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Heat Treatment to Improve the Torsional Properties of Hand-Tool Steels

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Since 2021, Taiwan has been the third-largest exporter of hand tools in the world. Among those, torque-offering tools like sockets, wrenches, and screwdrivers are the largest export items. Therefore, the torsional properties of these tools are critical. In the current research, heat treatment techniques to improve the torsional performances of hand-tool steels including torsional strength and torsional fatigue resistance were systematically studied. For general quench and temper (Q & T) treatment, with the microstructure of mainly tempered-martensite, the torsional strength would be highest after quenching, and gradually lowered during tempering, which was relative to the trend of hardness and tensile strength. In contrast, the elongation increased during tempering, as the torsional fatigue resistances improved as well. Furthermore, carbon potential (CP) control was found effective in improving the torsional strength of steel, while the torsional fatigue resistance could be significantly enhanced by the compression residual stress treatment. The strengthening mechanisms were related to further optimization of the surface state, which noticeably postponed the progress of shear failure. As a result, the current work provides the heat treatment guide for balance upgrade of torsional properties of hand-tool steels, contributing to the manufacture of products with better quality and cost savings.

Keywords: Hand-Tool, Heat Treatment, Torsional Properties, Carbon Potential, Residual Stress

1. INTRODUCTION

Hand tools are essential for day-to-day jobs. They are of different types and can be used for many kinds of work, such as torque offering, striking and cutting, etc. In other words, they are the backbone of manufacturing. Common hand tools include sockets, wrenches, screwdrivers, pliers, hammers, etc. Since most of the materials used in hand tools contain steel, the process of producing hand tools often involves high-precision machinery to create product parts, and then heat treatment on steel to meet the designed properties. Finally, once the various parts of the tool have been manufactured, they were well-calibrated, and then tested for the job requirements and standards.

Taiwan has been the third-largest exporter of hand tools in the world since 2021. The total export value of hand tools from Taiwan nearly reached 140 billion Taiwan dollars annually, indicating that the domestic industry has played a leading role in manufacturing tools and hardware around the world. Nevertheless, owing to high competition among international business markets, local manufacturers still worked hard to produce better quality tools. Among these, sockets, wrenches, and screwdrivers are the largest export items. Given these products, torsional actions are often involved, so the torsional properties including torsional strength and torsional fatigue performances can be critical for product quality.

While the hand-tool industry has long been a solid customer of China Steel Corporation (CSC), a comprehensive understanding of the heat treatment properties of steel should be taken into consideration for improving the torsional properties of hand-tools. Jang et al. analyzed the torque strength of four carbon steels applied to a screwdriver bit(1). McClaflin et al. investigated the torsional behavior of SAE 9254 with 0.57% Carbon(2). However, studies about the torsional behaviors of carbon steels were still very limited, and the effects of heat treatment were lacking in systematic organization. As a result, in the current research, the relationships among hand-tool steels, heat treatments, and mechanical properties will be extensively studied and summarized.

The widely used hand-tool steel SAE 4140 was applied to general quench and temper (Q & T) heat treatments. The corresponding mechanical properties including hardness, tensile behaviors, torsional strength, and torsional fatigue resistances were analyzed. In addition, the control of carbon potential (CP) and residual stress state on torsional performances were further investigated. A comprehensive, systematic guide on heat treatments for hand-tool manufacturing was developed.

2. EXPERIMENTAL METHOD

2.1 Materials

SAE 4140 is widely applied in hand tools like sockets and wrenches due to good strength with adequate toughness. The as-rolled φ14 mm wire steel SAE 4140 was produced by CSC. The main concentrations are shown in Table 1[3]. The C content is near 0.4%, and Cr and Mo are added for solid-solution strengthening.

2.2 Q & T Heat Treatment

For common quench & temper (Q & T) heat treatments, the austenitizing temperature was evaluated by JMatPro software[4]. Meanwhile, the continuous-cooling-transformation (CCT) diagram was calculated using bringing the compositions and grain size of material into JMatPro (General steel database). In general, it is suggested that the optimum austenitizing temperature should be at Ac_3 + 30~50°C[5]. Consequently, based on the simulated CCT diagrams, the austenitic condition for SAE 4140 was set at 840°C with 1 hour holding, and followed by oil quenching. As for temper, to cover practical applications, the temperatures were set from 200 to 500°C, with 1.5 hours of holding. To simplify the description of heat treatment conditions, the following paragraph uses as-Q for quench samples, and as-Q & T for quench & temper. The number after T- is the tempered temperature.

