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A modified hockett-sherby model to simulate discontinuous yield behavior

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ABSTRACT

Abstract: In this paper, x80 pipeline steel was treated by three aging ways. The influences of heating time, heating temperature and prestraining on the transition from continuous yield to discontinuous yield in stress-strain curves were studied. Meanwhile, the correlation of the discontinuous yielding curves and the tensile performances of x80 pipeline steel were also studied. Furthermore, a modified Hockett-Sherby (H-S) model was proposed to simulate the stress-strain curves of discontinuous yield. The results indicated that the simulative results agree with the experimental results.

KEYWORDS

Discontinuous yield;
Tensile performances;
A modified hockett-sherby model.

INTRODUCTION

Discontinuous yield is the phenomenon that when the elasticity of the metal fails it does so in a spectacular fashion, with a sharp drop in stress to the lower yield point before normal metallic work-hardening properties are exhibited[1]. Pipeline steel is a low-carbon and micro-alloy rolled steel. Its cold deformation and heating in the process of corrosion coating may induce strain aging behavior[2] and usually discontinuous yield appears in stress-strain curves. Although discontinuous yield has few effect on the strength design, it has a great impact on the deformation capacity of pipeline and materials[3,4]. With the increase of pipeline steel grade, the influence of discontinuous yield on its performance is more and more significant. Therefore, the study for the discontinuous yield of pipeline steel has been an integral part of new materials, especially for 550 and above steel grades.

In this paper, firstly, x80 pipeline steel was treated by three aging ways and the influences of heating time, heating temperature and prestraining on the transition from continuous yield to discontinuous yield in stress-strain curves were studied. Furthermore, the effects on the tensile performances of x80 pipeline steel were studied as the curves transformed from continuous yield to the discontinuous one. Thereafter, a modified H-S model was proposed to overcome the insufficiency of H-S model in simulating stress-strain curves of discontinuous yield. It indicated that the simulative results were in a very good agreement with the experimental results.

MATERIAL AND EXPERIMENTAL PROCEDURE

The material used in the experiment was x80 pipe-

TABLE 1 : Chemical composition of x80 pipeline steel.

Elements	C	Si	Mn	P	S	Ni	Cr	Cu	Mo	Nb	Ti	Ceq
Content (%)	0.06	0.17	1.81	0.012	0.003	0.27	0.03	0.18	0.27	0.07	0.016	0.45

line steel manufactured by JFE holdings Inc. and its chemical composition was shown in TABLE 1.

In the experiment, a certain size of x80 pipeline steel was put into the salt bath furnace to heat for some time and then cooled to room temperature. And three aging ways were adopted during the experiment. The first one was to heat x80 pipeline steel using different temperatures varying from 25ºC to 250ºC and then insulated for 5 minutes; the second one was to heat it in the same way, and then insulated for 60 minutes; the third one was to prestrain 2% of x80 pipeline steel before heating it in the same way, and then insulated for 60 minutes. After treatment by the three aging ways, the materials were machined to the tensile samples and the sizes were shown in Figure 1. Lastly, tensile test was carried out in instron 8001 testing machine and the stress-strain curves obtained by different aging ways were compared and analyzed.

