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Research Article

Effects of heat treatment on microstructure and hardness of D2 tools

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ABSTRACT

D2 high chromium tool steel is widely used to produce tools and components that work at significant dynamic loads, such as dies, punches and rollers. The steel must have a good combination of strength and toughness, which heat treatment can obtain. Therefore, this study discusses the effect of normalising, hardening, and tempering on the microstructure and hardness of D2 tools. Normalising and hardening were carried out respectively at 1020°C for 30 minutes, followed by rapid cooling using oil. Tempering was realised by reheating the quenched sample at 250°C and 400°C with variations in holding time of 15 minutes, 30 minutes, and 45 minutes. The hardness of the specimens was measured using a Rockwell hardness tester, whereas the microstructure was observed with an optical microscope. The results indicated that the microstructure changes to martensite and carbide after quenching, while the microstructure becomes tempered martensite and carbide after tempering. Normalising and hardening have almost no impact on hardness, and the increase in temperature and holding time causes a decrease in hardness. The reduction in hardness is noticeable for steels tempered to 400 °C and held for 45 minutes.

1. INTRODUCTION

Tool steels are categorised into six classes: cold work, hot work, shock resisting, mould, high speed, and special-purpose tool steels. The most important class is cold work tool steels [1]. Cold work tool steel consists of three classes of steel: American Iron and Steel Institutes (AISI) type O, A and D, which represent oil-hardening, air-hardening and high carbon-chromium, respectively. According to the AISI, it is classified as high-carbon steel, which contains 0.60 to 1.00% carbon. AISI D2 contains high carbon (1.5–2.35 wt.% C) and high chromium (~12 wt.% Cr) content for high hardness and high wear resistance (~12 wt.% Cr) within the cold work environment [2]. The typical applications are deep drawing and forming dies, cold drawing punches, lamination and stamping dies, master tools and gauges, thread rolling & wire dies, and extrusion dies [3-4]. D2 tool steels are widely used in industry because of their excellent wear and abrasion properties [1]. It is due to the high-volume fraction of carbides precipitating during the eutectic reaction. The wear resistance can be further improved by reducing the size and evenly distributing carbides [5].

D2 tool steels are high-quality cold working die steels with high hardenability, good wear resistance, and small quenching deformation [6-8]. The steels are air-hardening with maximum dimensional stability during heat treatment and offer high hardness and wear resistance [9-11]. The superior mechanical properties are due to its chemical composition (high carbon and alloying elements) and specific processing conditions that allow the formation of various types of strong phases (e.g. martensite and bainite) and hard second phase particles [12].

The recommended austenitising temperature for tool steel D2 is between 950°C and 1100°C [12-14] to allow higher dissolution of alloying elements in the austenite and partial carbides dissolution before quenching [15]. Phase transformation during conventional quenching of this steel has received much interest because of the high hardness (close to 63 HRC), i.e., the material's brittleness after quenching. The subsequent tempering process in the temperature range of 150–500°C reduces brittleness by transforming more austenite to martensite, relieving internal stresses, and precipitating temper carbides [16-17]. The final microstructure of these steels is composed of martensite matrix, primary carbides, and secondary carbides (formed during the tempering step) and some undesired retained austenite [18]. Based on the TTT diagram of D2 tool steel, if D2 tool steel is cooled rapidly from 980–1030°C and reaches 190°C (martensite start/MS temperature) before 100 seconds, it will produce martensite. D2 tool steel contains high chromium, so the large martensite area and rapid or moderate cooling can form martensite [19].

Conventional quenching and tempering (Q-T) are applied to steel to produce a good combination of strength and toughness of the martensitic structure [20-22]. The martensite formed by quenching is too brittle to use in a practical application, and therefore it must be tempered [15]. Temper is one of the most critical processes affecting hardness, which has twofold effects: recovery (decreasing hardness) and formation of secondary carbides (increasing hardness) [8]. As far as the tempering behaviour of D2 steel was concerned, the former effect outweighed the latter one, and the hardness of steel indicated an insignificant drop during the tempering stage. But hardness decreased rapidly at high temperatures (above 500°C) [23].

