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Numerical Analysis of Metals Under The Influence of Electromagnetic Field at Different Current Values

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ABSTRACT

The primary factors of the widespread use of induction melting furnaces are uniform metal and heat distribution due to its mixing features, low alloy losses, excellent temperature and composition control, versatility in processing different materials, the ability to quickly start the process from a cold state when needed, and the absence of air pollution problems. In induction heating, not all sides of the part to be heated receive an equal amount of heat. Only if the part to be heated is of the type that conducts heat very well can all sides of the part be heated close to each other. Induction heating produces high heat on the surface, less on the inner parts, and least on the center of the material. This heating varies depending on the frequency of the current source and the penetration depth. In this study, a model was created in ANSYS numerical analysis program by taking the current, which is one of the electromagnetic and thermal parameters affecting the temperature distribution in the metalic material in induction heating, at different values. In the simulation model created, three-dimensional numerical analysis results of a cylindrical metallic material were obtained. In the simulation program, the power and frequency required for the design of the induction coil and the magnetic permeability, resistivity, heat transfer coefficient of the material and the position of the material in the inductor are determined as boundary conditions. Depending on these variables, the temperature and magnetic field distributions on the material were obtained. In addition to the numerical analysis, a cylindrical metallic material with known properties was placed in a specially manufactured induction coil and the temperature values on the material were measured to verify the numerical analysis. ANSYS modeling results with the same material dimensions, properties, and other parameters used in the experiment, were given and examined in comparison with the experimental results.

Farklı Akım Değerlerinde Elektromanyetik Alan Etkisi Altındaki Metallerin Sayısal Analizi

MAKALE BİLGİSİ

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Anahtar Kelimeler:
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Akım
Elektromanyetik alan

ÖZET

Ergitme ocaklarında karıştırma özelliği dolayısıyla düzgün bir metal ve ısı dağılımı, alaşım kayıplarının azlığı, sıcaklık ve bileşim kontrolünün çok iyi olması, işlem görecek malzeme özelliklerinin sınırlı olmaması, istenildiği zaman kısa süre içerisinde soğuktan işletime alınabilmesi hava kirliliği probleminin olmayışı indüksiyon ergitme ocakları kullanımının yaygınlaşmasında temel faktörlerdir. İndüksiyonla ısıtmada, ısıtılacak parçanın her tarafı eşit miktarda ısı almamaktadır. Yalnız ısıtılacak parça ısıyı çok iyi ileten cinsten ise, parçanın her tarafı birbirine yakın miktarda ısıtılabilmektedir. İndüksiyon ısıtma parçanın yüzeyinde çok yüksek, iç kısımlarında az, merkezinde ise daha az bir ısı meydana getirmektedir. Bu ısınma akım kaynağının frekansına ve nüfuz derinliğine bağlı olarak değişmektedir. Bu çalışmada, indüksiyonla ısıtmada metal malzemedeki sıcaklık dağılımını etkileyen elektromanyetik ve termal parametrelerden biri olan akım değeri farklı akım değerlerde alınarak ANSYS sayısal çözümleme programında bir model oluşturulmuştur. Oluşturulan simülasyon modelinde silindirik bir metalik malzemede

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üç boyutlu olarak sayısal çözümleme sonuçları elde edilmiştir. Simülasyon programında indüksiyon bobini tasarımı için ihtiyaç duyulan güç ve frekans ile malzemenin manyetik geçirgenlik, özdirenç, ısı iletim katsayısı ve malzemenin indüktör içerisindeki konumu sınır şartları olarak belirlenmiştir. Bu değişkenlere bağlı olarak malzeme üzerindeki sıcaklık ve manyetik alan dağılımları elde edilmiştir. Sayısal çözümleme yanında sayısal çözümlemenin doğrulanabilmesi için, özel olarak imal edilmiş bir indüksiyon bobini içerisine özellikleri bilinen silindirik metal malzeme yerleştirilerek ısıtılmış ve deneysel olarak malzeme üzerindeki sıcaklık değerleri ölçülmüştür. Deneyde kullanılan malzeme boyutları ve özellikleri ile diğer parametreleri aynı seçilen ANSYS modelleme sonuçları deneysel sonuçlarla karşılaştırmalı olarak verilmiş ve irdelenmiştir.

