Research on the martensitic transformation induced by cryogenic treatment on stainless steel

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The effects of cryogenic treatment on the microstructure and mechanical properties of austenitic stainless steel were investigated in the present work. In situ magnetic method is used to study phase transition during cryogenic treatment. The results showed that cryogenic treatment could promote the transformation of austenite into martensite in AISI 321 stainless steel. It can be inferred that the stability of austenite in stainless steel at cryogenic temperature had great relationship with the chemical composition. The examination of microstructure in AISI 321 stainless steel revealed that transformation of austenite into martensite could occurred in the stages of cooling, heating and soaking during cryogenic treatment. The transformation amount of austenite is closely related to the cryogenic treatment temperature, and the lower the temperature, the greater the transformation amount. The transformation of austenite into martensite improved the tensile strength and yield strength significantly, while reduced the plasticiy of AISI 321 steel. It also showed that the lower the cryogenic treatment, the higher the improvement in strength.

Keywords: *Cryogenic treatment, stainless streel, austenite, martensite, tensile properties*

1. Introduction

Cryogenic treatment is an effective approach of material modification which has been acknowledged for many decades [1]. It has been reported that hundreds years ago Swiss watchmakers used to store high-wear watch parts in high mountain caves to allow cold conditioning for stability and wear resistance. Castings were often left outside in the cold for months, even years, to age and stabilize [2]. Nowadays, industries like aerospace, automotive and electronic have used this process in their production line to improve wear resistance and dimensional stability of components [3].

As a complementary process of conventional heat treatment, cryogenic treatment usually needs to combine with the conventional heat treatment in order to achieve the best effects. What's more, the process parameters such as minimum temperature, soaking time, cooling rate, heating rate and the subsequently temper of cryogenic treatment all have influence on the effects of this treatment. Therefore, the process of cryogenic treatment is one of the most key factors to determine the treatment effects.

There are several acknowledged theories about the mechanisms of cryogenic treatment in tool steels: the transformation of retained austenite to martensite, the precipitation of ultra-fine carbides particles [4] and the release of residual stress [5]. Although these mechanisms are not appropriate for non-ferrous metals, researchers also suggest that cryogenic treatment improved the mechanical properties, dimensional stability, wear resistance and even more thermal conductivity of aluminum alloys [6, 79], magnesium alloys [8, 9] and copper alloys [10]. However, the mechanism behind improvement in the ferrous has not been totally clarified.

Austenitic stainless steel is widely used in fields such as liquefied natural gas and aerospace rocket launch, due to the stability of austenite at cryogenic temperature. Traditionally, cryogenic treatment on most austenitic stainless steel cannot induce obvious martensitic transformation. Therefore, the cryogenic treatment of austenitic stainless steel has not received much attention However, the difference of chemical composition in austenitic stainless steel can also affect the stability of austenite. Considering long-term service at low-temperature environments, it will have significant impact on material properties if phase transformation occurs. In the present work, cryogenic treatment on the AISI 321 stainless steel is investigated. The changes of mechanical properties and microstructure induced by cryogenic treatment are examined.

2. Experimental details

2.1 Materials and cryogenic treatment

The raw material employed in this work was solution treated AISI 321 stainless steel plate with the thickness of 5 mm. The chemical composition is given in Table 1. Tensile samples were cut from the plates and divided into six groups, with one group is in the original state (RT), the other five groups were experienced cryogenic treatment at -60 ℃, -80 ℃, -120 ℃, -196 ℃ and -253 ℃, separately.

Tab. 1 Chemical composition of AISI 321 stainless steel (wt. %)

C	Cr	Mn	Si	Ni	Ti	S	P	Fe
0.022	17.77	1.53	0.47	9.06	0.20	0.002	0.031	Bal.

2.1 Tensile properties and microstructure

Tensile tests were conducted by the MTS-SANS CMT5000 Electronic Universal Tensile Testing Machine at room temperature according to the Chinese Standard of GB/T228-2002. Microstructure of samples treated by different process were detected by the method of in-situ magnetization measurement and Transmission Electron Microscope (TEM) (JEM-2100).

3. Results and discussion

3.1 Mechanical properties

The tensile properties of AISI 321 stainless steel treated by cryogenic treatment with different temperature are shown in Figure 1. It can be observed that cryogenic treatment can improve the tensile and yield strength obviously, and the improvement gets more significant with the decrease of temperature. As for tensile strength, the maximum improvement can be obtained by cryogenic treatment at -196 ℃, which increases by 104 MPa compared with that of RT. The tensile strength has no change when the temperature down to -253 ℃ compared with that at -196 ℃. The increase in yield strength is more significant compared to tensile strength. It increases by 84 MPa after cryogenic treatment at -60 ℃, while the change of tensile strength is slightly at this temperature. The yield strength continues to increase with the decrease of cryogenic temperature. The maximum improvement can be obtained by cryogenic treatment at -253 ℃, which is increased by 228 MPa compared with that of RT.

