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MODIFIED ZERILLI-ARMSTRONG MODEL FOR 21-4N HEAT-RESISTANT STEEL

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The Gleeble - 1500D thermal simulator was used to conduct the isothermal compression test of 21 - 4N heat-resistant steel under the T range of 1 273 - 1 453 K and $\dot{\varepsilon}$ of 0,01 – 10 s^{-1}. Using the obtained stress - strain data, various parameters of the modified Zerilli-Armstrong (m – Z - A) model were calculated. The constitutive equations of 21 - 4N heat-resistant steel based on the m – Z - A were established. The m – Z - A model can well describe the rheological behavior of 21 - 4N heat-resistant steel. The simulation process can be completed successfully, indicating that the established models can be used for the simulation study of thermal deformation of 21 - 4N heat-resistant steel and are correct. The results can provide some important basic data for the simulation of 21 - 4N heat resistant steel on plastic deformation process.

Key words: 21-4N, Zerilli-Armstrong, hot deformation behavior, heat-resistant steel

INTRODUCTION

21 - 4N is a nickel-plated austenitic heat-resistant steel successfully developed in the 1 950. Since it contains a large amount of Cr, it has high oxidation resistance and corrosion resistance. 21 - 4N is mainly hardened by carbon and nitride precipitation, it exhibits high wear resistance and toughness at high temperatures, and it has cold and heat alternating microstructure stability. Therefore, 21 - 4N is the preferred material for production of high-power internal combustion engine valves operating under high temperature conditions, and is widely used in automobiles, space shuttles, ships and other fields [1]. The constitutive model is a mathematical model of the macroscopic properties of the reactive materials. It plays a crucial role in predicting the flow stress of actual production [2]. The more common constitutive materials. It can provide a reliable theoretical basis for models currently used are the Arrhenius model, Johnson - Cook (J - C) model, Zerilli-Armstrong (Z - A) model, Artificial Neural Network (ANN) and Fields - Backofen (F - B) model.

In recent years, many scholars have studied various constitutive models of different materials. Chan [3] used the F - B model to describe the constitutive relationship of AZ31B magnesium-based alloy. The calculated results are consistent with the experimental results. Tsao et al [4] used the F-B equation to establish and obtained good prediction results. Xu et al [5] established the m - F - B model of AA5083 alloy to predict its high temperature rheological behavior, and obtained good prediction results. Samantaray et al [6] Z - A model and Arrhenius model to describe the flow behavior of 9Cr - 1Mo steel.

This paper based on the isothermal compression test, the modified Z - A model of 21 - 4N were established by using stress and strain data. In the end, the accuracy was verified.

MATERIALS AND EXPERIMENTAL

The experimental material in this study is 21 - 4N, and its composition is: 0,48 - 0,58 % C, 0,35 % Si, 8 - 10 % Mn, 0,04 % P, 0,03 % S, 20 - 22 % Cr, 3, 25 - 4,5 % Ni, 0,35 - 0,5 % N, Bal. Fe.

The test was carried out on a Gleeble - 1 500D thermal simulator. The deformation temperature was set as 1 273, 1 333, 1 393, 1 453K, the strain rate was 0,01, 0,1, 1, 10 s^{-1}, and the maximum deformation degree was 60 % (the true strain is 0,916). The sample was heated by resistance, and the heating temperature of the sample was measured by thermocouples welded to the specimen. During the test, the two ends of the sample are padded with graphite lubrication sheets to reduce friction, and the experimental data are collected by computer. The size of the test sample is φ 8 mm × 15 mm. During the test, the sample was heated to a preset temperature at a heating rate of 10 K / s, held for 3 minutes, and then heat-compressed at a constant rate. Finally, water quenching immediately after the test was completed.

