

# Analysis of The Effect of Heat Treatment on Changes in Mechanical Properties and Electronic Performance of Thin Foil for Electronic Components

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**Abstract.** The rapid development of the electronics industry creates a need for small-sized materials with good mechanical properties and electronic performance to improve efficiency during production. However, in thin materials deformation is prone to occur during the production process which can damage the mechanical properties of the material. To minimize the deformation that occurs, heat treatment is performed. Heat treatment is carried out at temperatures of 400 °C, 650 °C, and 900 °C and different cooling, namely furnace cooling, air cooling, and water cooling. Observations to evaluate the effect of heat treatment, with heating at various temperatures and different cooling rates on the mechanical properties and electronic performance of 304 stainless steel thin foil. Tensile tests were conducted to determine changes in the mechanical properties of the samples, while the electronic performance to be observed is the conductivity carried out by the steady state method on two hot plates. The results show that the higher the temperature and the faster the cooling rate during heat treatment, the conductivity of the sample increases, the best conductivity is obtained from the water cooling sample heated at 900 °C with a conductivity value of 20.38 W/mK with a time range of 515 seconds. Although conductivity increased after heat treatment, the average value of mechanical properties decreased, from the tensile test conducted, the highest UTS sample was 847.75 MPa in the water cooling sample with 650 °C heating. The rapid development of the electronics industry creates a need for small-sized materials with good electrical conductivity. Surface roughness (Ra) was measured using Aziz equation which was found in 2022.

## 1 Introduction

The development of technology continues to increase which brings progress in the field of electronic industry, especially in the field of microelectronics and telecommunications. New high-tech electronic devices with portable models such as smart phones with slim models are increasingly being developed, unlike in the past where the more sophisticated the technology, the larger the electronic devices will be [1]. The rapid development has brought a new era in the trend of device miniaturization and electronic packaging density. Increasing miniaturization while maintaining device integration requires thin materials and better performance for electronic components, so micro and nano fabrication methods are the solution for miniaturization with the use of thin foil as raw capacitors, diodes, transistors or other small components [2].

Materials used for raw materials for making electronic components must meet certain requirements such as good mechanical properties including hardness, elasticity and corrosion resistance and electronic

performance such as thermal and electrical conductivity are also good [1]. Stainless steel 304 is one of the materials that is widely used in this industry, the selection of this type of material is of course due to the advantages of its mechanical properties and the material is still easily available at a more affordable price when compared to materials that have similar mechanical properties at a more expensive price. In addition, 304 stainless steel has good ductility, hardness, strength, and corrosion resistance coupled with good electrical and thermal conductivity and is easy to shape making 304 stainless steel thin foil the main option used [3]. However, the superior properties of 304 stainless steel are susceptible to changes due to deformations that occur during the manufacturing process [4]. Corrosion resistance coupled with good electrical and thermal conductivity and is easy to shape making 304 stainless steel thin foil the main option used [3]. However, the superior properties of 304 stainless steel are susceptible to changes due to deformations that occur during the manufacturing process [4].

Dislocations, changes in grain boundaries, and increased surface roughness (Ra) affect the thin foil

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because these are related to the size effect. Surface roughness (Ra) along with dislocations that occur will change the strength and hardness of the material and disrupt electron flow so that the conductivity of the thin foil is disrupted. To improve it, heat treatment is carried out by considering temperature, holding time, and cooling rate in order to obtain the appropriate mechanical properties and electronic performance. Determination of the right process parameters is not only intended to improve the mechanical properties of the material, but is also expected to maintain and even improve the electronic performance of 304 stainless steel thin foil [5].

Therefore, this study aims to determine how much influence the temperature and cooling rate during heat treatment have on changes in mechanical properties and electronic performance of 304 stainless steel thin foil to be used in the production of electronic components. Where the temperatures to be used are 400 °C, 650 °C, and 900 °C with furnace cooling, air cooling, and water-cooling methods. The mechanical properties observed are tensile strength, elongation, and sample microstructure. As for the electronic performance that will be observed is the electrical conductivity of the sample by applying steady-state testing between two hot plates.

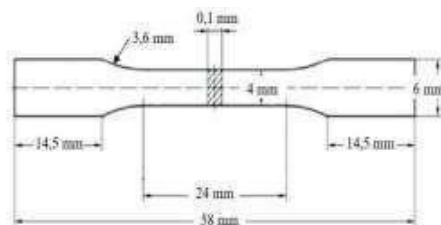
## 2 Methods

The main material used in this study is 304 stainless steel thin foil with the composition as shown in Table I.

