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Research Article

Investigation of heat treatment strategies for improvement of production capacity of *coin stamping dies*

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ABSTRACT

This paper presents a study on the production capacity of stamping dies for minting coins under different heat treatment processes, particularly austenite temperatures, using a vacuum furnace. In the study, the specimen material was made from Bohler K340 steel. The first heat treatment strategy included heating the specimens to a stable austenite temperature at 1080°C, then holding them for 120 minutes and cooling them rapidly with gas quenching media with a pressure of 5 bar. Tempered treatment was performed at 500°C. Another strategy was similar to the first one, except for the heating temperature at 1060°C and double tempering at 575°C. After the heat treatment process, microstructure observation and hardness testing were carried out. Finally, the production of the die capacity testing on the coining machine was conducted. The results of the specimen surface photographs of the two heat treatment strategies show a significant difference in the microstructure, similarly with the hardness value obtained from single tempering is 61.98 HRC and from double tempering is 57.94 HRC. The production capacity test result indicates that the average capacity of the first and second dies are 101,250 coins and 171,150 coins, respectively. It means that the second dies to exceed the minimum standard production capacity of dies as determined by the Quality Control department, which is 150,000 coins.

1. INTRODUCTION

A public company engaged in printing banknotes, non-money securities, and coins had a shortage of a specific type of coin production due to a lower quality of stamping dies that led to a shorter production capacity. The blank coin materials are aluminium and nickel-plated steel, and the type of tool steel used to make stamping dies are Bohler K455 and Bohler K340.

This study focus on the production capacity of stamping dies for producing Rp 1,000 coins. The stamping dies are made from Bohler K340, while the coin is made from nickel-plated steel. At the time of initial observation, the production capacity of the dies was less than 150,000 coins, which is below the standard set by the Quality Control department. This problem became a challenge to the dies manufacturing department in improving the dies production capacity.

Two alternatives to solve this problem are using the material engineering approach or replacing the material with a higher grade. In this study, the material engineering approach is selected, and the material used for the stamping dies the same as the previous material, i.e., Bohler K340 steel, having a chemical composition of 1.10% C, 0.90% Si, 0.40% Mn, 8.30% Cr, 2.10% Mo and 0.50% V.

The heat treatment process has a significant influence on the improvement of the mechanical properties of the dies. The desired material properties are obtained by controlling the heat treatment process. The hardness of the material will increase as austenitising temperature increases [1]. However, austenitising temperature alone does not significantly affect the hardness [2]. An appropriate quenching and tempering should follow it. Sanij et al. [3] suggested that double quenching and double tempering could improve the mechanical properties, particularly impact toughness, compared to the conventional quenching and tempering condition. Fitrullah et al. [4] revealed that the hardness resulting from single tempering was 62.9 HRC, while double tempering was 61.49 HRC. The double tempering process yields a lower hardness but produces a finer microstructure and higher toughness.

The impact toughness was remarkably increased after the second tempering treatment due to the carbide shape change [5]. The tempering temperature must be appropriately selected as it is found that higher hardness could be obtained at a tempering temperature of around 500°C and lower hardness at tempered above 500°C [6].

Conventional cooling technologies, such as oil or polymer, exhibit inhomogeneous conditions. These inhomogeneous cooling conditions cause tremendous components' thermal and transformation stresses and subsequent distortion [7]. Using circulated nitrogen, high-pressure gas quenching in vacuum furnaces has already become standard practice. This technology has several known advantages, such as substantially reduced size change and distortion of the workpieces; no need to wash the parts after quenching and ecological acceptability compared to quenching in oil or other liquid quenchants [8].

In addition, Atraszkiewicz et al. [9] proposed helium as an alternative cooling medium due to its higher quenching power than nitrogen. Despite several reports stating that replacing nitrogen with helium could cause an increment in distortions, they observed no adverse effect of helium cooling medium on surface layer microstructures and level of distortions.

