Uniaxial Ratcheting Behaviours of Materials with Different Crystal Structures

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Abstract

This report overviews the influence of asymmetric fatigue cycling on the nature of accumulation of ratcheting strain of different materials with varying crystal structures which include aluminium alloy, interstitial free steel and AISI 304LN stainless steel. Stress-controlled fatigue tests have been carried out at room temperature (300 K) under various combinations of mean stress (σ_m) and stress amplitude (σ_a). The results highlight that accumulation of ratcheting strain is dependent on the magnitude of employed levels of σ_m and/or σ_a for all the investigated materials. The nature of strain accumulation has been corroborated with plastic damage occurring during cyclic deformation, dislocation cell formation during asymmetric cyclic loading, martensitic transformation in 304LN stainless steel as well as variations of the crystal structure and corresponding stacking fault energies of the materials.

Keywords: *Ratcheting, stress amplitude, mean stress, dislocation density*

1. Introduction

Ratcheting is known as the phenomenon of strain accumulation during asymmetric cyclic loading of metallic materials under application of non-zero mean stress at different stress amplitudes [1-7]. This phenomenon is of considerable importance for the purpose of design and safety assessment of engineering components, as accumulation of ratcheting strain degrades fatigue life [2, 3] of structural components, and consequently limits the predictive capability of the well known Coffin-Manson relation [3]. Over the past two decades, studies on the ratcheting behaviour of materials have received critical attention by several investigators for both experimental data generation and examination of the phenomenon through simulation studies [8,9]. The existing reports provide the state of understanding primarily related to uniaxial and multiaxial ratcheting behaviour of metallic materials as well as polymers. It can be observed that strain accumulation varies for different materials. Therefore it is necessary to establish parameters, on which the nature of strain accumulation depends. Since the ratcheting deformation is microscopically related to the mobility of dislocations during the cyclic loading [5, 6] it is hypothesized that the metals with different crystal structures or stacking fault energies should lead to different ratcheting behaviours. With this motivation, ratcheting behaviours of the materials with different crystal structures/ stacking fault energies are examined under asymmetric stress-controlled cyclic loading tests with nonzero mean stress values.

2. Materials and Experimental Details

Three materials- an aluminium alloy, a interstitial free steel and an AISI 304LN stainless steel- are selected for this study. These materials were subjected to different heat treatments. The selected aluminium alloy was examined in both as-received and annealed conditions. A set of as-received rods were annealed by heating at a temperature of 300°C for 30 minutes, followed by furnace cooling. The IF steel was subjected to stress relieving annealing by soaking the specimen blanks at 400°C for one hr followed by furnace cooling. The AISI 304LN stainless steel was solution annealed by annealing at 960°C for 1 hour followed by quenching.
Microstructural examinations were carried out with the help of an optical microscope (Leica, model: DMILP, Bannockburn, IL 60015, USA) connected to an image analyzer (Software: Biovis Material Plus, Version: 1.50, Expert Vision Labs Private Limited, Mumbai, India). Hardness measurements were done with the help of a Vickers hardness tester (Leco, model: LV 700, Michigan, USA). Tensile tests were carried out on cylindrical specimens of 6 mm gauge diameter and 25 mm gauge length at a cross-head speed of 1 mm/min. This cross-head speed corresponds to a nominal strain rate of $6.6 \times 10^{-4}\ s^{-1}$ at the room temperature of 298 K.
Specimens having configuration similar to cylindrical tensile blanks but with 6 mm diameter and 12.5 mm gauge length were designed and fabricated for ratcheting experiments. Uniaxial ratcheting experiments were carried out at room temperature using a 250 kN servo-hydraulic testing system (Instron, model: 8800R, High Wycombe, Buckinghamshire, UK). The system was attached to a computer for test control as well as for data

Table 1: Different loading parameters for ratcheting tests.

