1 Introduction

Dr. Ruben Schlutter

The potential of molding markets of various countries depends on their tooling competence and their production volume, and can be separated into what can be colloquially termed “all-stars”, “established”, “rookies”, and “rising stars”.

Currently China, the USA, Japan, South Korea, and Germany belong to the all-stars. These countries are characterized by a high tooling competence and a large production volume. China is at the lower competence limit of the all-stars, but has by far the largest production volume. The USA is the second largest moldmaking market in the world and belongs to the top group for all examined tool categories in terms of production as well as export and import volumes. Germany, Japan, and South Korea, and also Switzerland, which is not an all-star, have the highest moldmaking competence in the world. A large number of organizational and technological innovations in moldmaking have their origin here. They all have a very highly developed manufacturing industry and are known for their automotive industry. The importance of these three markets will continue in the foreseeable future, not just for the respective local industries, but also for the global procurement of highly complex tools. In 2020, the mold markets of the all-stars had a volume of over €22 billion for injection molds. All all-star markets are suitable for the procurement of complex, complete tools, with the market sizes allowing tool packages to be handled quickly in large volumes [1].

Just as the quality of injection molds continues to rise, so do the demands on the plastic molded parts produced. In addition to the requirements for the design and surface of the plastic molded part, production also plays an essential role in the profile of requirements. For this purpose, the injection molds must withstand more and more physical and chemical loads, be it through the use of abrasive or corrosion-promoting plastics, fillers, and reinforcing materials or additives, or also through technological requirements, such as achieving a certain flow path or the optical lamination of a weld line. Within the injection molding process, a wide variety of defects can occur on the molded parts and the molds, which can be solved or minimized by the use of coatings in the molds.

This book summarizes the current state of science and technology in the field of coating technology. The selection of suitable coatings is always an interplay between the moldmaker, the manufacturer of the plastic molded parts, the customer of the plastic molded parts, and the coater, and we reflect this throughout the text.

1.1 Defect Patterns in Injection Molding

Gloss differences and tiger lines

The gloss of a molded part results from the fact that light shining on the molded part is reflected. The smoother and more uniform the surface of the molded part, the more uniformly the light is reflected and the greater the scattering angle of the reflected light. Structured surfaces in the mold, and also different representations of the molded part cavity by the plastic, lead to differences in the degree of gloss. In the area of cooling channels, ejectors, or wall thickness differences, gloss differences often occur because of differences in the local mold wall temperature, which lead to a different representation accuracy of the mold wall compared to the surrounding molding cavity. Coatings also influence the gloss level. Due to the different properties and modes of action of the coatings, no generally valid statement can be made here [2].

"Tiger lines" are a special case in the occurrence of gloss differences. They occur mainly when blends or multiphase systems are used. Due to the different impression of the molding cavity by the respective phase, alternating gloss impressions occur, which lead to an optical stripe formation. The main causes of tiger line formation are partial crystallization of the surface layer under high shear stresses and differences in melt elasticity. The change of the flow front velocity can also support the occurrence of tiger lines [2].

Dull spots in the gate area

In the gate area, the polymer chains of the melt are strongly stretched and oriented. Since the melt freezes immediately at the mold wall, these strains and orientations cannot be reduced by relaxation. The areas of high orientation therefore have poor mechanical properties and are very susceptible to cracking. As the melt flows under the solidified layer, the layer cracks, allowing the melt to flow into the cracks and re-solidify on the mold wall. Micro-notches are formed, which lead to a strongly scattered light reflection in the area of the gate [2].

Weld lines

When several flow fronts meet in the cavity, a weld line is formed. When they meet, the flow fronts are flattened, partially intermix, and stick together, forming a notch at the mold wall. In the case of structured surfaces, additional gloss differences can occur, resulting in optical and mechanical defects [2].

