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Effect of power and diameter on temperature and frequency in induction heating process of AISI 4140 steel

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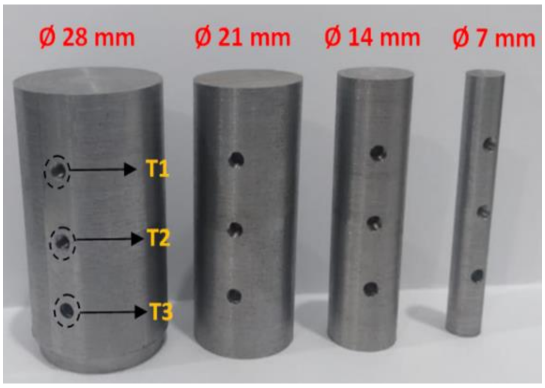

Highlights:

- The effect of the size of the heated material on the characteristics of induction heating were studied
- The increase in penetration depth due to changes in the diameter of the heated specimen impact on the temperature and frequency gradient pattern
- There are two stages that occur in induction heating, ferromagnetic and paramagnetic

Abstract

This research aims to design an induction heating system and to investigate the effect of power supply and specimen diameter on specimen temperature and frequency on the coil. This study began with the development of an induction heating system that made use of circulating coolers outfitted with Thermoelectric Cooler Materials (TEC). It was intended to keep the temperature of the coil and the Printed Circuit Board (PCB) as low as possible. This study used AISI 4140 steel material with diameter variations of 7 mm, 14 mm, 21 mm, and 28 mm, with power levels of 60 W, 240 W, 540 W, and 960 W. The temperature was measured using a thermocouple connected to the specimen, and the frequency value obtained was measured using an oscilloscope. The research findings show that varying the applied power affects the frequency of the coil and the temperature of the specimen, with the higher the power, the faster the temperature of the specimen rises. The 60 W power can heat the specimen at an average temperature of 470°C and a frequency of 102 kHz. When the power variation is 960 W, the temperature in the specimen is 746°C, and the frequency is 110 kHz. On the temperature and frequency gradient pattern in the 0-600 s period, there are two stages, the first of which is ferromagnetic and the second of which is paramagnetic.

Keywords: Induction heating; Thermoelectric cooler materials, Heating temperture

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1. Introduction

Nowadays, the development of material science, especially metals, is growing rapidly, as well as the process of forming metal materials which is required to be in line with the development of metal materials [1], [2]. The desired criteria, especially in the processing of metal materials, include the use of easy heating devices, high levels of productivity, being able to utilize existing resources, and being friendly to the environment. One of the metals forming processes is heat treatment.

Heat treatment is a means of heating treatment to change the physical and mechanical properties of the material [3]–[5]. There are two types of heating methods, namely conventional and non-conventional heating. The conventional heating method is a type of heating that uses a fossil-fueled furnace and petroleum which produces quite a lot of gases such as carbon monoxide, carbon dioxide, and other hydrocarbons, causing a lot of pollution [6]. Meanwhile, non-conventional heating is a heating method that is environmentally friendly, more efficient, safer, has small dimensions, and has a short working time.

It has been a long time since induction heating was used in industry to melt metals. Later, it was used in the aircraft and automotive industries [7]. Now, it is used in many manufacturing enterprises for the metal hardening process for engine parts such as valves, crankshafts, camshafts, connecting rods and starter rings, transmission, suspension, etc [8]–[10], induction heating is a technology that has been widely developed because it does not use fire to heat objects but by inducing what is obtained from an alternating electric current flowing through a coil made of copper. The working principle of induction heating is the generation of heat on the metal exposed to the induction of a magnetic field [11]. This is because in the metal there is an eddy current or eddy current whose direction is circular around the magnetic field [12]. The occurrence of eddy currents is caused by magnetic induction which causes a magnetic flux to penetrate the metal, thereby causing heat to the metal. Induction heaters are closely related to the winding of the working coil, the diameter of the coil, the workpiece, and the load to be heated to produce the temperature in the required time according to its use. Each of these factors has an influence on the characteristics of the heater to be made.

