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## Design of a two-pole electromagnet and its analysis under different load conditions

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## ABSTRACT

Electromagnets can be used in devices, such as motors, generators, and transformers, and in tasks, such as lifting and transporting object. This study aimed to lift and transport iron blocks in iron and steel factories and rolling mills. The design and analysis of a two-pole electromagnet with a carrying capacity of up to 1.5 tons were performed. It was aimed to design an electromagnet in such a way that it would provide transport with minimum copper loss without reaching the saturation at an appropriate ampere-turn value according to the type and size of the load to be carried. By performing analytical calculations, a suitable model for the requirement was designed and Finite Element Analysis (FEA) was conducted. In the analysis, magnetic flux density, winding current ratios, and force values were examined. Analyses were investigated for different load quantities and numbers.

## I. INTRODUCTION

Unlike conventional magnets, electromagnets show their magnetic properties only when an electric current is applied. Electromagnets are obtained by passing the current through a conductor spirally wound on an iron core [1, 2]. Their magnetic property continues as the current passes through the coil [3]. The force of attraction of electromagnets can be adjusted by the applied current and the number of windings of the coil [4]. When conventional magnets reach Curie temperatures, they irreversibly lose their magnetic properties. Electromagnets lose their magnetic properties when the current is removed. However, they regain their magnetic properties when the current is applied. The magnetic field obtained from electromagnets can be larger compared to conventional magnets [3].

Electromagnets can be used for carrying and lifting the load in electrical machines and high-speed trains [5-8]. The electromagnet's performance can be optimized by the materials used, the excitation current, the position of the winding, and the design of the magnetic circuit [9-11]. By altering the geometry of the poles of the electromagnet, losses can be reduced, and efficiency can be increased. In the study conducted as part of a magnetic robotic platform, a series of electromagnet designs and optimizations were carried out. The coil design was created considering the workspace size and magnetic field performance [12]. A similar study has been conducted on the shape optimization of the inner and outer electromagnets used in a superconducting linear acceleration system. In the optimization carried out using a genetic algorithm, the pellet speed was increased [13]. In a different application of the electromagnet, a design has been carried out for medium-speed maglev trains. Through mathematical modeling and analysis of the electromagnet, controllability at all speed values has been achieved [14]. In a study

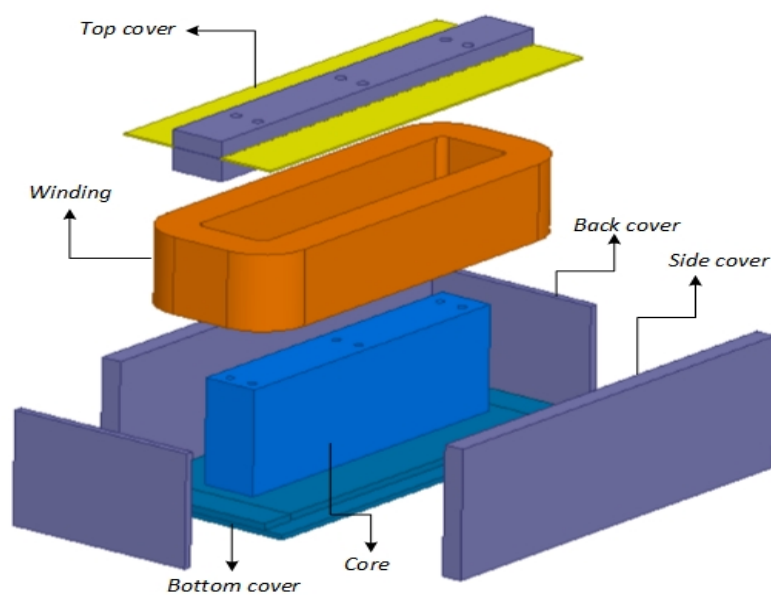
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where a cylindrical electromagnet was designed and manufactured, the electromagnet design was carried out by considering both magnetic and thermal behavior [15]. By changing the geometry of the electromagnet's poles, it is possible to reduce losses and increase efficiency. In the study by Makarichev and Ivannikov, the electromagnet also increased energy efficiency by reducing the effect of high harmonics. However, a small decrease was determined in the force of attraction of the electromagnet [16]. There are also studies on winding, another variable that affects performance. The higher force was obtained at the small volume and same excitation by replacing the coils of the electromagnet having aluminum coils with a superconductor [17].