Demolding grooves

Demolding grooves occur during ejection of the molded part. Particularly with structured surfaces and moldings with large lateral surfaces, the demolding force increases sharply. Due to the structuring or the surface roughness, which lies on the side surfaces transverse to the direction of demolding, microscopic undercuts are formed, which can lead to demolding grooves [2].

Sonic plate effect

Sonic plate effects occur primarily with high-viscosity plastic melts in combination with a low injection speed. During injection, the surface layer behind the flow front solidifies. At the same time, the flow front area close to the wall also cools, making it more difficult for the melt to flow in the direction of the mold wall. The hot melt flowing towards the mold therefore cannot be conveyed as far as the flow front and contact the mold wall. Instead, it causes expansion within the flow channel. When the pressure increases, the flow front comes into contact with the mold wall again. However, since these areas of the flow front are strongly cooled, no complete contact with the mold wall can be formed [2].

Rough surface due to plaque formation

Plastics such as POM, PP, ABS, PC, PET, and PBT tend to form plaques. In addition, increased plaque formation can be observed when flame retardants, UV absorbers, and colorants or lubricants are used. When using additives, the formation of plaque is often due to a mixing incompatibility between the polymer and the additive. In some cases, the use of additives also promotes chemical reactions within the polymer or oxidative degradation of the polymer chains [2].

On the other hand, an unfavorable mold design or process control can support the formation of plaque. Especially in case of a long dwell time or high shear of the polymer melt, plaque formation in the mold cavity can occur. Poor mold venting can prevent the air and outgassing from the plastic melt from escaping from the mold cavity. The use of lubricants and release agents also leads to the formation of plaque [2].

Deformation during demolding

During demolding, forces are applied to the plastic part by the demolding system. The plastic molded part can be deformed by this demolding force, which is why the demolding force must be kept small. Shrinkage has a direct effect on the demolding force and can be favorably influenced by the process. In parallel, various plastics tend to adhere to metallic surfaces, which leads to a significant increase in the demolding force. The use of variothermal process control can also lead to an increase in the demolding force, especially with semi-crystalline plastics, since the mold cavity can be formed in greater detail by the plastic melt [2].

Ejector marks and white cracks

In addition to gloss differences in the area of ejectors, visible marks can also be caused by the ejectors in the molded part. These can have various causes, such as incorrect fitting of the length of the ejector pins or an incorrect dimensioning of the demolding system. On the process side, high demolding forces or an early demolding, or also high temperature differences within the mold or between the mold and the ejector, can lead to ejector marks [2].

White cracks occur when a maximum permissible material-dependent deformation is exceeded, and arise because they reduce the stresses that have been introduced. White cracks frequently occur during demolding under residual pressure or in the area of ejectors. In this case, the outer layers of the molded part are stretched by the inner layers [2].

Incompletely filled molded parts

In the case of an incompletely filled molded part, the cavity is not completely filled. There can be various reasons for this. In addition to insufficient dosing volume and venting difficulties, the injection pressure is often insufficient, or the flow path length is too high, so that the plastic melt freezes before it reaches the end of the flow path [2].

1.2 Preparation of a Specification Sheet and Functional Specification Sheets

In the product development environment, a three-stage development and documentation process consisting of the specification sheet, the functional specification sheet, and the requirements list has become widely accepted. Table 1.1 describes the purpose, contents, and boundaries of the documents [3–5].

The specification sheet is first prepared by the client and describes all requirements and constraints from the client's point of view. It serves as the basis for the invitation to tender and the offer.

The functional specification sheet is prepared by the supplier. It contains the specification sheet and describes the customer specifications with the corresponding requirements and how they are to be processed and solved.

The requirements list contains a systematic compilation of all data and information. It is written by the developer and is used for exact clarification of the task. After the approval by the client, the functional specification and the requirements list are binding documents [3–5].

