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Simulation of Magnetic Anisotropy Energy Surfaces for Cubic Crystals Using MATLAB in Remote Material Physics Lectures

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Abstract

The physical characteristics of a crystal can be viewed from the distribution of magnetic energy contained in it so that a simulation is needed which helps in visualizing the magnetic energy of the crystals. This study aims to present a simple solution for constructing a simulation of the physical properties of cubic crystals using MATLAB software. MATLAB can also be used to help organize physics lectures remotely. This is because MATLAB can be operated by anyone, anytime, and anywhere without being connected to the internet network to help visualize the material magnetization concept in the form of 2- and 3-dimensional graphics. The simulation aims to visualize the magnetic anisotropy energy surface for cubic crystals. This simulation can visualize the magnetic anisotropy energy surface of 3 types of cubic crystals, namely simple cubic, body-centered cubic, and face-centered cubic. In this simulation, the difference between the 3 types of crystals is the anisotropy energy constant. The mathematical equations in the magnetic anisotropy energy surface for cubic crystals are quite complicated. This simulation can help students in exploring mathematical equations and studying the magnetic anisotropy energy surface for cubic crystals more. Students can also develop mathematical representation skills and creative visual representations of the magnetic anisotropy energy surface for cubic crystals.

Keywords: Anisotropy energy, Cubic crystals, Magnetic, MATLAB, Visualization

Introduction

The advancement of material and magnetic technology that is developing so fast nowadays has become a major focus in the world of industry, research, and education. The need for material and magnetic technology with various costs and capabilities is the main reason for increasing product quality and quantity. Besides, in the field of research, the study of magnetic field of material needs to be studied more deeply to find materials that have characteristics that make them efficient and easier for humans to use. This of course can be realized easily if every human being from an early age has been introduced to the material, its characteristics, and its benefits for human life. Therefore, the field of material physics education plays a role in introducing various materials contained in the universe which include their characteristics and benefits to students [1]. In introducing the characteristics of the material and its benefits to students, an educator needs to integrate it with existing technology and that is often used by students. One form of interpreting physics concepts with the help of technology so that it is easy for students to understand is simulating the magnetic properties of ferromagnetic materials using MATLAB and Vampire software [2,3]. The integration of physics concepts with the help of this technology aims to make students easy to accept and easily understand educators' explanations about these materials. Educators and students also need to collaborate in developing material physics science in a practical and easy-to-understand holistic manner. However, students need to be given flexibility in constructing simulations from physics concepts.

The simulation of material physics concepts, especially in the magnetic study of a crystal that forms 3-dimensional graphic visualizations, is rarely done by educators and students. This happens because most educators and students only simulate physics concepts related to vibrations and waves which only produce 2-dimensional graphic visualization so that it does not attract students' interest to learn more about the concepts of material physics [4]. This is of course a problem when educators and students are faced with physical phenomena that occur in everyday life that are not only related to vibrations and waves. Besides, the form of simulating physics concepts which are mostly done by educators is only integrated with the help of technology which can only visualize 2-dimensional graphics [5]. This results in limited use when used to simulate more complex physics equations and produce 3-dimensional graphs. It is different from simulating the material magnetic physics concept that integrates technology such as MATLAB which can be used by educators and students anytime and anywhere without an internet network [6]. Besides, the MATLAB software can also simulate complex physics equations and produce output in the form of 3-dimensional graphics [7]. Thus, with the help of technology such as MATLAB which is used in simulating the concept of magnetic material, physics lectures are expected to run more effectively.

Through simulations that visualize the concept of material magnetization integrated with MATLAB, of course, it can make it easier for educators and students to develop material physics science [8]. Besides, the integrated material magnetization concept simulation with MATLAB can also provide software options that can be used to easily visualize the material magnetization concept and obtain the best results. Furthermore, this statement is also supported by the results of research conducted by Manh *et al*. [9]. that simulations that visualize the backscattering diffraction of electrons in steel can be done using MATLAB which produces a more interactive 3-dimensional visualization [9]. The results of this study are also supported by the results of other studies which reveal that the modeling of the energy dispersion of graphene crystals with the help of MATLAB software results in visualization of the energy dispersion by the results of direct experiments through scanning electron microscopy [10]. MATLAB is a computational software that is used to easily visualize a mathematical equation of physical phenomena that does not require an internet connection and produces 3-dimensional graphics that are much more interactive than other graphic software [11]. Thus, the existence of simulations that visualize the abstract, non-observable, concept of magnetization of materials is required in physics education and research.

MATLAB is software that has not been installed directly on the computer, so it is necessary to install it first if you are going to operate it. MATLAB is a graphical computing software used to visualize mathematical equations with the results of 3-dimensional graph visualization [12]. Matrix Laboratory or often abbreviated as MATLAB is a graphical and numerical computation software that requires a programming language to operate [13]. By using MATLAB, educators and students can manipulate a matrix, plot mathematical functions, and equations, implement an algorithm and create an interface [14]. MATLAB can also be used in supporting physics research activities, especially in analyzing and visualizing mathematical equations from simple to complex material magnetization phenomenon [15]. Besides, MATLAB software can also be used to help organize physics lectures remotely. This is because MATLAB can be operated by anyone, anytime, anywhere without being connected to an internet network to help visualize the concept of material magnetization in 2 and 3-dimensional graphical form [16].

The implementation of MATLAB in physics education can support simple visual constructs of any physics equation [17]. The implementation of MATLAB can also have a positive impact on the abilities of students. This is by the results of research that reveals that physics courses that integrate graphic visualization produced through MATLAB can improve students' mathematical representation abilities [18]. Visual and graphic representation abilities in students can also be developed by applying physics courses assisted by MATLAB [19]. After students have good mathematical representation skills, they can use MATLAB to visualize mathematical equations of other material magnetization phenomena creatively [20]. This is because MATLAB is a graphical and numerical computation software capable of visualizing physical phenomena and their equations from simple to complex in a complete and easy-to-understand manner. Besides, MATLAB is also one of the software that has been widely used by educators in helping them to teach abstract physics material to students [21]. Furthermore, several findings reveal the application of MATLAB software in physics research and education.

MATLAB software has been used to simulate a grid-connected photovoltaic system [22]. MATLAB can also be used to help simulate single-slit diffraction experiments that are often carried out by educators and students [23]. The use of this software in physics research and lectures is used to help computerized lectures in undergraduate physics courses by connecting a cell phone and MATLAB to study oscillatory motion [24]. Although the MATLAB software has been implemented in many physics research and lectures, the implementation of MATLAB on the topic of anisotropy energy in magnetic materials is still rare. This can occur because the translation of the mathematical equation for the anisotropy energy of the magnetic material is much more complicated than the mathematical equation for basic physics concepts [25]. Therefore, with the various uses of MATLAB in research and physics education and the rare visualization of magnetic anisotropy energy from cubic crystal structures using MATLAB, it is necessary to innovate in the development of simulations to visualize magnetic anisotropy energy from cubic crystal structures using MATLAB's assistance.