1. INTRODUCTION (GIRIŞ)

The basic principle of induction heating is based on the conversion of electromagnetic energy into heat energy. As seen in Figure 1, when alternating current is applied to a coil, a variable magnetic field is formed around the coil according to Ampere's Law. This magnetic field induces a voltage on the part to be heated according to Faraday's Law. This induced voltage causes eddy currents to flow in the workpiece placed in the induction coil which is in the magnetic field according to Lenz's Law.

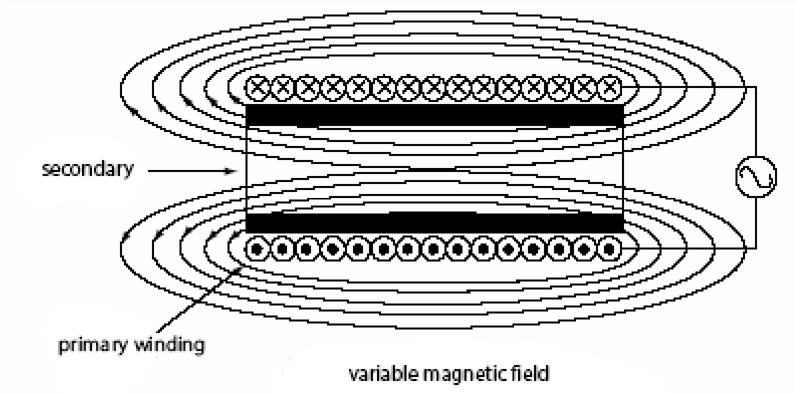


Figure 1. Basic principle of induction heating (İndüksiyonla ısıtmanın temel prensibi) [1].

Drobrenko et al. [2], in their study, made a mathematical simulation of the induction heating of metals with high electrical conductivity to high temperatures. Thermal modeling of solid cylinder stainless steel was carried out and in light of the numerical results, it was determined that the temperature increase depends on the electrical conductivity and magnetic characteristics of the material. Values for stainless steel were examined comparatively with both electrical conductivity and magnetic characteristics. Non-static mathematical model; They combined it with polarized and magnetizable opposing symmetrical solids, in which electromagnetic fields are proposed to be produced by external currents, as well as electromagnetic and thermal processes. The parameters of the process are correlated with the temperature dependence of the heat source and material characteristics. In their study, they investigated the change of magnetic permeability of materials with temperature increase by considering the induction heating process of a finite steel cylinder. Jang and Chiu investigated the heating of hollow cylinder steel with electromagnetic induction step by step and compared them with their numerical analysis. They conducted their studies by taking the forms of the same material in three different lengths, diameters, and wall thicknesses [3]. Shen et al. [4], made mathematical modeling of electromagnetic and temperature distributions in high-frequency induction heating using Maxwell's equations. To develop the temperature field according to Maxwell's equation, a mathematical model was created for the high-frequency induction heating case and an equation was obtained by combining the electromagnetic and temperature fields to be solved. They simulated this modeling in the FEMLAB program and compared the program data with the experimental results. The effects of high-frequency heating parameters and plate-coil distance were investigated through this model. In another study, Magnabosco et al. [5], compared the thermal analysis of an induction-heated ISO C45 steel bar numerically and experimentally. By considering two sample materials that were normalized and annealed, they analyzed the metallurgical and thermal analysis of the materials with the Sysweld-2000 numerical modeling program and formed the thermo-metallurgical model of the material in the induction heating process with experimental results [6]. Zhao and his group [7] investigated the temperature distribution and structural deformation of steel during continuous casting under a high-frequency electromagnetic field. They also carried out numerical modeling of the thermal behavior of the material in this electromagnetic field. Several numerical modeling strategies with different limitations have been developed to model the induction heating process. Various magnetic vector potential formulations for the eddy current problem are reviewed by Biro and Preis [8], where special attention is paid to the uniqueness of the vector potential formulation. The solution strategies are implemented using the finite element method and hysteresis and anisotropic effects are neglected. In the work by Bay et al. [9], ferromagnetic nonlinear effects are taken into account, but only temperatures below the Curie temperature are considered and the effect of magnetic hysteresis is neglected. Areitioaurtena et al. proposed an approximate solution based on a semi-analytical modeling strategy [10, 11]. In their work, an analytical electromagnetic approach is followed to solve the coupled electromagnetic-thermal problem by determining the initial model based on the harmonic approximation and performing the finite element solution. In another study in this model, Jankowski et al. presented an approximate solution for the induction heating of a solid cylinder in a cylindrical induction coil [12]. Comparisons between their work, finite element analysis and experimental data show that the analytical solution is able to capture the frequency and temperature evolution during heating quite well for paramagnetic materials. In addition to these studies, finite element method is frequently used in various studies in the field of engineering [13, 14].