Table 1.1 The Various Documents for Task Clarification [4]

	Specification sheet	Functional specification sheet	Requirements list
Definition	The scope of supply and services, based on the customer's requirement	A summary of all requirements	A compilation of data and information needed for product development
Author	Customer	Supplier	Designer/Developer
Task	Definition of what is to be solved, and for what purpose	Definition of how this is to be done, and the corresponding requirements	Definition of purpose and properties of requirements
Remark	The specification sheet contains all requirements and boundary conditions	The functional specification sheet contains the specification sheet with the summary of the requirements	The requirements list corresponds to an extended requirements specification

This procedure can also be transferred to the development of coatings, whereby the questions that arise from the various necessary individual aspects (including the molded part to be manufactured later, the component to be coated, and the subsequent manufacturing process) must be defined and answered. This results in the basic structure of the specifications for the selection and development of a suitable coating process:

- Requirements for the molded part
  - Part geometry
  - Part surface and relevant surfaces
  - Plastic used.

- Requirements for the mold
  - Tool material to be coated
  - Surface to be coated (roughness, texture, etc.)
  - Coating technologies to be considered
  - Principle development of the coating.
- Requirements for the functionality of the coating
  - Targeted injection molding parameters
  - Methods for mold cleaning
  - System-specific specifications and restrictions.
- Functional tests
  - Measurement and characterization methods
  - Tests to check the layer quality and layer adhesion
  - Application in the production tool
  - Efficiency tests.

From this basic structure, the methodology for developing the coatings is developed according to Figure 1.1. First, possible deposition processes are simulated in order to be able to estimate the process window and the position of the component to be coated in the reactor. In the second step, the actual coating is carried out. In addition to the component to be coated, metal coins are always positioned at various points in the reactor. The subsequent tests are carried out on these coins in order not to damage the component. Here, the coating thickness is analyzed. The structure of multilayer coatings, the presence of coating defects, and the adhesion of the coating to the substrate or the hardness of the coating can also be examined at this point. An evaluation of the coating surface is also possible. Depending on the purpose of the applied coating, further investigations are carried out to examine the properties of the coating and ensure its suitability with regard to the requirements defined in the specification sheet and the requirements list. However, the practical suitability of the coating must then always be determined in a real application. In this case, the coatings are analyzed in their original condition and then again after the coating has been applied, in order to be able to characterize any abrasion or damage to the coating.

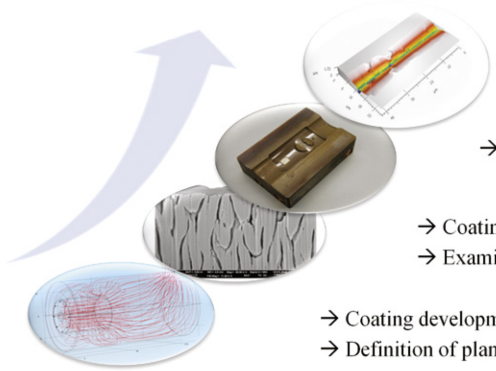

Figure 1.1 Procedure for the development of coatings (Image source: Non-profit KIMW Forschungs-GmbH)

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2 Tool Steels and Their Coatability

Markus Pothmann

2.1 Introduction

2.1.1 Definition of Tool Steels

Tool steels are a group of high-strength, highly wear-resistant steels specifically designed for use in the manufacture of molds, tools, and other components that are subject to repeated impact, abrasion, and high loads. These steels typically have high hardness, toughness, and resistance to deformation, making them ideal for use in applications that require high precision and long tool life.

The specific properties of tool steels are achieved through careful alloying and heat treatment. Alloying elements such as tungsten, molybdenum, chromium, and vanadium are added to the steel to improve its strength, wear resistance, and other important properties. The exact combination of these elements varies depending on the specific requirements of the tool to be produced.

Tool steels are typically divided into several categories based on their specific properties and intended use. For example, high-speed steels are designed for use in high-speed machining applications, while cold work steels are designed for use in applications where the tool is exposed to extremely low temperatures. Other categories of tool steels include hot work steels, steels for plastic injection molds, and impact resistant steels.

