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Tensile and fatigue behavior of thin-walled cylindrical specimens under temperature gradient condition

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Abstract In the present study, a temperature gradient system was designed with the aim of carrying out the tensile and fatigue test of thin-walled cylindrical alloyed steel (30CrMnSi). The tensile test under different temperatures was first carried out to obtain the static mechanical parameters. And then a three-dimensional (3D) finite element model was constructed to further study the deformation behavior under temperature gradient by the finite element analysis (FEA). The FE result was in good agreement with that of the experiment. Following this, the tensile fatigue test was performed under cooled air and no-cooled air to investigate the influence of the temperature gradient on fatigue life-time, respectively. The influence of cooled air under the lower nominal stress on fatigue life was not obvious than that of higher nominal stress. Finally, the scanning electron microscopy (SEM) was employed to investigate the fracture mechanism. The microstructure revealed that the fracture first occurred at the zone where there was a lower temperature.

Introduction

The mechanical behavior of material at constant temperature has been studied widely. But the environmental effects, such as temperature gradient, have been rarely reported. In fact, the influence of temperature on the mechanical behavior is very important. Many structures such as cooling blade have obvious temperature gradient [1–3], and the temperature gradient has remarkable influence on the mechanical behavior. In previous works, Yokobori [4–5] concerns the effect of temperature gradient to apply the method of introducing a very sharp pre-crack as compared with a fatigue pre-crack. Shah [6] conducted fracture tests on fatigue pre-cracked three-point bend specimens to establish the effects of a temperature gradient on the crack initiation fracture toughness. The tests were made on specimens subjected to various temperature gradients while the crack-tip temperature of the specimen was kept constant. The results show that the fracture toughness of material is influenced in a similar fashion and is dependent upon the degree of the temperature gradient along the crack line. Wong [7] provided adaptation factors to estimate the moment capacity of a steel beam subject to temperature gradient. And the suitability of the adaptation factor value adopted by the code was discussed and recommendation was given. Bernd Baufeld [8] developed a new thermal gradient mechanical fatigue (TGMF) testing equipment to study the fatigue performance at TGMF conditions. And the studied material system was the single-crystalline superalloy CMSX-4 with a NiPtAl oxidation protection. The results show that the cracks appear at the inner specimen surface. Brendel [9] carried out the TGMF tests on Ni90 specimens with two induction coil configuration and with two different heating and cooled rate. And the experimental results were reported and discussed on the basis of the measured and simulated results. Up to now, many researchers are interested in studying the tensile and fatigue behavior under temperature gradient.

To investigate the influence of the temperature gradient, an experimental system with cooled air system is developed. Thin-walled cylindrical alloyed steel specimen is designed to carry out tensile and fatigue test under temperature gradients. Based on the relation between true

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stress and true strain at different temperatures, the FEA simulation was performed under temperature gradient. The fatigue tests with cooled air and without cooled air are carried out to investigate the fatigue performance under temperature conditions. The SEM is used to investigate the fracture mechanism under temperature gradient.

Experimental procedure

Temperature gradient testing apparatus

Using the CSS-280 testing machine, the new high-temperature grip is redesigned. The new grip is hollow, and the cooled air produced by air compressing engine can flow through the grip. The high-temperature furnace is used to heat up the outside of specimens. The cooled air is used to cool the inside of specimen to generate the temperature gradient between the outside and inside of the specimen. The flux of cooled air is controlled and measured by the flowmeter. And the outer temperature of specimen is controlled by the temperature controller. The experimental system under temperature gradient is shown in Fig. 1. The material used in this experiment is the alloy steel (30CrMnSi). And all the specimens have been carried out heat processing to improve the performance before testing. The chemical composition of the alloyed steel is shown in Table 1. The geomentrical shapes and dimensions of the thin-walled cylindrical specimens are shown in Fig. 2.

Tensile and fatigue test procedure

Before the testing, the high-temperature furnace and air compressing engine are turned on to generate temperature gradient between the outer specimen and the inner specimen.