2.3 CP Control Process

In addition, a gas carburizing process was applied during Q & T heat treatments. The samples went through austenitization heating while carbon potential (CP) was controlled. In general, the CP would be close to the carbon content of steel for surface protection against oxidation. Hence, in the current study, a general 0.4% CP, and a high 0.8% CP were applied for comparison.

2.4 Residual Stress State Control Process

For surface residual stress control, smooth torsional test specimens were further shot-peened after Q & T treatment. The shot-peening was conducted under a pneumatic machine. Cast steel shot with a diameter of 0.5 mm was used. Since the Almen intensity test can be a common process control variable in peening applications, which represents the combined effect of all parameters, the shot peening intensity f_A was analyzed[6]. The arc height measured with the standard A-type Almen strip was 0.5 mm.

2.5 Mechanical Tests

The mechanical tests include hardness, tensile, torsional strength, and torsional fatigue tests. The hardness test was referred to as the Vickers hardness test standard [7]. The indenter load was 300 g, and every test load was maintained for 10 seconds at each point. Each hardness result was the average value from at least five points. The tensile tests were also referred to as the ASTM standard[8]. The samples were typical round bar types with a 6 mm diameter of the parallel zone, and the tensile strength (UTS) and elongation (EL) during tensile were recorded.

As for torsional tests, samples were similar to tensile test ones. During the torsional strength test, the torque load on each sample gradually increased from 0 to rupture, and the maximum value during tests was recorded. For torsional fatigue tests, the 60~80% maximum torque load for each sample was set. The torsional load would repeatedly be 0 to the set torque (R=0), and the total cycles till ruptured were recorded. Each torsional strength and cycle value were the average of three tests.

2.6 Metallographic Analyses

The heat-treated and mechanical-tested samples would carry out the standard metallographic procedures. An optical microscope (OM, Olympus DSX-CB) and scanning electron microscope (SEM, Zeiss Sigma 300 VP) were used to analyze the microstructure and fracture surface characteristics of samples.

As for residual stress measurements, a portable μ-X360S device produced by Pulstec Industrial Co., Ltd was used. The stress analyzer was based on the cosα method[9], and the diameter of the X-ray beam was regulated by the collimator with 1.0 mm.

3. RESULTS AND DISCUSSION

3.1 Q & T Heat Treatment Properties

Figure 1 shows the microstructures of SAE 4140 after Q & T. From Fig.1(a), after 840°C / 1h oil quench, a typical martensitic phase with acicular morphology formed. Then, followed by temper at 300°C, Fig.1(b), and at 500°C, Fig.1(c), through the excess carbon in solid solution segregation to a matrix, less sharp tempered martensite distributed throughout the matrix, indicating that the samples were properly heat treated.

The results of torsional strength are shown in Figure 3. The as-quenched sample also exhibited the highest

Table 1 The main concentrations of SAE 4140 (unit: wt%)

Fe	C	Si	Mn	Cr	Mo
Bal.	0.41	0.24	0.75	1.04	0.16

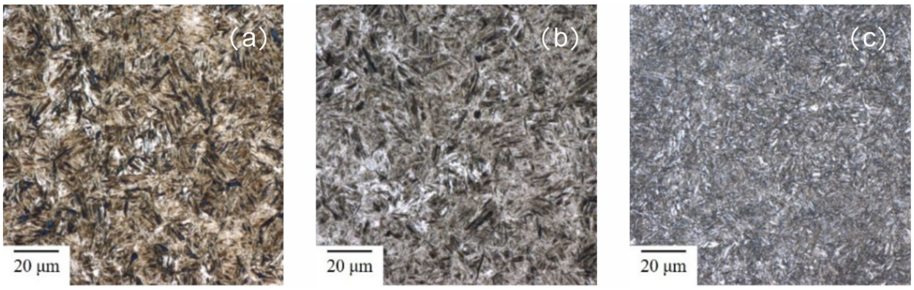

Fig.1. The (a) as-Q (quenched), (b) as Q & T-300, (c) as Q & T-500 microstructures of SAE 4140.

torque strength and gradually decreased with greater temper, which was highly correlated with the trend of hardness and UTS.

