

The field of defense and security requires ballistic resistant materials for self-protection. Ballistic resistant materials must be able to withstand projectile spin rate and absorb impact energy. A combination of hardness on the surface and ductility on the other side is required to make the projectile resistance plate. Hardness is required to withstand the projectile rate, while ductility is required to reduce cracking, brittle fracture and absorption of impact energy. The objective of this study is to find the effect of the coil shape on microstructure and hardness distribution on the steel plate that is carried out by surface hardening using an induction machine. Medium carbon steel plate with the thickness 8 mm is austenitized using the induction heating machine with coil dimension and shape variations. Austenizing on the surface and rapid quenching in oil media are up to 900 °C. A micro-observation was conducted on quench plates and hardness distribution on their cross-section. The result of microstructure observation and micro Vickers hardness test of coil variation at a diameter 5 mm and with the number of turns of 2 and 3 is microstructures on all sides formed with martensite structure and equal hardness on the entire cross-section, so that no surface hardening formed. Micro-observations showed martensite structure on the surface side and the ferrite and perlite structures are still visible on the middle and lower sides using 8 mm diameter coils and 2 turns. The maximum hardness is 497 HVN on the upper side surface and 257 HVN on the lower side surface using an 8 mm diameter coil and 2 turns. An increased hardness on one of the plate surfaces while maintaining the ductile on the opposite side can be proposed as a candidate for a ballistic-resistant plate through further research.

Keywords: heating coil, induction heating machine, surface hardening, hardness distribution, ballistic material

AN ANALYSIS OF COIL DIMENSIONS ON INDUCTION HEATING MACHINE AGAINST MICROSTRUCTURE AND HARDNESS DISTRIBUTION AS NEW CANDIDATE OF PROJECTILE-RESISTANT STEEL PLATES MATERIALS

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1. Introduction

Ballistic resistant material is really needed in the field of defense and security. Ballistic resistant material is used to protect ourselves from the enemy attacks, whether it is in the form of projectiles or other weapons with a very high veloci-

ty impact. Steel plate is one of the materials used as ballistic resistant material (armor). Armor steel plate is used to build military vehicles including tanks and other military tactical vehicles. The demand for armor plates is still very high until now. Ballistic resistance is continuously improved through material engineering and construction design.

In materials engineering, ballistic resistance is a complex combination of hardness, toughness and tensile strength [1]. The harder the steel, the more its ballistic resistance is, but the less impact energy absorption ability is target hardness is required to hold the projectile tip, while ductility is used to absorb impact energy. With the simulation, the maximum absorption of impact energy is able to withstand the projectile's rate when an impact occurs with the target [2]. Installing a hard material on one side and a ductile material on the other side is done to increase its ballistic resistance. Therefore, there have been many studies, which have combined different types of materials in the form of layers or sandwich [3–5].

Improving the ballistic resistance through heat treatment has also been carried out. One of the materials is a medium carbon steel whose hardness can be increased through quench heat treatment. Quenching is the hardening of steel by heating the material until it reaches austenite temperature and then followed by rapid cooling using a cooling medium. As the hardness increases, the strength of the steel also becomes higher. Steel with high hardness has a weakness, which is decreased ductility so that it has brittle characteristics. Therefore, after conducting the quenching process, it is followed by a tempering process to decrease the residual stress and increase ductility. Quenching process, which is followed by the tempering process, has been widely used to improve ballistic performance in steel [1, 6–8].

2. Literature review and problem statement

Layered or sandwich panels manufacturing is done to increase the ballistic resistance and decrease the density. The paper [9] reported that to increase the ballistic resistance of steel plates, polyurea coating needs to be done. The addition of polyurea on the front side of the target plate indicates better ballistic performance compared to steel plates with low hardness. Polyurea also has the capacity to absorb high energy, therefore it is considered a very good material for structural protection. The report [10] also added polyurea to the core of the sandwich plate and compared it to the rubber core. The results of ballistic testing with various levels of projectile velocity in a simulation show that the addition of polyurea cores can significantly improve ballistic performance compared to rubber cores. The best ballistic resistance performance was attained with metal – fabric layered structures [11]. A high-strength steel plate is positioned on the front and lightweight, good impact absorbing aluminum was tested using a 7.62 mm projectile at a velocity of 800–850 m/s. Ballistic performance increases by 50 %, while the density decreases by 25 % compared to a single plate [12].

