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# Damage in edge cracking of rolled metal slabs

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ABSTRACT

Materials get damaged under shear deformations. Edge cracking is one of the most serious damage to the metal rolling industry, which is caused by the shear damage process and the evolution of anisotropy. To investigate the physics of the edge cracking process, simulations of a shear deformation for an orthotropic plastic material are performed. To perform the simulation, this paper proposes an elasto-aniso-plastic constitutive model that takes into account the evolution of the orthotropic axes by using a bases rotation formula, which is based upon the slip process in the plastic deformation. It is found through the shear simulation that *the void can grow in shear deformations due to the evolution of anisotropy and that stress triaxiality in shear deformations of (induced) anisotropic metals can develop as high as in the uniaxial tension deformation of isotropic materials, which increases void volume.* This echoes the same physics found through a crystal plasticity based damage model that *porosity evolves due to the grain-to-grain interaction.* The evolution of stress components, stress triaxiality and the direction of the orthotropic axes in shear deformations are discussed.



## 1. Introduction

Edge cracking (see Fig. 1) is a serious problem in the rolling industry where the edge cracked area is scrapped and thus is a significant energy loss.

However, the edge cracking phenomenon is not explained by the ductile fracture theory that the current academy and industry possess since the physics behind it is unknown. The current ductile fracture theory is based upon the growth of voids by positive hydrostatic stress while in rolling the dominant stress state is compressive, *i.e.*, hydrostatic stress is negative. Due to this discrepancy, edge cracking cannot be understood well by the current ductile damage/fracture theory. Noticing the limitation of the current theory, this paper aims to reveal the micro-mechanics of void growth in shear deformations that include the boundary condition of the edge cracked area in rolled metal slabs through shear simulations that mimic the deformation in the edge cracked area.

Since the current ductile fracture theory, *i.e.*, the Gurson model [6], is based upon void growth by positive hydrostatic stress, the variation of it cannot explain the shear ductile fracture phenomenon where hydrostatic stress is near zero or negative. To explain the shear damage process, researchers postulated that damage is related to another stress invariant than the first and second ones (*i.e.*, hydrostatic stress and the von Mises equivalent stress, respectively). In this approach, the Lode parameter [14] was utilized as an indicator of the shear damage amount since the Lode parameter represents the amount of shear stress components. However, the evidence that void grows proportional or related to the Lode parameter when stress triaxiality is zero is weak.

Recent works [17,18,15] revealed many aspects of shear damage. However, void growth in shear deformations when hydrostatic stress is zero is not clearly understood. Motivated by the need for a more physically based explanation for shear damage, recent works by [8,11] investigated the phenomenon from a different perspective looking into the grain level mechanics. The experimental and theoretical work by [11] indicated that nonzero hydrostatic stress develops within grains in shear deformations; the development and variation of hydrostatic stress in grains were experimentally validated by a recent experimental work [2]. The theoretical and computational work by [8] revealed in more detail the micro-mechanics of the shear damage process, which is that porosity evolves due to meso-scale positive hydrostatic stress developing through the grain-to-grain interaction, *i.e.*, the interaction of anisotropy, even when macroscopic hydrostatic stress is zero. The source of damage in shear was further investigated by a macro-scale continuum description using an anisotropic ductile fracture model in [9], which showed that anisotropy of the matrix and its evolution make the main contribution to the damage in shear.

The evolution of microstructure in metals must be taken into account in the analysis of damage since damage occurs after a large

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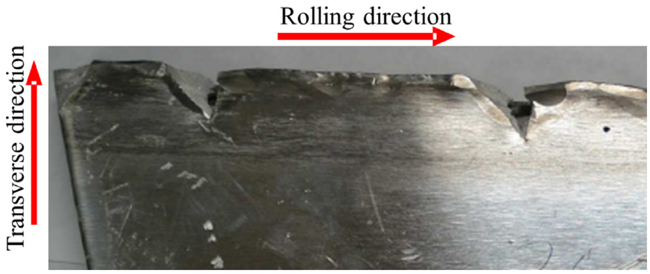


**Fig. 1.** Edge cracked rolled slab (AA2024), showing evidence of (anisotropic ductile) shear damage.

plastic deformation during which their microstructure changes, *i.e.*, texture evolves. Taking into account the texture evolution in the macro scale plasticity is a challenging task. [3,5,19,20] introduced the concept of plastic spin $\mathbf{W}^{\mathrm{p}}$ to take into account the rotation of the orthotropic axes, which occurs due to texture development.