Research that discusses induction heating has been carried out by previous researcher Oscar Lucia [12], in his journal explaining that induction heating has many advantages including efficiency, fast heating, safety, cleanliness, and accurate control. Research conducted by K. Sandesh et al. [13], which aims to identify the comparison of the effects of induction heating with LPG heating, states that induction heating conditions are more effective and economical. Another study was proposed by Jiangchoa Wang et al. [14], in their journal which aims to validate experimental results with simulations in the study of bending ship iron using induction heating. In 2018, Smusz et al. [15] conducted a study on the effect of heating conditions on the temperature distribution of steel plates. Piroi Ion et al. [16] analyzed the heating or melting process using an induction heating system with frequency variations based on the temperature of the specimen. This study presents a mathematical model of an induction heater with a variable frequency in two cases. The results show that the frequency load will be greater depending on the temperature caused by variations in magnetic permeability (the magnetic ability of the specimen) and material resistivity (ability to conduct electric current).

Luozzo et al. [17] in their research aimed to coat/combine tubular carbon steel material and amorphous material as a coating material with a thickness of 20 m. Induction heating and argon gas are used for the process. Data collection in the form of frequency shows that there are two stages that occur, namely the first stage is a ferromagnetic stage while the second stage is paramagnetic where the frequency curve that is formed tends to be asymptotic. Then in 2018, Shuzhe Mei et al. [18] conducted a study that focused on regulating temperature uniformity in specimens and increasing the efficiency of high-temperature induction heating systems using the Finite Element Method (FEM). The results of the simulation show that the skin effect and heat conduction are not uniform, but the temperature similarity can be increased by increasing the air gap in the coil layer. This study also suggests that higher temperatures and faster heat rates can be obtained by increasing the frequency and current of the coil.

Research related to induction heating has been done by many previous researchers. The results showed that the power in the form of frequency and current in the coil had an effect on the rate of induction heating. In addition, the type of material being heated also affects the induction heating process. Magnetic field properties of a material are strongly influenced by chemical composition, heat treatment process, grain size, frequency, magnetic field intensity and temperature [19]. For example, in **Figure 1** shows that carbon steel with grades with the same frequency and temperature treatment can produce very different relative magnetic permeability values because of the difference in power in the coil [20]. However, the effect of the size of the heated material on the temperature and frequency characteristics that occur in the heating coil is still rarely studied. Therefore, in this article, we attempt to examine more deeply the effect of the dimensions of the heated material AISI 4140 steel on the temperature and frequency of the specimen for each variation of the study.

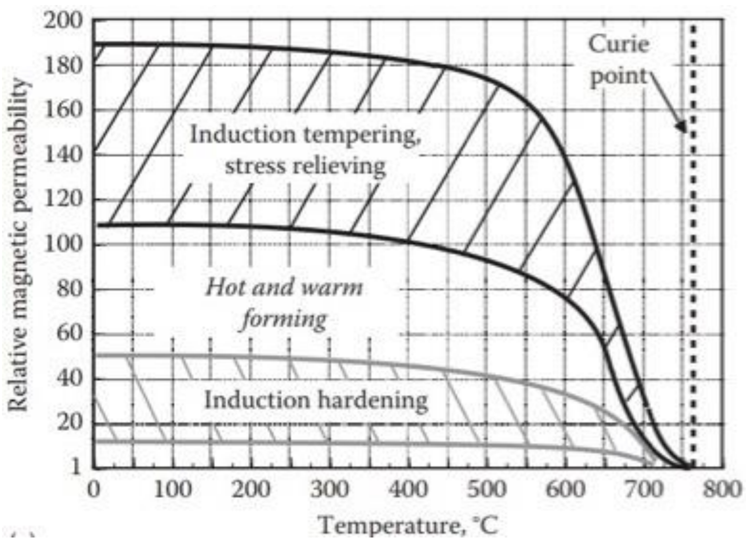

Figure 1. The phenomenon of the relative magnetic permeability that occurs in carbon steel under different temperature conditions [21]

