Study on Control Strategy of Impurity Elements and Influence of Mechanical Properties during Hot Working of Regenerated Titanium Alloy TC4

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Abstract: With the deepening of the concept of sustainable development, the research and application of recycled titanium alloy TC4 have attracted much attention. This paper focuses on the hot working process of regenerated titanium alloy TC4, and studies the influence of impurity elements on its mechanical properties and control strategies. By expounding the basic theory of regenerated titanium alloy TC4, this paper analyzes the effects of temperature, strain rate and other parameters on the behavior of impurity elements during hot working, puts forward the control strategy of impurity elements including pretreatment, real-time control of hot working and post-treatment, and discusses the influence mechanism of interaction and distribution of impurity elements with alloy matrix on mechanical properties. It is found that thermal processing parameters significantly affect the diffusion and distribution of impurity elements, and reasonable control strategies can effectively manage impurity elements. Finally, it is concluded that comprehensive and targeted impurity element control strategy can improve the quality and mechanical properties of recycled titanium alloy TC4, and provide support for its high-quality application in various fields.

1. Introduction

In the process of modern industrial development, titanium alloys have been widely used in many fields such as aerospace, biomedicine and automobile manufacturing because of their excellent specific strength, corrosion resistance and good biocompatibility [1]. Among them, TC4 titanium alloy, as the most commonly used one, plays an important role in various industries [2]. The production of primary titanium alloy not only consumes a lot of resources, but also brings high environmental costs [3]. With the idea of sustainable development deeply rooted in people's hearts, recycled titanium alloy technology came into being, and recycled titanium alloy TC4 gradually became the focus of research and application.

Hot working process is very important to improve the properties of regenerated titanium alloy TC4. Through hot working, the microstructure of the alloy can be improved, its comprehensive properties can be improved, and the strict requirements for material properties in different fields can be met [4]. However, in the hot working process, the existence of impurity elements will significantly affect the properties of regenerated titanium alloy TC4 [5]. Impurity elements may come from recycled raw materials themselves, or may be mixed in the process of recycling. Their types, contents and distribution will have complex effects on the mechanical properties of the alloy. If the impurity elements are not properly controlled, the mechanical indexes such as strength, plasticity, toughness and fatigue performance of regenerated titanium alloy TC4 may fluctuate, and even can not meet the practical application requirements in serious cases [6]. Therefore, it is of great practical significance to study the control strategy of impurity elements in the hot working process of regenerated titanium alloy TC4 and clarify the influence law of impurity elements on its mechanical properties, so as to improve the quality stability of regenerated titanium alloy TC4, expand its application scope and promote the recycling of resources.

At present, although the research results of primary titanium alloy are abundant, the research on

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the control of impurity elements and the influence of mechanical properties of regenerated titanium alloy TC4 during hot working is still insufficient [7]. Many key issues, such as the migration and transformation mechanism of impurity elements in different stages of thermal processing, effective real-time monitoring and precise control means, still need to be further explored. The purpose of this paper is to systematically study the control strategy of impurity elements in the hot working process of regenerated titanium alloy TC4, and deeply analyze the influence mechanism of impurity elements on its mechanical properties, so as to provide reference for the high-quality application of regenerated titanium alloy TC4.

2. Basic theory of regenerated titanium alloy TC4

As a typical α+β titanium alloy, titanium alloy TC4 is mainly composed of titanium (Ti), aluminum (Al) and vanadium (V). Among them, aluminum can improve the strength and thermal stability of the alloy, while vanadium can improve the machinability and toughness of the alloy [8]. This combination of alloy components endows TC4 with good comprehensive properties. The preparation of regenerated titanium alloy TC4 is based on the recycling of waste titanium alloy materials. In this process, firstly, the recycled waste materials are sorted and cleaned to remove the pollutants attached to the surface. Then, it is re-cast by smelting and other processes to obtain the regenerated titanium alloy ingot. In this process, it is necessary to accurately control the composition and process parameters to ensure the quality of the recycled alloy.