The high strength and wear resistance of tool steels make them an ideal material for use in a variety of industrial applications, including injection molding. However, selecting the appropriate tool steel for a particular application can be a complex process that requires careful consideration of factors such as the type of plastic to be molded, the desired surface finish, and the required tool life.

2.1.2 Development of Tool Steels

The development of tool steels has been driven by the need to improve the performance and durability of tools used in various industrial applications. Over time, advances in metallurgy, heat treatment, and manufacturing techniques have led to the creation of a wide range of tool steels with different properties and characteristics.

An important milestone in the development of tool steels was the invention of crucible steel in the middle of the 19th century. This new type of steel was produced by melting iron and adding various alloying elements to achieve a more homogeneous and consistent material. It was also possible to produce larger quantities of crucible steel than other types of steel, making it more accessible to manufacturers.

In the late 19th and early 20th centuries, new alloying elements were added to tool steels, including tungsten, molybdenum, chromium, and vanadium. These elements significantly improved the strength, toughness, and wear resistance of tool steels, making them more suitable for demanding industrial applications.

During the Second World War, the demand for tool steels increased dramatically, as they were used extensively in the manufacture of military equipment. This led to further advances in tool steel technology, including the development of high-speed steels that could withstand the high temperatures generated by high-speed machining.

Today, tool steels remain an important material for a variety of industrial applications, including injection molding. Technological advances continue to push the boundaries of what is possible with tool steels, and new materials and manufacturing techniques are constantly being developed to improve their performance and reliability.

2.1.3 Types of Tool Steels

Tool steels are classified into different types based on their properties and intended use. The classification is typically based on the alloying elements and heat treatment required to achieve certain properties.

Carbon tool steels

Carbon tool steels such as C75 or C100S are the oldest and simplest type of tool steel. They have a carbon content of 0.6% to 1.5%. These steels are inexpensive and easy to heat-treat, making them ideal for small tools that do not require high precision. Carbon tool steels are commonly used for chisels, knives, and hand tools.

High-speed steels

High-speed steels are designed for high-speed machining applications where the cutting speed exceeds 50 m/min. They contain tungsten, molybdenum, and vanadium as alloying elements. These steels have a high degree of hardness, wear resistance, and toughness, making them ideal for cutting and drilling tools. High-speed steels are commonly used for cutting tools in the automotive, aerospace, and medical industries.

Impact-resistant tool steels

Impact-resistant tool steels such as 1.2714 or 1.2355 are designed to withstand impact loads. They contain chromium, molybdenum, and vanadium as alloying elements. These steels are used for applications that require high toughness and resistance to cracking, such as cold chisels, hammers, and other hand-held tools.

Hot-work steels

Hot-work steels such as 1.2343 or 1.2344 are designed for use in high-temperature applications where the tool is exposed to high stress and wear. They contain tungsten, molybdenum, and chromium as alloying elements. These steels have a high degree of toughness, wear resistance, and thermal stability, making them ideal for use in forging tools, extrusion dies, and other hot work applications.

Cold-work steels

Cold-work steels such as 1.2379 or 1.2510 are designed for use in cold-work applications where the tool is exposed to high stress and wear. They contain tungsten, molybdenum, and vanadium as alloying elements. These steels have a high degree of hardness, toughness, and wear resistance, which makes them ideal for use in punching tools and other cold-work applications.

Plastic mold steels

Plastic mold steels such as 1.2311 or 1.2738 are intended for use in injection molding and other plastic molds. They contain chromium, molybdenum, and vanadium as alloying elements. These steels have a high degree of hardness, wear resistance, and thermal conductivity, which makes them ideal for use in plastic molding applications.

