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Heat Treatment Processes of Common Metal Materials for Stamping Dies

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Abstract: *In order to improve hardness, toughness, and wear resistance, extend die service life, and reduce production costs, this paper focuses on optimizing the heat treatment processes of common metal materials used in stamping dies. By employing theoretical analysis and case studies, the research mainly explores the effects of annealing, quenching, tempering, and vacuum heat treatment parameters on die performance. The study finds that optimizing heat treatment parameters — such as temperature control and holding time — can significantly enhance the comprehensive performance of die materials, especially for high-carbon high-chromium die steels and high-speed steels. Therefore, the reasonable selection of metal materials combined with precise heat treatment processes can greatly improve the performance of stamping dies, providing effective technical support for the manufacturing industry.*

Keywords: *Stamping Die; Common Metal Materials; Heat Treatment; Process*

1. Introduction

With the rapid development of modern manufacturing, higher requirements have been proposed for the performance and service life of stamping dies in China, aiming to ensure product quality and production efficiency [1]. The heat treatment process of metal materials, through precise control of heating, holding, and cooling stages, can significantly improve the hardness, wear resistance, and toughness of dies, providing crucial technical support for performance optimization. At present, materials such as high-carbon high-chromium die steel and high-speed steel are widely used in complex stamping applications due to their excellent mechanical properties, but the realization of their full potential highly depends on the adaptability of the heat treatment process [2]. However, improper temperature control during heat treatment can easily cause deformation and internal stress, which may lead to premature die failure and increased production costs. Therefore, conducting an in-depth study on the heat treatment processes of common metal materials for stamping dies, and exploring the synergy between process parameters and material properties, is of great practical significance for breaking through the lifespan bottleneck of dies and promoting high-quality development in the manufacturing industry.

2. Overview of Common Metal Materials for Stamping Dies

The common metal materials used for stamping dies mainly include carbon tool steel, high-carbon high-chromium tool steel, matrix steel, and alloy tool steel. Among them, carbon tool steel is low-cost and easy to process, but it has poor hardenability and insufficient wear resistance, making it suitable for light-duty dies. High-carbon high-chromium steel features high wear resistance and slight deformation, but repeated upsetting and drawing are required to improve carbide segregation, making it suitable for high-precision stamping dies [3]. Matrix steel achieves a balance between strength and toughness through compositional adjustment, offering excellent overall performance and suitability for complex working conditions. Alloy tool steel enhances hardenability and heat resistance through the addition of elements such as Cr and Mo, and is suitable for medium- and high-load dies. In addition, low-alloy steel improves quenching deformation and wear resistance based on carbon steel, while high-carbon medium-chromium steel ensures both uniform carbide distribution and dimensional stability. The selection of materials should comprehensively consider factors such as strength, wear resistance, processing cost, and production volume — for example, carbon steel is used for simple dies, while

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alloy steel is used for high-demand applications. The classification diagram of common metal materials for stamping dies is shown in Figure 1.

