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RESEARCH ON THERMAL DEFORMATION CONSTITUTIVE MODEL OF 304 STAINLESS STEEL BASED ON TRAVEL INSULATION CUP METAL MATERIAL

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In order to improve the quality of people ‘s travel and improve the performance of travel insulation cup, the thermal deformation behavior of 304 stainless steel, the edible grade material of travel insulation cup, was studied by Gleeble-3800 thermal / mechanical simulation machine. The true stress-strain curve of 304 stainless steel was obtained by hot compression test with deformation temperature of 800~1 100 °C and strain rate range of 0,001 ~ 1 s^{-1}. According to the real stress-strain curve, the Arrhenius constitutive model of 304 stainless steel was constructed. The results show that the flow stress of 304 stainless steel increases with the increase of deformation temperature and strain rate. The theoretical stress value predicted by the constitutive model is fitted with the experimental results, and the correlation is 0,995, indicating that the model has high prediction accuracy.

Keyword: Travel insulation cup; 304 stainless steel; Arrhenius constitutive model; stress; strain

INTRODUCTION

Nowadays, travel has become a part of people ‘s daily life, and how to improve people ‘s travel quality has become an important research direction. As a carrying tool for going out, the travel thermos cup can improve the comfort when traveling[1]. Therefore, it is of great significance to study the thermal deformation of 304 stainless steel used in travel insulation cups[2].

Austenitic stainless steel 304 has excellent ductility, oxidation resistance, corrosion resistance and mechanical properties. It is widely used in aviation manufacturing, transportation, nuclear industry, medical treatment, building materials, chemical industry and food processing[3]. In the modern processing technology of thermal insulation cup, in order to ensure that it can meet its unique shape and practicability, higher requirements are put forward for the mechanical properties of its materials. Since austenite is a single-phase structure that cannot be refined by heat treatment, it is necessary to systematically study its hot deformation behavior.

In this study, the hot compression test of 304 stainless steel under different conditions was carried out by Gleeble-3800 thermal / mechanical simulation test machine to study its hot deformation behavior and construct the Arrhenius constitutive equation of 304 stainless steel[4]. It provides theoretical and experimental guidance for the thermal processing process simulation and process optimization of the material.

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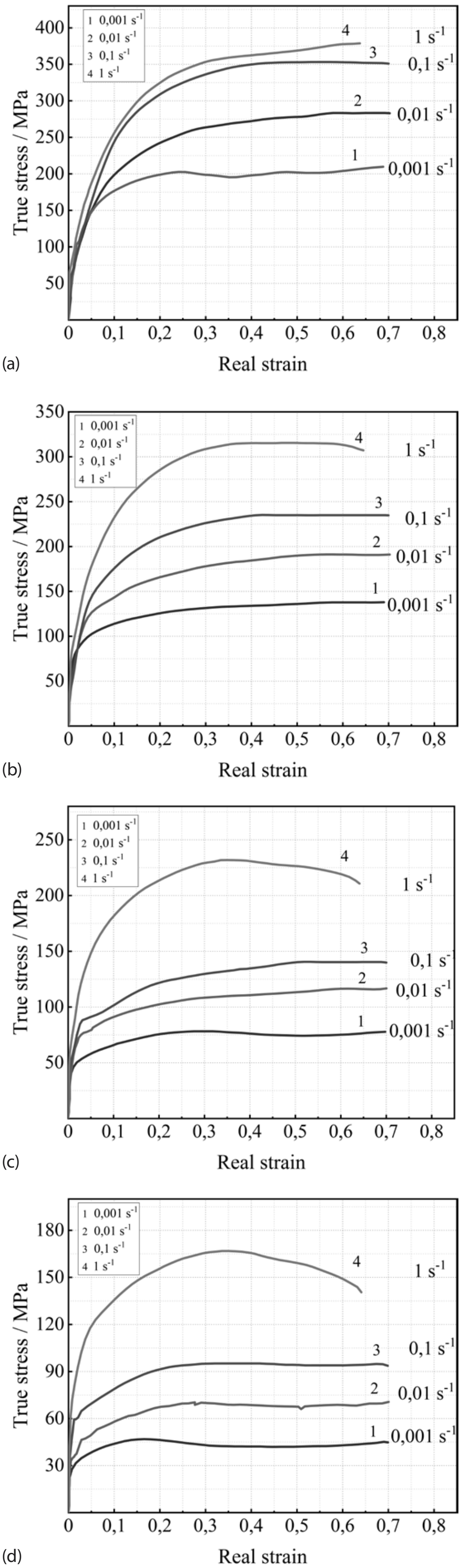
Experiment

