Journal of Materials Processing Technology 213 (2013) 598–605

Contents lists available at SciVerse ScienceDirect

Journal of Materials Processing Technology

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

The initiation and propagation of edge cracks of silicon steel during tandem cold rolling process based on the Gurson–Tvergaard–Needleman damage model

Yuxi Yan[a,b], Quan Sun[a,b], Jianjun Chen[a,b,*], Hongliang Pan[a,b,*]

[a] School of Mechanical and Power Engineering, East China University of Science and Technology, Shanghai 200237, China
[b] Key Laboratory of Pressure Systems and Safety, Ministry of Education, East China University of Science and Technology, Shanghai 200237, China

ARTICLE INFO

Article history:
Received 13 March 2012
Received in revised form 29 October 2012
Accepted 3 November 2012
Available online 10 November 2012

Keywords:
GTN model
Damage
Tandem rolling process
Edge crack
Silicon steel

ABSTRACT

Edge cracking is a commonly observed phenomenon during the cold rolling process of silicon steel, which may cause the rupture of strips in the rolling mill. In this paper the initiation and propagation of edge cracks under the tandem cold rolling condition were investigated by using the Gurson–Tvergaard–Needleman damage model. The damage parameters were obtained from the tensile tests data and the SEM analyses. Different cold rolling experiments were carried out by a non-reversing two-high rolling mill and the experimental results agreed well with the finite element calculation results. Parametric studies were carried out and revealed that the crack propagation increases with the increasing of total reduction, friction coefficient, and unit tension. A bigger work roll is beneficial to reduce the edge crack growth as well.

1. Introduction

The silicon steel, generally called electrical steel, has excellent electrical and magnetic properties, which makes it widely used as a core material in electric transformers and motors. Cold rolling is an essential process to produce the silicon steel sheet. However, edge cracking is commonly observed during the cold rolling process of silicon steels, which may cause the rupture of strips in the rolling mill and reduce the production efficiency.

Edge cracking during cold rolling process of steels can be regarded as a result of ductile fracture (Ghosh et al., 2004). There are two main approaches to derive constitutive equations of ductile damage. The first one is based on a phenomenological description of damage and is often referred to as continuum damage mechanics (CDM). A typical model was proposed by Lemaitre (1985) on the concept of effective stress and the damage was considered to be linear with equivalent strain and influenced by triaxiality. Up to the present day, a large amount of studies based on Lemaitre's work have been carried out. Soyarslan and Tekkaya (2009), for instance, presented a modified Lemaitre model and studied the prevention of internal cracks in metal forming. Mashayekhi et al. (2011) investigated the strip tearing in a tandem cold rolling process with the improved Lemaitre damage model. This approach is derived on a thermodynamic framework and it takes no account of the mechanical behavior of micro defects in the material.

The other approach relies on a micromechanical description of the material and the damage occurring during plastic deformation is generally identified as the nucleation and growth of microvoids. McClintock (1968) first proposed a microvoid model with an ellipsoidal hole in the ductile matrixes and deduced an analytical solution of volume expansion. Rice and Tracey (1969) then studied the evolution of spherical holes and set the foundation for numerous studies on the micromechanics associated with the void growth. Based on these researches, Gurson (1977) deduced a flow potential for void growth on an ideal plastic material, which is the classical mechanics model for plastic materials containing voids. The Gurson model was extended by Tvergaard and Needleman (1984) (the GTN model) to take into account the interactions between the neighboring voids when the localized internal necking of the matrix occurs. The GTN model, which modified the von Mises yield potential by introducing a single scalar damage quantity, can describe the nucleation and coalescence of voids. Many different improved damage models based on Gurson's work have been proposed and successfully applied to interpret the damage evolution in structures under different load conditions. Nahshon and Xue (2009) used a modified Gurson model to investigate the development of through-thickness cracks under the low triaxiality condition. Considering the anisotropy of mechanical property, different modified models have been presented. Le Maout et al. (2009) studied the hemming process for aluminum alloys using the GTN damage model combined with Hill type plastic anisotropy. Chen and Dong (2009) predict the damage evolution of anisotropic ductile materials with a modified GTN yield criterion based on a quadratic anisotropic yield criterion and an isotropic

* Corresponding authors. Tel.: +86 021 64253622.
E-mail addresses: jjchen@ecust.edu.cn (J. Chen), hlpan@ecust.edu.cn (H. Pan).

0924-0136/$ – see front matter
http://dx.doi.org/10.1016/j.jmatprotec.2012.11.006

hardening rule. Furthermore, many studies indicated that void distortion also contributed to the ductile fracture. An extension of the GTN model incorporating damage growth under shear-dominated stress states was proposed by Nahshon and Hutchinson (2008). Using the Gurson porous model including a shear modification, Soyarslan et al. (2012) investigated the crack initiation at the convex surface and its propagation during bending. Dunand and Mohr (2011) evaluated the predictive capabilities of the shear modified Gurson model in the tensile and the punch experiments over a wide range of stress triaxialities and Lode angles.

In recent decade, a lot of studies have been carried out on the ductile fracture in cold rolling process and different damage criteria have been presented as well. Ghosh et al. (2004) predicted the occurrence of edge crack of aluminum alloys during cold rolling by considering the effective stress, equivalent plastic strain as damage parameters. Rajak and Reddy (2005) developed a ductile fracture criterion for damage evolution along with a simple criterion based on the nature and magnitude of hydrostatic stress to predict the initiation of central burst and split-end in plane strain rolling. Zhang et al. (2011) analyzed the plastic-damage of Mg alloy sheet in rolling with Crockroft–Latham criterion which assumed that damage was caused by the maximum tensile principal stress.

