Simulation of caulking process using Abaqus Explicit

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Abstract: *This paper showcases the capabilities of Abaqus explicit solver to simulate and solve problems involving huge plastic deformation due to caulking process. Caulking is a mechanical joining process achieved by plastically deforming a material in order to hold another material. This method is in research phase and being examined by engineers at Daimler and University of Erlangen-Nuremberg (Germany). This technique is mainly used in Permanent Magnet motors to hold the magnets in the rotor stacks. The objective of the simulation is to find optimum tool geometry, depth of tool penetration and location of penetration for caulking process. The process involves huge plastic deformation and is successfully simulated using Abaqus Explicit. This illustrates the effectiveness of numerical simulations, helping the designers in reducing the need for actual test bench with numerous high cost fabricated hardware setup and thereby saving huge R &D cost and time.*

Keywords*: caulking, deformation, Abaqus Explicit, Laminates, Rotor segment, Electric motor, Magnet stress, Tool penetration.*

1. Introduction

Due to the rising environmental awareness across the world because of high levels of emissions and noise in the urban areas, attention is increasingly turning towards emission free and almost noise free electric motors. Today the "permanent magnet (PM) electric motors are widely used across the world for electric vehicles and it is under constant research. They are magnets that maintain their own persistent magnetic fields. Rare earth magnets, powerful magnets made from rare earth metals, are typically used for this purpose. Rare earth magnets are not particularly rare, they just happen to come from the class of metals known as rare earth metals. There are other metals that only become magnetic when magnetized by an electric field and only stay magnetized as long as that electric field is in place. This concept is at the heart of how PM motors work.

Caulking is a new methodology to hold the permanent magnet intact within the rotor segment during operation. This method is in research phase and being examined by engineers at Daimler and University of Erlangen-Nuremberg (Germany). In PM motors, a wire winding serves as an electromagnet when electricity passes through it. The electromagnetic coil is attracted to the permanent magnet, and this attraction is what causes the motor to rotate. When the source of electrical power is removed, the wire loses its magnetic qualities and the motor stops. In this way, the rotation and motion of PM motors can be managed by a motor driver that controls when and for how long electricity and, by extension, the electromagnet, allows for rotation of the motor.

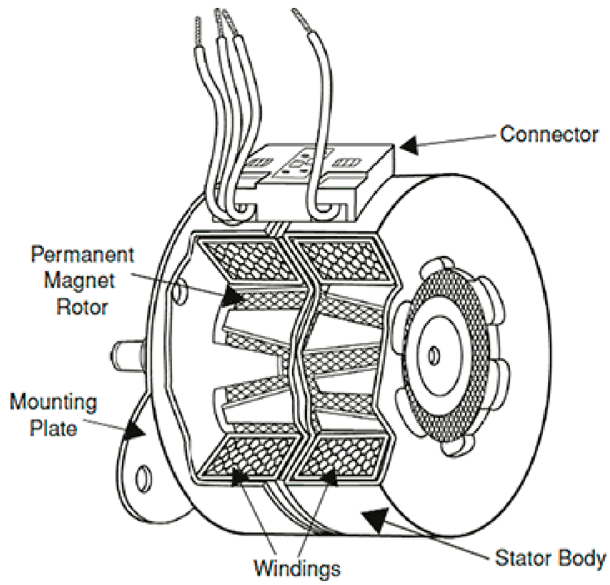

Figure 1. PM motor assembly.

Figure 1 depicts a permanent magnet motor, or “PM” motor. The rotor contains a permanent magnet, giving PM motors their name. Permanent magnet step motors work on the same principles as hybrids but use a slightly different geometry. PM rotors are radially magnetized, north and south poles alternating along the circumference of the rotor. Both the rotor and the stator assemblies of PM motors are smooth. Permanent magnets are expensive because they contain are earth metals such as Neodium and Dysprosium which are mined primarily in china, and as the demand for these materials increases, so too will their price.

2. Permanent magnet electric motor construction

The Permanent magnet electric motor consist mainly two components, stator and the rotor. As the name suggests the stator is the static component and the rotor is the rotating component. The rotor consists of a number of rotor segments and each rotor segment is made of several laminates stacked on top of each other. The laminates are glued with one another to form a perfect bond.