High-strength low-alloy (HSLA) tool steels

HSLA tool steels such as S700MC are designed for use in high-strength applications where the tool is exposed to high stress and wear. They contain molybdenum, chromium, and vanadium as alloying elements. These steels have a high degree of hardness, toughness, and wear resistance, which makes them ideal for use in highly stressed applications such as gears and shafts [1].

Powder metallurgical tool steels

Powder metallurgical tool steels are produced by mixing and pressing fine metal powders, which are then sintered at high temperatures. These steels have a high degree of density, toughness, and wear resistance, making them ideal for use in heavy-duty applications such as cutting tools, dies, and other precision components.

High-alloy tool steels

High-alloy tool steels such as 1.3247 are designed for use in applications that require high strength and wear resistance. They contain a high proportion of alloying elements such as tungsten and molybdenum.

2.2 Injection Molding Tool Steels

2.2.1 Introduction

Injection molding is a manufacturing process used to produce a wide range of molded plastic parts and products. In injection molding, plastic pellets or granules are melted and injected into a mold cavity where they cool and solidify to form the desired molded part. Injection molding is a highly efficient and cost-effective process, making it one of the most popular methods for producing molded plastic parts.

Injection molds are a critical component of the injection molding process. The tools must be designed and manufactured to withstand the stresses of the molding process. Injection molding tool steels are specifically designed for use in injection molds and must have a unique combination of properties to withstand the stresses of the molding process.

Tool steels are a group of high-strength steels used for cutting, forming, and shaping materials. They are known for their high hardness, wear resistance, and toughness. Injection molding tool steels must have similar properties to standard tool steels, but must also have specific properties to withstand the high pressures, temperatures, and abrasion associated with the injection molding process.

The properties of injection molding tool steels are influenced by their composition, microstructure, and heat treatment. The composition of the steel is crucial for determining its mechanical properties, including hardness, toughness, and wear resistance. The microstructure of the steel, which is influenced by the heat treatment process, plays a crucial role in determining the mechanical properties of the steel.

Selecting the appropriate injection molding tool steel for a particular application is critical to the success of the molding process. Factors to consider when selecting a tool steel include the type of plastic to be molded, the expected production volume, and the expected tool life.

In summary, injection molding tool steels are a critical component of the injection molding process. They must be carefully selected to ensure that they have the necessary properties to withstand the stresses of the molding process. The specific properties of injection molding tool steels and their influence on suitability for different applications are discussed in more detail in the next section.

2.2.2 Properties of Injection Molding Tool Steels

Injection molding tool steels are selected for their ability to withstand the stresses of the injection molding process. They must have certain properties to ensure that they can withstand the high pressure, high temperature, and abrasion associated with the injection molding process. This section discusses the important properties of injection molding tool steels and how these affect their suitability for use in injection molding.

Hardness

The hardness of injection molding tool steels is an important property that determines their resistance to wear and deformation. The harder the tool steel, the more resistant it is to wear and deformation under high-pressure molding conditions. However, the toughness of the tool steel decreases with increasing hardness. In order for the tool steel to withstand the stresses of the forming process, a balance must be found between hardness and toughness.

Toughness

Toughness is the ability of a material to resist cracking or breaking under conditions of high stress. During injection molding, tool steels are subjected to high stresses, and must have a high toughness to prevent cracks or fractures. Toughness is influenced by the microstructure of the tool steel as well as its alloying elements and heat treatment.

Wear resistance

Injection molding tool steels must have a high wear resistance to prevent damage of the tool surface. Wear resistance is influenced by the hardness of the tool steel as well as its microstructure and alloying elements. Tool steels with high wear resistance are typically used in applications where the tool surface is exposed to a high degree of abrasion, such as in the production of abrasive materials or parts with rough surfaces.

Corrosion resistance

Corrosion resistance is an important property for tool steels used in injection molding, as the injection molding process can be corrosive. Tool steels with high corrosion resistance are typically used in applications where the tool is exposed to corrosive materials or environments. The corrosion resistance of tool steels is influenced by their alloying elements, particularly chromium and molybdenum.