Layered or sandwich ballistic resistant plates have weaknesses in their manufacturing. Different types of materials cause difficulties in construction, especially in the manufacture of military vehicles. Damage to the first layer can lead to decreased resistance towards projectiles. The use of a layer material also causes an increase in thickness, so that the volume effectiveness decreases, even the density calculated also decreases.

Another reported ballistic-resistant material manufacturing is through quench heat treatment. The stability between the hardness and brittleness of the steel is affected by the austenizing temperature and tempering tempera-

ture [13]. Quenching through oil media can increase the hardness and the hardness slightly decreases after the tempering process. The higher the tempering temperature, the greater the decrease in hardness and increase in ductility [6]. The higher the tempering temperature, the higher the projectile depth of penetration in the steel [14]. Austempered steels are more resistant to the Adiabatic Shear Band (ASB) formation during high-velocity impact deformation, consequently slowing the cracks initiation and propagation of ASBs [7]. High hardness has an effect on increasing vulnerability. This will also affect the decrease in ballistic resistance.

Single plate with both high hardness and high ductility at the same time continues to be studied to further improve its ballistic resistance. One of the methods is surface hardening. The plate was hardened on one side, while the other side is left to remain soft and ductile. Such surface hardening method is usually applied to wear-resistant components.

There are not many reports on the manufacture of ballistic-resistant plates by surface hardening with quench heat treatment, one of them which has been done is through surface strengthening. Surface hardening through surface strengthening by carburizing and boronizing the medium carbon steel can improve the ballistic resistance and is able to exceed the ability of wear-resistant steel [15]. Case hardening increases perforation resistance by more than 20 %, and is able to reduce the capacity compared to layered plate manufacturing [16].

Surface hardening can also be done by heating using an induction heating machine. This machine is able to heat the steel until it reaches austenite temperatures in a very short time. Many studies have been conducted to improve heating efficiency using coil wire shapes and styles for wear-resistant steel applications. The use of induction heating machine with certain coil shapes and sizes is able to heat up to austenite temperatures in a very short time. The efficiency of induction can be maximized by the number of turns multiplied by the number of strands [17]. The multi-layered coil provides a high heating speed and better heat distribution than conventional single-layered coils [18]. The coil design must be adapted to the heated shape and object. The electromagnetic induction power is affected by the amount of current and resistance in the coil. The greater the current and the smaller the resistance, the greater the induction power. Furthermore, other than the shape and size of the coil, the shape of the workpiece also affects the heating speed, in which the thicker the workpieces, the slower the heating process, which results in rapid heat dissipation after the induction heating [19].

The manufacture of ballistic-resistant materials using the layered or sandwich method is inhibited on the manufacturing and volume, while the hardening process decreases the toughness and increases the brittleness. The potential for making ballistic-resistant materials by surface hardening is still open and needs to be studied further.

To increase ballistic resistance on steel plates, surface hardening is used. Surface hardening on steel plates is performed through surface heat treatment process. The front surface of the plate with high hardness is able to hold and break the tip of the projectile. Meanwhile, the middle and back sides need high ductility to prevent the growth of cracks and brittle fractures and to be able to absorb impact energy.

Surface hardening is generally applied to wear-resistant materials. Plate surface hardening for ballistic-resistant materials has not been much found. Due to the surface hardening on relatively thin and wide media as on a plate, it is difficult to obtain. Austenizing speed is required on the thin and wide surface, while on the other side it is maintained. The shape and dimensions of the coil affect the amount of current resistance and the resulting frequency. This will affect the speed of heating to the desired temperature. Shorter time is needed to reach the austenizing temperature on the surface, while the other parts and sides have not yet reached the austenizing temperature. In such conditions, if a rapid quench process is done, then the microstructure changes and the hardness can vary. The shape of the sample in the form of a relatively thin plate requires the right parameters, so that the hardening of one surface can be maximized, while the ductility on other parts and surfaces can be maintained. To get the surface hardening on the thin plates, proper austenization is required. It requires a surface heating rate and resists thermal conductivity to propagate on the other side of the surface.