The 304 stainless steel was processed into ϕ 6 *mm*×8 *mm* cylindrical compression sample by wire cutting, turning, grinding and other processes. The equipment used in the hot compression test is Gleeble-3800 thermal / mechanical simulation testing machine. Before hot compression, the surface of the sample was wiped with alcohol to reduce the influence of surface impurities. The hot deformation behavior of 304 stainless steel with a maximum strain of 0,7 was studied with temperature and strain rate as control variables. The deformation temperature of metal is set to 800,900,1 000 and 1 100 °C, and the strain rate is set to 0,001,0,01,0,1 and 1 s^{-1}. After the sample is installed, the sample is first preheated and heated to 1 100 °C for 5 min to homogenize the microstructure of the sample. After that, the temperature of the sample was reduced to the temperature of the hot compression test at a speed of 5 °C/*s*, and the hot compression deformation was carried out after holding the temperature for 20 s. After the test is completed, the sample is quickly taken out for water cooling to maintain the hot deformation structure to the maximum extent. After the completion of the test, the original test data recorded on the hot die machine were sorted out and analyzed, and the true stress-strain curves of 304 stainless steel under various deformation conditions were drawn.

Experimental data and ontological modeling

The true stress-strain curve of 304 stainless steel is shown in Figure 1. It can be seen from Figure 1 that



(a) 800 °C (b) 900 °C (c) 1 000 °C (d) 1 100 °C

Figure 1 The true stress-true strain curves of 304 stainless steel during compression at different deformation temperatures and strain rates were obtained.

when the strain rate is fixed, the flow stress required for metal hot deformation will decrease with the increase of temperature; when the temperature is fixed, the flow stress required for metal hot deformation will decrease with the decrease of strain rate.

In order to explore the high temperature deformation of 304 stainless steel, Arrhenius model was introduced to describe the dynamic relationship between flow stress, strain rate and thermodynamic temperature during deformation. The Arrhenius model is expressed as follows:

$$\dot{\varepsilon} = A_1 \sigma^{n_1} \exp(\frac{-Q}{RT}) , \quad \alpha\sigma \le 0,8 \qquad (1)$$

$$\dot{\varepsilon} = A_2 \exp(\beta\sigma) \exp(\frac{-Q}{RT}) , \quad \alpha\sigma \ge 1,2 \qquad (2)$$

$$\dot{\varepsilon} = A\left[\sinh(\alpha\sigma)\right]^n \exp(\frac{-Q}{RT}) , \quad \text{for all } \sigma \qquad (3)$$

where R is the molar gas constant, the value is 8,314J·(mol/K)$^{-1}$, σ is stress/MPa and Q/J/mol is the apparent activation energy of hot deformation. A, A_1, A_2, α, β, n and n_1 are temperature-independent material constants, and $\alpha = \beta/n_1$; T is the deformation temperature, K.

When the temperature T is a fixed value, Q, A, R, T are constants, so the value of and can be calculated by

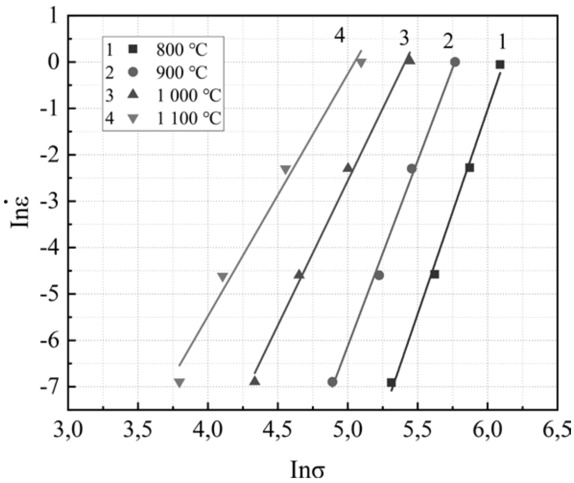


Figure 2 Relation curves of ln $\dot{\varepsilon}$ and ln σ

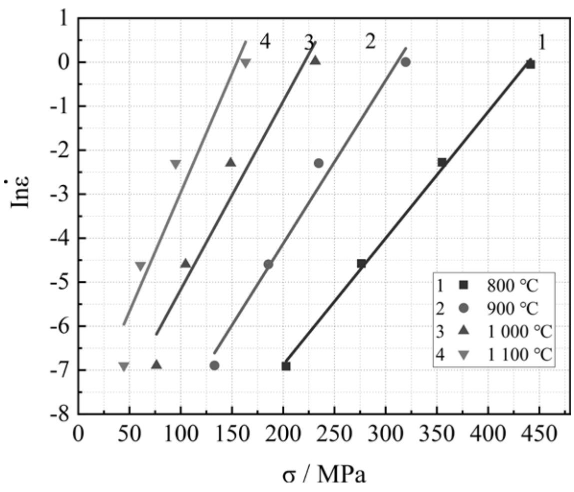


Figure 3 Relation curves of ln $\dot{\varepsilon}$ and σ

combining Eq. (1) and Eq. (2). The specific calculation formula is:

$$In\dot{\varepsilon} = InA_1 + n_1 In\sigma - \frac{Q}{RT} \quad (4)$$

$$In\dot{\varepsilon} = InA_2 + \beta\sigma - \frac{Q}{RT} \quad (5)$$

As shown in Figure 2 and Figure 3, the test data are substituted into Eq. (4) and Eq. (5). By fitting the slopes of $\ln\dot{\varepsilon} - \ln\sigma$ and $\ln\dot{\varepsilon} - \sigma$, $n_1 = 7{,}063325$ and $\beta = 0{,}040665$ are obtained. According to the relationship between n_1, β and α, α = 0,005757204MPa^{-1} is obtained. Taking logarithm of pair (4), the following result is obtained:

When the strain rate is constant, R, n, A and α are constants, and the thermal deformation activation energy Q will change with temperature. Combined with Eq. (3), Q and lnA can be calculated. The specific calculation formula is:

$$Q = Rn\left[\frac{\partial \ln[\sinh(\alpha\sigma)]}{\partial(1/T)}\right]_{\dot{\varepsilon}=cons\tan t} \quad (6)$$

$$\ln A = \ln\dot{\varepsilon} + \frac{Q}{RT} - n\ln[\sinh(\alpha\sigma)] \quad (7)$$

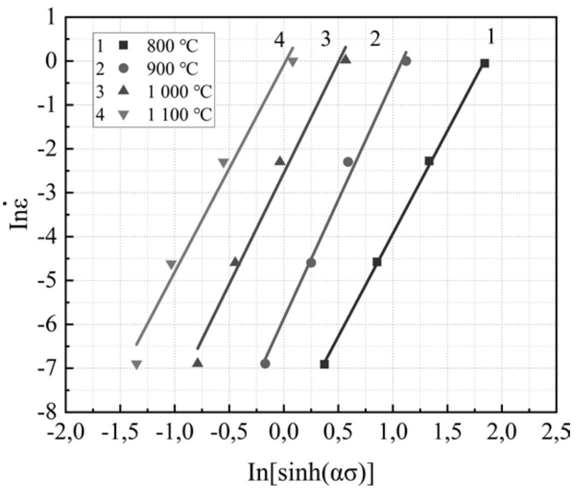


Figure 4 Relation curves of ln $\dot{\varepsilon}$ and ln[sinh($\alpha\sigma$)]

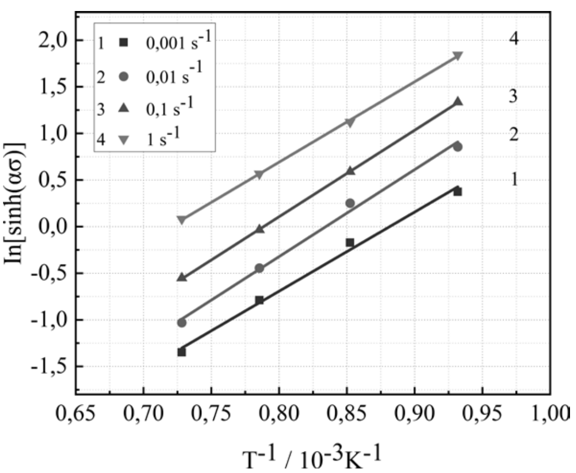


Figure 5 Relation curves of ln[sinh($\alpha\sigma$)] and 1/T

As shown in Figure 4 and Figure 5, through linear regression, the average value of the slope of the regression line is calculated by $n = 4{,}9673025$ and $K = 8\,933{,}26$ respectively, and Q = 368 927,138 J/mol is calculated according to $K = Q/nR$.