RESULTS AND DISCUSSION

The improved Z - A model takes into account isotropic hardening, temperature softening, strain rate

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hardening and the coupling effect of temperature and strain, strain rate and temperature on flow stress, and has a good predictive ability. He et al. [7] have done a lot of researches on modified Z - A model of different materials. Based on the characteristics of the stress - strain curves of 21 - 4N, this paper further modifies the Z - A model. And the modified equation is as follows:

$$\begin{cases} \sigma = \left(A_0 + A_1\varepsilon + A_2\varepsilon^2 + A_3\varepsilon^3\right) \\ exp[-\left(B_0 + B_1\varepsilon + B_2\varepsilon^2 + B_3\varepsilon^3\right)T^* \\ +(C_0 + C_1T^* + C_2T^{*2} + C_3T^{*3})ln\dot{\varepsilon}^*] \\ \dot{\varepsilon}^* = \dfrac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \\ T^* = T - T_{ref} \end{cases} \quad (1)$$

In the equation: σ - flow stress, MPa; ε - strain; $\dot{\varepsilon}^*$ - dimensionless strain rate; $\dot{\varepsilon}$ - strain rate, s^{-1}; $\dot{\varepsilon}_0$ - reference strain rate, s^{-1}; T* - dimensionless deformation temperature; T - deformation temperature, K; T_{ref} - reference deformation temperature, K; A_0, A_1, A_2, A_3, B_0, B_1, B_2, B_3, C_0, C_1, C_2, C_3 - constants related to materials.

When calculating model parameters, it is divided into two conditions: on the one hand, the strain rate is in the range of 0,01 - 0,1 s^{-1}, at which time dynamic recrystallization is the main softening mechanism. On the other hand, the strain rate is in the range of 1 - 10s^{-1}, at which time dynamic recovery is the main softening mechanism.

Condition 1: When the strain rate is in the range of 0,01 - 0,1 s^{-1}, set 0,01 s^{-1} as the reference strain rate. At this point, the solution process of parameters A_0, A_1, A_2, A_3, B_0, B_1, B_2, B_3, C_0, C_1, C_2 and C_3 is as follows:

When the strain rate is the reference strain rate ($\dot{\varepsilon} = \dot{\varepsilon}_0 = 0{,}01\ s^{-1}$), Equation (1) can be rewritten as:

$$\sigma = (A_0+A_1\varepsilon+A_2\varepsilon^2 + A_3\varepsilon^3)\ exp\ [-(B_0+B_1\varepsilon + B_2\varepsilon^2 + B_3\varepsilon^3)\ T^*] \quad (2)$$

Taking the logarithm of both sides of Equation (2):

$$ln\sigma = ln\ (A_0+A_1\varepsilon+A_2\varepsilon^2 + A_3\varepsilon^3) - (B_0+B_1\varepsilon + B_2\varepsilon^2 + B_3\varepsilon^3)\ T^* \quad (3)$$

Figure 1 shows the functional relationship between $ln\sigma$ and T* at different strain. It can be seen from Figure 2 that $ln\sigma$ is linear with T*, $ln\sigma = ln\ (A_0+A_1\varepsilon+A_2\varepsilon^2 + A_3\varepsilon^3)$ is the intercept, $-(B_0+B_1\varepsilon + B_2\varepsilon^2 + B_3\varepsilon^3)$ is the slope. Let $K_1 = ln\ (A_0+A_1\varepsilon+A_2\varepsilon^2 + A_3\varepsilon^3)$, $K_2 = ln - (B_0+B_1\varepsilon + B_2\varepsilon^2 + B_3\varepsilon^3)$. The values of K_1 and K_2 under different deformation conditions can be obtained by calculation, as shown in Table 1.

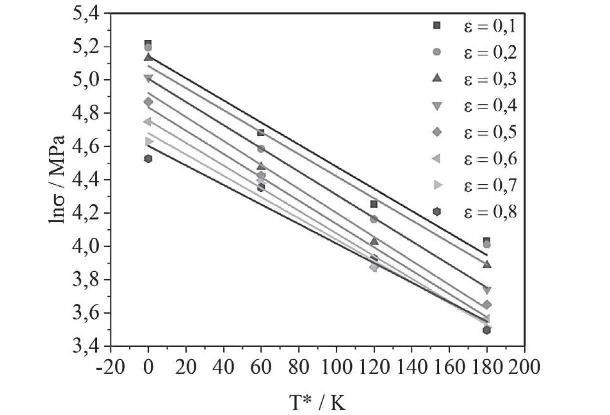

Figure 1 The relationship between lnσ and T* at different strain

Table 1 **The valves of K1, K2 at different strain.**

Strain	0,1	0,2	0,3	0,4
K_1	5,14 275	5,08 331	5,00 735	4,92 121
K_2	0,00 664	0,00 662	0,00 697	0,0 072
Strain	0,5	0,6	0,7	0,8
K_1	4,83 546	4,75755	4,67 963	4,60 333
K_2	0,00 701	0,00 679	0,00 639	0,00 586