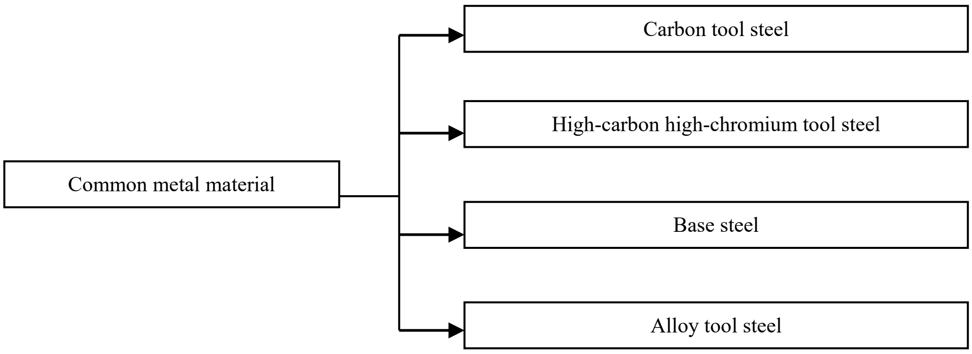

Figure 1 Schematic Diagram of Common Metal Material Categories for Stamping Dies

3. Common Heat Treatment Processes for Metal Materials of Stamping Dies

3.1 Annealing Process

The annealing process improves material properties through heating, holding, and slow cooling. The purpose of annealing is to reduce hardness, enhance machinability, eliminate residual stress to prevent deformation and cracking, and refine grains to lay the foundation for subsequent processes [4]. According to material composition and application requirements, annealing can be divided into several types: full annealing is suitable for hypoeutectoid steel, which is heated to 30–50 C above Ac_3 and then furnace-cooled to optimize the structure of castings or forgings; it is not recommended for hypereutectoid steel, as network cementite may reduce toughness. Spheroidizing annealing, applied to eutectoid or hypereutectoid steels, involves heating to 20–30°C above Ac_1 followed by slow cooling to promote carbide spheroidization, significantly improving machinability and quenching stability—making it the preferred process after forging die steel. Isothermal annealing rapidly cools the material to the pearlite region and holds it isothermally, shortening the cycle and producing a uniform microstructure, which is particularly suitable for alloy steels. Stress-relief annealing, performed at 500–650°C, removes machining stress and creates stable conditions for subsequent processing steps.

3.2 Quenching Process

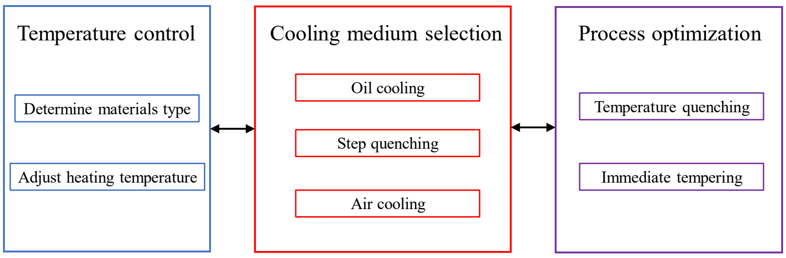

Figure 2 Quenching Process Flowchart

Quenching is the core process in the heat treatment of stamping dies. Through rapid cooling, the steel forms a high-hardness martensitic structure, which significantly enhances wear resistance and deformation resistance. The key process points are as follows: (1) Temperature Control: The heating temperature should be adjusted according to the material type. For example, carbon tool steel (such as T10A) requires quenching at 760–810°C, while high-carbon high-chromium steel such as Cr12 needs

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to be heated to 950–980°C to eliminate carbide segregation. Excessive temperature may lead to grain coarsening, whereas insufficient temperature may result in incomplete austenitization [5]. (2) Selection of Cooling Medium: Oil cooling is commonly used for thin-plate blanking dies to reduce deformation; for thick-section dies, step quenching can be adopted — holding first in a salt bath and then air cooling — to avoid cracking. (3) Process Optimization: For dies with complex shapes, isothermal quenching can balance hardness and toughness, making it suitable for high-precision blanking dies. After quenching, tempering should be performed immediately to relieve internal stress and stabilize the microstructure.

This process directly affects die service life. For instance, after high-temperature quenching of Cr12MoV steel used in silicon steel sheet punching dies, wear resistance is greatly improved, making it suitable for mass production. However, attention should be paid to the deformation risk of carbon steels during quenching; parameters must be carefully selected based on workpiece quantity and material type. The flowchart of the quenching process is shown in Figure 2.