Table 1 Chemical compositions (wt%) and mechanical properties

C	Mn	Si	S	P	Cr	Cu
0.25–0.35	0.80–1.10	0.90–1.20	≤0.015	≤0.025	0.80–1.10	≤0.25

The experiment is carried out after the temperature gradient of the specimen is steady for 30 min. And it should be turned off the air compressing engine immediately when the specimen is fractured. During the tensile tests, the specimens are tensed under different constant temperatures and different temperature gradients. The tensile rate is 0.05 m/s. Under temperature gradient condition, the outer temperature of specimens is 450 °C, and the flow rate of cooled air are 2 and 3 m^3/h, respectively.

During the fatigue tests, the outer temperature of specimens is 450 °C, and the flow rate of cooled air is 2 m^3/h. Triangular-wave type tensile stresses are applied, as shown in Fig. 3. The stress ratio R and mean stress σ_m are defined as follows:

$$R = \frac{\sigma_{\min}}{\sigma_{\max}} \quad (1)$$

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2} \quad (2)$$

In this article, the stress ratio R is 0.1, and all fatigue tests are run with frequency of 0.33 Hz.

Experimental results and discussion

Tensile test

Figure 4 shows the load–displacement curves under different temperatures. Figure 5 shows the yield strength of

Fig. 1 Experimental system at temperature gradient

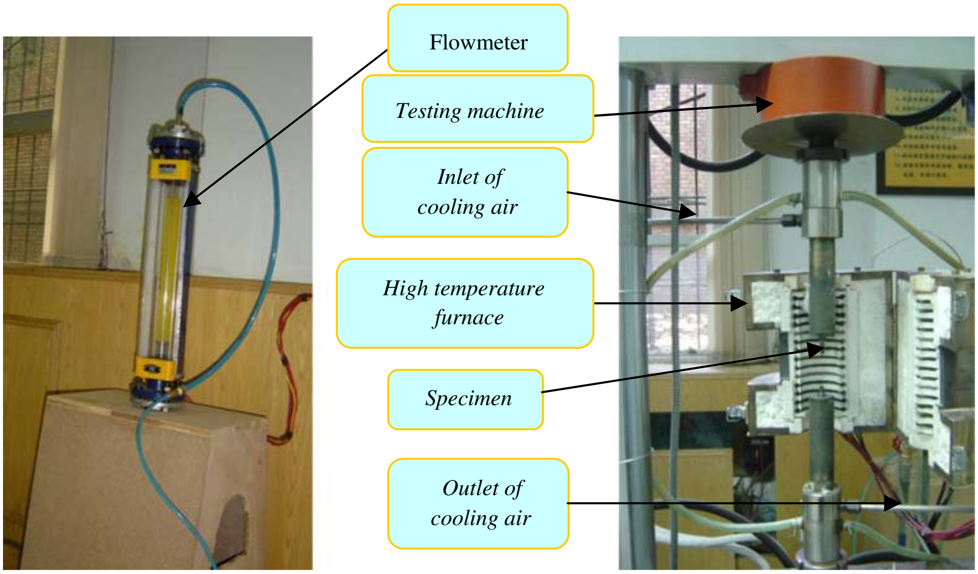
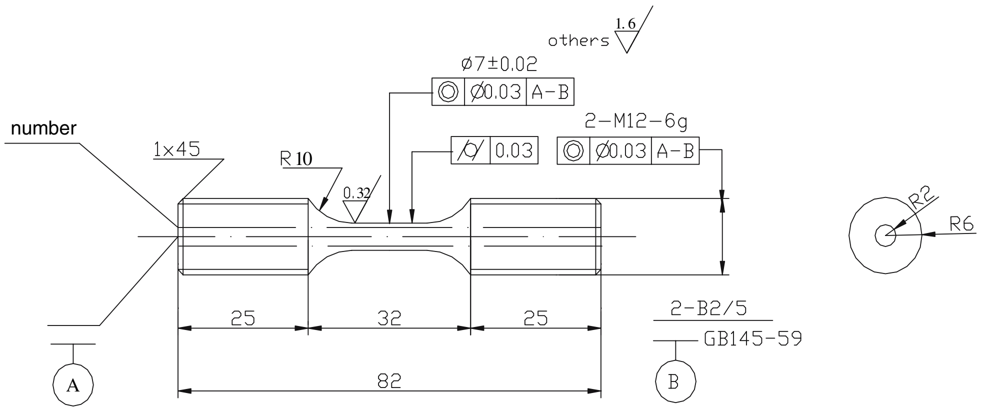


