Stress Ratio Effect on Ratcheting Behavior of AISI 4340 Steel

K Divya Bharathi* and K Dutta
Department of Metallurgical and Materials Engineering, National Institute of Technology, Rourkela-769008, India
*E-mail: k.divya.212@gmail.com

Abstract. Ratcheting is known as accumulation of plastic strain during asymmetric cyclic loading of metallic materials under non-zero mean stress. This phenomenon reduces fatigue life of engineering materials and thus limits the life prediction capacity of Coffin-Manson relationship. This study intends to investigate the ratcheting behavior in AISI 4340 steel which is mainly used for designing of railway wheel sets, axles, shafts, aircraft components and other machinery parts. The effect of stress ratio on the ratcheting behaviour in both annealed and normalised conditions were investigated for investigated steel. Ratcheting tests were done at different stress ratios of -0.4, -0.6 and -0.8. The results showed that the material responds to hardening behavior and nature of strain accumulation is dependent on the magnitude of stress ratio. The post ratcheted samples showed increase in tensile strength and hardness which increases with increasing stress ratio and these variations in tensile properties are correlated with the induced cyclic hardening.

1. Introduction

Ratcheting is a secondary phenomenon of cyclic plasticity that can accelerate fatigue damage or even act as the failure mechanism itself [1]. It occurs during asymmetric cyclic loading, in presence of positive or negative mean stress and thus plastic strain gets accumulated during each cycle in the direction of the applied mean stress. Accumulation of ratcheting strain can substantially reduce the fatigue life of a component [2-7]. In practice, machine components can come across both ratcheting and fatigue simultaneously and therefore failure of a component can occur due to fatigue, ratcheting or due to combination of both the effects. So it will be a-priori to understand effect of ratcheting of a material before designing for a particular application to define its proper fatigue life and to avoid catastrophic failure.

AISI 4340 steel is a kind of medium carbon steel which is traditionally used in aerospace applications (e.g. crank shafts and landing gears) and in automotive industries (e.g. connecting rods and axles); the steel is known to be normalising heat treatment before being designed to any component [8]. One cannot rule out the presence of ratcheting deformation during applications of such machine components. Generally, in mechanical design, loading condition is usually presented by maximum stress and stress ratio, responding to the maximum load and cyclic features respectively. Therefore the maximum stress and stress ratio are chosen as control parameters to describe the stress features. Currently, only few reports exist on stress ratio effect and almost negligible amount of reports exist that focus ratcheting and fatigue interaction of such steel [9-10]. Hence it is of utmost importance to investigate the ratcheting behavior at different stress ratios of such steel.

Therefore, in the present work, effect of stress ratio on ratcheting behavior of AISI 4340 steel with different heat treated (annealed and normalised) conditions has been studied. Post ratcheting tensile and hardness tests also carried out to correlate the properties with ratcheting effect on investigated steel.
2. Experimental details

2.1 Material selection and specimen specification
The sample selected for the current investigation was a medium carbon steel designated as AISI 4340. The steel was available in the form of rods of 18 mm diameter. The chemical composition of the selected material was assessed using optical emission spectrometer as in wt%: C-0.35, Ni-1.52, Cr-1.44, Mo-0.18, Mn-0.69, Si-0.31, S-0.02, P-0.03 and balance Fe. The as-received steel rods were subjected to stress relief annealing and normalising at a temperature of 750°C and 870°C respectively with soaking time of 2 h. Specimens with approximate height of 10 mm with cross section were cut from the annealed materials for microstructural characterizations and determination of hardness. The microstructural constituents of the investigated steel have been examined using an optical microscope (Carl Zeiss, model no.: 332700403, Germany) connected to an image analyzer (Software: Axio vision release 4.8 S.P 3) and a series of representative photographs have been recorded. The microstructure of the investigated steel exhibited larger grains for annealed samples and smaller grains for normalized ones. Using Vickers hardness tester (LECO LV400, US), the hardness has been measured at a load of 20kgf with dwelling time of 15s. Tensile and fatigue test specimens have been fabricated as per ASTM standards E8M [11] and E-606 [12] respectively from heat treated rods.

2.2 Ratcheting test
Ratcheting tests were carried out at room temperature at a constant stress rate of 50MPa/s and stress ratios of -0.4, -0.6 and -0.8. The maximum stress selected as 80% of ultimate tensile strength i.e., 800 MPa and 1300 MPa for annealed and normalised specimens respectively. All these details are listed in Table 1.

