566. Modeling of electromagnet for application in nano-finishing of internal tubular surfaces using ferrofluid and rotating magnetic field system

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Abstract. This paper presents data on the modeling of an electromagnet for the finishing equipment, which provides flexible and effective work. The modeling was performed by using Finite Element Method Magnetics (FEMM) software intended for solving 2D planar and axisymmetric problems in low frequency magnetics. The modeling data demonstrates the best shape, shape-and-size-ratio of electromagnet, which would ensure maximum efficiency when using the aforementioned device. An electromagnetic field generator, consisting of four electromagnets, was constructed. Subsequently it was determined that generated magnetic field was far smaller than in the model.

Keywords: control of ferrofluids, modeling of electromagnets, low frequency magnetic

Introduction

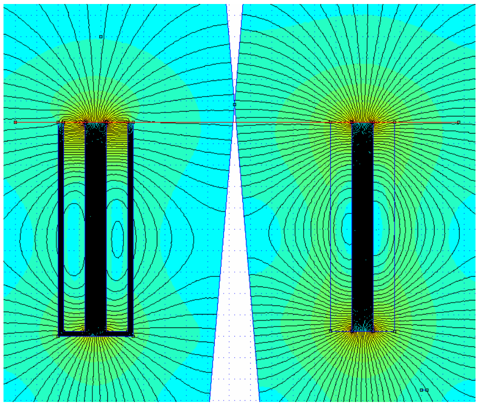
In today's advanced engineering industries, the requirements for components are very demanding. For example, extraordinary properties of materials, complex-shaped 3D components, miniature features, nano-level surface finish on complex geometries, which are not feasible to achieve by any traditional methods [1,2]. Recent application of smart media for magnetic field assisted micro and nano finishing processes, using magnetic fluids (Ferro Fluids (FFs), magnetoelectrorheological fluids (MERFs)) in the manufacturing processes has become of interest [1,3-5].

The modeling of electromagnets

The modeling of electromagnet, which would posses necessary properties for effective control of FF in the system for cleaning/polishing of cylindrical internal surfaces, was carried out using Finite Element Method Magnetics (FEMM) software, which allows solution 2D planar and axisymmetric problems in low frequency magnetics.

In the case of device under consideration, where the point of the device is to create a travelling electromagnetic wave to induce a flow of certain volume of FF, which is injected into the cleaning zone of a closed space. The running wave then drives the FF in a circular manner thus creating an abrasive effect in the contact zone of nano-particles of FF and the contaminant material.

Because magnetically responsive metal is much more magnetically permeable than air the magnetic lines of force will seek the path of least reluctance magnetic material (core and side plates). A comparison was made between electromagnet with and without outer layer of magnetic material (Fig. 2).



a) b)

Fig. 2. Electromagnet: a) with outer shell, b) without outer shell

Data in Table 1 indicates that outer layer increases magnetic field (magnetic flux density [*B*] values). For high currents (~10A) the outer layer induces no change in the field, but at low current (~1A) *B* values increase with the presence of outer layer.

Table 1. Magnetic flux density [*B*], depending on electromagnet's construction and current

Current, |*I*|,A	With shell, |*B*|, T (max)	Without shell, |*B*|, T (max)
10	0.92	0.92
5	0.66	0.63
2	0.38	0.25
1	0.22	0.12

Next was evaluated the width of windings part of electromagnet. The test current was 1A flowing through 4000 copper wire windings. Modeling was done by using core of 4 mm and 6 mm wide at three different magnet lengths and width of windings. Data in Table 2 reveals that it is preferable to have a cross-sectional area of windings grater that the width of the core for the core to be fully magnetized.

Table 2. Magnetic flux density [*B*], depending on electromagnet's dimensions

Electromagnets' dimensions, Length/Core width/Windings width, mm	|*B*|, T (max)
50/6/4	0.6
50/4/4	0.6
20/6/8	0.68
20/4/8	0.7
100/6/4	0.5
100/4/4	0.45

The measurements above were taken at the surface of electromagnets with solid core. To evaluate the strength of electromagnet with different types of core, solid and plated cores (plates were 0.5 mm thick and 0.1 mm apart) were modeled. Left side graph, in Fig. 5, demonstrates the magnetic flux density values of plated core (peaks are at the edges of side plates of core) and right side – solid core.

