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How heat treatment affects tool steels

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Abstract: The properties of steels cannot be determined solely by their chemical composition. Their final characteristics depend to a large extent on the applied processing methods - whether thermal, chemical, a combination of chemical and thermal, or thermomechanical treatment. When these processes are carried out properly, steels gain the required qualities and their durability is extended. This paper presents an overview of heat treatment techniques for tool steels. Understanding these principles is essential for the effective application of heat treatment and for minimizing the extent of subsequent finishing operations.

Keywords: heat treatment, mechanical properties, the steels.

INTRODUCTION

The production of steel, one of the fundamental materials shaping modern society, has its origins in the Iron Age, approximately 3200 years ago. Despite such a long historical trajectory, the relevance of steel remains undiminished. On the contrary, continuous research and the development of advanced steel grades underscore its strategic importance. Owing to its versatile properties, steel has become indispensable in a wide range of applications from consumer goods and automotive manufacturing to civil engineering, aerospace, and space technologies. Each application requires steels with carefully tailored properties, a demand that, together with the growing diversity of steel types, has resulted in their systematic classification. The criteria for such categorization may include chemical composition, functional purpose, processing method, or other parameters [1].

Yet, chemical composition alone cannot guarantee the required performance. Post-production treatments thermal, chemical, thermo-chemical, or thermo-mechanical are essential for achieving the desired material properties and extending service life. Heat treatment, however, also introduces potential drawbacks; thus, knowledge of these effects is indispensable for its correct application and for minimizing subsequent finishing operations [1, 2].

Tool steels, belonging to class 19, represent high-quality materials typically produced by arc or induction melting. They are expected to exhibit properties such as hardness, temper resistance, toughness, wear resistance, cutting efficiency, hardenability, and dimensional stability. Meeting these requirements depends on a relatively high carbon content, in combination with carefully chosen alloying elements most notably *manganese*, *silicon*, *chromium*, *nickel*, *molybdenum*, *tungsten*, *vanadium*, or *cobalt*. An increase in *carbon* content raises hardness but simultaneously reduces toughness. Secondary alloying elements help mitigate these adverse effects while enhancing other necessary properties. Furthermore, the functional performance of tool steels is strongly influenced by a high carbide content, provided by carbide-forming alloying elements. The effectiveness of heat treatment, as well as additional surface modifications, plays a decisive role in prolonging the service life of tools [3].

1 STEELS

1.1 Carbon Steels

Carbon tool steels typically contain 0.25 to 0.6 % *carbon*, which is sufficient to achieve the necessary hardness. *Phosphorus* and *sulfur* levels are kept below 0.06 %. When hardened, these steels develop hardness only on the surface (up to 2 to 3 mm), while the core remains unhardened. This feature is sometimes advantageous, as the tough, impact-resistant core improves performance in specific applications. Such steels are mainly used for manufacturing low-stress tools. Their working temperature does not exceed 200°C, since most steels in this group lose hardness above 150°C. Common uses include cutting tools and hand tools [4].

1.2 Alloy Steels

The alloyed, or low-alloy tool steels, exhibit greater resistance to mechanical stress compared to plain *carbon* steels. Their key alloying elements are the carbide formers chromium and *tungsten*, typically added in amounts of 1 to 2 %, as carbides enhance cutting performance. Depending on application requirements, additional alloying elements include *manganese*, *silicon*, *nickel*, and small amounts of *vanadium*, bringing the total alloy content to 3 to 5 %. For cold-forming, shearing, and machining tools, the steel may contain up to 12 % *chromium* and 2 % *cobalt*. This group is characterized by high hardness and wear resistance, making it suitable for both cold and hot working tools [5, 6].

