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A Review of Recent Advances in Temperature-Dependent Constitutive Models and Ductile Fracture Models for Advanced High-Strength Steels in Automotive Applications

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Abstract

Lightweight design is a global trend in the automotive industry. The extensive application of advanced high-strength steel in automobiles enables lightweight design, while its higher tensile strength ensures the safety of vehicle passengers. However, advanced high-strength steel suffers from defects such as edge cracking and spring-back during cold forming, which hinders its extensive application in automotive manufacturing. Thus, numerous researchers have incorporated temperature control into the forming process of advanced high-strength steels and found that this approach effectively enhances their formability without compromising tensile strength. Investigating temperature-dependent constitutive models and ductile fracture criteria for advanced high-strength steels can facilitate better understanding of their deformation behavior and more accurate cracking prediction, thus broadening their application prospects. Currently, temperature-dependent constitutive models and ductile fracture criteria for advanced high-strength steels are primarily categorized into two types: macroscopic and microscopic approaches. The macroscopic approach involves performing uniaxial tensile and other basic mechanical tests or constructing constitutive models that describe the stress-strain response through combining piecewise function fitting with continuum mechanics. On the microscopic scale, research primarily involves observing dislocation density, lattice distortion, grain orientation, etc., and constructing constitutive models that reveal deformation mechanisms and structural evolution laws by integrating dislocation dynamics and phase transition theory. Taking advanced high-strength steels as the research object, this paper reviews the current state of temperature-dependent constitutive models and analyzes three typical ductile fracture criteria.

Keywords

Lightweighting; Advanced High-strength Steels; Warm Forming; Temperature-dependent Constitutive Modeling; Temperature-dependent Ductile Fracture Modeling.

1. Introduction

A lightweight automotive body is crucial for enhancing passenger safety in modern vehicles. High-strength and ductile steels enable the use of thinner steel sheets while ensuring that the vehicle's structural integrity is maintained under load conditions[1]. The incorporation of these advanced steels not only meets the high-strength requirements but also ensures sufficient ductility for forming intricate shapes. This dual property is crucial for promoting innovation and enhancing design flexibility in vehicle manufacturing. Consequently, the pursuit of lightweight materials not only enhances vehicular safety but also drives innovation in automotive design and production.

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Third-generation ultra-high-strength steels, such as Quenching-Partitioning (QP) steels, medium-manganese steels, and multiphase steels, offer diverse material options for modern automotive body applications. These materials not only facilitate the lightweighting of vehicle bodies but also uphold stringent safety standards while ensuring cost efficiency. However, while they exhibit enhanced mechanical properties compared with previous generations, this improvement presents increased manufacturing challenges and costs[2]. Specifically, the higher content of alloying elements like Al, Mn, and Si in their compositions can potentially lead to defects such as edge cracking and thickness variations during manufacturing. Therefore, developing third-generation ultra-high-strength steels with excellent performance, low cost, and high manufacturability is crucial for the automotive industry. This progress not only drives advancements in materials science but also brings new challenges and opportunities in automotive design and manufacturing.

Thermoformed steel is widely used in automotive body manufacturing, and the thermo-forming properties of these body materials serve as a crucial safety guarantee for drivers during driving[3], However, thermoforming has issues such as high forming temperature, difficult manufacturing processes, and severe material surface oxidation[4]. Additionally, it suffers from poor plasticity and low elongation at room temperature, as well as potential cracking and wrinkling during stamping. Warm forming, however, offers advantages like good plasticity, high elongation, lower forming temperature, relatively simple manufacturing processes, less severe surface oxidation, and high strength. Thus, warm forming is gradually replacing thermoforming in automotive manufacturing.

In the field of forming processing, accurately understanding the damage progression and fracture toughness of materials presents a challenging problem. Especially for advanced high-strength steels, predicting ductile fracture is not only a technical challenge but also directly impacts the performance optimization of automotive components and the innovation of manufacturing processes[5]. Introducing warm forming technology into the manufacturing process of advanced high-strength steels is a highly promising processing method. Extensive research has been conducted on the plastic flow behavior of advanced high-strength steels at room temperature, while less research has focused on constitutive models and fracture criteria under warm forming conditions.