3.3 Tempering Process

Tempering is primarily used to eliminate internal stress generated during quenching and to optimize material properties. The quenched die steel has a brittle martensitic structure, which may cause deformation or cracking; therefore, tempering is necessary to stabilize the microstructure and adjust mechanical performance. According to temperature differences, tempering processes are divided into three categories: low-temperature tempering (150–250°C) retains high hardness (58–64 HRC) while reducing brittleness, suitable for improving the wear resistance of high-carbon steel dies; medium-temperature tempering (350–500°C) forms tempered troostite, providing high elasticity and toughness, and is often used for strengthening spring-type dies; high-temperature tempering (500–650°C) produces tempered sorbite, offering the best combination of strength and plasticity, commonly applied to structural parts subjected to alternating loads, and often combined with quenching to form a quenching and tempering treatment [6]. For precision dies, vacuum tempering can be adopted, in which heating occurs in an oxygen-free environment to minimize surface oxidation, maintain metallurgical integrity, and control distortion. The tempering process must strictly follow holding time and temperature parameters; for complex dies, the holding time should be extended to fully eliminate residual stress. Through selective tempering, dies can achieve the property of a "hard surface and tough core," meeting the dual requirements of wear resistance and impact resistance under stamping conditions.

3.4 Vacuum Heat Treatment Process

The vacuum heat treatment process is carried out in a vacuum environment, effectively preventing oxidation and decarburization, and significantly improving the wear resistance and service life of dies. Its principle is to use vacuum heating, controlling the temperature range between 950°C and 1050°C to induce phase transformations within the metal, such as austenitization. This is followed by rapid cooling (quenching) to form a high-hardness martensitic structure, and subsequent tempering to balance toughness and hardness. For example, high-carbon high-chromium steel such as Cr12MoV can achieve a hardness of over 60 HRC after vacuum quenching while maintaining a low deformation rate, making it suitable for precision stamping dies. Vacuum heat treatment also reduces surface defects, improves material uniformity and fatigue resistance, and is particularly suitable for mass-produced dies such as those used in automobile body stamping and forming.

4. Application of Heat Treatment Processes for Metal Materials of Stamping Dies

4.1 Heat Treatment of Carbon Steel

In stamping die manufacturing, the heat treatment process of carbon steel — through precise control of heating, holding, and cooling — significantly improves the material's mechanical properties and service life. First, annealing involves heating the die steel above its critical temperature, holding it, and then slowly cooling it in the furnace. This effectively reduces hardness, improves machinability, and eliminates internal residual stress to prevent deformation and cracking in subsequent processes [7]. For example, full annealing is suitable for hypoeutectoid steels, refining grains and establishing a structural foundation for final heat treatment, while spheroidizing annealing targets hypereutectoid steels, promoting carbide spheroidization to enhance toughness and wear resistance. Second, the quenching

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process rapidly cools the heated die, forming a martensitic structure that provides high hardness and strength; however, tempering must follow to eliminate brittleness. Low-temperature tempering (150–250°C) reduces internal stress while maintaining hardness, whereas medium-temperature tempering (350–500°C) increases the elastic limit, making it suitable for high-load die components. The treatment process of carbon steel is illustrated in Figure 3. As shown in Figure 3, during the heat treatment of carbon steel, the selected material is 45# steel, and the temperature used is above 200°C. During processing, martensitic laths (M) and troostite (T) form. In the process, black blocks appear as troostite forms gradually. As the holding time increases and furnace treatment completes, white martensitic laths (M) and black troostite blocks (T) are formed, and the temperature gradually decreases, thus completing the carbon steel heat treatment process.