3. The aim and objectives of the study

This study aims to determine and analyze the effect of coil shape and size on the frequency and heating rate be produced, martensite structure formation and hardness distribution in the cross-section of the plate with a thickness of 8 mm on commercial medium carbon steel.

To accomplish the aim, the following objectives were set:

- austenizing the medium carbon steel plate to temperatures of 900 °C by the induction machine and rapid quench in oil medium;
- records of the resulting frequency, increase in sample temperature and the time it takes to reach the austenite temperature on the induction machine board;
- cross-sectional characterization using an optical microscope and a micro-hardness Vickers tester and analyzing it on each variable.

4. Material and methods

Commercial medium carbon steel plates with chemical composition as shown in Table 1 are cut with dimensions 130×130×8 mm. The steel plate is heated to austenitizing temperature (900 °C) by using an induction heating machine as shown in Fig. 1. Temperature change is monitored using a thermocouple and infrared thermometer on the surface. The induction machine is set at a maximum current of 1,424 A. The heating coil is installed on the induction machine. The shape and size of the coil are varied to get the heating rate and frequency on the machine display. Coil dimensions and shapes used in this study are shown in Table 2. If the austenitizing temperature is obtained, then the sample undergoes rapid quenching in oil media as much as 15 liters of oil at room temperature (30 °C).

To obtain the microstructure transformation and hardness distribution, observation and testing are done on the cross-section of the sample as shown in Fig. 2. The upper side is defined as the plate surface, which is heated using an induction coil machine, while the lower side is defined as the plate surface, which is not directly exposed to




heat by the induction coil. To avoid damage to the sample during the cutting process, a wire cutting machine is used. Each specimen was taken in three different places. Each variation of the coil shape is repeated three times.

Table 1
Commercial medium carbon steel plate chemical composition

Unsure	wt%
C	0.4667
Mn	0.5584
Cr	0.0556
Ni	0.0411
Si	0.2441
Nb	0.0002
Al	0.0163
V	0.001
S	0.0106
Mo	0.0013
W	0.0016
P	0.0195
Cu	0.0577
Ti	0.0044
N	0.0078
B	0.0002
Sb	0.0064
Ca	0.0003
Mg	0.0009
Zn	0.0004
Co	0.0108
Fe	balance

The cross-section was smoothed using sandpaper and etched using 2 % nital for microstructure observation. The microstructure is observed at three points; those are on the upper, middle and lower side of the cross-section. The hardness distribution is carried out using micro Vickers hardness tester as many as 20 points of the cross-section from the upper side to the underside or with the distance between points of 0.4 mm with a load of 0.5 N.

Table 2
Variations in shape, size, and coil coding

Coil Code	Coil Configuration	Pipe Diameter (mm)	Coil Length (mm)	Number of Turns
A		8	930	2
B		5	930	3
C		5	1,120	2