Normalising, hardening and tempering are the most important heat treatments often used to modify engineering materials' microstructure and mechanical properties, particularly steels [24-25]. D2 high chromium tool steel is widely used to produce tools and components that work at significant dynamic loads, such as dies, punches and rollers. The steel must have a good combination of strength and toughness, which heat treatment can obtain. Only a few research discussed SKD 11 or D2 tool steels. Most of these only discuss cryo-treatment [16], [18], [26-33], [34-37], and only a few discuss oil quenching. This study aims to determine the effect of normalising, oil quenching, and tempering on SKD 11 or D2 tool steels.

2. MATERIAL AND METHODS

The study used a commercial tool, steel type D2, with a diameter of 19.25 mm, in experiments. The material was made by hot rolling. The hardness of D2 steel is 15.44 HRC. The chemical composition is given in Table 1. Based on the test using a spectrometer, it was found that the carbon composition was only 0.693%; this is less than the standard, which should reach 1.4%. Meanwhile, the chromium composition is higher than the standard.

Table 1. The chemical composition of the steel used in the study and standards.

Elements	Weight %		
	Used	JIS G4404 [2]	ASTM A681 [2]
C	0.693	1.40 – 1.60	1.40 – 1.60
Si	0.18	<= 0.40	0.10 – 0.60
Mn	0.225	<= 0.60	0.10 – 0.60
P	0.592	<= 0.030	<= 0.030
S	0.15	<= 0.030	<= 0.030
Cr	11.2	11.00 – 13.00	11.00 – 13.00
Mo	0.719	0.80 – 1.20	0.70 – 1.20
V	0.15	0.20 – 0.50	0.50 – 1.10

The microstructure of the D2 tool steel is shown in Figure 1. The microstructure is made up of carbide (C) and pearlite (P). The dark area is pearlite, and the bright area is carbide. The samples in the form of 19.25 mm diameter steel cylinders and 20 *mm* height are shown in Figures 2 and 3.

Figure 4 shows the flow of the heat treatment process. Figure 5 shows the normalising process curve, and Figure 6 shows the hardening-quenching curve followed by tempering (Q-T or quenching-tempering). The heating process used a heat treatment furnace with 3-phase AC electricity, a potential difference of 400V, a frequency of 50/60Hz, and a current of 28.8A and 20kW, which results in a maximum furnace temperature of 1280°C. Normalising was performed at 1020°C for 30 minutes and then cooling using free air. Hardening was carried out at 1020°C for 30 minutes, followed by rapid cooling using iso-rapid oil, special oil for quenching. The material properties of iso-rapid oil are presented in Table 2. Tempering was carried out by reheating the quenched sample using iso-rapid oil at 250°C and 400°C with variations in holding time of 15 minutes, 30 minutes, and 45 minutes, then continued with cooling in free air.

A calliper measured the thickness of the sample with an accuracy of 0.02 *mm*. The chemical composition of the material has been tested with an emission spectrometer. Microstructures were observed with an optical microscope (Nikon X1005TTEPL) and etching material using nital with ASTM E 407-99 standard. Nital is a mixture of 5 *ml* HNO3 (nitric acid) and 100 *ml* ethanol/methanol (95%) [38]. The hardness of steel was carried out using a Rockwell hardness tester with ASTM E 18-97a standard [39].