In general, anisotropy is the variation in the physical properties of a crystal atom concerning its measurement direction. In an anisotropic medium, a certain physical parameter has a different value if the parameter is measured at 2 different orientations [26]. Meanwhile, in an isotropic medium, the certain physical parameter will be the same in all measurement directions or orientations. Meanwhile, magnetic anisotropy energy is the energy that depends on the direction of magnetization and the crystallographic axis. Magnetic anisotropy energy comes from spin-orbital interactions and depends on the direction of magnetization to the crystallographic direction [27]. Many crystalline anisotropies are owned by ferromagnetic materials known as magnetocrystalline anisotropy [28]. Based on the problems described above, this research presents the magnetic anisotropy energy surface for cubic crystals using the help of MATLAB software. The simulating magnetic anisotropy energy surface of this cubic crystal can be used to support remote lectures that cannot be done face-to-face. The graphical computation software used in this research is MATLAB which can be used to visualize the magnetic anisotropy energy surface for cubic crystals at various anisotropy constants such as cubic crystals.

Theory

The dependence of magnetic properties on the direction of measurement gives rise to magnetic anisotropy. Consider a single ferromagnetic domain in which the magnetization is oriented at an angle θ to the z-axis taken along the principal axis of crystal symmetry [29]. Furthermore, for a crystal with a single axis with high symmetry, the equation for the uniaxial anisotropy energy can be written as shown in Eq. (1). Uniaxial anisotropy energy equations are generally closely related to the effort to assist in realizing the behavior of materials. This is because work is a change in energy that occurs in a material [30]. Therefore, energy is a component that is closely related to work.

$$E_{anis} = K_u sin^2\theta \tag{1}$$

Eq. (1) shows that θ is the angle between the z-axis of the poles and the magnetization vector as shown in **Figure 1** and K_u is the uniaxial anisotropy energy constant.

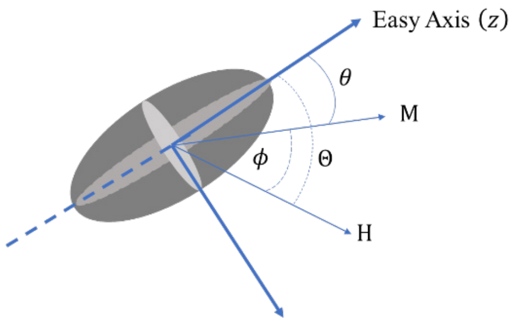

Figure 1 A single domain magnetic particle in the form of a prolate ellipse.

Based on **Figure 1** it can be shown that several components of the physical symbol consisting of M are a magnetization vector, H is a magnetic field vector, ϕ is the angle between the magnetization vector and the magnetic field vector, and Θ is the angle between the applied field and the easy axis. Meanwhile, in other words, uniaxial anisotropy is a characteristic of elongated particles [31,32]. If the uniaxial anisotropy energy equation is as shown in Eq. (1) with the equation $\mathcal{E}_d = \frac{1}{4}\mu_o V {M_s}^2 sin^2\theta$, it will be found that the 2 equations have similar angular symmetry dependencies. In the most common cause, the multiplication anisotropy constant K_u can be either positive or negative. Meanwhile, for $K_u > 0$, the minimization of E_{anis} to angle θ results in a 0 value. This shows that the z-axis is an easy magnetization direction. In this case, the z-axis is known as the easy axis. Furthermore, for $K_u < 0$, $\theta = \pi/2$ the direction of magnetization of the easy axis lies in the xy (basal) plane of the crystal. Such ferromagnets are known as easy-field types and there are also directions where the magnetization is difficult to straighten and are known as hard axes [33,34]. In the magnetic domain, the magnetization directions tend to align along the easy axis. Different materials have different easy axes as shown in **Figure 2** below.

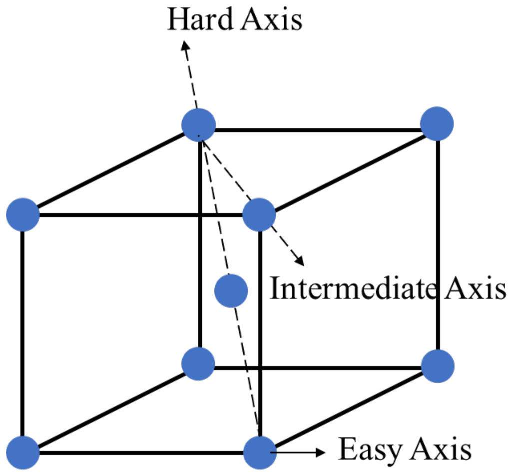

Figure 2 Easy, medium, and hard axes for a Ferrum unit cell.

Meanwhile, magnetocrystalline anisotropy is an intrinsic property of a material that is determined by crystal symmetry [35,36]. The anisotropy energy equation can be expressed in terms of the cosine of the direction of the magnetization vector $(*\,\theta_1, \theta_2, \theta_3)$ or in terms of a harmonic set of orthonormal spheres (θ, ϕ). Furthermore, the magnetocrystalline anisotropy equation for the cubic system can be shown as in Eq. (2) below.

$$E_{anis} = K_0 + K_1({\alpha_1}^2{\alpha_2}^2 + {\alpha_2}^2{\alpha_3}^2 + {\alpha_3}^2{\alpha_1}^2) + K_2({\alpha_1}^2{\alpha_2}^2{\alpha_3}^2) \tag{2}$$

Based on Eq. (2), the angle ϕ to the x-axis in the basal plane (azimuth angle) and the polar angle θ is measured about the z-axis. Meanwhile, the explicit equation for the cosine of the magnetization direction in the spherical harmonic variable can be shown as in Eqs. (3) to (5) below.

$$\alpha_1 = sin\theta\ cos\phi \tag{3}$$

$$\alpha_2 = sin\theta\ sin\phi \tag{4}$$

$$\alpha_3 = cos\theta \tag{5}$$

Meanwhile, the magnetic anisotropy energy equation of a cubic crystal without the influence of a magnetic field can be obtained by substituting Eq. (2) with Eqs. (3) to (5), so that the equation can be written as in Eq. (6) below.

$$E_{anis} = K_0 + K_1\begin{pmatrix} (sin\theta\ cos\phi)^2(sin\theta\ sin\phi)^2 + \\ (sin\theta\ sin\phi)^2(cos\theta)^2 + \\ (cos\theta)^2(sin\theta\ cos\phi)^2 \end{pmatrix} + K_2((sin\theta\ cos\phi)^2(sin\theta\ sin\phi)^2(cos\theta)^2) \tag{6}$$

The equation of the magnetic anisotropy energy surface for cubic crystals in the presence of the effect of a magnetic field can be realized if Eq. (6) is added with the components of the magnetic field as shown in Eq. (7) below.

$$H = \frac{h}{\sqrt{3}}(\alpha_1 + \alpha_2 + \alpha_3) \tag{7}$$

Meanwhile, to simulate the magnetic anisotropy energy surface for cubic crystals in the presence of a magnetic field, Eq. (6) needs to be added to Eq. (7). Therefore, the equation of the magnetic anisotropy energy surface for cubic crystals can be shown in Eq. (8).

$$E_{anis} = K_0 + K_1\begin{pmatrix}(sin\theta\ cos\phi)^2(sin\theta\ sin\phi)^2 + \\ (sin\theta\ sin\phi)^2(cos\theta)^2 + \\ (cos\theta)^2(sin\theta\ cos\phi)^2\end{pmatrix} + K_2\begin{pmatrix}(sin\theta\ cos\phi)^2 \\ (sin\theta\ sin\phi)^2 \\ (cos\theta)^2\end{pmatrix} + \frac{h}{\sqrt{3}}(\alpha_1+\alpha_2+\alpha_3) \quad (8)$$

After Eq. (8) is obtained, the next step is to substitute Eq. (8) with Eqs. (3) to (5). Therefore, the equation of the magnetic anisotropy energy surface for cubic crystals simulated using MATLAB can be shown as in Eq. (9) below.

