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Study on Defect Evolution of Molybdenum-Rhenium Alloy under High-Temperature Irradiation Conditions

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Abstract: The defect evolution of molybdenum-rhenium alloy under high-temperature (irradiation) conditions is a complex and critical issue that directly impacts the material's performance and stability. This paper comprehensively discusses the formation mechanisms, control, and optimization strategies of defects in molybdenum-rhenium alloy under irradiation conditions, focusing on the research progress in alloy composition regulation, optimization of preparation process parameters, and design of heat treatment regimes. By analyzing the influence of alloy composition on defects, optimizing the preparation process parameters, and designing heat treatment regimes, this study aims to control and optimize the defect evolution of molybdenum-rhenium alloy under high-temperature (irradiation) conditions, providing important references for improving its irradiation resistance and stability.

Keywords: high temperature; irradiation; molybdenum-rhenium alloy; defect evolution

1. The Importance of Molybdenum-Rhenium Alloy under High-Temperature Irradiation Conditions

Molybdenum-rhenium alloy exhibits significant application value and importance under high-temperature (irradiation) conditions. As an alloy composed of molybdenum and rhenium, it possesses outstanding high-temperature strength, high-temperature oxidation resistance, and irradiation resistance, making it widely applicable in high-temperature environments. Firstly, its superior high-temperature strength and resistance to creep enable the alloy to maintain structural stability and strength under high-temperature conditions, making it suitable for structural materials in high-temperature work situations. Secondly, its good high-temperature oxidation resistance allows it to operate stably for long periods in oxidizing atmospheres without undergoing oxidation corrosion, making it suitable for applications in high-temperature atmospheres. Thirdly, its irradiation resistance enables it to maintain the stability of its material structure and properties when subjected to irradiation (such as in nuclear devices), thus making it extensively used in the nuclear industry for reactor structural materials or other materials in radiation environments. Furthermore, due to its excellent performance, molybdenum-rhenium alloy finds important applications in various fields such as aerospace, nuclear industry, chemical industry, fuel cells, and medical devices, providing material solutions for these fields under high-temperature and irradiation conditions. Lastly, its excellent high-temperature strength and oxidation resistance confer it with a long service life and reliability, thereby providing strong support for the long-term stable operation of equipment.

2. Characteristics and Applications of Molybdenum-Rhenium Alloy

2.1 Basic Characteristics of Molybdenum-Rhenium Alloy

Molybdenum-rhenium alloy is an important high-performance alloy composed of molybdenum and rhenium. It possesses excellent physical and chemical properties, making it widely used in various industrial fields. Firstly, molybdenum-rhenium alloy exhibits outstanding high-temperature strength and hardness, maintaining structural stability and strength in extremely high-temperature environments, thus making it a crucial material option in aerospace and nuclear industries. Secondly, the alloy demonstrates good corrosion resistance, making it suitable for manufacturing corrosion-resistant equipment in chemical and marine environments. With a low coefficient of thermal expansion, molybdenum-rhenium alloy resists thermal expansion under high-temperature conditions, making it suitable for manufacturing high-temperature engineering components. Additionally, the alloy exhibits excellent electromagnetic properties, widely used in medical device manufacturing and electronic technology fields. Its good irradiation stability makes it suitable for use in nuclear industry applications such as reactor structural materials and other irradiation-affected equipment.

In practical applications, molybdenum-rhenium alloy finds wide application in aerospace industries for spacecraft components, rocket engine parts, etc. In the nuclear industry, it serves as structural materials for nuclear reactors and fusion reactors. In the medical field, it is used to manufacture X-ray tubes and CT scanning equipment. In the chemical industry, it is employed for corrosion-resistant equipment and pipeline manufacturing. Moreover, it is used in shipbuilding for manufacturing high-temperature, high-pressure components. With its excellent high-temperature strength, corrosion resistance, low coefficient of thermal expansion, good electromagnetic properties, and irradiation stability, molybdenum-rhenium alloy plays a crucial role in various fields, providing reliable solutions for extreme conditions. Its multifaceted excellent characteristics make it an important material in numerous fields.

