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A Performance Evaluation of Heat-Treated Tool Steels – A Review

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Abstract

Tools or machine components undergo extensive damage due to abrasive wear. The contact between the working surface and hard particles that are mostly mineral particles initiates this action. Applying abrasion-proof materials or developing robust, protective and damage proof coatings on component surface is the means for extending their lifetime. The selection of the tool plays a major influence on productivity. One of the emerging tool materials is tool steel which is employed in a broad variety of applications. Alloying methods that create carbides, such as chromium, vanadium, molybdenum, and tungsten, are used to make tool steels. The impact of heat treatment techniques on different tool steels and also the cryogenic process is studied. Understanding how various tool steels behave under various heat treatment conditions is the main goal of the current study, which further looked at how heat treatment affects the microstructure of various tool sheets of steel, the influence of heat treatment on metallurgical properties and surface topography are also discussed here.

Keywords: *Cryogenic Treatment, Heat Treatment Processes, Tool Steel, Wear Resistance.*

1.0 Introduction

The term “tool steel” belong to a variety of carbon and alloy steels that are used in the production of cutting tools. They are ideal because of their unique hardness, resistance to abrasion, capacity retain sharpness of cutting edge, and/or aversion to deformation at elevated temperatures. Usually, heat-treated, carbonized tool steel is used for this purpose. Tool steels, after heat treatment, demonstrate exceptional resilience, and wear resistance. Tool steels are formed under regulated conditions to obtain the desirable quality, with a composition ranging from 0.7% to 1.5%. Low manganese concentration is frequently maintained to reduce the chance of cracking after water quenching. However, for sufficient performance, these steels must undergo suitable heat treatment, and several providers offer tooling blanks for oil quenching[1,2].

In last few years, there has been greater interest in studies on cryogenic treatment, which focuses on its impact on tool steels. Cold treatment, which takes place at around -80°C, and deep cryogenic treatment, which takes place around -196°C with liquid nitrogen, are two common techniques for low-temperature machining operation. Cryogenically treating finished steel items like drills, cutters, and other tools in recent years has seen a larger interest in small enterprises, with claims of considerable increases in wear resistance[3-5]. The majority of specialists believe that greater wear resistance is a result

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of cryogenic treatment, which fosters the development of martensite from residual austenite.

Heat treatment is carried out to alter a metal's physical and mechanical properties without changing its original form. Heat treatment procedure has been found to enhance subsequent machining, improving formability, or retaining ductility after a cold working operation. Heat treatment is generally carried out to raise the strength of the material. Because of this, it is a very enabling technique that may aid another manufacturing process and enhance product reliability by enhancing strength and other beneficial properties[1]. "Heat treatment" refers to the process of heating a metal or its alloy to a pre-decided temperature, soaking them there for different periods of time, and then allowing them to cool at certain ranges. The type and arrangement of the internal constituents which govern the properties of an alloy are function of regulated heating and quenching process. Therefore, the essential function of heat treatment should be to modify a metal's or alloy's qualities by changing the structure of the alloy. The following are the functions of the various heat treatment procedures[2]:

- To eliminate or alleviate strains or stresses brought on by non-uniform cooling of hot metal (such as welding) or cold working (drawing, bending, etc.) of metal: Annealing
- Hardening: Increasing a material's strength or hardness to make it more resistant to wear.
- Annealing increases machinability
- Annealing is used to soften the material.
- To enhance ductility and toughness while reducing hardness to resist high impact (Tempering)
- To enhance the ability of tools to cut.
- To alter or modify a material's physical characteristics, such as its electrical or magnetic qualities.
- Qualities like heat and corrosion resistance.
- Elimination of the brittleness-causing H_2 gas that is dissolved during pickling or electroplating[2] as shown in Table 1.

2.0 Literature Survey on Different Tool Steels

A Bahrami *et al.*,[4] carried out studies regarding the impact of conventional heat treatment procedure on the wear resistance behaviour of AISI H13 grade tool steel. The frictional behavior of AISI H13 tool steel and the depth of the strain-hardened region under wear impressions were assessed. Pin-on-disc system at two loads were used. SEM and X-ray techniques were employed to analyse wear tracks and debris. Martensitic structure delivered the maximum wear resistance at a load of 29.4N. The specimens that were tempered for 30 to 60 minutes had the maximum wear resistance when subjected to greater load value of 98 N. An increase in friction resulted in the surface tempering phenomenon[4].

