Effect of pre-strain on ratcheting behavior of A668 Class D steel

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Abstract. The aim of this investigation is to study the effect pre-strain (0%, 2%, 4% and 8%) on ratcheting behavior of ASTM A668 Class D steel in different heat treatment conditions (normalized and hardened-tempered). Ratcheting tests were carried out at room temperature on cylindrical specimens having 12.5 mm gauge length and 6 mm gauge diameter. The results include reduced strain accumulation with increasing pre-strain level due to work hardening of the pre-strained samples. Further, cyclic hardening takes place during ratcheting deformation.

1. Introduction

ASTM A668 class D steel is a kind of plain carbon steel which is potentially being used in various engineering sectors that include aerospace, automotive and defense applications. In all these kinds of applications, the much needed property requirement is good fatigue and fracture behavior of the material. It is known that almost 90% of all service failures are due to fatigue [1] and hence it is indeed important to know the fatigue behavior of a material before being considered for any application. Traditionally, strain-controlled low cycle or stress-controlled high cycle fatigue studies are being performed to assess the fatigue behavior of a material, but in recent days, considerable attention is being paid by investigators towards generating information regarding the stress-controlled low cycle fatigue behavior of a material; the phenomenon is known as ratcheting. Ratcheting deformation is pronounced when the studies are done in presence of some positive or negative mean stress. Accumulation of ratcheting strain during cyclic loading reduces low cycle fatigue life of a material. Therefore it is one of the important factors that should be considered in the design of any structural component [2]. Further, it is known that application of pre-strain causes variations in the mechanical properties of a material. In last few years, effects of mean stress, stress amplitude etc. on ratcheting behavior of a material were being reported [3-6], however, not much reports are existing considering the effect of pre-strain on ratcheting behavior of metallic materials. This investigation aims to fulfill this gap.
2. Experimental details
The material selected for this investigation is class D steel, of ASTM standard A668 which was subjected to two types of heat treatments viz. normalizing and quenching followed by tempering at 600°C. For initial characterization of the material, microstructural analyses, hardness and tensile tests were done.

Tensile and fatigue test specimens were fabricated as per ASTM standards E8M [7] and E-606 [8] respectively. Ratcheting tests were done at a constant stress rate of 50 MPa/s on specimens subjected to varying pre-strain levels of 2%, 4% and 8% (strained at a nominal strain rate of 0.001 s⁻¹) for both, normalized and hardened-tempered conditions. In both the cases, the maximum stress values for cyclic loading were chosen as 50% of the ultimate tensile strength value. The nature of strain accumulation was examined for specimens without pre-strain also, which is designated as 0% pre-strain level in this paper.

3. Results and discussion

3.1 Microstructure, hardness and tensile properties
The optical microstructures of the investigated material under normalized and hardened-tempered conditions are shown in figure 1. Figure 1(a) shows the microstructure in normalized condition which clearly shows ferrite and pearlite phases whereas figure 1(b) illustrates the microstructure of the hardened-tempered steel showing tempered martensite. This also contains some amount of precipitates.

![Optical microstructures of (a) normalized (b) hardened-tempered steel](image)

The results of hardness tests indicate that the average hardness of normalized steel was 230 VHN while that for the hardened-tempered steel was 274 VHN. Figures 2(a) and (b) show the engineering stress-strain curves of the steel in normalized and hardened-tempered condition respectively. Results of tensile tests are summarized in Table 1. In both the cases it was observed that there are no sharp yield points; thus yield strength values were determined by the stress corresponding to the intersection of the stress-strain curve and an offset line parallel to the elastic portion of the curves at a strain of 0.2%.

3.2 Effect of pre-strain on ratcheting behavior in normalized steel
The results of ratcheting tests conducted on normalized samples up to 100 cycles under various pre-strain conditions (0%, 2%, 4% and 8%) are shown in figure 3(a) and typical nature of obtained hysteresis loops (for 0% pre-strain condition) are shown in figure 3(b). It can be noted from figure 3(a) that accumulation of ratcheting strain decreases with increasing the level of pre-strain, and it is maximum when there is no
Figure 2. Engineering stress-strain curves for (a) normalized and (b) hardened-tempered steel.