1.3 High-Speed Steels (HSS)

High-speed steels of this class were named after their application to tools that operate at high speeds. Their structure is *martensitic*. They are characterized by extremely high stability of properties up to temperatures of 650°C. This stability is obtained thanks to the high content of additives above 10 %. The *carbon* content is 0.7 to 0.9 %. The content of the main additive, which is *tungsten*, ranges from 10 to 18 %. Other elements are *chromium*, the content of which is around 4%, which makes the steel more resistant to *oxidation* even at higher temperatures, and 1 to 4% *vanadium*. *Vanadium* significantly affects the formation of stable carbides. However, a higher proportion of *vanadium* requires an increase in the *carbon* content to prevent loss of toughness. For more demanding applications, some steels replace part of the *tungsten* with *molybdenum* up to a content of 5%, or 3 to 10% *cobalt*. It is important to keep the *manganese* and *phosphorus* content at minimum levels, as these elements significantly increase the brittleness of steels and cause cracking during hardening. Annealing at a temperature of 800 to 840°C is used as a heat treatment. It is hardened at very high temperatures of 1260 to 1300°C and the holding time at these temperatures is around 100 s. The high temperature is necessary in order to achieve the desired chemical composition of austenite, which is achieved by dissolving the necessary concentration of alloying elements and carbon. The disadvantage is grain growth. Heating is gradual and slow in order to achieve temperature equalization throughout the cross-section. Due to the high content of carbon and alloying elements, they have poor thermal conductivity, therefore, thanks to the gradual heating, smaller stresses are formed between the surface and the core. After hardening, tempering is followed by tempering at a temperature of 560 to 580°C and is repeated 2 or 3 times. After quenching, a matrix consisting of alloyed *martensite* and a large amount of residual austenite is obtained. This structure does not have high hardness, therefore, a high tempering follows, during which alloying elements and *carbon* are precipitated from the *austenite*. The thus depleted *austenite* is less stable and upon subsequent cooling from the tempering temperature it easily decomposes into *martensite*. The residual *austenite* is alloyed and therefore very stable and multiple tempering is necessary for its decomposition. In the case of the production of very precise measuring instruments, the residual *austenite* is reduced by freezing [7].

1.4 Maraging Steels

A special subgroup of class 19 steels includes maraging steels, known for their exceptional strength and toughness. The name derives from *martensite* aging, referring to *martensitic* transformation followed by age-hardening. Unlike conventional steels, maraging steels are classified by strengthening mechanism rather than chemical composition. They contain very low *carbon* (< 0.03 %) to avoid *titanium* carbide formation, which would otherwise reduce impact strength and ductility. Instead, they are alloyed with 17 to 19 % *nickel*, along with *cobalt* (8 to 12 %), *molybdenum* (3 to 5 %), *titanium* (0.2 to 1.8 %), and small amounts of *aluminum* (0.1 to 0.15 %).

Their production involves heating to about 850°C and slow cooling, which results in a *martensitic* rather than *ferritic*/*pearlitic* structure. This *martensite* is softer compared to *carbon* steel *martensite* but offers better ductility and toughness without tempering. Strengthening is achieved by precipitation hardening (*aging*) at 480 to 500°C, where fine particles form, improving hardness without causing large dimensional changes. However, due to the high *cobalt* content, these steels are significantly more expensive [7, 8].

2 THERMOMECHANICALLY PROCESSED STEELS (TMP/TMCP)

This group of steels reaches strength levels of 2500 to 3000 MPa, with special cases up to 3500 MPa, while maintaining acceptable ductility and toughness. Their properties result from thermomechanical processing, which combines plastic deformation with heat treatment. Although applicable to various steels, it is most effective in low- to medium-alloy steels with 0.4 to 0.6 % carbon.

Applications include pipelines, skyscrapers, bridges, ships, car bodies, and railways. *TMP* involves controlled hot working of stable austenite, with deformation levels of 40 to 90 %, followed by quenching and tempering to refine the martensitic microstructure. Both high-temperature and low-temperature *TMP* exist, with the latter being more common due to cost efficiency. Depending on processing conditions, steels can achieve strengths up to 3000 MPa while balancing toughness and machinability. Advanced TMP techniques also combine high- and low-temperature deformation to produce ultrafine-grained structures with improved mechanical properties [9, 10].