S.Z. Qamar *et al.*,[5] studied the results of heat treatment techniques on the important mechanical properties of H11 tool steel (Hot worked) in which Precision milling and EDM were used to create test specimens for tensile and impact. These samples had been exposed to various heat treatment patterns including annealing, quenching, and tempering at varied temperatures. Later, the hardness was assessed mechanically. Following observations were recorded: (a) hardness reaches a peak value and then decreases; (b) toughness reduces to its lowest and later ascends; (c) yield strength declines in value, later rises, and (d) ultimate tensile strength initially surges to a peak and later drops; and (e) ductility drops until 600°C [5]. Figure 1 shows the TEM micrographs of M2 tool steel after non-cryogenic treatment and treatment and tempering.

Table 1: Alloying elements for obtaining various tool steel properties[3]

Characteristic	Elements(a)
Hot hardness	W, Mo, Co (with W or Mo), V, Cr, Mn
Wear resistance	V, W, Mo, Cr, Mn
Deep hardening	Mn, Mo, Cr, Si, Ni, V(b)
Minimum distortion	Mo (with Cr), Cr, Mn
Toughening by grain refinement	V, W, Mo, Mn, Cr

(a) Elements are arranged roughly in order of decreasing potency when added in usual amounts for the characteristic desired. (b) Provides deep hardening if austenitized at high enough temperature to dissolve vanadium carbide.

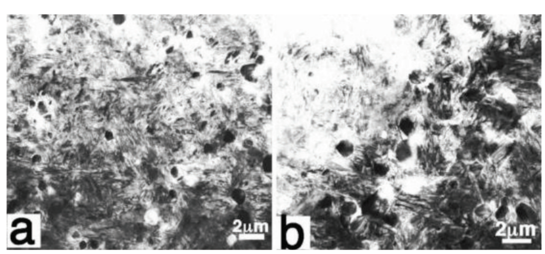

Figure 1: TEM micrographs of M2 tool steel after non-cryogenic treatment and tempering. It is observed that carbides in **(a)** are small, while those in **(b)** are large.

J.Y. Huang *et al*.,[6] scrutinized the inherent structure of cryogenically handled M2 tool steel in which it was heated at austenitizing temperature of 1000°C for 1 hour in a nitrogen environment at 20 Pa before quenching in cold nitrogen gas. The samples had to undergo a one-week cryogenic exposure, and microstructural patterns of M2 variant prior and post the cryogenic treatment were assessed. It was elucidated that cryogenic treatment can promote carbon concentration and raise the carbide density, enhancing the wear resistance. Figure 2 shows TEM micrographs of M2 tool steel post cryogenic treatment.

The results of this study indicate that in addition to promoting carbide production and increasing the volume percentage and population of carbides in the martensite base, cryogenic treatment may uniformize the carbide distribution.

B. Podgornik *et al*.,[7] studied the performance of cold worked tool steel (A1, A2) and HSS (B1). The toughness, hardness, wear-resistance, and weight-bearing capacity were studied and the microstructure analysis after cryogenic treatment was done. Figure 3 shows the microstructure observation of A1 cold work tool steel after heat treatments.

The results in this study showed that high-speed steel's cold work characteristics can be increased by up to 70%. After severe cryogenic treatment, the characteristics of cold work tool steels with high carbon and vanadium contents might even decline. Jun Seok Park *et al*.,[8] carried out experimentation on the direct metal tooling technique. Changes in the steel lined of the coated tool steels post heat treatment were studied. Figure 4 shows the schematic of Deposited Metal Treatment (DMT) apparatus and test sample and also Figure 5 shows microstructural observations of substrate, deposited metal and the heat-treated deposited metal in H13 steel.

Results show that the hardness of the coated variant D2 was secondary to that of the worked D2, and that of the coated H13 steel was significant compared to wrought H13 steel substrate. Also, fine carbides in tempered martensite formed the internal structure of the coated D2 steel post heat treatment. Figure 6 shows the microstructures of substrate, deposited metal and heat-treated deposited metal in D2 steel.