Al-Ezzil et al. [10] argue that hardness is a significant property responsible for the performance of punch dies as the dies undergo severe wear during the punching of mechanical components. However, increasing the production capacity of stamping dies needs an appropriate heat treatment to obtain higher durability of dies that may not solely result from higher hardness. Therefore, this research aims to investigate a proper heat treatment procedure on Bohler K340 steel to increase the production capacity of dies.

2. MATERIALS AND METHOD

2.1. Specimen preparation

Before the heat treatment and testing processes, the dies specimen made of K340 Isodur material produced by Bohler Edelstahl GmbH & Co Germany was formed using a CNC lathe and EDM machines. The shape of the dies or test specimens is shown in Figure 1.

Figure 1. Sample of the specimen (Photo was taken by the author).

2.2. Heat treatment

In this research, two different heat treatment procedures were performed in a vacuum furnace, namely, the austenitising temperature at 1080°C with single tempering at 550°C and austenitising temperature at 1060°C with double tempering at 575°C. Both procedures employed a gas quenching method using nitrogen as media. Although both techniques used different austenitising temperatures, these temperatures were still within the range of high austenitising temperature that produces lower bainite-martensite microstructure compared to low austenitising temperature (900-1000°C) [11].

The First Procedure

In the experiment, the specimen was undergone heat treatment at an austenitising temperature of 1080°C and single tempering at 500°C. The procedures are described below and illustrated in Figure 2:

1. Four specimens were heated for 60 minutes to a temperature of 650°C and held within 15 minutes for pre-heating. Then, the temperature was raised to 800°C for 50 minutes and kept within 15 minutes for final heating. After that, the temperature was raised again for 50 minutes until it reached a temperature of 1080°C and holding time for 120 minutes. Interestingly, initial heating, pre-heating, and final heating, with a holding time of 15 minutes, were effective in preventing cracking that may arise from thermal shock [12].
2. After heating, the specimens were cooled with Nitrogen quench gas to reach a temperature of 50°C continuously for 20 minutes with a pressure of 5 Bar.
3. Finally, the tempering process was immediately carried out for 180 minutes at a temperature of 500 °C, then the specimens were cooled again with Nitrogen gas quench gradually to a temperature of 50°C for 20 minutes with a pressure of 5 Bar.