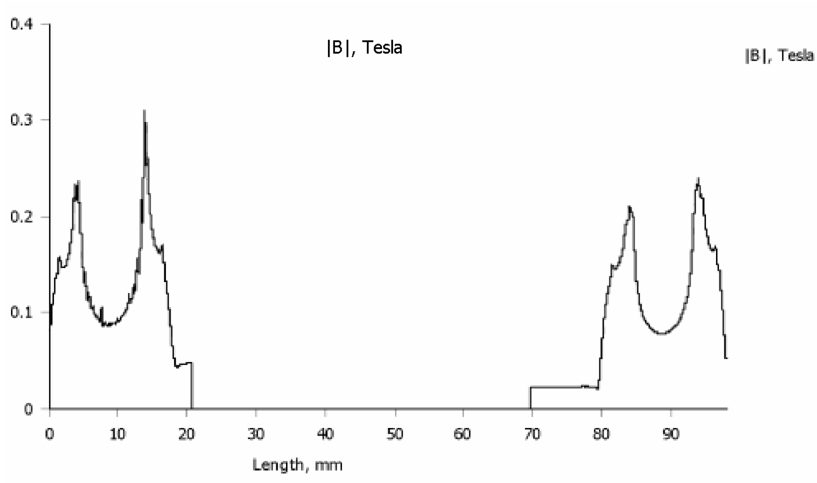


Fig. 5. Left graph - plated core; right graph - solid core

The first graph indicates slightly greater *B* values at the surface of the core due to the fact that thinner core (and in this instance the core is made of multiple cores) is magnetized stronger with respect to a thicker one. But from theory of electromagnets it is known that solid cores are preferred because of greater amount of material which gives stronger net magnetization of core then core made of plates (DC electromagnets). Although model shows grater magnetization at the surface of plated core the value of *B* diminishes more rapidly than of solid core when increasing the distance from the core surface.

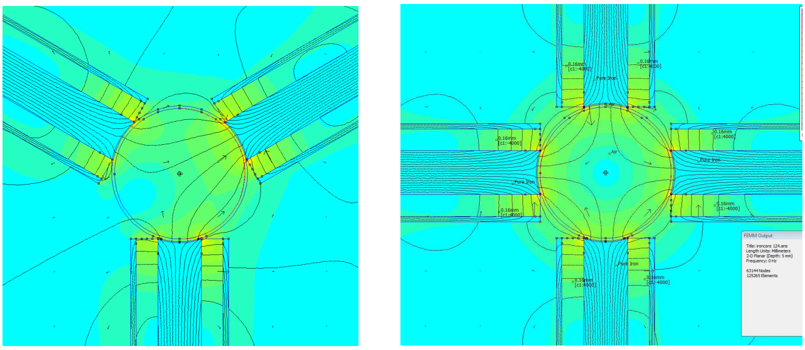
Subsequently width of the core (solid structure) was modeled. Distance of measured points from surface of electromagnet is 10 mm. From obtained results (Table 3) it is evident that the wider the core the stronger is the magnetic field.

Table 3. Magnetic flux density [*B*], depending on electromagnet's core width

Core width, mm	|*B*|, T (max)
4	0.065
8	0.085
6	0.09
10	0.1
12	0.105
14	0.11
16	0.115
18	0.12

Determining the number of electromagnets for positioning on a tubular body

A cylinder with diameter of 20 mm and wall thickness of 1 mm was chosen as the modeling object. The magnets were set with different polarities on every second pole near the cylinder surface. But as it can be observed in Fig. 3 a gap appears in magnetic field as two electromagnets get to be with the same polarities at the ends, thus creating a repelling effect which is not desirable.



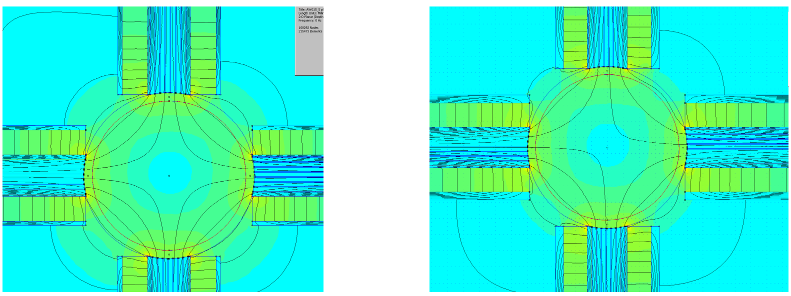
a) b)

Fig. 3. Magnetic field: a) created by 3 electromagnets, b) created by 4 electromagnets

Situation improves when one more electromagnet is added (Fig.4), thus making it clear that even number of electromagnets should be used.

Magnetic field in cylinder when overall width of magnets varies

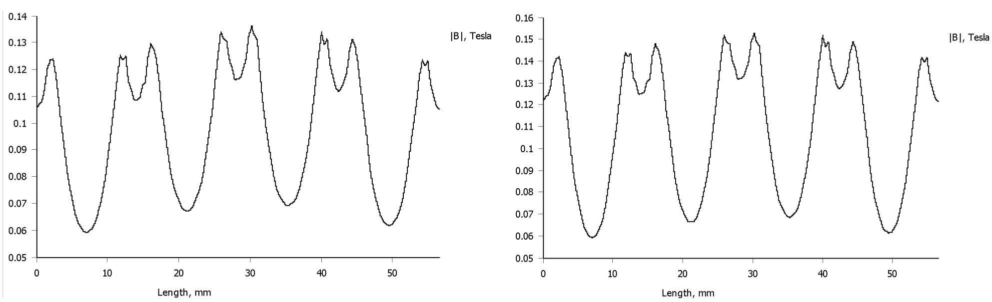
Last modeling criterion was overall width of an electromagnet with respect to working zone of the electromagnetic field. First model (Fig. 6) showed that increasing thickness of outer shell walls, from 0.5 mm (Fig. 6a) to 1 mm (Fig. 6b) increases magnetic field (Fig. 7).