The values of A_0, A_1, A_2, A_3, B_0, B_1, B_2, and B_3 can be obtained by fitting $expK_1$ - ε and K_2 - under different strain with the least square method, as shown in Figure 2. And the results are shown in Table 2.

Table 2 **Parameters for the modified Z-A model.**

Parameter	A_0	A_1	A_2
Value	181,199	-89,310	-82,581
Parameter	A_3	B_0	B_1
Value	84,461	0,006	0,002
Parameter	B_2	B_3	
Value	0,0 014	-0.0063	

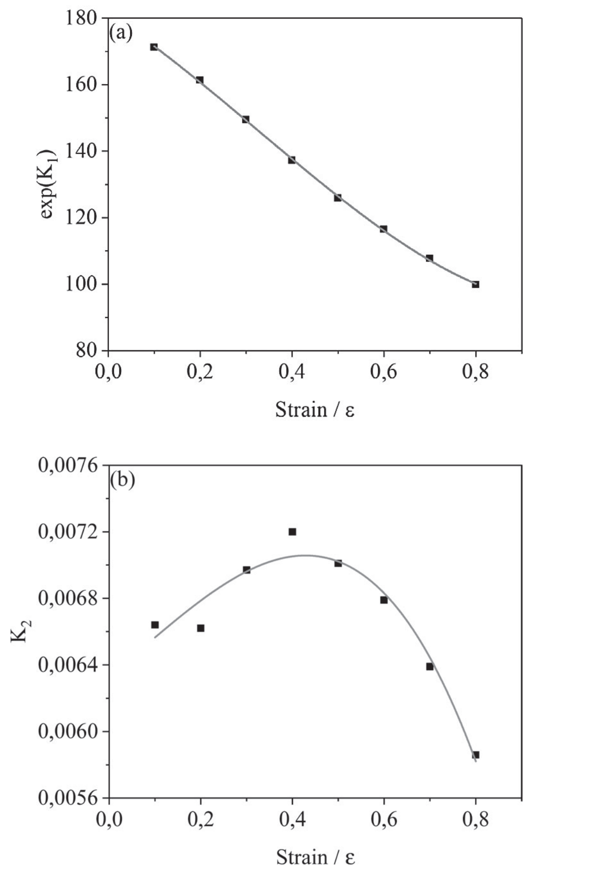

Figure 2 The relationship between $expK_1$ and ε, K_2 and ε at different strain

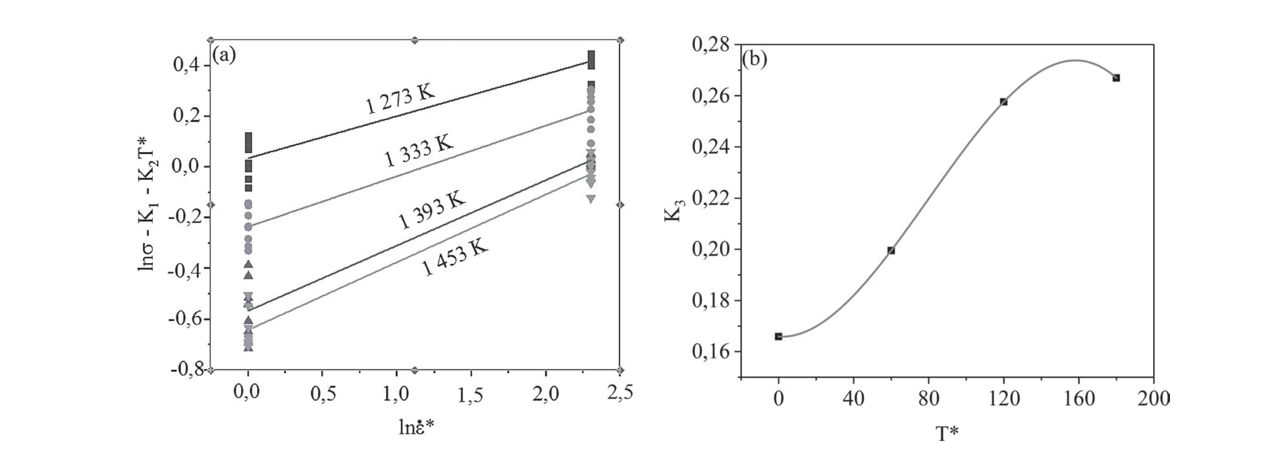

Figure 3 The relationship between *lns* – K_2 – T_2T^* and *ln*$\dot{\varepsilon}^*$, K_3 – T^* at different deformation conditions

Taking K_1 and K_2 at different deformation conditions into Equation (2), and fitting $ln\sigma - K_1 - K_2T^*$ and at $ln\ \dot{\varepsilon}$ different deformation conditions (Figure 3 (a)), the valves of $C_0 + C_1T^* + C_2T^{*2} + C_3T^{*3}$ (let $K_3 = C_0 + C_1T^* + C_2T^{*2} + C_3T^{*3}$) can be obtained, as shown in Table 3.

Table 3 **The valves of K_3 at different deformation conditions.**

T/K	1 273	1 333
K_3	0,16 593	0,19 953
T/K	1 393	1 453
K_3	0,25 761	0,26 693

By fitting K_3 - T^* under different deformation conditions (Figure 3 (b)), the values of C_0, C_1, C_2 and C_3 can be obtained, as shown in Table 4.

Table 4 **Parameters for the modified Z-A model**

Parameter	C_0	C_1	C_2
Value	0,166	$-5{,}089 \times 10^{-5}$	$1{,}357 \times 10^{-5}$
Parameter	C_3		
Value	$-5{,}651 \times 10^{-8}$		

Condition 2: When the strain rate is in the range of 1 - 10 s^{-1}, set 1 s-1 as the reference strain rate. At this