Table 1. Tensile properties of ASTM A668 Class D steel in normalised and hardened-tempered conditions

| Property                        | Normalized | Hardened-Tempered |
|---------------------------------|------------|--------------------|
| Yield strength (MPa)            | 355        | 592                |
| Ultimate tensile strength (MPa) | 530        | 655                |
| Uniform elongation              | 0.29       | 0.10               |
| Total elongation                | 0.77       | 0.71               |
| Strain hardening exponent (n)   | 0.32       | 0.11               |

pre-strain (0%, as indicated in the figure). It is noted that the strain accumulation can vary from 0.21% to 0.44% with decreasing pre-strain. Wang et al. [9] reported that if the level of pre-strain is increased, dislocation gets piled up and as a result back stress is generated. The back stress generated during pre-straining causes hindrance to accumulate strain during subsequent ratcheting deformation. The extent of back stress increases with the level of pre-strain and accordingly accumulation of ratcheting strain gets reduced during a test done with positive mean stress. The decrease of ratcheting strain with increase in pre-strain is in accordance with the results reported by Wang et al. [9] and De et al. [10].

Figure 3. (a) Effect of pre-strain on ratcheting behavior and (b) hysteresis loops produced during ratcheting (for 0% pre-strain condition) in normalized steel.
A set of hysteresis loops are illustrated in figure 3.3 (b) which were produced from a ratcheting test conducted without any pre-strain. One can note that the loops shift from its initial position towards right. This fact indicates that a considerable amount of plastic strain gets accumulated during each cycle. When the loop area was calculated individually, it was seen that loop area decreases with increase in number of cycles. This indicates that the selected material shows cyclic hardening behavior.

3.3 Effect of pre-strain on ratcheting behavior in hardened-tempered steel

It is understood that the microstructure of a material can alter its deformation behavior and thus the nature of strain accumulation due to ratcheting must be dependent on the microstructural constituents. One of the major applications of the steel is in hardened-tempered condition for making hydro turbines, where ratcheting deformation should be a major concern. Therefore, a set of steel samples were hardened-tempered and tested for the effect of pre-strain on strain accumulation due to ratcheting up to 100 cycles. The nature of strain accumulation and a set of hysteresis loops (0% pre-strain) are shown in figure 4 (a) and (b), respectively. Here also, the strain accumulation reduces with increasing the level of pre-strain. It may be inferred that with pre-strain, the strength of a material increases due to work hardening and thus the material accumulates lower amount of ratcheting strain.

![Figure 4](image.png)

**Figure 4.** (a) Effect of pre-strain on ratcheting behavior and (b) hysteresis loop produced during ratcheting in hardened-tempered steel.

Although considerable amount of strain accumulation takes place both in normalized and hardened-tempered conditions, severity of ratcheting was on normalized samples; in association to this, pre-strain can cause seizing of strain accumulation.

4. Conclusions

The ratcheting behavior of ASTM A668 class D steel has been investigated in this study in two different heat treatment conditions along with varying levels of pre-strain. The conducted experiments and their pertinent analyses lead to the following conclusions:

1. Accumulation of ratcheting strain decreases with increase in the level of pre-strain and it is maximum when there is no pre-strain (i.e. at 0% pre-strain), both in normalized and hardened-tempered samples of ASTM class D A668 steel. The decrease in strain accumulation with increasing pre-strain can be explained with formation of dislocations during cyclic loading. The
nature of strain accumulation is similar in normalized and hardened-tempered samples; however, the extent is more in normalized samples.

2. The area under the stress-strain hysteresis loops decrease continuously which indicates that the steel is cyclically hardenable in nature.

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