2. MATERIAL AND METHOD (MATERYAL VE YÖNTEM)

2.1. Induction Heating Theory (İndüksiyonla Isıtma Teorisi)

Induction heating is a method that generates heat by inducing eddy currents and hysteresis losses in the part by the alternating magnetic field formed on the surface of the part. The alternating magnetic field is created by an alternating current flowing induction coil that surrounds the workpiece or is held parallel to the workpiece. Applying alternating voltage to the induction coil causes alternating current to flow in the coil. In this case, a time-varying magnetic field is formed in the environment and the frequency of this field is the same as the frequency of the applied current. When the electromagnetic field is changed, a magnetic force is created in any conductive material. If the current flow is allowed on a whole path through the material, the induced force creates a current along that path. Due to the resistance of the material, the Joule effect is observed and heat generation occurs in proportion to $I R^2$. Here, I is the magnetic current and R is the resistance of the material [15]. In the case of continuous current, the resistance of a homogeneous material with a uniform cross-sectional area is defined as (Ohm, Ω).

Induction heating is based on the development of the joule effect on the material in the adjacent areas of the material close to the coil. In Figure 2, the heat generation in the material placed in the magnetic field is presented schematically.

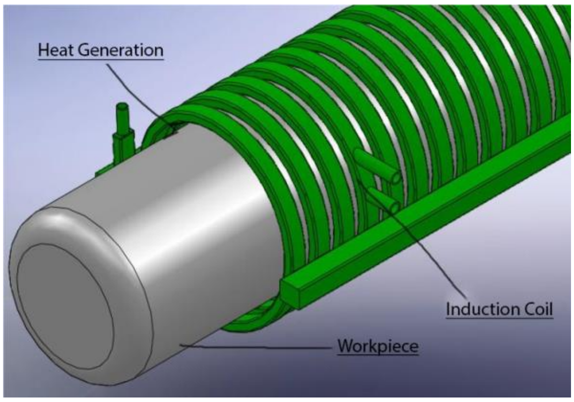


Figure 2. Heating inductor and workpiece (Isıtma indüktörü ve iş parçası)

By how many degrees the temperature of the metallic material is desired to be increased, the temperature changes of the material values between those temperatures should be transferred to ANSYS for both electromagnetic and thermal analysis. Solving the problem should be done sequentially. First, the electromagnetic analysis should be resolved harmonically, and then the thermal analysis based on time. Finally, the electromagnetic analysis should be repeated at various time intervals so that the time-related properties of the temperature that will affect the solution are confirmed and the heat is transferred to the metallic material. (Figure 3)