Figure 2 shows the hardness, tensile strength (UTS), and elongation (EL) of SAE 4140 after Q & T. The as-quenched sample exhibited the highest hardness and UTS owing to the strengthening from the martensitic structure and decreased along greater temper. By contrast, the increase of elongation from temper could be obvious.

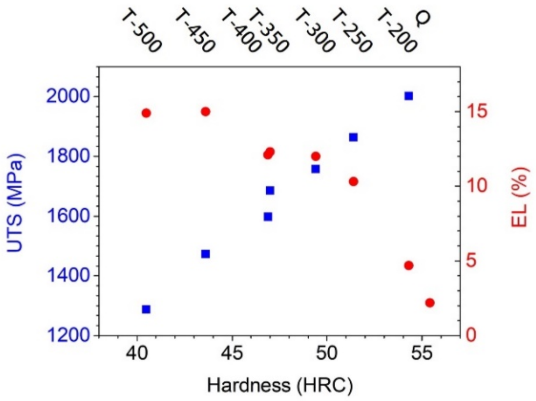

Fig.2. The hardness, UTS, and EL of SAE 4140 after Q & T.

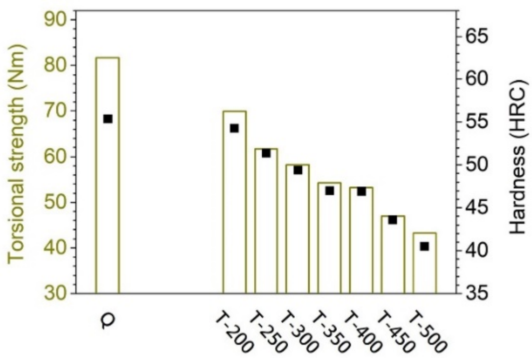

Fig.3. The torsional strength and hardness of SAE 4140 after Q &T.

For the torsional fatigue resistances, cyclic loads were set from 0 to 70% maximum torque of each sample, and the results are shown in Figure 4. It was noted that with the increase of tempering temperature, the fatigue cycles were significantly prolonged, as the trend of EL, demonstrates a positive correlation between torsional fatigue resistance and the ductility of steel.

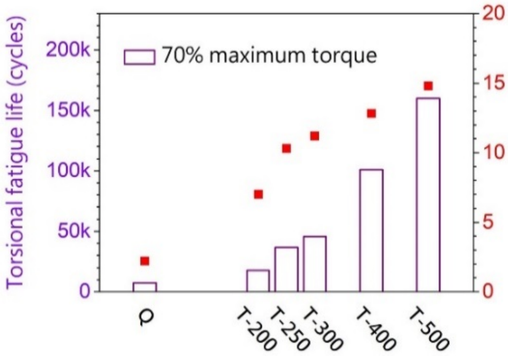

Fig.4. The torsional fatigue cycles of SAE 4140 after Q & T.

Figure 5 shows the cross-section of the torsional fractured surface. From Fig.5(a), the surface of the outer area was relatively smooth with a clear trace of torsion flow. Towards the inner, Fig.5(b), there was a radiating junction area, which presented the narrow tearing dimple characteristics. As for Fig.5(c), within the center region, the fractured morphology was like a honeycomb, where the dimple structure tended to be equiaxed. Through the above-fractured characteristics, the deformation mechanism could be deduced. Once the outer area bearded the largest shear stress during torsion, the crack may initiate from the surface. While the equiaxed dimples within the center region indicated that the rupture occurred at the final step. That is to say, when the outer surface started to break, the center was still connected. Therefore, the torque would cause the broken top and bottom surfaces to rub against each other, leading to a smooth morphology with serious torsional trace on the near-surface region. In addition, due to significant shear deformation from the outer area, the dimple morphology in the junction area was elongated as tearing dimple morphology.

