A New Structural Bonding Process for Ferromagnetic Sheet Stacking used in Electric Motors (Rotors, Stators…)

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Abstract

A new structural bonding process has been developed for the assembly of the thin iron sheet stacking used in electrical motors. This process, based on screen printing technology, improves the stack cohesion and allows very precise geometrical dimension machining. A stator has been assembled based on such a structurally bonded stack, and it has been submitted to a complete qualification test sequence similar to an existing space-qualified stator with a potted stack. Process development, test results, and comparisons are presented hereafter.

Introduction

A new onset of brushless DC motors for space was developed at SOTEREM for a satellite platform application. This electrical motor is a large and powerful one, whose performance at high rotation speeds is disturbed by eddy current. To lower the eddy current, ferromagnetic thin sheet stacking must be used for the stator. The potting employed to maintain this stack was already qualified but was deemed difficult to produce and has some industrial constraints for large diameter stators.

So, in parallel, a structural technique of bonded assembly was developed by CLIX Industries under CNES funding, to solve the stator ferromagnetic sheet stacking issue. The objectives were to increase cohesion and rigidity, to reduce the structural mass, to increase electromagnetic performance, to improve the workability of stacking without delamination, and finally to obtain better manufacturing precision. The difficulty with the structural bonding technique is to obtain very thin uniform adhesive joints (of about few microns), which increases the iron/insulator ratio and generates an insulating layer at any point to limit iron losses.

The first part of the article presents a new process that relies on a technique of adhesive serigraphy adapted to adhesive rheology properties. Screen printing technology is used for assembling thin ferromagnetic sheet stacks with structural bonding. This technology makes the depositing of very thin and regular adhesive films on to the elementary parts of a stator stack possible. All kinds of resins can be applied including structural adhesives with a wide range of viscosities and tacks.

In addition, this structural bonding technology makes stacks machinable. An original method of wire electro-erosion machining was developed to cut out the stacks (insulating layer & conductor sheet) after gluing. This technique makes it possible to avoid tolerance issues of elementary components and to increase precision of the final stator geometry.

The second part of the article presents the test results of the evaluation campaign towards space and launch environment that has been performed on the motor equipped with the previous potted stator. A comparison with a similar space-qualified stator, based on a varnished structurally bonded stack, is also given.

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First Part: Development of a New Stack Bonding Process

Technical context

A laminated stator (Figure 1) generally consists of a thin sheet stacking (ferromagnetic material) with notches designed for windings (Figure 2). The central opening of the ring is intended to house the rotor. The resins used for bonded stacking are often winding impregnation varnishes and in all cases synthetic resins with very low viscosity.

Low viscosity is a necessary characteristic because it facilitates sheet capillary impregnation and stack pressing. In addition, these resins correspond to the electric motor industry's standard norms both in thermal and dielectric terms. However, these resins have adhesive and mechanical properties often unsuited to stator bonding and to its mechanical environment.

Figure 1. Brushless DC motor stator : 18001-2 (SOTEREM)

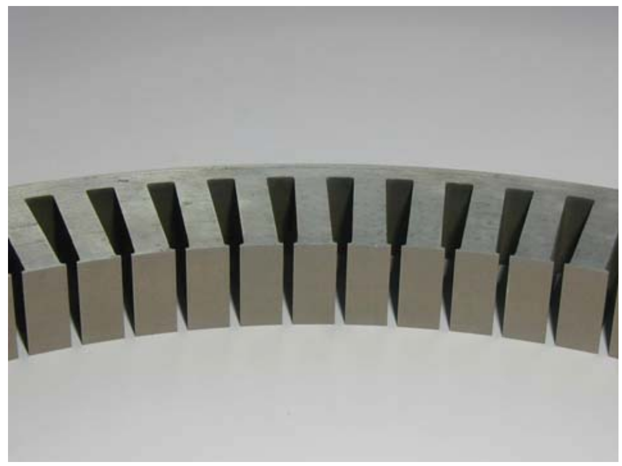

Figure 2. Thin sheet stacking with notches

Sometimes, delamination of the metal stack may occur either during motor manufacturing or handling, in general because of excessive stress or shock. Delamination may also be due to defective adhesion or lack of adhesive. During stack pressing, for example, disparities of sheet thicknesses and of oxidation treatment can create localized contact points between sheets where fluid resin is pressed out. Lack of adhesive is, of course, related to the intensity of applied pressure and to affinities between ferromagnetic sheets and resin (viscosity and wettability).

Sheet stack bonding is one of the main improvements in stator manufacturing. Using structural bonding for stack assembling can reduce the risk of delamination through mechanical or thermal constraints or shocks. It also means that stacking reinforcements, such as housing, bolting or welding are no longer necessary. Furthermore, rigidified stacking is much more machinable.