Electromagnets are commonly used for transporting iron blocks (billets) in the iron and steel industry [9, 18]. The transport process can be used in industry with only magnets or hybrid systems formed by the combination of magnets and electromagnets. However, the mass of the load in the iron and steel industry and the risk of breaking the magnet in case of impact bring the use of only electromagnets to the fore. Nevertheless, since the magnetic field is provided by both magnets and the coil in electromagnets with a permanent magnet, the flux density distribution is complex [19]. Adjusting the force value by the trial-and-error method for load lifting in electromagnet lifters is an adverse condition in terms of both time and occupational safety. In this study, the excitation value of the winding required to lift different loads and the magnetic flux distributions on the core were obtained by both analytical and FEA. Suitable ampere-turn ratio is analyzed, different load types are tested with examined design.

## II. ELECTROMAGNET MODEL

The force generated by electromagnets on the load varies in direct proportion to the number of windings and the applied current [20]. In the study, a two-pole electromagnet model capable of lifting loads of different sizes and quantities was designed using ANSYS EM. The detailed view of the two-pole electromagnet model designed to lift the load is shown in Figure 1.



**Figure 1.** Detailed view of the designed electromagnet

Steel\_1010 has been used as the core material and copper has been used as the winding material in the design of the electromagnet. The side cover dimensions are 1,080×376×50 mm, while the back cover dimensions are 480×330×20 mm. The part specified as the core is designed to be 815×306×135 mm. Since there was no magnetic flux transition in the upper cover, an insulating material was preferred by graphite material. A mild steel material was used in the lower base part. The BH curve of the Steel\_1010 material used in the core is shown in Figure 2 [20]. It was observed that the core reached saturation at a value of approximately 2.2 T.

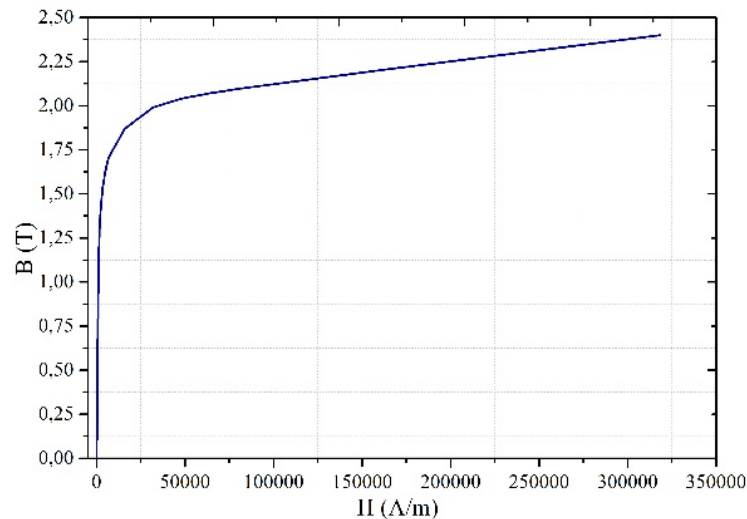


Figure 2. BH Curve of Steel\_1010

In the study, the value of the lifting (holding) force that would occur on the loads was analyzed by the Finite Element Method (FEM). The process steps in Figure 3 were followed. The model of the electromagnet is designed according to the determined parameters. The model, to which the FEM is applied, is analyzed by considering variables such as magnetic flux density and the desired force. If the desired values are not within the specified limits, the model is revised until the final model is achieved.

