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CONSTITUTIVE MODEL OF LOW CARBON ALLOY STEEL (LCAS) EXPANDABLE TUBULAR

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The downhole expansion process of the expansion tube is the dynamic deformation process of the expansion tube metal material at different temperatures. In this paper, the dynamic tensile test is used to measure the dynamic tensile stress-strain curve of low-carbon alloy steel in the temperature range of 25 – 300 °C. upon analyzed the dynamic tensile test results, with the strain rate factor Z and McCormick physical model, the paper set up low carbon alloy steel constitutive equation of underground temperature field. The calculation results of the Sellars creep equation are compared with the residual stress value after expansion in the finite element analysis of the solid steel pipe expansion to verify the actual application reliability of the steel for the expansion pipe with high expansion rate.

Keywords: LCAS; tubular expansion; stress-strain curves; temperature; constitutive model

INTRODUCTION

Expansion casing technology is to use mechanical or hydraulic pressure to expand the casing radially to the plastic deformation zone, and plastic permanent deformation occurs, so that the outer wall of the casing is close to the inner wall of the pipe string, so as to save the diameter of the borehole and save the cost of well construction, etc. Purpose of a drilling and completion technology. Taking into account the current exploitation methods of the oil and natural gas industry and the development of ultra-deep wells, we determined the downhole expansion temperature of the expansion pipe to be in the middle of 0 - 300 °C. The deformation of the expansion tube in this temperature environment is actually a dynamic deformation process of the base metal material of the expansion tube at different temperatures.

The numerical simulation of the downhole expansion process of the expansion tube must consider the relationship between the flow stress and the plastic strain of the material during warm processing. According to the experimental results of dynamic tension and the theory of dynamic recovery and strain aging of metals, with the help of strain rate Z factor and McCormick physical model, the constitutive equation of low-carbon alloy steel in the downhole temperature field is established [1]. The establishment of the constitutive equation can not only accurately reflect the dynamic characteristics of the plastic. Deformation of the material, but also establish a certain quantitative relationship for the numerical simulation and analysis of the plastic deformation of the expansion tube, providing a theoretical basis, and has very important theoretical and practical significance [2].

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Constitutive relationship between flow stress and thermal deformation conditions

The flow stress in the metal thermal deformation process mainly depends on the deformation temperature T, the strain rate $\dot{\varepsilon}$, the amount of strain ε, and the structure before deformation (such as composition, grain size and deformation history, etc.) [3]. Due to the complexity of the influence law of tissue characteristics, only the influence of thermal deformation conditions is considered. Therefore, the flow stress expression is [4,5];

$$\sigma = f(T) \cdot f(\dot{\varepsilon}) \cdot f(\varepsilon) \tag{1}$$

Zener and Hollomon studied high-speed tensile experiments of steel [6] and proposed a method to describe high-temperature flow stress with a parameter Z including T and $\dot{\varepsilon}$.

$$f(\sigma) = f(Z, \varepsilon) \tag{2}$$

Equation (2) can be further expressed as.

$$f(\sigma) = Z = \dot{\varepsilon} \cdot \exp\left(Q / RT\right) \tag{3}$$

Where; Z-Zener-Hollomon parameter (temperature compensated strain rate factor); R - molar gas constant / 8,314·mol^{-1}·K^{-1}; Q - Thermal deformation activation energy/J·mol^{-1}; T - absolute temperature /K.

Sellars et al. [7] used a modified Arrhenius equation including thermal deformation activation energy Q to describe the above relationship:

$$Z = A[\sinh(\alpha\sigma)]^n \tag{4}$$

$$\dot{\varepsilon} = A[\sinh(\alpha\sigma)]^n \exp\left(Q / RT\right) \tag{5}$$

Carrying out Taylor series expansion on formula (5), two expressions under different stress levels are obtained:

1) At low stress levels ($\alpha\sigma < 0,8$), formula can be simplified as:

$$\dot{\varepsilon} = A_1\sigma^m \exp(-Q/RT) \tag{6}$$

2) At high stress levels ($\alpha\sigma > 1{,}2$), formula can be simplified as:

$$\dot{\varepsilon} = A_2 \exp(\beta\sigma)\exp(-Q/RT) \tag{7}$$

Where-strain rate /s^{-1}; A_1, A_2, A - structure factor is related to the material; flow stress /MPa; m - stress index; α, β - stress level parameter /MPa^{-1}; R -Molar gas constant and R = 8,314J/(mol·K); *Q* - deformation activation energy (J/mol); T - deformation temperature /K

Use the multiple regression method to solve the material constant, and take the natural logarithm on both sides of equation (5).

$$\ln\dot{\varepsilon} = \ln A + n\ln\left[\sinh(\alpha\sigma)\right] - Q/RT \tag{8}$$

When the deformation temperature is constant, the *Q / RT* term and lnA term in the above three formulas are both fixed values, and the formula can be simplified to:

$$\ln\dot{\varepsilon} = \ln A + n\ln[\sinh(\alpha\sigma)] \tag{9}$$

Take partial derivatives of the formulas:

$$n = \frac{\partial\ln\dot{\varepsilon}}{\partial\ln\left[\sinh(\alpha\sigma_s)\right]} \tag{10}$$

The Arrhenius relationship including the activation energy *Q* describes the relationship between the steady-state flow stress and the strain rate and the deformation temperature during the thermal deformation of the material:

$$\dot{\varepsilon} = A[\sinh(\alpha\sigma)]^n \exp\left(Q/RT\right) \tag{11}$$

The constitutive relationship of alloy steel under the environment of underground temperature field

It has been proved that the temperature and strain rate also affect the strain at the beginning of steady-state deformation during the expansion and deformation process of the steel for expansion pipe in the downhole temperature field. This strain varies between $\dot{\varepsilon}$ = 0,1 ~ 0,5. The strain rate $\dot{\varepsilon}$ has an exponential function relationship with temperature T, steady-state flow stress σ_s, and activation energy *Q*:

$$\dot{\varepsilon} = A\cdot\sigma_S^n\cdot\exp(-Q/RT) \tag{12}$$

If it is assumed to be independent of temperature and stress, and set

$$Z = \dot{\varepsilon}\exp(Q/RT) \tag{13}$$

Then *Z* can represent

$$Z = \dot{\varepsilon}\exp(Q/RT) = A\sigma_S^n \tag{14}$$

Where: Z-Zeller-Hollomon. is the temperature-corrected deformation rate; $\dot{\varepsilon}$, T can usually be expressed as a function of Z.

For the dynamic tensile experiment of alloy steel in the temperature range of 25 – 300 °C, the constitutive equation under the condition of fixed strain rate:

$$\dot{\varepsilon} = A[\sinh(\alpha\sigma)]^n \exp\left(Q/RT\right) \tag{15}$$

When the temperature T is constant

$$\left.\frac{\partial\ln[\sinh(\beta\sigma)]}{\partial\ln Z}\right|_{T=constant} = \frac{1}{n} \tag{16}$$

when the strain rate is constant

$$Rn\left.\frac{\partial\ln\left[\sinh(\alpha\sigma)\right]}{\partial(1/T)}\right|_{\dot{\varepsilon}=constant} = Q \tag{17}$$

Establish the constitutive equation of expansion deformation of low-carbon alloy steel in the downhole temperature field environment.

Experiment on dynamic tension of alloy steel

According to the actual working conditions of the oil and gas field, the dynamic tensile experiment of alloy steel is carried out in the temperature range of 25 – 300 °C, and the dynamic tensile experiment is selected at 25 °C,100 °C,150 °C,200 °C,250 °C,300 °C, test strain rate is 3mm/s. [8]The measured stress-strain curves at different deformation temperatures are shown in Figure 1.