$$E_{anis} = K_0 + K_1\begin{pmatrix}(sin\theta\ cos\phi)^2(sin\theta\ sin\phi)^2 + \\ (sin\theta\ sin\phi)^2(cos\theta)^2 + \\ (cos\theta)^2(sin\theta\ cos\phi)^2\end{pmatrix} + K_2\begin{pmatrix}(sin\theta\ cos\phi)^2 \\ (sin\theta\ sin\phi)^2 \\ (cos\theta)^2\end{pmatrix} + \frac{h}{\sqrt{3}}\begin{pmatrix}(sin\theta\ cos\phi) + \\ (sin\theta\ sin\phi) + \\ (cos\theta)\end{pmatrix} \quad (9)$$

All anisotropy constants have dimensions of energy per unit volume. Meanwhile, the anisotropy parameters in the form of K_0, K_1, and K_2 are anisotropy constants with different values for each crystal [37,38]. In the component of the magnetic field H, there is an h element whose value is equal to one. Furthermore, in the absence of an anisotropy energy term, the magnetization vector does not choose a particular direction in space. The amount of energy required by the orientation of the ferromagnetic vector is the same for all possible orientations in space. However, with the introduction of anisotropy, the spherical symmetry of the system is broken [39,40]. In general, the magnetocrystalline energy equation is a complicated function of the parameters and angle of the anisotropy. Thus, to display and extract important information about anisotropy, interpretation is often carried out by visualizing the magnetic anisotropy energy surface for cubic crystals as was done in this study using MATLAB assistance.

Materials and methods

A simulation of the magnetic anisotropy energy surface for cubic crystals is carried out in this article using the help of MATLAB software. The purpose of using MATLAB is to visualize the magnetic anisotropy energy surface for cubic crystals. With this, it is obtained a way to simulate the magnetic anisotropy energy surface for cubic crystals which is easy to do in helping materials physics courses. MATLAB software is used to help simulate the magnetic anisotropy energy surface for cubic crystals because it can strengthen the mathematical understanding of the concepts of material physics and produce smooth visualizations [41]. Besides, MATLAB also has a feature to visualize graphs with a variety of shape options, both 2-dimensional and 3-dimensional, so that it can be used to plot the visualization of the magnetic anisotropy energy surface for cubic crystals based on Eq. (9). In simulating the magnetic anisotropy energy surface for cubic crystals with the help of MATLAB software, several steps need to be done to obtain a visualization of the magnetic anisotropy energy surface for a smooth cubic crystal. The steps that need to be done are preceded by replacing several physical symbols in Eq. (9). This is done so that the mathematical equations of the magnetic anisotropy energy surface for cubic crystals inputted in the MATLAB workspace can be processed properly and produce smooth visualization. Besides, the purpose of replacing some physical symbols in Eq. (9) is intended because the graph of the magnetic anisotropy energy surface for cubic crystals formed is on the x, y, and z axes.

The physical symbol that is replaced in Eq. (9) includes $\theta = x$, $\phi = y$, so that Eq. (9) can be written as in Eq. (10) below.

$$E_{anis} = K_0 + K_1\begin{pmatrix}(sinx\ cosy)^2(sinx\ siny)^2 + \\ (sinx\ siny)^2(cosx)^2 + \\ (cosx)^2(sinx\ cosy)^2\end{pmatrix} + K_2\begin{pmatrix}(sinx\ cosy)^2 \\ (sinx\ siny)^2 \\ (cosx)^2\end{pmatrix} + \frac{h}{\sqrt{3}}\begin{pmatrix}(sinx\ cosy) + \\ (sinx\ siny) + \\ (cosx)\end{pmatrix} \quad (10)$$

Eq. (10) can be inputted into the MATLAB workspace to simulate the visualization of magnetic anisotropy energy surface for cubic crystals. However, there are still physical quantities, namely the anisotropy constant K_0, K_1, and K_2 which are the differentiators for each cubic crystal form. Therefore, in this article, a variation of the 3 anisotropy constants is carried out to determine the difference resulting from the 3 cubic crystal magnetic anisotropy energies. The variations of the anisotropy constants K_0, K_1, and K_2 that are inputted in the MATLAB workspace consist of the values $K_0 = K_1 = K_2 = -1,0,1$. The reasons for taking the constant values as –1,0, and 1 are to determine the visualization of material behavior which includes magnetic anisotropy energy surfaces formed from cubic crystals at a value of –

1.0, and 1. Another reason is to determine changes in magnetic anisotropy energy. surfaces formed from cubic crystals at constant values that differ only by one. In addition, this study only uses the constant values as –1,0, and 1 for the reason that the visualization of the magnetic anisotropy energy surfaces of cubic crystals is not too much and provides an opportunity for researchers and students to independently simulate other constants that are much smaller or far away. larger according to the instructions in this article. This is done so that students can understand and practice independently the simulation of magnetic anisotropy energy surfaces formed from cubic crystals.

Visualization of the magnetic anisotropy energy surface for cubic crystals when there is no magnetic field influence, the magnetic field component in the MATLAB workspace syntax is inputted with a value of 0. When there is an influence of a magnetic field, the magnetic field component in the MATLAB workspace syntax is inputted with a value of 1. Thus, the syntax containing Eq. (10) and the components needed to simulate the visualization of the magnetic anisotropy energy surface for cubic crystals in MATLAB software are as follows.

```
% Simulate the magnetic anisotropy energy surface of cubic crystal
% Simulate with and without magnetic field
% By Himawan Putranta
clear;
% declaring the anisotropy constants
K0 = -1; K1 = -1; K2 = -1;
% definining the anisotropy energy surface projections along x,y, and
z
ecubic = @(x,y,K0,K1,K2,H) (K0+ K1*(((sin(x).*cos(y)).^2).*...
((sin(x).*sin(y)).^2 + ((cos(x)).^2).*((sin(x).*sin(y)).^2)+...
((cos(x)).^2).*((sin(x).*cos(y)).^2)))+ K2*(((sin(x).*cos(y)).^2).*...
((sin(x).*sin(y)).^2).*((cos(x)).^2))+ ...
(H/sqrt(3))*(sin(x).*cos(y)+sin(x).*sin(y)+cos(x)));
fcubicx = @(x,y,K0,K1,K2,H) (sin(x).*cos(y)).*ecubic(x,y,K0,K1,K2,H);
fcubicy = @(x,y,K0,K1,K2,H) (sin(x).*sin(y)).*ecubic(x,y,K0,K1,K2,H);
fcubicz = @(x,y,K0,K1,K2,H) (cos(x)).*ecubic(x,y,K0,K1,K2,H);
rotate3d on;
colormap(copper);
subplot(1,2,1)
ycubic = ezsurf(@(x,y) fcubicx(x,y,K0,K1,K2,0),@(x,y) ...
fcubicy(x,y,K0,K1,K2,0),@(x,y) fcubicz(x,y,K0,K1,K2,0),[0 pi],[0
2*pi]);
title('H = 0 (0 field)');
% view(45,45)
% plot with magnetic field for the crystal cubic lattice
rotate3d on;
colormap(copper);
subplot(1,2,2)
ycubich = ezsurf(@(x,y) fcubicx(x,y,K0,K1,K2,1),@(x,y) ...
fcubicy(x,y,K0,K1,K2,1),@(x,y) fcubicz(x,y,K0,K1,K2,1),[0 pi],[0
2*pi]);
title('H = 1 (Strong field)')
% view(45,45)
```

The workspace display of the MATLAB software that has been inputted with Eq. (10) and the components needed to simulate the visualization of the magnetic anisotropy energy surface for cubic crystals can be shown in **Figure 3** below.