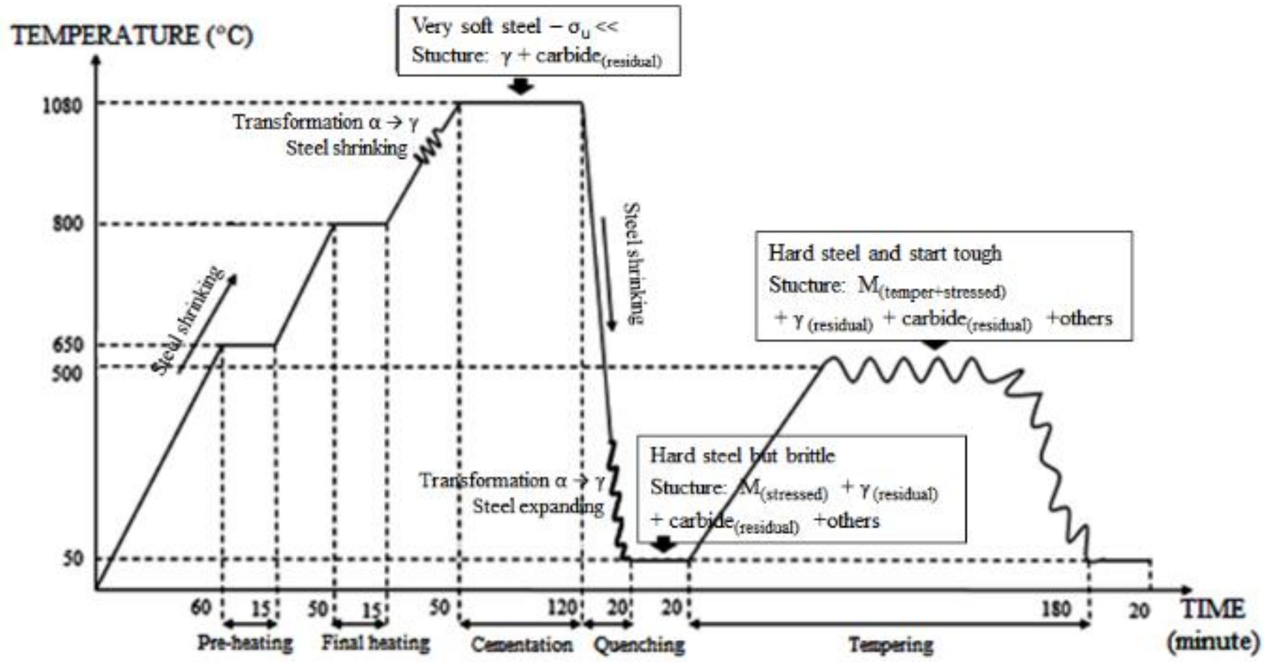


Figure 2. Heat treatment at an austenitising temperature of 1080 °C and single tempering at 500 °C

The Second Procedure

For this procedure, the specimen was undergone heat treatment at an austenitising temperature of 1060°C and double tempering at 575°C. The procedures are described below and illustrated in Figure 3:

1. Four specimens were heated for 60 minutes until they reached a temperature of 650°C and held within 15 minutes for pre-heating. Then, the temperature was raised for 50 minutes to 800°C and kept within 15 minutes for final heating. After that, the temperature was raised again for 50 minutes until it reached a temperature of 1060°C and holding time for 120 minutes.
2. After heating, the specimens were cooled with a nitrogen gas quench to reach a temperature of 50°C continuously for 20 minutes with a pressure of 5 Bar.
3. After the hardening process, the tempering process was immediately carried out for 180 minutes at a temperature of 570°C. The specimens were again cooled with quench gas to a temperature of 50°C for 20 minutes with a pressure of 5 Bar.
4. The tempering process was then repeated using the same procedure.

Both heat treatment procedures were carried out according to Bohler K340's recommendation [13]. With double tempering, the impact toughness or energy absorption was expected to be improved due to a predominantly bainitic microstructure [14]. Single quenching with double tempering produced the best-combined result of tensile strength, yield strength, elongation, and considerably increased toughness modulus [15]. The best mechanical properties were obtained from tempered martensite microstructure, free from rest martensite and secondary carbide.

