International Journal of Mechanical Sciences 105 (2016) 41–57

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

Coupled modeling of anisotropy variation and damage evolution for high strength steel tubular materials

H. Li [a],*, H. Yang [a],*, R.D. Lu [a], M.W. Fu [b]

[a] State Key Laboratory of Solidification Processing, School of Materials Science & Engineering, Northwestern Polytechnical University, Xi'an 710072, PR China
[b] Department of Mechanical Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, PR China

ARTICLE INFO

Article history:
Received 11 August 2015
Received in revised form
27 September 2015
Accepted 29 October 2015
Available online 5 November 2015

Keywords:
Strain hardening
Anisotropy variation
Damage evolution
Constitutive modeling
Tubular materials

ABSTRACT

High strength stainless steel tube (HSST) presents promising applications in many clusters as one of key lightweight materials. While, over thinning and further crack in plastic deformation are prone to occur due to limited strain hardening and high yield-strength ratio. To avoid this phenomenon, the accurate prediction of forming limit of HSST needs to be achieved considering uneven deformation induced fracture. Via the digital speckle correlation method (DSCM) based tension, both the diffuse necking limited hardening and the variation of Lankford coefficient *R* along tube deformation are studied, modeled and coupled into the Hill'48 anisotropic yield framework; then by replacing the Mises effective stress with the extended Hill's anisotropic one and using a stepwise inverse method for damage parameter calibration, both the GTN and Lemaitre ductile fracture criteria (DFCs) coupled with anisotropy evolution are established and numerically implemented; thus, regarding several indexes in cases of uniaxial tension, flaring and mandrel bending of HSST, four individual anisotropic plasticity models and two coupled models are compared and evaluated. Due to considering the interplay between inhomogeneous deformation and damage evolution, the coupling model with the improved anisotropic plasticity provides the most accurate prediction of overall performance in all cases. The significance of the coupling DFCs with the anisotropic plasticity on overall simulation of complex forming processes of tubular materials is thus recognized.

1. Introduction

The structural integrity, complexity and weight reduction of products are now becoming overriding issues in industries, and tubular components are thus attracting increasing applications in tandem with these as a kind of key lightweight parts for structure loading bearing or 'bleeding' transforming [44,45]. Among so many types of tubular materials such as Al-alloys, Mg-alloys and Ti-alloys, high strength stainless steel tube (HSST) obtains promising usages in aviation, aerospace and automobile industries due to its higher specific strength than that of Al-alloys and lower price compared to Ti-alloys. However, due to minor strain hardening effect and high yield-strength ratio (shown in Table 1), over thinning, necking and further crack may so much easily occur in forming processes of HSST parts, which strongly reduces the forming quality of tubular materials. The unique plastic deformation characteristics and thus suitable constitutive model as well as ductile fracture criterion should be identified, developed or even coupled such that the overall deformation behaviors and forming limits of HSST materials in complex forming processes can be accurately represented.

Up to now, great efforts have been conducted on characterizing the deformation characteristics of tubular materials [23] and modeling different forming processes for tubular formed parts [22,45]. Kulkarni et al. [20] introduced a geometric imperfection in the form of wall thickness reduction to trigger necking of Al-alloy tube after significant bulging and found the used Hill's anisotropic plasticity has an important effect on tube bulging and localized necking. While, the Lankford coefficient *R* (normal anisotropic exponent or plastic strain ratio) is constant and the DFCs are not considered. Korkolis and Kyriakides [21] revealed that, compared with the results of Hosford [16] and Karafillis-Boyce models [24], the nonlinear strain paths in hydroforming of Al-alloy tubes can be successfully predicted by the Yld2000-2d model considering deformation-induced anisotropy [3]. However, the rupture strain cannot be sufficiently predicted possibly due to the fact that the strain hardening characteristics or the damage accumulation of Al-alloy tube are not considered. Gholipour et al. [12] used the Gurson-based damage model to predict the deformation behaviors of tube bending and sequent hydroforming, while the burst pressure was not well predicted by using the Mises model. Shi et al. [39] used the crystal plasticity (CP) theory to predict the localization of

---

* Corresponding authors. Tel./fax: +86 29 88495632.
E-mail addresses: liheng@nwpu.edu.cn (H. Li), yanghe@nwpu.edu.cn (H. Yang).

http://dx.doi.org/10.1016/j.ijmecsci.2015.10.017
0020-7403/© 2015 Elsevier Ltd. All rights reserved.

Table 1
Mechanical properties of different tubular materials.

Materials	21-6-9		5052-O	1Cr18Ni9Ti
	$\Phi31.75 \times t$ 0.508		$\Phi50 \times t$ 1.5	$\Phi38 \times t$ 1.0
Specification	Arc	Tubular	Arc	Arc
Young's modulus E (GPa)	182	176	55	200
Fracture elongation δ (%)	18.6	28	22	60
Initial yield stress $\sigma_{0.2}$ (MPa)	972	928	90	213
Ultimate tensile strength σ_b (MPa)	1085	1061	206	689
Strength coefficient K (MPa)	1277	1231	431	1591
Strain hardening exponent n	0.036	0.031	0.262	0.54
Material constant b	0.0059	0.0071	0	0
Lankford coefficient R	1.72	1.32	0.55	0.94
$\sigma_{0.2}/\sigma_b$	0.90	0.87	0.43	0.31

Al-alloy tube under internal pressure, while the huge computation cost and the complexity of CP theory deter its efficient application in complex forming processes. Huang et al. [17] improved the prediction accuracy of Ti–3Al–2.5V tube bending deformation by considering the R variation with plastic straining, while the damage induced hardening deterioration (softening) is not incorporated. The above prior arts confirm the suitable plasticity models and DFCs should be developed or even coupled to provide a reliable prediction of deformation and damage evolution in forming of tubular materials. While, the significance of coupling plasticity models and DFCs on overall simulation of metal forming subjected to complex loading conditions has not been fully recognized.