2. Material and Methods

This research begins with designing and assembling an induction heating system as shown in **Figure 2**. The purpose of this study was to determine the temperature and frequency of the specimens AISI 4140 Steel with dimensions of 7 mm, 14 mm, 21 mm, and 28 mm using various power inputs of 60 W, 240 W, 540 W, and 960 W. The input power selection is adjusted to the specifications of the induction heating system which has a maximum input power of 1000 W. The outer spiral coil has a diameter of 6 cm and an inner diameter of 5.8 cm with 7 turns. To keep the printed circuit board (PCB) and spiral coil temperatures low, a forced water-cooling system is used. The cooling system utilizes circulating pure water flow and is combined with a thermoelectric cooler (TEC) module which aims to keep the circulating pure water at a low temperature. Curie temperature is the limit temperature at which a material undergoes a phase change process from a ferromagnetic phase to a paramagnetic phase [22]. In this research paper, AISI 4140 steel is the specimen that is heated. The heating process was carried out for 10 minutes and the temperature in the specimen was measured using a thermocouple type K combined with a multimeter USB. The position of the temperature measurement on the specimen can be seen in **Figure 3**. Meanwhile, the measurement of the frequency value that works on the induction heating system is carried out using a digital oscilloscope.

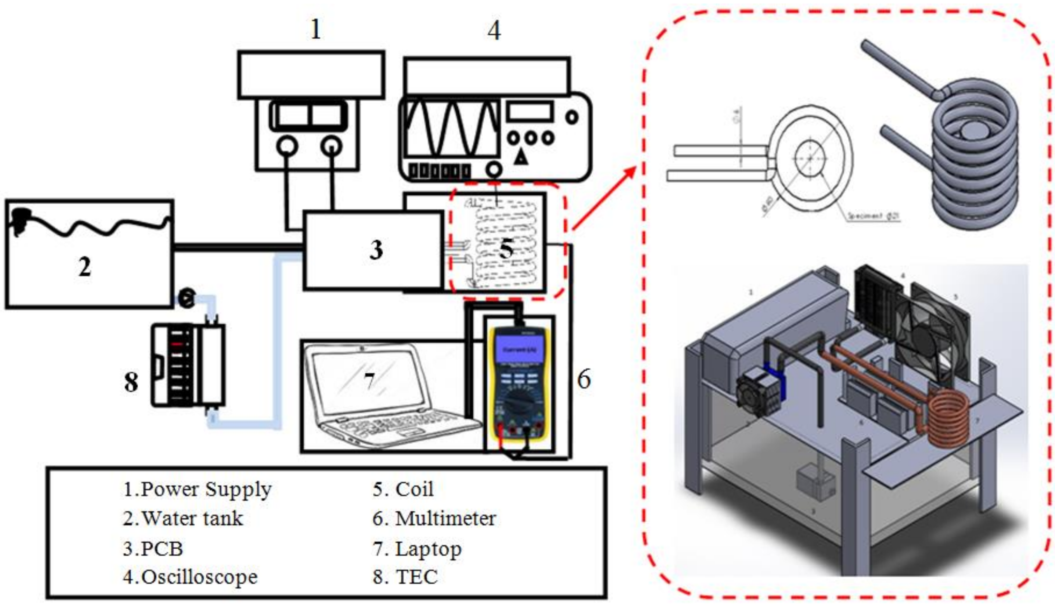

Figure 2. Schematic of an induction heating system with circulating TEC coolant

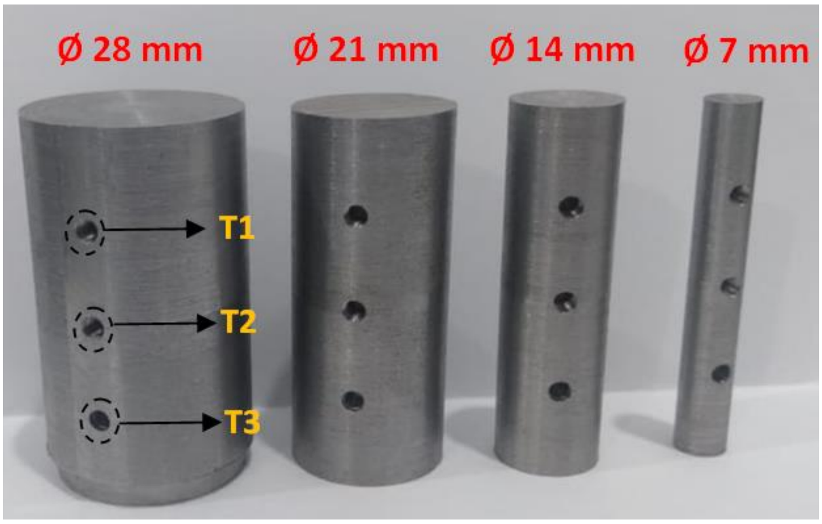

Figure 3. Position of the thermocouple hole on the specimen

3. Results and Discussion