2.2 Advantages and Application Fields of Molybdenum-Rhenium Alloy in High-Temperature Environments

Under high-temperature conditions, molybdenum-rhenium alloy exhibits many excellent characteristics, making it widely used in various fields. It possesses outstanding high-temperature strength and oxidation resistance, maintaining structural stability and strength, and resisting the effects of oxidation and creep in high-temperature environments. This makes molybdenum-rhenium alloy an important material in aerospace engineering, used for manufacturing high-temperature engineering components such as aircraft engine components and rocket engine parts. With excellent heat resistance and high-temperature stability, it finds important applications in the nuclear industry. In reactor structures, molybdenum-rhenium alloy can provide long-term stable performance and radiation stability, suitable for structural components of nuclear reactors. It is also widely used in the medical device field, particularly in the manufacture of X-ray tubes that require high temperatures. Molybdenum-rhenium alloy with good electromagnetic properties enables efficient operation of medical imaging equipment, improving equipment performance and stability. In the chemical industry, its corrosion resistance and high-temperature stability make it an ideal material for manufacturing corrosion-resistant equipment and pipelines. In high-temperature and corrosive environments, the alloy maintains good performance stability and can operate reliably for long periods. In shipbuilding, molybdenum-rhenium alloy also plays a significant role. Its high-temperature corrosion resistance makes it suitable for manufacturing high-temperature, high-pressure components for ships, enhancing ship durability and safety.

3. Defect Evolution of Molybdenum-Rhenium Alloy under High-Temperature Conditions

Despite its many excellent characteristics, molybdenum-rhenium alloy may face potential defect evolution issues under high-temperature conditions. In such extreme environments, the alloy may exhibit the following defect evolution phenomena:(1)Grain Boundary Diffusion: At high temperatures, the diffusion rate at the grain boundaries of molybdenum-rhenium alloy accelerates, leading to atomic migration near the grain boundaries. This can result in grain boundary embrittlement and a decrease in mechanical properties, thereby affecting the stability and lifespan of the material.(2). Grain Growth: Under high-temperature conditions, grains in molybdenum-rhenium alloy are prone to grow larger. Grain growth may reduce the strength and ductility of the material, induce stress concentration under applied stress, and increase the material's susceptibility to brittle fracture.(3). Precipitation of Dispersed Phases: Some dispersed phases present in the alloy may precipitate and grow at high temperatures, forming new grain boundaries or electron structures. This can lead to degradation of material properties, including reduced strength, and changes in hardness.(4). Accumulation of Internal Stress: Internal stress accumulation within the material, caused by differences in thermal expansion coefficients, for example, may induce fatigue cracking and fracture failure of the material under prolonged high-temperature exposure.(5). Oxidation and Corrosion: In high-temperature oxidative environments, molybdenum-rhenium alloy is susceptible to oxidation and corrosion, resulting in the formation of oxides and corrosion products. This damages the material surface, weakens its corrosion resistance, and renders it unstable in application.

4. Defect Evolution of Molybdenum-Rhenium Alloy under Irradiation Conditions

4.1 Defect Variation under Different Irradiation Intensities

Under irradiation conditions, molybdenum-rhenium alloy undergoes a series of defect evolution processes. Irradiation causes the material to be influenced by nuclear radiation, leading to a series of atomic displacements and defect generation, thereby affecting the structure and properties of the material. The defect evolution of molybdenum-rhenium alloy may vary under different irradiation intensities. Under low irradiation conditions, there is typically an accumulation and diffusion of point defects such as vacancies and interstitials, along with some dislocation pile-ups. This may result in changes to the material's microstructure, increase in dislocation density at grain boundaries, and subsequently affect the material's mechanical properties and durability. Under high irradiation intensities, due to increased atomic displacements, the defect density significantly increases, with more grain boundary dislocations, voids, and interstitials appearing. These abundant defects significantly impact the material's macroscopic properties, such as embrittlement, reduced ductility, and a sharp decline in mechanical performance. Under high irradiation conditions, a certain amount of irradiation-induced stress may also be generated, increasing the material's internal stress and further affecting its performance and stability.

4.2 Mechanisms of Irradiation-Induced Defect Formation

Under irradiation conditions, molybdenum-rhenium alloy experiences irradiation-induced defect evolution, which is caused by nuclear radiation interacting with the material atoms. Nuclear radiation interacts with material atoms, leading to deviations in atomic arrangements. In this scenario, displacement production effects occur in the material, namely dislocations and vacancies. These dislocations and vacancies are the most fundamental irradiation-induced defects, leading to changes in the material's structure. During irradiation, atomic migration and diffusion occur in the material, resulting in changes in local atomic concentration. This atomic diffusion may lead to various defects near grain boundaries, such as vacancy and interstitial clusters, thereby affecting the material's stability and properties. Irradiation also leads to an increase in dislocation density. Dislocations move and pile up in the crystal, forming phenomena such as dislocation loops and dislocation creep. The increase in these dislocations affects the material's deformation and plastic processing properties. Irradiation-induced defects may also include voids, interstitial clusters, creep swelling, solute precipitation at grain boundaries, and other complex defects. The formation of these defects alters the material's microstructure, thereby affecting its macroscopic properties.