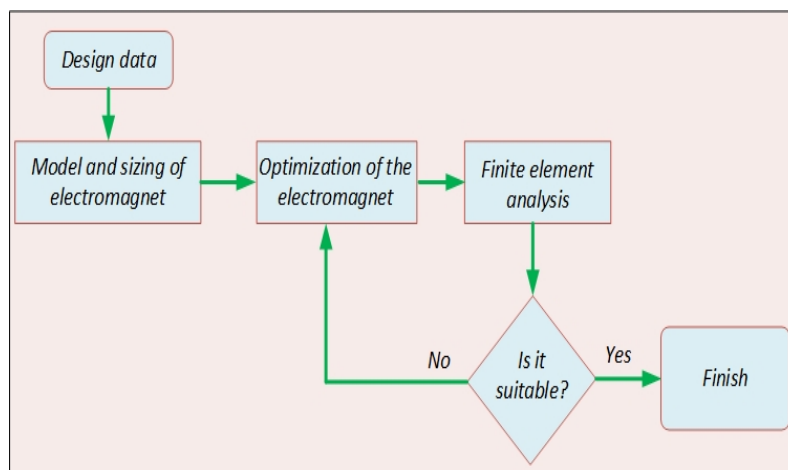
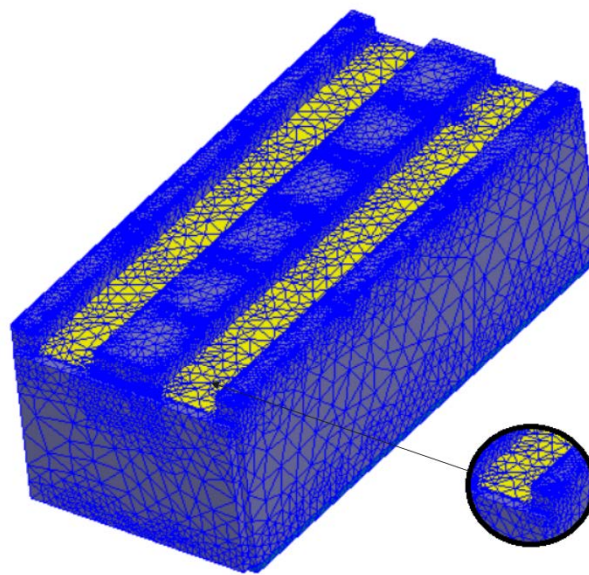


Figure 3. Process steps used in the design

The FEM is frequently used in many different sectors such as electrical-electronic, construction, materials and biomedical sectors [9,21]. This method emerged to solve problems whose changes over a certain area can be expressed by partial differential equations. It is possible to reach satisfactory results in problems using the FEM through computer programs and mathematical methods [22]. In this method, the solution region is divided into many small, interconnected subregions, called finite elements. In the solution stage, all these small finite elements are combined at points, called nodal points, and approximate results are found. FEA can be performed by creating a 3D model of the billet and electromagnet model with a computer-aided design program in order to apply the FEM to an electromagnet design. Thus, it is possible to obtain the desired design and behavior model of the system. It will be beneficial for the designer to use this method in terms of time and economy [23].



**Figure 4.** Mesh model of the electromagnet

The finite element mesh structure of the designed electromagnet is shown in Fig. 4. The solution regions were divided into many regions, and the results were obtained. From the solutions, it was observed that the number of meshes was higher at the sharp edges.

### III. ANALYTICAL CALCULATIONS

The value of the force required to lift the load was calculated analytically, and the number of windings and the current value of the electromagnet were determined. The obtained current and winding values were used as ampere-turn values in the analysis, and magnetostatic analyses of the electromagnet were performed. From Eq. (1), the value of the force required to lift a single load is found by multiplying the mass of the load by gravitational acceleration [24].

$$F = m \cdot g \quad (1)$$

In the equation,  $m$  represents the mass of the load, and  $g$  represents gravitational acceleration ( $m/s^2$ ). The volume of the load with the given dimensions was calculated as  $0.1872 \text{ m}^3$ . Since  $1 \text{ m}^3$  of Steel\_1010 material was identified as  $7,872 \text{ kg}$ , mass of the single load was found as  $1,473.6 \text{ kg}$ . Accordingly, the value of the force required to lift single load was  $1,473.6 \times 9.81 = 14,456 \text{ N}$ . The ampere-turn value required to lift this force was obtained by conducting parametric analysis, as in Figure 5.