3.1. Effect of power and diameter on temperature

Figure 4 shows the results of data collection in the form of temperature characteristics on AISI 4140 steel material with specimen dimensions of Ø7 mm, Ø14 mm, Ø21 mm, and Ø28 mm which were heat treated with an induction heating system using power variations of 60 W, 240 W, 540 W and 960 W. The curve shows the same trend for all diameter variations where the temperature tends to increase, this result is in line with that done by Smush et al. [15], where the trend curve tends to rise from the beginning of the study. At a power application of 60 W the workpiece with specimen dimensions of Ø7 mm, Ø14 mm, Ø21 mm, and Ø28 mm, has a peak temperature (Tc) of 492 °C, 347.8 °C, 277.4 °C and 233.2 °C. At a power application of 240 W the specimen dimensions Ø7 mm, Ø14 mm, Ø21 mm, and Ø28 mm have a peak temperature (Tc) of 626 ^{o}C, 746^{o}C, 713 °C and 717 °C. At the application of power 540 W the specimen dimensions of 7 mm, 14 mm, 21 mm and 28 mm have peak temperatures (Tc) of 731 °C, 747 °C, 735 °C and 757 °C. At 960 W power applications workpieces with specimen dimensions of Ø7 mm, Ø14 mm, Ø21 mm andØ28 mmhave peak temperatures (Tc) is 740 °C, 737 °C, 733 °C and 746 °C. From data collection in **Figure 4** shows some information that the dimensions of the specimen influence the peak temperature, larger dimensions result in a decrease in the measured temperature of the specimen. This indicated that the distance between the coil with the specimen surface most affects the heating rate according to **Equation 1** which is used to find the current value where the current arising in the workpiece is an inverse function of the distance from the coil to the surface specimen [23].