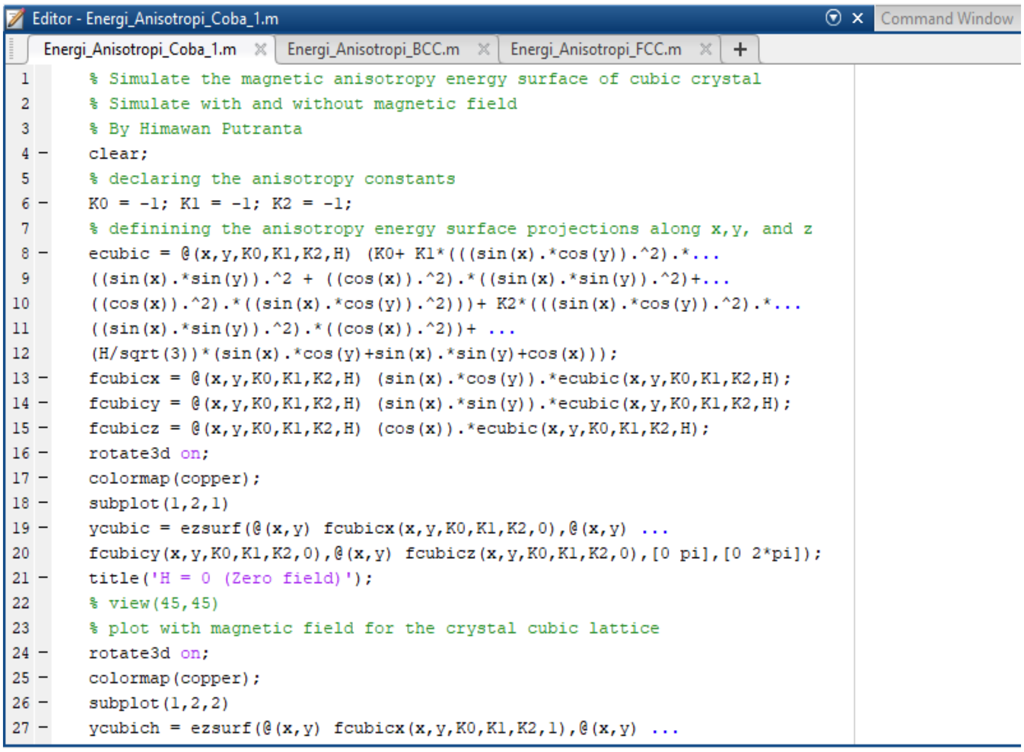

Figure 3 A MATLAB workspace view for simulating cubic crystal anisotropy energies.

After inputting Eq. (10) and the components needed to simulate the visualization of the magnetic anisotropy energy surface for cubic crystals as shown in **Figure 3**, the next step is to bring up the visualization of the magnetic anisotropy energy surface for cubic crystals. The step that needs to be done to bring up the visualization of the magnetic anisotropy energy surface for cubic crystals in MATLAB is by clicking the **Run** option on the taskbar **Editor** as shown by the red circle in **Figure 4** below. After the visualization of the magnetic anisotropy energy surface for cubic crystals appears, the next step is to analyze and classify each cubic crystal anisotropy energy visualization.

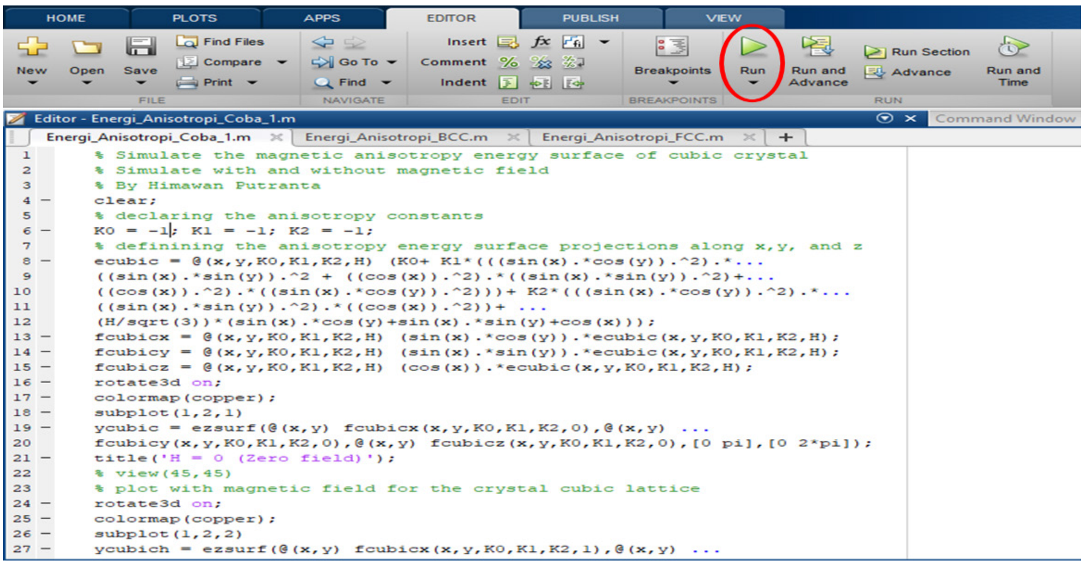

Figure 4 Run option to bring up a visualization of cubic crystal anisotropy energy.

Results and discussion

In this article, we demonstrate the process of simulating the magnetic anisotropy energy surface for cubic crystals using the help of MATLAB. The simulating of the magnetic anisotropy energy surface for cubic crystals was carried out by varying the anisotropy constant value consisting of the value $K_0 = K_1 = K_2 = -1,0,1$. Besides, variations are also carried out by providing a syntax to display the anisotropy energy visualization of cubic crystals that is influenced by magnetic fields and without magnetic fields. The range of the anisotropy constant used is one due to knowing the difference resulting from the 3 cubic crystal magnetic anisotropy energies. This is also done to determine the input and output processes in the form of simulations of the magnetic anisotropy energy surface for cubic crystals using MATLAB software which is easier and more interactive when used in physics lectures. Meanwhile, the simulation results of the magnetic anisotropy energy surface for cubic crystals using the help of MATLAB at the value of $K_0 = -1$ and the variation of $K_1 = K_2 = -1,0,1$ can be shown as in **Figure 5** below.