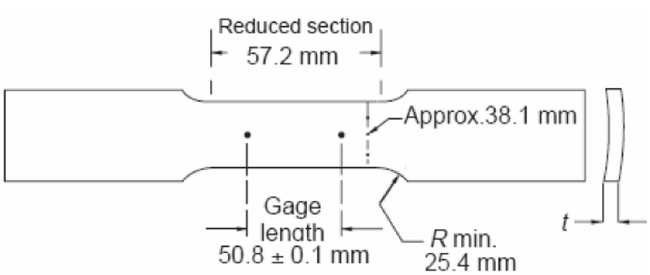


Figure 1 : the sizes of the tensile sample

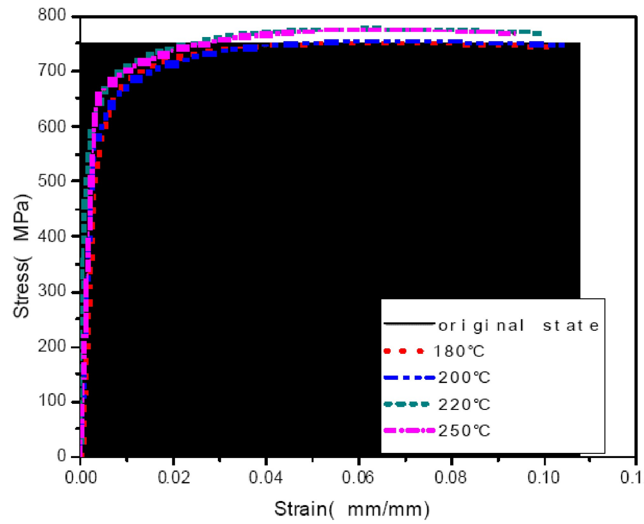


Figure 2 : 5min heating time at different temperatures

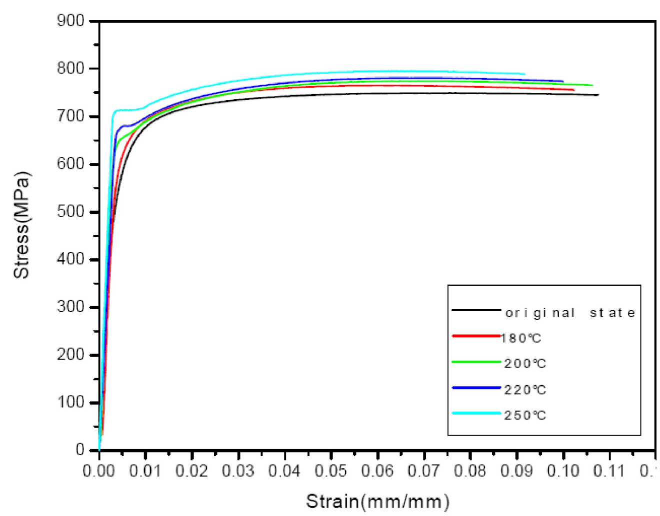


Figure 3 : 1h heating time at different temperatures

EXPERIMENTAL RESULTS

The stress-strain curves of tensile samples treated by the three aging ways were shown in Figure2, 3 and 4, respectively.

From the three figures we can find: for the second aging way, with the increase of temperature, the stress-strain curve transformed from continuous yield to the discontinuous one and the upper yield point appeared at 220ºC; for the third aging way, when the sample was only prestrained 2% at room temperature, the curve appeared a stress plateau, and when the sample was heated to 180ºC, the upper yield point existed obviously; whereas, for the first aging way, the stress-strain curve always remained continuous yield with the increase of temperatures. Further combining Figure 5 we can see that in the three aging ways, with the increase of heating temperature, the yield and tensile strengths were all increased, but the increase value of the yield strength treated by the third aging way was maximum, while the minimum appeared in the first aging way.

The influence of the upper yield point and lower yield point difference (Δσ) on the percentage total extension at maximum force (A_{gt}) and percentage total extension at fracture (A_t) was also studied for the discontinuous yield and the results were shown in Figure