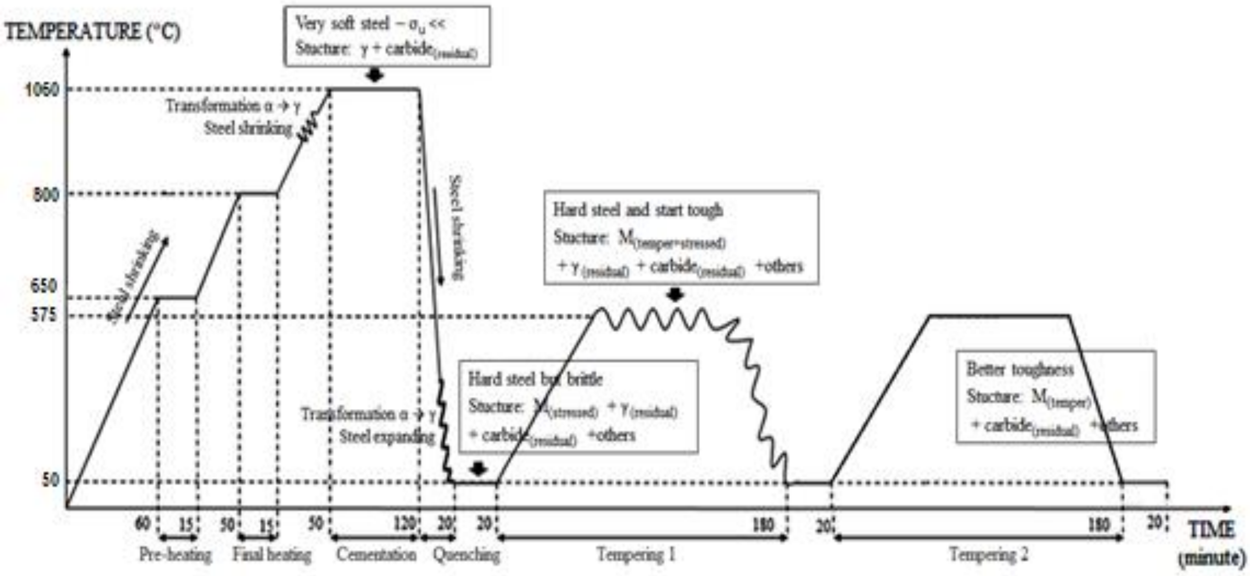


Figure 3. Heat treatment at an austenitising temperature of 1060 °C and double tempering at 575 °C.

2.3. Microstructure observation

After the heat treatment processes, the microstructures of the specimens were observed. The observation was performed using a Keyence camera with a magnification of 400 times. The steps taken in the process of observing the microstructure are:

1. After heat treatment, the dies were pounded at the bottom surface to obtain the specified size.
2. Polishing the surface of the dies (relief) using Kemet polishing media.
3. The surface of the dies was etched.

2.4. Hardness testing

The hardness test was performed on all the eight die specimens resulting from two different heat treatment procedures, using the Rockwell standard on the Buehler machine (see Figure 4). Each specimen was tested for hardness in four indentation points.

Figure 4. Buehler hardness tester, made in the USA. (The author took the photo).

2.5. Production capacity testing

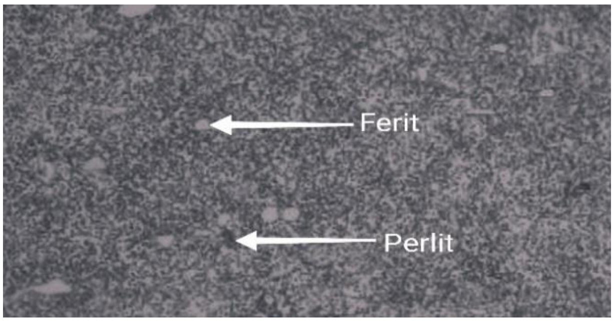
Eight dies from two heat treatment procedures were used in the production capacity testing. The test was carried out until the die was dull and could not produce good-quality coins according to the acceptance criteria set by the Quality department.

3. RESULTS AND DISCUSSION

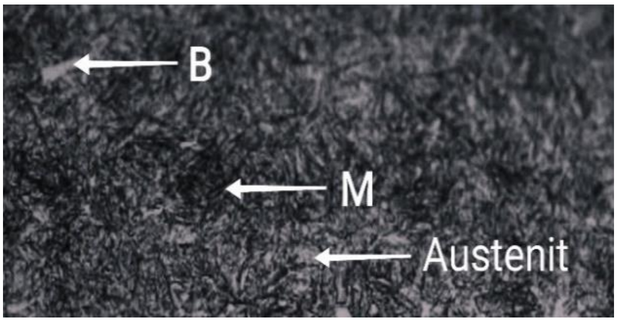
3.1. Result of microstructure observation

The observation of the microstructure aims to see the change or comparison of the microstructure after undergoing the heat treatment process with different austenitising and tempering temperatures. The magnification used in this observation was 400x using a Keyence camera. The microstructure photos were taken on die specimens, and Figure 5 shows the images from the observations.