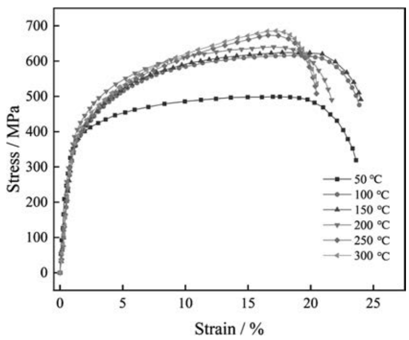

Figure 1 Tensile stress-strain curves under different temperature conditions of low carbon alloy steel

Calculation of activation energy Q for warm deformation Expansion of alloy steel

McCormick derived the relationship between the critical strain ε, the strain rate $\dot{\varepsilon}$, the alloy composition C_0 and the deformation temperature T for the appearance of the sawtooth wave:

$$\varepsilon_c^{(m+\beta)} = A\left(C_1/C_0\right)^{3/2}\dot{\varepsilon}\exp\left(Q_m/kT\right) \tag{18}$$

Where: C - dislocation concentration on the dislocation line when the dislocation is pinned; Q_m - vacancy formation activation energy; m - density of movable dislocations during deformation; β - vacancy concentration proliferation speed; A - effective barrier Constants related to the spacing.

When the alloy composition and strain rate are constant, the critical strain required for sawtooth yielding phenomenon has an exponential function relationship with the reciprocal of the deformation temperature.

$$\sigma = \frac{1}{\alpha}\ln\left\{\left(\frac{Z}{A}\right)^{1/n} + \left[\left(\frac{Z}{A}\right)^{2/n} + 1\right]^{1/2}\right\} \quad (19)$$

Where: K - constant; k - Boltzmann's constant, $k = 1{,}38\times10^{-23}\, J{\cdot}K^{-1}$.

taking the logarithm of both sides of equation, get:

$$\ln\varepsilon_c = \ln K - Q_m / kT \quad (20)$$

The average slope is the deformation activation energy $Q_{def} = 43{,}939\cdot \mathrm{kJ\cdot mol^{-1}}$.

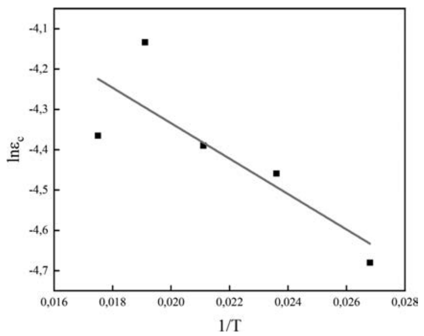

Figure 2 Relation curves of ln$\dot{\varepsilon}$ and 1 / *T*

Research [6] shows that there is a specific relationship between flow stress σ, temperature T and strain rate $\dot{\varepsilon}$, which can be expressed by the Sellars creep equation:

$$Z = \dot{\varepsilon}\cdot\exp\left(\frac{Q}{RT}\right) = A[\sinh(\alpha\sigma)]^n \quad (21)$$

Where: $\dot{\varepsilon}$ - strain rate / s^{-1}; R - molar gas constant /8,314·$mol^{-1}{\cdot}K^{-1}$; *Q* - Thermal deformation activation energy/J·mol^{-1}; A and α - the material constants related to the steel grade, the α changes very little, and is taken as 0,012 according to the literature; n-stress sensitivity factor, which represents the change of the flow stress caused by the change of the strain rate. Substitute *Q* into equation (21) to find the Z value at different temperatures, and the results are listed in Table 1.

When $T = \dfrac{tem + 273}{1\ 000}$:

$$Z = \dot{\varepsilon}\exp\frac{43\ 939}{RT} \quad (22)$$

When $T = tem + 273$;

$$Z = \dot{\varepsilon}\exp\frac{43939}{RT} \quad (23)$$

Table 1 **Parameter under different deformation temperatures**

temperature / °C	ReL / MPa	ε_c	Z	LnZ
100 °C	391	0,01108	4,31E6	15,2741
150 °C	369	0,01376	2,96E5	13,2385
200 °C	351	0,01653	2,14E5	12,4772
250 °C	362	0,01735	7,37E4	12,2085
300 °C	353	0,01956	5,05E4	11,8263

The constitutive equation of temperature deformation and expansion for alloy steel

Taking the logarithm of both sides of $Z = A\left[\sinh\sinh\left(\alpha\sigma_s\right)\right]^n$ get:

$$\ln Z = \ln A + n\ln\left[\sinh\left(\alpha\sigma_s\right)\right] \quad (24)$$

There is a linear relationship between lnZ and $\ln\left[\sinh\sinh\left(\alpha\sigma_s\right)\right]$. Using linear regression, the values of A and *n* can be obtained.