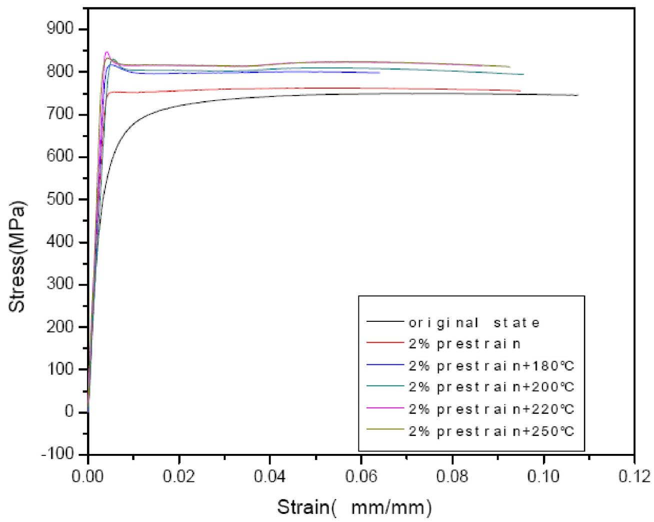


Figure 4 : 2% prestrain and 1h heating time at different temperatures

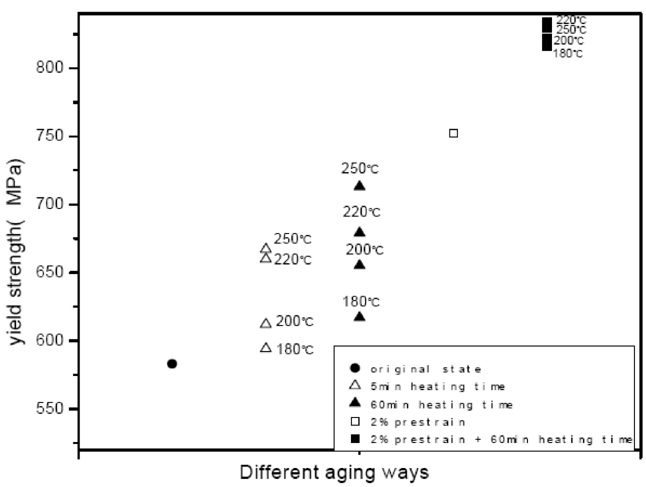


Figure 5 : the relationship of yield strength with different aging ways

6. As seen obviously, with the increase of $\Delta\sigma$, A_{gt} and A_t all decreased. Furthermore, the ratio of the stress corresponding to 1.5% extension ($R_{t1.5\%}$) and the stress corresponding to 0.5% extension ($R_{t0.5\%}$), $R_{t1.5\%}/R_{t0.5\%}$, and the ratio of the stress corresponding to 2.0% extension ($R_{t2.0\%}$) and the stress corresponding to 1.0% extension ($R_{t1.0\%}$), $R_{t2.0\%}/R_{t1.0\%}$, were investigated for the three aging ways. The results were given respectively in Figure 7 and Figure 8, from which we can see that the values of $R_{t1.5\%}/R_{t0.5\%}$ and $R_{t2.0\%}/R_{t1.0\%}$ for the original sample were the highest but those treated by the third aging way were the lowest. These implied that discontinuous yield had a great impact on the work hardening of samples.