**Table 1.** Chemical Composition Thin Foil Stainless Steel 304 [6]

Element	Cr	Ni	S	P	C	Si	Mn
Min	18.00	8.00	-	-	-	-	-
Max	20.00	10.50	0.030	0.045	0.08	1.00	2.00
-	18.01	8.03	0.004	0.030	0.05	0.39	1.10

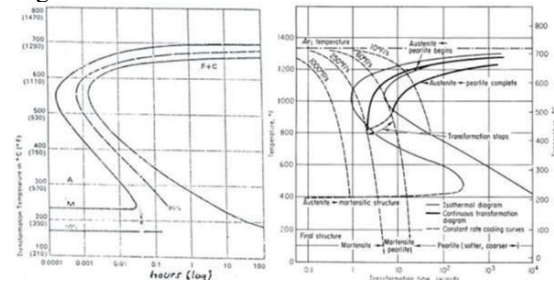
The 304 stainless steel thin foil to be used as a sample was prepared with dimensions of 58 mm length, 6 mm width, 24 mm gauge length, and 0.01 mm thickness from DIN125 tensile test standard.



**Fig. 1.** Dimensions of Test Specimens.

The holding temperatures and times used were previously determined using a TTT (Time, Temperature, Transformation) diagram. Meanwhile, the cooling method used was determined based on the CCT (Continuous Cooling Temperature) diagram. Based on these two diagrams, heating temperatures of 400 °C, 650 °C, and 900 °C were determined with a holding time of 60 minutes at each temperature. The rapid cooling method with water media (water cooling), cooling in the open air slowly (air cooling), and the slow cooling

method (furnace cooling) by letting the sample cool in the furnace, the TTT and CCT diagrams can be seen in Fig. 2.



**Fig. 2.** (a) TTT Diagram for Determining Temperature and Holding Time; (b) CCT Diagram for Determining Cooling Method [7]

The first step in this research was to heat treat the samples with a predetermined holding time and temperature. Samples that have been cut following the pattern in Fig. 1 are first cleaned using ethanol while preparing the furnace to be used. The samples were first heated at 900 °C and held for 60 minutes, then cooled using the furnace cooling method. After the sample is completely cooled, store the sample and mark the container, then continue heat treatment on the other samples at a predetermined temperature and cooling method.

The first test carried out on the heat treatment sample was a tensile test. A tensile test was also carried out on the sample without heat treatment for comparison. The samples to be tested were first measured and recorded the measurement results to calculate the initial cross-sectional area of the specimen. Before testing, the speed and tension of the tensile testing machine were calibrated first.

$$A_0 = t \times L \quad (1)$$

Both ends of the sample will be attached to the tensile test clamp, the load received (F) and the length mining (mm) are recorded. The load (F) and length gain (mm) data obtained are used to calculate the strain and stress experienced by the sample. The final dimensions of the sample after breaking were measured again and recorded for use in the elongation calculation. Each step of the test was repeated on another sample.

Furthermore, the thermal conductivity of each sample is carried out to determine whether there is a change in electrical conductivity due to heat treatment and tensile tests carried out. The sample to be tested is cut with a size of 1:1, both ends of the sample are paired with a thermometer or temperature measuring sensor. On one side of the sample, a heating device is attached and calibration is carried out, before the test is carried out, the initial temperature on both sides of the sample is recorded. Restart the heating device along with a stopwatch, stop and record the time required until the system reaches steady state, all data obtained during the test will be used to calculate the thermal conductivity of the sample with the following equation.