Fig. 2 Geomentrical shape and dimensions of the thin-walled cylindrical specimen (all dimension are in mm)



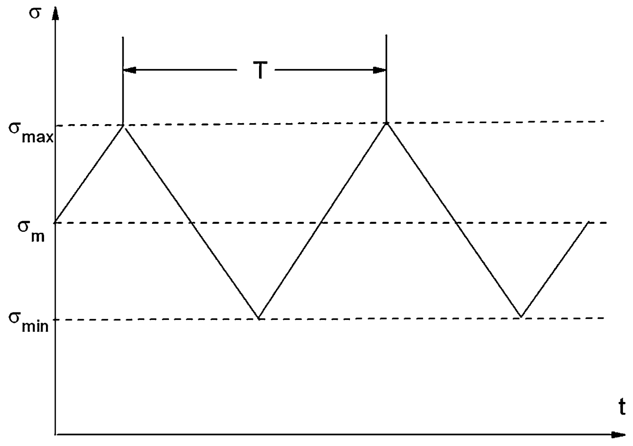


Fig. 3 Stress waveform

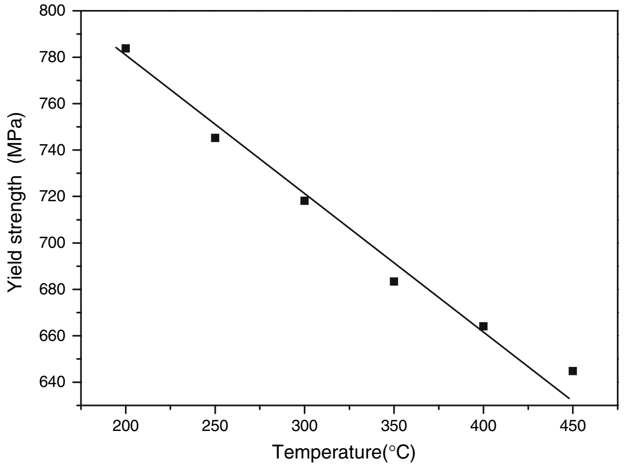


Fig. 5 Yield strength of specimens under different temperatures

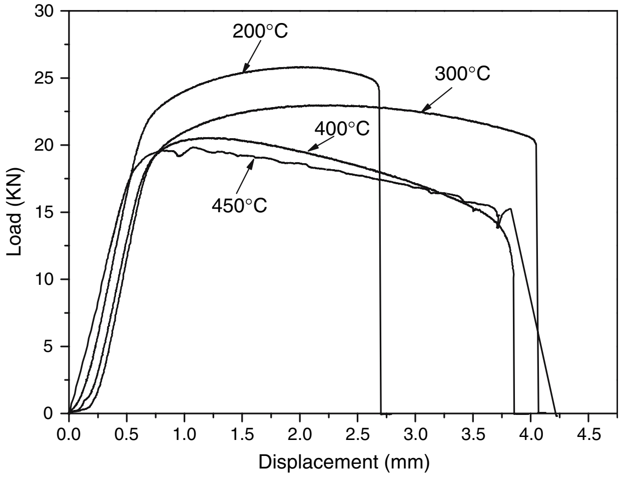


Fig. 4 Load–displacement curves under different temperatures

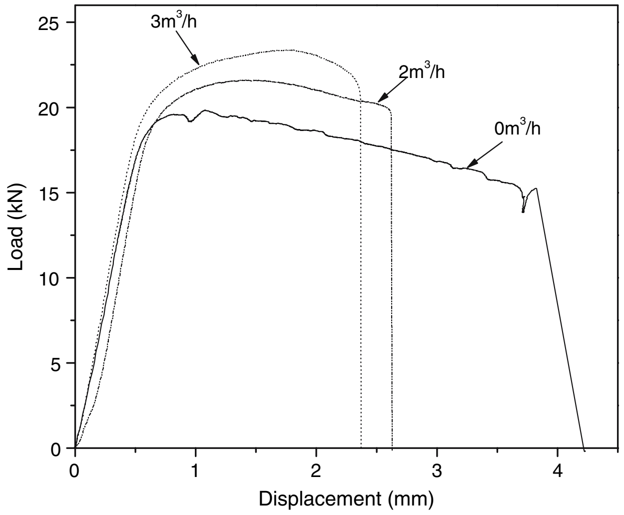


Fig. 6 Load–displacement curves under different temperature gradients

specimens under different temperatures. Figure 6 shows the load–displacement curves under different temperature gradients. It can be seen from Fig. 4 that the temperature has remarkable influence on the tension performance of the specimen. The tensile strength of the specimen at 200 °C is 25.84 kN, and it is much greater than the 19.75 kN at 450 °C. It can be seen from Fig. 5 that the yield stress is decreasing with the increase of the temperature, and the relationship between the yield stress and the temperature at some temperature range can be seen as linear. It can be

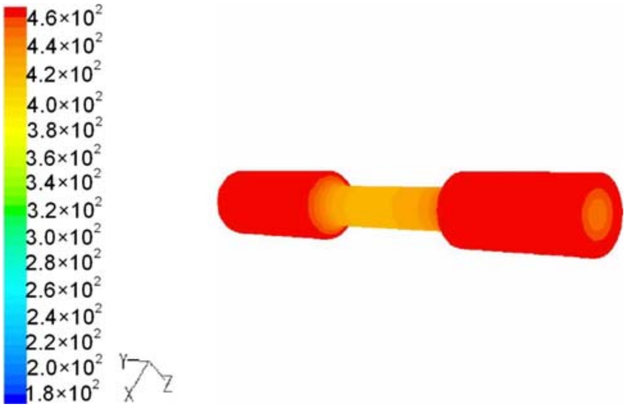


Fig. 7 Temperature distributions of specimen with 3 m^3/h cooling air