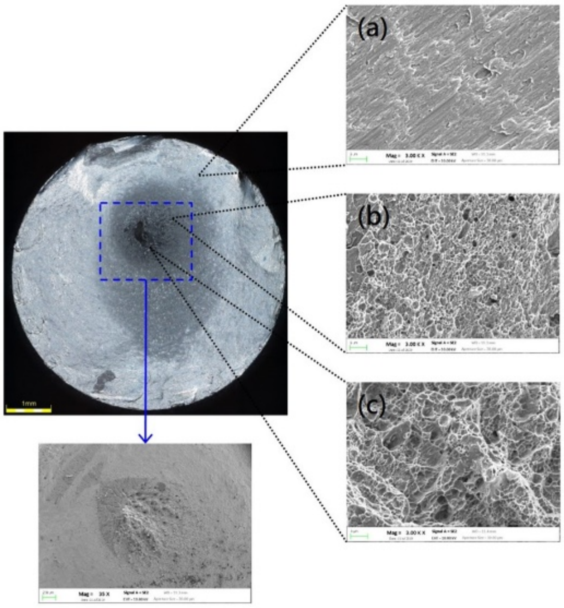

Fig.5. The fracture surface analyses after torsion test: (a) outer area, (b) junction area, (c) center area.

To sum up, the torsional strength tended to correlate with the hardness and tensile strength, as the torsional fatigue resistance related to the ductility of steel. Consequently, more balanced torsional properties of hand-tool steels could be achieved by accurate Q & T heat treatment designs.

3.2 The Effect of CP Control

For further upgrade of torsional properties of hand-tool steels, the effect of CP control was studied. Figure 6 shows the near-surface cross-section images of SAE 4140 (as-Q & T-200 samples) under 0.4% and 0.8% CP. From Fig.6(a), with a general 0.4% CP close to the Carbon content of steel, nearly no oxidation would occur on the surface. As for 0.8% CP, Fig.6(b), except for oxidation, a carburized layer formed from the surface. According to reference[10], through exposure to a high carbon potential atmosphere at temperatures within the austenitic phase field, the steel surface may proceed with the carburizing reaction as follows:

$$2CO + \gamma\text{-Fe} \rightarrow [\gamma \cdot \text{Fe-C}] + CO_2$$

$[\gamma \cdot \text{Fe-C}]$ indicates the austenite γ-Fe solute with activated carbon. Therefore, under a high 0.8% CP, carburization proceeded during heat treatment.

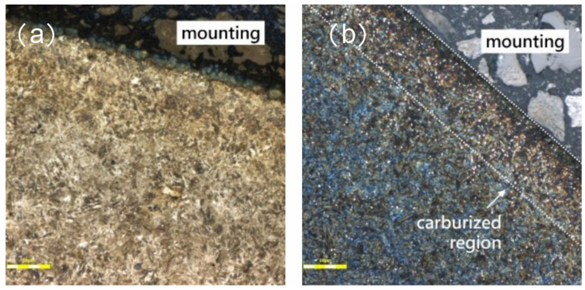

Fig.6. The near-surface cross-section image of (a) 0.4% and (b) 0.8% CP samples.

The 0.4 and 0.8% CP samples hardness distribution near the surface are shown in Figure 7. The load of the Hv indenter was changed to 20g to minimize the indentation area, and the gap between test points was 200 μm. It was seen that 0.4% CP sample remained stable with a hardness near 590 Hv from the outer surface towards the inner. By contrast, the near-surface hardness of 0.8% CP sample reached 820 Hv, demonstrating a significant surface hardening effect. The mechanism was due to the high carbon content layer formed by high carbon martensite during quench, which led to greater hardening at the outer area. As the depth increased to more than 200 μm, the hardness of the 0.8% CP sample returned to a similar level as 0.4% CP.