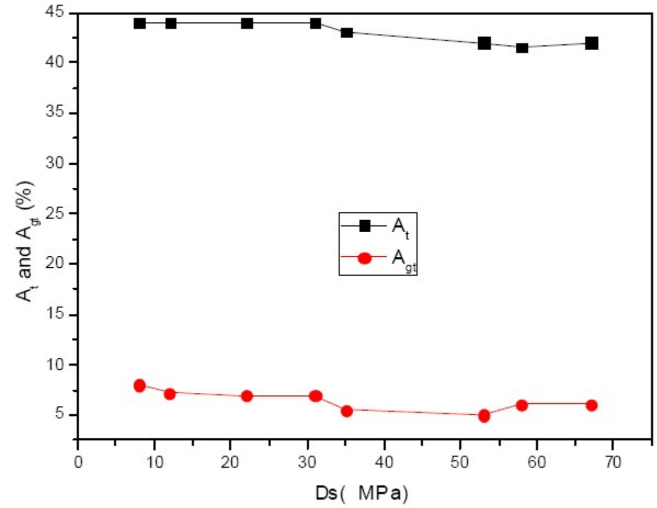


Figure 6 : The relationship of strength increment with Agt and At

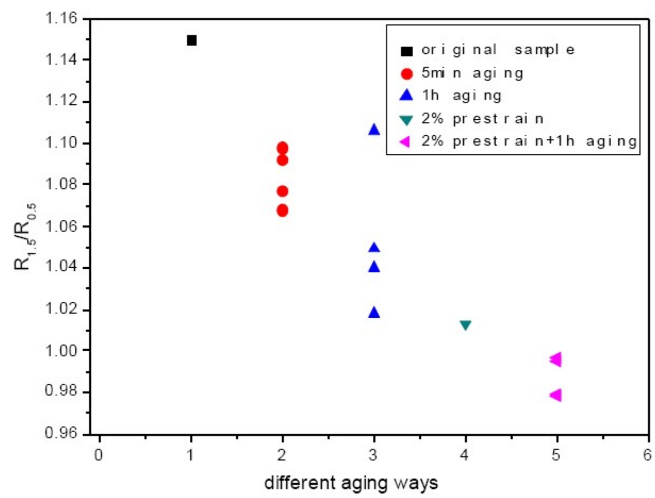


Figure 7 : Rt1.5/Rt0.5 at different aging ways

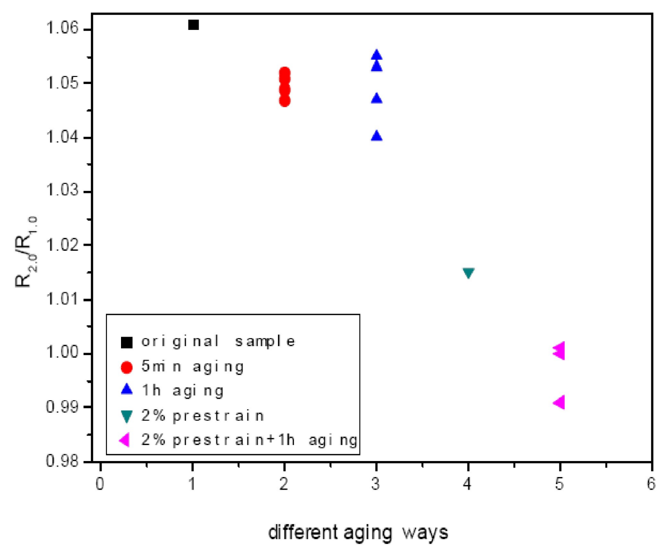


Figure 8 : Rt1.5 /Rt0.5 at different aging ways

Modified H-S model

From above experimental results it can be seen that when the stress-strain curves transformed from continuous to discontinuous yield, it had great effects on the yield strength, percentage total extension and work hardening etc. of pipeline steel. Up to now, there were a lot of models to represent the stress-strain curves, such as Hollomon model, Swift model, Ghosh model, Ludwik model[5], voce model[6], and Hockett-Sherby model (H-S model)[7] et al.

Hockett-Sherby model had a higher fitting accuracy and its numerical equation was as follows[8]:

$$\sigma = \sigma_s + \Delta\sigma[1 - \exp(-m.''\varepsilon^c)] \quad (1)$$

where σ_s is yield strength, $\sigma_{''}$ is saturation stress, $\Delta\sigma = \sigma_{''} - \sigma_s$, m is a material constant and c is a fitting parameter.

For the third aging way, its change of stress-strain curves was the most obvious in the three aging ways, so the H-S model was used to simulate its stress-strain curves and the results were given in Figure 9. As shown, for the original sample, its stress-strain curve was continuous yield and the simulative and experimental results were in a good agreement, like Figure 9(a), but for other samples, their stress-strain curves were discontinuous yield and the simulative and experimental results existed a big error in the yield point part, like Figure 9(b)-(f), which illustrated that H-S model was only applicable to the continuous yield and could not be directly used to discontinuous yield in the stress-strain curves. So, the H-S model needed to be modified for discontinuous yield.

In fact, the appearance of discontinuous yield was associated with the diffusion of solute atoms to arrested dislocations[9], giving rise to an additive contribution to the flow stress[10]. So, in the discontinuous yield total flow stresses should include two effects. One was the work hardening effect, and the other was the effect related to the solute atoms composition.

The effective solute composition at arrested dislocations is determined by the aging time, t_a, during which the diffusion of solute atoms to temporarily arrested dislocations occurs and may be expressed using Cottrell-Bilby strain ageing kinetics[11] modified for saturation[12] as

$$C_s = C_m\{1 - \exp[-C_0(KDt_a)^n / C_m]\} \quad (2)$$

where Cm is the saturation value of C_s, C_0 is the solute concentration of the alloy and K is a constant. D is the solute diffusion coefficient, $D = C_v D_0 \exp(-Q/kT)$, where D_0 is the diffusion frequency factor, T is the heating temperature, Q is the activation energy for solute migration and C_v is vacancy concentration, $C_v = K_1\varepsilon^m$, where K_1 and m are constants. The strain dependence of ρ and L is given by $\rho L = K_2\varepsilon^\beta$, where ρ is the mobile dislocation density, L is the effective obstacle spacing and K_2 and β are constants. In the original Cottrell-Bilby model, n =2/3. However, studies[13,14] indicated that n = 1/3 gives better agreement with experimental measurements. Combining constants gave $K' = KK_1K_2D_0$ and