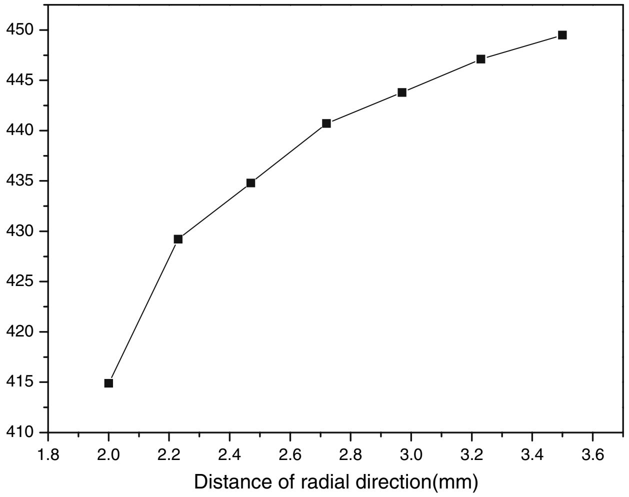


Fig. 8 The distribution of temperature on radial direction at middle section

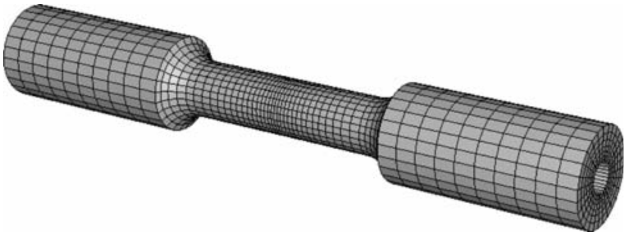


Fig. 9 FEA model

seen from Fig. 6 that cooled air has remarkable influence on the tensile performance of the specimen, and the influence at different flux of cooled air is different. Generally speaking, the tensile performance under temperature gradient with 3 m^3/h cooled air is better than that with 2 m^3/h cooled air.

To investigate the influence of the cooled air, we study the relationship of load and displacement by FEA. Firstly, we build the model of specimen using software of Gambit, and we solve the temperature distributions of specimen using CFD software of FLUENT. The temperature distributions of specimen with 3 m^3/h cooled air are shown in Fig. 7. The distribution of temperature on radial direction at middle section is shown in Fig. 8. It is found that there is remarkable temperature gradient along the radial of the hole. Secondly, we build the calculation model with the FEA software. The FEA model is according to the thin-walled cylindrical specimens. And the result of the temperature distributions is transferred to the FEA model by