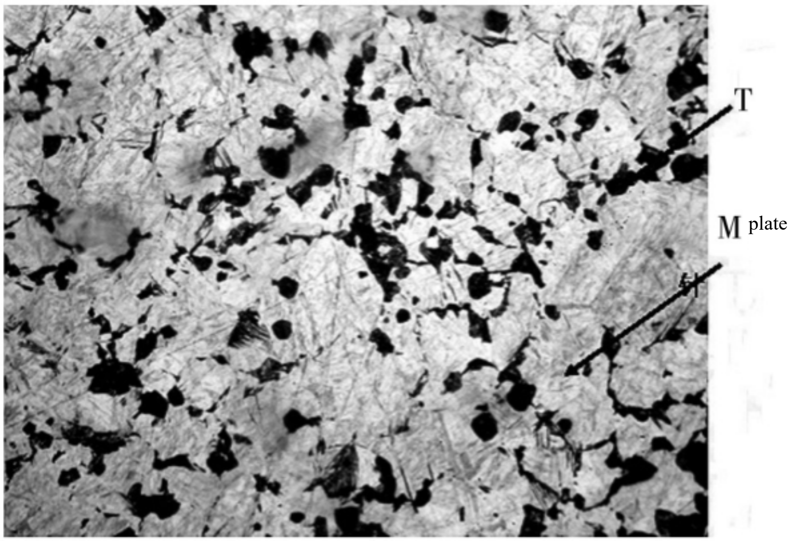

Figure 3 Carbon Steel Treatment Process

4.2 Heat Treatment of High-Carbon High-Chromium Steel

High-carbon high-chromium steel is widely used in stamping dies, and its heat treatment process — through precise control of quenching and tempering parameters — significantly enhances the die's wear resistance and deformation resistance [8]. Taking DC53 die steel as an example, its heat treatment process begins with a preheating stage, where the die is preheated at 600–650°C, effectively reducing internal thermal stress and laying the foundation for subsequent austenitization. Then, during the austenitizing stage at 1000–1040°C, the die is rapidly cooled by oil quenching or gas quenching, allowing the material to achieve a hardness of 60–62 HRC, ensuring high hardness while avoiding the risk of cracking [9]. In the tempering stage, high-temperature tempering at 520–530°C stabilizes the hardness at 62–63 HRC, balancing wear resistance and toughness, which is particularly suitable for precision blanking dies. In contrast, low-temperature tempering (180–200°C) is used for applications requiring extremely high hardness, maintaining 58–62 HRC and improving the die's wear resistance. In addition, nitriding treatment can further strengthen surface properties. After gas nitriding at 525°C, the surface hardness can reach 1250 HV, with wear resistance improved by more than three times, making it ideal for high-friction working conditions.

4.3 Heat Treatment of Matrix Steel

As one of the commonly used materials for stamping dies, the heat treatment process of matrix steel directly affects the service life and precision of the die. Through precise control of heating, holding, and cooling stages, this process significantly enhances the wear resistance, toughness, and dimensional stability of the die [10]. In practical applications, matrix steel must first undergo annealing to eliminate forging stress and refine grains, thereby laying the foundation for subsequent quenching. During the quenching stage, step heating or isothermal quenching techniques are adopted to avoid deformation and cracking risks while ensuring the formation of a high-hardness martensitic structure. After quenching, tempering must be carried out promptly. Low-temperature tempering (150–250°C) is used to relieve internal stress and adjust toughness, allowing the die to maintain high hardness while improving resistance to chipping. For example, Cr12MoV matrix steel can achieve a hardness of 58–62 HRC after

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quenching at 1020–1050°C and tempering at 180–200°C, making it suitable for high-precision blanking dies. In addition, for dies with complex structures, surface treatment processes such as shot peening are often combined to further suppress crack propagation and enhance fatigue resistance.

4.4 Heat Treatment of Alloy Materials

In the application of alloy materials, the heat treatment process — through precise control of heating, holding, and cooling — can significantly optimize the mechanical properties and service life of the material [11]. The heat treatment of alloy materials typically includes annealing, normalizing, quenching, and tempering. Annealing refines grains through slow cooling, reduces material hardness, and improves machinability, laying the foundation for subsequent forming operations. Normalizing uses air cooling to obtain a uniform microstructure, enhancing both toughness and strength. Quenching, as a critical step, rapidly cools the material to form a high-hardness martensitic structure, greatly improving wear resistance; however, it must be followed by tempering to relieve internal stress and prevent brittle cracking. For example, hot stamping technology combines forming and quenching processes, achieving plastic deformation of the metal at high temperatures while completing heat treatment. This is particularly suitable for high-strength steel used in automotive components, expanding the material's applicability and improving production efficiency.