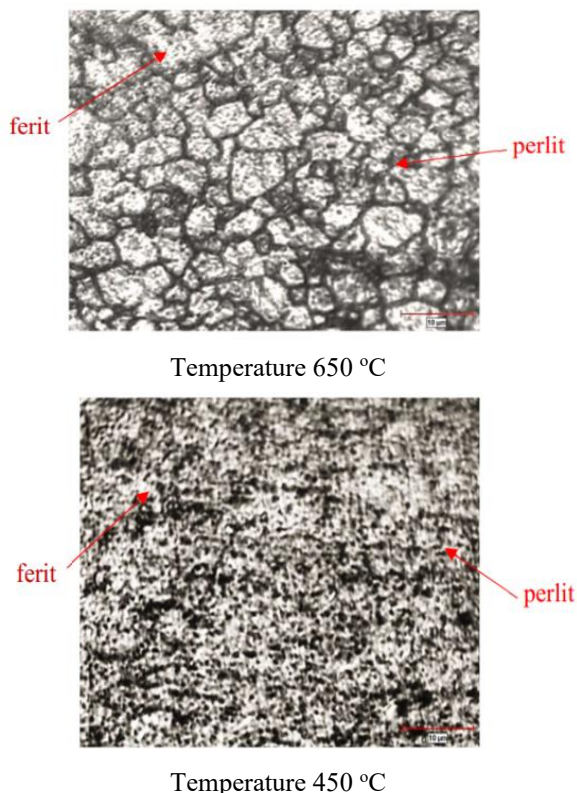
$$q = -kA(dT/dx) \quad (2)$$

The last test carried out is metallography with the aim of observing changes in microstructure and phase transformations that occur before and after treatment.

### 3 Result and discussion

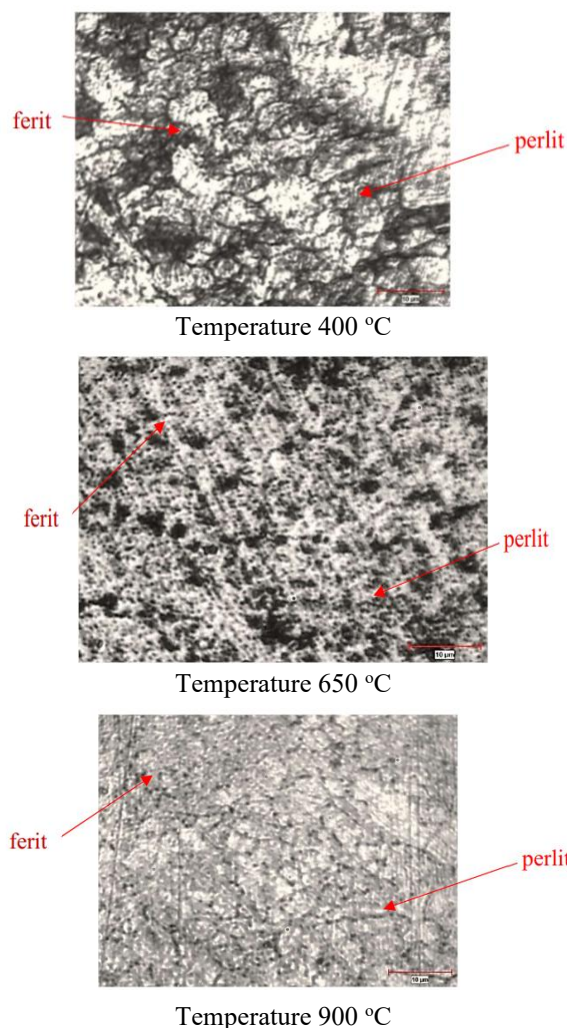
#### 3.1 Heat Treatment

The first samples observed were furnace cooling samples heated at 400 °C, 650 °C, and 900 °C with a holding time of 60 minutes. Furnace cooling is a slow cooling method carried out by leaving the sample in the furnace until it reaches room temperature with the aim of increasing the ductility of the material [7]. In the observation of the furnace cooling sample, it was found that the pearlite structure had a lamellar (layered) shape between the light-colored ferrite phase and darker cementite [8]. Microstructure observations were made using an optical microscope and image processing with ImageJ software.



**Fig. 3.** Microstructure of Furnace Cooling Samples at Temperatures of 450 °C and 650 °C

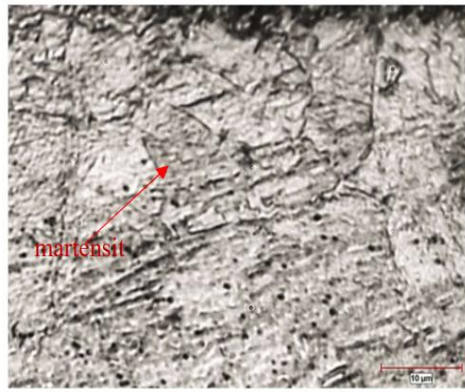
Furthermore, microstructure analysis is carried out on the sample of air cooling results, where the sample is cooled by the air cooling method. In general, air cooling aims to reduce residual stress in the material, the phases formed at this cooling rate are dominated by ferrite and pearlite with a more uniform size and distribution than the results of furnace cooling. From the tests previously carried out, it is known that the strength of the material has increased compared to the sample at a slow cooling rate. The thermal conductivity of the sample also reached the highest value in the air cooling sample.



