

The Influence and Mechanism of Cryogenic Treatment on the Mechanical Properties of Steel Materials

Jie Yang, Yuhan Zhang

Ningxia Tiandi Northwest Coal Meachine Limited Company, Shizuishan, 753000, China

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Abstract: Deep cryogenic treatment technology, as an advanced cold treatment process aimed at improving the performance and service life of metal materials, has attracted widespread attention in the field of materials science in recent years. This technology is not only widely used in the treatment of steel materials, but also shows good treatment effects on non-ferrous metal materials and composite materials. Through cryogenic treatment, the grain size of steel materials is refined, the number of grain boundaries is increased, thereby improving the strength and toughness of the material. At the same time, cryogenic treatment can also promote the transformation of residual austenite into martensite, further improving the hardness and wear resistance of steel materials. In addition, the precipitation of carbides and the adjustment of residual stress during the cryogenic treatment process also play a crucial role in improving the performance of steel materials. However, the impact mechanism of cryogenic treatment on the mechanical properties of steel materials is complex and involves multiple factors. The interaction between grain refinement, residual austenite transformation, carbide precipitation, and residual stress adjustment collectively affects the properties of steel materials. This article explores the influence and mechanism of cryogenic treatment on the mechanical properties of steel materials.

1. Introduction

The application of cryogenic treatment has been frequently integrated into industrial production since the 1950s, and its impact is profound and widespread [1]. Deep cryogenic treatment, a process method, refers to placing the processed material in a specific environment, artificially controlling the temperature to construct an extremely low temperature field, in order to achieve optimization and improvement of the material's microstructure [2]. The core lies in enhancing or optimizing the physical and chemical properties of materials by altering their microstructure, in order to meet the specific application requirements [3]. Traditional cold treatment processes often have some problems when dealing with metal materials, such as high residual austenite and susceptibility to material cracking [4]. These issues not only affect the performance of materials, but also limit their application scope in the industrial field. However, the emergence of cryogenic treatment provides effective solutions to these problems. The tool steel, high-speed steel, and other materials manufactured after cryogenic treatment not only greatly improve the wear resistance and toughness of the tools, cutting tools, and workpieces, but also significantly extend their service life. These excellent properties have led to the widespread promotion and application of cryogenic treatment in

the industrial field, as well as the attention and favor of many researchers [5].

The reason why cryogenic treatment can improve the performance of materials is due to the influence of low-temperature environment on the microstructure of materials [6]. At extremely low temperatures, the grain size of the material is refined and the number of grain boundaries increases, which improves the strength and toughness of the material [7]. At the same time, cryogenic treatment can also promote the transformation of residual austenite into martensite in the material, further improving the hardness and wear resistance of the material. In addition, during the cryogenic treatment process, the stress state inside the material will also change, and residual stress will be adjusted, thereby improving the comprehensive performance of the material. Compared with traditional cold treatment processes, cryogenic treatment has many advantages. Firstly, the cost of cryogenic treatment is relatively low, the equipment is simple, and the operation is convenient, which makes it highly cost-effective in practical applications. Secondly, cryogenic treatment consumes less energy and causes less environmental pollution, which is in line with the current green and environmentally friendly production concept. Finally, cryogenic treatment can significantly improve the performance of materials, enhance product quality and reliability, and bring greater economic benefits to enterprises.

In the industrial field, the application range of cryogenic treatment is very wide. Whether it is high-end manufacturing industries such as automobile manufacturing and aerospace, or traditional industries such as mechanical manufacturing and electronics, cryogenic treatment plays an important role. Through cryogenic treatment, the wear resistance, fatigue resistance, corrosion resistance and other properties of materials can be improved, thereby extending the service life of products and enhancing their competitiveness. In addition, cryogenic treatment has shown great potential in the field of new material research and development. With the continuous progress of science and technology, new metal materials, composite materials, etc. are constantly emerging. These materials often have excellent performance, but at the same time, there are also some insurmountable problems. Deep cryogenic treatment, as an effective material modification method, can provide strong support for the research and application of these new materials.