Material		σ_m (MPa)	σ_a (MPa)
Aluminium	As-received	10	130,140,150
		20	130,140,150
		30	130,140,150
	Annealed	6	83,89,95
		12	83,89,95
		18	83,89,95
IF Steel		10	130,140,150
		20	130,140,150
		30	130,140,150
AISI 304LN SS		50	300, 350, 400
		100	300, 350, 400
		150	300, 350, 400

acquisition. All tests were done in stress-control mode up to a specified number of cycles. Cyclic loading was done using a triangular waveform with constant stress rate of 50MPa /s. The tests were conducted either at (i) constant σ_a with varying σ_m, or at (ii) constant σ_m with varying σ_a conditions. The combinations of the adopted σ_a and σ_m values for different tests are listed in Table 1**.** It may be noted that all specimens were subjected to deformation under tension-compression cycles. The strain was measured during cyclic deformation using an axial extensometer having 12.5 mm gauge length. During each test, the data pertaining to stress-extension as well as actuator displacement were continuously recorded; attempts were made to acquire at least 200 data points per cycle for subsequent analyses. A few transmission electron microscopic (TEM) experiments were carried out on thin slices cut out from the ratcheted specimens. X-ray diffraction studies were done for AISI 304LN stainless steel to examine the possible formation of deformation induced martensite.

3. Results and Discussion

The characteristics of the microstructural features and the conventional mechanical properties of the selected materials are described in section 3.1 while their uniaxial ratcheting behaviour and associated microstructural and substructural variations are dealt in sections 3.2 to 3.5.

3.1. Microstructure, hardness and tensile properties

Typical microstructures of all the investigated materials are illustrated in Fig. 1. The microstructure of the aluminium alloy is illustrated in Fig. 1a. It exhibits a number of inclusions. The microstructure of the IF steel as depicted in Fig. 1b exhibits equiaxed ferrite grains. This steel contains very fine inclusions, although their volume fraction is considerably low. The microstructure of AISI 304LN stainless steel is shown in Fig. 1c exhibiting nearly equiaxed austenite grains; annealing twins are present at several locations.

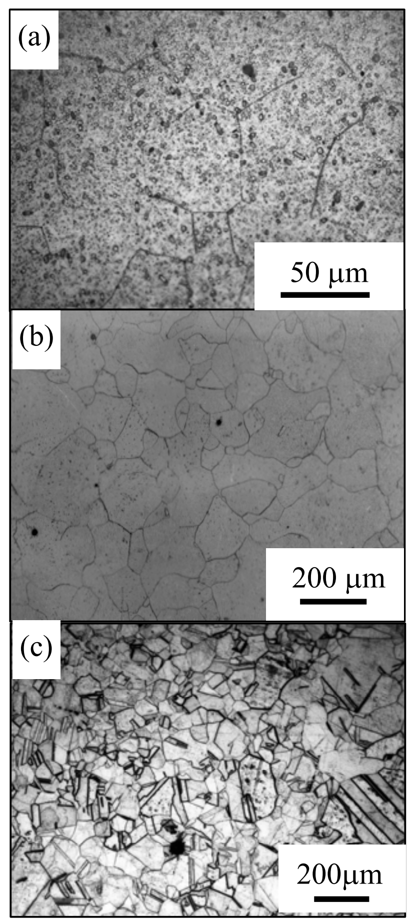

Fig.1 Microstructures: (a) Aluminium alloy, (b) Interstitial free steel and (c) AISI 304LN stainless steel.

The Vickers hardness (HV_5) values of as-received and annealed specimens of the investigated aluminium alloy are found to be 84 ± 1.7 and 47 ± 0.6 respectively. The Vickers hardness value of the IF steel is 71 ± 1.8 (HV_{10}) and that of the AISI 304LN stainless steel is 205 ± 4.6 (HV_{20}). The results of the tensile tests of the investigated materials indicate that the tensile strength values are 220 MPa, 91 MPa, 238 MPa and 683 MPa for as-received aluminium alloy, annealed aluminium alloy, IF steel and AISI 304LN stainless steel respectively. It can be noticed that there is considerable variation in the tensile strength values of the materials in as-received and annealed conditions. Although the pre-history of the as-received commercial aluminum alloy is not known, but considering the large variations in hardness and tensile strength values it can be inferred that the as-received material is in highly cold worked.