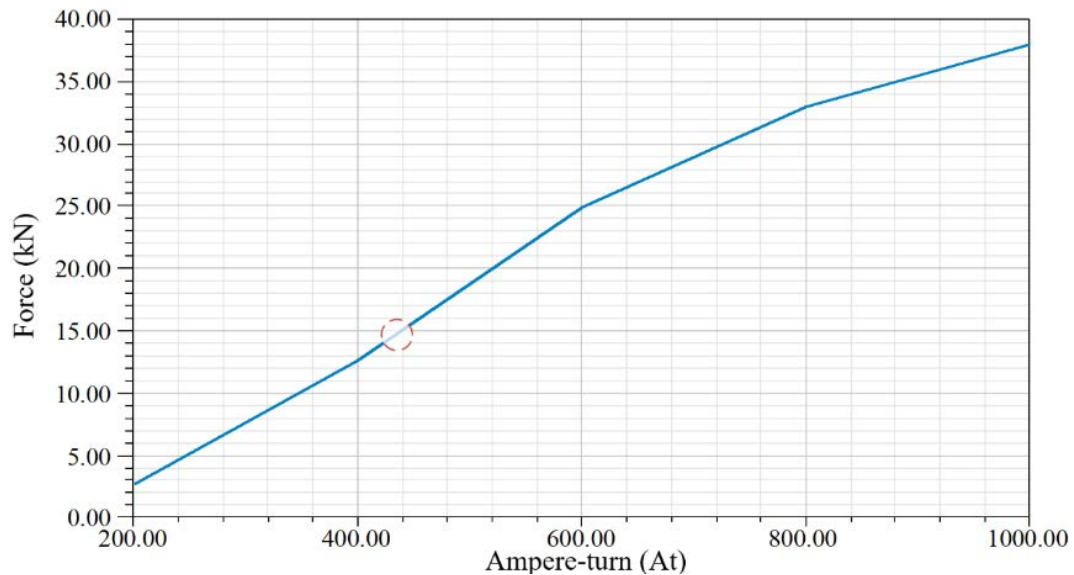


Figure 5. Ampere-turn value

As a result of the analysis,  $440 \text{ At}$  excitation current was applied to the electromagnet.  $N=110$  turns were utilized by applying a conductor with a cross-section of  $1 \text{ mm}^2$  to the electromagnet.  $4 \text{ A}$  current was applied from the formula of magnetomotive force in Eq. (2).

$$\mathfrak{F} = N \cdot I \quad (2)$$

The dimensions, volume, and calculation results of other loads intended to be transported are given in Table 1.

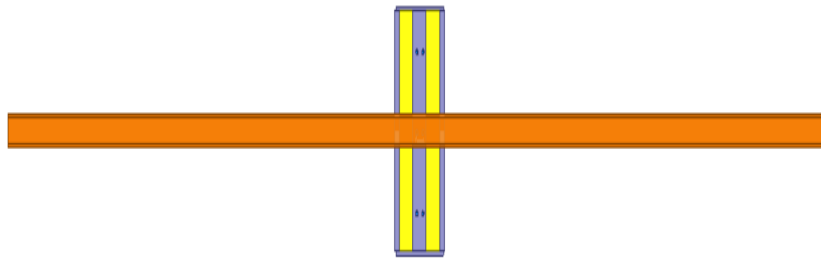
Table 1. Volume and force calculation of the loads used

Load Dimension (mm)	Volume ( $\text{m}^3$ )	Mass (kg)	Required Force(N)
150×150×8,320	0.1872	1,473.6	14,456
280×360×8,320	0.5495	4,325.6	42,434.1
400×500×8,320	0.9304	7,324.1	71,849.4

As a result of the analytical calculations, the magnetostatic analysis of the electromagnets was conducted with the appropriate ampere-turn value, and the simulation results were provided. In the analyses, the load models in different numbers and models were used, and their effects on the results were examined.