The conventional rotor is assembled by placing the permanent magnets in the slots provided in the rotor segments and the gaps between the magnet and the rotor segment slots are filled with molten plastic resin. This ensures the permanent fixation between the magnet and the rotor segment.

The assembly process involves two steps, in the first step the magnets ae carefully positioned in the rotor segments and in the second step the magnet is fixed to the rotor segment by pouring the molten plastic resin in the gaps between the magnet and rotor segment sots. The rotor segments are then stacked together to form the rotor.

3. Caulking process

Caulking is a mechanical joining process used to rigidly hold two parts together. In Electric motors the permanent magnets can be held rigidly inside the rotor segment by caulking the rotor segments. Caulking is achieved by applying surface pressure on rotor segment with the help of a punching tool made of tool steel and thus deforming the rotor laminates plastically. The material deforms and flows towards the magnet and presses against the magnet surface. The compressive force between the protruding rotor segment and the magnet holds the magnet in the rotor firmly during the operation.

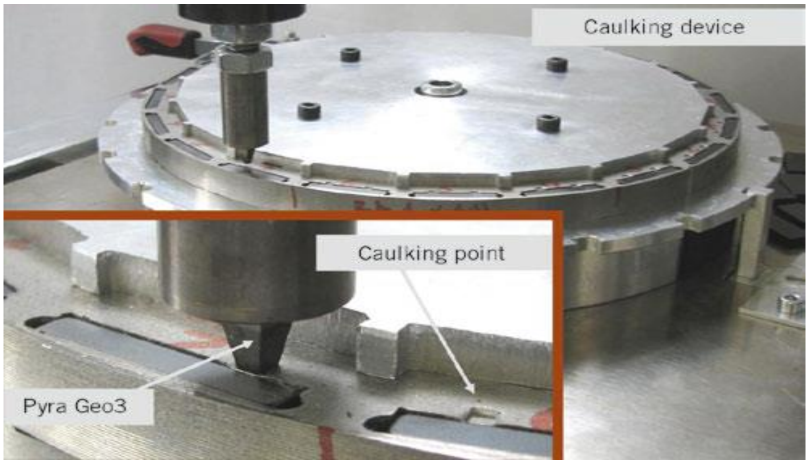

Figure 2. Caulking test setup.

Caulking is a positive locking mechanism meaning it is direct bonding of two components or metals without using an adhesive or binding material in-between. It is helpful in improving the efficiency of the motor as the air gap between the magnet and the rotor is considerably reduced.

This eliminates the use of plastic resin which is not environmental friendly. Also it eliminates the two step assembly procedure used in conventional electric motor assembly process. As a result it also reduces the manufacturing cost. The effectiveness of caulking process depends mainly on tool geometry, depth of caulking and location of caulking.

4. Scope

For effective caulking, the optimal tool geometry, location of caulking and the depth of caulking are to be predicted. The combination of above mentioned parameters need to be found out such that, post caulking, the magnet is intact without chipping and the extraction force required for the magnet to come off the rotor segment is within a specified optimal range. The tool geometry plays an important role in caulking as the shape influences the stress concentration in the magnet. The caulking location and finally the depth of caulking influences the force required for caulking process thereby helps in finding the tool life.

4.1 Tool geometry

The tool geometry plays an effective role in the caulking process. Different tool geometries displace the rotor material in different ways. The effective material displacement decides the fit between the magnet and the rotor segment. The material displaced should not be very sharp that it creates stress concentration on the magnet thereby damaging it and the material displaced should not be too wide too, as it produces less contact pressure between the components thereby resulting in slipping of magnet during operation. Currently three different tools are used for caulking simulation and their effects on the rotor segment and magnet are studied.

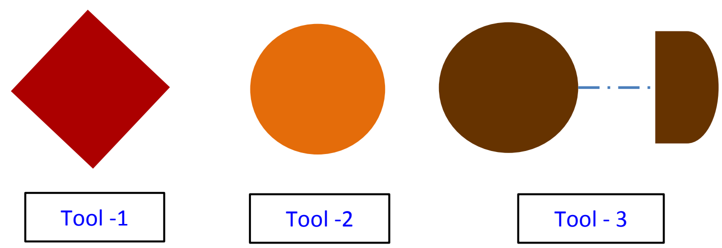

Figure 3. Tool cross section.