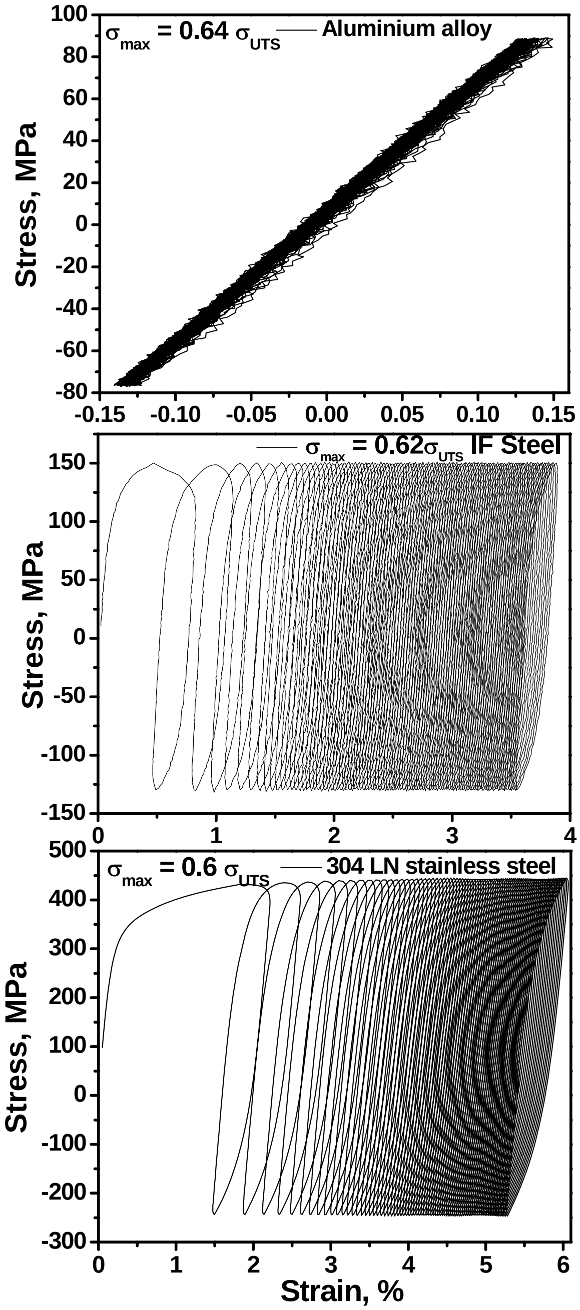

Fig.2: Unclosed hysteresis loops of the investigated materials.

3.2. Uniaxial ratcheting: Nature of hysteresis loops

Typical cyclic stress-strain hysteresis loops generated from the uniaxial ratcheting experiments on the investigated materials under positive mean stress are presented in Fig. 2. It is known that asymmetrical cyclic loading with non-zero mean stress produces unclosed hysteresis loops; this is reflected as shifting of the loops and is accounted by the strain accumulated in a particular cycle. The shifting of the hysteresis loops in terms of accumulated plastic strain towards increased plastic deformation is less pronounced for the aluminium alloy whereas it is significant for IF steel and AISI 304LN stainless steel. From all other employed test conditions, it can be observed that accumulation of ratcheting strain for aluminium alloy in any combination of 'mean stress and stress amplitude' is considerably less, as compared to that for IF steel or for AISI 304LN stainless steel [10,11].

3.3. Accumulation of ratcheting under varying stress amplitudes at constant mean stress

In this section, the ratcheting behaviours of the materials with different crystal structures, i.e. FCC aluminium alloy, BCC IF steel and FCC austenitic stainless steel are examined and discussed. Variations of accumulated ratcheting strain (ε_r) with number of cycles (N) for different combinations of σ_a and σ_m for the investigated materials are illustrated in Fig. 3. Figures 3(a) and (b) indicate the results related to aluminium alloys under as-received and annealed conditions respectively. The results of ε_r *vs.* N for IF steel and AISI 304LN stainless steels are illustrated in Fig. 3(c) and Fig. 3(d) respectively. It can be noted from the results that ε_r monotonically increases with increasing N for any particular combination of σ_a and σ_m for all the investigated materials. Interestingly one can note that the nature of strain accumulation for the as-received and annealed aluminium alloys is different when applied stress amplitude increases at constant σ_m. For as-received samples, the magnitude of ε_r decreases with increasing σ_a, while for annealed samples, ε_r increases with increasing σ_a. However, for both annealed and as-received samples, the total strain accumulation due to ratcheting is considerably low.