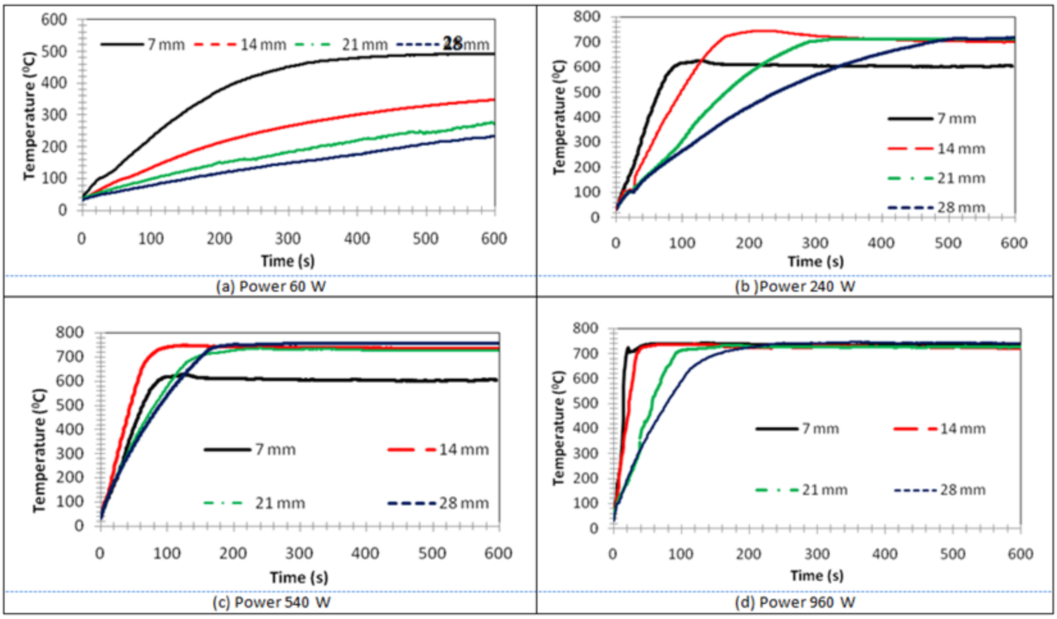

Figure 4. Temperature characteristics (Tc) of AISI 4140 steel at a specimen dimensionsof Ø7-28 mm with power variations: (a) 60 W; (b) 240 W; (c) 540 W; (d) 960 W

$$I = I_O e^{-y/\delta} \quad (1)$$

where, I is the current density at a distance y from the surface (A/m^2), I_O is the current density at the specimen surface (A/m^2), y is the distance from the surface to the core (m) and δrepresents the penetration depth (m).

To facilitate the analysis of the effect of power and diameter on the temperature of the specimen, a bar graph is made as shown in **Figure 5**. The visual results of the graph show that the temperature value at Ø7 mm is 60 W with temperature of 492 °C, a specimen dimensions of Ø14 mm indicates that the value at a temperature of 745 °C, a specimen dimensions of Ø21 mm indicates that the temperature value is 757 °C and at a specimen dimension of Ø28 mm indicates that the temperature value is 747 °C. At a power of 60 W with variations in the dimensions of the material 7-28 mm it has not yet entered the paramagnetic phase. This is because the carbon steel with 0.4-0.5% of Carbon has a curie temperature of more than 600 °C [22]. **Figure 6** shows the curie temperature point at Fe-Fe3C phase equilibrium diagram for steel. In contrast, when the coil power is increased to 240-960 W, the temperature of the specimen is more than 700 °C, resulting in a phase change process from ferromagnetic to paramagnetic. The coil power of 960 W produces a paramagnetic phase with a shorter time compared to the lower power.