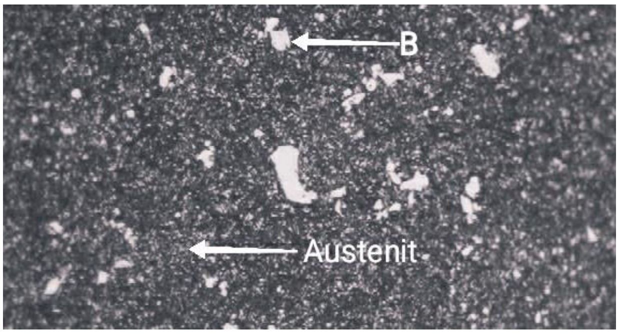
It can be seen that martensite is formed due to the existence of trapped carbon during the process of cooling rapidly from a stable austenite temperature. This trapped carbon does not get enough time to diffuse out of the austenite. This finding agrees with a previous study that stated that martensite was seen in the quenching process using nitrogen [16]. Because the tempering temperatures are 500°C and 575°C, the upper bainite is formed. The diffusion of carbon in austenite takes place at a relatively higher transformation temperature, leading to the creation of the localised carbon-depleted regions within the metastable austenite [17-20]. Moreover, dies subjected to double tempering have less bainite structure, making them more resilient and increasing their usage capacity.



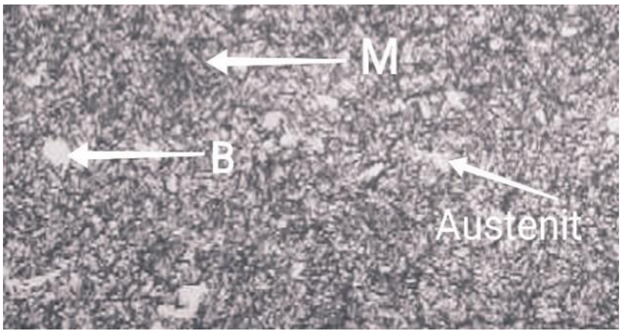
(a) Raw material



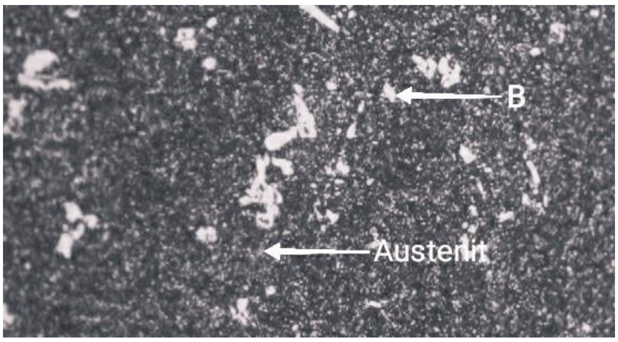
(b) Austenitising temperature 1080°C



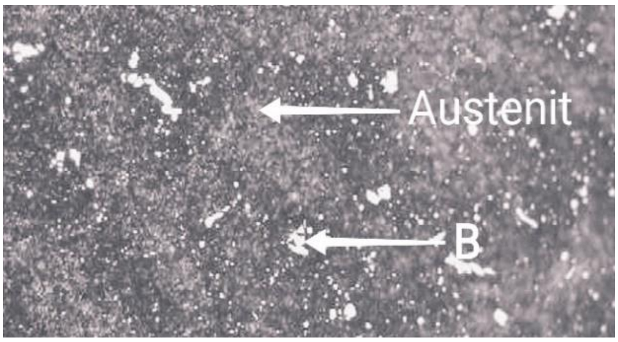
(c) Tempering temperature 500°C



(d) Austenitising temperature 1060°C



(e) Tempering 1 at a temperature of 575°C



(f) Tempering 2 at a temperature of 575°C

Figure 5. Microstructure observation at 400x magnification, where B indicates bainite and M is the martensite.