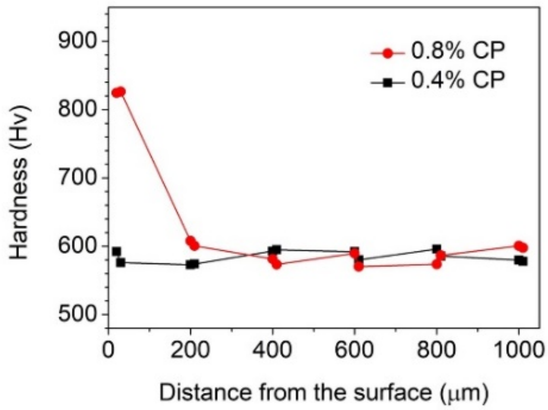

Fig.7. The hardness distribution of 0.4% and 0.8% CP samples.

The torsional strength of 0.4 and 0.8% CP samples are shown in Figure 8. It was clear that with surface carburization, the maximum torque of 0.8% CP sample further improved. Hence, heat treatment of a high CP control technique was developed for strengthening the torsional strength of hand-tool steels.

3.3 The Effect of Residual Stress Control

In the current work, the heat treatment technique for strengthening the torsional fatigue property of hand-tool steels was also studied. According to references, the benefits of compressive treatment were noteworthy. The surface plastic deformation such as shot-peening to produce compression residual stress could be a very useful way to enhance the axial fatigue strength of components(11-13). Therefore, the effects of residual stress control on torsional fatigue resistance were analyzed. Figure 9 shows the surface residual stress of SAE 4140 after Q & T treatments, and then further shot-peened. It was obvious that Q & T samples tended to show tensional residual stress. In contrast, after further shot-peened, compression residual stress would be introduced.

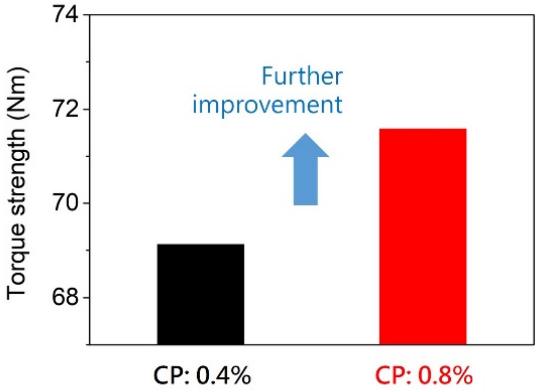

Fig.8. The torsional strength of 0.4% and 0.8% CP samples.

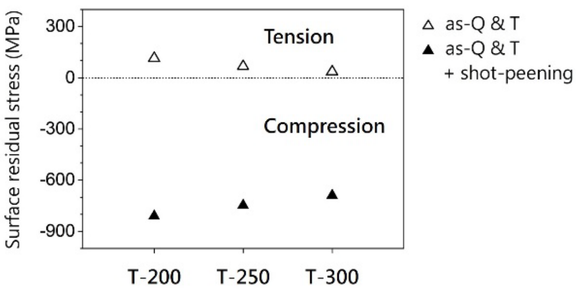

Fig.9. The surface residual stress of SAE 4140 after Q & T, and then shot-peened.

Figure 10 analyzed the depth of compression residual stress after shot-peened using the electrolytic etching method. The compression stress may sustain to 140 μm, demonstrating that the near-surface area was covered with a compressive stress field.

The torsional strength results are shown in Figure 11. It was noted that after being shot-peened, the torsional strength seemed close to those of as-Q & T. It indicated that the change of residual stress state on the surface may not affect the torsional strength of bulk material much. Nevertheless, significant improvement was found as regards torsional fatigue resistance. Figure 12 shows the torsional fatigue cycles under 70% maximum torque of each sample. With further shot-peening, the torsional fatigue life multiplied.

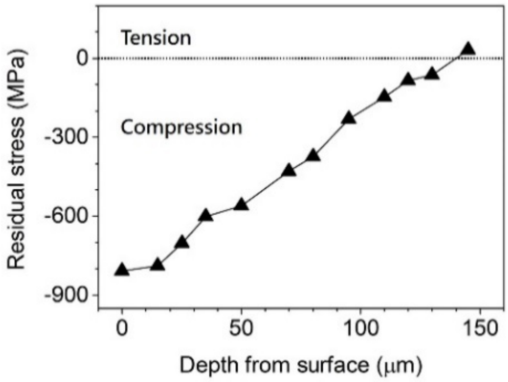

Fig.10. The depth of residual stress field of SAE 4140 after Q & T-200 + Shot-peened.