$$.p_2 = C_0[K' \exp(-Q/kT)]^n / C_m \quad (3)$$

Therefore,

$$C_s = C_m[1 - \exp(-p_2 t_a^n \varepsilon^l)] \quad (4)$$

and the stress related to the solute atoms composition can be represented as follows:

$$\sigma_D = B_1 C_m[1 - \exp(-p_2 t_a^n \varepsilon^l)] \quad (5)$$

where l and B_1 are constants.

Finally, we could assume a combination to include effects of both work hardening and solute atoms composition, thus, a modified H-S model was represented below:

$$\sigma = \sigma^* + \sigma_D \quad (6)$$

in which σ* represents the work hardening effect, $\sigma^* = \sigma_s + \Delta\sigma(1 - \exp(-m\varepsilon^n))$, whereas σ_D denotes as solute atoms composition effect, $\sigma_D = B_1C_m[1-\exp(-p_2 t_a^n \varepsilon^l)]$.

Therefore, the modified H-S model was finally expressed as follows:

$$\sigma = \sigma_s + \Delta\sigma(1 - \exp(-m\varepsilon^c)) + B_1C_m[1 - \exp(-p_2 t_a^n \varepsilon^l)] \quad (7)$$

By using the modified H-S model the stress-strain curves treated by the third aging way were simulated, as shown in Figure 10. It indicated that the experimental and simulative results were in a good agreement.

DISCUSSION

In this paper, the appearance of discontinuous yield was closely related to the aging ways. From the equations (6) and (7) it can be seen that σ_D was related to p_2 and t_a. With the increasing of p_2 and t_a, σ_D increased. Because of $p_2 = C_0[K'\exp(-Q/kT)]^n / C_m$, the influence of p_2 on σ_D was in accordance with the influence of T on σ_D. Furthermore, because during prestraining vacancies