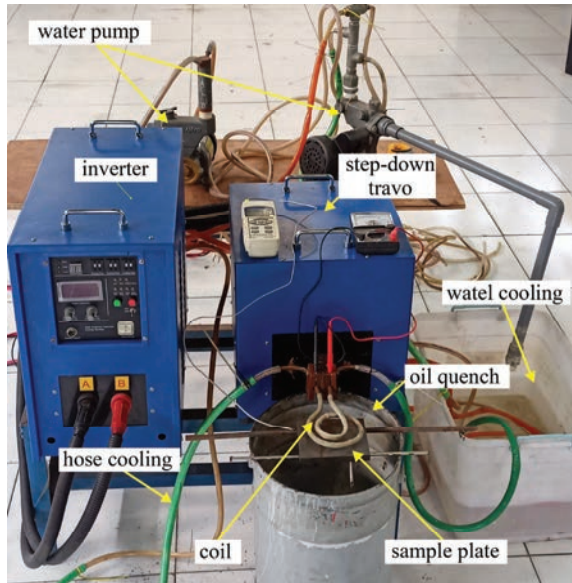


Fig. 1. Induction heating machine

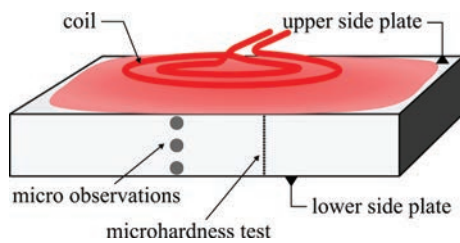


Fig. 2. Specimens for microstructure and microhardness tests

coils *A*, *B* and *C*, respectively: 68.00 s, 88.33 s and 104.67 s. From the data of frequency and time measurements, it can be seen that the lower the frequency produced by the coil, the longer it takes to heat the sample to the austenite temperature.

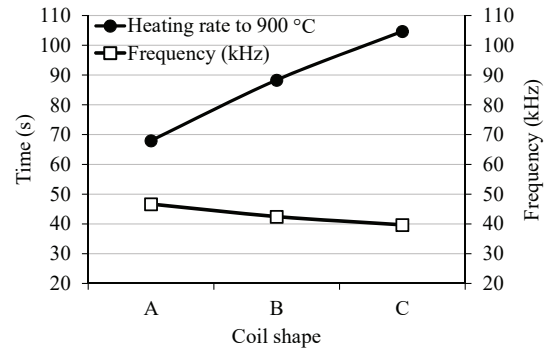


Fig. 3. Effect of the shape and size of the coil on the resulting frequency of the coil and heating time up to 900 °C of the austenitizing temperature

5. 2. Microstructure

The microstructure of the plate cross-section on the upper, side and lower sides of each coil shape variable is shown in Fig. 4–6. Microstructural observations were made to see the transformation in each part and each sample variable. Microstructural changes due to rapid quenching of the austenite phase can serve as the basis for mechanical changes.

5. Results

5. 1. Frequency and heating rate

The results of using variations in the shape and size of the coil in an induction heating machine are shown in Fig. 3. The frequency generated by the engine is affected by the current resistance on the coil. While the resistance is influenced by the size and number of coil turns.

The number of turns and coil dimensions that affect the resulting frequency are determined. The measurement results on coil *A* have the highest frequency value, which is 46.67 kHz. While coil *B* and *C* are 42.33 kHz and 39.67 kHz, respectively. The frequency produced by each coil is different, so the time to reach the austenite temperature in the sample is also different. Time to reach the austenite temperature (900 °C) in