Table 2 Material parameters of alloy steel under different temperatures

Temperature (°C)	Yield strength σ_y (MPa)	Tensile strength σ_B (MPa)	Young's modulus (MPa)
350	768.3	1,212.2	42,465.2
450	730.1	1,186.9	36,998.8

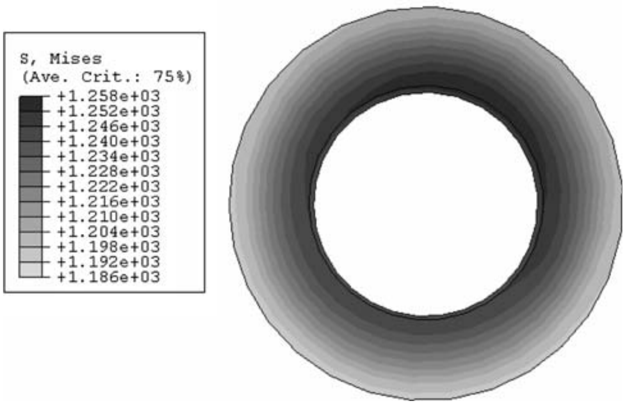


Fig. 10 Mises stress of neck section under temperature gradient

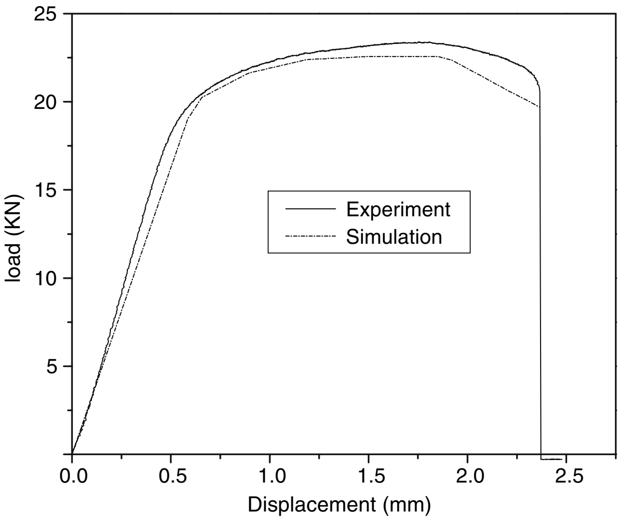


Fig. 11 The load–displacement curves at flux of 3 m^3/h

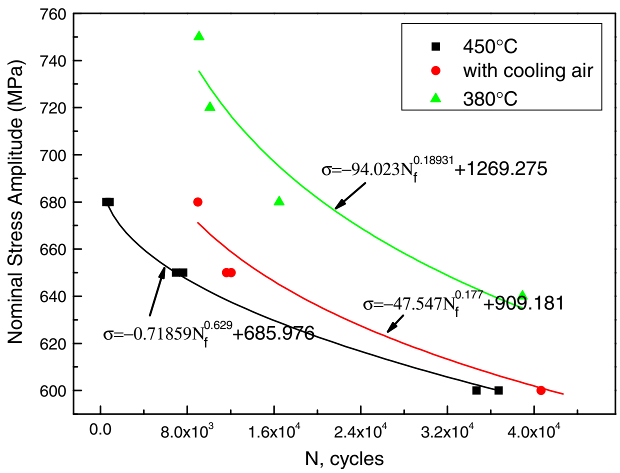


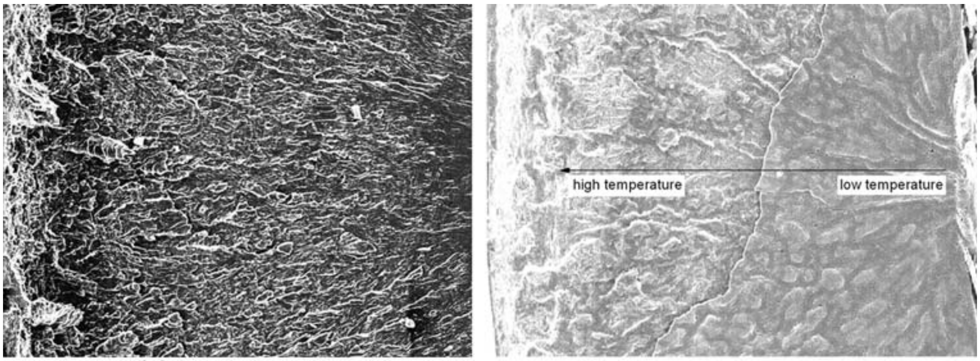
Fig. 12 The S–N curves at different temperature conditions