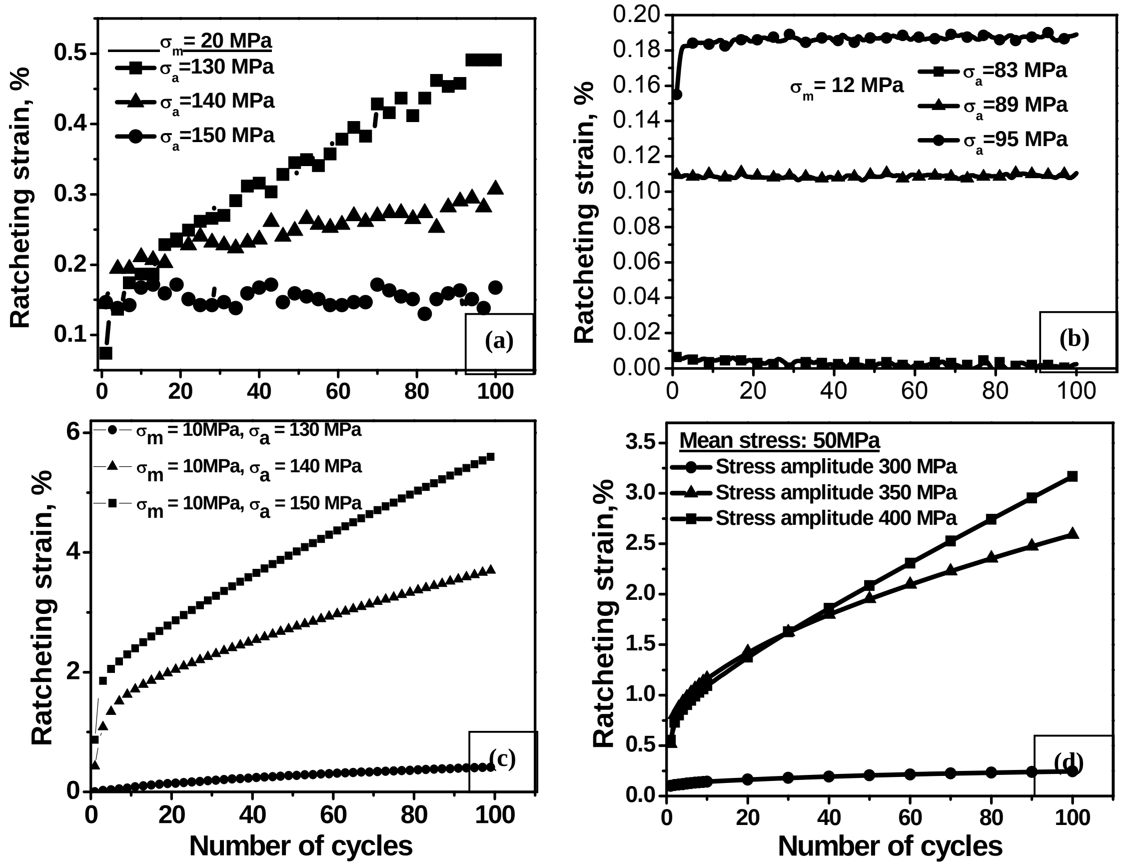

Fig.3: Variation in uniaxial ratcheting strain with number of cycles for (a) As-received aluminium alloy, (b) annealed aluminium alloy, (c) IF Steel and (d) AISI 304LN stainless steel.

The variation in the nature of strain accumulation in as-received and annealed samples can be explained using the pre-history of the materials. It can be considered that the as-received samples are initially strain hardened due to cold working and thus result in high initial dislocation density in their sub-structures. As the magnitude of stress amplitude increases during cyclic loading, the sub-structure of the as-received materials attains stable dislocation configuration in a rapid manner; this leads to lower strain accumulation. On the other hand, the cold-worked state of the as-received material changes during annealing, leading to softening of the material with low dislocation density. When σ_a increases, the dislocation density of the annealed samples starts increasing, and it takes relatively more time to get saturated; thus strain accumulation increases.