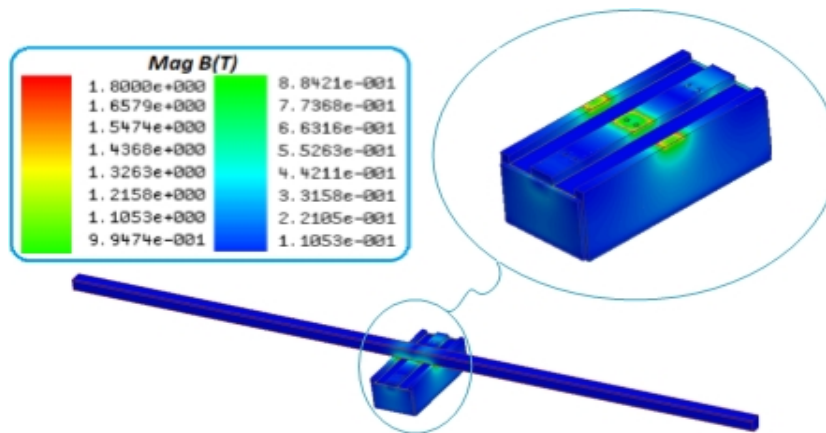
**IV. FEM ANALYSIS**

First, the billet load of 150×150×8,320 mm, whose 3D view is presented in Figure 6, was intended to be lifted using an electromagnet. The volume value of the load was known as 0.1872 m<sup>3</sup> from Table 1. Since the density of Steel\_1010 material was identified as 7,872 kg/m<sup>3</sup>, mass of the single billet was 1,473.6 kg. Accordingly, the force required to lift single billet was 14,456 N.



**Figure 6.** Load model (150×150×8,320 mm)

The magnetostatic analysis of the electromagnet was conducted after the analytical calculations, and the magnetic flux densities obtained as a result of the analysis are shown in Figure 7.



**Figure 7.** Magnetic flux density of the electromagnet and load

The analysis showed that the magnetic flux was concentrated in the regions where the load contacted the electromagnet. Upon examining the BH characteristics of Steel\_1010, it was observed that the electromagnet did not reach the saturation point. The magnetostatic analysis was conducted on the 3D model using different numbers of loads. The following analyses were carried out using with two electromagnets to ensure the moment balance of the load and provide more reliable transport. Since the force required to lift single load was calculated as 14,456 N, the value of the lifting force required for 3 loads was 43,368 N. From the results of the parametric analysis, magnetostatic analyses were performed by giving 1,000 At. excitation to each electromagnet, and the magnetic flux density distribution is shown in Figure 8. 9.1 A current of was applied using 110 turns in the electromagnets.

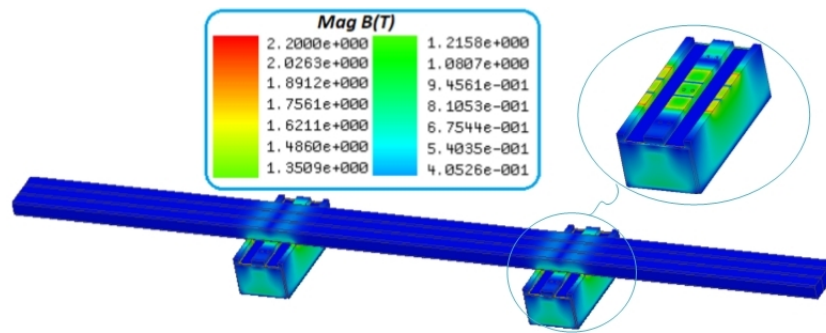


Figure 8. Magnetic flux distribution of 3 billets

Figure 9 shows the results of the magnetostatic analysis of the model created using 5 loads. The value of the force required to lift 5 billet loads was calculated as 72,280 N. 1,500 At excitation was given by applying 13.6 A to each electromagnet.

