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Effect of Heat Treatment on the Properties of Tool Steel

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Abstract

Tool production has deep importance for the industry. The developed tool steels are suitable for the requirements. These tool steels contain large amounts of alloying elements and carbon. The required properties are determined by the chemical composition and microstructure of the tool steel. High hardness, wear resistance, strength, toughness, and corrosion resistance can be achieved by heat treatment which can modify the microstructure. Sub-zero treatment, shallow cryogenic treatment, and deep cryogenic treatment technology, and the resulting microstructure, are given a prominent place in this paper. The review is summarized based on literature research on the experimental results of heat treatment of tool steels..

Keywords: *tool steel, heat treatment, retained austenite, high tempering temperature, cryogenic treatments.*

1. Introduction

Tool steels are unalloyed or alloyed steels, which are primarily used for processing and forming other materials. The applicability of tool steels is determined by their properties. The main properties of tool steels are wear resistance, hardness, toughness, heat resistance, corrosion resistance, polishability, compressive strength, nitriding ability, coating ability [1]. These properties are influenced by the chemical composition and microstructure. Thus, for example, carbon determines the available hardness, strength, hardenability and the start (Ms) and finish (Mf) temperature of the martensitic transformation [2]. Chromium increases hardenability, wear resistance, edge durability and corrosion resistance [3]. Vanadium refines the primary grains, thereby increasing toughness, wear resistance, edge retention and heat resistance. The tungsten carbides increase the heat resistance and high temperature wear resistance. Cobalt prevents grain growth at high temperatures [4–6].

The structure and grain size of the tool steels also have an effect on the properties [7, 8], which may depend on the manufacturing technology of the raw material, i.e. conventional, remelted or powder metallurgy, hot or cold forming and heat treatment [9– 11].

Tool steels are widely used where wear resistance, high strength, toughness and corrosion resistance are required. The microstructure can be modified or adjusted by heat treatment [12, 13]. Heat treatment technologies consist of three cycles : heating, temperature maintaining (ramping or holding time) and cooling [14]. Stress relieving, annealing, normalizing, hardening and tempering are the most important heat treatments that are often used to modify the microstructure of steel and achieve the desired mechanical properties [15]. Heat treatment may be applied before, during or after production. For example, during the production of a tool , the starting raw material is subjected to soft annealing heat treatment in order to make it easily workable, during production a stress relieving heat treatment is performed to reduce the stresses created in the material. The finished tool is hardened and then tempered to the desired hardness and if required surface treated or coated [16–18].

Based on the above, it can be concluded, that heat treatment can be one of the technologies to obtain the desired properties of the tools. In my work I will discuss in more detail the optimal heat treatment procedures required for the appropriate hardness of tools and the importance of the surface treatments and coatings.

2. Hardening of tool steels

The hardening consists of heating to the austenitizing temperature, holding to this temperature an quenching faster than the critical cooling rate (**Figure 1**).

Figure 1 shows the hardening diagram of steel as a function of temperature and time. During heating, thermal stresses arise in the material, which can cause dimensional changes and distortions. To avoid this problem, slow heating is recommended. In the heating process below the transformation temperatures, a ramping step is performed at 650°C and 850°C, to equalize the temperature between the core and the surface of the tool. In Figure 1, the green curve shows the temperature measured on the surface of the material, while the blue curve shows the temperature in the core of the tool. At the austenitization temperature, after the ramping step (when the core of the parts in the furnace reach the chosen temperature) the temperature is maintained constant for a certain amount of time. This is for the formation of homogeneous austenite and it called the holding time **[16]**.

The austenitization temperature of a specific steel grade can also affect the properties. Austenitization can be carried out at lower or higher temperatures within the austenitic area. The hardness of the Sverker 21 cold work tool steel manufactured by Uddeholms AB after quenching and tempering at 1020°C was 62 HRC, and at 1075°C was 61 HRC **[17]**. The lower hardness value after high-temperature hardening is due to the amount of retained austenite that has not been transformed to martensite due to the increased austenite grains **[18, 19]**.