This paper presents a finite element formulation employing an elasto-aniso-plastic constitutive model which takes into account the evolution of microstructure, *i.e.*, the rotation of the orthotropic axes. The proposed formulation is simple and can be used for any metal forming process; the effect of induced anisotropy exists and is critical in any metal forming process due to texture development, *i.e.*, even in case of initially isotropic materials. Results of the shear simulation performed by the proposed formulation where a void is geometrically modeled with a mesh and the deformation field mimics that in the edge cracked area are presented, followed by discussion and conclusion.

The following is notation used in this work. Scalars are denoted by non bold letters without an under bar. A first order tensor, *i.e.*, a vector, is denoted by non bold letters with an under bar. Second and fourth order tensors are denoted by bold letters. Tensor operations are defined such that $\mathbf{A}\underline{b}=A_{ij}b_j$, $\mathbf{AB}=A_{ij}B_{jk}$, and $\mathbf{A}:\mathbf{B}=A_{ij}B_{ij}$. The subscript m indicates the average of the diagonal components of a second order tensor as following, $A_{\mathrm{m}}=A_{kk}/3$. The subscripts $S$ and $A$ indicate the symmetric and anti-symmetric parts of a 2nd order tensor. The summation convention is employed, *i.e.*, all repeated subscripts are summed.

## 2. Anisotropic ductile fracture model

In this section, a finite element formulation employing an elasto-aniso-plastic constitutive model is proposed. To take into account the microstructure evolution, an objective stress rate related with the rotation of the orthotropic axes is introduced.

The additive decomposition of the symmetric part of velocity gradient $(\mathbf{D}=(\nabla\mathbf{v})_S)$ with an objective stress rate is employed to take into account the large deformation effect. The elastic part of the symmetric velocity gradient is governed by the hypoelastic law as following,

$$\mathbf{D}^{\mathrm{e}}=\mathbb{C}^{\mathrm{e}-1}:\overset{\triangledown}{\mathbf{\Sigma}}\quad \mathbf{D}=\mathbf{D}^{\mathrm{e}}+\mathbf{D}^{\mathrm{p}} \tag{1}$$

where $\mathbf{\Sigma}$ is the Cauchy stress, $\mathbb{C}^{\mathrm{e}}$ is the isotropic elastic tensor and $\overset{\triangledown}{\mathbf{\Sigma}}$ is an objective stress rate defined by:

$$\overset{\triangledown}{\mathbf{\Sigma}}=\dot{\mathbf{\Sigma}}+\mathbf{\Sigma}\boldsymbol{\omega}-\boldsymbol{\omega}\mathbf{\Sigma},\quad \boldsymbol{\omega}=\mathbf{W}-\mathbf{W}^{\mathrm{p}} \tag{2}$$

The objective rate above is related with the evolution of the microstructure via $\boldsymbol{\omega}$. In visco-plastic crystal plasticity where the elastic stretching part is ignored, the equation for the antisymmetric part of the velocity gradient is written as following. $\mathbf{W}=\boldsymbol{\omega}+\mathbf{W}^{\mathrm{p}}$, $\boldsymbol{\omega}=\dot{\mathbf{R}}\mathbf{R}^{T}$, $\mathbf{W}^{\mathrm{p}}=\sum_{\alpha=1}^{N_s}\dot{\gamma}^{\alpha}(\underline{s}^{\alpha}\otimes\underline{m}^{\alpha})_A$, where $\mathbf{R}$ is the rotation part in the elastic deformation gradient, $N_s$ is the number of slip systems, $\underline{s}^{\alpha}$ and $\underline{m}^{\alpha}$ are the slip plane normal and the slip direction of the $\alpha$-th slip system, and the subscript $A$ indicates the anti-symmetric parts of a 2nd order tensor. Employing the kinematics in visco-plastic crystal plasticity, additive decomposition is applied to the skew-symmetric part of velocity gradient $(\mathbf{W}=(\nabla\mathbf{v})_A)$,

$$\mathbf{W}=\boldsymbol{\omega}+\mathbf{W}^{\mathrm{p}} \tag{3}$$

where $\mathbf{W}^{\mathrm{p}}$ denotes the amount of the spin in the plastic slip process and $\boldsymbol{\omega}$ indicates the rotation of the orthotropic bases.