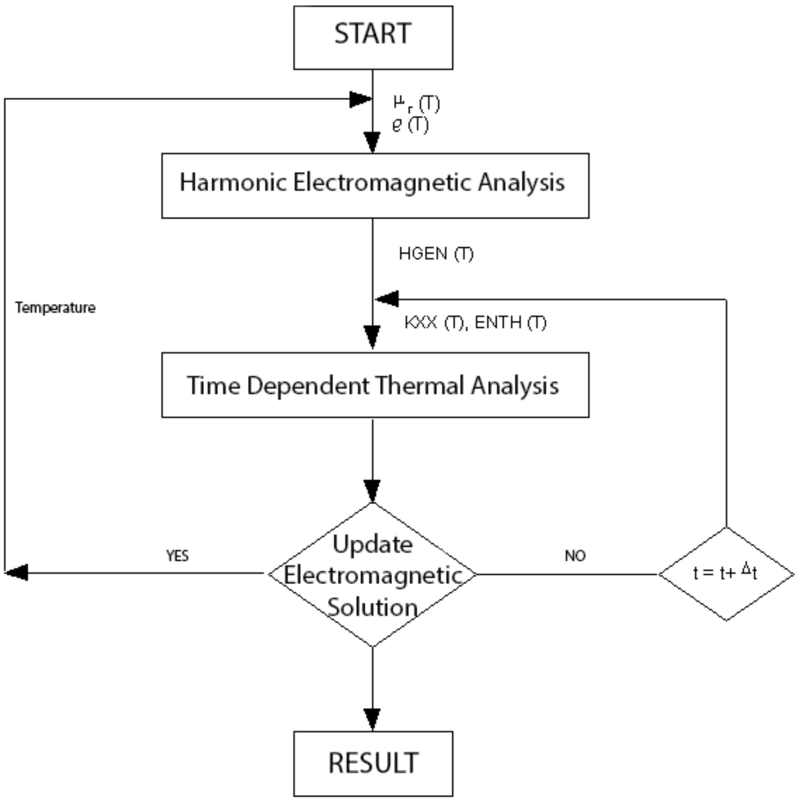


Figure 3. Electromagnetic-thermal analysis flow chart (Elektromanyetik-termal analiz akış şeması)

2.2. Three Dimensional Electromagnetic Thermal Analysis (Üç Boyutlu Elektromanyetik Termal Analiz)

By modeling a real induction furnace's dimensions and material dimensions, electromagnetic and thermal changes are solved in three dimensions on the xyz space.

2.2.1. Element selection (Eleman seçimi)

In three-dimensional analysis, firstly, analysis types will be introduced. By specifying the degrees of freedom of the selected element types, the suitability for their analysis will be explained.

Solid 236 geometry

This element type was used for electromagnetic analysis. The geometry of the object, the applicable boundary condition values, and the degrees of freedom made this element type suitable for electromagnetic analysis. Solid 236 is a 3-dimensional, 20-node element type containing electromagnetic fields. This element type has magnetic and electrical degrees of freedom (Figure 4).

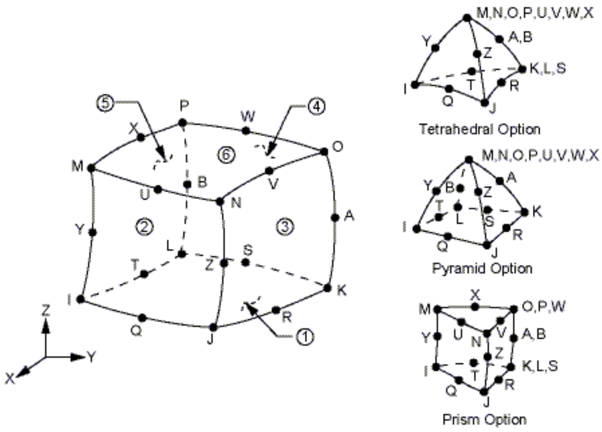


Figure 4. Solid 236 element type geometry (Solid 236 eleman tipi geometri) [16]

Solid 90 geometry

This element type was chosen for thermal analysis. The suitability to the geometry of the object, the applicable boundary conditions, and degrees of freedom make this element type suitable for thermal analysis. Solid 90 is a 3-dimensional, 20-node element type with thermal degrees of freedom (Figure 5).

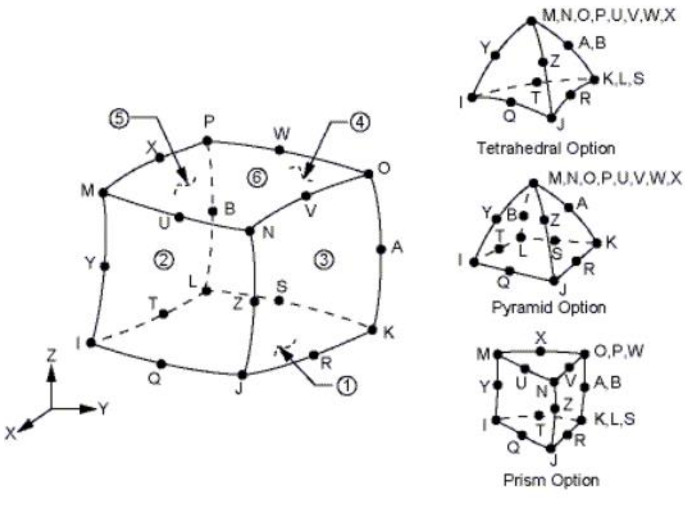


Figure 5. Solid 90 element type geometry (Solid 90 eleman tipi geometri) [16]

2.2.2. Entering material properties (Malzeme özelliklerini girme)

Due to the structure of the induction furnace, the properties of the inductor, air and the material to be heated will be defined and calculations will be made on these properties. Magnetic permeability, resistivity, enthalpy values, and thermal conductivity values depending on the temperature of the material to be heated are included in the analysis. The numerical values of these properties are given in the table below.