In practice, the most common procedure is deformation before transformation. In high-temperature forming, steel is intensively formed in the stable austenite region. The degree of forming is usually high and ranges from 40 to 90 %. During this deformation, recovery and recrystallization occur in the grains. The formation of recrystallized grains is followed by hardening, as a result of which very fine *martensite* is formed in the structure, which is further tempered. High-temperature thermomechanical processing achieves strengths of 2500 MPa. Low-temperature thermomechanical processing is more common than high-temperature processing, also due to more acceptable costs. Deformation with a minimum value of 50 % and more occurs at temperatures in the range of 500 to 600°C and subsequent tempering is carried out at a temperature of 200°C. Uncrystallized *austenite* grains contain large amounts of lattice defects, which contribute to the formation of fine *martensite*. Low-temperature thermomechanical processing enables the production of steels with a strength of 3000 MPa. By combining high-temperature and low-temperature processing, we obtain a combined thermomechanical processing, where austenite is first deformed at a temperature just above *Ac*3 and then cooled and deformed at temperatures in the metastable *austenite* region and finally hardened to *martensite*. The procedure, where steel is first deformed hot or cold and then annealed at a temperature of 300°C, then rapidly austenitized and hardened, is called preliminary processing. Deformation during transformation is carried out in the *pearlitic* and *bainitic* transformation region, which follows rapid cooling from the austenitization temperature. In these regions, the steel is intensively formed and then allowed to cool in air or hardened to a mixture of lower *bainite* and *martensite*. Deformation in the *pearlitic* region does not significantly increase strength, but there is a noticeable increase in toughness. Deformation in the bainitic region, on the other hand, increases strength at the expense of toughness and machinability. Deformation after transformation is applied between the first and second tempering, in which case it is deformation tempering. The second option is deformation directly during tempering at temperatures of 150 to 200°C, in which case it is dynamic deformation aging of *martensite*. With a slight decrease in ductility, a significant increase in the yield strength is achieved [11].

2.1 TRIP Steels (Transformation-Induced Plasticity Steels)

TRIP steels have a matrix of *ferrite* with retained *austenite*, along with 25 to 40 % *bainite*, and sometimes *martensite*. They contain 0.20 to 0.25 % *carbon*, sufficient for both weldability and lowering the *martensite* start temperature (*Ms*) below room temperature. During deformation, retained *austenite* transforms into *martensite*, which strengthens the steel - a phenomenon known as transformation-induced plasticity (*TRIP*).

To achieve this effect, 5 to 15 % retained *austenite* is required, controlled mainly by carbon and *silicon* (up to 0.3%). Other alloying elements include *aluminum*, *manganese*, *chromium*, *molybdenum*, *niobium*, and *titanium*. *TRIP* steels typically achieve strengths of 500 to 1050 MPa, with elongation between 20 to 80 %, making them highly formable and resistant to thinning during shaping. Their production involves solution annealing at 1120°C, followed by controlled deformation above the *Md* temperature.

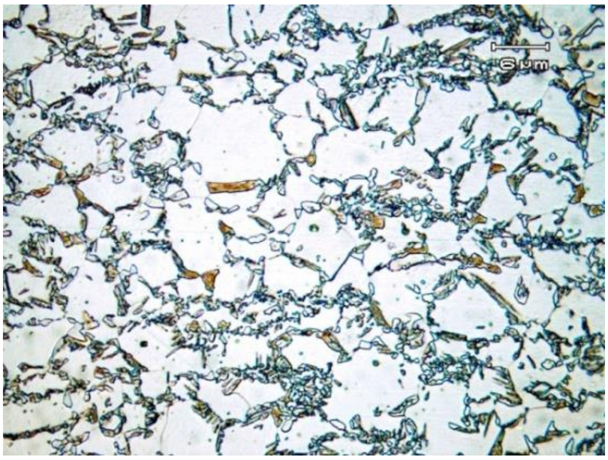

Fig. 1. TRIP steel [11]