This paper focuses on advanced high-strength steels, introducing the research progress of constitutive models and ductile fracture criteria for warm forming of advanced high-strength steels. The aim is to enhance the understanding of warm forming properties of advanced high-strength steels, which is of great significance for promoting their engineering applications.

2. Current Status of Research on Temperature-dependent Constitutive Modeling of High-strength Steel Materials

Temperature-dependent constitutive models are mathematical models that characterize the macroscopic properties of materials, typically relating stress, stress rate to strain, strain rate, temperature, and other thermo-mechanical relationships. They are key factors for accurately predicting forming performance. Currently, there are two methods to construct constitutive models: one is to build them through basic material parameters (such as elastic modulus) using linear regression fitting and other means, and the other is to establish them by deriving macroscopic relationships from microstructures like dislocation density and activation energy[6][7].

2.1 Temperature-dependent Macroscopic Image-only Ontological Modeling

A phenomenological constitutive model refers to a mathematical model that describes the macroscopic mechanical behavior of materials, established through experimental observations rather than physical concepts. This model quantitatively describes the mechanical response of materials via mathematical equations, relying on empirical or semi-empirical equations derived from fitting experimental data without depending on micro-mechanical mechanisms. It aims to characterize the thermo-mechanical relationships among stress, stress rate, strain, strain rate, and temperature using the fewest parameters and the most concise equations.

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Gao F et al.[8] aimed to obtain material parameters in the microstructure that are not specific to a certain strain, select those capable of describing the dynamic softening stage of the entire flow curve and peak stresses corresponding to similar deformations. To overcome the issue of invalid stress ratios derived from calculations, a constitutive model is constructed by dividing stress data into low-stress and high-stress regions. Yu Fei Liu.[9] proposed that to study the stress-strain behavior of QP980 steel under thermo-mechanical friction effects during deformation, the N-H constitutive model was simplified based on the varying degrees of strain rate sensitivity at different temperatures. Seshacharyulu K et al.[10] studied the formability of DP590 at high temperatures (500°C–820°C) by comparing the KHL constitutive model with other models. They found that the KHL model exhibited the best predictive performance within the temperature range of 500°C–820°C and strain rate range of 0.001 to 0.1 s^{-1}. Gao S et al.[11] investigated the deformation mechanisms of Usibor1500 and Ductibor500 high-strength steels. They obtained basic mechanical properties through uniaxial tensile tests at different temperatures; after analyzing the results, they established a temperature-dependent N-H constitutive model. Simulating uniaxial tensile tests with this model showed that it had high fitting accuracy. Tang J et al.[12] proposed an improved Johnson-Cook (J-C) constitutive model considering the thermal softening effect, which they applied to simulate the deformation behavior of high-strength steels. The results show that this model exhibits high accuracy. Venkata Ramana A et al.[13] calibrated the relevant parameters for the modified Arrhenius model and used this calibrated model for temperature-dependent simulations. Through comparisons of the correlation coefficient and mean absolute relative error, the results show that the Arrhenius model can accurately simulate temperature-dependent metal forming processes. Hu S S et al.[14] established a modified Johnson-Cook (J-C) constitutive model considering the interactive effects of deformation parameters. They applied this model to simulate uniaxial tensile tests of MS1180 steel at different temperatures, and the results show that the modified J-C constitutive model exhibits good predictive performance for the flow stress of MS1180. Fan S et al.[15] took austenitic stainless steel as the research object, carried out temperature-dependent uniaxial tensile tests, analyzed the experimental data, and proposed a simplified constitutive model. The constitutive model was divided into two parts: the first part adopted the R-O model, and the second part used a linear expression simplified by MATLAB. Simulations using the constructed constitutive model showed that the simplified constitutive model was feasible and accurate. Wang T et al.[16] incorporated the S-W model into Abaqus for warm forming simulations of DP780 steel and used a response surface method for quantitative evaluation. The results show that the S-W model accurately describes the material flow behavior of DP780 steel during warm forming. Wang L et al.[17] studied high-strength bainitic steel by conducting temperature-dependent compression tests. They obtained basic mechanical parameters (such as the hardening index) from stress-strain curves and proposed an improved KME model to predict the stress-strain relationship of the material. The results show that the predicted curves are in good agreement with the experimental curves. Zhong X et al.[18] modified the strain rate enhancement term and temperature term in the Johnson-Cook (J-C) constitutive model, then used the modified model to describe and simulate the flow behavior of Weldox700E steel. The results show that the simulation results at different strain rates are in good agreement with the experimental results.