Table 1. Some temperature-dependent material properties for ferrous material

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
Temperature	0	27	127	327	527	727	765	927		
Enthalpy	7.89×10^{-27}	9.16×10^{11}	4.53×10^{12}	1.27×10^{13}	2.25×10^{13}	3.34×10^{13}	3.55×10^{13}	4.35×10^{12}		
Temperature	0	730	930	1000						
Thermal Conductivity	60.64	29.5	28	28						
Temperature	25.5	160	291.5	477.5	635	698	709	720.3	742	761
Magnetic Permeability	200	190	182	161	135	104	84	35	17	1
Temperature	0	125	250	375	500	625	750	875	1000	
Resistivity	1.84×10^{-7}	2.72×10^{-7}	3.84×10^{-7}	5.12×10^{-7}	6.56×10^{-7}	8.24×10^{-7}	1.03×10^{-3}	1.15×10^{-3}	1.2×10^{-6}	
Temperature	0									
Emissivity	0.68									

In addition to what is shown in the chart, the magnetic permeability value of the air and the inductor is entered as 1.

2.2.3. Separation into elements (Elemanlara ayırma)

Figure 6 shows the inductor and the iron rod separated into its elements. There is an iron bar inside and an inductor on the outside. The outermost material seen in red is air. As seen in the picture, the geometries prepared for analysis were taken in a quarter volumes. The reason for this is to prevent the analysis from taking too long due to the excess that will occur in the number of meshes, and therefore in the number of nodes, if the system is taken at full volume. Because the system is symmetrical, any change that will occur in the one-quarter volume will occur in the same shape and ratio in the entire volume.

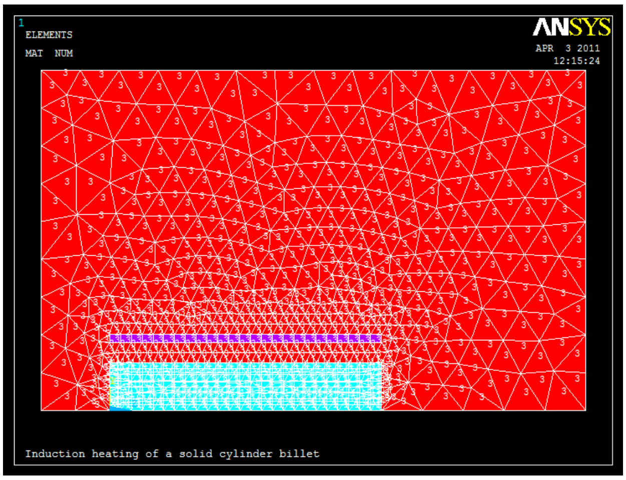


Figure 6. Meshed view of the 3D system (3B sistemin mesh görünümü)

2.2.4. Process (İşlem)

By how many degrees the metallic material temperature is desired to be increased, the changes in material values between those temperatures should be transferred to the ANSYS program for both electromagnetic and thermal analysis. Solving the problem should be done sequentially. First, the electromagnetic analysis should be resolved harmonically, and then the thermal analysis based on time. Finally, the electromagnetic analysis should be repeated at various time intervals and the time-related properties of the temperature that will affect the solution should be verified and the heat must be transferred to the iron rod.

2.2.5. Boundary conditions (Sınır şartları)

Figure 7 shows the boundary conditions applied to the inductor and the iron rod. These are the current value applied to the inductor, the irradiance value applied to the iron bar, and the insulation applied to both.

