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A study of dynamic plasticity in austenite stainless steels with a gradient distribution of nanoscale twins

Linli Zhu [a,*], Chunsheng Wen [b], Chongyang Gao [c,*], Xiang Guo [d], Jian Lu [b]

[a] *Department of Engineering Mechanics and Key Laboratory of Soft Machines and Smart Devices of Zhejiang Province, Zhejiang University, Hangzhou 310027, China*
[b] *Department of Mechanical and Biomedical Engineering, City University of Hong Kong, Kowloon, Hong Kong, China*
[c] *The State Key Lab of Fluid Power and Mechatronic Systems, College of Mechanical Engineering, Zhejiang University, Hangzhou 310027, China*
[d] *School of Mechanical Engineering, Tianjin University, and Tianjin Key Laboratory of Nonlinear Dynamics and Control, Tianjin 300072, China*

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ABSTRACT

The dynamic plastic behavior related to the gradient distribution of twin spacing in 304 stainless steel thin wires is investigated experimentally with the strain rate varying from 1×10^{-3}/s to 1.5×10^{4}/s. Such gradient-nanotwinned structures are prepared by surface mechanical attrition treatment. A mechanism-based dynamic plastic model is developed to describe the strain-rate dependent stress-strain response in gradient-nanotwinned austenite stainless steels. A good agreement between experimental data and simulations was achieved, and further theoretical predictions demonstrated that the dynamic plastic behavior is sensitive to the twin spacing and volume fraction of gradient-nanotwinned region in austenite stainless steel wires.

The quest for a good combination of high strength and good ductility has led to the development of metallic materials with designed various nano-scale microstructures [1–3]. In face-centered-cubic (fcc) polycrystalline metals, experimental studies have demonstrated that generating nanotwins in grains can give rise to materials possessing high yield strength and good ductility [4]. Recently, nanostructured metallic materials with gradient nanoscale-microstructures also exhibit the high strength together with a good ductility [5–9]. It should be emphasized that these excellent mechanical properties in nanotwinned metals or gradient-nanostructured metals are all measured in the quasi-static conditions. The target applications of these advanced metallic materials, such as the energy absorption parts and structural reinforcements in automobile systems, demand us to understand their plastic behaviors in the shock loading region. So far, a few studies have been carried out for the dynamic plasticity in nanotwinned metals to investigate the contribution of twin lamellae on the strain rate-dependent stress-strain response [10]. The ballistic properties of gradient-nanograined and nanotwinned 304ss thin plates were explored by experiments and the strain-rate dependent stress-strain relations were measured [11,12]. However, there are few works to give insights to the dynamic plastic response in gradient-nanostructured metals.

In order to exploit the relationship between mechanical properties and the nanoscale twin lamellae, mechanism-based models [13–16] and finite element methods [17–20] have been developed and utilized to predict the twin spacing-dependent strength and ductility. Atomistic simulations [21–27] have also been performed to reveal the deformation mechanisms in nanotwinned metals. For the gradient-nanostructured metals, the finite element method combined with the mechanism-based plasticity models was applied to investigate the influence of the gradient nanostructure distribution on the mechanical performance [7,28,29]. However, these theoretical approaches are unable to analyze the dynamic plasticity of nanotwinned metallic materials. Even though a large number of phenomenological models [30,31] and physics-based constitutive models [32–34] have been presented to predict the mechanical behaviors of metals at different strain rates and temperatures within the framework of continuum mechanics, these models still lack the capability of describing the dynamic plastic behavior of nanotwinned metals, particularly gradient-nanotwinned metals. Therefore, a mechanism and physics-based theoretical model needs to be developed to characterize the stress-strain behavior of gradient-nanotwinned metals at different strain rates.

In this work, the gradient-nanotwinned austenite stainless steel (AISI 304 stainless steel) was prepared by surface mechanical attrition treatment (SMAT). Under various shock loadings rates, stress-strain relations for SMATed samples were measured with the strain rate varying from 1×10^{-3}/s to 1.5×10^{4}/s. It was observed that the yield strength and hardening behaviors are related to the strain rate for gradient-nanotwinned metals. A new constitutive model for the gradient-nanotwinned metals is developed through considering the twin

* Corresponding authors.
E-mail addresses: llzhu@zju.edu.cn (L. Zhu), lxgao@zju.edu.cn (C. Gao).

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spacing-related athermal activation and rate-related thermal activation. The numerical analyses showed that the proposed model can describe the dynamic plasticity of such gradient-nanostructured metals very well. It is believed that the present results could be helpful to high strength metallic materials with good ductility, by quantitatively understanding the rate-dependent plasticity of gradient-nanotwinned metals.

