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Ratcheting and fatigue properties of the high-nitrogen steel X13CrMnMoN18-14-3 under cyclic loading

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ABSTRACT

High-nitrogen steel X13CrMnMoN18-14-3 has been used in manufacturing expanding metallic stents with 0.1 mm diameter, and such medical implant is subjected to complicated and asymmetrical cyclic loading during service. But there is no test data published for the thin wire of the material under cyclic loading. In this study, a series of tests were conducted on X13CrMnMoN18-14-3 stainless steel under uniaxial cyclic loading with mean tensile stress. The yield stress and ultimate strength were higher than that of large size specimen with diameters of 5 mm and 7 mm. The effects of stress amplitude, mean stress, loading history and stress rate on the ratcheting behavior of high-nitrogen steel were analyzed, respectively. It can be concluded that the ratcheting strain amplitude and ratcheting strain rate of X13CrMnMoN18-14-3 steel increases with increasing stress amplitude or mean stress correspondingly. At the meantime, experimental results reveal that the material exhibits a strong memory of the previous loading history, the stress cycling with higher stress amplitude or mean stress greatly restrains the ratcheting of subsequent stress cycling with lower ones. The ratcheting strain rate was very sensitive to the applied cyclic stress rate, and the accumulation of ratcheting strain under stress rate of 21.2 MPa/s is much faster than that under stress rate of 106 MPa/s. In addition, comparison of the fatigue life between bulk specimen and thin wire indicates that the size effect has significant influence on fatigue properties of the material. In the case of the test conducted under stress amplitude of 400 MPa, the fatigue life of small specimen is approximately ten times longer than that of bulk specimen under the same loading conditions.

1. Introduction

Since austenitic stainless steels provide fairly high toughness combined with high mechanical strength and high fatigue endurance limit, they are in common use for medical applications, especially for orthopaedic and cardiovascular implants [1]. However, due to these steels contain a high amount of Nickel, the corrosion and reaction of the implant surface will release Ni metal ions into body fluid, which cause Ni-allergy for a growing amount of patients. In order to solve this problem, many Ni-free austenitic stainless steels have been developed, which combine high strength and ductility with good corrosion properties. Among these new materials, a high-nitrogen and Ni-free stainless steel X13CrMnMoN18-14-3 (1.4452) was developed and considered as a promising alternative for conventional Ni-base alloys [1,2].

In practice, the medical implants made from the X13CrMnMoN18-14-3 stainless steel are always subjected to asymmetrical cyclic loadings, meaning the existence of mean stress in a completed cycle. Under such loading conditions, the cyclic accumulation of plastic strain, which is called ratcheting, will take place. The ratcheting deformation will accelerate damage accumulation and eventually reduce the fatigue life of the device [3–7]. Actually, the ratcheting and fatigue behavior of high-nitrogen and Ni-free X13CrMnMoN18-14-3 stainless steel had already been investigated [8,9]. It can be found that the 1.4452 steel has better cyclic fatigue behavior than the conventional 316L-type steel, and the reason is attributed to the low stacking fault energy and the characteristic corrosion mechanisms [9].

Recently, X13CrMnMoN18-14-3 stainless steel was explored to use in manufacturing expanding metallic stents with 0.1 mm diameter. In this situation, the thin steel wire was subjected to complicated and asymmetrical cyclic loading. However, all of the ratcheting and fatigue tests performed on X13CrMnMoN18-14-3 stainless steel in literature were using bulk specimens with large diameter [1,2,8,9]. There is no test data published for the thin wire under cyclic loading. As a matter of fact, size effects have significant influence on the mechanical and ratcheting response for many

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metal alloys [10–15]. The conclusions drawn from the bulk specimen tests may have great deviations from those obtained by super small and thin specimens. For the sake of understanding the cyclic ratcheting and fatigue behavior for this new material in small size, it is necessary to carry out a systematic research on X13CrMnMoN18-14-3 stainless steel specimens with diameter of 0.1 mm, which has the same size as it is used in reality.

In this study, uniaxial ratcheting and fatigue behavior of X13CrMnMoN18-14-3 stainless steel was experimentally investigated under various loading conditions. The effects of stress amplitude, mean stress, loading history and stress rate on ratcheting will be observed thoroughly, and the fatigue life of thin wire will be used to compare with that of bulk specimen. The results obtained in this study are very useful to understand the influence of loading condition and size effect on ratcheting and fatigue behavior of the material.

2. Materials and testing apparatus

The chemical composition of the X13CrMnMoN18-14-3 stainless steel is shown in Table 1. Approximately 0.4% nitrogen content can be retained on interstitial lattice sites under atmosphere pressure, whereas nitrogen content up to 1% can be obtained in a pressure electro slag remelting process. According to Gavriljuk and Berns [16], the material can be named as austenitic high-nitrogen Steels (HNS) if the nitrogen content is intentionally raised to gain a good combination of strength, ductility, wear resistance and corrosion resistance.

