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PROCEEDINGS

Nonlinear Variation of Chord Modulus of Mild Steel During Cyclic Loading-Unloading at Different Temperatures

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ABSTRACT

By using the continuous cyclic loading-unloading tensile test method, the nonlinear variation behavior of the chord modulus of mild steel under different temperature conditions was systematically investigated, and the corresponding relationship between plastic strain and chord modulus during the cyclic loading-unloading process was clarified. Through the analysis of test data, the variation trends and quantitative corresponding models of plastic strain and chord modulus at different temperatures were established. The research results show that under constant temperature conditions, as the plastic strain increases to 10%, the chord modulus attenuation process presents a significant two-stage characteristic - in the initial stage ($\varepsilon_p \leqslant 0.02$), it shows a rapid decline; in the subsequent stage ($\varepsilon_p > 0.02$), the attenuation rate significantly decreases and tends to stabilize. The temperature effect analysis shows that although the variation trends under different temperature conditions remain consistent, the decline rate of the material's chord modulus decreases as the tensile temperature increases. Further analysis reveals that when mild steel is in the temperature range of 20 - 300℃, the influence of plastic strain on its chord modulus has engineering significance, and the nonlinear mechanical behavior's impact on structural deformation should be fully considered in the design of precision welding processes.

KEYWORDS

Plastic strain; chord modulus; temperatures; mechanical behavior

1 Purpose

As a typical low-alloy high-strength steel, mild is widely used in various welded structural parts. However, during the welding process, the material faces a complex temperature environment and stress state, and its mechanical properties will change significantly. If only the single variable change of chord modulus with temperature is considered, it is difficult to fully characterize the nonlinear mechanical behavior of the material under such complex working conditions. In the design of precision welding processes, the completeness of the material constitutive model directly affects the prediction accuracy of the welding deformation of structural parts. Therefore, in-depth revelation of the coupling mechanism between the mechanical behavior of the material and the temperature and stress state is of great engineering value for accurately predicting the welding deformation of precision components.

2 Materials and Tests

The test material is mild hot-rolled steel plate produced by a steel plant with a thickness of 2.0 mm. The steel plate has a rolling orientation. In order to strictly control the experimental variables, all samples are cut along the rolling direction (see Fig. 1). The sample is prepared by mechanical processing and the entire surface is polished with fine sandpaper to eliminate the test error caused by stress concentration. The polished sample is shown in Fig. 2.