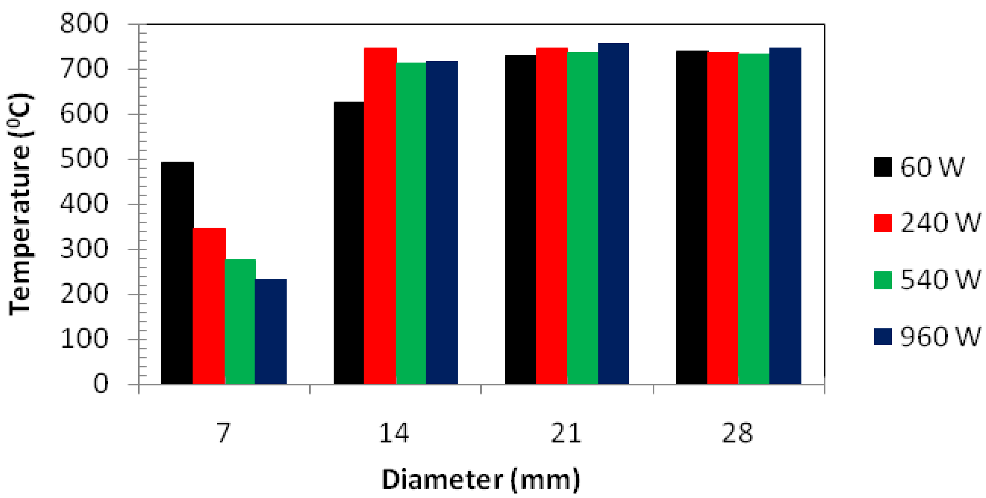

Figure 5. Temperature results for variations in specimen dimensions Ø7 mm, Ø14 mm, Ø21 mm andØ28 mm AISI 4140 steel specimens

