circuit and control architecture of SYNCHRO-SYM as the exception,[3] all electric machine systems for electric airplane propulsion are actually the same century old asymmetric electric machine circuit and control architectures with a "passive" rotor assembly of permanent magnets, DC field windings, slip-induction windings, or reluctance saliencies that only achieve distinguishable performance enhancement by introducing a refined selection of available (or futuristic) high performing material, winding, packaging, manufacturing, thermal management or electronic control techniques. For instance, development in high frequency electronic control for high speed electric machine systems are being pursued to reduce the size of the electric machine system and thereby, reducing the volume of preciously expensive rare-earth permanent magnets while seemingly disregarding the compounding size, cost, and inefficiency of the necessary but extraneous gearbox and high power, high frequency (HP-HF) magnetic cores for the electric machine, which includes the HP-HF transformer of the electronic controller. This brings us to the common understanding that "we need better magnetics," such as magnetic material, conductors, and insulation or enabling manufacturing techniques, such as 3D Printing.[4, 5] In response, Best Electric Machine is fabricating a patented additive manufacturing tool (or 3D Printer), called MOTORPRINTER, that additively manufactures HP-HF wound, axial flux, high electromagnetic performance amorphous metal (or nanocrystalline) ribbon electric machine cores with integral frame and bearing assembly.

3D Printing is additively layering material with effectively dynamic 2D shapes to form a 3D dimension. Ideally, layering is at the atomic level but in reality, it is the material substrate level, such as powders, resins, etc., which is premanufactured to be compatible with the 3D Printer and not the product being manufactured. Therefore, there is always waste in the neighborhood of 10-30%, which in most cases is always better than the alternative of subtractive manufacturing. Besides low waste, a major benefit of 3D Printing is the ability to manufacture shapes, such as internal shapes, that is impossible with subtractive manufacturing.

II. PERFORMANCE ELECTRICAL STEEL RIBBON

Since its invention (circa 1950s), amorphous (or glass) metal ribbon has been a magnetic core material, such as electrical steel ribbon, with excellent high power and high frequency magnetic properties, such as high permeability, low hysteresis and core losses, and high flux density saturation limit. Although successful in utility power transformers, amorphous metal ribbon is seemingly impractical for electric machines because of extreme tool wear or damage to its delicate magnetic properties when forming the precision flat air-gap surface or the slots for holding the permanent magnets, reluctance saliencies, or windings with conventional manufacturing methods. But compared to electrical steel ribbon, amorphous metal ribbon retains the same structural strength but reduces core losses by at least 80% and increases core permeability by at least a factor of ten for reducing magnetizing MMF, for reducing the amount of expensive rare earth permanent magnet material, or for providing narrower but deeper slots for smaller diameter electric machines. By annealing the amorphous metal ribbon core to a recrystallized state with extremely small, uniform grains, nanocrystalline metal ribbon, such as FINEMET, is a more recent advancement in electrical steel ribbon with much higher permeability, lower core loss, lower magnetostriction, and comparable flux density saturation than amorphous metal ribbon.[6]

Note: Because of the extreme difficulties of manufacturing amorphous metal ribbon electric machine cores, including electric transformer cores, with programmable shapes of precision slots and perfectly flat air-gap surfaces, an alternative is the 3D Printing of soft magnetic composite (SMC) material by a patented innovative method of sputtering layers of melted metal droplets (or grains) into a magnetic core shape, all of which is enclosed in a sealed chamber of gas that deposits an oxidized coating of insulation on each droplet. Like all SMC cores, the encompassing insulation layer on each droplet does provide lower loss magnetic cores but detrimentally shows magnetic cores with very low magnetic permeability and structural strength, if compared to amorphous metal ribbon cores.

III. MOTORPRINTER CONCEPT OF OPERATION

MOTORPRINTER is the only practical additive manufacturing means for any family of high power, axial-flux electric machine cores, such as synchronous, asynchronous, reluctance electric motors, generators, and transformers, with amorphous or nano-crystalline metal ribbon, which is the strongest and highest performing HP-HF electromagnetic material available, and with integral frame and bearing assembly.

Note: Theoretical considerations by Polard showed the axial-flux (or adjacent rotor and stator disk form) electric machine reduces copper utilization by 13-14% and reduces iron utilization by 21.5-32.5% over a similarly rated but very common radial-flux (or cylinder inside a cylinder form) electric machine, while providing higher torque density and fine adjustment control of the air-gap depth without rotor and stator surface contention during speed.[7] Already, the axial-flux form is dominant for the electric vehicle traction motor market and should be dominant for electric airplane propulsion.