Thermal conductivity

The thermal conductivity of injection molding tool steels is important to maintain a uniform temperature throughout the mold. Tool steels with high thermal conductivity are better able to dissipate heat from the molded part surface, reducing the risk of hot spots and improving the overall quality of molded parts. The thermal conductivity of tool steels is influenced by their alloying elements, particularly copper and nickel.

Machinability

Machinability is an important property for injection molding tool steels, as they need to be machined to form the complex shapes required for injection molding. Tool steels with good machinability are easier to machine and result in less wear on the cutting tools. Machinability is influenced by the microstructure of the tool steel as well as its alloying elements and heat treatment [2].

In summary, the properties of injection molding tool steels play a critical role in determining their suitability for various applications. The properties discussed in this section, including hardness, toughness, wear resistance, corrosion resistance, thermal conductivity and machinability, must be carefully considered when selecting a tool steel for injection molding. The next section will introduce the different types of tool steels and their specific properties that are commonly used in injection molding.

2.2.3 Composition of Injection Molding Tool Steels

Injection molding tool steels such as 1.2344 or 1.2311 are high-performance materials that can withstand the extreme conditions of the injection molding process. These steels are specially formulated to provide excellent strength, toughness, wear resistance, and thermal stability, to ensure a long life and consistent performance of the injection mold. The composition of injection molding tool steels plays a crucial role in determining their properties and suitability for various applications. This chapter presents the different types of tool steels used in injection molding, and their compositions.

Low-alloy tool steels

Low-alloy tool steels are often used in the manufacture of injection molds due to their excellent combination of toughness and wear resistance. These tool steels contain a low percentage of alloying elements, typically less than 5%, including chromium, molybdenum, and vanadium. The carbon content in these tool steels is between 0.3% and 0.6%, and they are often heat-treated to achieve the desired properties.

High-alloy tool steels

High-alloy tool steels are designed to provide exceptional wear resistance, toughness, and corrosion resistance. These tool steels contain a higher proportion of alloying elements than low-alloy tool steels, often over 5%. Chromium, molybdenum, vanadium, and tungsten are commonly used alloying elements in high-alloy tool steels. The carbon content in high-alloy tool steels is between 0.7% and 1.5%, and they are typically heat-treated to achieve the desired properties.

High-speed steels

High-speed steels are used to manufacture injection molds that require high cutting speeds and temperatures, such as those used for processing thermoset plastics. These tool steels typically contain high levels of carbon, tungsten, molybdenum, and chromium. The high carbon content in high-speed steels ranges from 0.8% to 1.5%, while the alloying elements are typically present in quantities of 7% to 20%. High-speed steels are heat-treated to achieve the desired properties, including high hardness, wear resistance, and toughness.

Hot-work tool steels

Hot-work tool steels are designed to withstand the high temperatures and pressures of injection molding. These tool steels typically contain a high percentage of chromium, molybdenum, and vanadium, as well as other alloying elements such as tungsten, cobalt, and nickel. The carbon content in hot work tool steels is between 0.4% and 1.4%, and they are heat-treated to achieve the desired properties, including high hardness, toughness, and thermal stability.

Cold-work steels

Cold-work tool steels are used to manufacture injection molds that require high wear resistance, toughness, and dimensional stability. These tool steels typically contain a small percentage of alloying elements, including chromium, molybdenum, vanadium, and tungsten. The carbon content in cold work tool steels is between 0.5% and 1.5%, and they are often heat treated to achieve their desired properties.

Maraging tool steels

Maraging tool steels are high-strength, low-alloy steels that are commonly used in the manufacture of injection molds. These tool steels contain a small percentage of carbon, typically less than 0.03%, and a high percentage of nickel, cobalt, and molybdenum. Maraging tool steels are heat-treated to achieve their desired properties, which include high strength, toughness, and wear resistance.