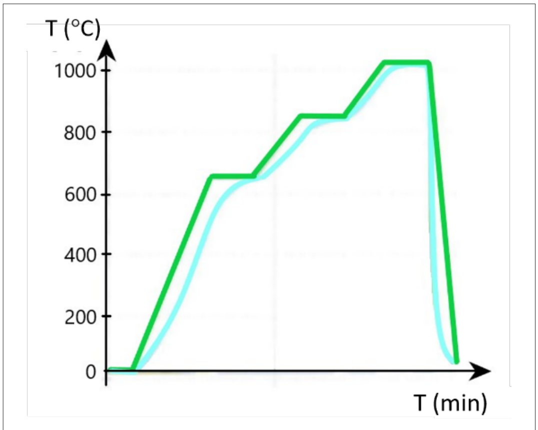

Figure 1. *Hardening diagram.*

Retained austenite is formed during quenching, when a part of the austenite can not transform into martensite. This transformation is a diffusion-free transformation that begins at M_s: the martensite starts and ends at M_f, which is the martensite finish transformation. The M_s and M_f temperatures are determined by the carbon content of the steel, which is high in the case of tool steels. In this case M_s is at low temperatures, and M_f is in the negative range **[45]**. This is the reason why cryogenic treatment is necessary. The retained austenite is an undesirable phase in tool steels because it causes stress and dimensional changes. The stress is generated within the material where the untransformed austenite is found, because the volume of the austenite is smaller than that of the martensite, thus drawing-compression stress is generated between the phases. Retained austenite is a soft and unstable phase, which in addition to reducing the hardness during the operation of the tool, transforms into martensite due to stresses and thus can cause cracks in the tool and tool breakage **[20–22]**. Cryogenic treatment is the most effective method for reducing the amount of retained austenite after quenching **[23–25]**.

2.1. Cryogenic treatment and its effect

Cryogenic treatment means that steel is cooled to a negative temperature in order to achieve the specific properties of the material.

Cryogenic treatment can be divided into three different temperature ranges. The first is the range below 0°C called subzero treatment, and ranges down to minus 80°C. In this range, most of the retained austenite transforms into martensite, the fatigue resistance of the steel improves, the dimensional stability and the wear resistance increases **[26]**. The second domain, called shallow cryogenic treatment, covers the range between minus 80 and minus 160°C. In this range, the amount of retained austenite can be reduced below 1,8%, which ensures dimensional stability, wear resistance and, last but not least an increase in tool life **[27, 28]**. **Table 1** shows the X-ray diffraction test results of a K340 Böhler cold work tool steel produced by electroslag remelting method, one sample heat treated conventionally (CHT), and another heat treated with shallow cryogenic treatment at minus 150°C. The result shows that the retained austenite content of the shallow cryogenic treated specimen is more than three times less than the conventionally heat-treated specimen, and the carbide content is 20% higher,

Table 1. *Steel K340, XRD analyses results* [27]

Phases (mass %)	1- CHT	2- SCT (–150 °C)
Martensite	62.8	55.8
Retained austenite	6.2	1.8
M_2C (V,Nb)	5.2	4.8
M_7C_3 (Cr, Fe)	16.7	24.6
$M_{23}C_6$ (Cr, Fe)	9.1	5.3
M_3C_2(Cr,Fe)	0	7.7

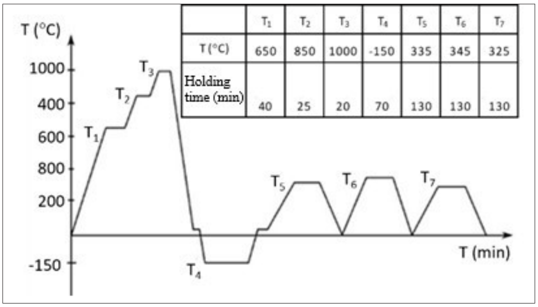

Figure 2. *Böhler M340 ISOPLAST steel cryogenic heat treatment*

which is due to secondary carbide precipitation. In addition to an increase in hardness, this also ensures better wear properties for the steel.