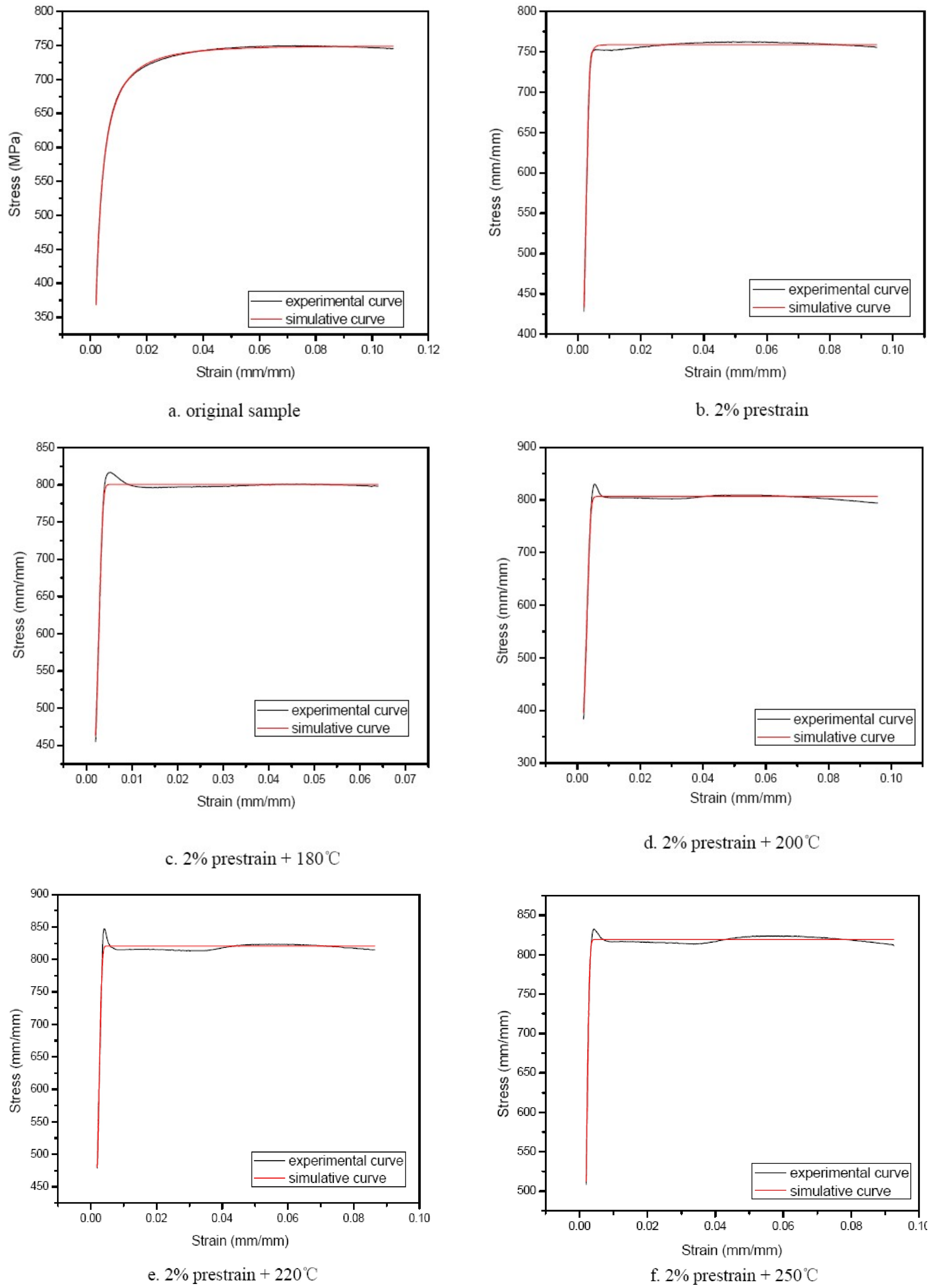
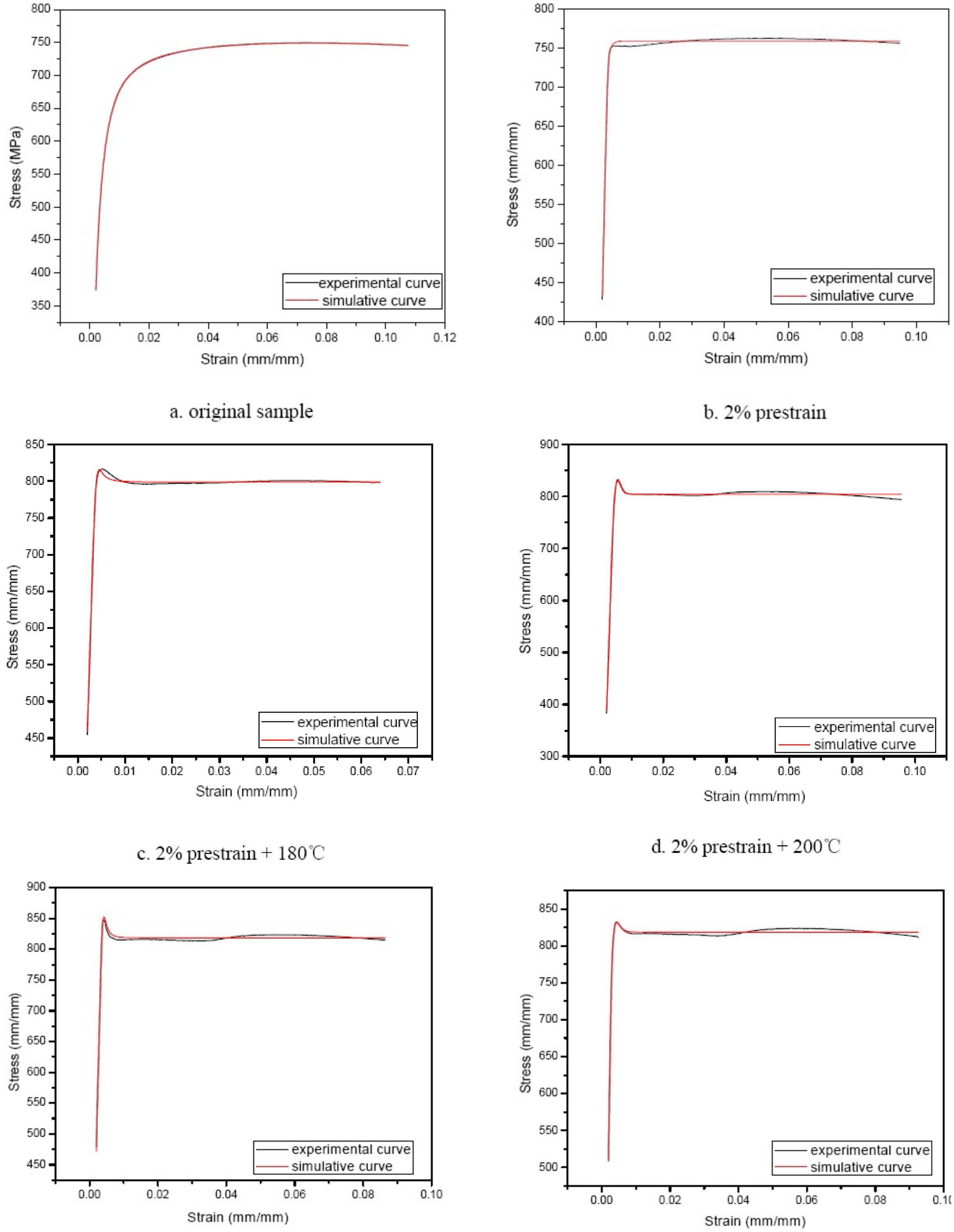