It can be found from the above researches that the GTN model has been widely used to describe the damage evolution in ductile fracture, but it is still limited in the study of cold rolling due to its complex working process. On the other hand, in the existing cold rolling fracture criteria the stress and damage were not coupled and the damage has no link with the development of the microvoids. Thus, in the present work, the GTN damage model was employed to investigate the onset of the crack near the edge flaw and the crack propagation under rolling condition. Both the cold rolling experiments and three dimensional finite element simulations were performed to analyze the effects of rolling process parameters such as total reduction, friction coefficient, roll radius and unit tension on the crack initiation and propagation during the tandem rolling.

2. The GTN damage model

2.1. Yield surface

The micromechanical damage model developed by Gurson (1977) takes into account the degradation of the load carrying capacity due to the presence of porosity in isotropic materials. Tvergaard and Needleman (1984) modified the original Gurson model by concerning the coalescence of voids. The yield surface is given by

$$\Phi(\Sigma_{ij}, \sigma_e, f*) = \left(\frac{\Sigma_{eq}}{\sigma_e}\right)^2 + 2f*q_1\cosh\left(\frac{q_2\sigma_{kk}}{2\sigma_e}\right) - 1 - q_1^2 f*^2 = 0 \tag{1}$$

where q_1 and q_2 are the fitting parameters proposed by Tvergaard (1981) to amplify the hydrostatic stress effect for all strain levels. The current void state is characterized by f^*, which is a function of the void volume faction f, the von Mises equivalent stress $\sum_{eq} = \sqrt{3s_{ij}s_{ij}/2}$, where $s_{ij} = \sigma_{ij} - 1/3\sigma_{kk}\delta_{ij}$ is the stress deviator, σ_e is yield stress of the undamaged matrix material. The function f^*, which takes into account the final decrease in load, is given by (Tvergaard and Needleman, 1984).

$$f* = \begin{cases} f, & f \le f_c \\ f_c + Z(f - f_c), & f > f_c \end{cases} \tag{2}$$

In the above relation f is the volume fraction of voids or porosity, f_c is the critical value of the void volume fraction, and Z is the coalescence rate of microvoids. The coalescence rate Z can be obtained from the void volume fraction as:

$$Z = \frac{f_u - f_c}{f_F - f_c} \tag{3}$$

where f_F is the void volume fraction at final failure and $f_u = 1/q_1$.

2.2. Void evolution

The total change of f due to the plastic deformation is corresponding to the void growth and the nucleation of new voids:

$$\dot{f} = (\dot{f})_{growth} + (\dot{f})_{nucleation} \tag{4}$$

$$(\dot{f})_{growth} = (1 - f)\dot{E}^p_{kk} \tag{5}$$

where $(\dot{f})_{growth}$ is the increment of volume fraction caused by the void growth and controlled by the trace of plastic strain increment tensor $\dot{E}^p_{kk}$.

Assuming the plastic strain only controls the nucleation as a result of particle debonding and cracking. The effective damage increment ratio is given by Chu and Needleman (1980) as

$$(\dot{f})_{nucleation} = A\dot{\bar{\varepsilon}}^p_{eq} \tag{6}$$

where $(\dot{f})_{nucleation}$ is the increment of volume fraction caused by the void nucleation which is controlled by the equivalent plastic strain rate $\dot{\bar{\varepsilon}}^p_{eq}$.

The parameter A is defined as a function of the matrix equivalent plastic strain

$$A = \begin{cases} \dfrac{f_n}{S\sqrt{2\pi}} \exp\left[-\dfrac{1}{2}\left(\dfrac{\varepsilon_e{}^p - \varepsilon_N}{S}\right)^2\right] & , \Sigma_m \ge 0 \\ 0 & , \Sigma_m < 0 \end{cases} \tag{7}$$

where ε_N is the mean strain for nucleation, f_n is the void nucleation volume fraction which determines the void volume fraction when the nucleation begins and S is the standard deviation of ε_N which represents the degree of homogeneity of materials.

2.3. Determination of the parameters

The material parameters in the GTN model can be determined by the tensile tests. The load–displacement curve up to six stages can be distinguished in the simple tensile test as shown in Fig. 1. Each of the necessary material parameters ($E, \upsilon, K, n, q_1, q_2, f_0, \varepsilon_N, S, f_n, f_c, f_F$) exhibits its influence in the tensile test at different stages (Cuesta et al., 2010).

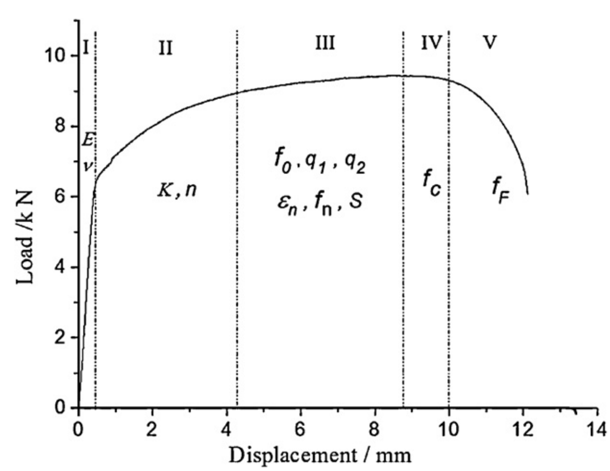

Fig. 1. Stages in load–displacement curve of simple tensile test.