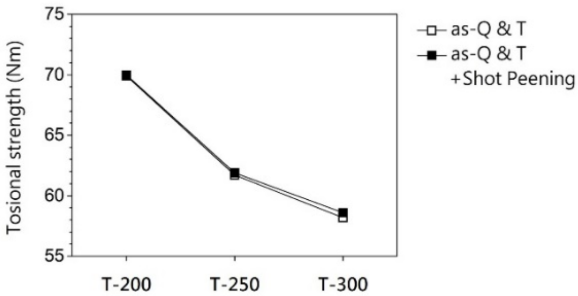

Fig.11. The torsional strength of SAE 4140 after Q & T, and then shot-peened.

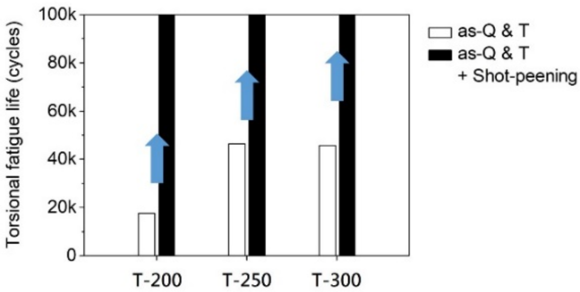

Fig.12. The torsional fatigue life of SAE 4140 after Q & T, and then shot-peened

Since the fatigue performances were commonly characterized by a stress vs. cycles (S-N) plot, the torque of each sample was calculated into shear stress by the typical shear stress conversion formula of a cylinder object[14]. The torsional fatigue S-N curves are summarized in Figure 13. First, it again proved that with greater temper to enhance the ductility of steel, longer torsional cycles would present, demonstrating better resistance against torsional fatigue failure. Also, with a shot-peened compressive residual stress field, SAE 4140 could withstand a given number of fatigue cycles without breaking under higher stress. The strengthening mechanism referred to as the compression surface state may result in higher fatigue strength, negating the fatigue crack initiation.

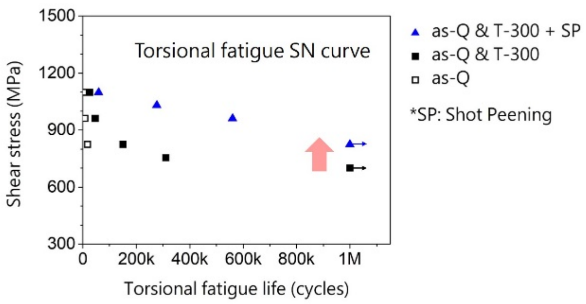

Fig.13. The torsional fatigue S-N curves of SAE 4140 after Q & T, and then shot-peened.

In summary, heat treatments should be the key to optimizing the torsional properties of hand-tool steels. Through proper quenching, the torsional strength could be high, as the following temper gradually enhanced the torsional fatigue resistance. Therefore, with accurate Q & T design, more balance upgrades of torsional properties would be achieved. Also, high CP control was effective in improving the torsional strength of hand-tool steel. The mechanism was related to the surface hardening from carburization, which could hinder the progress of shear failure. Furthermore, compressive residual stress control significantly strengthened the torsional fatigue resistance of steel. It was due to a much stronger fatigue limit, impeding the fatigue crack initiation. As a result, the current study provides heat treatment guides to improve the torsional properties of hand-tool steels, which may contribute to the manufacturing of domestic hand-tool products for better quality and cost savings.

4. CONCLUSIONS

Heat treatments to improve the torsional properties of hand-tool steel were studied. After proper Q & T, with mainly tempered martensite, the hardness, tensile strength, and torsional strength were all highest after quenching, and then lowered during tempering. In contrast, the elongation gradually increased, as well as the trend of torsional fatigue resistance. In addition, with the CP control technique, the torsional strength of steel can be further upgraded owing to surface hardening from carburization. Besides, the effect of compression residual stress control for strengthening the torsional fatigue resistances was confirmed. Consequently, a balanced upgrade of the torsional properties of hand-tool steels could be achieved by the optimization of heat treatments.

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