Comparative inspection and calculation of B-field of an openable pulsed electromagnetic coil(Pancake coil) made up of different materials

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Abstract - **Designing of the coil is very crucial in the pulsed electromagnetic process. Openable coil assembly is the heart of the forming process. This paper describes a comparative study performed on COMSOL multiphysics simulation software to give knowledge of B-field produced by different conducting materials in the same dimension of the coil. It was seen that Be-Cu produces a maximum field of 45Tesla compared to hard drawn copper with 36Tesla and SS304 with 25Tesla. In this paper, a simplified analytical calculation of the helical disc coil has been developed with 2D modeling aiming to partly verify the analytical approach.**

keywords - **multi-turn helical disc coils, electromagnetic forming process, 2D simultaion magnetic field**

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1. INTRODUCTION

Open-able coil or pancake coil is a super electromagnet used for the generation of extremely high magnetic fields capable of producing B-field up to a tremendous range of 30T and above. The designing of such coils is quite different compared to an ordinary electromagnetic coil. As the name suggests there are various layers of the coil staged together on one another to form a pancake structure. These coils are sometimes also referred to as bitter coils. Alternate layers of conducting discs and insulating material discs are kept to provide a flux pinning action which produces a high magnetic field. The flat coil assembly at end plates has a complete disc whereas the inner segments are made up of conducting material cut in sectors each comprising 30mechanical degrees. These coils find applications mostly in the electromagnetic forming process. The electromagnetic forming process is a state of an art process, it is a high-speed forming process produced using time-varying magnetic fields by the coil.

The time-varying current passing through the coil produces a magnetic field and Lorentz force inside the coil. This force exerts pressure on the work-piece surface causing deformation of the work-piece.[1] The pressure is used for compression in this case. The design of the pancake coil is as below in Figure 1

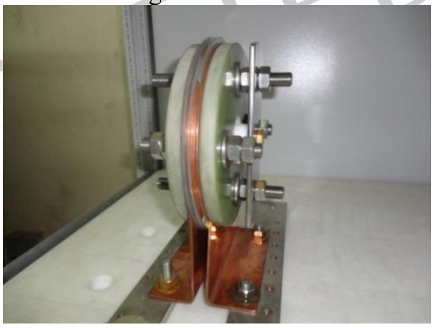

Figure 1.1 complete assembly of helical disc based coil

2. DESIGN METHODOLOGY AND CALCULATIONS

Mainly theoretical knowledge is available for the design of such coils but a complete guideline is still not available for the design methodology. This shortcoming has inspired us to develop such coils by analyzing the academic theoretical models stated in the [2] that can sustain large pulsed currents, extreme pressure, and thermal conditions with minimum physical damage.The analytical approach cannot be applied to these coils due to its unequal helical structure These coils require prerequisite knowledge of coil and work-piece gap(which should be as minimum as possible for a proper mutual inductance phenomenon),work-piece geometry and also the various parameters of the pulse generator assembly. All these parameters depend on the industrial requirement.The flat helical disc coil has 3 turns with an active length of 15 mm with an outer diameter of 200 mm and an inner diameter of 50 mm with each having a thickness of 3mm. There is 6 flat disc with 5 sector discs to be placed in between them. Alternate layers of conducting discs insulating material and sectors are placed to form a complete coil assembly.

2.1 INITIALLY REQUIRED PARAMETERS

The current supplied from the pulsed generator I_{max} should be known in order to calculate the B-field, the inductance Lsys, and $R_{sys}$and capacitance $C_{sys}$and also the short circuit frequency f_{sc}..The pulse generator is a simplified series RLC circuit [3] with basic equation 1 as given below

$$V_o = \left(\frac{1}{sC_{sys}} + sL_{sys} + R_{sys}\right) i(t) (1)$$

The maximum current required by the coil to produce B-field is given by solving the above equation in Laplace domain we get equation 2 as

$$I_{max} = i(t) = \left(\frac{V_O}{L_{sys}}\right)\left(\frac{e^{-\xi\omega_n t}}{\omega_d}\right) \sin \omega_d (2)$$