the interpolation method. The FEA model of specimen is shown in Fig. 9. Thirdly, we obtain the basic parameters of specimen from the testing result. The material parameters of alloy steel under different temperatures are shown in Table 2. Lastly, we analyze the model with temperature gradient based on the parameters under different temperatures. Since the relationship between the yield stress and the temperature can be seen as linearity as shown in Fig. 5, the material parameters of alloy steel under any temperature can be solved by the linear interpolation method. Figure 10 shows the Mises stress profile of neck section under temperature gradient. The Mises stress at inner specimen is 72 MPa larger than that at outer specimen. Figure 11 shows the load–displacement curves at flux of 3 m^3/h. It is found that the simulation result agrees with the experimental result. This means that the tensile performance under temperature gradient can be simulated using above method.

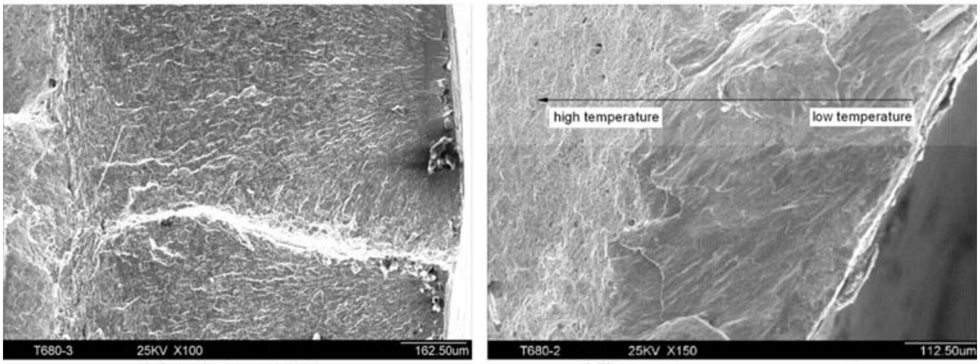
Fatigue life of specimen with and without cooled air

The fatigue test results with cooled air and without cooled air for the alloyed steel are shown in Fig. 12. Figure 13 shows the fracture surface of the specimen at different maximum nominal stress and different temperature conditions. It can be seen from Fig. 12 that the N_f at 450 °C is smaller than that at 380 °C with the same nominal stress amplitude. The N_f at temperature gradient is larger than that at 450 °C which is the maximum temperature of the specimen, and it is smaller than that at 380 °C which is the minimum temperature of the specimen. The N_f at temperature gradient is not the average value of the N_f at 450 and 380 °C, and the influence of the cooled air at higher nominal stress amplitude is more remarkable than that at lower nominal stress amplitude. It can be seen from Fig. 13 that the fracture surface under temperature gradient is different from that under constant temperature. In Fig. 13a, crack appears at the inner specimen surface. In Fig. 13c,

Fig. 13 The fracture surface of the specimen at different maximum nominal stress and different temperature conditions



(a) 650MPa at 450℃ **(b)** 650MPa at temperature gradient



(c) 680MPa at 450℃ **(d)** 680MPa at temperature gradient crack appears at the outer specimen surface. In Fig. 13b and d, crack appears at the inner specimen surface, and there are obvious boundary between low-temperature and high-temperature in the fracture surface. It can be concluded that cracks appear at the inner specimen surface under temperature gradient.

Conclusions

The experimental system with cooled air is developed, and thin-walled cylindrical alloyed steel specimen is designed to carry out tensile and fatigue test. The result of the article is as follows:

(1) The temperature has remarkable influence on the tension performance of the specimen. Based on the relation between true stress and true strain at different temperatures, the tensile performance of the specimen under temperature gradient can be simulated.

(2) The number of cycles to failure at temperature gradient is larger than that at the maximum temperature of the specimen, and it is smaller than that at the minimum temperature of the specimen. The influence of the cooled air at higher nominal stress amplitude is more remarkable than that at lower nominal stress amplitude.

(3) The experiment result shows that the specimen will fracture from the place where the temperature is lower.

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