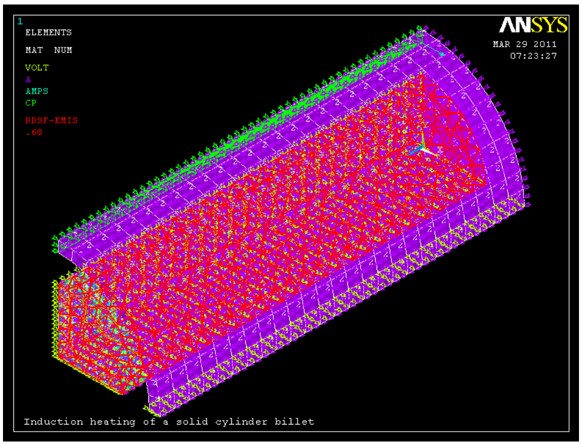


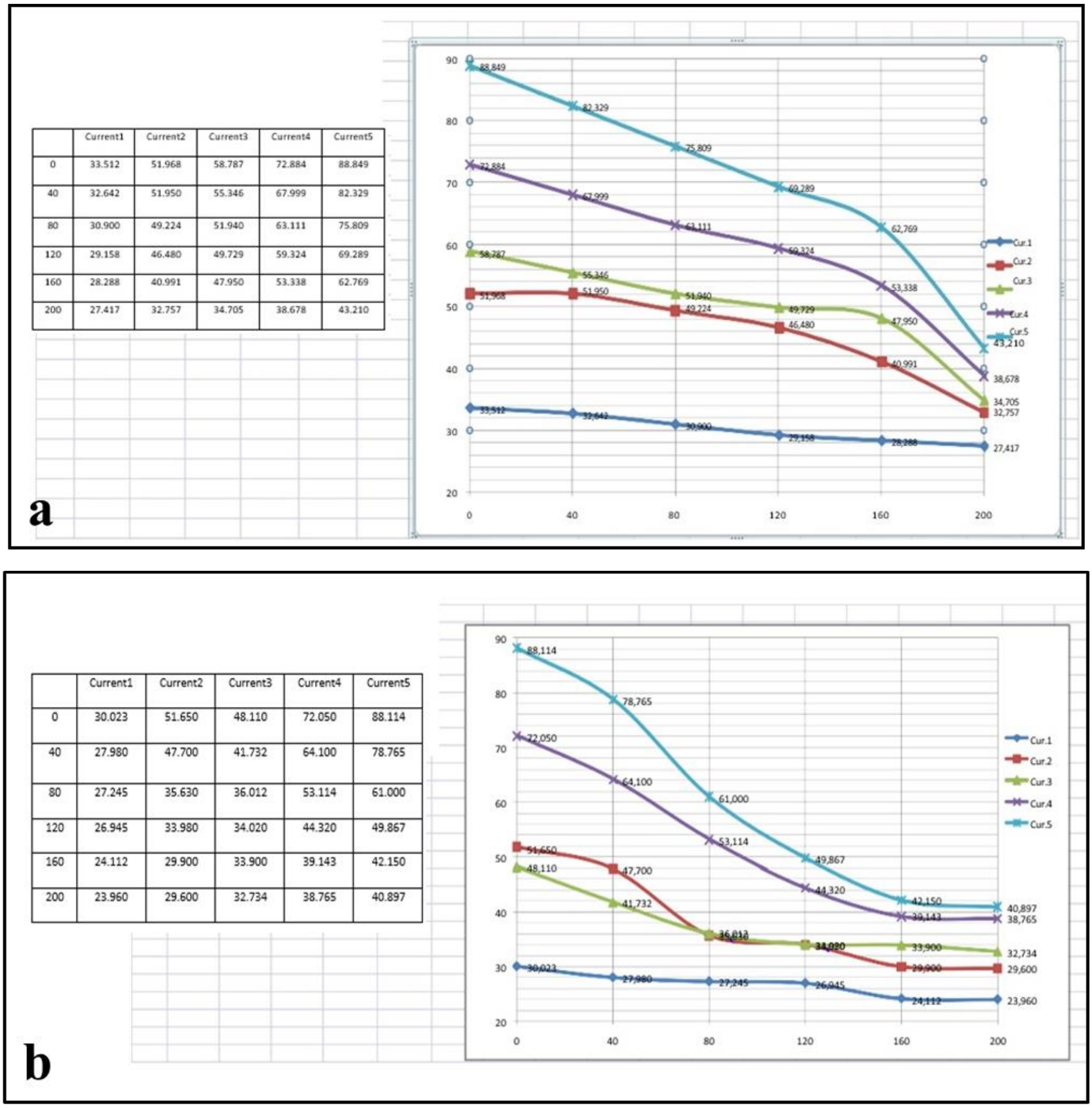
Figure 7. Boundary conditions and loadings of the 3D model (3B modelin sınır koşulları ve yüklemeleri)