MOTORPRINTER follows the less common method of additive manufacturing (or 3D Printing), called laminated object manufacturing 3D Printing.[8] Accordingly but without providing other trade secret details, MOTORPRINTER builds the final form of the desired axial-flux electric machine magnetic core with any optimized slot shape by “adding” one thin layer of metal ribbon at a time, such as amorphous metal ribbon, with the shape template of the immediate layer removed by a laser cutter before layering on the previous layers of the axial-flux core with the new layer of slots perfectly aligned into slot channels. Laser cutting the slot template on a single pre-layer significantly reduces heat stress and damage to the electromagnetic properties of the ribbon. In contrast, today’s seemingly traditional means of 3D Printing deposits a thin layer of metal powder that is fused to the layered shape template of the final form by laser welding the immediate layer of metal powder to the previous layers with any electromagnetic performance properties of the powder material destroyed by welding. Both methods show waste, such as the removal and reprocessing metal cuttings or the non-fused metal powder, but with a dramatic reduction in comparative waste to the common subtractive manufacturing method that “removes” one layer of material at a time from an oversized bulk piece of solid material but preserving the properties of the bulk material.[9] Further, only the pre-manufactured raw material of MOTORPRINTER, such as amorphous metal ribbon, is inherently compatible with the electromagnetic properties of the magnetic core being manufactured, which is very different from pre-manufactured raw powder metal material for the traditional 3D Printers that must be compatible with the operation of the 3D Printer instead of the desired properties of the core shape being produced. Unlike all other 3D Printers, the raw material for MOTORPRINTER is third party lowest cost, volume manufactured with the most optimized electromagnetic and structural properties possible, which are retained by MOTORPRINTER during the 3D Printing.

After the core is additively manufactured, MOTORPRINTER automatically wraps the winding set by a laminated object manufacturing method of adding one winding-turn at a time, while coating each winding wrap (with epoxy or ceramic) to improve overall winding insulation and structure. During any annealing process to bring the additively wound amorphous metal core to a nanocrystalline state, a magnetic core aligning current is applied to the heated wires of the windings, which will provide the annealing core alignment with the wires naturally assuming the air-gaps between windings, such as provided by square magnetic wire, and between the slot surfaces for the ideal densely packed winding arrangement.

IV. MOTORPRINTER PERFORMANCE ATTRIBUTES

Different from other Laminated Object Manufacturing 3D Printers, MOTORPRINTER comprises at least the following proprietary and trade secret attributes for manufacturing axial-flux electric machine cores:

- The layered core shape template with any programmable desired slot or shape for holding permanent magnets, reluctance saliencies, or windings, is remotely, precisely, and dynamically cut on the next individual thin layer of ribbon before being wrapped onto the previous layer of the axial-flux core by a proprietary method that precisely and automatically aligns the previous cut slots of the axial-flux toroid without regard to the dynamically varying tolerances of ribbon thickness or core diameter, which would confuse any dynamic calculation method;
- Without discussing additional trade secrets or the empirical studies that were fully orchestrated by BEM with Metglas, an amorphous metal foundry, and several fiber laser cutter companies, such as IPG Photonics, the laser cutting on a single layer of ribbon controls heat stressed to significantly reduce damage to the delicate material;
- The air-gap edge of the ribbon takes the precision flat airgap surface on each wrap to eliminate secondary tooling processes with extreme tool wear and material damage, such as Blanchard grinding;

- The robust frame and bearing bezel assembly of pre-manufactured structural stock, such as steel bar stock, composite stock, etc., is additively attached to the finished core;
- Pre-Manufactured raw materials are readily available from off-the-shelf material stock, such as amorphous metal ribbon, magnet wire, or building materials, which are already performance pre-optimized at the molecular level under the most optimized, volume production, lowest cost manufacturing processes.
- Empirical studies fully orchestrated by Best Electric Machine demonstrated high cutting speeds, which reasonably translates to scalable annual production rates of many thousands of axial-flux electric machines within a single MOTORPRINTER footprint of a standard shipping container;
- MOTORPRINTER will globally democratize the prototyping and manufacture of performance electric machines with the highest performance materials available for electric airplane propulsion.
- MOTORPRINTER additively manufactures high frequency transformer cores (PDF-HFT) within the wasted annulus space of the low frequency axial-flux SYNCHRO-SYM cores on the same frame and bearing bezel assembly for another level of power density for electric airplane propulsion.
- A computer aided design (CAD) tool, called BEM-CAD, was specifically developed to interface with MOTORPRINTER for the design and manufacture of axial-flux electric machines, including frame and thermo considerations;

V. CONCLUSION

Until MOTORPRINTER, there is no known implementation of a practical additive manufacturing technology for highly efficient amorphous or nanocrystalline metal ribbon axial-flux electric machine or high power, high frequency electric transformer cores, both of which are essential for the next level of electric airplane propulsion advancement.

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