The third range (from minus 160 to minus 196 °C) is called deep cryogenic treatment, which not only ensures the dimensional stability of the tool, but also significantly increases its wear resistance, hardness and strength, and, in some cases, even its corrosion resistance [29, 30].

Due to the positive effects of deep cryogenic treatments, they have found application in many areas, such as in the case of additive manufacturing processes[31], electrodes [32], welded joints [33], and during the processing of materials [34–36]. The applications of deep cryogenic treatment are also widespread in nanotechnology [37] and in other industries such as medicine, space research, music, and the automotive industry [38–40]. The tool life is also extremely dependent on the applied heat treatment technologies. Deep cryogenic treatment can greatly improve the mechanical, thermo-chemical and tribological properties of tool steels [41, 42].

Cryogenic treatment has great potentional for improving the properties of metallic materials and increasing the lifetime of tools.

We compared the Böhler M340 Isoplast electroslag remelted plastic mould steel cryogenic treated and three times high temperature tempered specimen properties with a conventionally heat-treated sample without cryogenic treatment [43]. Figure 2 show the cryogenic treated specimen diagram.

The hardness of the cryogenic treated specimen was with 1HRC higher than that of the conventionally treated specimen, its wear coefficient was 45% more favourable, while the corrosion mass lost was reduced by 15%.

Cryogenic treatment is usually performed after quenching and before tempering [44].

3. Tempering and its effect

The martensitic microstructure, after quenching, is brittle and is not recommended for practical use. The material should be tempered immediately after quenching (unless cryogenic treatment is used). When heated to 200-600°C, the stresses are relieved. The microstructure of tool steels after quenching contains martensite, retained austenite and primer carbides, but reheated to a specific temperature below A_{c1} (phase transformation temperature), its stresses and the amount of retained austenite are decreased.

During tempering of tool steels, the goal is to achieve a homogeneous spheroidic microstructure.

With low temperature tempering, only the martensite tempering can be achieved, while with high temperature tempering, the amount of retained austenite can also be reduced.

After the first tempering, in the case of a high temperature tempering, the microstructure contains tempered martensite, newly formed martensite from retained austenite, retained austenite and carbides. In this case new carbides are formed (precipitated) called secondary carbides which can increase the hardness with the newly formed martensite. This is called secondary hardening.

Tool steels must be tempered at least twice at high temperatures. After the first tempering, the martensite that has been tempered becomes spheroidite, and the retained austenite transforms into martensite.

A third high temperature tempering is recommended for high-speed steels, hot work tool steels, especially for casting tools, for the heat treatment of larger plastic mould tools, and for highly dimensionally accurate pieces with complex geometry. The essence of the third tempering is the achievement of homogenous spheroidite microstructure and the stress reduction of the material after heat treatment.

Patricia Jovicevic-Klug and her colleagues investigated the changing properties of high-speed steels as a result of deep cryogenic treatment (DCT) [45], and concluded that deep cryogenic treatment increases the compressive strength, and improves fatigue resistance, increases compressive strength, and improves impact performance and thus toughness. However, in addition to deep cryogenic treatment, all these properties are affected by the austenitization temperature and the tempering temperature. Their research also shows that a low austenitization temperature and a high temperature tempering provide more favourable properties for high-speed steels than a high austenitizing temperature and low temperature tempering.

Based in our research, we found that the mechanical properties of the Böhler K110 cold work tool steel are most favourable using high austenitizing temperature, cryogenic treatment, and triple high temperature tempering [46]. After high temperature austenitizing (1070 °C) and low temperature tempering (200 °C), the hardness was 641 HV, while high temperature austenitizing (1070 °C), subzero cooling treatment (-80 °C) and three times high temperature tempering (480 °C), we measured 738 HV hardness, which represented a 14% increase.

Experiments prove that the favourable properties of tool steels can be achieved by forming homogenous spheroidite microstructures with small uniformly distributed secondary carbides. This microstructure can be achieved by using high austenitizing temperature followed by cryogenic treatment and high temperature triple tempering. This microstructure has high hardness, good toughness, high wear resistance, corrosion resistance and last but not least, an increase in service life. Achieving these properties requires a well-developed optimal heat treatment technology. Higher surface hardness and wear resistance can be achieved through surface treatment.