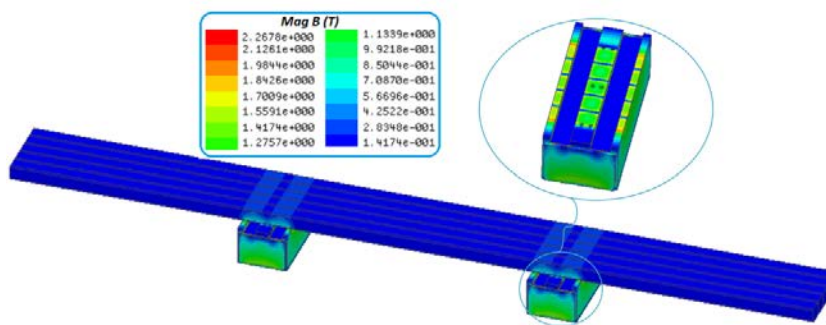


Figure 9. Magnetic flux distribution of 5 billets

It was observed that the ampere-turn ratio increased when the number of billets used was increased. Since the force of attraction was generated at the contact points of the billets with the electromagnet, the magnetic flux was concentrated at these points. Considering the magnetic flux distribution, it was observed that the core did not reach saturation. The force of attraction can be increased by increasing the applied ampere-turn value. When the same electromagnets were analyzed by establishing a different load model, it was seen from the parametric analyses that the required ampere-turn value and, accordingly, the number of windings changed. The load called beam blank with different models and dimensions is shown in Figure 10.

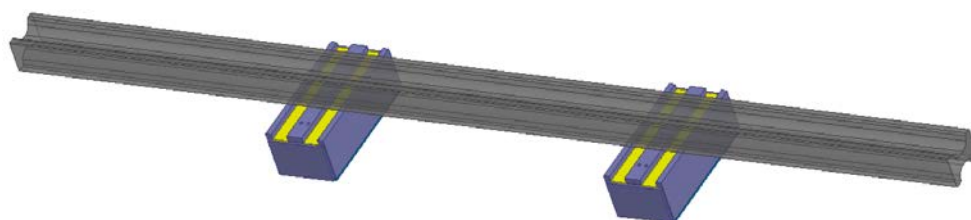


Figure 10. Beam blank load model



The volume of this load with dimensions  $280 \times 360 \times 8,320$  mm has been calculated as  $0.5495 \text{ m}^3$  due to its structure. Since Steel\_1010 material had a density of  $7,872 \text{ kg/m}^3$ , mass of the single load was  $4,325.6 \text{ kg}$ . From here, the value of the force required to lift single beam blank load was  $4,325.6 \times 9.81 = 42,434.1 \text{ N}$ . For single load,  $1,640 \text{ At}$  excitation current was given to each electromagnet,  $110$  windings were used, and  $14.9 \text{ A}$  was applied. The obtained magnetic flux distributions are given in Figure 11.

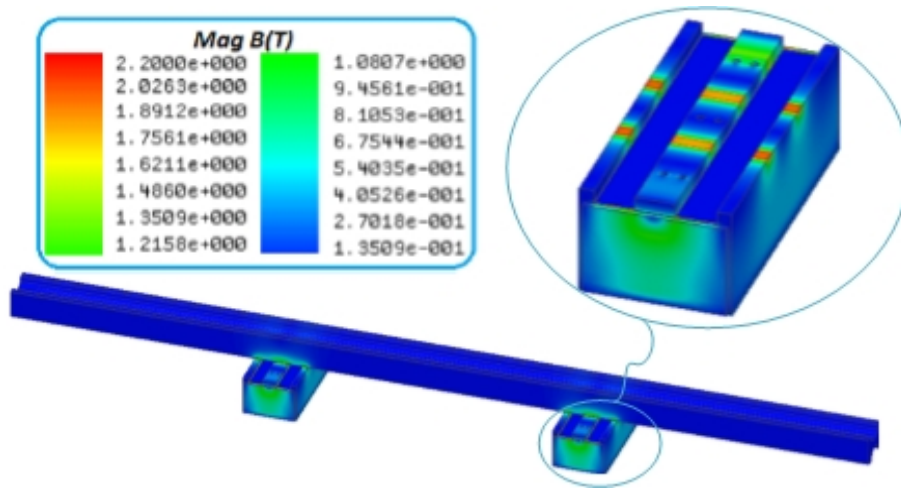


Figure 11. Magnetic flux density for beam blank load

The flux densities obtained as a result of the ampere-turn values applied in the parametric analysis are displayed in Figure 12. It was observed that the flux density increased as the ampere- turn value increased.