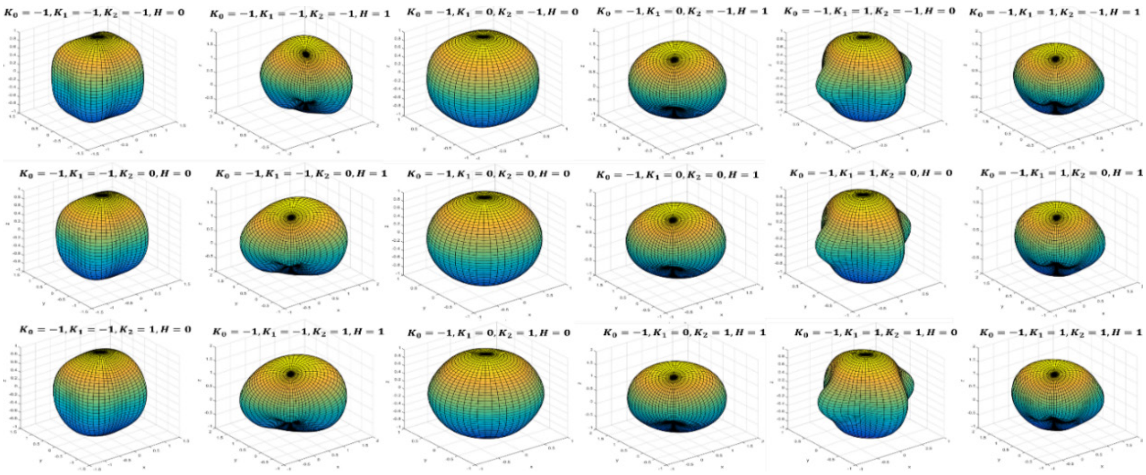

Figure 5 Magnetic anisotropy energy surface for cubic crystals at values of $K_0 = -1$ and variations of $K_1 = K_2 = -1,0,1$.

Based on **Figure 5** shows that the simulation of the magnetic anisotropy energy surface for cubic crystals at the value of $K_0 = -1$ and variations of $K_1 = K_2 = -1,0,1$ results in the visualization of various anisotropy energies. The visualization of the cubic crystal anisotropy energy for the value of $K_0 = -1$ and the variation of $K_1 = K_2 = -1,0,1$, which is in the form of a perfectly round sphere, a round sphere tends to be oval, a round sphere tends to be cubic and an oval sphere with 2 protrusions on the side. Simulation of the magnetic anisotropy energy surface for cubic crystals at the value of $K_0 = -1$ and the variation of $K_1 = K_2 = -1,0,1$ also shows the energy intervals as well as the boundary intervals on the x, y, and z axes. In general, the visualization of the magnetic anisotropy energy surface for cubic crystals shown in **Figure 5** is appropriate and as smooth as the theoretical visualization. This can happen because careful simulations have been made by minimizing errors in inputting Eq. (10) and other physical quantities on the MATLAB workplace. Based on **Figure 5**, shows that the magnetic anisotropy energy surface for cubic crystals at the value of $K_0 = -1$ and the variation of $K_1 = K_2 = -1,0,1$ in the presence of the influence of the magnetic field or $H = 1$ is visualized like a compressed flat sphere so that it can be said to be its shape like a shrinking sphere. With increasing the value of the anisotropy constant used, the visualization of the magnetic anisotropy energy surface for cubic crystals that are affected by the magnetic field becomes wider. This can be shown in **Figure 5** that when the anisotropy constant used is $K_0 = K_1 = K_2 = -1$, then the visual width of the magnetic anisotropy energy affected by the magnetic field is only at coordinate 0 on the y-axis. These results are consistent with the statement of Winklhofer *et al* [42]. which states that the magnetic anisotropy energy pattern affected by the magnetic field is at the origin of the coordinate axis [42]. Meanwhile, with the greater the anisotropy constant value, the visualization of magnetic anisotropy energy that is affected by the magnetic field becomes wider. This can be shown in the visualization of magnetic anisotropy energy when $K_0 = -1$, $K_1 = 1, K_2 = 1$ which has increased in width as far as 0.5 times the original.

Besides, the visualization of the magnetic anisotropy energy surface for cubic crystals that were not affected by the magnetic field was also broadened. This can be shown in **Figure 5** when $K_0 = K_1 = -1$ and K_2 are variations of $-1,0,1$, then the resulting visualization is in the form of a sphere compressed from all 4 sides so that the shape becomes compressed. When $K_0 = -1, K_1 = 0$, and K_2 is a variation of $-1,0,1$, the resulting visualization is spherical. There are 3 variations of the shape of the sphere that is generated at the variation in these constant values. When $K_0 = -1$, $K_1 = K_2 = 0$, the resulting visualization is a perfect sphere. Visualization of the magnetic anisotropy energy surface for cubic crystals when $K_0 = -1$, $K_1 = K_2 = 0$ is the manifestation of the magnetic anisotropy energy surface for the simple cubic. This is by the findings of previous studies that the magnetic anisotropy energy surface for cubic crystals at $K_0 = -1$, $K_1 = K_2 = 0$ is a manifestation of the isotropic or simple cubic system [43]. When $K_0 = -1$, $K_1 = 0, K_2 = 1$, the resulting visualization is in the form of a sphere that is compressed on both parts so that the shape tends to be oval. Meanwhile, when $K_0 = -1$, $K_1 = 1$, and K_2 are variations of $-1,0,1$, the resulting visualization is in the form of an oval sphere that has 2 tonnes on its side. Based on **Figure 5**, it can be stated that when K_0 is fixed and K_1 and K_2 are getting bigger, then the visualization of the magnetic anisotropy energy surface for cubic crystals is not influenced by the magnetic field that is formed is more oval and has protrusions. Furthermore, the visualization of spherical magnetic anisotropy energy as shown in **Figure 5** does not have anisotropy, thus indicating the insensitivity of the system energy to the selected magnetization direction. However, with the introduction of magnetic fields, the surface begins to squeeze with a distinctive evolution of the orientation axis [44]. Meanwhile, the simulation results of the magnetic anisotropy energy surface for cubic crystals using the help of MATLAB at the value of $K_0 = 0$ and the variation of $K_1 = K_2 = -1,0,1$ can be shown as in **Figure 6** below.

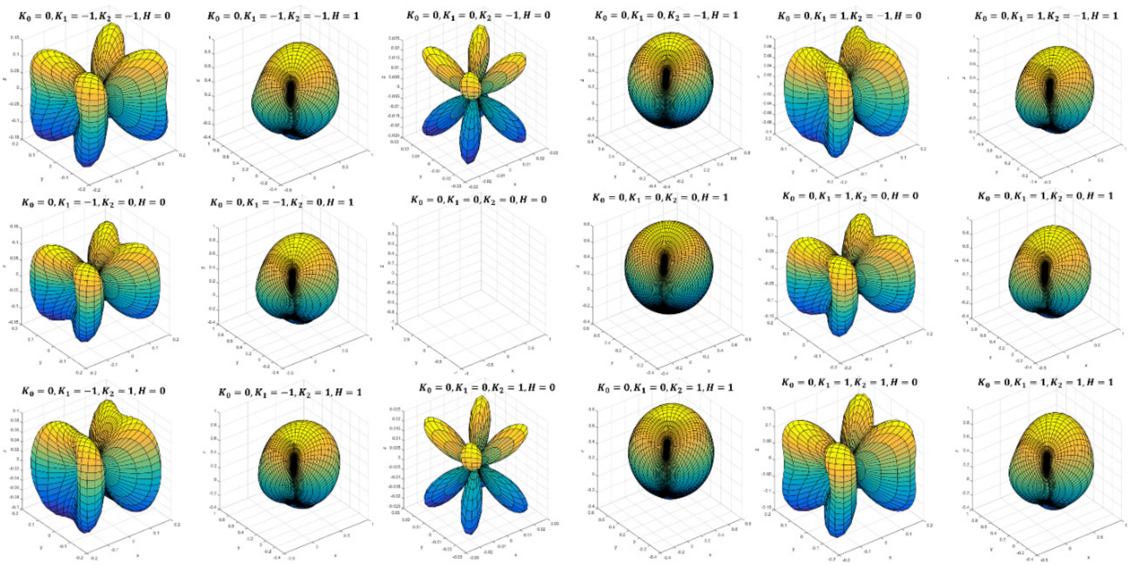

Figure 6 Magnetic anisotropy energy surface for cubic crystals at a value of $K_0 = 0$ and variation of $K_1 = K_2 = -1,0,1$.