Table 1: Text matrix for ratcheting tests at varying stress ratios

| S. No. | Stress ratio (R) | Annealed | Normalised |
|--------|-----------------|----------|------------|
|        |                 | σa (MPa) | σm (MPa)  | σa (MPa) | σm (MPa) |
| 1      | -0.4            | 560      | 240        | 910      | 390      |
| 2      | -0.6            | 640      | 160        | 1040     | 260      |
| 3      | -0.8            | 720      | 80         | 1170     | 130      |

During each test, the load extension as well as the actuator displacement data has been continuously recorded by using the attached software to the computer. It was aimed to acquire at least 250 data points per cycle during test. All fatigue tests have been done up to 100 cycles and then post ratcheting tensile test were done for further analysis on these samples. Post ratcheting tensile test has been done for ratcheted specimens and post ratcheting hardness tests were done by cutting the transverse sections of the gauge portion of the ratcheted samples with approximate height of 10 mm, after cutting the portion containing the fracture surface.

3. Results and discussion

3.1 Study of mechanical properties
A comparison of the hardness values of annealed and normalised samples indicates that average hardness of the normalised samples was 321 VHN which was higher as compared to the annealed samples with average hardness of 228 VHN. The normalised samples are being subjected to faster cooling rate showed increase in its hardness value. These results are in accordance with a few published reports [8], hence it can be stated that the heat treatment of investigated steel was proper.

3.2 Tensile test
Typical engineering stress-strain diagrams for the investigated steel for annealed and normalised specimens are illustrated in Figure 1(a) and (b). Both annealed and normalised specimens showed
continuous yielding behavior from elastic to plastic region and hence their yield strength is estimated by 0.2% strain oﬀ-set procedure, as suggested in ASTM standard E8M [11]. The tensile properties of the annealed and normalised samples are given in Table 2. All the values which are tabulated were almost near to standard values of this particular selected steel as mentioned in ASM hand book [8]. Hence it can be stated that the heat treatment and specimen design of investigated steel were proper. The main focus to perform this test is that to calculate stress amplitude and mean stress from the ultimate tensile stress which were used in fatigue test and to compare the properties with standard values of this steel.

Estimating the stress values from the above stress strain plots for annealed and normalised specimens and comparing the results, the yield strength and ultimate tensile strength of the annealed specimen were found to be 616 MPa and 906 MPa which are less as compared to the normalised specimen which were 1300 MPa and 1467 MPa respectively. This shows that the normalised specimen has more strength compared to annealed specimen because of finer grain size induced due to air cooling as expected. The uniform elongation ($\varepsilon_u$) of annealed specimen found as 8.86% and for normalised specimen was 4.62%. The total elongation ($\varepsilon_t$) of annealed specimen and normalised specimen was 16.11% and 11.94% respectively. From this it can be concluded that the normalised specimen being stronger and less ductile and less elongation showed as compared to annealed specimen.

The strain hardening exponent ($n$) of the AISI 4340 steel was estimated by calculating the true stress ($\sigma$) and true strain ($\varepsilon$) values from the engineering stress and engineering strain respectively. The log(true stress) vs. log (true strain) plots in the strain range of 1.68 to 4.13 for annealed, 1.11 to 2.88 for normalised samples result into straight lines as shown in Figure 2(b). The strain hardening exponent values were calculated by using Hollomon equation $\sigma = K\varepsilon^n$, where $K$ is strength coefficient. The values of $n$ are summarized in the Table 2.

![Figure 1](image_url): (a) Engineering stress strain curve (b) comparison of the log ($\sigma$) – log ($\varepsilon$) plots for annealed and normalised samples of AISI 4340 steel.

| Strength                        | Annealed | Normalised |
|---------------------------------|----------|------------|
| Yield Strength (MPa)            | 616      | 1300       |
| Ultimate tensile strength (MPa) | 906      | 1467       |
| Strain Hardening Exponent (n)   | 0.18     | 0.10       |
| Uniform elongation ($\varepsilon_u$) % | 8.86    | 4.62       |
| Total elongation ($\varepsilon_t$) % | 16.11   | 11.94      |
3.3 Ratcheting by varying stress ratio

The results of cyclic tests conducted up to 100 cycles under various stress ratios in annealed and normalised conditions are presented and discussed in this section. Figure 2 (a) and (b) show the hysteresis loops of first, 50\textsuperscript{th} and 100\textsuperscript{th} cycles at stress ratio of R = -0.4 for both annealed and normalised specimens respectively. During stress controlled fatigue, the accompanying variation in strain range with progression of cycles is due to the change in hardening or softening response of the material.