It can be observed from Fig. 3 that the ratcheting behaviours of the materials with different crystal structures are entirely different. For both the annealed and as-received samples of the aluminium alloys, the total strain accumulation due to ratcheting is considerably low; only up to a maximum of 0.5% within the employed number of cycles. The strain accumulation for the AISI 304LN stainless steel is about 3.5% whereas for the IF steel the strain accumulation is about 6%. It is known that aluminium is having high stacking fault energy (SFE), whereas austenitic stainless steel and IF steel possess low SFE. The higher value of SFE generates mobile dislocations into the substructure of the material during deformation, and eventually leads to a stable configuration. This stable configuration of substructure does not allow accommodation of further strain to the material.

In order to understand ratcheting behaviour of the selected materials at different combinations of σ_a and σ_m, hysteresis loops generated during each cycle of the asymmetric cyclic loading tests were recorded and analyzed subsequently. Any increase in σ_{max} would induce higher extent of plastic deformation, and as a consequence, strain accumulation is expected to increase with increasing σ_a. This phenomenon can be correlated to the dislocation substructure of the material formed during cyclic loading. Due to asymmetric cyclic loading with positive mean stress, the number of dislocations generated in the loading cycles is reported [10] to be higher than that generated in the unloading cycles; however, only a part of the generated dislocations get annihilated during load reversal. As a result some amount of the generated dislocations would remain as residuals in the substructure of the investigated material. It is well known that higher is the remnant dislocation density in a material, higher is the accumulation of plastic strain and vice versa. Hence, it may be inferred that with increasing σ_a for a particular

σ_m, total strain accumulation will increase because of the increase in the remnant dislocation density. This proposition has been substantiated by some limited experiments using transmission electron microscopy (TEM).

3.4. Substructural and microstructural variations during ratcheting deformation

To understand the substructural variations associated with ratcheting deformation of the investigated materials, the deformed specimens were examined using TEM. Typical TEM bright field images of AISI 304LN stainless steel are illustrated in Fig. 4, which shows increased dislocation density with increasing stress amplitude but at constant mean stress. Gaudin and Feaugas [6] have reported that ratcheting deformation results in the formation and dissolution of dislocation cells during asymmetric cyclic loading. Dislocation cell formation is also evident from the TEM results of the present investigation for the aluminium alloy as well as for the stainless steel. A typical TEM image is shown in Fig. 5, indicating formation of dislocation cells during ratcheting deformation.

It is well known that austenitic stainless steel show phase transformation from fcc austenite to metastable ε-martensite and eventually to α′-martensite upon deformation [12]. Similar feature is also evident during ratcheting deformation of the investigated AISI 304LN stainless steel, which is confirmed by selected area diffraction pattern analysis of TEM as well as by x-ray diffraction analyses.