Figure 3 shows the different tool geometry (cross sections) used for the caulking. The first tool is pyramid shaped, the second tool is circular shaped and the third tool is circular shaped but with smoothened edges. Each tool has its own influence on the caulking process. The best of the three tools needs to be identified for effective caulking.

5. Caulking simulation

As mentioned earlier the caulking simulation involves huge plastic deformation of the laminates and thus requires special software to achieve a converged solution. The need for the simulation is that the permanent magnets are very costly and the availability in the market is also scarce. During physical hardware testing of caulking process, magnets can be damaged due to the high caulking forces. Thus huge investment for testing is required. It would be wise to do the simulation to find the optimal parameters for caulking and then do the hardware testing.

5.1 Model data

The rotor segment was modelled as a stack of laminates each of 0.3 mm thick. Each of the laminates was made to engage with adjacent laminate with help of frictional contact, thereby modelling the rotor segment close to reality. The tool was then modelled as per the required cross-section. The rotor segment material was modelled as nonlinear in nature whereas the magnet material was modelled as linear in nature.

Stopper plates were used on top and bottom of the rotor segment for replicating the hardware test setup. Since the model was cyclic symmetry in nature, in order to reduce the simulation time the symmetric portion of the rotor segment was considered for the analysis.

Appropriate boundary conditions like the cyclic symmetry on the side face of the rotor segment and translation constraints on the stopper face are applied to replicate test setup.

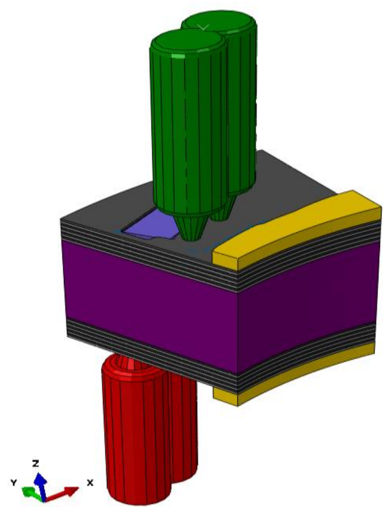

Figure 4. Simulation model setup.

The tools were modeled as rigid elements and general contact was applied between the tool and laminates.

5.2 Analysis

Abaqus Explicit was used to simulate the model due to its robustness in solving problems involving contacts and plastic deformation. Initially the model was simulated using other conventional explicit solvers available in the market. But results could not be achieved within the stipulated time. Without the help of the Abaqus /Explicit it wouldn’t have been possible to achieve a solution for the caulking process simulation. The space required for simulation results were also very less when compared with Abaqus /Implicit.

General contact was used for the whole model. General contact interactions typically were defined by specifying self-contact for the default automatically generated surface provided by Abaqus/Explicit. All surfaces used in the general contact algorithm could span multiple unattached bodies, so self-contact in this algorithm was not limited to contact of a single body with itself. With the general contact algorithm each slave node could see contact with multiple facets per increment.

Thus it helped solve problems which involve interaction between components undergoing huge plastic deformations. The assembly consisted of laminates stacked on top of each other and the magnet was placed in the slot provided in the rotor segment. General contact was applied between the rotor segment and the magnet contact surfaces. The tool was positioned on top of the rotor segment surface. In the first step the force was applied on the tool at a specified rate. In the second step the tool was retrieved to its original position to accommodate spring back in the rotor segment. The third and fourth steps were repetition of the first two steps for the other side tool.