Impurity elements are ubiquitous in regenerated titanium alloy TC4. Some of these impurity elements come from recycled waste materials, which may bring in various impurities due to the differences in the original use environment and processing technology. The other part is mixed into the recycling process due to factors such as equipment and environment [9]. Common impurity elements include iron (Fe), oxygen (O), nitrogen (N) and so on. Although iron can improve the strength of the alloy to a certain extent, excessive iron will reduce the plasticity and toughness; Oxygen and nitrogen will be dissolved in titanium alloy matrix, which will lead to lattice distortion, significantly improve the strength and hardness of the alloy, but greatly reduce the plasticity.

3. Influence of thermal processing on impurity elements

Parameters such as temperature and strain rate during hot working, like precise regulators, change the distribution, existing form and interaction of impurity elements in the alloy. Temperature plays a central role in the hot working process. When the hot working temperature is in a low range, the diffusion rate of impurity elements is relatively slow, and its distribution in the alloy changes little. However, with the gradual increase of temperature, the atoms of impurity elements gain more energy and begin to diffuse more actively in the lattice. Taking iron (Fe) as an example, at the hot working temperature of 600°C, the diffusion distance of iron atoms in the crystal lattice is limited, and its distribution is basically maintained in the initial state; However, when the temperature rises to 800°C, the diffusion of iron atoms intensifies and begins to migrate to the grain boundary region. This migration phenomenon will affect the grain boundary properties of the alloy and may change the strength and toughness of the grain boundary. Strain rate also plays an important role in the behavior of impurity elements. Higher strain rate will produce a large number of dislocations in the alloy, which will become the rapid diffusion channel of impurity elements. When the strain rate increases from $0.01s^{-1}$ s to $0.1s^{-1}$ s, the oxygen (O) impurity element diffuses along the dislocation line more easily, which accelerates its redistribution in the alloy. This difference in diffusion of impurity elements caused by the change of strain rate will affect the uniformity of microstructure of the alloy and then affect its mechanical properties.

The length of hot working time is also closely related to the behavior of impurity elements. In a short hot working time, impurity elements may not be able to fully diffuse and react, and their influence on alloy properties is relatively limited. However, with the extension of hot working time, impurity elements have more time to diffuse, aggregate and react with the matrix. For example, nitrogen (N) impurity elements have a relatively uniform content distribution in the alloy at the initial stage of hot working, but after a long period of hot working, they will gradually gather in some areas to form nitride precipitation phases, which will change the microstructure and properties of the alloy. Table 1 shows the influence of thermal processing parameters on the diffusion distance of impurity elements:

Table 1 Impact of Hot Working Parameters on the Diffusion Distance of Typical Impurity Elements

Impurity Element	Hot Working Temperature (°C)	Strain Rate (s^{-1})	Hot Working Time (min)	Diffusion Distance (μm)
Iron (Fe)	600	0.01	30	5.2
	800	0.01	30	12.5
Oxygen (O)	700	0.01	30	4.8
	700	0.1	30	8.6
Nitrogen (N)	750	0.01	20	3.9
	750	0.01	40	7.3

It can be clearly seen from Table 1 that the diffusion distance of impurity elements is obviously different under different combinations of thermal processing parameters. The diffusion distance of impurity elements will increase with the increase of hot working temperature, strain rate and hot working time. The change of diffusion distance of this impurity element directly affects its distribution uniformity in the alloy, and then has a far-reaching impact on the mechanical properties of regenerated titanium alloy TC4. Therefore, it is very important to understand the influence of hot working process on impurity elements for accurately controlling the quality and properties of regenerated titanium alloy TC4.

4. Impurity element control strategy

Table 2 Control Strategies and Expected Effects for Impurity Elements in Recycled Titanium Alloy TC4

Impurity Element	Control Method in Pre-treatment Stage	Expected Effect	Control Method in Hot Working Stage	Expected Effect	Control Method in Post-treatment Stage	Expected Effect
Iron (Fe)	Strictly screen high-iron-containing recycled materials; clean to remove surface iron contaminants	Keep iron content in raw materials at a low level	Monitor iron content in real time and adjust hot working parameters if necessary; add elements that can react with iron	Inhibit the diffusion and aggregation of iron, reducing its impact on plasticity and toughness	Homogenization annealing treatment	Make iron distribution more uniform and improve performance consistency
Oxygen (O)	Deep chemical cleaning; remove surface oxide layer	Reduce surface oxygen content of raw materials	Monitor oxygen content in real time, lower hot working temperature to inhibit oxygen diffusion; add rare earth element cerium	Reduce the solid solubility of oxygen in the alloy and decrease lattice distortion	Vacuum melting and refining	Remove some oxygen through volatilization and reduce oxygen content
Nitrogen (N)	Avoid exposing recycled materials to high-nitrogen environments; clean to remove nitrogen-containing impurities	Reduce initial nitrogen content in raw materials	Monitor nitrogen content in real time and adjust strain rate to inhibit nitrogen diffusion; add elements that can react with nitrogen	Prevent nitrogen from forming a large amount of nitride precipitation phases	Homogenization annealing combined with electron beam melting	Improve nitride distribution and reduce nitrogen content