The Arrhenius model can better understand and analyze the influence of strain rate and temperature on flow stress by introducing Z parameter. The specific formula is as follows:

$$Z = \dot{\varepsilon}\exp\left(\frac{Q}{RT}\right) = A\left[\sinh\left(\alpha\sigma\right)\right]^n \quad (8)$$

Combining Eq. (8) with Eq. (3), the logarithm is obtained:

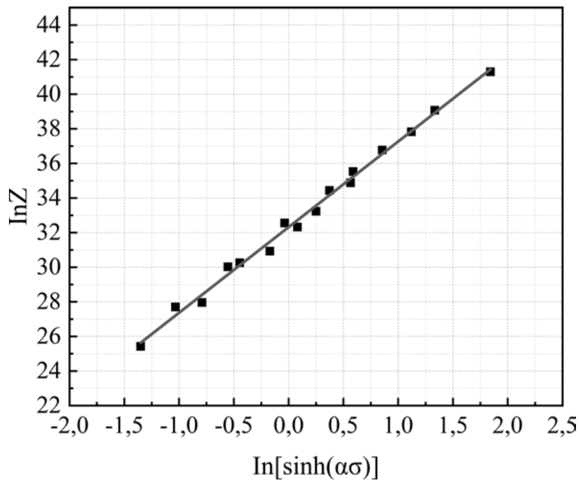


Figure 6 Relation curves of ln Z and ln[sinh($\alpha\sigma$)]

According to Formula (9), by fitting the relationship between ln Z and ln[sinh($\alpha\sigma$)], the intercept ln A = 32,32054 is finally obtained, and then the structural factor $A = 1{,}088\times10^{14}$ of the experimental alloy is obtained.

In summary, the constitutive model of 304 stainless steel under the peak conditions of deformation temperature of 800 ~ 1 100 °C and strain rate of 0,001 ~ 1 s^{-1} is:

$$\dot{\varepsilon} = 1{,}088\times10^{14}\left[\sinh(0{,}005757204\sigma)\right]^{4{,}9673025}\exp\left(\frac{-368\,927{,}1381}{8{,}314T}\right) \quad (10)$$

Simulation prediction and verification of constitutive model

In order to test the applicability of the Arrhenius constitutive model of 304 stainless steel, the flow stress data calculated by the constitutive model of 304 stainless steel are fitted with the experimental values, as shown in Figure 7. The correlation coefficient R^2 = 0,995 between the calculated results of the constitutive model of 304 stainless steel and the experimental values shows that the established constitutive model equation of 304 stainless steel can accurately describe the dynamic relationship between flow stress, strain rate and temperature of 304 stainless steel during high temperature deformation.

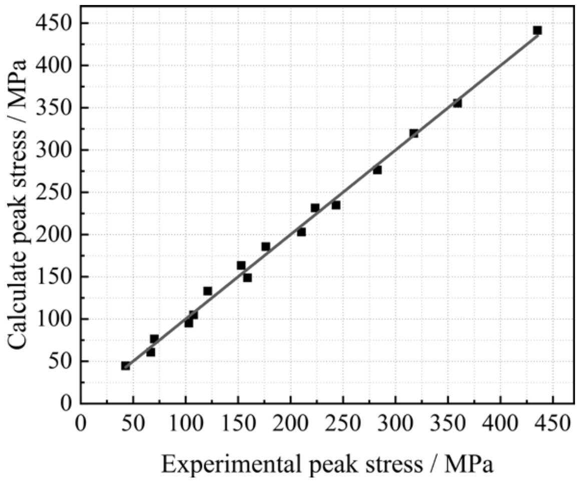


Figure 7 The peak stress calculation results are compared with the measured values

CONCLUSION

When the deformation temperature of 304 stainless steel is 800 ~ 1 100 °C and the strain rate is 0.001 ~ 1s^{-1}, the true stress-strain curve is greatly affected by temperature and strain rate. The specific performance is that the flow stress increases with the decrease of temperature and the increase of strain rate. The Arrhenius constitutive model of 304 stainless steel was established by introducing the temperature-compensated strain rate factor parameter Z. Through analysis and verification, the results show that the error between the predicted value of flow stress and the experimental value calculated by the constitutive model of 304 stainless steel established in this paper is small, and it has high prediction accuracy, which can provide some help and reference for the forming process of travel insulation cup.

REFERENCES

[1] Chen, A. Y., et al. "The influence of strain rate on the microstructure transition of 304 stainless steel." Acta Materialia 59. (2011) 9, 3697-3709.

[2] Mangonon, Pat L., and Gareth Thomas. "Structure and properties of thermal-mechanically treated 304 stainless steel." Metallurgical transactions 1 (1970), 1587-1594.

[3] Majidi, Azar P., and Michael A. Streicher. "The double loop reactivation method for detecting sensitization in AISI 304 stainless steels." Corrosion 40. (1984) 11, 584-593.

[4] Mangonon, Pat L., and Gareth Thomas. "Structure and properties of thermal-mechanically treated 304 stainless steel." Metallurgical transactions 1 (1970): 1587-1594.

Note: The responsible translator for English language Q. Liu – Harbin University, China