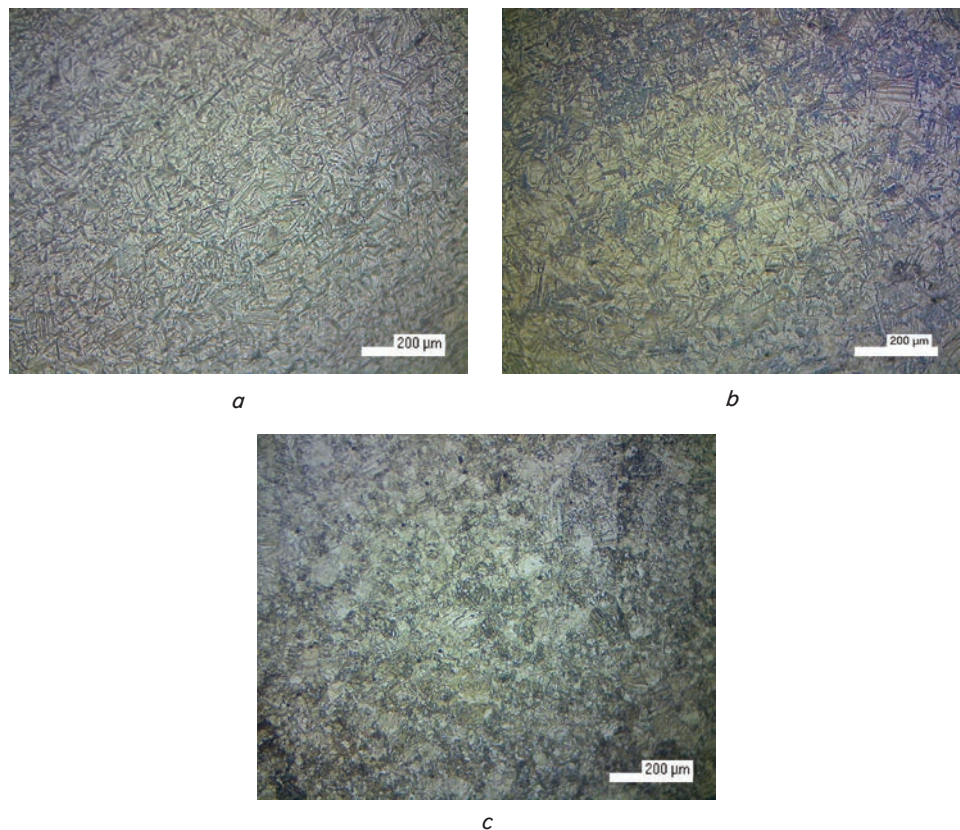


Fig. 4. Cross-sectional microstructure of the specimen using coil code *A*: *a* – fine martensite structure on the upper side; *b* – coarse martensite structure on the middle side; *c* – coarse martensite and some of the remaining perlite and ferrite structure on the lower side

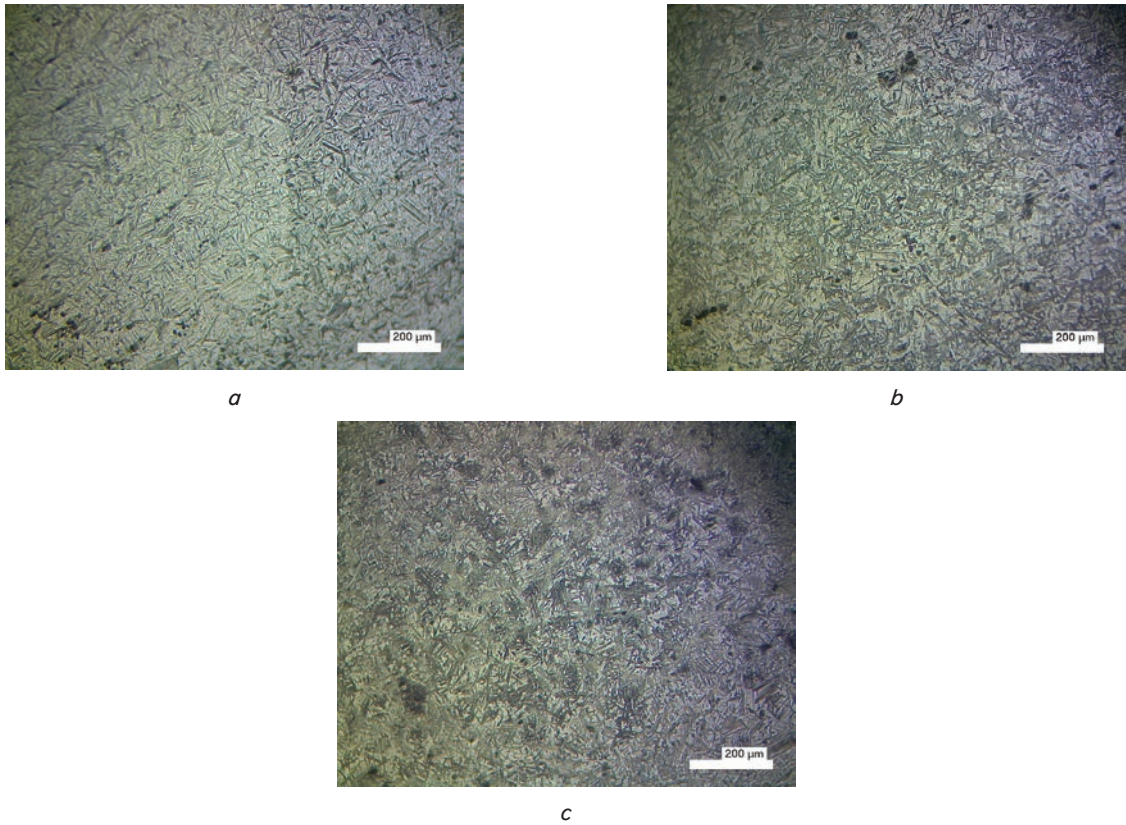


Fig. 5. Cross-sectional microstructure of the specimen using coil code *B*: *a* – fine martensite structure on the upper side; *b* – fine tends to be coarser martensite structure on the middle side; *c* – coarse martensite structure on the lower side