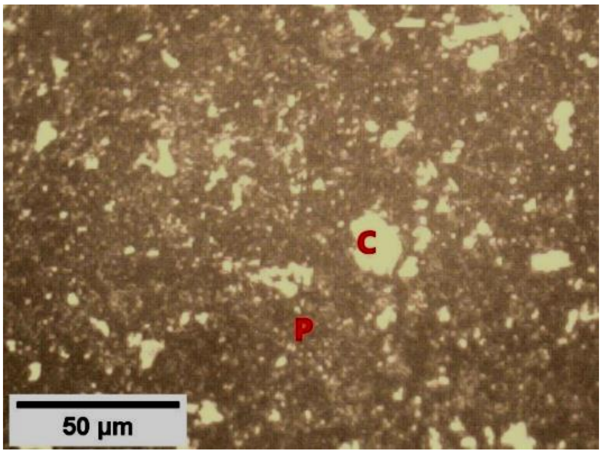


Figure 1. D2 tool steel microstructure before heat treatment (C is carbide: bright area, P is pearlite: dark area).

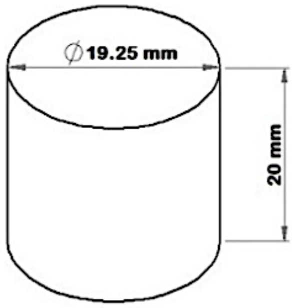


Figure 2. The size of the sample used for hardness test and microstructure observation.

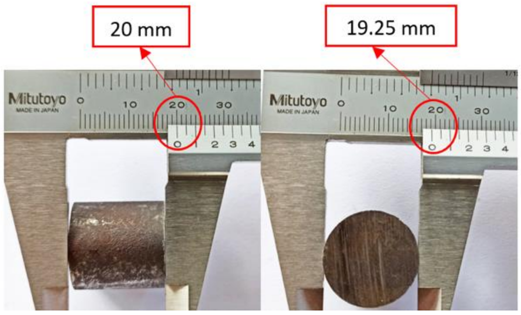


Figure 3. Sample sizing before hardening.

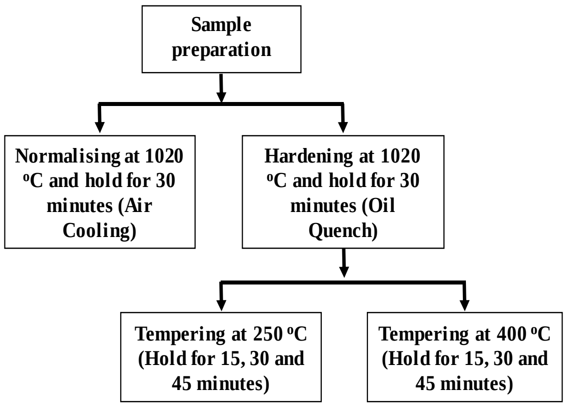


Figure 4. Heat treatment process.