5. Control and Optimization Strategies for Defect Evolution of Molybdenum-Rhenium Alloy under High-Temperature Irradiation Conditions

5.1 Influence of Alloy Composition on Defects

Controlling and optimizing the defect evolution of molybdenum-rhenium alloy under high-temperature (irradiation) conditions is crucial, and alloy composition plays a vital role in the formation and evolution of defects. Suitable alloy element additions can effectively alter the interatomic interaction strength and grain boundary stability of the material, thus slowing down the rate of defect formation. For instance, alloy element additions can act as solid solution strengtheners, impeding dislocation movement, restricting irradiation-induced defect diffusion, and enhancing the material's irradiation resistance. Alloy composition can influence the material's grain boundary energy and stability, thereby regulating grain boundary migration rates and dislocation-grain boundary interactions. By carefully controlling alloy composition, the strength and migration characteristics of grain boundaries can be altered, thereby suppressing defect diffusion and aggregation at grain boundaries, slowing down the material's creep rate, and reducing the accumulation of internal stresses. Alloy composition can also adjust the material's crystal structure and diffusion rate, controlling the processes of defect diffusion and aggregation. Through the design of added alloy elements, the material's grain boundary structure and defect diffusion behavior can be optimized, thereby improving its irradiation resistance and high-temperature stability. The selection and addition of alloy elements directly affect the material's defect formation mechanisms and evolution paths, providing important technical support and optimization strategies for enhancing the stability, reliability, and durability of molybdenum-rhenium alloy.

5.2 Optimization of Preparation Process Parameters

Controlling and optimizing the defect evolution of molybdenum-rhenium alloy under high-temperature irradiation conditions is crucial, and optimizing the preparation process parameters is a key factor affecting material performance and defect formation. During preparation, optimizing process parameters can influence the material's crystal structure and grain size, thereby affecting defect formation and diffusion. By optimizing heat treatment processes, preparation processes, and process parameters, the stability of grain boundaries and refinement of grains can be controlled, reducing the formation of grain boundary-biased defects and improving the material's irradiation resistance. Optimizing process parameters can control the material's stress state and thermal expansion properties, effectively reducing irradiation-induced stress generation and accumulation of internal stresses. Appropriate process parameters can reduce the risk of stress corrosion and stress corrosion cracking of materials under high-temperature irradiation conditions, prolonging the material's service life. Optimizing process parameters during preparation can also improve the material's surface properties and corrosion resistance, reducing its interaction with external media. Optimization of process parameters can form a protective film on the surface of molybdenum-rhenium alloy or alter its surface activity, reducing its reactivity with high-temperature oxidation environments and enhancing its oxidation resistance.

5.3 Design of Heat Treatment Regimes

Under high-temperature irradiation conditions, effective design of heat treatment regimes can control and optimize the defect evolution of molybdenum-rhenium alloy, improving its irradiation resistance and stability. Appropriate annealing treatments can eliminate stresses and defects in the alloy during preparation, improving the material's crystallization state and grain structure. By properly controlling annealing temperature and time, the strength and dislocation density of grain boundaries can be reduced, diminishing the formation of intragranular defects, and enhancing the material's fatigue life and thermal stability. Solution treatment and aging treatment can optimize the alloy's crystal structure and strengthening phase distribution, improving the material's deformation resistance and irradiation resistance. Through solution treatment and aging treatment, the mechanical properties and thermal stability of the alloy can be improved, reducing dislocation migration and grain boundary diffusion rates, and suppressing the diffusion and aggregation of irradiation-induced defects. Introducing new strengthening phases and local alloying treatments are also important means to enhance the irradiation resistance of molybdenum-rhenium alloy.

Conclusion

The defect evolution of molybdenum-rhenium alloy under high-temperature irradiation conditions is a highly researched area of interest, holding significant importance in fields such as nuclear energy and aerospace. Through in-depth studies on alloy composition regulation, optimization of preparation process parameters, and design of heat treatment regimes, a better understanding and control of the defect formation and evolution of molybdenum-rhenium alloy in high-temperature (irradiation) environments can be achieved. This provides technical support for material design, engineering applications, and safe operation.

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