M. M. Dhobe *et al*.,[9] carried out extensive trials on Surface Characteristics of Heat-Treated Tool Steel after Wire EDM (Cold Work Steel), and reflected upon the alteration in metallurgical characteristics and surface terrain brought on by the solution treatment of AISI D2 tool steel. An X-ray diffractometer and scanning electron microscope were used for surface characterization. Additionally, tests for hardness and surface roughness were conducted. Annealing, hardening, and tempering are carried on the workpiece material, and the results obtained by the investigation show that in comparison

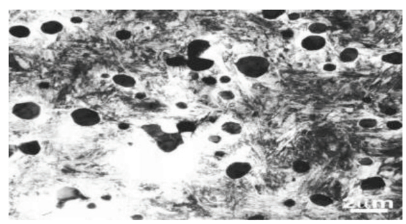

Figure 2: TEM micrographs of M2 tool steel post cryogenic treatment.

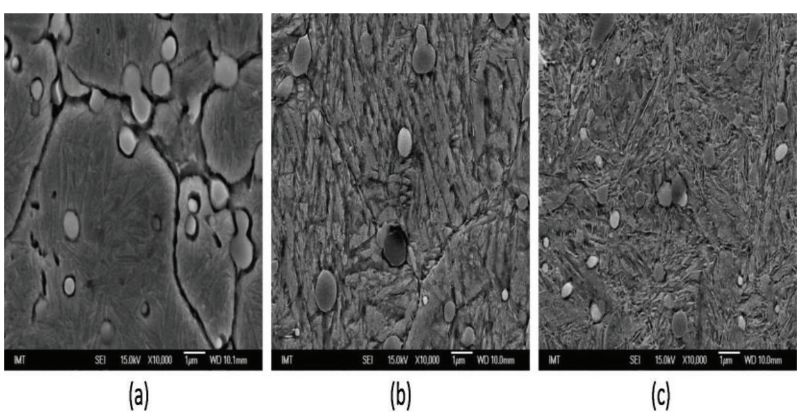

Figure 3: Microstructure observation of A1 cold work tool steel after **(a)** quenching, **(b)** conventional triple tempering (group 1), and **(c)** Deep Cryogenic Treatment (DCT) and single tempering (group 1P).

to single tempering at lower temperatures and elevated temperatures (450°C), AISI D2 steel shows improved hardness and toughness.

Hadi Ghasemi Nanesa *et al.*,[10] studied the impact of cold working on the AISI D2 tool steel's microstructure development following hardening heat treatment in which two different degrees of cold rolling were applied to plates of D2 steel that had 4 mm thickness before quench hardening. Comparing 10% and 20% cold-rolled plates with non-deformed ones, hardening heat treatment decreased the initial austenite grain size and carbide volume percentage and the influence of grain refinement on hardness were studied on the cold-rolled hardened sample and images from scanning electron microscopy showed that the martensite distribution in the cold-rolled samples was more uniform. Despite grain refining, increasing the degree of cold rolling led to lower PAGS and a decrease in the hardness values. It is claimed that the primary reason for reduced hardness values is a decrease in the volume percentage of carbides. Podgornik *et al.*,[11] carried out work with a single Fatigue Pre-cracked Tensile Bar test work part to study impact of the vacuum based heat-treatment technique on the material specific characteristics. Figure 7 and Figure 8 show the microstructure of quenched and tempered hot-worked tool steel at different temperatures.

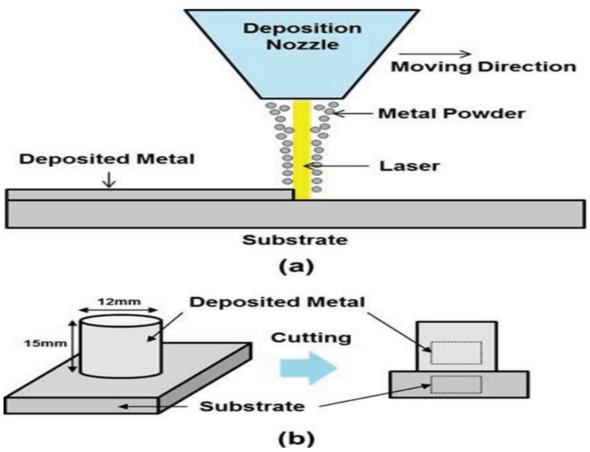

Figure 4: (Colour online) Schematic of **(a)** The DMT apparatus; **(b)** the test sample.