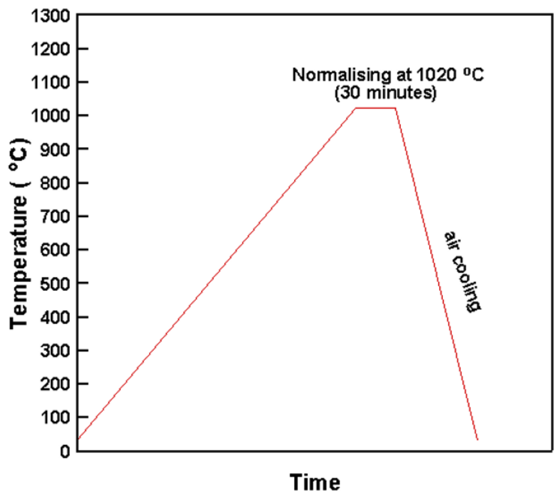
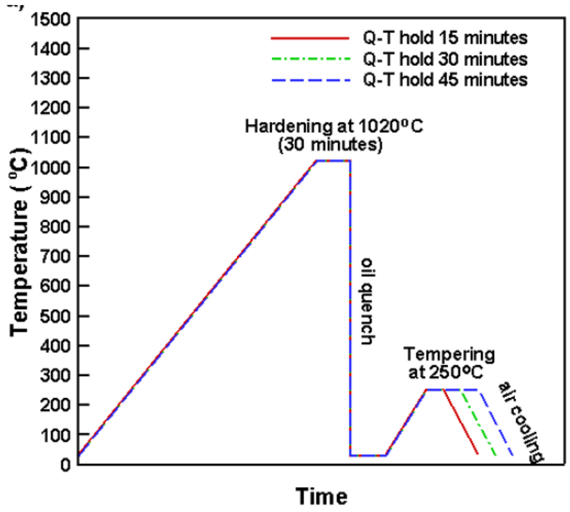
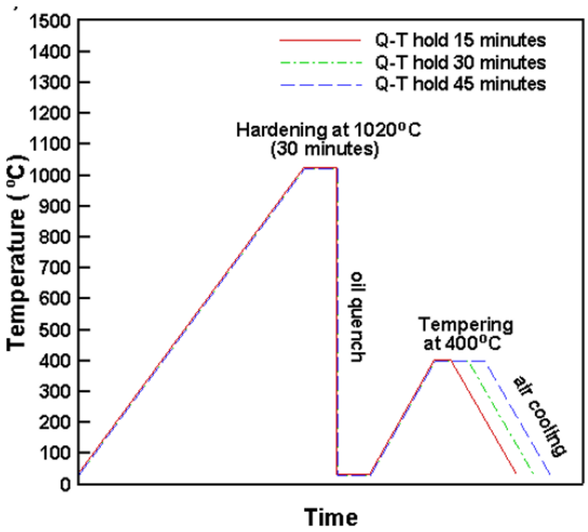


Figure 5. Normalising procedures.



(a) tempering at 250°C



(b) tempering at 400°C.

Figure 6. Hardening and tempering procedures,

Table 2. Mechanical properties of iso-rapid oil.

Properties	Amounts	SI Unit
Density at 20°C	0.868	g/cm³
Viscosity at 20°C	34.0	mm²/s (cSt)
Viscosity at 40°C	14.6	mm²/s (cSt)
Flash point	158	°C
Fire point	188	°C

3. RESULTS AND DISCUSSION

3.1. Microstructures

Microstructures of D2 tool steel after normalising and hardening quenching are shown in Figure 7. The microstructure observations showed that after normalising followed by air cooling and hardening followed by rapid cooling with iso-rapid oil, D2 tool steels had almost the same microstructure. The structures that appear are martensite and carbide, martensite in the dark area and carbide in the form of small islands in the light area. This corresponds to the D2 tool steel TTT diagram. The high chromium content in D2 tool steel causes a large martensitic area [19], so cooling with air, oil, or water will still produce a martensite phase. The as-quenched D2 sample showed the presence of martensite and carbide [2][40-41]. These carbides increase the strength of the steel at room temperature and high temperature [42].