5. Optimization Schemes for Heat Treatment Processes of Stamping Die Metal Materials

5.1 Process Parameter Optimization

The optimization of heat treatment processes for stamping die metal materials should focus on key parameters such as temperature control and holding time. Temperature control directly affects die hardness and wear resistance; excessively high temperatures can lead to coarse austenite grains, increasing the risk of deformation and cracking, while insufficient temperatures may cause inner hole shrinkage or expansion, affecting dimensional accuracy. It is recommended to adopt a staged heating strategy, preheating high-alloy steel dies to 520–580°C before raising to the quenching temperature limit, to reduce thermal stress and inhibit crack formation. Holding time should match the material composition and section thickness; overly long holding can induce structural brittleness, while too short a duration may result in incomplete phase transformation. The optimal window is best determined through simulation experiments. In addition, the tempering process should avoid both low-temperature and high-temperature brittleness. For precision dies, multiple tempering cycles are recommended to relieve internal stress, ensuring stability and toughness. Optimized parameters can synergistically enhance die life and fatigue resistance, meeting the demands of high-load stamping environments.

5.2 Equipment Improvement and Upgrading

Optimizing the heat treatment process of stamping dies relies on the deep integration of advanced equipment and intelligent technology. Modern heat treatment equipment integrates high-precision temperature control systems, which monitor furnace temperature differences in real time (deviation $< \pm 15$°C), ensuring uniform heating of metal materials and significantly reducing deformation or cracking caused by temperature fluctuations. For example, roller-bottom heating furnaces combined with robotic fast-transfer technology (material handling completed within 3 seconds) greatly shorten the process cycle and improve stability for batch processing. Intelligent control systems further optimize process parameters. Using infrared thermometers with short-wavelength technology, surface temperature changes of the metal can be precisely captured. Coupled with automated feedback mechanisms, heating rate and cooling time are dynamically adjusted, avoiding concentrated thermal stress typical of conventional processes. Moreover, the introduction of 4D quenching systems enables fixture-free quenching, controlling cooling paths to minimize deformation, particularly suitable for complex high-precision dies. Equipment upgrades should also emphasize energy efficiency and environmental protection. New heat treatment furnaces adopt waste heat recovery designs to reduce energy consumption, while exhaust treatment modules comply with emission standards to minimize harmful substance release.

5.3 Energy Management and Technical Training

Energy consumption in the heat treatment of stamping dies mainly stems from insufficient heating

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efficiency, aging equipment, and improper operation. In order to optimize energy saving management, the following measures can be taken. First of all, to upgrade the heating equipment, the use of high-efficiency resistance furnace or induction heating technology to reduce heat loss. Secondly, it is necessary to optimize process parameters, such as reasonable control of quenching temperature and tempering time to avoid overheating. At the same time, intelligent temperature control system is introduced to monitor energy consumption data in real time and dynamically adjust operation mode. Energy management not only reduces production costs but also decreases carbon emissions, aligning with green manufacturing trends. In addition, strengthening technical training continually improves operator skills. Systematic training should reinforce the understanding of heat treatment principles, such as the effects of quenching and tempering on material properties, and proper equipment operation. Training content should cover energy-saving operation techniques, like balancing rapid heating and holding time, to reduce energy waste. Regular case analyses should be organized to share successful experiences and common problem-solving approaches, enhancing practical capabilities. Skill improvement can significantly reduce human errors, extend die life, and ensure production stability and quality consistency.

6. Conclusion

This paper systematically studied the heat treatment processes of commonly used metal materials for stamping dies. By analyzing the characteristics of carbon steel, high-carbon high-chromium die steel, and high-speed steel, it explored the effects of annealing, quenching, tempering, and vacuum heat treatment on die hardness, toughness, and wear resistance. The study shows that optimizing heat treatment parameters can significantly extend die service life and reduce production costs. In the future, with the development of intelligent manufacturing and green manufacturing technologies, heat treatment processes will evolve toward automation, energy efficiency, and environmental protection, such as integrating artificial intelligence to control temperature curves and developing low-carbon-emission processes, further promoting high-quality development in the stamping die industry.

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