A series of ratcheting and fatigue tests in addition with uniaxial tensile tests were performed on a minitype tension-torsional fatigue testing apparatus, and the data collection was made using an automatic data acquisition system. Both the test apparatus and the data acquisition system were developed by CARE Lab, Tianjin University [17]. The specimens were manufactured to a thin wire with diameter of 0.100 mm and gage length of 20 mm.

Table 1
Chemical composition of the X13CrMnMoN18-14-3 stainless steel in weight-%.

Compositions	Fe	Co	Cr	Mo	Mn	Ni	N	C	Nb
Contents	Basis	–	18	3	14	<0.05	0.75–1.0	0.13	⩽0.25

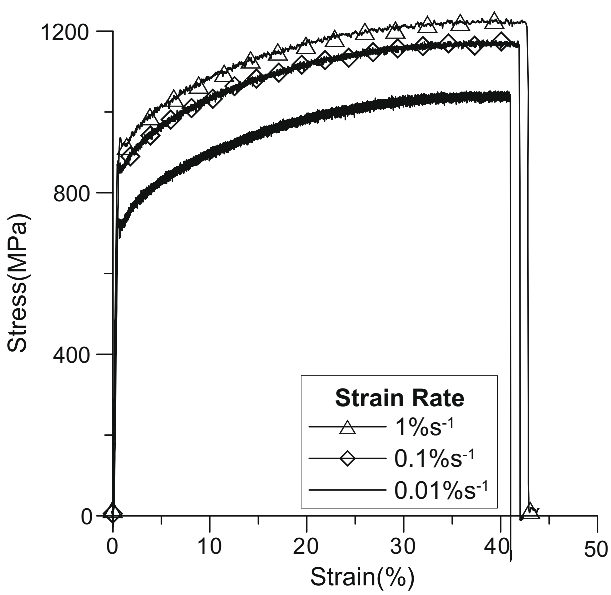

Fig. 1. Monotonic stress–strain curves at different strain rates, specimen diameter = 0.1 mm.

3. Results and discussions

3.1. Uniaxial tension

Three tensile tests were performed at three different strain rates of 0.0001 s^{-1}, 0.001 s^{-1} and 0.01 s^{-1}, and the experimental

Table 2
Mechanical properties of high-nitrogen steel with 0.1 mm diameter at strain rate of 0.001 s^{-1}.

Elastic modulus	Ultimate strength	Yield stress	Elongation
200 GPa	1150 MPa	830 MPa	40%

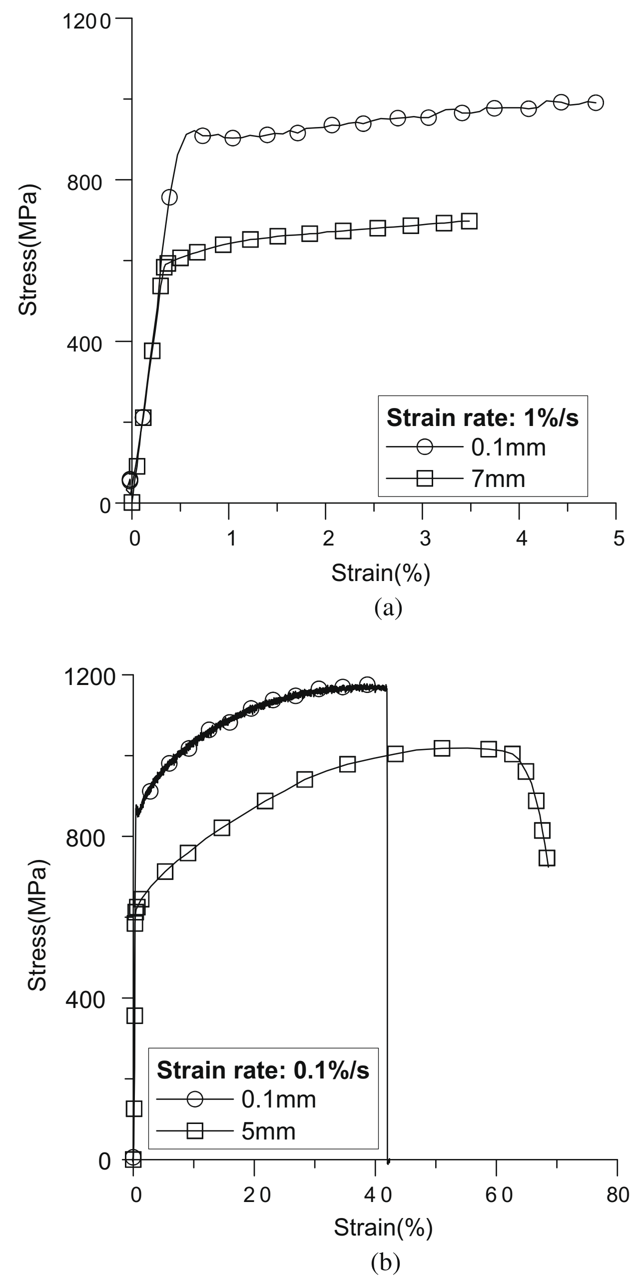

Fig. 2. Comparison of stress–strain relationship between bulk specimen and thin wire specimen (a) bulk specimen with 7 mm diameter and (b) bulk specimen with 5 mm diameter.