Compared with microscopic constitutive models, macroscopic phenomenological constitutive models have easier parameter identification, simpler model forms, and can comprehensively consider temperature softening, strain rate strengthening, and phase transformations, thus being widely used in macroscopic mechanical applications. Although macroscopic constitutive models offer advantages such as easy parameter identification and simple structures, they also have limitations. For example, they cannot be widely applied to other scenarios, are limited to specific experimental ranges, fail to explain the essence of material deformation, and an excess of fitting parameters easily leads to overfitting.

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2.2 Temperature-dependent Microscopic Ontological Modeling

Microscopic constitutive models describe void nucleation, growth, and coalescence in materials through microscopic parameters such as dislocation density and activation energy. Damage is determined by the volume fraction of void nucleation, growth, and coalescence, and constitutive models are obtained through specific laws. There are two most representative methods: one predicts the macroscopic properties of materials via microscopic models of the matrix, interface, etc., and the other describes the process of progressive damage until failure by embedding damage variables (such as crack density) into the model and combining fracture criteria.

Xiong Y B et al.[19] developed a constitutive model based on the deformation mechanisms of the three internal stages of the material, which they divided into two parts. The first part mainly describes deformation driven by dynamic recovery and work hardening, while the second part accounts for deformation attributed to dynamic softening. Wang X et al.[20], To describe the effect of temperature on hardening behavior, two equations are used: one is a martensite rate equation mainly describing martensite formation, and the other is an equation related to yield stress. Zhou Jing et al.[21] proposed a unified viscoelastic constitutive model based on dislocation density. The model decomposes strain into an inelastic part and an elastic part, in which the elastic component adheres to Hooke's law, while the inelastic part accounts for typical viscoelastic effects. Zhao M et al.[22] modified the Fields-Backofen constitutive model by considering the coupling effects of temperature, strain rate, and deformation. Additionally, to account for the influence of work hardening and dynamic softening on flow stress, they used a combination of the strain exponential function and strain power exponent function for description. Kumar R et al.[23] By comparing the results of tensile and compression tests with the predictions of the C-S model, it was found that the predicted results showed good agreement. Therefore, this model can assist in engineering design to predict flow stress under different strain rates.

Microscopic constitutive models have extremely high measurement requirements for the stress-strain of each phase, requiring consideration of the stress-strain of each phase and calculation of its flow stress behavior through complex computational methods. The constitutive model formulas mentioned above are shown in Table 1.

Table 1. commonly used constitutive models for metallic material

Constitutive Model	Formula
Modified Arrhenius model[8][13]	$\dot{\varepsilon} = \mathrm{A}[sinh(\alpha\sigma)]^{\mathrm{n}} \cdot exp\left(-\frac{\mathrm{Q}}{\mathrm{R}T}\right)$
N-H model[9][11]	$\sigma(\varepsilon_{\mathrm{p}}, \dot{\varepsilon}_{\mathrm{p}}, \theta)= K\, exp\left(\frac{\beta}{\theta}\right)\varepsilon_{\mathrm{p}}^{\mathrm{m}}\dot{\varepsilon}_{\mathrm{p}}^{\mathrm{m}}$
Khan-Huang-Liang model[10]	$\sigma = \left[\mathrm{A} + \mathrm{B}\left(1 - \frac{ln\,\dot{\varepsilon}}{D_p^0}\right)^{n_1} \varepsilon_p^{n_0}\right]\left(\frac{\dot{\varepsilon}}{\varepsilon_p^*}\right)^{\mathrm{c}}\left(\frac{T_m - \mathrm{T}}{T_m - \mathrm{T}_{ref}}\right)^{\mathrm{m}}$
Modified J-C model[12]	$\sigma(\varepsilon_p, \dot{\varepsilon_p}, T) = f(\varepsilon_p) \cdot g(\dot{\varepsilon_{pl}}) \cdot \{1 - [T_c + \mathrm{R} \cdot g(\dot{\varepsilon_p}) \cdot Y(\varepsilon_p)]^{\mathrm{m}}$
J-C model[14]	$\sigma = (\mathrm{a} + \mathrm{b}\varepsilon^{n})(1 + \mathrm{c}\, ln\,\dot{\varepsilon^*})(1 - T^{*\mathrm{m}})$
F-S model[15]	$\frac{\sigma}{E} + \mathrm{K} \times \left(\frac{\sigma}{\mathrm{a}}\right)^{n} \qquad \sigma \leq \sigma_{0.8,\mathrm{C}}$

