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Effect of crystallographic texture on the planar anisotropy of ratcheting response in 316 stainless steel sheet

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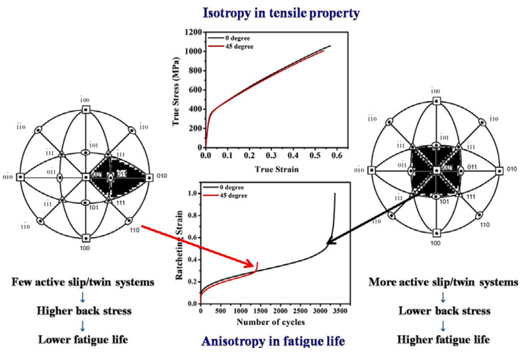
HIGHLIGHTS

- Anisotropy in ratcheting response is more pronounced than tensile property in SS 316.
- Rate of transition from planar to wavy slip controls cyclic creep rate.
- Multiple slip and twinning aids back stress relaxation during cyclic deformation.
- Lower the back stress higher is the fatigue life.

GRAPHICAL ABSTRACT



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ABSTRACT

The effect of crystallographic texture on planar anisotropy in tension and low cycle fatigue was investigated for samples machined along 0, 45 and 90° angle with respect to the rolling direction of hot rolled and annealed 316 stainless steel sheet using electron backscatter diffraction. The tensile behavior of the three different orientations showed little anisotropy. However, the fatigue life of samples obtained along rolling (0°) and transverse direction (90°) were similar while the sample along 45° to rolling direction showed higher cyclic creep rate (ratcheting) and minimum fatigue life at different stress cycling parameters in stress control mode. The anisotropic ratcheting behavior in SS 316 can be attributed to operation of higher slip systems in the rolling and transverse samples with ⟨100⟩ texture while ⟨101⟩ texture along 45° sample with restricted slip. This contributes to higher backstress and lower fatigue life in the latter. Also, deformation twinning that dominates in 0 and 90° sample in tension provides relaxation of backstress during cyclic loading by detwinning which further contributes to higher fatigue life compared to 45° sample.

1. Introduction

Anisotropy in mechanical properties is an inherent characteristic of metallic materials and has been studied extensively in monotonic loading [1]. In a polycrystalline material, anisotropy in plastic deformation behavior arises due to preferential orientation of grains or crystallographic texture that controls the mechanical response of the sample in monotonic loading. This gets manifested in terms of different Youngs modulus, yield strength, ultimate tensile strength and ductility values for samples obtained along different directions with respect to a fixed direction, say the rolling direction, for a rolled sheet of polycrystalline material. A thorough understanding of effect of texture in terms of anisotropic in-plane tensile properties for rolled sheets is established but

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that in cyclic loading is still unexplored. Single crystals represent the extreme case of anisotropy and their monotonic behavior has been well documented for different face centre cubic (fcc) materials. However, cyclic deformation behavior of fcc single crystals is not extensively investigated. Li et al. [2] studied cyclic deformation behavior of fcc single crystals of different orientations as a function of stacking fault energy (SFE). They showed that there is an evolution of distinct dislocation substructure for different orientations of fcc single crystal irrespective of the SFE, which can be explained on the basis of operation of different octahedral slip systems (primary, cross, conjugate and critical) for a given orientation. This leads to cooperative phenomenon for dislocation populations and there is competition between their mobility and non-linear interaction like creation, annihilation and pinning that contributes to formation of distinct inhomogeneous spatial patterns of dislocations. It was observed that strain controlled low cycle fatigue of ⟨100⟩ fcc single crystal led to the formation of labyrinth (two dimensional wall) substructure while veins (one dimensional) and cell walls (three dimensional) were observed in ⟨111⟩ single crystal. The ⟨101⟩ single crystal that has limited number of slip systems (four) compared to ⟨100⟩ and ⟨111⟩ orientation (eight and six respectively) showed a substructure comprising of persistent slip bands. Similar dislocation substructures are also observed in stress controlled tests with the cell structure dominating the microstructure due to higher value of accumulated plastic strain in the deformed samples. The dislocation substructure formed under strain and stress control mode affects the cyclic hardening/softening response of the crystal [3]. For a polycrystalline material, similar dislocation structures are observed in individual grains depending on their orientation while maintaining strain compatibility criteria with neighbouring grains. Therefore, it can be expected that crystallographic texture can affect the evolution of substructure thereby controlling the low cycle fatigue life in stress and strain control mode for polycrystalline samples.

The stress controlled cyclic deformation can be asymmetrically proportional and non-proportional. Fatigue failure under asymmetric cyclic loading in the elastic-plastic regime is of great concern for load bearing material in service. The presence of unannihilated remnant dislocations generated due to asymmetric cyclic load leads to accumulation of plastic strain (known as ratcheting strain) in the direction of mean stress in each cycle. The fatigue failure occurs when the remnant dislocation density is same as that in tensile sample at the ultimate tensile strength.