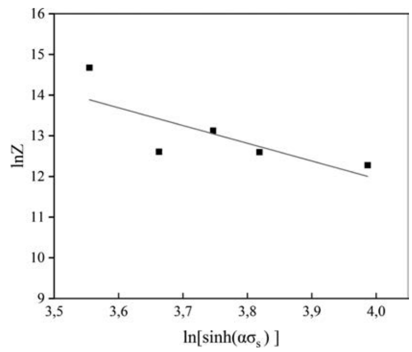

Figure 3 Relation curves of ln *Z* and ln[sinh($\alpha\sigma_S$)]

Obtain the intercept value and slope of the line from the graph, get.

$$n = \frac{\partial \ln Z}{\partial\ln\left[\sinh(\alpha\sigma_s)\right]} = 4{,}1612 \quad (25)$$

$LnA = 29{,}03965$

$A = 4{,}0903E12$

According to the definition and formula of hyperbolic sine function, σ can be expressed as a function of Z parameter;

$$\sigma = \frac{1}{\alpha}\ln\left\{\left(\frac{Z}{A}\right)^{1/n} + \left[\left(\frac{Z}{A}\right)^{2/n} + 1\right]^{1/2}\right\} \quad (26)$$

Finally, the calculated values of *A*, *α*, *Q* and n are substituted into equation (26) to obtain the flow stress constitutive equation.

$$\sigma = 83{,}333\ln\ln\left\{\left[\frac{\dot{\varepsilon}\exp\exp\left(\frac{5287{,}48495}{T}\right)}{4{,}0903E12}\right]^{1/4{,}1612} + \right.$$

$$\left. + \left[\left(\frac{\dot{\varepsilon}\exp\exp\left(\frac{5287{,}48495}{T}\right)}{4{,}0903E12}\right)^{2/4{,}1612} + 1\right]^{1/2}\right\} \quad (27)$$

Comparison of calculated flow stress and finite element analysis of residual stress

From Figure 4, it can be obtained that the Von-mises stress from 25 °C to the expansion of alloy steel is less than the flow stress value, and the difference is rela-

