Scripta Materialia 140 (2017) 76–81

Contents lists available at ScienceDirect

Scripta Materialia

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

Regular article

Butterfly effect in low-cycle fatigue: Importance of microscopic damage mechanism

C.W. Shao [a,b], P. Zhang [a,*], Z.J. Zhang [a], Z.F. Zhang [a,b,**]

[a] Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, People's Republic of China
[b] University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China

ARTICLE INFO

Article history:
Received 3 May 2017
Received in revised form 11 June 2017
Accepted 11 July 2017
Available online xxxx

Keywords:
High-Mn TWIP steels
Tension
Low-cycle fatigue
Damage mechanism
Life prediction

ABSTRACT

We report that materials with similar tensile properties can also exhibit quite different low-cycle fatigue (LCF) performances. Experimental results demonstrate that the LCF properties of twinning induced plasticity (TWIP) steels are naturally dominated by microscopic deformation mechanisms (mainly dislocation slip mode), which slightly influences the initial work hardening. However, such slight difference in the initial work hardening (the butterfly effect), corresponding to different damage mechanisms, accumulates and enlarges cycle by cycle during fatigue, finally leading to wide variations in cyclic stress response and fatigue life.

Traditionally, mechanical structures and components are usually designed based on monotonic mechanical properties although in recent years structural design using fatigue is gaining a growing recognition, considering most of these structural components are served under cyclic loading condition [1]. To be specific, obviating potential fatigue failure and precisely assessing the fatigue durability, not only to prevent catastrophes, but also to forestall breakdowns whose consequences are mainly economic, are becoming crucial and challenging tasks in the fields of modern aerospace, transportation, oil, automotive and energy industry [2]. However, the materials' fatigue properties are conventionally obtained from a series of strain or stress-controlled fatigue tests, which is a time and money-consuming process and also contains a lot of effort. Hence, it is highly desirable to estimate the fatigue property or fatigue life through relatively simple and labor saving tests without extensive experimental investment. One such fruitful attempt is to assess the fatigue properties from the more readily available monotonic mechanical data obtained in simple tensile tests [2–6]. In the low-cycle fatigue (LCF) regime, a long fatigue lifetime is commonly believed to be related to a high monotonic ductility [7]. However, there are also exceptions. In our previous work, a decrease of LCF resistance was found with the synchronously promoted strength and ductility in High-Mn steels [8], and a remarkable variation in LCF resistance can be performed in materials with similar tensile properties [9], indicating a subtle and undigested relationship between the monotonic and cyclic deformation.

In this Letter we investigated the behaviors of tensile and cyclic deformation of four Fe-Mn-C TWIP (twinning-induced plasticity) steels. The LCF is an accumulated process of monotonic deformation, and naturally represents an enlargement effect of mechanical property only in the initial stage of strain. Thus, judging the LCF properties from materials' macro tensile strength and/or ductility, as previous researchers usually do [2–6], can be invalid. Microscopic damage mechanism under small strain, by its very nature, should be the only connecting link between monotonic and cyclic deformation behaviors. The LCF performance is extremely sensitive to the dislocation slip mode, which can be qualitatively learnt from the work-hardening behavior in the initial stage of tensile deformation. This may endow us with a quick and convenient estimation of materials' LCF properties from a part of tensile data, and provides a guideline for material selection and optimal design in engineering application.

Four kinds of high-Mn TWIP steels with chemical compositions of Fe-xMn-0.6C ($x = 18, 22, 26, 30$ in wt%) are investigated in this study. Detailed processing in making these materials is given in [9]. Fig. 1a displays the tensile true stress-strain curves of the above four steels. Obviously, such Fe-Mn-C alloys exhibit an approximately equal same yielding strength of ~300 MPa and a small improvement of flow stress with decreasing Mn content at the later stage of deformation. Specifically, the flow behaviors for these four steels in the initial stage of strain (0–5%) are so similar that no obvious difference can be detected from the stress-strain curve directly (see Fig. 1b). However, the LCF properties (lives) of Fe-Mn-C steels are improved significantly with increasing

* Corresponding author.
** Correspondence to: Z. F. Zhang, Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, People's Republic of China.
E-mail addresses: pengzhang@imr.ac.cn (P. Zhang), zhfzhang@imr.ac.cn (Z.F. Zhang).