3.2. Result of hardness test

The hardness test in this study used the Rockwell standard with four indentation points on each specimen. Table 1 shows the results of hardness test data on each indentation point. From Table 1, it can be observed that:

1. At a single tempering of 500°C, the hardness of the specimen becomes high, with an average value of 61.98 HRC. It is because the microstructure of the dies specimens has more bainite, as seen in Figure 4(c).
2. At double tempering of 575°C, the hardness value is lower, with an average of 57.94 HRC. The bainite microstructure is more ignoble than single tempering (see Figure 4(f)). The main cause of the decrease in hardness during tempering bainite steel shall be attributed to the reduction in dislocation density, which agrees well compared with another study [21-24].

Table 1. Hardness test result on four indentation points.

No	Heat treatment	Dies number	Hardness (HRC)					Standard deviation
			1	2	3	4	Average	
1	Austenitising temperature 1080°C	1A	62.4	62.3	62.5	62.4	62.40	0.082
		1B	61.8	62.0	61.9	61.8	61.87	0.096
	Single tempering at 500°C	1C	61.6	61.5	61.7	61.6	61.60	0.082
		1D	62.1	62.0	61.9	62.2	62.05	0.129
			Total average				**61.98**	**0.336**
2	Austenitising temperature 1060°C	2A	57.8	57.9	58.0	57.8	57.87	0.096
		2B	58.4	58.2	58.3	58.2	58.27	0.096
	Double tempering at 575°C	2C	57.7	57.8	57.6	57.8	57.72	0.096
		2D	58.0	57.8	58.1	58.0	57.97	0.126
			Total average				**57.94**	**0.232**

Table 2. Production capacity test result.

No	Heat treatment procedures	Average hardness (HRC)	Dies number	Production capacity of dies (pcs of coin)
1	Austenitising temperature 1080°C	62.40	1A	96,000
		61.80	1B	102,000
	Single tempering at 500°C	61.60	1C	108,000
		62.05	1D	99,000
	Average	**61.98**		**101,250**
2	Austenitising temperature 1060°C	57.87	2A	172,600
		58.27	2B	166,800
	Double tempering at 575°C	57.72	2C	176,200
		57.97	2D	169,000
	Average	**57.94**		**171,150**

3.3. Result of production capacity test

In the heat treatment process, the austenitising and tempering temperatures affect the hardness of the dies. The hardness data of the dies produced and the actual coin production capacity of the dies data are compared to analyse the effect of austenitising and tempering temperatures on the production capacity of dies. A comparison of hardness testing with die capacity testing can be seen in Table 2.

In Table 2, it is found that the production capacity of dies treated with the second procedure at an austenitising temperature of 1060°C with double tempering at a temperature of 575°C for all variations is higher than the production capacity of dies treated with the first procedure at an austenitising temperature of 1080°C with single tempering at a temperature of 500°C. This is because the dies become more durable because of less bainite microstructure resulting from double tempering at 575°C.

The second procedure produces 171,150 pieces of coin, which complies with the standard set by the Quality Control department that each stamping die should produce 150,000 coins at the minimum.

4. CONCLUSION

Based on the observation and testing data results, it can be concluded that the second procedure gives production capacity that complies with the company's standard quality. The heat treatment process with an austenitising temperature of 1080°C with single tempering makes the stamping dies have a higher hardness but more brittle, and the average hardness value is 61.98 HRC. As a result, the production capacity is lower, with an average production of 101,250 coins.

The heat treatment process with an austenitising temperature of 1060°C with double tempering increases the toughness and ductility of the stamping die, and the average hardness value is 57.94 HRC. So that the production capacity is higher, reaching an average production of 171,150 coins. The bainite microstructure occurs due to the heat treatment with an austenitising temperature of 1060°C with double tempering.

CONFLICTS OF INTEREST

The author declares that there is no conflict of interest affecting this publication.

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