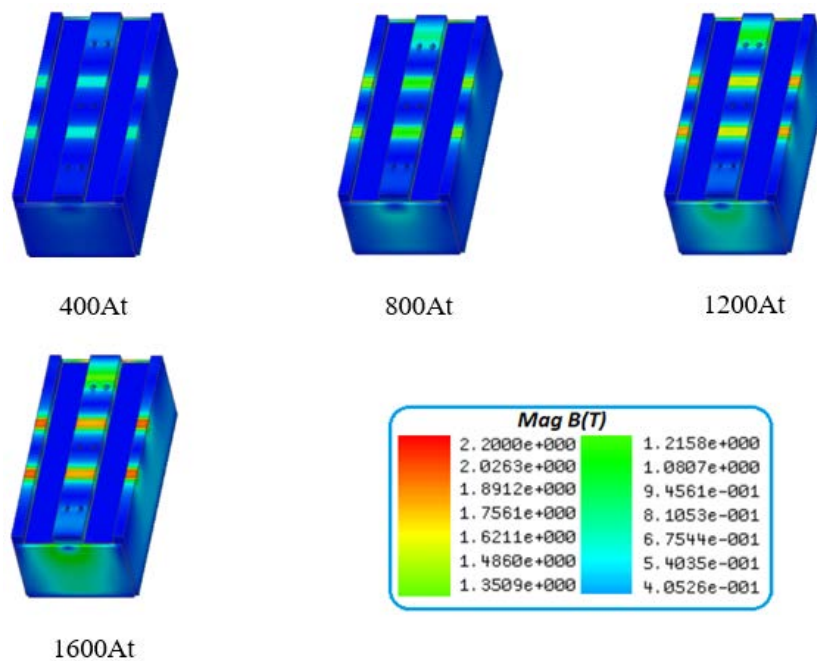


Figure 12. Flux densities obtained at different ampere-turns values



The magnetic flux distribution, which was designed using 3 loads and obtained as a result of the magnetostatic analysis, is shown in Figure 13. The force required to lift 3 loads was 12,7302.3 N. A current of 20 A was applied to 110 windings by applying 2,200 At excitation to each electromagnet. It is possible to reduce the applied current by increasing the number of windings.