2.2 PARAMETERS REQUIRED TO CALCULATE THE B-FIELD

A work-piece geometry characterized by an outer radius r_{out}, a wall thickness r_{thk} and a work area length (desirable weld length) l_{weld} as well as workpiece material properties represented by the conductivity **σ**, the heat conductivity **λ**, the specific heat capacity **c**, the yield strength **σ_y**, and the mass density **ρ_m** is known.

The skin depth of B-field inside workpiece geometry is given in equation 3 below

$$\delta = \left(\frac{1}{\sqrt{\pi\sigma\mu f}}\right) (3)$$

Effective no of turns of the coil (including the sectors) given in equation 4

$$N = \frac{Tol\ angle\ made\ by\ the\ current\ in\ inner\ dia\ of\ coil}{360^{\circ}} \quad (4)$$

Inductance if the coil L_{coil}given in equation (5)

$$L_{coil} = \left(\frac{\mu \times N^2 \times k \times effective\ are}{the\ active\ length\ of\ coil\ (l_a)}\right) (5)$$

$$k = \frac{l_a}{(1 + 0.45(inner\ dia + \delta))}$$

The pressure required to be generated over workpiece to weld it shown in equation (6)

$$P_g = \left(\frac{10 \times \sigma_y \times r_{thk}}{r_{out}}\right) (6)$$

B_{max}Max demanded field inside the coil and work-piece air gap shown in equation (7)

$$\left(\frac{\left(B_{max}{}^2\right) - \left(B_o{}^2\right)}{2\mu_o}\right) = P_g \, (7)$$

The maximum achievable field in coil and work-piece (B_o) given below in equation (8)

$$B_0 = B_{max} \times e^{\left(\frac{-r_{thk}}{\delta}\right)} (8)$$

Maximum current inside coil given by equation (9)

$$I_{coil} = \frac{B_{max} \times l_a}{\mu_o \times N} (9)$$

Table 1 Material properties

Properties	units	Stainless steel 304	Hard drawn copper	Beryllium copper
Conductivity σ	MS/m	1.2	58	14
Yield strength	MPa	240	300	800
Thermal limit	degree	1400	1085	870

3. SIMULATION AND RESULTS

The complete simulation visualization on COMSOL of B-field achieved by all the coils is shown in below fig 2, fig 3and fig 4 respectively. There is only 10% - 12% deviation between theoretically calculated values and simulated values obtained. Table 2 gives a brief comparison between theoretical and simulated values.

Table 2 Comparative analysis between theoretical and simulated values

Material	B-field theoretically calculated(Tesla)	B-field achieved by simulations (Tesla)
Be-Cu	50.4	45
Hard drawn copper	39.96	36
Stainless steel SS304	27.81	25

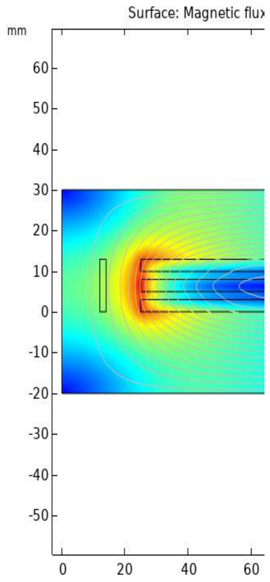

Figure 3.1 Max simulated B-field 45T achieved by Be- Cu coil with contour graph.