Powder metallurgical tool steels

Powder metallurgical tool steels are produced by a process in which powdered tool steel is mixed with a binder and the mixture is then compacted into a desired shape. These tool steels offer excellent wear resistance, toughness, and dimensional stability, making them ideal for use in injection molds. Powder metallurgical tool steels typically contain high levels of alloying elements such as chromium, molybdenum, and vanadium, and their carbon content ranges from 0.4% to 2.5%. They are heat-treated to achieve their desired properties.

Stainless steels

Stainless steels are a group of corrosion-resistant steels that are commonly used in the manufacture of injection molds. These tool steels contain at least 10.5% chromium, which provides excellent corrosion resistance. They also contain varying amounts of other alloying elements such as nickel and molybdenum, which can improve their mechanical properties. Stainless steels are available in several different grades, each with their own unique combination of properties, and they are often heat-treated to improve their strength and toughness.

Specialized tool steels

In addition to the tool steels already discussed, there are also several specialized tool steels that are used in injection molding. These include high-strength tool steels, impact-resistant tool steels, and wear-resistant tool steels. These tool steels are formulated to meet specific requirements of the injection molding process, such as the ability to withstand high impact forces, or resist wear and abrasion.

In summary, the composition of injection molding tool steels plays a decisive role in determining their properties and suitability for various applications. Tool steels can vary greatly in terms of their alloying elements, carbon content, and heat treatment. Therefore, it is important to select the right tool steel for the specific requirements of the injection molding process. In the next section, the heat treatment process used to improve the properties of injection molding tool steels is presented [3].

2.2.4 Heat Treatment of Injection Molding Tool Steels

Heat treatment (see Figure 2.1) is a crucial step in the manufacturing process of injection molding tool steels. Proper heat treatment can significantly improve the mechanical properties of the tool steel, including its hardness, toughness, and wear resistance. The heat treatment process typically includes the following steps:

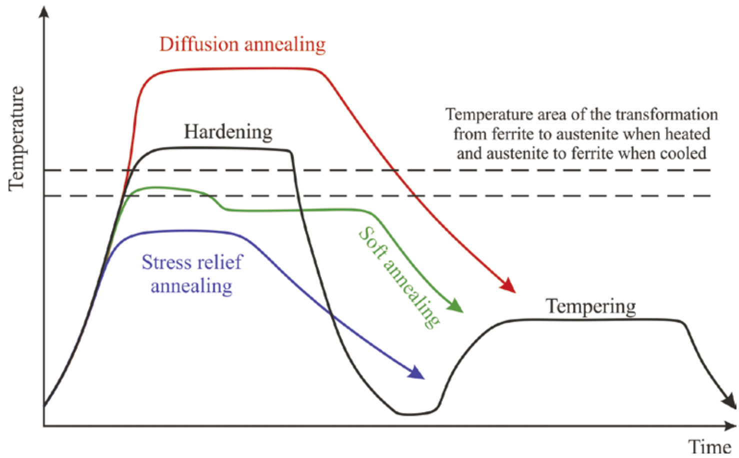

Figure 2.1 Heat treatment of steels (Image based on [4])

Annealing

During annealing, the tool steel is heated to a certain temperature and held there for a certain period of time before it is slowly cooled down. This process is used to relieve internal stresses in the tool steel and improve its machinability. Annealing also makes the tool steel softer and more ductile, which can be an advantage in certain applications.

Hardening

During hardening, the tool steel is heated to a high temperature and then quickly cooled to room temperature. This process forms a hard, wear-resistant surface layer on the tool steel while retaining a relatively soft and tough interior. Hardening can be carried out using various techniques, such as oil quenching, water quenching, or air cooling, depending on the composition and desired properties of the tool steel.

Tempering

Tempering is the reheating of the hardened tool steel to a certain temperature and subsequent cooling to room temperature. This process reduces the hardness and brittleness of the tool steel, and at the same time improves its toughness and ductility.

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