http://dx.doi.org/10.1016/j.scriptamat.2017.07.007

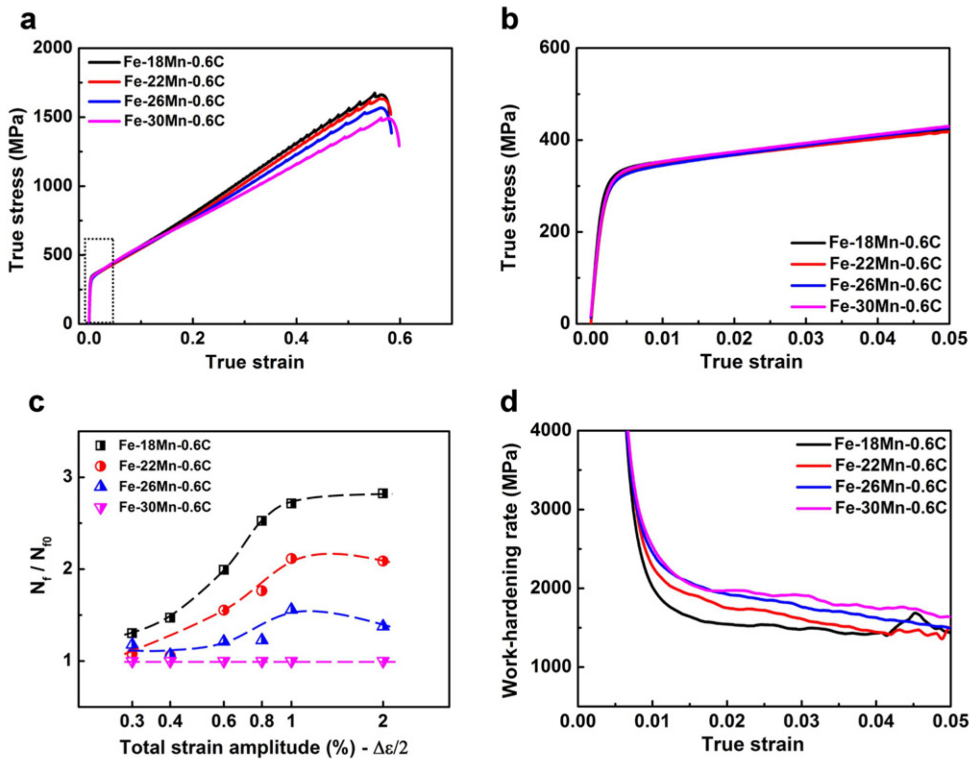

Fig. 1. Tensile and low-cycle fatigue behaviors of Fe-Mn-C TWIP steels. (a) Tensile true stress-strain curves. (b) Stress-strain behaviors at the initial stage of tensile deformation (detailed information in the dotted box in part figure a). (c) Comparison of fatigue lives at various strain amplitudes. (d) Work-hardening rate as a function of strain upon monotonic tension.

the Mn content, as seen in Fig. 1c. After a careful investigation of evolution of flow stress at the initial stage of tensile deformation, a monotone increasing ability of work-hardening is generally found by adding Mn content in Fe-Mn-C alloy (Fig. 1d). It is conjectured that this difference (so small that it can hardly be detected in the stress-strain curve in Fig. 1b) in hardening behaviors of the four alloys may accumulate cycle by cycle during fatigue.

Fig. 2a presents the cyclic stress response curves of the four experimental alloys at total strain amplitude ($\Delta\varepsilon/2$) of 1.0%. As we can see, all the four alloys exhibit a marked cyclic hardening behavior during

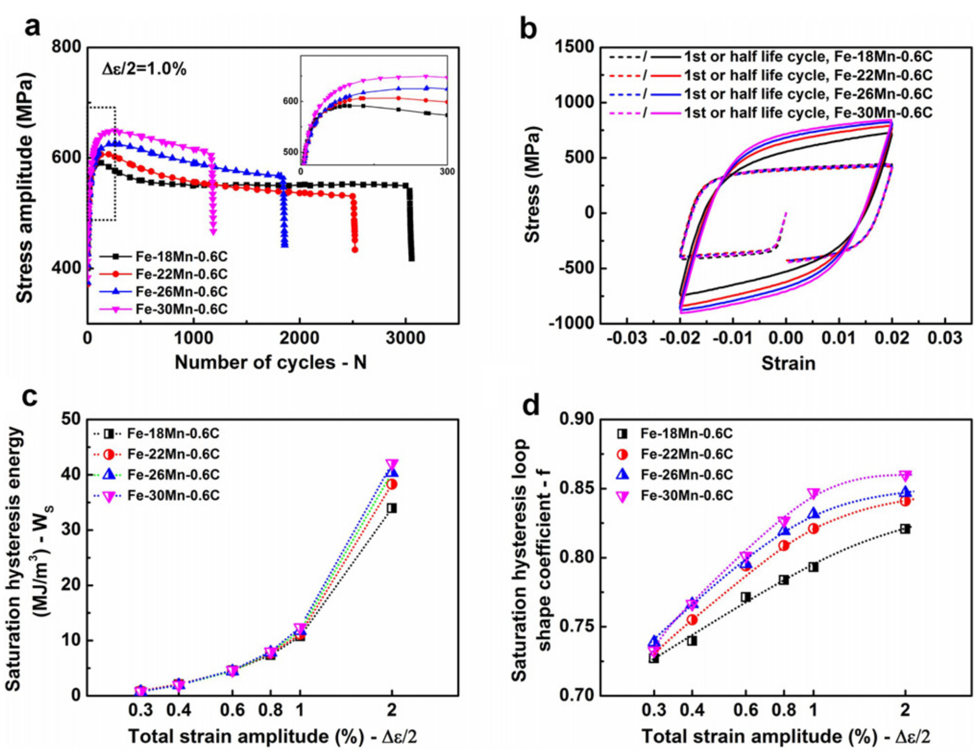

Fig. 2. Mechanical behaviors under cyclic deformation of Fe-Mn-C alloys. (a) Cyclic stress response curves. (b) Cyclic stress-strain hysteresis loops at first and half-life cycles. (c,d) Measured values of saturation hysteresis energy and loop form coefficient *f* at various strain amplitudes.