2. Development of Cryogenic Treatment Technology

Deep cryogenic treatment technology refers to a process method that places the processed material in an extremely low temperature environment and improves its performance by changing the microstructure of the material [8]. This technology originated in the 1950s, and with the continuous development of industrial production, its application scope and depth gradually expanded [9]. The core of cryogenic treatment technology lies in utilizing the influence of low-temperature environment on the microstructure of materials, promoting processes such as phase transformation, precipitation, and grain refinement, thereby improving the mechanical and physical properties of materials [10]. The development process of cryogenic treatment technology can be described as a history of continuous innovation and improvement. Initially, cryogenic treatment technology was mainly applied in fields with high material performance requirements, such as aerospace, nuclear industry, etc.

With the continuous progress of technology and the reduction of costs, cryogenic treatment technology is gradually being applied in a wider range of fields, including automotive manufacturing, mechanical manufacturing, electronics and appliances, etc. At the same time, the process parameters and methods of cryogenic treatment technology are constantly optimized and improved, making the treatment effect more significant and the application range more extensive. The development of cryogenic treatment technology has also driven the research and upgrading of related equipment. In order to meet the needs of different materials and processes, cryogenic

treatment equipment has undergone significant improvements and innovations in structural design, temperature control, cooling media, and other aspects. This makes the cryogenic treatment process more efficient, stable, and safe, providing strong technical support for improving the performance of steel materials.

3. The Influence of Cryogenic Treatment on the Mechanical Properties of Steel Materials

As one of the most widely used metal materials in the world, optimizing and improving the performance of steel materials has always been a research focus in the field of materials science. With the advancement of technology and industrial development, traditional heat treatment processes can no longer meet the high requirements of modern industry for the performance of steel materials. The rise and development of cryogenic treatment technology have opened up new avenues for optimizing the performance of steel materials. For steel materials, traditional heat treatment processes such as quenching and tempering can improve the hardness and strength of the material to a certain extent, but often come with the problem of retained austenite. Residual austenite not only reduces the hardness and strength of the material, but also affects its wear resistance and service life. The emergence of cryogenic treatment technology provides a new solution to this problem.

Firstly, cryogenic treatment can significantly improve the hardness and wear resistance of steel materials. Through cryogenic treatment, residual austenite in steel materials is further transformed, and the martensite content increases, thereby improving the hardness and strength of the material. At the same time, cryogenic treatment can also promote the precipitation and grain refinement process inside the material, further improving the wear resistance of the material. This enables steel materials that have undergone cryogenic treatment to have a higher service life and processing accuracy when manufacturing workpieces such as cutting tools, cutting tools, and molds. Secondly, cryogenic treatment can also improve the toughness and fatigue resistance of steel materials. During the cryogenic treatment process, the residual stress inside the material is adjusted, the microstructure is optimized, and the toughness of the material is enhanced. At the same time, cryogenic treatment can also reduce micro cracks and defects inside the material, and improve its fatigue resistance. This makes steel materials that have undergone cryogenic treatment have better resistance to damage when subjected to alternating and impact loads.

4. Mechanism Analysis

During the cryogenic treatment process, residual austenite in steel materials is further transformed, mainly into martensite, which significantly improves the hardness and strength of the material. The formula for the transformation of residual austenite can be expressed as:



Among them, A_r represents residual austenite, α' represents martensite, and γ_r represents other phases or precipitates that may be generated.

Deep cryogenic treatment, as an effective process, reduces the temperature of the material to the extremely low temperature range, promoting phase transformation inside the material and optimizing its performance. In steel materials, the main function of cryogenic treatment is to transform residual austenite into martensite, which has a significant impact on the dimensional stability, hardness, and strength of the material. According to Figure 1, as the insulation time of cryogenic treatment prolongs, the content of residual austenite gradually decreases. This is because during the cryogenic treatment process, the low-temperature environment provides a driving force

for the transformation from austenite to martensite, and the extension of the holding time makes this transformation process more complete and complete. Therefore, increasing the holding time can increase the conversion rate of residual austenite, allowing more austenite to transform into martensite. Residual austenite is prone to phase transformation under temperature changes or stress, resulting in changes in material size. Martensite, on the other hand, has a more stable crystal structure and is less prone to phase transformation. Therefore, increasing the content of martensite can improve the dimensional stability of the material, enabling it to maintain stable performance during long-term use.