Figure 9 : the simulative results using H-S model

were produced, which had an influence on the diffusion coefficient, the increase of prestrain had the same effect as the increase of T. So, in the experiment, when increasing heating temperature, heating time and



a. original sample

b. 2% prestrain

c. 2% prestrain + 180℃

d. 2% prestrain + 200℃

e. 2% prestrain + 220℃

f. 2% prestrain + 250℃

Figure 10 : the simulative results using modified H-S model

prestraining, the solute atoms composition effect σ_D became obvious and the discontinuous yield appeared.

According to the proposition of Cottrell and Bilby[1] the reasons could be presented below: increasing the heating temperatures varying from 180°C to 250°Cwould increase solute atoms diffusion and it was useful to pin dislocation cores, therefore, the discontinuous yield was from negligible to significant levels; increasing heating time from 5min to 60min would increase the time for diffusion of solute atoms to dislocations, therefore, the discontinuous yield was also from negligible to significant levels; that a 2% of prestrain was carried out before heating would reduce the diffusion distance and thus time required for a dislocation became locked by solute atoms. Therefore, prestrain combining with different heating temperatures treatment would be in favor of the appearance of discontinuous yield. Obviously, the proposition of Cottrell and Bilby was in accordance with the modified H-S model.

CONCLUSIONS

In this paper, x80 pipeline steel was treated by three aging ways. The influences of heating time, heating temperature and prestrain on the transition from continuous yield to discontinuous yield in stress-strain curves of x80 pipeline steel were studied. Meanwhile, when the curves transformed from continuous to discontinuous yield, the effects on the tensile performances of x80 pipeline steel were studied. Furthermore, a modified H-S model was proposed to overcome the shortcoming of H-S model in simulating stress-strain curves of discontinuous yield. The findings of this work were summarized as follows:

1) Increasing heating temperature, heating time and prestraining were useful for the appearance of discontinuous yield, but the effect of prestrain before heating was more obvious;
2) When discontinuous yield existed, the yield strength and tensile strength of x80 pipeline steel increased, and with the increase of $\Delta\sigma$, Agt and At decreased;
3) When the discontinuous yield appeared, Rt1.5/Rt0.5 and Rt2.0/Rt1.0 decreased, which implied that discontinuous yield has a great impact on the work hardening of samples.
4) A modified model was proposed. The simulative results using the modified H-S model were in a very good agreement with the experimental results.

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