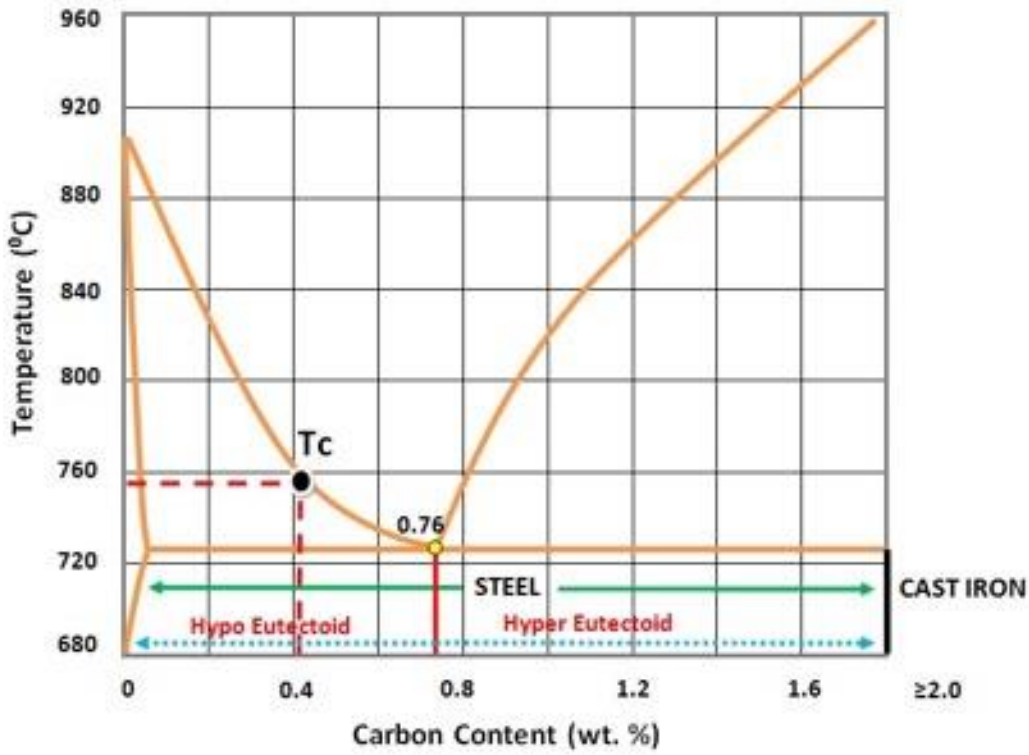

Figure 6. The curie temperature at Fe-Fe3C phase equilibrium diagram for steel

3.2. Effect of power and diameter on frequency

Figure 7 shows a comparison of the results of the frequency characteristics used for AISI 4140 steel specimens with specimen dimensionsof Ø7 mm, Ø14 mm, Ø21 mm andØ28 mm with a power variation of 60-960 W. The results show that the frequency curve shows the same trend, namely at the beginning and finally decreased. In **Figure 7 (b-d)** there are two stages that occur, namely the first stage is a ferromagnetic stage while the second stage is paramagnetic where the frequency curve that is formed tends to be asymptotic, this is in accordance following research conducted by Luozzo et al. [17]. When the curve has a downward trend then the stages are paramagnetic and vice versa if the curve experiences an uptrend, then the stages are ferromagnetic, the phenomena of paramagnetic and ferromagnetic stages in this study can be seen as **Figure 7**. At the use of 60 W power, the workpieces with specimen dimensions of Ø7 mm, Ø14 mm, Ø21 mm andØ28 mm, have temperatures of 492 °C, 347.8 °C, 277.4 °C and 233.2 °C with frequency values of 102.73 kHz, 103.15 kHz, 103.73 kHz and 102.25 kHz. At the use of 240 W power, the workpieces with specimen dimensions of Ø7 mm, Ø14 mm, Ø21 mm andØ28 mm, have temperatures of 626 °C, 746 °C, 713 °C and 717°C with a frequency value of 104.74 kHz, 104.37 kHz, 102.66 kHz and 104.28 kHz. On the use of 540 W power, the workpieces with specimen dimensions of Ø7 mm, Ø14 mm, Ø21 mm and Ø28 mm, have temperatures of 731 °C, 747 °C, 735 °C and 757 °C with frequency values of 105.69 kHz, 107.22 kHz, 107.96 kHz and 110.78 kHz. At the use of 960 W of power, the workpiece has a specimen dimension of Ø7 mm, Ø14 mm, Ø21 mm and Ø28 mm, has a temperature of 740 °C, 737 °C, 733 °C and 746 °C with a frequency value of 107.22 kHz, 108.46 kHz, 108.82 kHz and 110.91 kHz. This data shows that the higher the frequency, the greater the current flowing on the coil surface. In addition, the influence of the specimen dimensions also affects the frequency value of the heating coil. The greater the distance between the coil surface and the heated specimen surface, the higher the power consumption and current required to reach the curie temperature [22], as accordance with **Equation 2** [23].