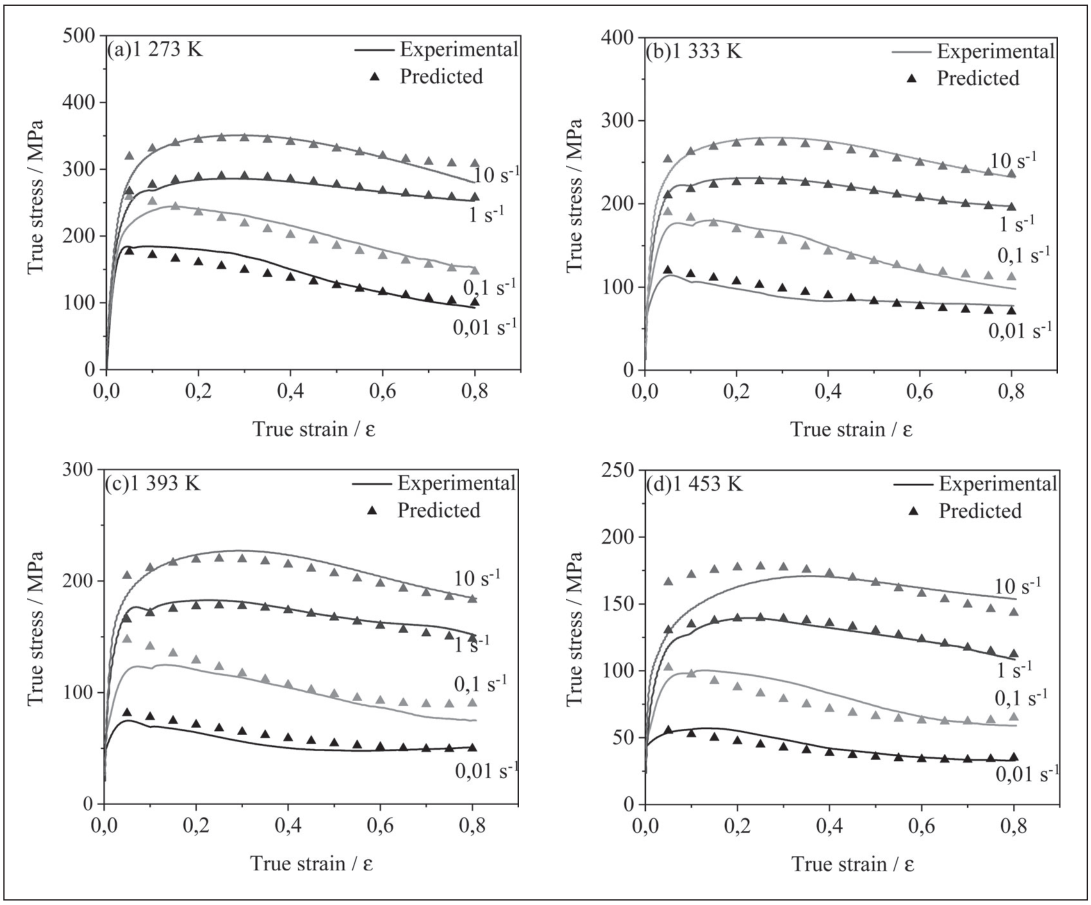

Figure 4 Stress prediction of modified Z - A model of 21 - 4N under different deformation conditions

point, the solution process of parameters A_0, A_1, A_2, A_3, B_0, B_1, B_2, B_3, C_0, C_1, C_2 and C_3 is the same as in condition 1, the results are shown in Table 5.

Table 5 **Parameters for the modified Z - A model.**

Parameter	A_0	A_1	A_2
Value	253,723	299,752	-736,575
Parameter	A_3	B_0	B_1
Value	459,933	0,004	$4{,}802 \times 10^{-4}$
Parameter	B_2	B_3	C_0
Value	$-7{,}024 \times 10^{-4}$	0,00 139	0,077
Parameter	C_1	C_2	C_3
Value	$-2{,}539 \times 10^{-5}$	$1{,}683 \times 10^{-6}$	$-3{,}735 \times 10^{-9}$

MODEL ACCURACY ANALYSIS

Figure 4 shows the calculated stress obtained by the modified Z - A model is basically on the experimental curves under different deformation conditions, indicating that the modified Z - A model has a high predictive ability and can describe the high temperature rheological behavior of 21 - 4N.

CONCLUSIONS

(1) The modified Z - A model is suitable for the prediction of σ under various deformation conditions in the study range.

(2) By comparing with the experimental value, it is shown that the constitutive relationship of 21-4N alloy can accurately predict the flow stress in the experimental range.

Acknowledgments

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REFERENCES