Like the simulation shown in **Figure 5**, the simulation results of the magnetic anisotropy energy surface for cubic crystals at the value of $K_0 = 0$ and the variation of $K_1 = K_2 = -1,0,1$ also resulted in the visualization of various anisotropy energies. The visualization of cubic crystal anisotropy energy for the value of $K_0 = 0$ and the variation of $K_1 = K_2 = -1,0,1$, which is in the form of 2 pairs of butterfly and star wings consisting of 8 lobes. Simulation of the magnetic anisotropy energy surface for cubic crystals at the value of $K_0 = 0$ and the variation of $K_1 = K_2 = -1,0,1$ also shows the energy intervals as well as the boundary intervals on the x, y, and z axes. In general, the visualization of the magnetic anisotropy energy surface for cubic crystals shown in **Figure 6** is appropriate and as smooth as the theoretical visualization. This can happen because careful simulations have been made by minimizing errors in inputting Eq. (10) and other physical quantities on the MATLAB workplace. Based on **Figure 6**, shows that the magnetic anisotropy energy surface for cubic crystals at the value of $K_0 = 0$ and the variation of $K_1 = K_2 = -1,0,1$ in the presence of the influence of the magnetic field or $H = 1$ is visualized like a compressed flat sphere so that it can be said to be shaped like the shrinking sphere.

Meanwhile, in contrast to the visualization shown in **Figures 5** and **6** shows that as the anisotropy constant value increases, the visualization of the magnetic anisotropy energy surface for cubic crystals is affected by a fixed magnetic field. Besides, the visualization of the magnetic anisotropy energy surface for cubic crystals unaffected also undergoes a different unique shape change than that shown in **Figure 5**.

This can be shown in **Figure 6** when $K_0 = 0, K_1 = -1$, and K_2 are variations of $-1,0,1$, then the resulting visualization is in the form of 2 pairs of butterfly wings or resembles a pair of ears. When $K_0 = K_1 = 0$ and K_2 are variations of -1 and 1, the resulting visualization is in the form of a star consisting of 8 lobes. However, when $K_0 = K_1 = K_2 = 0$, there is no visualization of the magnetic anisotropy energy surface for cubic crystals. This is by the explanation that each crystal has a different anisotropy constant, and no crystal does not have an anisotropy constant [45]. If a crystal does not have an anisotropy constant and there is no influence from a magnetic field, then the energy of the crystal system is not sensitive to its magnetization direction [46]. Meanwhile, when $K_0 = 0, K_1 = 1$, and K_2 are variations of $-1,0,1$, the resulting visualization is in the form of 2 pairs of butterfly wings or resembles a pair of ears as it does when simulating the magnetic anisotropy energy surface for cubic crystals at $K_0 = 0, K_1 = -1$ and K_2 are variations of $-1,0,1$. However, there are differences in the visualization arrangement of the magnetic anisotropy energy surface for cubic crystals. The visualization produced when $K_0 = 0, K_1 = -1, K_2 = -1$ is the same as the visualization produced when $K_0 = 0, K_1 = 1, K_2 = 1$. The visualization produced when $K_0 = 0, K_1 = -1, K_2 = 1$ is the same as the visualization produced when $K_0 = 0, K_1 = 1, K_2 = -1$. The visualization produced when $K_0 = 0, K_1 = -1, K_2 = 0$ is the same as the visualization produced when $K_0 = 0, K_1 = 1, K_2 = 0$.

Furthermore, the visualization of the magnetic anisotropy energy surface for cubic crystals when $K_0 = 0, K_1 = 1, K_2 = 1$ is the manifestation of the magnetic anisotropy energy surface for the body-centered cubic. Visualization of the magnetic anisotropy energy surface for cubic crystals when $K_0 = 0, K_1 = -1, K_2 = 1$ is the manifestation of the magnetic anisotropy energy surface for the face-centered cubic. With these results, it can be discussed in general that if there are 2 arrangements of cubic crystal anisotropy constants, each of which consists of 3 anisotropy constants with a pair of anisotropy constants that are the same in either sign or magnitude, then the visualization of the magnetic anisotropy energy surface of the 2 anisotropy constants of cubic crystals is the same. In other words, the positive and negative signs on a pair of anisotropy constants do not affect the visualization of the magnetic anisotropy energy surface for cubic crystals formed. Based on **Figure 6**, a spherical magnetic anisotropy energy visualization does not have anisotropy, so it shows the insensitivity of the system energy to the direction of its magnetization. However, given a magnetic field, the surface begins to be pinched with a special evolutionary axis orientation [47]. Meanwhile, the simulation results of the magnetic anisotropy energy surface for cubic crystals using the help of MATLAB at the value of $K_0 = 1$ and the variation of $K_1 = K_2 = -1,0,1$ can be shown as in **Figure 7** below.

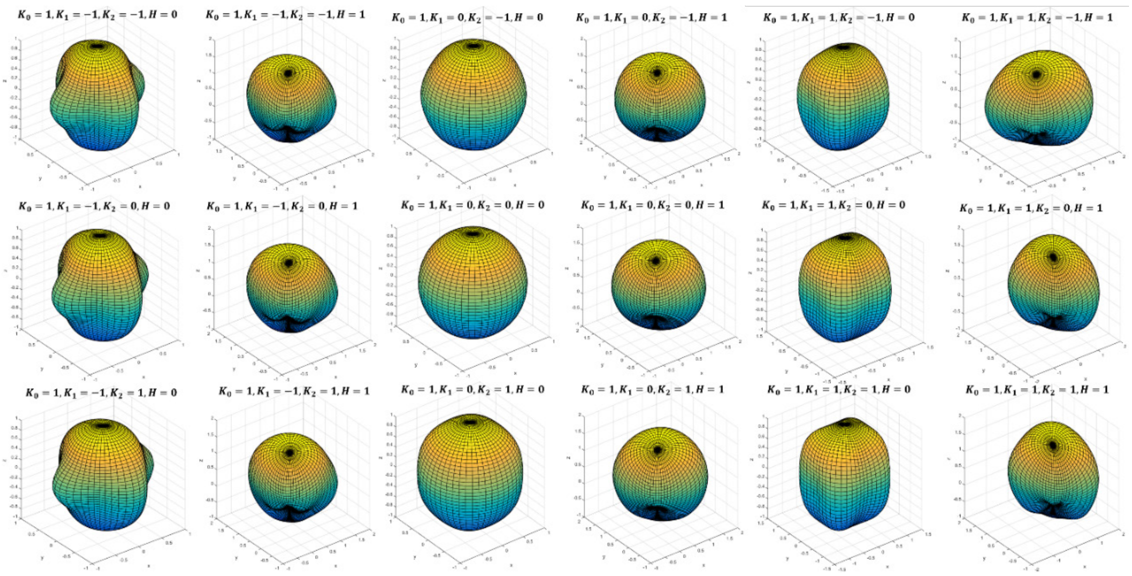

Figure 7 Magnetic anisotropy energy surface for cubic crystals at a value of $K_0 = 1$ and variation of $K_1 = K_2 = -1,0,1$.