4. Surface treatment of tool steels

The purpose of the surface treatment of the tool is to increase wear resistance, reduce adhesion and improve the quality of the finished tool.

During tool production, the most common surface treatments are nitriding and coating technologies.

4.1. Nitriding of tool steels

During nitriding, nitrogen atoms are diffused into the surface layer of the tool, which forms a hard wear-resistant compound with the nitride forming elements in the steel. The most suitable steels for nitriding are tool steels with a medium carbon content, which are alloyed with aluminium, chromium, molybdenum or vanadium. It is important that the last tempering temperature is below the nitriding temperature otherwise the hardness in the steel decreases.

The most common nitriding processes are gas nitriding and plasma nitriding.

4.1.1. Gas nitriding

The nitrided crust consists of a compound white layer and a diffusion layer. The compound layer is responsible for resistance to wear, friction and sticking, while the diffusion layer is for resistance to fatigue. The thickness of the compound layer is in the order of microns (around 10 μm), while that of the diffusion layer is around 0,1–1 mm.

Gas nitriding is usually carried out with ammonia in a nitrogen-rich gas. When ammonia comes into contact with the heated workpiece, it breaks into nitrogen and hydrogen, the nitrogen diffuses into the surface of the workpiece. The hardness of the nitrided layer on the surface of tool steel can reach 950–1200 HV. The gas nitriding temperature can vary between 500–570 °C. In the case of nitrided M50NiL steel, Guo-meng Li et al achieved the best wear resistance using a temperature of 500 °C [47].

4.1.2. Plasma nitriding

Plasma nitriding is usually performed at a temperature between 480–520°C. The great advantage of this process is that, compared to other nitriding process, it is well controllable, easily reproduceable, takes a short time, and can be performed at a relatively low temperature [48, 49].

Zoltán Kolozsváry investigated the structure and properties of the nitrided layer in his work [50].

During our experiments, we measured a hardness of 1144 HV on the 200μm thick layer after plasma nitriding at a temperature of 520°C on an H13 grade hot work tool steel [51]. Based on the determined wear coefficient, the sample with a plasma nitrided surface has better wear resistance than the hardened and tempered sample.

Dorina Kovács et al investigated the wear behaviour of stainless steel after plasma nitriding [52].

One variant of plasma nitriding is active screen plasma nitriding (ASPN). In Ilona Szilágyiné Bíró's thesis **[53]** she studied the edge effect causing discoloration on specimens during active screen plasma nitriding and then compared the nitried layer after conventional and active sreen plasma nitriding.

4.2. Surface coating of tool steels

Surface coating of tool steels has become a common practice. The general goal of this process is to create a surface layer with high hardness and low friction, which results in good wear resistance, minimizing the risk of adhesion and sticking.

The coating is typically a thin ceramic layer (below 4μm), characterized by very high hardness and low friction. The most commonly used coating processes are PVD (physical vapour deposition) and CVD (chemical vapour deposition).

During our experiments, we examined the properties of X40CrMoV5-1 quality hot work tool steel under the influence of different coatings **[43]**. The highest surface hardness of 2938 HV, was achieved with the TiN/AlTiN PVD coating, which also produced the best wear properties.

5. Conclusions

The properties of tool steels are determined by the manufacturing technology chemical composition and microstructure. The microstructure can be adjusted by heat treatment, which ensures the appropriate properties during the application of tools.

In my work, I reviewed the heat treatment technologies of tool steels using a number of relevant literatures, during which I compared the properties achieved by heat treatment. The main properties are hardness, wear resistance, strength, absorbency, resistance to cracking, heat resistance, corrosion resistance and dimensional stability. Based on the latest research results, the best properties of the tools and at the same time the longest service tool life can be achieved by using the cryogenic treatment. Wear resistance, surface hardness, and corrosion resistance can be improved even further with surface treatment and coating.

The use of optimal heat treatment technology is the key to achieving the desired properties and service tool life.

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