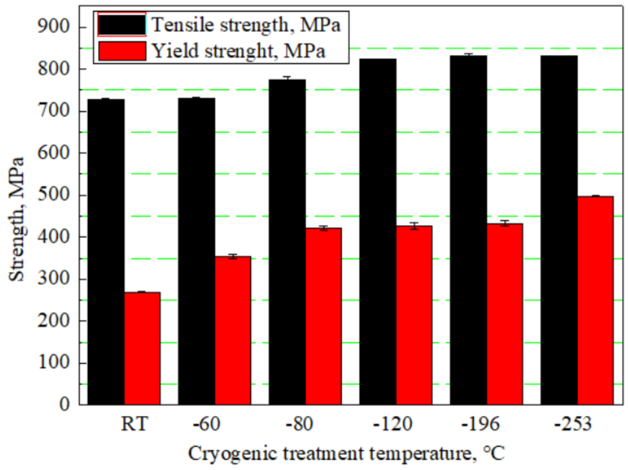

Figure 1 The changes of tensile strength and yield induced by cryogenic treatment

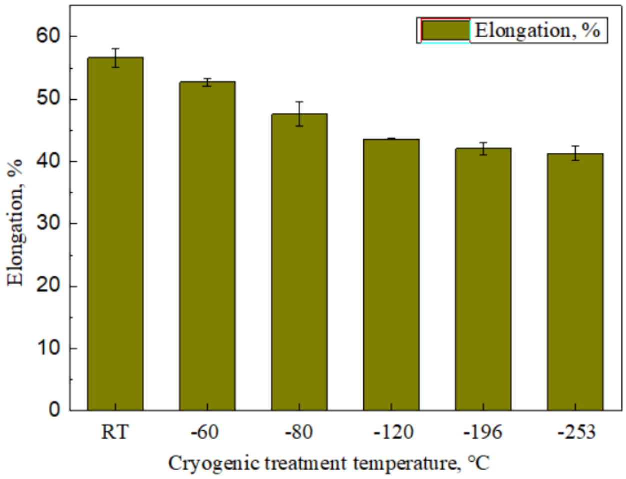

Figure 2 The changes of elongation induced by cryogenic treatment

However, the elongation of AISI 321 stainless steel is decreased by cryogenic treatment, which is more significant with the decrease of temperature, as shown in Figure 2. It can be inferred that cryogenic treatment has a significant strengthening effect on AISI 321 stainless steel.

3.2 Microstructure evolution

The strengthening of AISI 321 stainless steel by cryogenic treatment indicates that martensitic transformation may be induced by this treatment. Therefore, the in-situ magnetization measurement was adopted to investigate the phase transformation during the process of cryogenic treatment. Figure 3 shows the magnetic moment depending on temperature from 300 K to 77 K under different cooling/heating rates. Due to martensite is the only ferromagnetic phase and austenite is the only nonmagnetic phase in steels, the increase of magnetic moment can be attributed to the transformation of austenite into martensite.

It can be seen that the magnetic moment increases with the decrease of temperature significantly, which indicates the martensitic transformation. It can be seen that there is a plateau stage (approximately 300 K to 225 K) before the fast decrease on the transition curve during the continuous cooling process. A fast decreasing stage appears at 230-125 K, where the austenite is transformed into martensite with relatively high transformation rates. As the temperature is below 125 K, the transformation curve tends to be flat again and is almost retarded at 77 K. The martensitic transformation continues to occur in the subsequent heating process. After returning to room temperature, the magnetic moment of the material is much higher than the initial state, further indicating that the material undergoes irreversible martensitic transformation. It also can be observed that the lower cooling and heating rate is more beneficial to the martensitic transformation.

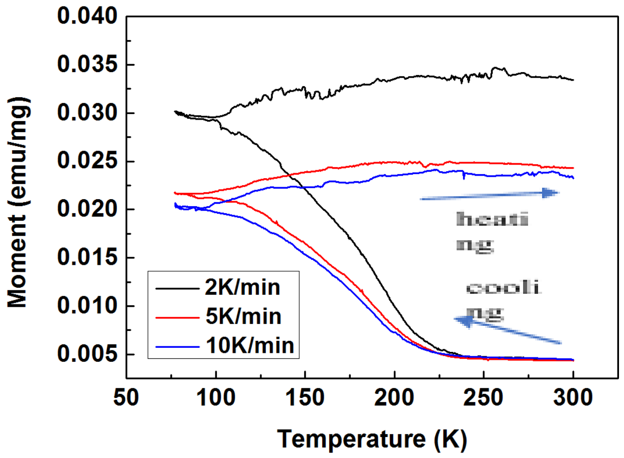

Figure 3 Volume fracion of retained austenite for continuous cooling/heating processes under different cooling and heating rates.