Screen printing

Screen printing is a printing method that can also be used to deposit all types of resins and, in particular, structural adhesives with high mechanical properties within a wide range of viscosities and tacks (1 to 400 000 mPa). Adhesive is pushed through a silkscreen (Figures 3 & 4). The screen consists of a fabric tightened over a rigid framework. The characteristics of the taffeta screening depend on thread diameter and spacing. Screening is selected according to rheological adhesive characteristics and required adhesive volume.

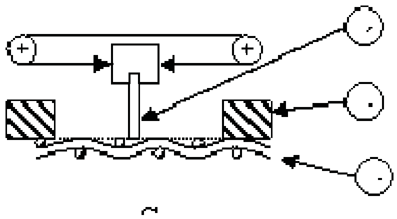

Figure 3. Screen printing method

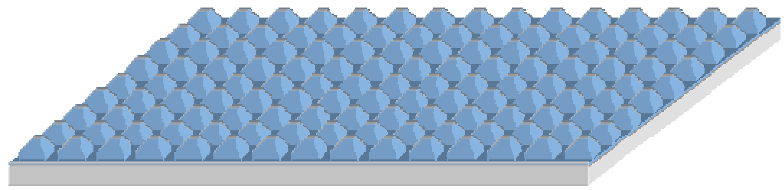

Figure 4. Depositing of thin adhesive film

Deposited adhesive films are very thin (from 1 to 20 microns), regular and repeatable. Thickness adjustment is very precise (±3%).

Adhesive selection depends on the ferromagnetic material that is to be assembled and on the life constraints of the product. The resin chosen for the serigraphy of the electric motors is a structural adhesive with high shear and peeling strength (rigidity and adherence).

Initially, sheets have a simple annular shape. They are screen printed then piled on top of each other with a pressing tool, which guarantees precise assembly height (Figure 5).

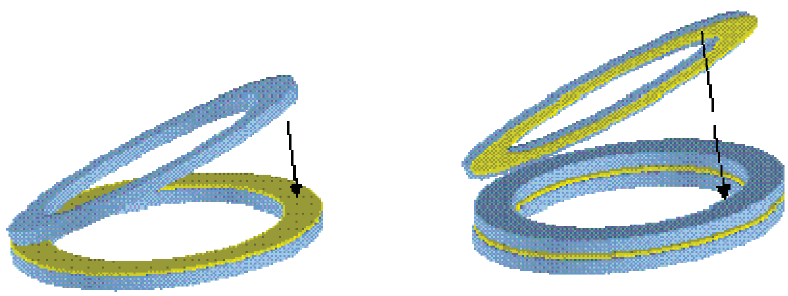

Figure 5. Sheets are piled on top of each other

Due to the thinness of the adhesive film, the stack has a very good iron / [iron + insulator] ratio (nearly 97%). For this application, the selected adhesive, which has a strong viscosity and a high tack, does not flow easily between sheets. So, the interlaminary space thicknesses are very homogeneous and regular. In addition, lack of adhesive due to air bubbles or sheet defects does not occur.

The "Structural adhesive bonding" of sheets with the silkscreen method aims to give them improved rigidity and make them machinable, without any risk of delamination. Moreover, stack machining precision is better than the precision of already machined assembled sheets. Good electro-magnetic performance results from good geometry.

Stack machining

When the stacking is polymerized, it can be machined. The machining method used is wire electro-erosion, which is a precise and safe technology. Indeed, notches are well aligned and assemblies are not at all stressed.

While the use of structural adhesives is a benefit to final stator rigidity and machining, the insulator layers are a problem for electro-erosion machining. Electro-erosion is based on capacitor discharges between an electrode wire and the part being machined. Each plate must be connected to the generator. The discharges generate micro-plasmas (locally about 10000°C) and sublimate all the materials (ferro-magnetic and synthetic resin).

The technique, used to make electro-erosion compatible with sheet stacking, consists of coating inner and outer slices with an electro-conductive resin to ensure that all metallic sheets have the same potential.

Electro-erosion does not create degradation of the structural adhesive joints. The resulting geometry of the stack is very precise; inner and outer diameters are coaxial, notches are aligned, and their geometry is symmetrical (Figure 6).

Figure 6. Stack Geometry

Second Part: New Bonded Stator Assembling and Validation Testing

To check the impact of the structurally bonded stack on motor performance, the second phase of development consisted of the following steps:

- manufacturing of a fully wound stator based on the structurally bonded stack
- testing a frameless motor, consisting of the bonded stack stator and an associated rotor, through a complete validation test sequence.
- for comparison, testing of a similar space-qualified motor.