The yield function for a plastically anisotropic material is described using the Hill tensor($\mathbb{h}$) as $\mathcal{F}(\mathbf{\Sigma})=0$

$$\mathcal{F}(\mathbf{\Sigma})=\sqrt{\frac{3}{2}\mathbf{\Sigma}:\mathbb{H}:\mathbf{\Sigma}}-\overline{\sigma} \tag{4}$$

where $\mathbb{H}$ is defined by

$$\mathbb{H}\equiv\mathbb{J}:\mathbb{h}:\mathbb{J},\quad \mathbb{J}\equiv\mathbb{I}-\frac{1}{3}\mathbf{I}\otimes\mathbf{I}. \tag{5}$$

$\overline{\sigma}$ is the yield stress of the material in one orthotropic direction. $\mathbb{h}$ is the Hill anisotropy tensor expressed in the deviatoric stress space. $\mathbb{h}$ needs to be written in terms of the rotating orthotropic bases $\underline{m}_i$ to take into account the evolution of the orthotropic bases. $\mathbb{J}$ is the deviatoric projection operator. $\mathbb{I}$ and $\mathbf{I}$ are the fourth and second order identity tensors, respectively.

The orthotropic axes ($\underline{m}_i$, *i.e.*, $\underline{m}_1=\underline{e}_L$, $\underline{m}_2=\underline{e}_S$ and $\underline{m}_3=\underline{e}_T$) rotate governed by the spin tensor $\boldsymbol{\omega}$ as following.

$$\overset{\triangledown}{\underline{m}}_i=\dot{\underline{m}}_i-\boldsymbol{\omega}\underline{m}_i\equiv\underline{0},\quad \dot{\underline{m}}_i=\boldsymbol{\omega}\underline{m}_i \tag{6}$$

The microstructural evolution is represented by the rotation of the orthotropic axes in this study. The rotation of the orthotropic axes is explained by the non-coaxiality between the macroscopic Cauchy stress($\mathbf{\Sigma}$) and the symmetric and plastic part of the velocity gradient ($\mathbf{D}^{\mathrm{p}}$) [19,5,7,4] as following

$$\mathbf{W}^{\mathrm{p}}=a_k\sqrt{\frac{\frac{1}{3}(h_1+h_2+h_3)}{\frac{3}{2}\mathbf{\Sigma}:\mathbb{H}:\mathbf{\Sigma}}}(\mathbf{\Sigma}\mathbf{D}^{\mathrm{p}}-\mathbf{D}^{\mathrm{p}}\mathbf{\Sigma}) \tag{7}$$

where $h_i$ ($h_1$, $h_2$ and $h_3$) are the diagonal elements of the Voigt representation of Hill's anisotropy tensor in deviatoric stress space, $\mathbb{h}$ and $a_k$ is a constant which describes the rate of change in the microstructural evolution.

The material is described to obey the power-law strain-hardening law as following

$$\overline{\sigma}=\sigma_S\left(1+\frac{\overline{\varepsilon}}{\varepsilon_0}\right)^{N} \tag{8}$$

where $\overline{\sigma}$ is the effective stress and $\overline{\varepsilon}$ is plastic strain. $\sigma_S$ is the initial yield stress. $\overline{\varepsilon}$ is defined as the cumulative plastic strain. $\varepsilon_0$ is a constant strain offset. $N$ is the hardening exponent.

The above elasto-aniso-plastic formulation based upon microstructural evolution is implemented into the author's own large deformation finite element code and an ABAQUS UMAT. An implicit time integration scheme and the consistent tangent matrix are employed in the implementation, where the detail of similar methods are referred to [12,13,10,16].

## 3. Simple shear simulation

### 3.1. Boundary value problem for the simple shear simulation

In this section, the boundary condition for a shear problem is described (see Fig. 2). This paper is motivated to reveal the physics in edge cracking of rolled metal slabs, where cracking occurs only at the boundary edge area of slabs, not at the central portion of slabs. Based upon the observation that the traction-free boundary