The findings demonstrate improvement in hardness values and the strain-hardening factor and also highlights the increase in bending strain with fracture toughness.

Halil Demir *et al.*,[12] carried work on the impact of heat treatment on the microstructure and machinability of H13 hot work tool steel in which the impact of heat treatment on the conditions of as-received (AR), water-quenched (Q), quenched and single-tempered (QST), and double-tempered (QDT) conditions were studied Also, turning tests were carried out using various cutting speeds. It was concluded that cutting forces were independent of steel micro structure. Figure 9 shows the apparatus with abrasive cloth for testing abrasive wear.

V. Kuklik *et al.*,[13] carried out work on various forms of thermochemical treatment on carbon and low-alloy

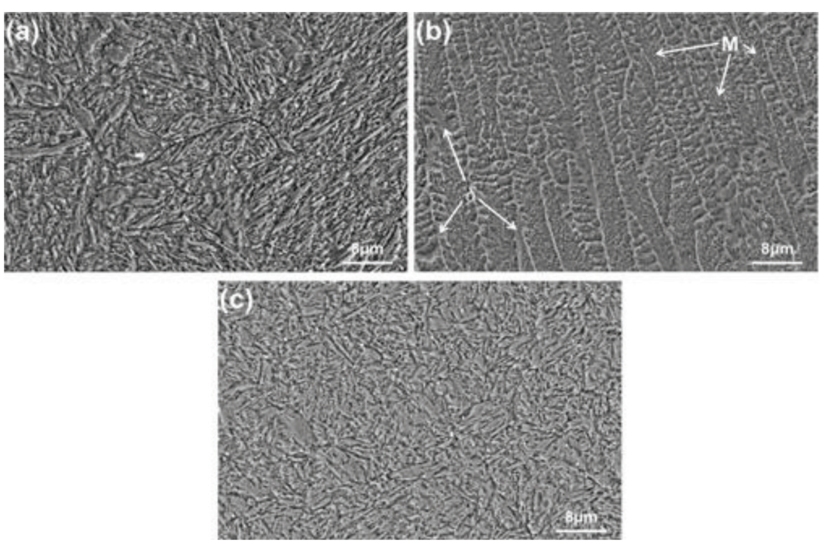

Figure 5: Microstructure observation of **(a)** substrate, **(b)** deposited metal, and **(c)** the heat-treated deposited metal in H13 steel.

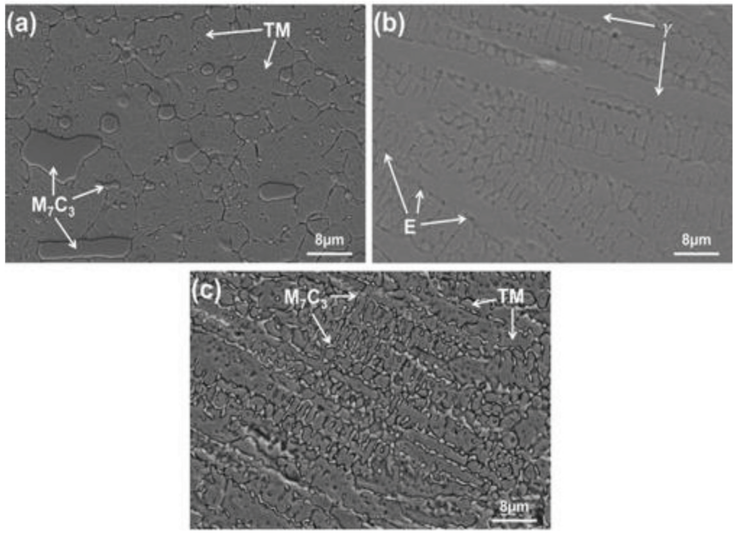

Figure 6: Microstructures of **(a)** substrate, **(b)** deposited metal, and **(c)** heat-treated deposited metal in D2 steel.