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	$\frac{\sigma-\sigma_{0.8,C}}{k}+\varepsilon_{0.8,C} \qquad \sigma \geq \sigma_{0.8,C}$
S-W model[16]	$\sigma=K(\varepsilon_0+\overline{\varepsilon_p})^n \times (1-c\times\overline{\varepsilon_p})$
KME mode[17]	$\dot{\varepsilon^p}=\dot{\varepsilon_0}\left(\frac{\sigma}{\bar{\sigma}}\right)^m$
Improved J–C Constitutive Model[18]	$\sigma=(A+B\varepsilon_p^n)[1+C(ln\,\dot{\varepsilon^*})^P]\,exp\left[-\frac{0.9(1+C(ln\,\dot{\varepsilon^*})^P)}{\rho C_p(T_m-T_r)}\left(A\varepsilon_p+\frac{B\varepsilon_p^{n+1}}{n+1}\right)\right]$
PB Constitutive Model[19]	$A'\sigma^{n'}\exp\left(-\frac{Q}{RT}\right)(\alpha\sigma<0.8)$ $A''\exp(\beta\sigma)\exp\left(-\frac{Q}{RT}\right)(\alpha\sigma<1.2)$ $A[\sinh(\alpha\sigma)]^n\exp\left(-\frac{Q}{RT}\right)$ (for all σ)
Hänsel model[20]	$\sigma=(B_{HS}-(B_{HS}-A_{HS})\,exp(-m\varepsilon^n+\varepsilon_0))(K_1+K_2T)+\Delta H_{\Upsilon\to\alpha}V_m$
Unified viscoelastic constitutive model[21]	$\dot{\sigma}=E[(1-D)(\dot{\varepsilon_T}-\dot{\varepsilon})-\dot{D}(\varepsilon_T-\varepsilon)]$
Modified of Fields–Backofen constitutive mode[22]	$\sigma=H\exp\left(\frac{H_0}{T}\right)\exp((H_1+H_2\dot{\varepsilon})\varepsilon)\,\varepsilon^{H_3+H_4\dot{\varepsilon}}\dot{\varepsilon}^{H_5+H_6/T}$
Cowper-Symonds Model[23]	$\frac{\sigma_d}{\sigma_{st}}=1+\left(\frac{\dot{\varepsilon}}{C}\right)^{\frac{1}{q}}$

Stake: σ is true stress; ε is real strain; $\dot{\varepsilon}$ is the strain rate; T is the deformation temperature of a metallic material;α is the stress multiplier (MPa−1);Q is the activation energy (kJmol−1);R is the gas constant (8.3145 Jmol−1 K−1);E is the modulus of elasticity at high temperature; n is the hardening index, Tref is the reference temperature; Tm is the melting temperature; $\dot{\varepsilon^*}$ is the equivalent plastic strain rate; $\dot{\varepsilon}_0$ is the reference strain rate; ρ is the dislocation density.; D is the damage value; $\dot{D}$ is the rate of change of damage; $\dot{\sigma}$ is the rate of change of stress; ε_T and $\dot{\varepsilon}_T$ is the temperature-dependent strain and strain rate; D1 is the inverse of the strain rate sensitivity, S is the stress index, Vm is Martensite volume fraction, (1-D)-γ1 is the scale factor; σ_d and σ_{st} Dynamic and static stresses, respectively; m; C1-C6, A, A, A, n, B, n0, n1 , C, q, BHS, AHS, K-K2, λ, nc, β1-β3, γ1 -γ5, ΔHγ→α′, H-H6 is Temperature-dependent material parameters.