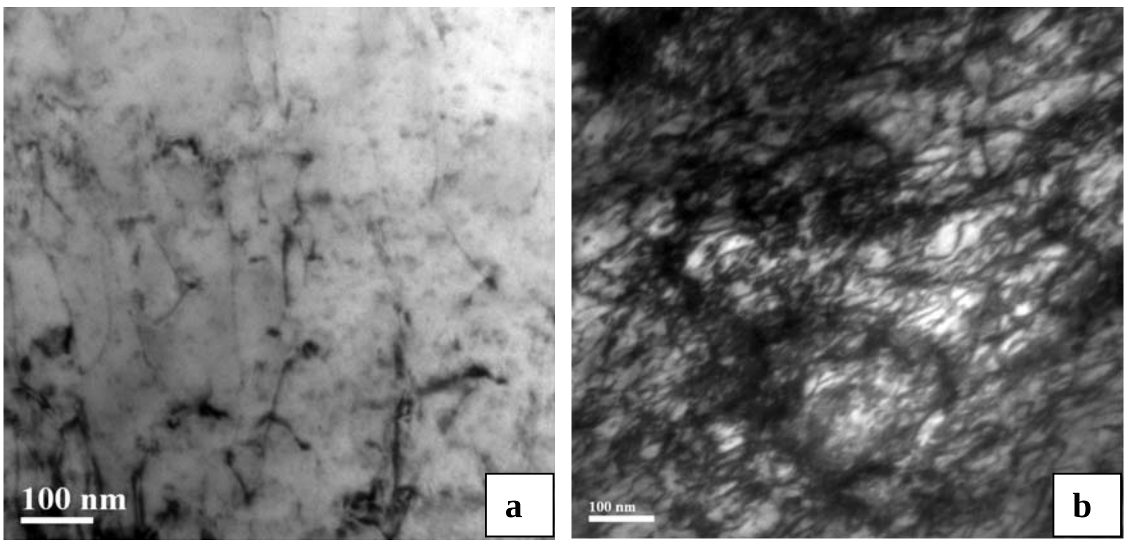

Fig. 4: Typical TEM bright field images of the ratcheting deformed samples with a loading condition of $\sigma_a = 350$ MPa and (a) $\sigma_m = 50$ MPa, (b) $\sigma_m = 150$ MPa.

3.5. Saturation of ratcheting strain

Typical variations in the rate of ratcheting strain ($\dot{\varepsilon}_r = d\varepsilon_r/dN$) with increasing number of cycles for IF steel is presented in Fig. 5. The results indicate that $\dot{\varepsilon}_r$ decreases with increasing number of cycles. Similar phenomenon has been observed for all the ratcheting experiments irrespective of the employed combinations of σ_m and σ_a. The decrease in $\dot{\varepsilon}_r$ is rapid up to about 10 to 40 cycles, after which the change in the magnitude of $\dot{\varepsilon}_r$ is insignificant.
The attainment of steady state in $\dot{\varepsilon}_r$ can be explained by the formation and distribution of dislocations associated with cyclic deformation. When a material is subjected to cyclic deformation, dislocations get generated resulting strain hardening. These dislocations initially form tangles and subsequently lead to the formation of

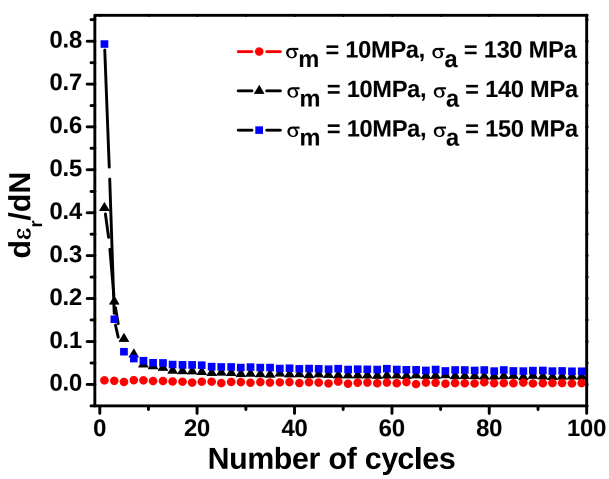

Fig.5: Typical variation in rate of ratcheting strain for IF steel.

dislocation cells with increasing number of cycles [10]. After certain number of cycling, depending on the magnitude of the imposed cyclic strain, the newly generated dislocations assume a relatively stable configuration and this leads to initiation of the steady state in $\dot{\varepsilon}_r$.

4. Conclusions

The obtained results and their pertinent analyses related to examination of ratcheting behaviour of materials with varying crystal structure at room temperature assist to infer:

- Higher the magnitude of stress amplitude (σ_a) at any constant mean stress (σ_m), higher is the accumulation of ratcheting strain (ε_r), in all the investigated materials except for the as-received aluminium alloys where accumulation of ratcheting strain decreases with increasing σ_a at any constant σ_m The observed increase in strain accumulation can be correlated with increased cyclic damage as well as increased dislocation density in the ratcheted samples.

- Accumulation of ratcheting strain is considerably low in the aluminium alloy, as compared to IF steel or AISI 304LN stainless steel; this behaviour is attributed to the stacking fault energy of the investigated materials. Aluminium is having high stacking fault energy, and hence has higher tendency to produce well defined dislocation substructure, which in turn induces lower amount of ratcheting strain.

- X-ray diffraction studies indicate that deformation induced martensite (DIM) forms during asymmetric cyclic loading of AISI 304LN stainless steel and the amount of the DIM increases with increasing ratcheting strain. Martensitic transformation provides additional dislocations in the cyclically deformed samples.

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