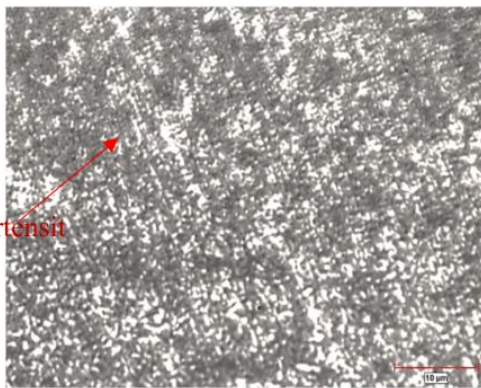
**Fig. 4.** Microstructure of Air-Cooling Samples at Temperatures of 400 °C, 650 °C, and 900 °C

The microstructure of the 900 °C temperature sample has an average grain size of 384.082 μm. The 650 °C temperature sample has an average grain size of 791.676 μm and in the 400 °C temperature sample the average grain size is 441.063 μm. In both air cooling and slow cooling with furnace cooling, the phases formed were ferrite and pearlite. The tensile test results on the water-cooled samples showed that the strength of the samples improved, besides that the thermal conductivity of the samples also reached its best value.

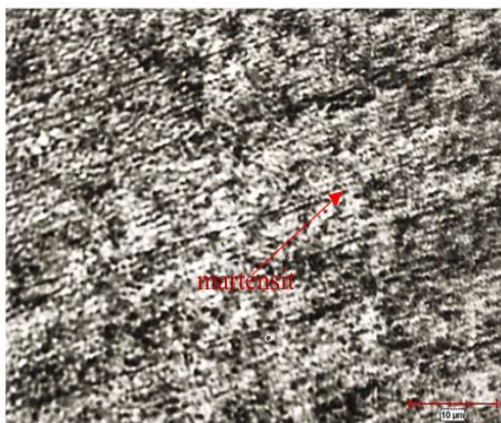
The last three samples were subjected to water cooling, where after heating, rapid cooling with water will be carried out [9]. This rapid cooling produces a small microstructure resembling a fine and tight needle because many atoms are trapped in the material's microstructure due to the diffusion process being too short. The microstructure of the sample is clearly visible in the metallographic results of the sample heated at 900 °C because austenization occurs so that recrystallization can occur properly. The average grain size of water-cooling samples is 215.336 μm at 900 °C, 102.902 μm at 650 °C, and 268.891 μm at 400 °C. Microstructure view of samples with water media after heat treatment at 900 °C, 650 °C, and 400 °C.



Temperature 900 °C



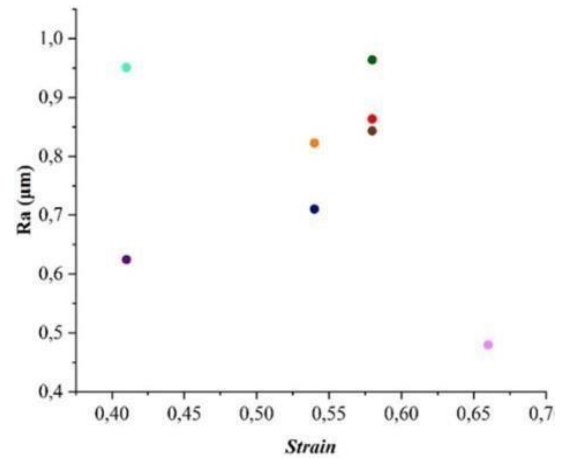
Temperature 650 °C



Temperature 400 °C

**Fig. 5.** Microstructure of Water-Cooling Samples at Temperatures of 400 °C, 650 °C, and 900 °C

Furthermore, the surface roughness of the material is observed, the metallographic results obtained are then processed using ImageJ software to determine the %area in the microstructure of the sample which will be used in the calculation of Ra. The increase in surface roughness on the material is the biggest factor in the deterioration of mechanical properties due to the influence of size effect. The deformation that arises from the tensile test previously carried out triggers an increase in the surface roughness of the material. The results of the Ra and strain comparison calculation are shown in Fig. 6.