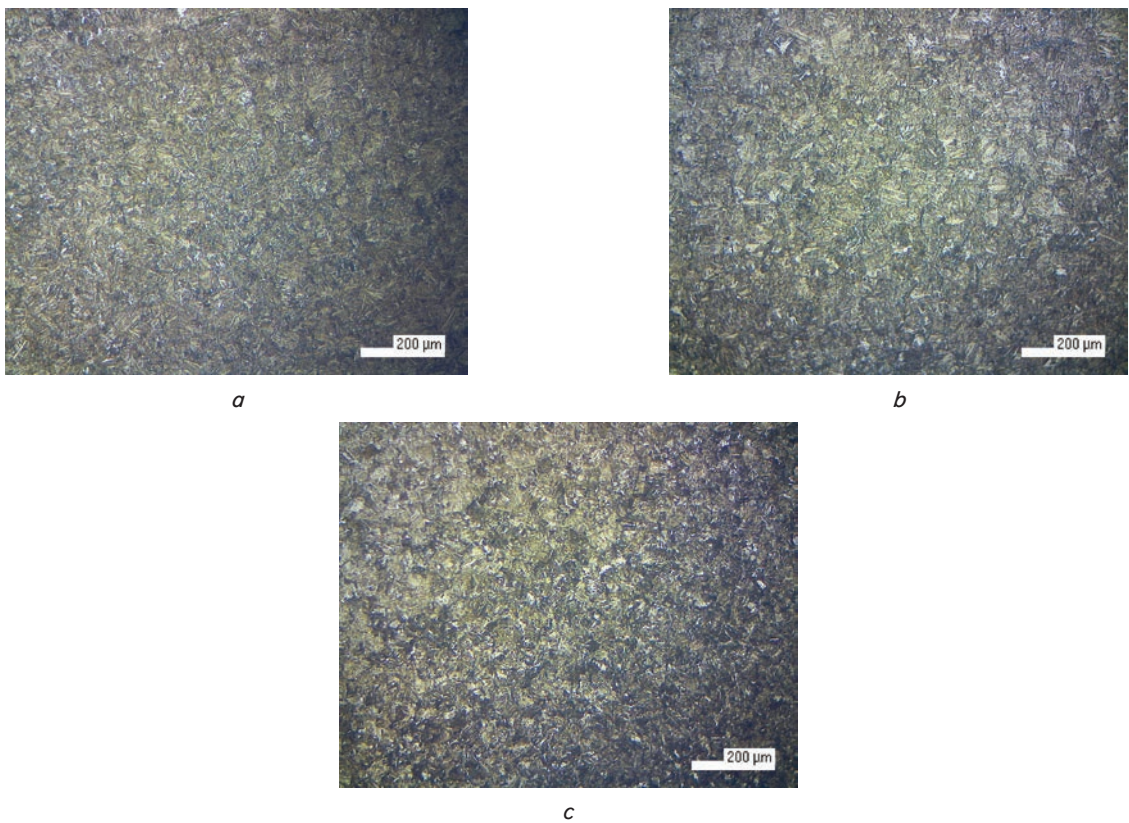


Fig. 6. Cross-sectional microstructure of the specimen using coil code *C*: *a* – fine martensite structure on the upper side; *b* – fine martensite structure on the middle side; *c* – fine martensite structure on the lower side

In the specimens using coil code *A*, the microstructure formed on the upper side plate is a fine martensite structure (Fig. 4, *a*), while the middle side (Fig. 4, *b*) shows a coarse martensite structure and the lower side (Fig. 4, *c*) tends to

still be visible ferrite and perlite structures. The use of coils with codes *B* and *C*, on all sides of the microstructure is a fine martensite structure.

5. 3. Hardness distribution

The micro Vickers hardness distribution on the plate cross-section of each variable coil is as shown in Fig. 7.