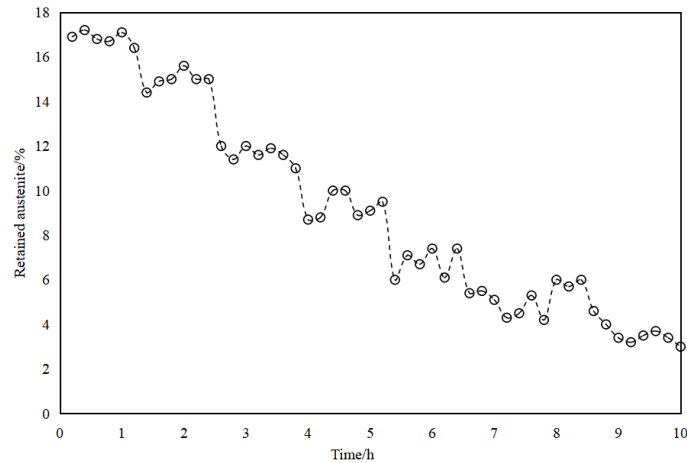


Figure 1: Percentage content of residual austenite under different insulation times

Table 1 shows the residual austenite content of the same steel material after different deep cooling treatments. Deep cooling treatment of the steel material before tempering can effectively reduce the residual austenite content in the steel material. This is because cryogenic treatment provides thermodynamic driving force for the transformation of austenite to martensite by lowering the material temperature, thereby reducing the amount of residual austenite. From the table, it can be seen that when the cryogenic time is extended from 1 hour to 12 hours, the decrease in residual austenite content is not significant. This is because within 1 hour of deep cooling, most of the transformable austenite has completed its transformation into martensite, so extending the deep cooling time has limited effect on further reducing the residual austenite content. After three cycles of deep cooling, the residual austenite content in steel materials significantly decreases. This indicates that cyclic cryogenic treatment can more effectively promote the transformation of austenite to martensite. Cyclic treatment gradually transforms austenite into martensite through multiple phase transformation processes, thereby significantly reducing the content of residual austenite.

Table 1: Residual austenite content/% of the same steel material after different cryogenic treatments

Cryogenic treatment process	Residual austenite content
No cryogenic treatment	6.5
Cryogenic treatment for 1 hour	5.3
Cryogenic treatment for 12 hour	5.2
Cryogenic treatment for 1 hour ×3	3.3

5. Conclusions

Steel materials that have undergone cryogenic treatment exhibit superior performance in all aspects. Deep cryogenic treatment, as an effective material modification method, optimizes the

microstructure and properties of materials by reducing the temperature of the material to the extremely low temperature zone, promoting phase transformation inside the material. Deep cryogenic treatment significantly reduces the residual austenite content in steel materials, promoting the transformation of austenite into martensite. This transformation process enhances the hardness and strength of the material, improves its wear resistance and fatigue resistance. Martensite, as a high-strength and high hardness microstructure, occupies a larger proportion in materials, enabling steel materials to withstand greater loads and more complex working conditions. Deep cryogenic treatment also improves the dimensional stability of steel materials. Residual austenite is prone to phase transformation under temperature changes or stress, resulting in changes in material size. And cryogenic treatment reduces the content of residual austenite, reduces the size changes caused by phase transformation, and enables the material to maintain stable performance during long-term use. In addition, cryogenic treatment may also have a positive impact on the toughness, corrosion resistance, and other properties of steel materials. By optimizing the microstructure and phase composition of materials, cryogenic treatment can improve their comprehensive performance, making them more adaptable to various complex working environments and application requirements. In summary, cryogenic treatment is an effective process that can significantly improve the performance of steel materials. By selecting and controlling reasonable cryogenic treatment process parameters, precise regulation and optimization of steel material properties can be achieved, providing higher quality material support for industrial production and application.

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