Stator manufacturing

The structurally bonded stack presented in the first part has been designed and manufactured in order to replace an existing space stator with the same stator geometrical dimensions and interfaces based on the same lamination sheet materials and design. It has been equipped with exactly the same windings as the existing referenced stator. However, it has been impregnated with a varnish that complies with space outgassing standards. Figure 1 shows the finished stator manufactured with the bonded stack. Figure 7 shows the existing referenced stator and the structurally bonded stack. Figure 8 shows a detail of the existing referenced stator.

Figure 7. Existing Referenced Stator and the Structurally Bonded Stack

Figure 8. A Detail of the Existing Referenced Stator

The differences between both stators are summarized in Table 1

Table 1. Stator Differences

	Existing space stator	**Structurally bonded stack stator**
Lamination sheet	Same material Same design	
Stack	Synthetic resin bonded stack	Structurally bonded stack
Coils	Same wires Same windings	
Coating and finish	Resin compound molding in order to protect windings, and increase stator rigidity	Varnish impregnation

One of the specificities of these stators, driven by the space application, is that fixation onto the equipment is done directly on the stack; this implies that the stack outer diameter must be designed with very stringent tolerances (diameter ±0.02 mm and concentricity tolerance in the range of 0.02 mm). Such constraints explain why the qualified stator had been designed with a rigid compound, which guarantees efficient winding protection, but also drastically increases mass.

For the new structurally bonded stator, and thanks to its good mechanical properties, development has been oriented towards a lighter version without any compound. This raises potential criticalities with regards to stator flexibility and to winding protection. To take into account the high flexibility of the non-molded stator, the development effort required adaptation of existing processes and the introduction of stiffening tools. The finished stator had a small ovalization, which was easily corrected by a shaping tool, making the average diameters and concentricity fully compliant with the required tolerances.

Stator Testing and Characterization

The stator is a part of a brushless frameless motor (DC three-phased motor). The other part is a rotor equipped with permanent Samarium Cobalt magnets. For characterization of the new developed stator and in order to compare with existing space referenced stator, both stators associated with the same rotor have been successively submitted to the same complete test sequence (Figure 7). The tested environmental conditions are those which are required for a space application on a satellite platform at qualification level. From the test results, the main characteristic variations between the two stators are given in Table 2.

Initial performance
- dielectric rigidity
- resistance insulation
- inductance, capacity
- mass dimensions
- time constant
- speed / torque characteristics
- wave shape, frequencies
- torque constant, back emf constant
- motor constant
- iron friction (constant and viscous), cogging

↓

Vibrations
Sine vibration: (level 40 g at 100 Hz)
Random vibration (21.4 grms)
in all 3 axes

↓

Post vibration performance
Ditto initial

↓

Thermal cycling
6 cycles between -50°C and 80°C

↓

Final performance
Ditto initial

Figure 7. Test Sequence

Table 2. Stator Test Results

	Existing space stator (A)	New structurally bonded stator (B)	Variation (B) / (A)
Torque constant	4.24 Nm/A	4.27 Nm/A	+0.8 %
Back EMF constant	4.18 V/rad/s	4.24 V/rad/s	+1.4 %
Dry iron losses	0.0301 Nm	0.0158 Nm	-47.5 %
Viscous iron losses	0.0008 Nm.s/rad	0.0013 Nm.s/rad	+ 62.5 %
Cogging	0.0621 Nm	0.0257 Nm	- 58.6 %
Motor constant	0.888 Nm/√w	0.897 Nm/√w	+1 %
Mass	1820 g	1484 g	-18.5 %

It can be seen that:

- the general performance (torque constant, motor constant) is equivalent; no significant variation.
- dry friction and cogging are lower; this might be the result of better insulation between the iron sheets and to the good final geometry quality of the new bonded stator.
- drastic mass reduction, due to the suppression of the molded compound, which results from the better mechanical behavior of the structural bonding.

Conclusion

Stack structural bonding is possible using the screen printing method. The goal of this type of bonding is to rigidify stackings and improve their cohesion. Serigraphy also guarantees optimal insulation between sheets. It makes it possible to machine stacks with electro-erosion, which gives them a precise and stable geometry.

Many advantages result from this process:

- Stiffness / geometry stability → better electro-magnetic performance, less dry iron losses (around 50% of friction reduction), weak cogging (around 60% of cogging reduction).
- Rigidity /cohesion → no reinforcement: lightness (around 20% of mass reduction), compactness, reduction in number of parts, protection against delamination.
- Sustainability / reliability → constancy of performance, protection of insulating layers.

Figure 8. Thin Sheet Stacking with Structural Bonding

Process patented under patent n°: FR 2888390, EP 06778850.5