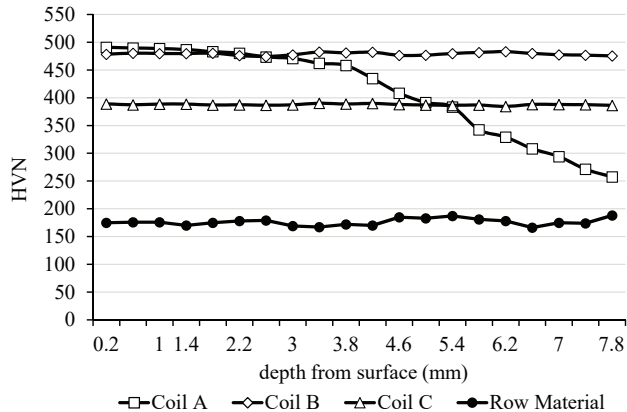


Fig. 7. Cross-sectional hardness distribution of the sample using variations in the shape and size of the coil

The microstructure transformation of the sample that has been carried out by rapid quenching affects the hardness. After the rapid quenching process on the steel plate from the austenite temperature, there was an increase in the hardness of both the variable coil code *A*, *B* and coil code *C*. The increase in hardness was caused by the change in the structure to martensite structure due to rapid cooling. In coils *B* and *C*, the distribution of roughness is relatively even from the upper side to the lower side. In coil *A*, the maximum hardness increases on the upper surface and the minimum hardness increases on the lower side.

6. Discussion of results

6. 1. Discussion of frequency and heating rate

The time to reach the austenite temperature is influenced by the frequency of the coil. The coil code *A* has a higher frequency value compared to coils code *B* and *C*. This is due to the shape and diameter of coil *A* larger than coil code *B* and *C* so that the current resistance is the lowest [17]. Frequency affects the heating rate, the greater the frequency, the greater the heating rate. It takes 68 seconds to reach the austenitizing steel temperature of 900 °C for coil *A*. As for coil code *B* and coil code *C*, 88 seconds and 104 seconds each. The lower the current resistance, the higher the resulting frequency, and the greater the eddy current generated, the faster the heating. The speed of temperature increases until it reaches the austenitizing temperature, which will greatly affect the hardness distribution and the microstructure formed. The velocity of reaching the austenitizing temperature at the plate surface is necessary to prevent the thermal conductivity from moving to the plate. The faster the austenitization occurs on the plate surface and the austenitizing temperature has not yet been conducted to the inner side and lower surface of the plate, the sooner the plate quenching process. So that the austenitizing temperature only occurs on the surface of the upper plate side near the

coil, while on the inner or middle side and the lower side of the plate surface there is no austenitizing temperature.

The frequency of induced current is influenced by the size of the current resistance in the coil. The lower the current resistance in the coil, the higher the working frequency of the induced current. When the working frequency of the induction is high, the concentration of eddy currents on the surface of the heated sample will not go deeper [21]. In other words, the heating will only occur on the surface. With a large frequency, the austenitization of the sample only occurs on the surface close to the coil. This shows that the high frequency will give a high power density effect only on the edge or surface of a sample. And otherwise with low frequencies, will give the effect of power density that goes to the inside of a sample [22]. This is what causes surface hardening if the austenitizing temperature has been reached on the surface and before heat conduction propagates into the core of the sample, a rapid quench process is carried out.

6. 2. Discussion of microstructure

The martensite structure that is formed tends to be needle-shaped martensite. The martensite structure formed tends to needle martensite, this is due to the medium carbon content in the sample [23]. This martensite is formed on steel with a carbon content of 0.4 % C, which is cooled by rapid quenching after austenitizing it. This martensite structure tends to be hard and brittle. Meanwhile, the middle and lower sides of the martensite are less visible. The structures seen on the middle and lower sides tend to be ferrite and perlite. These structures tend to be softer and more ductile. This is due to the fact that the austenite phase on the middle and lower sides has not yet been reached, so when the rapid quenching of the martensite phase is not formed completely. The sample structure using coil code *B* and *C* on the upper, middle and lower sides (Fig. 6, 7) tends to be martensite. This structure is formed because the austenitization process occurs completely in all parts of the sample and is carried out by rapid quenching. This can prove that the heating rate affects the distribution of the phase structure formation due to the uneven austenitization process.