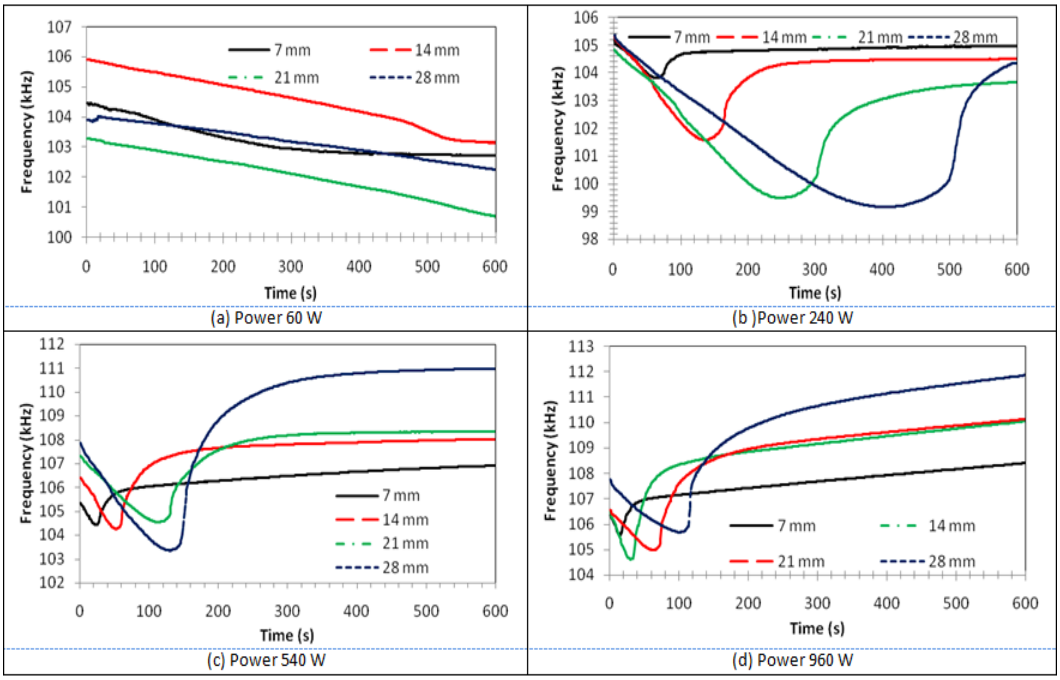

Figure 7. The frequency characteristics of AISI 4140 steel specimens with a diameter of Ø7-28 mm with various power: (a) 60 W; (b) 240 W; (c) 540 W; and (d) 960 W

$$\delta = 503\sqrt{\frac{\rho}{\mu r.F}} \quad (2)$$

where, δ is penetration depth (m), $\rho$is the electrical resistivity of the metal (Ώ.m), μ_r is the relative magnetic permeability and F is the Frequency, Hz (cycle/sec).

In order to facilitate the analysis of the influence of power and diameter on the frequency of the coil, a bar graph is made as shown in **Figure 8**. The visual results of the graph show that along with the increase in power in the coil has an impact on increasing the frequency of all diameter variations.

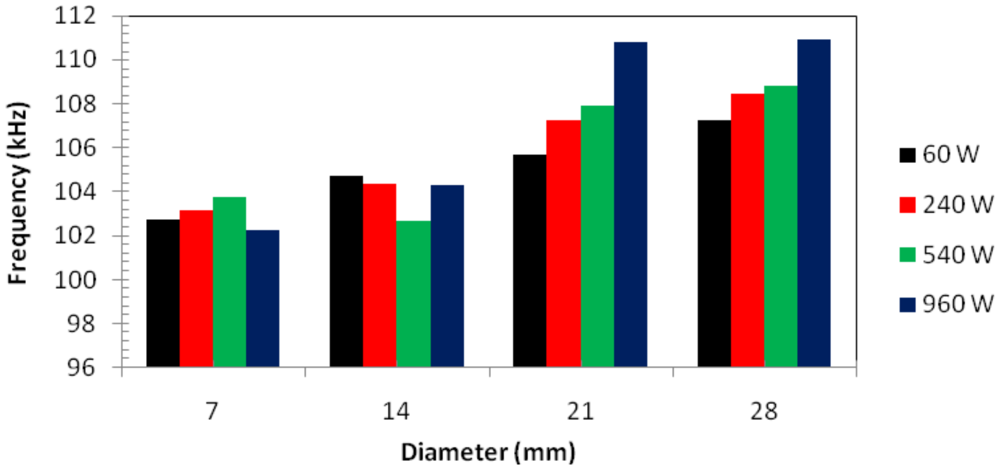

Figure 8. Frequency results for variations in the specimen dimensions of Ø7 mm, Ø14 mm, Ø21 mm andØ28 mm AISI 4140 steel specimens

4. Conclusion

From the results of the analysis and discussion in this study, it can be concluded that the design of an induction heating system using a spiral coil with an outer diameter of 6 cm and an inner diameter of 5.8 cm with 7 turns can heat the test specimen in the temperature range of 492 °C to 746 °C. Then, the variation of the given power will affect the frequency of the coil and the temperature of the specimen in the induction heating system. The greater the power on the induction heater, the faster the specimen temperature will reach the peak point. The power is 60 W with a temperature of 492 °C with a frequency of 102.73 kHz, while the power of 960 W shows that the highest temperature value is 746 °C with a frequency of 110.91 kHz. The increase in penetration depth due to changes in the diameter of the heated specimen has an impact on the temperature and frequency gradient pattern in the 0-600 s period. There are two stages that occur, namely the first stage is a ferromagnetic stage while the second stage is paramagnetic. Finally, the results of this research provide new insights and positive contributions to metal forming technology.

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Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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Availability of data and materials - All data are available from the authors.

Competing interests - The authors declare no competing interest.

Additional information – No additional information from the authors.

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