THE ROUTE TO SIMULTANEOUS HIGH STREGNTH AND HIGH DUCTILITY METALS THROUGH ENGINEERED NANOCRYSTALLINE INTERLAYERS

X. Guo [*], George J. Weng [**] & A. K. Soh [*** a)]
[*] *Department of Mechanics, School of Mechanical Engineering, Tianjin University, Tianjin 300072, China; Tianjin Key Laboratory of Nonlinear Dynamics and Chaos Control, Tianjin 300072, China*
[**] *Department of Mechanical and Aerospace Engineering, Rutgers University, New Brunswick, NJ, USA*
[***] *Department of Mechanical Engineering, The University of Hong Kong, Hong Kong*

Summary Combination of surface mechanical attrition treatment (SMAT) and co-rolling is a promising experimental methodology to design metals with simultaneous high strength and high ductility. Recent simulations have revealed that brittle nanograined interface layer (NGIL) can lead to good ductility of the co-rolled SMATed stainless steel (SS). Here the cohesive finite element method is used to show that the SS failure strain is significantly enhanced with the increase of fracture toughness of coarse-grained layers and failure strain of NGIL while the failure strain will decrease if the NGIL thickness is over 60 μm.

INTRODUCTION

A promising experimental approach to simultaneously strengthen and toughen metallic materials is a combination of surface mechanical attrition treatment (SMAT) and co-rolling, which can produce large-scale laminated nanostructured metals [1]. It has been successfully applied to generate laminated nanostructured 304 stainless steel (SS) [1]. Guo et al. employed the cohesive finite element method (CFEM) to correlate the SS ductility with the critical energy release rate of nanograined interface layer (NGIL) [2]. The simulation showed that the brittle NGIL developed high density of microcracks and this toughened the SS, which was a direct reflection of the non-local cracking proposed in [1]. Other factors including i) the NGIL failure strain, ii) the fracture toughness of the coarse-grained layer (CGL), and iii) the NGIL thickness can also affect the overall failure strain of the SS. Here it is found that each of them can have significant influence on the ductility of the material.

THE COHESIVE FINITE ELEMENT METHOD AND IMPLEMENTATION

The CFEM has proven to be effective in investigating fracture process, especially spontaneous multiple crack initiation, branching, and coalescence [3-6]. As most of the microcracks in NGILs are transverse cracks [1,2] and we focus on their nucleation and propagation, the CFEM is an appealing approach. The intrinsic CFEM has advantages in model implementation and results interpretation [5] and will be adopted here. Many cohesive laws have been developed for different conditions [6]. A bilinear cohesive law with the cohesive strength and the cohesive fracture energy is widely used for its simplicity (Fig. 1a). δ_m^f The quadratic strain criterion for damage initiation and evolution can account for the multiaxial stress state and will be adopted for the entire specimen.

The SS contains the CGL with a mean grain size of several microns and the NGIL with a mean grain size of ~50 nm. An analysis configuration with a length 1 mm and a width 0.9 mm is shown in Fig. 1b. The fine structured cross-triangular meshes with uniform size 10 by 10 μm are used. Unless otherwise stated, the NGIL thickness is taken as 40 μm, the same as that in experimental investigation [1]. The isotropic, elasto-plastic constitutive relations are applied to both phases. The density, Young's modulus, Poisson's ratio, and flow stress for the two phases are the same as those in Ref. [2]. The critical energy release rate of the CGL is obtained from its fracture toughness, which is taken as, unless otherwise stated, 100 $\mathrm{MPa}\sqrt{\mathrm{m}}$. To simulate the effect of the boundary between CGL and NGIL, two types of conditions are considered: i) a tough boundary with its cohesive parameters same as those of the CGL and ii) a brittle boundary with its cohesive parameters same as those of the NGIL.

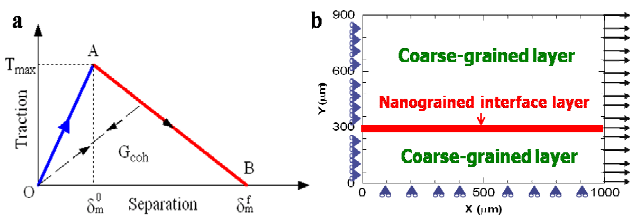


Fig. 1. (a) A bilinear cohesive law and (b) analysis configuration.

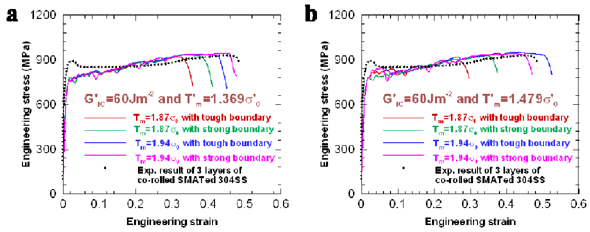


Fig. 2. Effect of NGIL failure strain. It is (a) 2.5% and (b) 3.26% ((b) taken from [2]).

a) Corresponding author. Email: aksoh@hkucc.hku.hk.