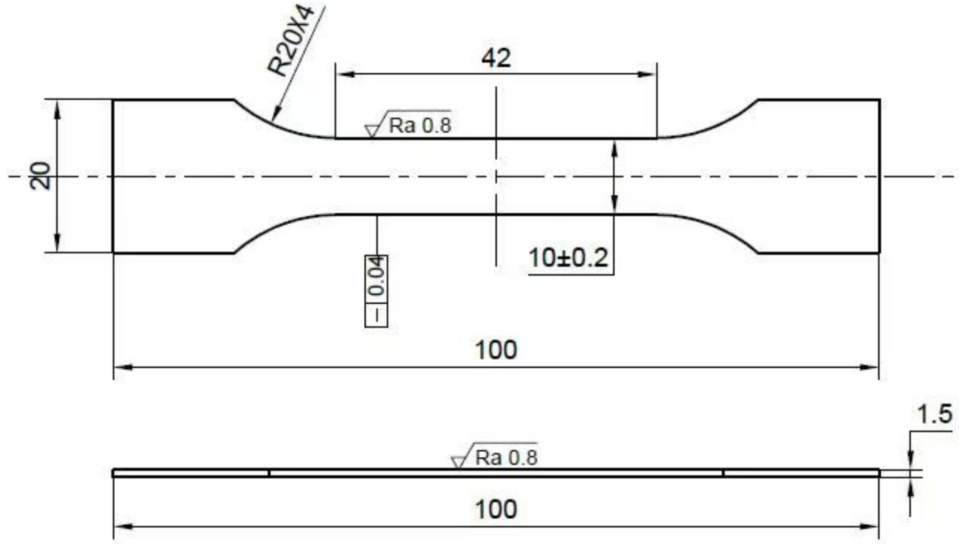

Figure 1: Tensile specimen

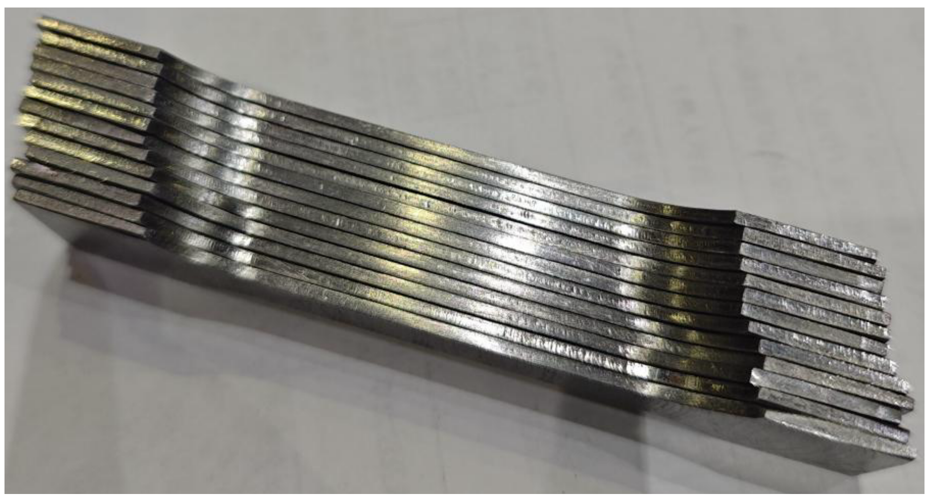

Figure 2: Side view of the actual specimen

The cyclic loading-unloading tensile test was carried out on the testing machine, and the tensile specimens complied with the national standard GB/T-228.1-2010. The test adopted the strain control mode, and the strain loading rate of each test was constant. The test preset 5 target pre-strain levels (2%, 4%, 6%, 8%, 10%), and adopted a step-by-step loading strategy: the same specimen was first loaded to 2% strain, and then linearly unloaded to zero load at the same rate after reaching the target strain; the next level of loading was immediately carried out after the unloading was completed, and the strain was loaded to 4%, 6%, 8% and finally 10% in sequence, and a complete unloading operation was performed after each level of loading; the load-displacement data was collected synchronously during the loading-unloading process to capture the nonlinear mechanical response characteristics of the material.

Based on the stress-strain curve measured in the experiment, the corresponding true stress-strain curve is first determined through data calibration; The chord modulus is calculated through the real stress-strain curve.

3 Results

The experimental results at four temperature gradients from 200℃ to 500℃ are shown in Fig. 3, and the elastic modulus statistics are summarized in Fig. 4:

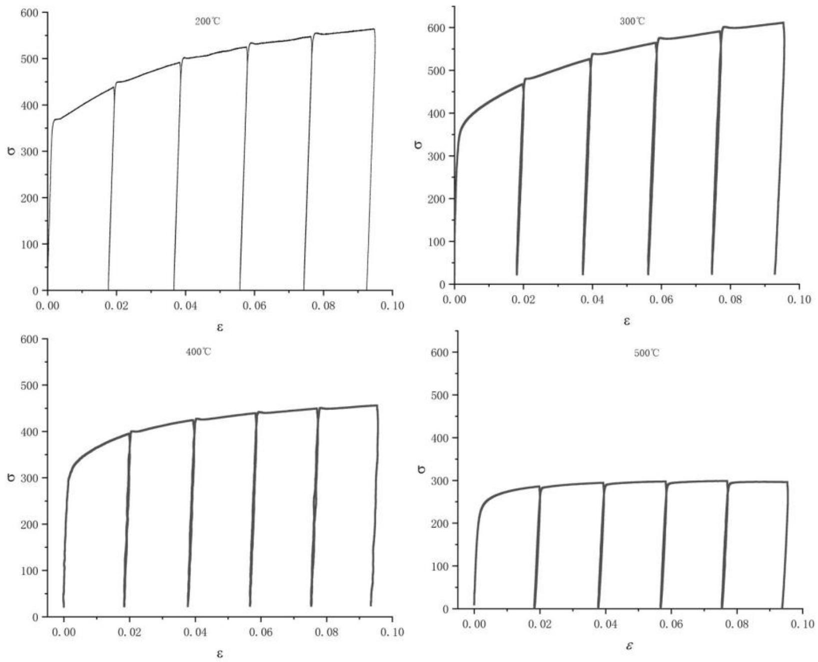

Figure 3: Experimental results

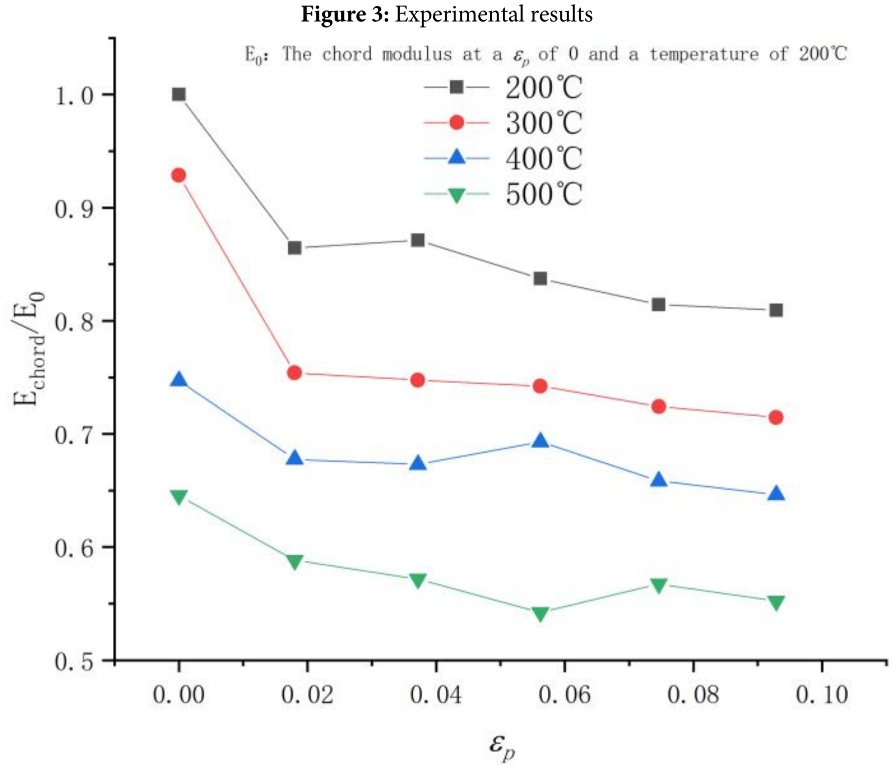

Figure 4. *E*-ε

3.1 Effect of Temperature on Mechanical Properties of Materials

Fig. 4 shows the stress response of mild steel in the temperature range of 200°C~500°Cand at different strain levels. In general, under the same strain conditions, the stress shows a significant downward trend with increasing temperature, reflecting the weakening effect of high temperature on the bearing capacity of the material. When the strain ε=0.02, the temperature rises from 200°C to 500°C, and the chord modulus decreases significantly; when ε_p=0.1, indicating that the increase in temperature causes a significant attenuation of the material strength. This phenomenon is consistent with the high-temperature mechanical behavior characteristics of metal materials: as the temperature increases, the thermal activation energy of atoms increases, the resistance to dislocation movement decreases, and the tendency of grain boundary sliding increases, resulting in a decrease in the macroscopic stress level.

3.2 Strain-Dependent Stress Response Law

Under single temperature conditions, the evolution of stress with strain presents different characteristics:

200°C and 300°C: the stress fluctuates slightly after the initial strain (ε_p=0.02) (the stress rises slightly at 200°C when ε_p=0.04), and then continues to decrease with the increase of strain, showing a typical stress softening behavior in the plastic deformation stage. This phenomenon is attributed to the fact that after the material enters the yield stage, the strain hardening effect is gradually dominated by the intracrystalline slip and dislocation annihilation process, resulting in a decrease in the slope of the stress-strain curve [1].

400°C: The stress shows an abnormal peak value at ε_p=0.06, which is higher than the adjacent strain points (ε_p=0.04 and ε_p=0.08), breaking the trend of monotonically decreasing with increasing strain. This anomaly may be caused by the measurement deviation caused by the instantaneous vibration of the load sensor or the data acquisition noise during the test; this phenomenon may be related to the blue brittle effect of the material near 400°C [2] - in this temperature range, interstitial atoms (C, N) diffuse to the dislocation and re-pin, resulting in local stress recovery; it may also be caused by local stress concentration caused by load fluctuations or surface defects of the sample during the test, which needs to be verified by repeated tests and fracture analysis.

500°C: The stress shows a gentle downward trend with increasing strain (a decrease of 20.3% when ε_p=0.02 to 0.1), which is significantly lower than that in the medium and low temperature range (a decrease of 23.9% at 200°C). This indicates that the plasticity of the material is significantly improved at high temperature and the strain hardening effect is further weakened, which is consistent with the mechanical behavior characteristics of the superplastic deformation or steady-state creep stage [3].

4 Conclusions

Under constant temperature conditions, as the plastic strain increases to 10%, the chord modulus decay process shows a significant two-stage feature - the initial stage ($\varepsilon_p \leq 0.02$) shows a rapid decline; the subsequent stage ($\varepsilon_p > 0.02$) the decay rate significantly decreases and tends to stabilize. Temperature effect analysis shows that although the change trend under different temperature conditions remains consistent, the rate of decline of the material's chord modulus shows a slowing trend as the tensile temperature increases. Further analysis shows that when mild steel is in the temperature range of 20~300°C, the effect of plastic strain on its chord modulus has engineering significance, and the influence of this nonlinear mechanical behavior on the structural deformation variable needs to be fully considered in the design of precision welding processes. Subsequent research combined with microstructural observations will reveal the deformation mechanism under the action of temperature-strain coupling, and provide more accurate material constitutive parameters for deformation prediction of high-temperature welded structures.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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