Furthermore, the isothermal martensite transformation is also evaluated by the in-situ magnetization measurement at different temperature, as shown in Figure 4. It can be seen that the changes of magnetic moment holding at 153 K and 193K are more significant than that holding at 77 K. This indicates that higher cryogenic temperature is more beneficial to the isothermal martensite transformation. However, the change of magnetic moment induced by isothermal holding is relative small, which means that the content of martensite induced by isothermal holding is small.

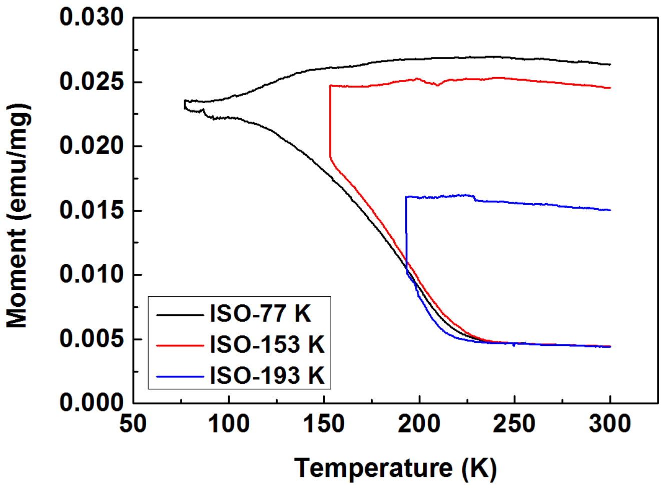

Figure 4 Isothermal martensite transformation at different isothermal temperatures

In order to further reveal the microstructure evolution induced by cryogenic treatment, microstructure of samples with RT and cryogenic treatment at -196 ℃ was examined by TEM, as shown in Figure 5. It can be seen that the microstructure of RT sample is consisted of equiaxed austenite grain. There are some

There are some fine needle like phases inside some austenite grains, which may be twins formed during annealing. After cryogenic treatment, there are a large amount of martensitic laths in the microstructure with different size. There are also some HCP martensite can be observed in the microstructure. Therefore, it can be demonstrated that cryogenic treatment can promote the formation of martensite in AISI 321 stainless steel.

During cryogenic treatment, the lattice contraction increases internal stress, promoting dislocation entanglement and increasing the driving force of shear deformation. In addition, as the lower fault energy at cryogenic temperatures, the initial temperature at which austenite undergoes transformation into martensitic increases, reducing the stability of austenite and promoting its transformation into martensite.

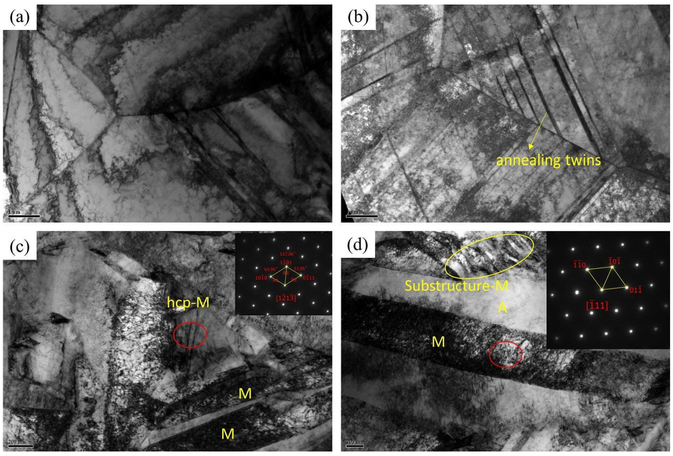

Figure 5 TEM micrographs of AISI 321 stainless steel with RT: (a), (b) and cryogenic treatment at -196 ℃: (c), (d)

4. Conclusion

1) Cryogenic treatment can improve the tensile strength and yield strength of AISI 321 stainless steel significantly. The lower temperature of cryogenic treatment, the higher improvement in strength, especially for yield strength. The maximum improvement in tensile and yield strength is by 104 MPa and 228 MPa, which are obtained by cryogenic treatment at -196 ℃ and -253 ℃ respectively.
2) The plasticity decreases with the decrease of cryogenic treatment temperature.
3) Martensitic transformation can be induced by cryogenic treatment during cooling, holding and reheating, and the maximum transformation occurs during the cooling process.

Acknowledgments

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