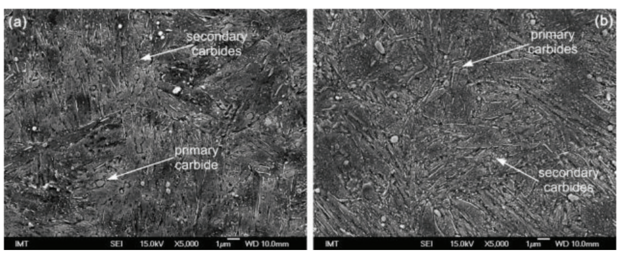

Figure 7: Microstructure of quenched and tempered hot-work tool steel, quenched from 990°C and tempered at **(a)** 550°Cand **(b)** 630°C.

Figure 8: Microstructure of quenched and tempered hot-worked tool steel, quenched from 1030°C and tempered at **(a)** 550°C and **(b)** 630°C.

steels and reported that thermochemical treatment has an impact on the abrasion resistance property of structural and tool steels. The use of ledeburite steels is another technique for improving the tool life. Also, it was examined how the microstructure of tested steels, and the impact of structural variables on abrasion resistance

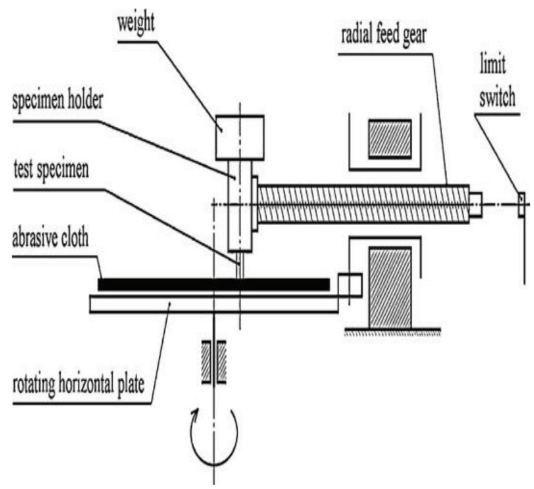

Figure 9: Apparatus with abrasive cloth for testing abrasive wear.

influence the wear resistance of these steels[13]. The maximum abrasion resistance in ledeburitic chromium variant of steel was obtained by quenching at 1100 °C, whereas the ideal quenching temperature in ledeburite chromium-vanadium steel was 1150 °C. Increasing levels of residual austenite resulted in growing abrasion resistance[13]. Kamran Amini *et al.*,[14] investigated the effects of various quench environments such as water, oil, air, 30 °C ethanol, and 195 °C liquid nitrogen. The cold worked tool steel was subjected to deep cryogenic treatment (D3 tool steel) and hardness, microstructural changes, wear behavior, and retained austenite have been discussed briefly and results show that reducing the remaining austenite prior to deep cryogenic heat treatment by increasing the quench severity results in a more uniform carbide. Owing to the greater thermal conductance, and less stable martensite structure of the ethanol-quenched samples, the wear rate and hardness exhibit increased values. Improvement of mechanical characteristics is also strongly correlated with the production of nanoscale carbide. Adhesive wear was found to be the main type of wear[14]. Jalal Hedjazi *et al*.,[15] in their work, studied the response of heat treatment on the internal structure of high chromium high Carbon AISI D3 Steel. To study the optimized impact of the homogenizing process on the morphology and microstructure of carbides optical microscope, SEM and EDS analyzer have been used.

3.0 Conclusion

In this paper, considerable study has been carried out about the influence of heat treatment process and cryogenic treatment on different tool steels. The following points are inferred:

- The most crucial procedures that must be carried out when using tool steel for cold work are tempering and hardening. The tempering enhances qualities like toughness and hardness; depending on the application, double- and triple-tempering may also be necessary.
- To achieve the necessary qualities, hot work tool steel grades needed to be annealed, tempered, and properly quenched.
- The method and temperature that are utilized to affect the microstructure of tool steels are important.
- Cryogenic treatment can increase the carbide density and encourage carbon clustering during heat treatment to increase wear resistance. It can also uniform the carbide dispersion.

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