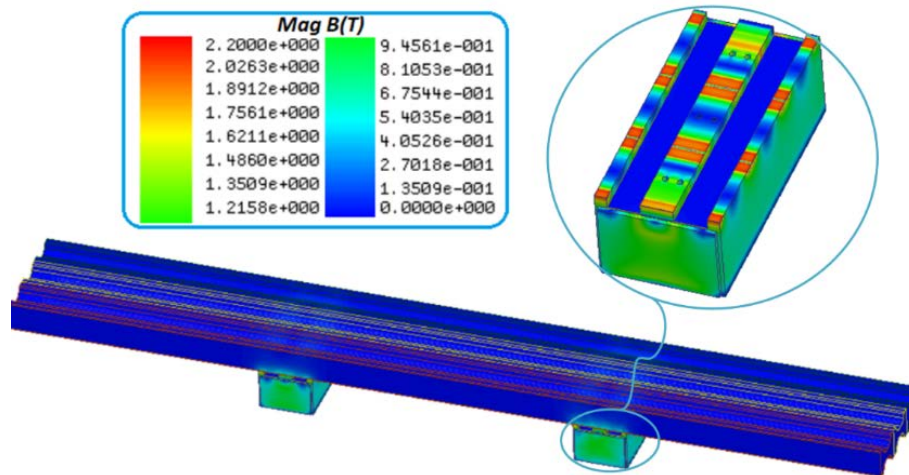


Figure 13. Magnetic flux distribution of 3 beam blanks

Since the contact surface of the load used was narrower compared to other loads, it was observed that the flux density was higher at the contact points. The magnetostatic analysis of the 3D model created for 2 loads with a dimension of 400×500×8,320 mm is given in Figure 14. The volume of the load is 0.9304 m<sup>3</sup>, due to its structure and the mass of the single load is 7,324.1 kg. A force of  $7,324.1 \times 9.81 = 71,849.4$  N is required to lift single load. The lifting force required for two loads was calculated as 143.7 kN. It was considered to use 200 turns by applying a current of 15 A with 3,000 At excitation to each electromagnet. As in the previous analyses, if 110 turns of winding are preferred, a current of 27.7 A needs to be applied.

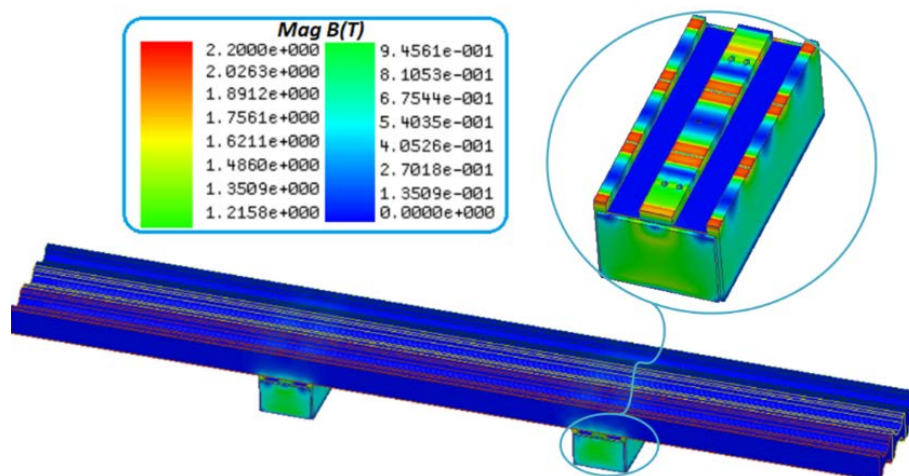


Figure 14. Magnetic flux distribution of two loads

The value of the magnetic flux density was concentrated on the adhesion surface of the load to the electromagnet. Since there was no interaction with any ferromagnetic material at other points of the electromagnet, the magnetic flux was very low at these points due to the magnetic field. Considering the magnetic flux distributions by examining the BH characteristics of the core material, it was concluded that the core could lift the loads desired to be carried without reaching saturation. The values of the applied current are an example of the design. It is also possible to transport larger loads at different ampere-turn values. Analyses can also be performed for this electromagnet using a high turn number with a lower current.

## V. CONCLUSIONS

In this study, a two-pole electromagnet was designed for lifting and carrying the loads with given dimensions, and its analyses were conducted by employing the FEM. The materials used in the design were determined, their properties were given, and the analytical calculations of the electromagnet were carried out by considering the desired lifting load. The goal was to provide transport without reaching saturation at the appropriate ampere-turn ratio according to the load to be transported. The forces that would occur on the loads used were calculated by performing the FEA on the electromagnet's 3D model, and the magnetic flux distributions on the model were obtained.

Considering the results of the magnetostatic analysis, it was concluded that parameters such as the number, dimension, and model of the load affected the ampere-turn ratio applied to the electromagnet. The ampere-turn ratio increased when the number of loads to be transported increased. Secondly, it was observed that the applied ampere-turn ratio should be increased for loads with a narrower contact surface with the electromagnet, as the required lifting force was higher. Due to the decreased reluctance in the regions where the electromagnet was attached to the load, it was observed that the magnetic field and thus the magnetic flux density were concentrated in these parts. When the magnetic flux distributions obtained by examining the BH characteristic of the core were investigated, it was found that transport could be achieved before the core was saturated. With this study, electromagnet design will be possible using real design criteria, which is considered to serve as a model for the design of electromagnets to be produce.

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