3. EXPERIMENT AND OPTIMIZATION RESULTS (DENEY VE OPTİMİZASYON SONUÇLARI)

It is known that the most important and decisive factors in the design of the induction coil are time, frequency, power, and reaching the specific temperature value for a certain point of the material to be heated. Considering these factors, the numerical analysis was solved at different current values, different frequency values, different time intervals, and by changing the position of the metal to be heated in the induction coil, and numerical analysis results were obtained.

3.1. Numerical Analysis Results at Different Current Values (Farklı Akım Değerlerinde Sayısal Analiz Sonuçları)

The length of the metallic material with a diameter of 70 mm in a 1 m long induction coil is taken as 200 mm. It is known that the current applied to the coil directly affects the system parameters. For this reason, the current value applied to the induction coil is taken as 1000 A, 2000 A, 3000 A, and 4000 A, respectively, a model is prepared and the numerical analysis results are obtained by entering the system parameters. The metallic material is positioned at the front of the coil. Temperature change in material along the z and x axis due to current change is given in Figure 8.



	Current1	Current2	Current3	Current4	Current5
0	33.512	51.968	58.787	72.884	88.849
40	32.642	51.950	55.346	67.999	82.329
80	30.900	49.224	51.940	63.111	75.809
120	29.158	46.480	49.729	59.324	69.289
160	28.288	40.991	47.950	53.338	62.769
200	27.417	32.757	34.705	38.678	43.210

	Current1	Current2	Current3	Current4	Current5
0	30.023	51.650	48.110	72.050	88.114
40	27.980	47.700	41.732	64.100	78.765
80	27.245	35.630	36.012	53.114	61.000
120	26.945	33.980	34.020	44.320	49.867
160	24.112	29.900	33.900	39.143	42.150
200	23.960	29.600	32.734	38.765	40.897

Figure 8. Temperature change in material along the z (a) and x (b) axis due to current change (Akım değişiminden dolayı z(a) ve x(b) ekseni boyunca malzemedeki sıcaklık değişimi)

4. CONCLUSIONS (SONUÇLAR)

The magnetic field strength depends on the current flowing through the induction coil, coil geometry, and coil distance. The alternating magnetic field creates eddy currents in the workpiece and other materials placed near the coil. The heat generation by eddy currents increases the temperature of the workpiece. As a result, as the current value applied to the workpiece is increased, the heat generation value will also increase, and the maximum temperature value of the workpiece will also increase.

In the studies conducted, it was seen that the simulation results and the experimental results showed a significant similarity. This situation has led to a positive opinion that induction heating modeling and simulation can be performed on the ANSYS program. This study will make a very important contribution to the design of the power unit and heating coil of the induction furnace.

As it is known, induction heating is used in a wide variety of areas, from hardening the teeth of gear wheels to welding works. In general, the heating inductor is developed based on experience and there is no data on its efficiency. With this study, efficient heating coil design will be possible for any situation where induction heating simulations can be performed by using the electromagnetic module of the ANSYS program, provided that it is modeled correctly.

The model was created based on a specially manufactured induction coil and an Ø70mmx200 mm iron material in cylindrical geometry, whose material properties are known and which is frequently used. This model, which was created in the ANSYS package program, was solved with one, two, and three-dimensional models as a couple analysis and the results were obtained as both animation, graphic, and list values. One, two, and three-dimensional analysis results were obtained parallel to each other. This shows that the established model and analysis are reliable, there is no mismatch in the boundary and initial conditions, and it gives correct results. Three-dimensional analyzes are associated with an ideal inductor length and material dimensions that will meet the needs of the industry and numerical analyzes have been reproduced by changing the parameters of induction furnaces and materials, and it has become possible to make the necessary approaches to improve the inductor design. In the analysis, the current value was changed by keeping the material properties, frequency value, and other boundary conditions constant, and it was determined that the magnetic field intensity and heat generation amount in the material increased with the increase in the current value. The general result of the equations consisting of Ampere's law, Gauss's law, and Faraday's law specified in Maxwell's equations will be like this.

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