Focusing on the plasticity behaviors and damage evolution of sheet/tube metallic materials, a series of anisotropic constitutive models [15,16,24,3,7] and physical-based DFCs [13,2,25,34] have been individually developed and implemented into FE models for robust simulation of forming processes. More recently, regarding the plasticity modeling of newly developed materials, from aspects of yield functions, strain hardening and flow rules, the advanced anisotropic behaviors and their evolutions along plastic strain are modeled and evaluated/applied [14,30,35,41,48]. Meanwhile, via macro/micro-scaled experiments and theoretical analysis [19,26,4,42,6], great efforts have also been conducted on establishing/extending or evaluating of the different kinds of DFCs by correlating the damage evolution rules with so many internal variables such as stress states, strain states, strain rates, geometrical factors, temperature and microstructure [11,18,32,37,49]. The criterion can be critical stress, critical strain, critical energy, critical void volume fraction and the critical damage factors; The DFCs can be in the form of the forming limit diagram (FLD) [10], Continuum Damage Mechanics (CDM)-based formulas, CP-based model [39,43] or even stochastic/statistical models [6]. Nowadays, the continuum based anisotropic constitutive models and the internal variable based CDM theory have been the promising way for representing the deformation of complex forming of sheet/tube materials such as HSST.

Though the plasticity models and DFCs are studied individually, the plastic deformation and damage evolution actually interplay each other. It is shown that the plasticity behaviors such as strain hardening and local strain heterogeneity influence the damage distribution greatly [43]; vice versa, the deterioration effect of damage may remarkably affect the plastic deformation [33]. Considering isotropic hardening and isotropic ductile damage, Cherouat et al. [8] attempted to use the coupled material model to simulate the hydroforming of Al-alloy tube, while the anisotropic plasticity is not considered. Chung et al. [9] combined the triaxiality-dependent DFC with the Hill [15] and Yld2000 anisotropic yield function to describe the deformation of advanced high-strength grade steel sheets. Luo et al. [29] used the Yld2000 yield function and an anisotropic fracture model to predict the deformation of Al-alloy extrusions under multi-axial loading. While, the above plasticity models and the damage models are uncoupled, i.e., the interaction between unequal deformation and void-induced softening is not considered. Recently, by introducing a damage effect-tensor for defining the effective stress variables, the Lemaitre-based criterion was attempted to be coupled with the Hill [15] based plasticity for clarifying the anisotropic damage effect on the elastic–plastic behavior of the 316L stainless steels [36], which further indicates the importance of coupling plasticity model and DFCs for robust simulation of metal forming.

In tandem with the above status, thorough experimental and numerical studies are conducted for overall prediction of plastic deformation of HSST. By combining uniaxial tension with digital image correlation(DIC), the special strain hardening and anisotropy evolution along plastic strain are investigated, modeled and introduced into the Hill yield framework to represent the unique deformation features of HSST; Since the GTN-based criteria [13,34] and the Lemaitre-based one [25] are the two most widely used coupling DFCs [27], the above extended anisotropic plasticity models are then introduced into these two DFCs and the coupling framework of the anisotropic plasticity and the DFCs is then established, numerically realized, evaluated and applied into three most typical practical processes, i.e., uniaxial tension, tube flaring and mandrel bending; Deformation behaviors, ductile damage evolution and their interplay against different loading conditions are thus discussed using multiple indexes.

2. DSCM based uniaxial tension of HSST

2.1. Uniaxial tensile tests of arc and tubular specimens

21-6-9 (Cr21Ni6Mn9) aerospace tube is a FCC austenitic stainless steel with a high manganese nitrogen solid solution strengthening [38]. The specification of the HSST used in this study is $\Phi31.75$ mm × t 0.51 mm (outer diameter D × wall thickness t).

The uniaxial tensile tests of both arc curved specimens and full-size tubular specimens are conducted with the velocity of 2 mm/min. As shown in Fig. 1(a), the curved clamp die is designed ensuring the uniaxial tension of the arc specimens; for comparison, the tubular specimen is also prepared as shown in Fig. 1(b). Both the longitudinal and vertical strains are simultaneously measured by the longitudinal and the vertical extensionsometers. The Swift function $\sigma = K(\varepsilon + \varepsilon_0)^n$ is used to represent the strain hardening. For the curved arc specimens, the instant Lankford

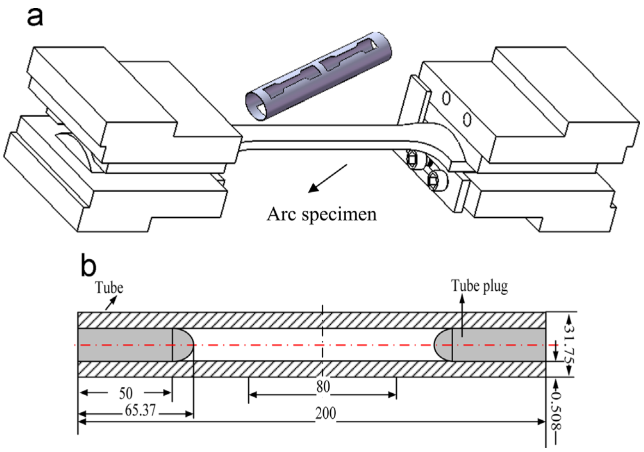

Fig. 1. Specimen design of HSST for uniaxial tensile test (a) clamp die for curved specimen; and (b) tubular specimen.