Figure 1 shows the *TRIP* steel annealed at 775°C for 5 mins and then hold at 400°C for 40s for *austenite* stabilization The largest grains are *ferrite*, the darker regions are *bainitic*, and the smaller white grains are the retained *austenite*, which will transform to *martensite* when a stress is applied (micrograph 740 from the micrograph library) [11]. Depending on the type of steel, this temperature is around 100°C. The degree of deformation reaches 80 %. The deformation causes an increase in the temperature *Md* by approximately 100°C and a decrease in the temperature *Ms* by the same amount. These steels have found application mainly in the automotive industry [12, 13].

2.2 TWIP Steels

This group of steels belongs to the new perspective types. These are ultra-strong high-alloy manganese steels. Their designation is from the English Twinning Induced Plasticity Steel. The R_e values reach 280 to 1350 MPa and R_m 580 to 1470 MPa. The ductility values are in the range from 15 to 95 %. With these ductility values, *TWIP* steels can be compared to deep-drawn steels, but they have several times higher strength values. They achieve their properties thanks to the *austenitic* structure, which does not transform into *martensite* even at higher deformations. Instead, twinning occurs in the structure during deformations, at all temperatures and throughout the entire volume. The best result of twinning can be observed at a *manganese* content above 20 %. If the *manganese* content is below 15 %, the *TRIP* effect occurs. Steels are further alloyed with *aluminum*, which suppresses the transformation of austenite to martensite, and silicon to improve strength. It has found significant use in the automotive industry in the construction of frames, also due to its ability to absorb impact energy, ease of pressing and reduction of the overall weight of the vehicle. It is also used in the construction of ships and transport pipelines [13, 14].

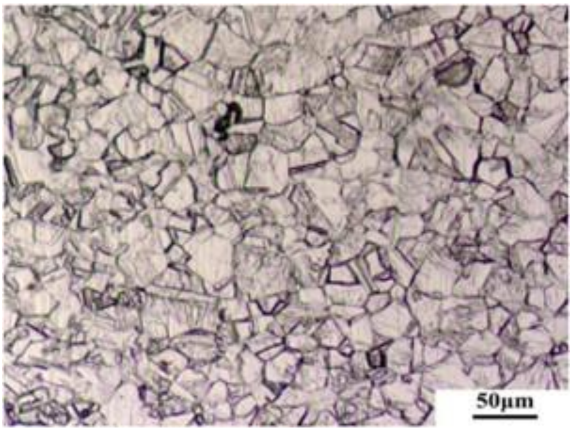

Fig. 2. Microstructure of the *TWIP* steel [14]

TWIP steel is a typical austenitic steel, and its optical microscope morphology is shown in Figure 1. It can be seen that the phase of *TWIP* steel is mainly single-phase *austenit*e and the annealing twins are evenly distributed among them. Twins play an important role in the excellent mechanical properties of *TWIP* steels [14, 15].

Tab. 1. mechanical properties of selected high-strength steels

Steel marking	R_e [MPa]	R_m [MPa]	A [%]	Characteristics
18*Ni*200 grade	1450	1460	15	maraging
40*Cr*5*MoV*	2600	2800	9	*TMS*
HCT*690*T	400-520	690	23	*TRIP*
Fe*-0.7*C*-15*Mn	630-652	999-1035	56-59	*TWIP*

CONCLUSION

Each subgroup from *carbon* steels, alloy steels, and high-speed steels to advanced maraging, *TRIP*, or thermomechanically processed steels is designed to meet specific performance requirements. Their proper selection and processing enable the production of tools and components with high hardness, wear resistance, strength, and toughness, ensuring long service life and reliability in industrial applications.

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