Based on **Figure 7** shows that the simulation of the magnetic anisotropy energy surface for cubic crystals at the value of $K_0 = 1$ and the variation of $K_1 = K_2 = -1,0,1$ produces anisotropy energy visualization that is similar to the visualization when $K_0 = -1$ and variations of $K_1 = K_2 = -1,0,1$, but a different arrangement of shapes. As for the arrangement of the form of visualization of the anisotropy energy of cubic crystals for the value of $K_0 = 1$ and the variation of $K_1 = K_2 = -1,0,1$, which is in the form of an oval sphere with 2 protrusions on the side, perfectly round, round tends to be oval, and round tends to be cubic. Simulation of the magnetic anisotropy energy surface for cubic crystals at the value of $K_0 = 1$ and the variation of $K_1 = K_2 = -1,0,1$ also shows the energy intervals as well as the boundary intervals on the x, y, and z axes. In general, the visualization of the magnetic anisotropy energy surface for cubic crystals shown in **Figure 7** is appropriate and as smooth as the theoretical visualization. This can happen because careful simulations have been made by minimizing errors in inputting Eq. (10) and other physical quantities on the MATLAB workplace. Based on **Figure 7**, shows that the magnetic anisotropy energy surface for cubic crystals at the value of $K_0 = 1$ and the variation of $K_1 = K_2 = -1,0,1$ in the presence of the influence of the magnetic field or $H = 1$ is visualized like a compressed flat sphere so that it can be said to be shaped like the shrinking sphere. As the anisotropy constant value increases, the visualization of the magnetic anisotropy energy surface for cubic crystals affected by the magnetic field becomes narrower.

This can be shown in **Figure 5** that when the anisotropy constant used is $K_0 = 1, K_1 = -1$, $K_2 = -1$, then the visual width of the magnetic anisotropy energy affected by the magnetic field is at coordinates 0.5 on the y-axis. However, when $K_0 = 1$, $K_1 = 1, K_2 = 1$ visualize the magnetic anisotropy energy experiencing shrinkage of 0.5 times the original width. Besides, the visualization of the magnetic anisotropy energy surface for cubic crystals that were not affected by the magnetic field also experienced a narrowing. This can be shown in **Figure 7** when $K_0 = 1$, $K_1 = -1$, and K_2 are variations of $-1,0,1$, then the resulting visualization is in the form of an oval sphere with 2 protrusions on the side. When $K_0 = 1, K_1 = 0$, and K_2 is a variation of $-1,0,1$, the resulting visualization is spherical. There are 3 variations of the shape of the sphere that is generated at the variation in these constant values. When $K_0 = 1$, $K_1 = K_2 = 0$, the resulting visualization is perfectly spherical. Visualization of the magnetic anisotropy energy surface for cubic crystals when $K_0 = 1$, $K_1 = K_2 = 0$ is the manifestation of the magnetic anisotropy energy surface for the simple cubic. This is by the findings of previous studies that the magnetic anisotropy energy surface in the same anisotropy constant pair is a manifestation of the isotropic or simple cubic system. When $K_0 = K_1 = 1$ and the variation of $K_2 = -1,0,1$, the resulting visualization is in the form of a sphere that is compressed on both parts, so that the shape tends to be oval. Meanwhile, when $K_0 = 1$, $K_1 = -1$, and K_2 are variations of $-1,0,1$, the resulting visualization is in the form of an oval sphere that has 2 protrusions on its sides. Based on **Figure 7**, it can be stated that when K_0 is fixed and K_1 and K_2 are getting bigger, then the visualization of the magnetic anisotropy energy surface which is not influenced by the magnetic field formed will form a cube.

Meanwhile, when $K_0 = 1, K_1 = -1$, and K_2 are variations of $-1,0,1$, the resulting visualization is in the form of an elliptical sphere with 2 protrusions on the same side as the visualization when $K_0 = -1, K_1 = 1$, and K_2 is the variation of $-1,0,1$. When $K_0 = 1, K_1 = 0$, and K_2 are variations of $-1,0,1$, then the resulting visualization is the same spherical as the visualization when $K_0 = -1, K_1 = 0$, and K_2 is variation $-1,0,1$. When $K_0 = 1, K_1 = 1$, and K_2 are variations of $-1,0,1$, then the resulting visualization is in the form of a sphere compressed on all 4 sides to form a spherical cube that is the same as the visualization when $K_0 = -1, K_1 = -1$, and K_2 is the variation of $-1,0,1$. With these results, it can be discussed that the positive and negative signs on a pair of anisotropy constants do not affect the visualization of the magnetic anisotropy energy surface for cubic crystals formed. Besides, Eq. (10) is also used to simulate the magnetic anisotropy energy surface of Ferrum and nickel crystals. The anisotropy constants for Ferrum crystals are $K_0 = 0, K_1 = 54{,}800 \, ^{J}/_{m^3}$, and $K_2 = 1{,}960 \, ^{J}/_{m^3}$. The anisotropy constants for nickel crystals are $K_0 = 0, K_1 = -126{,}300 \, ^{J}/_{m^3}$, and $K_2 = 57{,}800 \, ^{J}/_{m^3}$ [48]. The simulation results of the magnetic anisotropy energy surface for Ferrum and nickel crystals can be shown in **Figure 8** below.

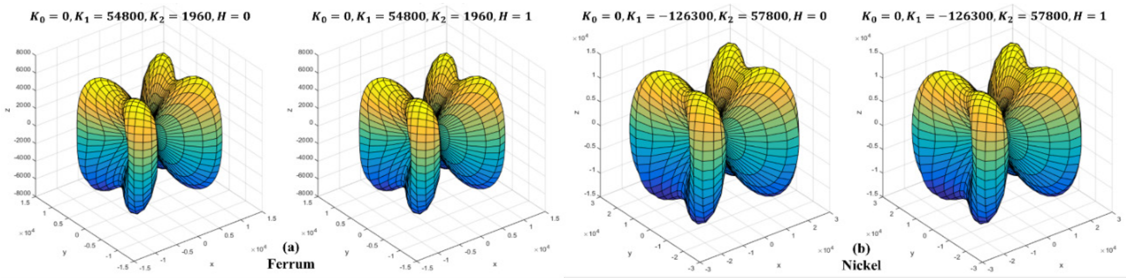

Figure 8 Magnetic anisotropy energy surface, a) Ferrum and b) Nickel.

Based on **Figure 8**, the visualization of the magnetic anisotropy energy surface for Ferrum and nickel crystals has a similar shape, but for nickel crystals, it has a more convex shape than Ferrum. These results also show that the visualization of magnetic anisotropy energy from Ferrum crystals is the same as when $K_0 = 0$, $K_1 = 1, K_2 = 1$ which is the manifestation of the magnetic anisotropy energy surface for body-centered cubic. Meanwhile, visualization of magnetic anisotropy energy from nickel crystal is the same as visualization when $K_0 = 0$, $K_1 = -1, K_2 = 1$ which is the manifestation of the magnetic anisotropy energy surface for face-centered cubic. Thus, these results indicate that if there are 2 arrangements of cubic crystal anisotropy constants, each of which consists of 3 anisotropy constants with a pair of anisotropy constants that are the same in either sign or magnitude, then the visualization of the magnetic anisotropy energy surface of the 2 cubic crystal anisotropy constants is the same. Magnetic anisotropy studies make it possible to reconstruct the magnetic structure and texture of a rock which is influenced by all mineral fractions that make up the rock. In addition to cubic symmetry, there are many other types of crystal symmetry, including uniaxial symmetry. Another major natural magnetic mineral, hematite (Fe2O3), is dominated by uniaxial symmetry. Therefore, the magnetization of hematite is much more complicated than the magnetization of magnetite [49]. Meanwhile, energy anisotropy opposes changes in magnetic direction so that ferromagnetic materials could maintain their magnetization, even though the magnetic field that causes magnetization has changed or been removed [50].

