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Modeling of temperature dependent yield strength for stainless steel considering nonlinear behavior and the effect of phase transition

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HIGHLIGHTS

- An assumption about critical yield energy density is proposed.
- A physics-based temperature dependent yield strength model for stainless steel is established.
- The nonlinear behavior of material and effect of phase transition are considered.
- The good agreement between theory and experiment is obtained.

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ABSTRACT

In this paper, a physics-based temperature dependent yield strength model for stainless steel is developed based on a kind of equivalence between the deformation energy and the heat energy. A critical yield energy which comprises the deformation energy and the corresponding heat energy is then introduced. Meanwhile, the nonlinear behavior of stainless steel before the yielding of materials and the effect of phase transition are considered in the theoretical model without any fitting parameters. These stainless steels studied in this paper are from European brands, Japanese brands and interior brands. Excellent agreement between the theoretical model predictions and the experimental results of austenitic stainless steel and ferritic stainless steel fully validates the reasonability of this model. The theoretical model is convenient and practical to predict the temperature dependent yield strength of stainless steel, which is expected to be applied for the appropriate assessment of fire resistance of stainless steel.

1. Introduction

Stainless steel has been widely used in the construction industry due to the excellent performance of high strength, fire resistance, corrosion resistance and durability [1–5]. In the design of stainless steel structures, it is of primary importance to preserve the load bearing capacity at the situation of fire exposure [6]. As is known, the yield stress of materials is a key parameter for the research of allowable stress in the design of engineering structures, which has a high sensibility to temperature [7]. It leads to the urgent demands for the acquirement of yield strength of stainless steel in high temperature environment. In the past, numerous researchers have done many fruitful studies to characterize the temperature dependence of the yield strength of stainless steel. Gardner [4] studied the mechanical performance of unprotected stainless steel materials in fire. The strength and stiffness of stainless steel are superior to that of carbon steel beyond 600 °C, due to the advantageous effect of alloying elements. Moreover, the mechanical properties of typical stainless steel at elevated temperatures are investigated by European Convention for Constructional Steelwork (ECCS) [8,9] in European Normalization (EN). Sakumoto [10] also reported the high temperature mechanical properties of stainless steel. The stainless steel grades were from Single UNIX Specification (SUS) in Japanese Industrial Standards. Chen [11] studied the mechanical properties of stainless steel by steady state test method where the specimen was heated up to a given temperature then loaded until it failed at that time maintaining the same temperature and transient state tensile tests method where the specimen was under a certain tensile stress level when the temperature was raised. Meanwhile, he proposed a unified model for characterizing yield strength, ultimate strength and elastic modulus at elevated temperature. However, this is a phenomenological model with four fitting parameters. The utilization of the model depends on fitting a large number of experimental data, which is very inconvenient. In addition, the current researches with respect to the temperature dependent yield strength of stainless steel mostly adopted phenomenological

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models and experimental method, which leads to the inconvenience and difficulties in application. Therefore, it is prominently important and necessary to study the mechanical behavior and establish a physics-based temperature dependent yield strength model for stainless steel.

It is well known that plastic slip in most crystalline materials was caused by the dislocation slip [12]. The dislocation slip is easier to start owing to an increase in temperature. Then, grain boundary of materials premelt occurs under applied stress when temperature is lower than melting point [13]. It can be observed that the thermal fluctuations cause the yielding of materials, which is partially similar to the contribution of melting process of stainless steel to the yielding of materials [14,15]. Meanwhile, it is clearly that temperature rising and stress increasing have a kind of equivalence to the yielding of materials. Hence, both the heat energy and deformation energy make contributions to the onset of yielding of materials. The Von Mises yield criteria states that materials get into yielding state when the elastic deformation energy per unit volume of materials reaches a certain value. However, the effect of temperature on materials properties is not considered in the yield criteria. In our team's previous work, Li proposed a novel temperature dependent yield strength model for metallic materials based on the modeling idea of the equivalence between heat energy and deformation energy [7,16]. In the previous work, it is assumed that materials get into yielding state at temperature *T* when the storage of energy which comprises the elastic strain energy and the corresponding heat energy at temperature *T* reaches a certain value. Meanwhile, there is a kind of equivalent relationship between the above two parts energy on the basis of their contribution to the yielding of materials.

In this work, the nonlinear stress-strain relation before the yielding of stainless steel and the effect of phase transition on the maximum storage energy density are considered. The deformation energy density (for volume) is calculated by employing the Ramberg-Osgood model modified by Hill, which considers the nonlinear behavior of stainless steel [17–19]. The phase transition of stainless steel materials appears in the process of temperature rising. It can be observed that the more thermal energy can be stored owing to the phase transition [20,21]. Accordingly, a modeling idea based on the above assumption was proposed.