Due to the higher frequency of the coil with code *A*, the density effect on the sample does not enter too deep from the sample surface. The concentration of eddy currents does not go too deep from the sample, so the austenitizing temperature only occurs on the upper side, so that the martensite transformation occurs perfectly when the immersion process is carried out in the oil medium. On the lower side, the austenitizing temperature has not been reached, the heat conduction from the upper side has not propagated, so the martensite transformation is not sufficient. So, on the lower side, the ferrite and pearlite structures are still visible, which are generally in medium carbon steel.

6. 3. Discussion of hardness distribution

The distribution of raw material hardness was 172.60 HVN. The increase in hardness occurs in all samples using coil code *A*, *B* and *C*. As can be seen from the graph in Fig. 7, the hardness distribution of coil *B* and coil *C* tends to be even from the upper to the lower side. The increase in the hardness of the *C* coil from the raw material is up 120 % or becomes 387.64 HVN. The average increase in the hardness of coil *B* was up 171.83 % or increased to 478.96 VHN. The hardness of the coil *B* and *C* samples' cross-sectional values did not result in surface hardening. On all sides, hardness

tends to be the same. This occurs because the sample structure is martensite on all cross-sides (Fig. 5, 6). It differs from the distribution of hardness in the cross-section of the sample using coil A. The hardness on the upper side increased 178.54 % or became 490.80 HVN, while on the lower side, it only increased by 46.14 % or only 257.50 HVN. High hardness up to the test point of 10 or a depth of 4 mm from the upper side plate's surface. For a depth of more than 4 mm, the hardness decreases until it reaches the lowest hardness on the lowermost side. This proves that the martensite phase, which is formed on the upper side, has high hardness, while on the middle and lower sides with the less perfect martensite phase are lower.

The martensite transformation occurs in carbon steel as a result of the austenization process and is followed by a rapid cooling process. The high frequency on the code A coil accelerates the austenization process and the density effect on the sample does not go too deep from the sample surface. So the hardness of the plate using the code A coil increased significantly at a depth of 0.2 to 3.8 mm from the surface. While the deeper the surface, the hardness did not increase significantly from the raw material. This is because the depth of more than 3.8 mm of the sample does not reach the perfect austenite phase, so when it is immersed, it transforms completely into martensite so that the hardness is not too high.

Different hardness distributions in the experiment using coil code A between the upper and lower sides can cause different properties as well. High hardness has high strength but tends to be brittle when exposed to the impact force. The high hardness is capable of breaking and crushing the tip of the projectile compared to soft materials. The higher the hardness, the smaller the penetration depth of a projectile into the plate [1]. However, high hardness also tends to cause adiabatic shear band (ASB) formation, and ASB induced cracking when exposed to high-velocity impact loads such as projectiles [14]. This ASB will lead to crack growth

and failure. Very high hardness can also reduce ballistic resistance due to the failure process caused by shifting and cracking to holes due to projectile impacts [20]. Soft material will not be able to withstand the projectile rate, but soft material has ductile properties and can prevent cracks and crack propagation.

7. Conclusions

1. The shape and size of the coil affect the frequency produced by an induction heating machine. This frequency will affect the heating speed. The faster the austenitizing temperature on the plate surface and the rapid quenching process carried out, the plate's inner side and the underside that not directly exposed to the coil will not have time to form an austenite phase. This condition will result in the formation of the microstructure and the level of hardness.

2. Higher hardness on one side of the plate surface and lower hardness on the reverse side theoretically and literary can improve ballistic resistance. The high hardness on the front cover of the target plate can withstand ballistic rates while preventing cracks and perforation due to ductility on the target plate's back. The use of a coil with a diameter of 8 mm and the number of turns 2 can increase the hardness on the upper side to 497 HVN while on the lower side it is 257 HVN. The plates processed by this method can be proposed as a ballistic resistant plate candidate. Further studies are needed both in simulation and experiment on ballistic impacts.

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