a) b)

Fig. 6. Comparison of *B* values a) when shell wall is 0.5 mm; b) when shell wall is 1 mm

It is due to the fact that larger amount of magnetic material gathers more magnetic flux lines, thus concentrating magnetic field in the needed area.



a) b)

Fig. 7. Comparison of *B* values: a) when shell wall is 0.5 mm thick; b) when shell wall is 1 mm thick

In the third model, core diameter was increased from 5 mm (Fig. 6) to 10 mm (Fig. 8) to cover all area of cylinder outer surface, but thickness of shell wall had to be decreased back to 0.5 mm in order to accommodate wider core. In addition, the core-arc radius was increased to accommodate the workpiece deeper into the core to minimize the distance from effective magnetic field to the inner surface of cylindrical body.

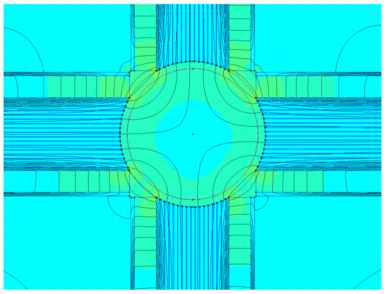


Fig. 8. Electromagnets cover the outer surface of cylindrical body.

It is known that the magnetic field intensity is increased towards the corner of the pole, in the case of solid permanent magnet, and in the case of electromagnet, towards the corner of core and windings outer-cover. A change in pole orientation (non 0^0 angle with respect to workpiece/cylinder surface) was proposed in [6] to reduce the clearance locally, increasing the magnetic field intensity at the finishing area adjacent to the near pole corners. But in this model the gap between working/inner surface of cylinder and the core of electromagnet was minimized by making the core surface in arc-like shape. Modeling electromagnet with a core, protruded from its surface, demonstrated that although larger magnetic field intensity at the edges is exhibited, but it also diminishes more rapidly (with respect to case of model presented in this paper) at some distance from the core.

Obtained results (Fig. 9) show that compared to model in Fig. 6 (b) the magnetic field has a worse distribution over the length of inner surface of cylinder. In graphical representation of model with thicker core (Fig. 8) one can observe that due to very close proximity of each electromagnet magnetic field is weakened (magnetic field from one magnet disturbs magnetic field from another magnet).

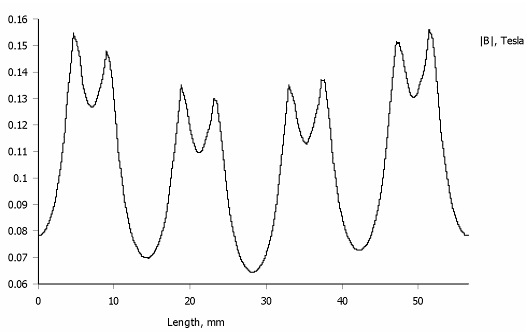


Fig. 9. Core is 10 mm wide, shell wall is 0.5 mm thick

Nevertheless, it is important to have as wide core as possible, because the force F, exerted by electromagnet on to the magnetic object is directly proportional to the core area A, given in Maxwell force formula [7]:

$$F = B^2 A / 2\mu_0 \qquad (1)$$

where B^2 – magnetic flux density of core material, μ_0 – magnetic permeability of air.

Constructed magnetic field generator

A magnetic field generator was constructed according to modeling data (Fig. 13). Four electromagnets were made of 0,2 mm copper wire, 2500 windings per magnet. Core thickness was 5 mm, width - 20 mm and length - 50 mm. Obtained power varies in a range of 10 – 30 W with available DC power supply. Traveling magnetic wave was generated in this device using DC source. Nevertheless, as the magnets were hand-wound inaccuracies in windings cross-section and number of windings, compared to FEMM model, occurred. Plates of transformer were used as core and shell material, with unknown *B-H* characteristics. Thus at the surface of electromagnet only 0.04 – 0.06 T were obtained. This indicates that hand-wound electromagnets are inefficient.

Conclusions

Obtained results indicate that it is important for an electromagnet to have an outer shell in order to produce a stronger electromagnetic field as compared to one without shell, when current is low. It is very important to balance the width of core, width of windings cross-section, width of shell walls and length of electromagnet with respect to system parameters. Performed research work revealed that hand-made electromagnets are inefficient and cannot be used to obtain accurate real-time experimental results.

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