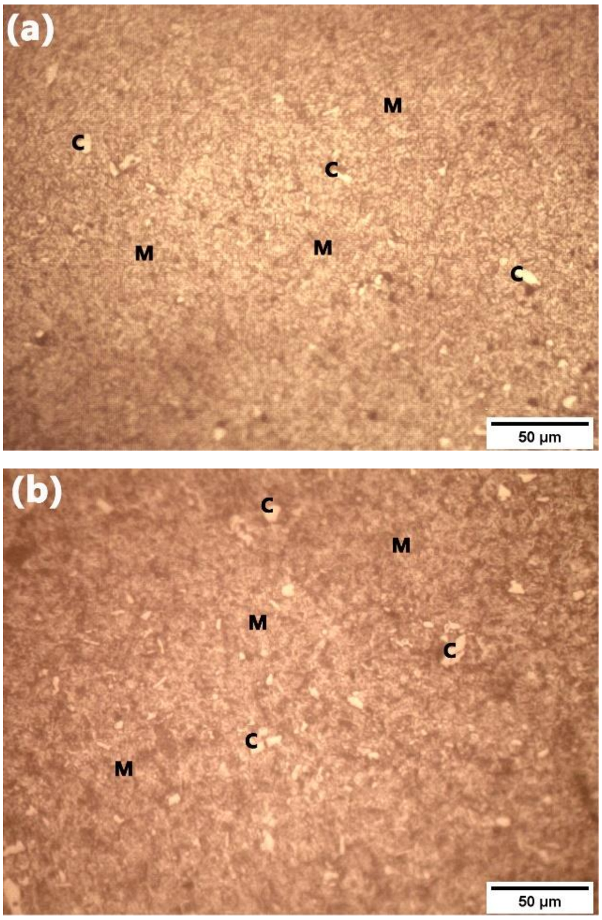


Figure 7. The SKD 11 tool steel microstructure after hardening (a) air cooling and (b) oil quench.

Microstructures of D2 tool steels after tempering are shown in Figures 8 and 9. The microstructure of tempered steels consists of carbide (C) and tempered martensite (M). This microstructure is the same as described by the previous researcher. The microstructure of D2 tool steel after tempering is a martensite matrix, primary carbides, and secondary carbides [18].

In Q-T samples, the microstructure is homogeneous at any tempering temperature, consisting of tempered martensite with the dispersion of very fine secondary carbides [8]. There was decreasing martensite and retained austenite volume fraction after the tempering process. The mentioned phases were normally transformed into bainite or ferrite phases (tempered martensite). On the other hand, the carbide percentage increased after tempering for all samples. This happened because the carbon elements are released into the matrix during the transformation of retained austenite, and some of the raw martensites reacted with carbide former, i.e., chromium, thus forming a chromium carbide [43].