In the hot working process of regenerated titanium alloy TC4, effective control of impurity elements is the key to ensure that the alloy has excellent mechanical properties. According to the characteristics of impurity elements in different stages of hot working, a series of comprehensive and detailed control strategies need to be formulated. In the pretreatment stage of thermal processing, the first task is to strictly screen the recycled materials. The recycled materials have a wide range of sources, complex components and great differences in impurity content. Through advanced nondestructive testing technology and chemical composition analysis, materials with excessive impurity content can be accurately identified and eliminated, and the risk of impurity elements entering the recycled alloy can be reduced from the source. For example, X-ray fluorescence spectrometry can be used to quickly and accurately determine the content of various elements in recycled materials, including impurity elements. At the same time, it is also very important to deeply clean the recycled materials. Using appropriate chemical cleaning agents and physical cleaning methods can remove oil, dust and other pollutants attached to the surface of materials and prevent these substances from introducing impurities in the subsequent processing.

Real-time monitoring and control in hot working process are also indispensable. With the help of advanced on-line monitoring equipment, such as inductively coupled plasma emission spectrometer (ICP-OES), the content change of impurity elements in alloy melt can be monitored in real time. Once the content of impurity elements is found to be close to the preset control upper limit, corresponding control measures shall be taken immediately. The control means include adjusting the thermal processing parameters to inhibit the diffusion and reaction of impurity elements; Or adding specific alloying elements to make them react with impurity elements to form stable compounds, thus reducing the negative influence of impurity elements on alloy properties. In the post-treatment stage of hot working, the content of impurity elements can be further reduced or their distribution can be improved through appropriate heat treatment and refining technology. The control strategy and expected effect of TC4 impurity elements in regenerated titanium alloy are shown in Table 2.

5. Influence mechanism of impurity elements on mechanical properties

Although the content of impurity elements in regenerated titanium alloy TC4 is relatively small, it is like the initial variable in the "butterfly effect" and has a great influence on the mechanical properties of the alloy. Behind these influences, there is a complex and subtle mechanism. The interaction between impurity elements and alloy matrix is an important factor affecting mechanical properties. Taking the element oxygen (O) as an example, the radius of oxygen atom is smaller than that of titanium atom, and it is easily dissolved in titanium alloy matrix, resulting in lattice distortion. This distortion will hinder the dislocation movement and increase the strength of the alloy, but at the same time it also limits the plastic deformation ability of the material and leads to the plastic decline. The action mechanism of nitrogen (N) element is similar to that of oxygen. After solid solution, it also causes lattice distortion, which significantly improves the hardness and strength of the alloy, but reduces its toughness. The distribution of impurity elements also has a far-reaching influence on mechanical properties. When impurity elements segregate at grain boundaries, the properties of grain boundaries will be changed. Table 3 shows the influence of impurity elements on the mechanical properties of regenerated titanium alloy TC4:

Table 3 Impact of Impurity Elements on the Mechanical Properties of Recycled Titanium Alloy TC4

Impurity Element	Content Change (%)	Tensile Strength Change (MPa)	Yield Strength Change (MPa)	Elongation Change (%)	Impact Toughness Change (J/cm²)
Oxygen (O)	0.1-0.2	+50-+80	+40-+70	-5--8	-10--15
Nitrogen (N)	0.05-0.1	+40-+60	+30-+50	-4--7	-8--12
Iron (Fe)	0.2-0.3	+20-+40	+15-+30	-3--5	-6--10

As can be seen from Table 3, with the increase of impurity element content, the tensile strength and yield strength of the alloy show an upward trend, but the elongation and impact toughness gradually decrease. This shows that impurity elements not only improve the strength of the alloy, but also damage its plasticity and toughness. Impurity elements comprehensively affect the mechanical properties of regenerated titanium alloy TC4 by changing the crystal structure, dislocation movement and grain boundary properties of the alloy.