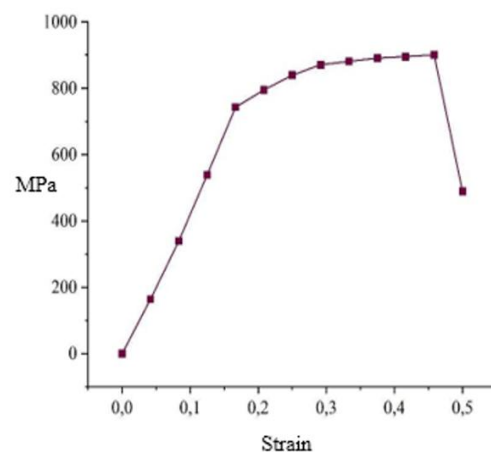


**Fig. 6.** Comparison of Ra and Strain After Heat Treatment

Surface roughness on the sample is one of the most avoidable factors of thin material applications. Increased surface roughness in thin materials can damage the mechanical properties of the material increased surface roughness can reduce strength to shorten the life of the material due to increased corrosion potential. As additional data, calculations are made from the data obtained from the ImageJ results and it is found that the sample heated at 650 °C with water cooling has the highest surface roughness of 0.96 μm in the figure marked with a green dot. While the sample with the lowest surface roughness is the sample heated at 650 °C with water cooling with a value of 0.48 μm in the figure marked with light purple dots.

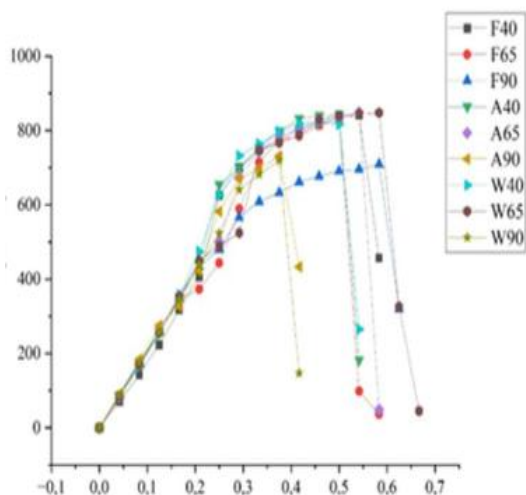
### 3.2 Tensile test

In untreated samples, in general, the mechanical properties will be below the mechanical properties of heat-treated samples, because precipitation has not yet formed on the microstructure [10]. It is known that the tensile strength of the untreated sample is in the range of 900.25 MPa with a yield strength of 742.75 MPa. The elongation of the sample during the test reached 50% of its original size, while the elastic modulus of the sample was in the range of  $4464.6 \times 10^6$ . The tensile test stress-strain graph of the untreated 304 grade stainless steel thin foil is shown in Fig. 7



**Fig. 7.** Stress-Strain Graph of Test Sample Without Heat Treatment

Comparison of the tensile test results of the samples as a whole can be seen in Figure 8, and it is known that the sample with water cooling heated at 650 °C has the highest tensile strength of 847.75 MPa. The sample with the lowest tensile strength is the sample with the furnace cooling method heated at 900 °C, where the tensile strength value is only 709 MPa. In this experiment, the heat treatment carried out affects changes in microstructure and phases formed according to the cooling rate applied. The microstructure of the samples in both slow cooling with furnace cooling and air cooling was almost identical, with the phases formed being pearlite and ferrite.



**Fig. 8.** Stress-Strain Curve of Sample After Heat Treatment

The difference lies in the sample with slow cooling furnace cooling has a larger grain size and is not uniform, from the structure and phase formed this produces a sample with better strength and ductility. Whereas in rapid cooling with water cooling the resulting microstructure is finer and tighter with the dominant martensite phase formed. Further factors that can affect changes in the mechanical properties of the material are dislocations, defects, and increased surface roughness. Deformation due to the tensile test increases dislocations, defects, and surface roughness of the sample which can be noted from the strength of the sample which decreases due to deformation after the tensile test.