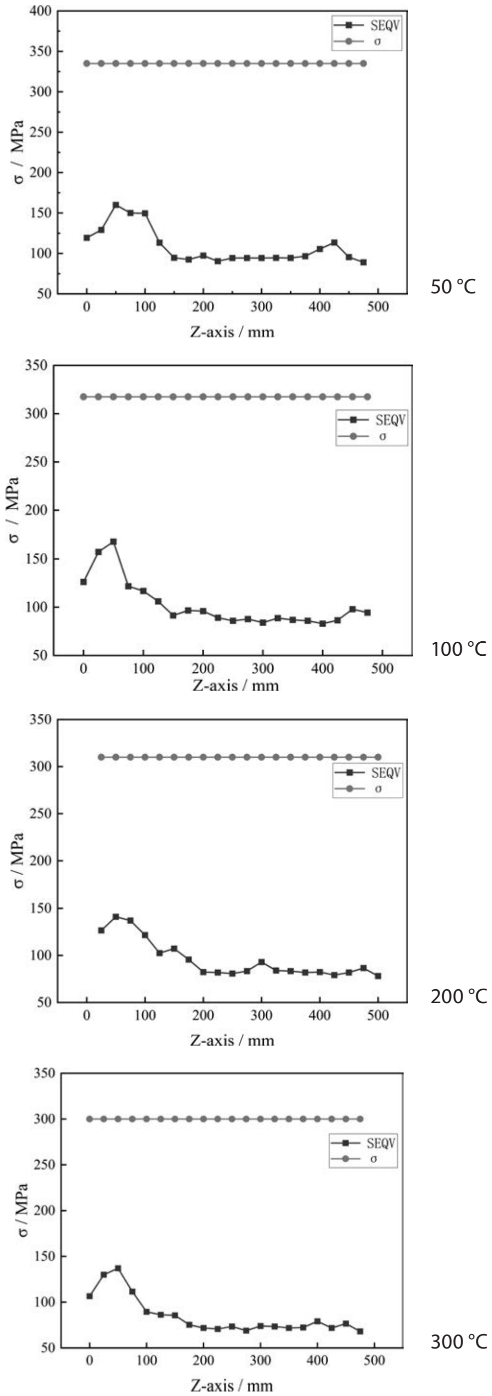

Figure 4 Comparison of calculated flow stress and simulated

tively large, exceeding 150 MPa and higher, which can account for the flow stress corresponding to the temperature of each difference. 40 % to 52 % of the value. It can be seen that after the expandable casing is expanded and deformed, most of its deformation stress is released, and the residual stress value is very different from the flow stress required for deformation. This is related to the high energy absorption of alloy steel. Therefore, the comparison between the calculated flow stress and the finite element analysis of the residual stress also just shows that the theoretical calculation of the flow stress model is correct, and the flow stress value derived from the constitutive equation is also consistent with the actual situation.

CONCLUSION

This article introduces the theory of dynamic recovery and dynamic strain aging under warm working, applying the theory of warm working deformation, studying the relationship between flow stress and plastic strain of alloy steel under warm working conditions, applying dynamic recovery theory and dynamic strain aging Theoretical establishment of constitutive equations under temperature deformation conditions, so as to realize the calculation of flow stress under different temperature conditions .

Starting from the results of the dynamic tensile experiment, the McCormick method is used to obtain the deformation activation energy by using the linear relationship between $\ln \varepsilon_c$ and 1/T. The Sellars equation is used to obtain the temperature-compensated strain rate factor Z value corresponding to each temperature. By processing the Sellars equation, using the linear relationship between lnZ and $\ln[\sinh \sinh(\alpha\sigma_p)]$, the regression method is used to obtain the constants A and n in the Sellars equation, and finally the value of the alloy steel in the downhole temperature field environment is established. Expansion deformation constitutive equation. The flow stress value calculated by the established model and the residual stress value calculated by the finite element are compared and analyzed, and it is concluded that the established constitutive equation is correct.

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REFERENCES

[1]. O Dai, A Shawn, B Li, et al. Chester Ultimate swelling described by limiting chain extensibility of swollen elastomers Int. [J], Mech. Sci 144 (2018), 531-539.

[2]. Deformation, Processing, and Structure [C]. ASM Materials Science Seminar 2 (1984), 5-10.

[3]. X. S. Liao, Y. K. Qi, X. H. Zhu, Failure analysis and solution study of 203 mm solid expandable tubular.Eng [J]. Fail Anal 106 (2019), 212-215.

[4]. Marketz, F. Welling, R. W. Fan, Expandable Tubular Completions for Carbonate Reservoirs[J]. SPE Drilling & Completion, 12 (2007), 39-45.

[5]. R. D. Mack, T. Mc, L. Ring, How in Stiu Expansion Affects Casing and Tubing Properties[J]. World Oil 20 (1999), 69-71.

[6]. C. Zener, H. Hollomon, Effect of strain-rate upon the Plastic flow of steel[J]. Journal Application Physics 15 (1944), 22-27.

[7]. McCormick PG. A model for the Portevin-Le Chatelier effect in substitutional alloys[J]. ActaMetall 20 (1972), 351-354.

[8]. Peng J , Zhou C , Dai Q , et al. Isochronous Stress-strain Curves of CP-Ti at Low and Intermediate Temperatures[J]. Rare Metal Materials and Engineering, (2016).

Note: The responsible translator for English language is M. L. Gao-North China University of Science and Technology, China