Most scholars select temperature-dependent constitutive models by comparing multiple models and choosing those that fit experimental curves well. Meanwhile, to improve model accuracy, they modify the models by adjusting material parameters, selecting different polynomial orders, or deriving new constitutive models through linearly combining two different models. In terms of prediction accuracy, it is difficult to capture non-uniform deformations such as crack propagation and local shearing. In terms of revealing physical mechanisms, most macroscopic mechanical constitutive models rely on empirical formulas, which makes parameter calibration relatively simple, but empirical formulas lack descriptions of the essential mechanisms of deformation. In terms of cross-scale adaptability, macroscopic constitutive models fail to combine with microstructures for analysis and optimization. In contrast, microscopic constitutive models excel in prediction accuracy by explaining damage initiation, such as void growth and evolution. In revealing physical mechanisms, they can quantify the influence of microscopic mechanisms on material properties. Regarding cross-scale applicability, they support the performance design of microstructures. Although microscopic constitutive models are more accurate and applicable than macroscopic ones, they require significantly more time and high-resolution equipment for parameter calibration and computational efficiency compared to macroscopic models. In general, the choice between a macroscopic and microscopic constitutive model should be based on constraints like time and equipment availability.

3. Current Status of Research on Temperature-dependent Ductile Fracture Modeling of Metallic Materials

During the forming process, metallic materials undergo transitions from the elastic to plastic deformation stages. In the plastic stage, excessive plastic deformation can lead to material fracture. To accurately predict fracture, many scholars have conducted extensive research, including methods such as forming limit diagrams and maximum thinning rates. The fracture toughness criterion, defined by a functional formula based on damage mechanisms in material deformation, is more widely and flexibly applied than other methods[24][25]. Toughness fracture criteria for room-temperature forming often ignore the effects of temperature and strain rate, but the influence of temperature and strain rate must be considered in toughness fracture criteria for warm forming.

Liu J et al.[26] considered that damage initiation and propagation are significantly influenced by temperature and strain rate, and modified the existing damage model to accurately describe damage behavior at high temperatures, and a Bonora damage model modified by combining strain rate ratio and temperature was proposed. Zhou J et al.[27] proposed a modified GTN model to account for shear damage. They compared this modified model with the original model through experiments, and the results showed that the modified model exhibited greater effectiveness than the original one. Camberg A A et al.[28] To address the issues of temperature-dependent strain and insufficient model fit for all experimental data, the GISSMO model was proposed. This model not only incorporates the relationship between equivalent plastic fracture/instability strains and temperature but also comprehensively considers temperature paths and nonlinear strain. Li Y et al.[29] Parameters of the MCC criterion at different temperatures were calibrated using data from tensile and shear tests. The relationships between each parameter and temperature were studied and finally verified through tensile-bending tests of U-shaped parts. Niu L et al.[30] By studying the effect of temperature on micro-voids, a damage criterion considering temperature-induced void changes was established. The fracture trajectory of 316LN stainless steel was constructed using the DF criterion, and the criterion was validated. The results show that the DF criterion can effectively predict crack propagation behavior under different temperatures and stress states. Li H et al.[31] An H-MC criterion considering the effects of temperature, strain rate, and stress state was established. High crack-sensitive steel was selected as the research object, and warm tensile and compression tests were conducted to obtain stress-strain curves. Through simulating compression and tensile tests, the stress-strain curves from experiments and simulations were compared. The results show that the H-MC criterion can accurately describe the warm deformation fracture behavior under different stress paths. Tang B et al.[32] Taking 22MNB5 steel as the research object, the Louh criterion was extended, and equivalent plastic strain, stress triaxiality, and Lode angle parameters under three different stress states were calibrated by a hybrid method. By comparing the stress-strain curves obtained from the Louh criterion with experimental results, it was found that the extended Louh criterion can well describe the fracture

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process of the material. Zhang R et al.[33] A unified viscoelastic model based on the Continuum Damage Mechanics (CMD) model was developed. By replacing strain components with stress components, the model simulates the dependence of material deformation on stress paths. The accuracy of the developed model was validated through warm stamping experiments on 22MnB5 steel. The results show that the developed CDM model can accurately obtain the necking and fracture limit strains under warm stamping conditions. The mathematical expressions of the above model are shown in Table 2.