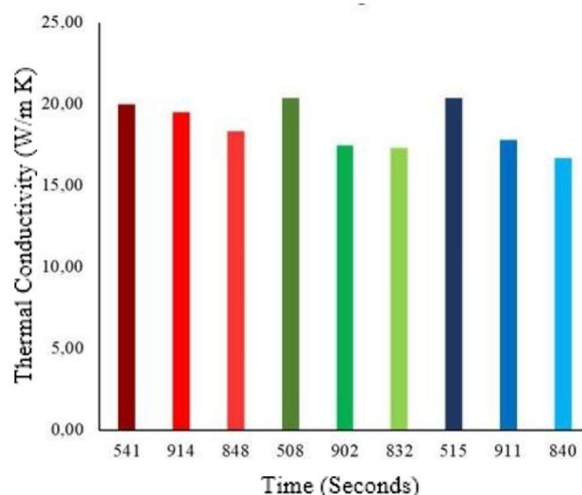
However, if a comparison is made with the mechanical properties of the untreated sample, it can be seen that the decrease in sample strength is quite significant. The parameters used during heat treatment were re-examined and it was found that factors that can affect the final properties of the material include heating temperature, holding time, cooling medium, and the composition of the material used itself. The material used for all the samples was 304 stainless steel in the form of a thin foil. The variations in the tests were based on the cooling medium and heating temperature employed. The last factor that is not varied is holding time, all samples experience the same holding time.

The use of holding time should be adjusted to the temperature and cooling medium to be used. Because it will give the effect of different mechanical properties, holding time that is too long has the opportunity to

reduce the hardness and strength of the material [11]. In addition, the high temperature used makes it easier for diffusion to occur so that the phase continues to overgrow coupled with a slow holding time, the more opportunities for atoms to diffuse. Even though rapid cooling is carried out, the strength of the sample still decreases due to overheating and softening of the sample due to dislocations that are free to move at high temperatures [11].

### 3.3 Thermal conductivity test

Samples used in thermal conductivity testing have previously been formed with a size of 1: 1. Each sample was tested for thermal conductivity as much as 3× testing, then made the average value. For the sample without treatment, the average time required to reach a steady state was approximately 1312 seconds, with a thermal conductivity value of 16.20 W/mK. The results of the thermal conductivity test samples after heat treatment are shown in Fig. 9.



**Fig. 9.** Comparison of Conductivity Test Results of Samples after Heat Treatment with average deviation standard below 0.02%

The red color indicates the sample group that uses furnace cooling, the green color for the air-cooling sample group, and the blue color for the water-cooling sample group. The lighter the color used indicates the lower the temperature used. Judging by the thermal conductivity value, the water cooling and water-cooling samples at 900 °C have the highest value. In addition to the thermal conductivity value, the time required for the system to reach steady state is also taken into account, therefore the water cooling sample at 900 °C becomes the sample with the best electrical or heat conductivity with a time of 508 seconds. Based on the result, the thermal conductivity and electrical conductivity are in the good agreement. When the thermal conductivity increase, the electrical conductivity increase. This condition occur, because both of thermal conductivity and electrical conductivity are inversely proportional to electrical resistance. Overall, heat treatment has a good effect on the conductivity of the sample compared to the untreated sample. the green color for the air-cooling sample group, and the blue color for the water-cooling

sample group. The lighter the color used indicates the lower the temperature used. Judging by the thermal conductivity value, the water cooling and water-cooling samples at 900 °C have the highest value. In addition to the thermal conductivity value, the time required for the system to reach steady state is also taken into account, therefore the water cooling sample at 900 °C becomes the sample with the best electrical or heat conductivity with a time of 508 seconds. Based on the result, the thermal conductivity and electrical conductivity are in the good agreement. When the thermal conductivity increase, the electrical conductivity increase. This condition occur, because both of thermal conductivity and electrical conductivity are inversely proportional to electrical resistance.

The higher the temperature used increases the thermal conductivity of the sample because recrystallization is better formed. It should be noted that cooling too fast can damage the thermal conductivity of the sample, tight and fine microstructures formed on rapid cooling complicates the movement of electrons on the surface of the sample [12,13]. Cooling with the air cooling method is the most appropriate choice to improve the conductivity of 304 stainless steel thin foil samples, because the microstructure has a uniform size distribution and is not as dense as rapid cooling [13,14,15].

## 4 Conclusions

Based on the results of the research that has been carried out, it is known that the temperature and cooling rate used during the heat treatment process of the sample in the form of 304 stainless steel thin foil affect changes in the mechanical properties and electrical conductivity of the sample. The sample with the best mechanical properties is the sample resulting from water cooling at a heating temperature of 650 °C with a UTS of 847.75 MPa. As for the sample with the best electrical conductivity produced from the water-cooling sample at a heating temperature of 900 °C with a thermal conductivity value of 20.38 W/mK. In addition, it is known that the highest surface roughness changes in the highest conductivity value. Water cooling sample with 650 °C heating, the calculated surface roughness of 0.96 µm.

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