6. Conclusions

In this paper, the control strategy of impurity elements in the hot working process of regenerated titanium alloy TC4 and the influence mechanism of impurity elements on its mechanical properties are deeply studied. In the control strategy of impurity elements, strict screening and deep cleaning of recycled materials before hot processing reduce the introduction of impurity elements from the source. In the hot working process, the content of impurity elements is monitored in real time with the help of advanced online monitoring equipment, and the behavior of impurity elements is effectively regulated by adjusting process parameters and adding specific alloy elements. The heat treatment process and refining technology after hot working further optimize the content and distribution of impurity elements. This series of control strategies form a complete and comprehensive system, which provides a feasible way to accurately control impurity elements.

In the mechanism of the influence of impurity elements on mechanical properties, impurity elements cause lattice distortion and hinder dislocation movement by interacting with alloy matrix, thus improving strength but reducing plasticity and toughness. At the same time, the segregation of impurity elements at grain boundaries changes the properties of grain boundaries and becomes the source of cracks, which seriously affects the toughness and fatigue properties of the alloy. The study clearly reveals the negative effects of impurity elements on other properties while improving some properties of the alloy. Only by deeply understanding the behavior law of impurity elements in the hot working process and the influence mechanism on mechanical properties, and strictly implementing the control strategy of impurity elements in each stage, can the quality and mechanical properties of recycled titanium alloy TC4 be effectively improved and the wide application of recycled titanium alloy TC4 under the background of sustainable development be promoted.

References

[1] Han F X, Sun X P, Zheng N Q, et al. Effect of thermal processing on microstructure and properties of TC4 titanium alloy bar for blades[J]. Titanium Industry Progress, 2022, 39(06): 7-12. DOI: 10.13567/j.cnki.issn1009-9964.2022.06.011.

[2] Zhang B, Li D C, Cao H D, et al. Effect of temperature change rate on mechanical properties of TC4 titanium alloy during hot deformation[J]. Journal of Materials and Metallurgy, 2023, 22(05): 495-499. DOI: 10.14186/j.cnki.1671-6620.2023.05.013.

[3] Lan Z L, Wang Y F, Yin L S, et al. Research progress on effect of heat treatment on microstructure and properties of wire arc additive manufactured TC4 titanium alloy[J]. Foundry, 2024, 73(09): 1197-1209.

[4] Liu H D, Liu W J, Bian H Y, et al. Effect of local heat treatment on microstructure and properties of electron beam welded TC4 titanium alloy[J]. Modern Machinery, 2021, (03): 90-94. DOI: 10.13667/j.cnki.52-1046/th.2021.03.021.

[5] Li C Y, Zhong Y H, Huang Z G, et al. Microstructure and properties of TC4 alloy electronic packaging materials under different heat treatment conditions[J]. Transactions of Materials and Heat Treatment, 2020, 41(02): 51-58. DOI: 10.13289/j.issn.1009-6264.2019-0369.

[6] Li C F, Zhang J S, Zhou S Y. Microstructure and mechanical properties of CMT wire arc additive manufactured Ti-6Al-4V titanium alloy[J]. The Chinese Journal of Nonferrous Metals, 2022, 32(9): 2609-2619.

[7] Zhou J, Luo N, Liang H. Microstructure Analysis of TC4/Al 6063/Al 7075 Explosive Welded Composite Plate via Multi-scale Simulation and Experiment[J]. Rare Metal Materials and Engineering, 2025, 54(1): 27-38.

[8] Wang P Q, Wu M J, Wang Y Y. Research development on microstructure and properties of LAM TC4 titanium alloy with different heat treatment processes[J]. Aeronautical Manufacturing

Technology, 2020, 63(10): 56-65.

[9] Zhou H, Xi M, Liu R. Microstructures and mechanical properties of the forging TC11 titanium alloy repaired by the laser deposition and point-mode forging process[J]. Journal of Manufacturing Processes, 2024, 132: 935-947.