Changes in magnetic direction and magnetization can occur if the material is disturbed so that its magnetic moments can overcome the barrier in the form of anisotropic energy which then leads to a new magnetic field. This disturbance can be in the form of a high magnetic field or an increase in temperature [51]. In general, the degree of magnetic anisotropy is directly proportional to the current, the slope of the deposition site, and the degree of compaction. This can be exemplified in Ferrum (Fe) with a cubic crystal structure having an easy axis along (100) with an anisotropy constant K greater than 0. Meanwhile, Nickel (Ni) has an easy axis along (111) with an anisotropy constant K of less than 0 [52]. Furthermore, the shape of the anisotropy indicates the fact that the magnetic material depends on the direction of measurement. For a given crystal, the magnitude of the energy of the magnetic moments has a value that varies depending on the crystal axis [53]. For example, in the mineral magnetite (Fe3O4) which has a cubic structure, the greatest energy is in the directions of the axes ([100], [010], [001], while the lowest energy is in the diagonal direction [111]. in magnetite, it is commonly referred to as the easy axis or direction. On the other hand, the axes ([100], [010], [001]) are referred to as the hard axis or direction.

Furthermore, this simulation of the magnetic anisotropy energy surface for cubic crystals has an important purpose in the field of physics education and research. In the field of physics research, the benefit obtained from this simulation is to determine the visualization of the magnetic anisotropy energy surface for crystals that will be used as a strong magnet. This is by the need that advances in technology, especially in the material field, require a sufficiently strong crystal magnetization, such as rare earth which have strong magnetocrystalline anisotropy, so they can be used as good permanent magnets [54]. Besides, utilization of the magnetic energy of a crystal is used to determine the material that forms the storage medium. If a crystal has magnetic anisotropy energy that is stable to heat, then the crystal can be used as one of the elements forming the data storage media on the recording media [55]. This is due to crystals that have high magnetic anisotropy energy, so these crystals will find it difficult to lose their energy when given the heat [56]. The simulation of the magnetic anisotropy energy surface for cubic crystals also supports the implementation of remote physics lectures. This can be done by asking students to analyze the magnetic anisotropy energy levels of each type of cubic crystal. Students are then asked to explore the mathematical equation of the magnetic anisotropy energy surface for cubic crystals. After the students know the details of the mathematical equations of the magnetic anisotropy energy surface for cubic crystals, then the students are asked to simulate the mathematical equations in the MATLAB software.

The simulation results of magnetic anisotropy energy in cubic crystals can be used as one of the variations in the implementation of distance physics lectures. This can be done considering that the simulation of magnetic anisotropy energy in cubic crystals is more dominant or focuses the simulation process on students. In other words, the process of simulating magnetic anisotropy energy in cubic crystals carried out by students is centered on the students and not on the lecturer. The implementation of the magnetic anisotropy energy simulation process on cubic crystals in physics lectures can be done using the project lecture technique. Lectures with project techniques allow lectures to be carried out flexibly and do not have to be done on campus so that the lecture process that applies this simulation process can be carried out using project lecture techniques [57]. Moreover, the current conditions during the Covid-19 pandemic require that face-to-face lectures be minimized so that lectures with project techniques to simulate magnetic anisotropy energy in cubic crystals can be used as an alternative to lectures. The implementation of the project lecture to simulate magnetic anisotropy energy in cubic crystals is done by asking students to simulate the magnetic anisotropic energy equation in cubic crystals and then report the simulation results periodically through online lecture facilities such as zoom or google meet. By applying the lectures of this project, students will have a long time to study and simulate magnetic anisotropy energy in cubic crystals. Meanwhile, the lecturers are also open and willing to guide every student who has problems understanding and simulating magnetic anisotropy energy in cubic crystals. Thus, the lecture process that applies project techniques to simulate magnetic anisotropy energy in cubic crystals through MATLAB can be used as an alternative to lectures during the Covid-19 pandemic or distance physics lectures.

Besides, the activity of simulating the magnetic anisotropy energy surface for cubic crystals can be a link between mathematical equations and material physics experiments easily, can be done anytime and anywhere. This simulation activity is also able to make it easier for students to apply mathematical equations of a material physics phenomenon that they get during lectures [58]. The activity of simulating mathematical equations of material physics phenomena can support the implementation of remote physics courses. Physics lectures that implement this simulation activity can be carried out well if students can be actively involved in understanding mathematical equations of material physics phenomena and virtual experiments with the help of MATLAB. Furthermore, through the activity of simulating the magnetic anisotropy energy surface for cubic crystals using MATLAB assistance, students can develop mathematical representation skills and creative visual representations. Besides, students' science process skills and critical thinking skills also improve. This is because before simulating the magnetic anisotropy energy surface for cubic crystals, students need to explore the characteristics and mathematical equations of the magnetic anisotropy energy surface for cubic crystals in detail. With the current global condition that is being hit by the COVID-19 pandemic, physics courses that implement this simulation process can support remote physics lectures [59]. This is because physics lectures are conducted on a virtual project basis and students can be motivated to learn material physics concepts.

Conclusions

In this research, the magnetic anisotropy energy surface for cubic crystals has been simulated using MATLAB software. In this study, different magnetic anisotropy energy surfaces for cubic crystals were obtained for each constant used. When the value of K_0 used is –1 or 1, the visualization of the magnetic anisotropy energy surfaces produced is the same, namely in the form of variations of cubes and spheres, but only in different locations. However, when the value of K_0 used is 0, then the visualization of the magnetic anisotropy energy surfaces produced is shaped like an ear mushroom or butterfly. In addition, visualization of magnetic anisotropy energy surfaces for Ferrum and Nickel crystals shows shapes that also resemble ear mushrooms or butterflies. Furthermore, MATLAB software is used to simulate the magnetic anisotropy energy surface for cubic crystals. The MATLAB software was chosen to simulate the magnetic anisotropy energy surface for cubic crystals because it is one of the computational software that is easy to operate, capable of visualizing mathematical equations of complex material physics phenomena, and producing graphical visualizations in 2 and 3 dimensions, making it easy to use. by students or novice programmers. This simulating activity can make it easier for students to understand and implement mathematical equations of a material physics phenomenon, especially regarding the magnetic anisotropy energy surface for cubic crystals into a virtual experiment. The activity of simulating the magnetic anisotropy energy surface for cubic crystals can support the implementation of remote materials physics courses. Furthermore, the results of this study can also be used as a reference source for future researchers or students to be able to simulate the magnetic anisotropy energy surface for crystals other than cubic crystals. Meanwhile, the limitations in simulating this model are that the magnetic anisotropy energy surface is visualized only for cubic crystals, the constant values used are only –1, 0, and 1, and the computational program used to simulate is only in the form of MATLAB. Thus, other researchers and students need to complete the limitations contained in this study to obtain more complete simulation results and increase knowledge to the public. It is necessary to carry out other simulations by improving the limitations in this study by simulating the magnetic anisotropy energy surface for other crystal forms, increasing the variation of the constant value, and simulating the magnetic anisotropy energy surface using other computing devices such as a spreadsheet that is easy to operate.

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