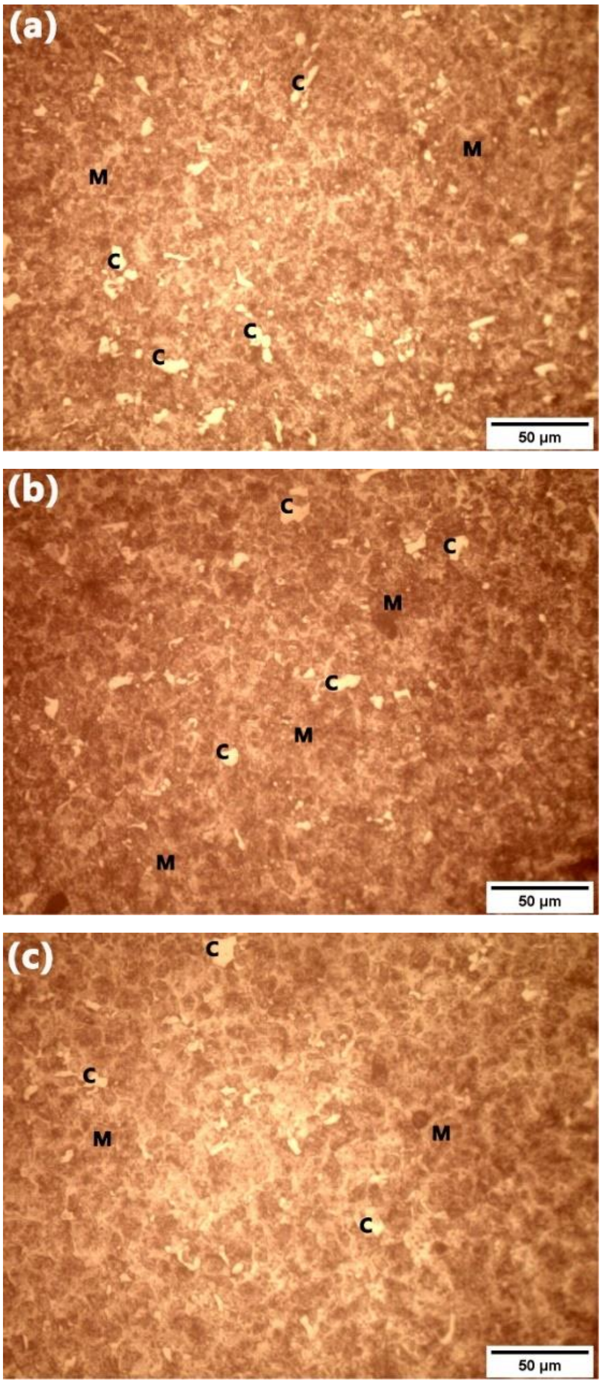


Figure 8. Microstructure of SKD 11 tool steel after tempering at 250°C, variations in holding time (a) 15, (b) 30, and (c) 45 minutes.

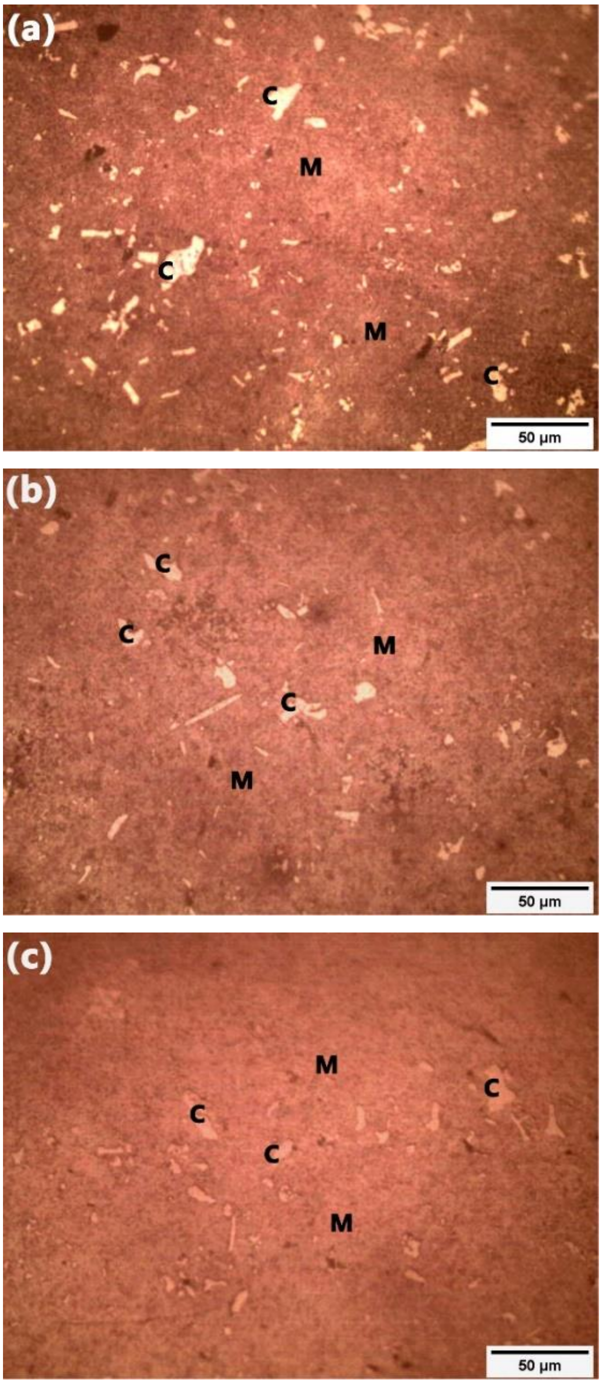


Figure 9. Microstructure of SKD 11 tool steel after tempering at 400°C, variations in holding time (a) 15, (b) 30, and (c) 45 minutes.

3.2. Hardness

The comparison chart of the hardness value of the D2 tool steel after normalising and hardening-quenching is shown in Table 3. The hardness of the iso-rapid oil quenched sample was higher than the air-cooled (normalising) sample. The hardness of the air-cooled sample increased up to 299.05 %, from 15.44 to 61.61 HRC.