Table 2. Commonly used ductile fracture models for advanced high-strength steel

Fracture Model	Formula
The new damage model based on Bonora damage model [26]	$D(T,\dot{\varepsilon}) = A_2 \varepsilon^{\dot{B}_2} \exp\left(C_2 \frac{Q}{RT}\right)$
Extended GTN [27]	$\phi = \left(\frac{\sigma_e}{\sigma_m}\right)^2 + 2q_1 f^* \cosh\left(-\frac{3q_2\sigma_h}{2\sigma_m}\right) - [1 + (q_1 f^* + D_s)^2 - 2D_s] = 0$
GISSMO[28]	$D = \left(\frac{\dot{\varepsilon}_p}{\varepsilon_p[\eta, T]}\right)^n$
Modify MMC[29]	$D = \frac{K}{a_2 + b_2 e^{\frac{T}{m_1}}}\left[(a_3T + b_3) + \frac{\sqrt{3}}{2-\sqrt{3}}(1-(a_3T+b_3))\left(\sec\left(\frac{\bar{\xi}\pi}{6}\right)\right)\right] \times \left[\sqrt{\frac{1+\left(a_1 + b_1 e^{\frac{T}{m_1}}\right)}{3}}\cos\left(\frac{\bar{\xi}\pi}{6}\right) + \left(a_1 + b_1 e^{\frac{T}{m_1}}\right)\left(\eta + \frac{1}{3}\sin\left(\frac{\bar{\xi}\pi}{6}\right)\right)\right]$
DF[30]	$D = (C_n T - 25)\left(-0.06 + 0.36\exp\left(\frac{3\eta}{2}\right) + \eta + \frac{(3-\xi)}{3\sqrt{\xi^2+3}}\right)^{C_g}\left(\frac{2}{\sqrt{2+3}}\right)^{C_C}\varepsilon_f$
H-MC[31]	$D = \int_0^{\varepsilon} \frac{1}{\left(K\dot{\varepsilon}_p^{b+dT}\exp\left(\frac{f}{T}\right)\right)^{-\frac{1}{a+cT}}\{c_2\left[\sqrt{\frac{1+c_1^2}{3}}\cos\left(\frac{\xi\pi}{6}\right) + c_1\left(\eta + \frac{1}{3}\sin\left(\frac{\xi\pi}{6}\right)\right)\right]} d\varepsilon$
Louh[32]	$\frac{1}{C_3}\int_0^{\varepsilon_f}\left(\frac{2}{\sqrt{\xi^2+3}}\right)^{C_1}\left(\frac{3}{4}\left(\eta + \frac{3-\xi}{3\sqrt{\xi^2+3}}\right) + C_{offset}\right)^{C_2} d\varepsilon = D(\varepsilon)$
CDM[33]	$D_1 = \left[\frac{\dot{\omega}_1}{(\alpha_1+\alpha_2+\alpha_3)\varphi_1}\right]\left(\frac{\alpha_1 + 3\alpha_2\sigma_H + \alpha_3\sigma_e}{\sigma_e}\right)^{\phi_1}\frac{(1-\omega_1)}{(1-\omega_2)^{\eta_1}}(\dot{\varepsilon}_e^p)^{\eta_2}$ $D_2 = \left[\frac{\dot{\omega}_2}{(\alpha_1+\alpha_2+\alpha_3)\varphi_1}\right]\left(\frac{\alpha_1 + 3\alpha_2\sigma_H + \alpha_3\sigma_e}{\sigma_e}\right)^{\phi_2}\frac{1}{(1-\omega_1)(1-\omega_2)^{\eta_1}}(\dot{\varepsilon}_e^p)^{\eta_2}$

Stake: εp is the equivalent plastic strain at fracture; σ_m is principal stress; $\dot{\varepsilon}_P$ is the strain rate; ε_p^{ins} is the equivalent plastic strain at instability; T is temperature; Tc is the critical temperature; R is the gas constant 8.3144 J·mol−1·K−1;Q is the thermal activation energy.αis the damage evolution index, D is the total damage, DS is shear damage; ε_f^s is the strain at fracture in pure shear.; σ_e is the equivalent force; ξ is Rodriguez angle; ε_f is the equivalent plastic strain; K is the hardening factor; n is the hardening index; a1-a3, b1-b3, m1-m2 is the value of the fitting coefficient; A1-A4, B1-B4, C1-C4, q1, q2, α, β is a material parameter; C_n is the temperature sensitivity factor for the cumulative coefficient of pore nucleation damage; C_g is the stress state sensitivity factor for damage accumulation due to pore growth; C_c is the cumulative triaxiality sensitivity factor for damage due to pore aggregation; a-d and c2 are material parameters; C_{offset} is the stress triaxiality cutoff; σ_e constant force; σ_H hydrostatic stress; $\dot{\varepsilon}_e^p$ Equivalent plastic strain rate; ω_1-ω_2; $\dot{\omega_1} - \dot{\omega_2}$; $\phi_1 - \phi_2$; α_1-α_3; η_1-η_2 is the temperature-dependent material parameter.