Ratcheting behavior of industrially relevant interstitial free (IF) steel [4], 20MnMoNi55 steel [5], SA333 [6,7], 42CrMo steel [7,8] and austenitic stainless steels like SS304 [9–11] and SS316 [12–15] have been extensively studied in the recent past. In addition to the aforementioned ferrous alloys, non-ferrous metals and alloys [16,17] have also been investigated. The interaction of fatigue and ratcheting has been discussed by Varvani et al. [18,19] for uniaxial and multi-axial loading conditions. These studies are based on the effect of stress cycle parameters (mean stress and stress amplitude) on ratcheting response of materials. The general ratcheting response is characterized by a decrease in fatigue life with increase in stress amplitude or mean stress. It has been found that effect of stress amplitude is more pronounced than mean stress on fatigue life. Ratcheting strain and ratcheting strain rate have been found to be a function of mean stress and depend on cyclic hardening/cyclic softening behavior of the material [8,20]. It is proposed that the amount of backstress increases with increase in mean stress leading to increase in the cyclic yield stress that alters the ratcheting strain accumulated in the material and consequently the fatigue life [21]. Ratcheting life has been found to increase with decrease in stress amplitude and mean stress in most of the above mentioned alloys except for SS 304 steel. This anomalous behavior of SS 304 which shows increase in ratcheting life with increase in mean stress beyond a certain value was attributed to the increase in remnant dislocation density, formation of deformation induced martensite and larger dislocation cell size in the substructure that enabled accumulation of more strain at higher mean stress [22].

Nevertheless very few investigations have been carried out on anisotropy in fatigue behavior of materials with the exception of few results on spring steel [23] and forged steel [24]. The anisotropy in fatigue strength in these materials has been attributed to the morphology and orientation of oxides and sulphide inclusions with respect to the loading direction. A recent study carried out by Paul [25] has shown the anisotropy in ratcheting behavior of body centre cubic IF steel deforming by pencil glide. The effect of twinning which plays significant role in deformation of low stacking fault energy fcc material and its influence on anisotropic behavior in ratcheting has not been studied yet. Thus, the study of ratcheting response and the underlying micromechanisms as a function of orientation is required in low stacking fault energy fcc material like stainless steel [26] where octahedral slip and twinning play a dominant role during plastic deformation. Moreover, this investigation will form the basis to modify the mathematical formulations provided by previous researchers [7,27] for estimation of ratcheting life in future.

Stainless steel (SS) 316 has been chosen for present investigation which is an established material for nuclear pressure vessels, steam turbines and various power machineries and is often exposed to asymmetrically proportional loading during service. In the present investigation, three different combinations of stress amplitude and mean stress have been applied on three different (0, 45 & 90°) orientation of the loading axes with respect to rolling direction. The micro-mechanisms of ratcheting behavior in differently oriented SS 316 samples will be established from the analysis of microstructure and micro-texture using electron backscatter diffraction (EBSD) technique.

2. Experimental

Hot rolled and annealed 200 mm × 200 mm × 3 mm sheet of SS 316 steel were used to investigate the effect of in-plane anisotropy in the present investigation. Flat specimens of dimension following ASTM Standard E606 were machined from the sheet in such a way that the loading axes of the specimens were making an angle of 0, 45 and 90° to the rolling direction. Fig. 1a and b show schematic of different orientations and specimen dimensions respectively.

All the experiments were conducted on the above specimens at room temperature using BiSS Nano Plug 'n' Play servo-hydraulic universal test machine of 25KN capacity. Tensile tests were carried out on the above specimens at constant strain rate of $5 \times 10^{-2}\ s^{-1}$ to obtain mechanical properties of the material. Engineering stress controlled uniaxial asymmetrical stress cycling was imposed on the specimens. The test parameters were selected based on the work carried out by Kang et al. [12]. Different combination of stress amplitude/yield stress (σ_a/σ_y) and mean stress/yield stress (σ_m/σ_y) ratio are given in Table 1. A sinusoidal waveform was used to perform the tests and the cyclic frequency was kept at 0.5 Hz for all the tests. Tests were continued till failure and stress–strain data acquired throughout the test to obtain 200 data points per stress cycle. Tests were conducted under software control running on a computer interfaced to the control system of the testing machine. The as-received material was sectioned at mid-thickness and polished before subjecting it to bulk texture measurement. Bulk texture

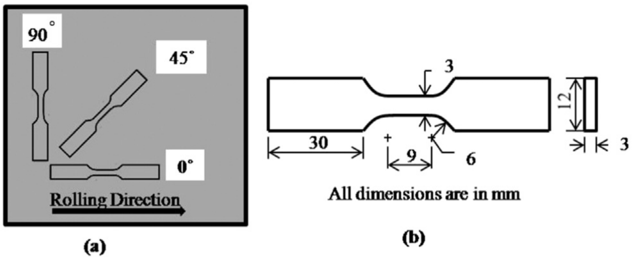

Fig. 1. (a) Schematic of different specimen orientations (b) E-606 standard specimen dimension.