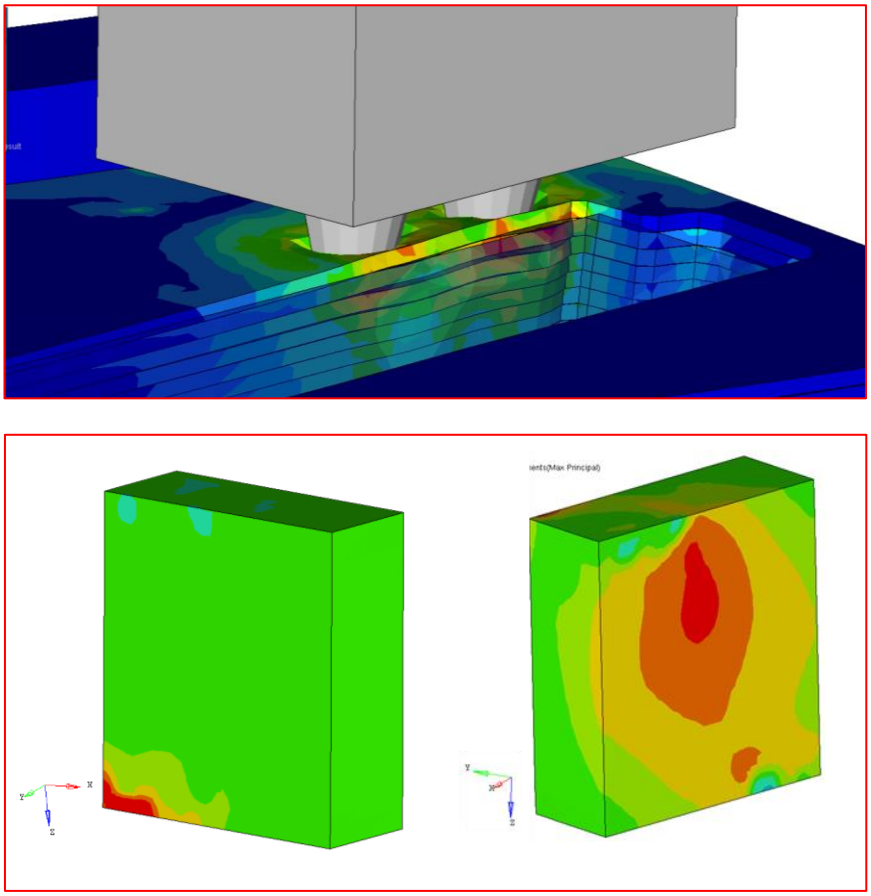

Figure 5. Stress in magnet post caulking.

From Figure 5 one can observe the stress contour in the magnets post caulking simulation. The stress in the magnet depends on tool geometry, depth of penetration and position of caulking.

5.3 Assembly intactness

One of the main criteria for a successful caulking is the intactness of the magnet in the rotor segment post caulking. The magnet should remain intact not just during assembly but also during high speed operation of motor. Even a slight relative motion between the magnet and rotor segment can cause catastrophe during operation. In order to avoid this it is mandatory to check the force required to extract the magnet at high operating speeds. This is best done by applying displacement control on top of the magnet and checking the reaction force. If the force is within a safe limit then it can be concluded that the magnet is safely secured in the rotor segment.

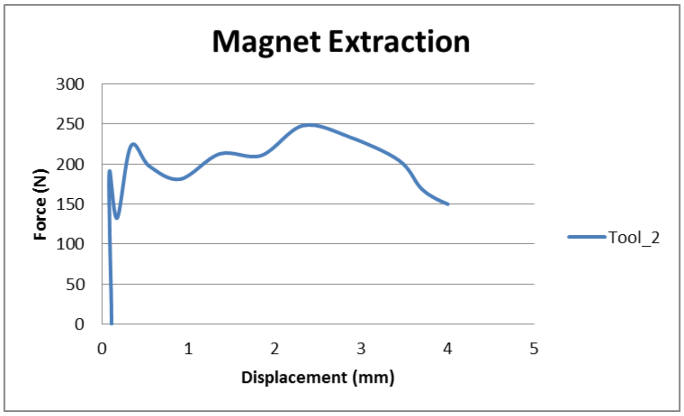

Figure 6. Magnet extraction.

Figure 6 shows the Force Vs displacement graph plotted for magnet extraction. The graph helps in finding the effectiveness of the caulking done by a set of combination of parameters.

6. Conclusion

The best possible solution for an optimized set of parameters was successfully figured out with the help of Abaqus/Explicit by checking the stress in the magnet and its intactness in the assembly. The combination leading to high stress in the magnet or lesser intactness in the assembly was eliminated. From the simulation, the best possible tool geometry, depth of penetration of tool and the location of caulking was found and same was implemented in the hardware test. The test suggested good co-relation with the simulation results.

7. Acknowledgement

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