SIMULATION RESULTS

During applying CFEM, plastic deformation and damage process competes with each other so that the failure strain is a natural outcome of the combined effects of constituent response and interfacial behavior. Thus the cohesive strength can be calibrated by comparing the simulation with experimental results. The effect of the NGIL failure strain on the SS ductility is of interest. The NGIL critical energy release rate is taken as 60 Jm^{-2} [2] and its cohesive strength is calibrated as 1.479 and 1.369 times of its yield stress when its failure strain is 3.26% and 2.5%, respectively. With the calibrated results, simulations are carried out at two levels of CGL cohesive strength and for two types of boundaries and the results are shown in Fig. 2. The scattered curves indicate that both the CGL cohesive strength level and the boundary type play significant roles. It is observed that, when the NGIL failure strain increases from 2.5% to 3.26%, the largest overall failure strain of the specimen increases from 45% to 51%.

The CGL serves as the substrate for the NGIL, so an investigation on the effect of its fracture toughness on the overall failure strain can provide insights into whether the combination of SMAT and co-rolling can toughen other SS. We used the same parameters as those in Fig. 2b, but with two different K_{Ic} for CGL. The results show that the largest overall failure strain increases from 28% to 51% as it increases from 80 to 100 $\mathrm{MPa}\sqrt{\mathrm{m}}$ and that all four overall failure strains reach a level of 44-52% as it further increases to 120 $\mathrm{MPa}\sqrt{\mathrm{m}}$.

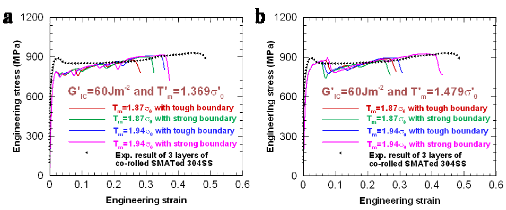
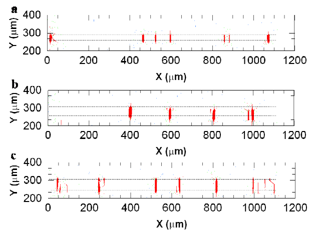


Fig. 3. Stress-strain curves for the SS at NGIL thickness 60 μm with failure strain (a) 2.5% and (b) 3.26%.

Fig. 4. Damage distribution in the SS with NGIL thickness (a) 40, (b) 60, and (c) 80 μm.



The dependence of the failure strain on the NGIL thickness deserves careful investigation. We use the same NGIL cohesive strength as those in Fig. 2, but with the NGIL thickness 60 μm, and the results are shown in Fig. 3. A comparison between Figs. 2 and 3 shows that the ductility significantly decreases at this large NGIL thickness. Fig. 3 also shows that the CGL cohesive strength level has a larger influence on the overall failure strain than the boundary type, since the one with the slightly larger cohesive strength has larger overall failure strain than the one with the smaller cohesive strength. Fig. 4 illustrates the damage distribution in the SS with the overall strain 0.12 for the cases of larger cohesive strength and tough boundary. It can be seen that the size of damaged zones is relatively easy to reach the level of the NGIL thickness. Therefore, the SS with thick NGILs will have longer microcracks. This explains the observed substantial decrease in the SS ductility when the NGIL thickness increases.

CONCLUSIONS

We have employed the intrinsic CFEM to study the effect of multiple factors on the failure strain of the co-rolled SMATed 304SS. The SS ductility can be enhanced with increased NGIL failure strain and CGL fracture toughness while thick NGIL is found to be detrimental to the SS ductility. Thus to enhance the SS ductility, the microcracks not only need to be sufficiently dense but also adequately small, which requires comparatively thinner NGILs. Comprehensive experimental investigations on these factors are expensive to carry out, so this systematic simulation can provide significant insights into the complex nature of the deformation process until failure of the SS.

Acknowledgements: Support from the RGC of the Hong Kong Special Administrative Region (Project no. CityU8/CRF/08) is gratefully acknowledged. X. Guo acknowledges the support from National NSF of China (Project no. 11102128), and G.J. Weng thanks the support of the HKU Visiting Research Professor Scheme 2010-2013.

References

[1] Chen A.Y., Li D.F., Zhang J.B., Song H.W., and Lu J.: Make Nanostructured Metal Exceptionally Tough by Introducing Non-localized Fracture Behaviors. *Scripta Mater* **59**:579-582, 2008.

[2] Guo X., Leung A.Y.T., Chen A.Y., Ruan H.H., and Lu J.: Investigation of Non-local Cracking in Layered Stainless Steel with Nanostructured Interface. *Scripta Mater* **63**:403-406, 2010.

[3] Needleman A.: A Continuum Model for Void Nucleation by Inclusion Debonding. *ASME J. Appl Mech* **54**:525-531, 1987.

[4] Camacho G.T. and Ortiz M.: Computational Modelling of Impact Damage in Brittle Materials. *Int J. Solids Struct* **33**:2899-2938, 1996.

[5] Zhang Z., Paulino G.H., and Celes W.: Extrinsic Cohesive Modelling of Dynamic Fracture and Microbranching Instability in Brittle Materials. *Int J. Numer Methods Eng* **72**:893-923, 2007.

[6] Chandra N., Li H., Shet C., and Ghonem H.: Some Issues in the Application of Cohesive Zone Models for Metal–ceramic Interfaces. *Int J. Solids Struct* **39**: 2827-2855, 2002.