[1] Ji H C, Liu J P, Wang B Y, et al. Microstructure evolution and constitutive equations for the high-temperature deformation of 5Cr21Mn9Ni4N heat-resistant steel. Journal of Alloys & Compounds 693 (2017) 674-687.

[2] Spigarelli S. Constitutive equations in creep of Mg-Al alloys. Materials Science & Engineering A 492 (2008) 153-160.

[3] Chan L C. Finite-Element Damage Analysis for Failure Prediction of Warm Hydroforming Tubular Magnesium Alloy Sheets. The Journal of The Minerals, Metals & Materials Society 67 (2015) 450-458.

[4] Tsao L C, Wu H Y, Leong J C, et al. Flow stress behavior of commercial pure titanium sheet during warm tensile deformation. Materials & Design 34 (2012) 179-184.

[5] Xu X F, Wang G C, Dong H B, et al. Description on tensile deformation behavior of AA5083 alloy based on temperature changing. Journal of Plasticity Engineering 18 (2011) 96-100.

[6] Samantaray D, Mandal S, Bhaduri A K. A comparative study on Johnson Cook, modified Zerilli-Armstrong and Arrhenius-type constitutive models to predict elevated temperature flow behaviour in modified 9Cr-1Mo steel. Computational Materials Science 47 (2009) 568-576.

[7] He A, Xie G L, Zhang H L, et al. A modified Zerilli-Armstrong constitutive model to predict hot deformation behavior of 20CrMo alloy steel. Materials & Design 56 (2014) 122-127.

Note: The responsible translator for English language is W.C. PEI North China University of Science and Technology, China