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Mesh dependence of transverse cracking in laminated metals with nanograined interface layers

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ABSTRACT

Combination of surface mechanical attrition treatment (SMAT) and co-rolling can produce large-scale laminated nanostructured metals with both high strength and high ductility. For the co-rolled SMATed metals with nanograined interface layers, numerical investigation based on the cohesive finite element method focuses on effects of shape of the cohesive law and mesh size. Simulations show that the shape of the bilinear cohesive law varies peak stress and normal opening displacement significantly and that larger thickness of brittle phase allows use of coarser meshes while not to consider lower bound of the mesh size may lead to unreasonable results.

1. Introduction

Surface mechanical attrition treatment (SMAT) and co-rolling can be combined to produce large-scale laminated nanostructured metals with both high strength and high ductility [1,2]. Therefore, it is believed to have a good future to be applied in structural engineering, compared with other newly-developed experimental approaches to design structural materials with both high strength and high ductility. Through the SMAT, a nano-crystalline surface with a thickness 10–50 μm can be generated for various metals to enhance their yield stress and thus the fatigue life without altering their chemical compositions [3–6]. When such SMATed metals are placed on top of each other and then warmly co-rolled, the co-rolled SMATed metals with nanograined interface layers (NGILs) can be produced. This approach of combining SMAT with warm co-rolling has been successfully applied to generate laminated nanostructured 304 stainless steel (SS). The tensile experimental specimen of such SS with a length 20 mm and a width 1.8 mm showed that its yield stress could reach 878 MPa and its failure strain 48%, three times that of the work-hardened steel with the same yield stress [2].

A computational framework for damage and fracture analysis is in need to investigate toughening mechanism in the experimental approach of combining SMAT with warm co-rolling. Among the multiple numerical approaches to investigate damage and fracture process, the cohesive finite element method (CFEM) and the eXtended finite element method (XFEM) have manifested their effectiveness. Both of them can obtain similar crack speeds and crack paths while current difficulty with the XFEM is modeling of spontaneous multiple crack nucleation, branching, and coalescence [7]. In contrast, the ele-

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Nomenclature

G_{coh}	critical energy release rate
T	effective traction
T_{max}	cohesive strength
T_n	cohesive traction in the normal direction
T_s	cohesive traction in the tangential direction
δ	effective separation
δ_m^0	characteristic separation at which T reaches T_{max}
δ_m^f	critical separation beyond which the traction becomes zero
δ_n	normal separation across the cohesive surfaces
δ_s	tangential separation across the cohesive surfaces
η	tension-shear coupling constant
σ_0	yield stress of the coarse-grained layer
σ_0'	yield stress of the nanograined interface layer
CFEM	cohesive finite element method
CGL	coarse-grained layer
NGIL	nanograined interface layer
SMAT	surface mechanical attrition treatment
SS	stainless steel
XFEM	eXtended finite element method

ment deletion method performs very poorly and is unable to predict crack branching although it is easy in implementation [7]. Our main concern for the co-rolled SMATed 304SS with the NGILs is the nucleation and propagation of non-localized microcracks and not on keeping track of a single microcrack, since most of the microcracks in the NGILs are transverse cracks. Therefore, the CFEM is an appealing approach for investigating the non-localized cracking in the NGILs.

The CFEM can model damage initiation/evolution and fracture processes explicitly and has been used to investigate brittle and ductile fracture extensively [8–12]. In a framework of the CFEM, two approaches are available when damage initiation sites or crack paths are not known in advance. The (global) intrinsic CFEM embeds cohesive elements along boundaries of all volumetric elements as part of the physical model [8]. The extrinsic CFEM inserts the cohesive elements into the model as fracture develops, based on an extrinsic fracture initiation criteria [9]. Compared with the intrinsic CFEM, the extrinsic one involves some issues both in model implementation and in results interpretation [12]. Therefore, the intrinsic CFEM was adopted in our former studies [13,14]. We have shown that both the critical energy release rate and the thickness of the NGIL play critical roles in determining the overall ductility of the co-rolled SMATed 304SS [13,14]. However, the dependences of the simulation results on both shape of the cohesive law and the mesh, important issues in using the intrinsic CFEM, have not been addressed [13,14].

In this paper, the bilinear cohesive law used in the intrinsic CFEM and the associated mesh dependence issue are discussed in Section 2. Numerical framework including analysis configuration and constitutive laws is given in Section 3. Numerical results and discussions, including dependences of the simulation results on (1) the damage criteria, (2) the shape of the bilinear cohesive law, and (3) the mesh size, are detailed in Section 4. This study enables a further understanding in using the intrinsic CFEM to study transverse cracking in the laminated metals.

2. Mesh dependence in using the intrinsic CFEM

Many cohesive laws, which specify constitutive relationships between traction and separation across cohesive surfaces, have been developed for different problems (see [10] and references therein). The bilinear cohesive law, the geometrically simplest form, was used in Guo et al. [13,14], as shown in Fig. 1. T_{max}, cohesive strength, is the stress at which the damage initiates and the separation is δ_m^0. G_{coh}, critical energy release rate, is the work required to fully break a unit surface area of

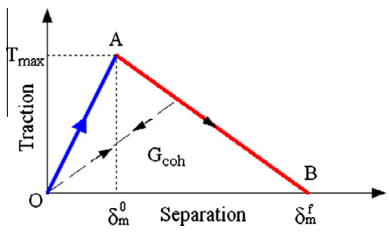

Fig. 1. Bilinear cohesive law.