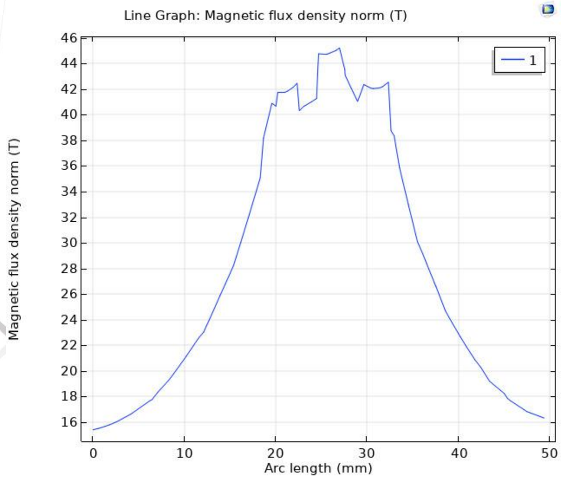

Figure 3.2 Simulated line graph of B-filed for Be –Cu

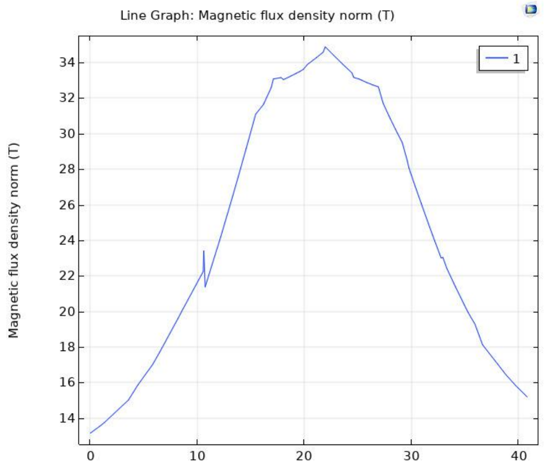

Figure 3.3 Simulated line graph of B-field for hard drawn copper

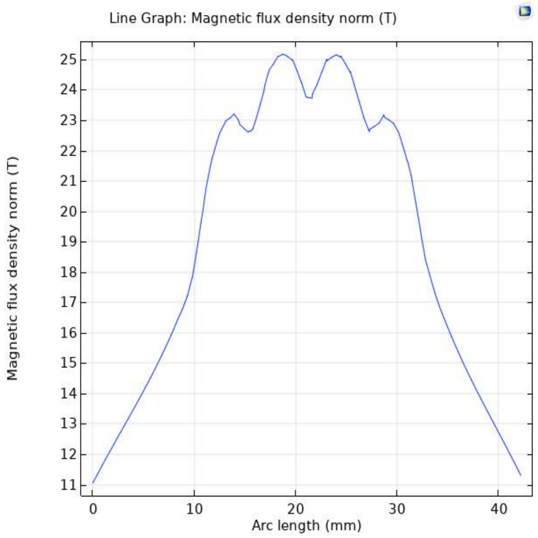

Figure 3.4 simulated line graph of B-field for Stainless steel SS304

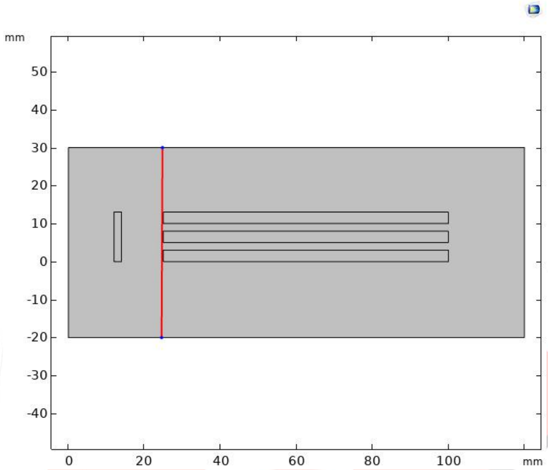

Figure 3.5 Position of the line graph cut for all coils

4. CONCLUSION

From this paper, we can conclude that the new alloy of beryllium copper (2% beryllium) proves to provide more B-field when compared to the other two materials. Also, it is seen that the development of the pancake coil produces a high B-field due to its unique design.

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