Meanwhile, the hardness of the sample quenched with iso-rapid oil increased by 318.17%; from 15.44 HRC, it rose to 64.57 HRC. Other researchers have reported a similar increase in hardness. Conventional quenching of D2 tool steel produces a high hardness of up to 63 HRC [16-17] and oil-quenched samples which a hardness value was 822 HV (65 HRC) [43]. The hardness value shows that the steel's cooling speed is faster when quenched with iso-rapid oil than cooled with free air. This is the same as what was done by previous researchers, that the faster cooling rate resulted in higher hardness [44].

The difference in hardness after cooling and normalisation is only 3.27 HRC. This is related to almost the same microstructure. According to the TTT diagram of D2 tool steel, the high chromium content in D2 tool steel causes a large martensite area [19], so cooling with air, oil, or water will still produce the martensite phase. In general, the martensitic structure's content will affect a product's mechanical properties because the martensitic structure has hard, strong, and brittle properties [20-22].

Table 4 shows the results of the hardness test of D2 tool steel after tempering. The hardness of steel after being tempered at 250°C and held for 15 minutes decreased by 9.36%, from 64.57 HRC to 58.52 HRC. Those held for 30 minutes decreased by 13.02% to 56.16 HRC, and those held for 45 minutes decreased by 13.96% to 55.55 HRC.

The hardness of steel after being tempered at 400°C and held for 15 minutes decreased by 11.06%, from 64.57 HRC to 57.43 HRC. Those held for 30 minutes decreased by 17.15% to 53.50 HRC, and those held for 45 minutes decreased by 17.34% to 53.37 HRC. These results indicate that the hardness decreases with increasing holding time. This is the same as previously stated by researchers on AISI M42 high-speed steel and AISI 4340: the hardness decreased as the tempering temperature [42-45] and the holding time increased. The decrease in hardness is primarily due to the coarsening and coalescence of carbides and an excess decomposition of the martensitic matrix [45].

Table 3. Hardness after normalising and hardening-quenching.

Heat treatments	Cooling Medium	Hardness (HRC)	Deviation	% increase in hardness
Non-heat treatment	-	15.44	0.32	-
Normalising	Air	61.61	0.13	299.05
Hardening-quenching	Oil	64.57	0.33	318.17

Table 4. The hardness of D2 tool steel after tempering.

Heat treatments	Hardness (HRC)	Deviation	% decrease in hardness
Hardening-quenching	64.57	0.33	-
Tempering at 250°C			
Hold 15 minutes	58.52	0.29	9.36
Hold 30 minutes	56.16	0.12	13.02
Hold 45 minutes	55.55	0.22	13.96
Tempering at 400°C			
Hold 15 minutes	57.43	0.22	11.06
Hold 30 minutes	53.50	0.28	17.15
Hold 45 minutes	53.37	0.26	17.34

4. CONCLUSION

The effects of heat treatment on microstructure and the hardness of D2 tools have been studied experimentally. D2 tool steel was normalised at 1020°C for 30 minutes, followed by cooling in air, hardened at 1020°C for 30 minutes, followed by cooling in iso-rapid oil and tempered at 250°C and 400°C with various holding times of 15, 30, and 45 minutes. Based on the hardness test and observations of the microstructure, it can be concluded that the microstructure is of pearlite and carbide before heat treatment. After the tempering process, it changes to martensite and carbide. The hardness after oil quenching (hardening) is higher than after air cooling (normalising). The hardness of the air-cooled sample increases up to 299.05 %, from 15.44 to 61.61 HRC.

Meanwhile, the hardness of the sample quenched with iso-rapid oil increases from 15.44 HRC to 64.57 HRC. The hardness after tempering decreases with increasing tempered temperature and holding time. The highest reduction in hardness after tempering occurred in steel tempered at 400°C and held for 45 minutes, from 64.57 HRC to 53.37 HRC.

CONFLICTS OF INTEREST

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

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