A temperature dependent yield strength model for stainless steel considering nonlinear behavior and the effect of phase transition was established, which is convenient and practical to predict the temperature dependent yield strength of stainless steel. Furthermore, this theoretical model is expected to be applied for the appropriate assessment of fire resistance of stainless steel, which avoids the difficulties of experimental operation at high temperature.

2. Theory

The phase transition of stainless steel at elevated temperature results in the diversification of organization structure and the jump of specific heat capacity [20]. More thermal energy can be stored effectively due to the phase transition of materials [21]. Since the maximum storage of energy per unit volume (W_{Total}) was considered a certain value in the process of modeling based on the above assumption, there exists the equivalent phase transition energy per unit volume in stainless steel contributing to the maximum storage of energy density when the phase transition of materials does not take place, which can be considered as a constant value for a particular material.

Accordingly, based on the above assumption [7,16], the maximum storage of energy per unit volume W_{Total} can be written as:

$$W_{\text{Total}}(T) = k(W_T(T) + \Delta H) + W_d(T) + Q \tag{1}$$

where the constant value W_{Total} is the maximum storage of energy density corresponding to the onset of the yielding of materials, which depends on the types of materials and their microstructure. k is the assumed ratio coefficient between the deformation energy density $W_d(T)$ and the heat energy density $W_T(T)$ as their incompletely equivalence of effects on the mechanical properties of materials, which can be regarded a s a constant value for a particular material. Therefore, the constant k is not needed to be determined individually in calculation. It can be eliminated automatically in the theoretical model derivation.

$W_d(T)$ is the deformation energy density (for volume) corresponding to the yielding of materials at temperature *T*. Because unidirectional quasi-static tensile test is widely used to test the mechanical properties of materials in the engineering application and material science, the uniaxial tension condition was considered here. Under uniaxial tension condition, the deformation energy density (for volume) before the yielding of materials can be written as:

$$W_d(T) = \int_0^{\varepsilon(T)} \sigma(T) d\varepsilon(T) \tag{2}$$

where $\sigma(T)$ and $\varepsilon(T)$ are the engineering stress and strain at temperature *T*, respectively. Before the yielding of materials, there exists the monotonous stress-strain relation. Thus, if $\sigma(T)$ are taken as an independent variable, the above formula (Eq. (2)) can become the following expression:

$$W_d(T) = \sigma(T)\varepsilon(T) - \int_0^{\sigma(T)} \varepsilon(T) d\sigma(T) \tag{3}$$

Because stainless steel have no sharply defined yield point and show an early departure from linear elastic behavior with strain hardening, the structural performance differs from that of carbon steel [1]. Therefore, when materials have no clearly yield point, it is thus usual to define the yield point in terms of a 0.2% proof stress ($\sigma_{0.2}$). In fact, the stress at a 0.2% offset is the yield strength, as the 0.2% yield strength ($\sigma_{0.2}$) is the intersection point of the stress-strain curve and the proportional line offset by 0.2% strain. In addition, the nonlinear behavior of stainless steel is described by the Ramberg-Osgood model [18]. When the stress value is less than the 0.2% proof stress ($\sigma_{0.2}$), the temperature dependent stress-strain relation of stainless steel can be obtained from the expression modified by Hill [19]:

$$\varepsilon(T) = \frac{\sigma(T)}{E_T} + 0.002\left(\frac{\sigma(T)}{\sigma_{0.2}(T)}\right)^{n_T} \tag{4}$$

where E_T is the Young's modulus at temperature *T*. n_T is the exponential coefficient in order to characterize the degree of nonlinearity at temperature *T*.

Substituting Eq. (4), the point $(\varepsilon_{0.2}, \sigma_{0.2})$ where $\varepsilon_{0.2}$ is the total strain corresponding to $\sigma_{0.2}$ into Eq. (3), the critical yield energy density of stainless steel at temperature *T* can be expressed as follow:

$$\begin{aligned} W_d(T) &= \varepsilon_{0.2}(T)\sigma_{0.2}(T) - \int_0^{\sigma_{0.2}(T)} \varepsilon(T) d\sigma(T) \\ &= \frac{\sigma_y^2(T)}{2E_T} + \frac{0.002 n_T \sigma_y(T)}{n_T + 1} \end{aligned} \tag{5}$$

The heat energy density (for volume) of stainless steel $W_T(T)$ can be written in the form:

$$W_T(T) = \int_0^T \rho C_P(T) dT \tag{6}$$

where $C_P(T)$ is the specific heat capacity for constant pressure and temperature *T*; ρ is the density (here, ρ is regarded as a constant