Gradient-nanotwinned samples were prepared from 1.5 mm-diameter wires of coarse-grained 304 stainless steel (304ss). A gradient of nano-scale twin spacing can be generated through the process of SMAT with the treatment time of 20 mins, which is the optimal time for achieving the good mechanical performance [35]. The corresponding schematic drawing is shown in Fig. 1(a). For the shock dynamics testing, the testing samples were cut from the SMATed wires with a diameter 1.5 mm and a length 2.0 mm. The stress-strain curves for the lower strain rate, i.e., 0.1/s, 1/s, 50/s, and 100/s were conducted in the MTS RT/30 Electro-Mechanical Material Testing System (MTS) at room

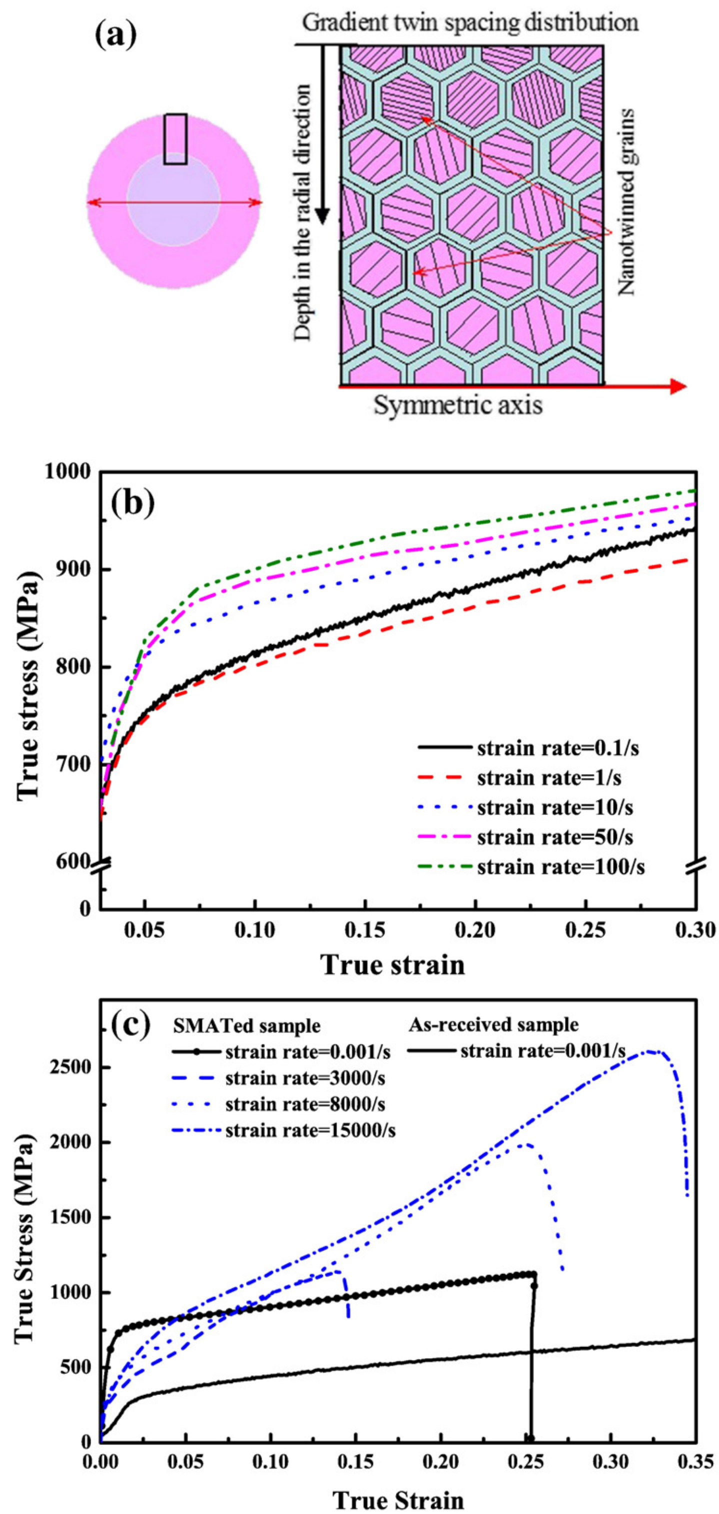

Fig. 1. A schematic drawing of the 304ss with gradient distribution of nanotwins (a), and the experimental measurements of stress-strain responses with the strain rate from 0.1/s to 100/s (b), and with the strain rate of 3000/s, 8000/s, and 15,000/s (c).