So far, the most common temperature-related fracture criteria include three types: the GTN model as a typical porous material model, the Louh model representing continuum damage mechanics models, and the MMC model as a non-coupled fracture criterion. The porous material model mainly considers the processes of void nucleation, growth, and coalescence during material deformation until fracture. The change in void volume fraction is determined by both nucleation (formation of new voids) and void growth (void expansion), with the nucleation rate related to plastic strain. Dittmann M et al.[34] demonstrated that combining the phase-field method with the GTN model enables this combined approach to explain the relationship between temperature and pore growth at the microscale, as well as the relationship between temperature and crack initiation/propagation at the macroscale. Sun Quan et al.[35] conducted studies to validate that the shear-modified GTN model can account for the effect of micro-void shear distortion on material damage. They used small punch tests to obtain material parameters and applied this modified GTN model to describe the material deformation behavior. The results show that the modified model exhibits greater accuracy than the original one. Pascon J P et al.[36] investigated the effects of yield criteria and damage evolution in the GTN model on material deformation behavior, adjusting these factors to evaluate their impact. They also simulated the influence of anisotropy on material mechanical properties. The results show that a simple anisotropic model can more flexibly capture complex ductile fracture processes.

The CDM criterion is a typical representative of continuum damage mechanics models. Its main idea is to quantify the cumulative effect of defects such as micro-cracks and voids in materials by introducing damage variables, thereby predicting the entire process of material deformation, damage, and failure. Kumar M et al.[37] conducted experiments to verify whether the CDM criterion can accurately describe the influence of temperature on damage laws. They performed warm tensile tests on high-temperature structural steel, and the results of these tests were compared with simulation results. It was found that ductile fracture (as predicted by the criterion) occurs in areas with higher damage, and the damage growth laws from experiments and simulations are consistent. Zhang R et al.[38] modified the CDM criterion and applied this modified criterion to warm stamping simulations of 22MnB5 steel. The results show that the CDM criterion can accurately describe the flow behavior of 22MnB5 steel under complex stress states. Zeng C et al.[39] proposed and calibrated a rate- and temperature-dependent CDM damage criterion. They conducted temperature-related uniaxial tensile tests on H340 steel under different loading rates and compared the results with simulation outputs. The results show good consistency between the experimental and simulated load-displacement curves and local strain evolution.

The MMC criterion is a typical non-coupled fracture criterion, whose main feature is to directly determine whether the material fractures by threshold values of stress or strain states, without coupling the influence of damage evolution on plastic deformation. Li Y et al.[40] studied DP780 steel as the research subject, calibrating the MMC criterion parameters at different temperatures through temperature-related uniaxial tensile and shear tests. They applied the calibrated MMC criterion to warm stamping simulations, and the results demonstrate that this criterion can accurately predict the fracture of automotive components. Li H et al.[41] developed an MMC criterion applicable to different temperatures. Using high-strength crack-sensitive steel as the research subject, they conducted uniaxial tensile and compression tests at different temperatures. By comparing simulated and experimental results, it was found that the MMC criterion can accurately describe the fracture behavior during thermal deformation under different stress paths.

4. Conclusion

The rapid development of new energy vehicles has made vehicle lightweighting more important. The warm forming process of advanced high-strength steels plays a crucial role in vehicle lightweighting. This process can significantly improve the formability of advanced high-strength steels and reduce springback, but it cannot address deformation issues caused by asymmetric springback. Selecting efficient and high-precision constitutive models and ductile fracture models can significantly mitigate such problems. Current temperature-related constitutive models are still dominated by phenomenological ones, which cannot reflect the micro-deformation mechanisms of materials. With the development of science and technology, new techniques will emerge to achieve high-precision and efficient constitutive models and ductile fracture criteria, providing effective means for the research of more advanced materials in the future.

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