Kang et al. [14] explained that the ratcheting strain increases gradually and stress–strain hysteresis loops become wider, if there is cyclic softening feature of the material. As one can visualize that, if the hysteresis loop area increases, a material shows cyclic softening behavior and if the hysteresis loop area decreases there exists cyclic hardening [15-18]. This hardening/softening feature of materials depends greatly on the different heat treatments experienced [15]. From Figure 2, it is clear that hysteresis loops shift towards more strain direction during ratcheting deformation, which in turn induces plastic strain to the material. Strain accumulation is calculated by taking the average of minimum and maximum strain in particular cycle. The loop area decreased from first cycle to last cycle i.e., the strain accumulation is decreased from first cycle to last cycle. This indicates clearly that the selected material shows cyclic hardening behavior.

Yoshida et al. [18] reported that the strain accumulation for R = -0.4 is slightly larger than the R = 0.8, 0.0, -0.8 and -1.0. But the difference in the magnitude of strain accumulation is not so large between stress ratios of others. Kang et al. [14] explained that the most significant ratcheting occurs at the stress ratio of 0.889, even if the increasing stress ratio also results in a weaker ratcheting behavior in 42CrMo steel. Figure 3 (a) and (b) depict the variations in ratcheting strain with number of cycles at different stress ratios in both annealed and normalised conditions. As the stress ratio increases ratcheting strain also increases in both annealed and normalised samples and the magnitude of strain accumulation in ratcheting of R = -0.4 is slightly higher than that in case of R= -0.6 and -0.8. Larger strain accumulation at a given number of stress cycles is found at stress rate of R = -0.4. All these details summarized in Table 3. These features are partially similar to those obtained by Yoshida et al. [18], for SUS304 stainless steel but totally different from 42CrMo steel [14]. This fact causes increased amount of dislocation generation when stress ratio is increased to higher level. The increase in strain accumulation with increasing stress ratio can be described as a consequence of increasing dislocation density, at higher stress ratio levels.

![Figure 2: Typical hysteresis loops generated during ratcheting tests at R= -0.4 for (a) annealed (b) normalised specimens](image)
Xia et al. [20] observed that the rate of accumulation of ratcheting strain, i.e., the increment of ratcheting strain in each cycle decreases gradually with the number of cycles due to its cyclic hardening feature in ASTM A-516 Gr.70 steel. Chen et al. [21] observed that the ratcheting strain increases in high-nitrogen steel X13CrMnMoN18-14-3 whereas its rate decreases continuously with increasing number of cycles. Dutta et al. [22] observed that rapid accumulation of ratcheting strain in the initial few cycles followed by attainment of a steady state value in ratcheting rate are the characteristic features of the asymmetric cyclic deformation behavior of IF steel. All these studies indicate that strain accumulation takes a saturation plateau after few cycles of loading. In this study also, the nature of attainment of steady state has been examined. Figure 4 (a) and (b) depict the variations in ratcheting strain rate effect with number of cycles at different stress ratios in both annealed and normalised conditions respectively. From Figure 4, it can be seen that the rate of strain accumulation decreases continuously up to initial few cycles after that it reaches saturation level in both annealed and normalised conditions. It can also be stated that there is no much variation in ratcheting strain rate at different stress ratios. One can note that the saturation level for annealed steel is about 30 cycles while that for normalized steel is about 15 cycles.

| S. No. | Stress ratio (R) | Ratcheting strain% |
|--------|----------------|--------------------|
|        |                | Annealed | Normalised |
| 1      | -0.4           | 1.16     | 1.0        |
| 2      | -0.6           | 0.62     | 0.94       |
| 3      | -0.8           | 0.40     | 0.81       |

![Table 3: Ratcheting strain variation with respect to stress ratio](image)

**Figure 3:** Effect of stress ratio on ratcheting strain at R= -0.4, -0.6 and -0.8 in (a) annealed (b) normalised specimens

Xia et al. [20] observed that the rate of accumulation of ratcheting strain i.e., the increment of ratcheting strain in each cycle decreases gradually with the number of cycles due to its cyclic hardening feature in ASTM A-516 Gr.70 steel. Chen et al. [21] observed that the ratcheting strain increases in high-nitrogen steel X13CrMnMoN18-14-3 whereas its rate decreases continuously with increasing number of cycles. Dutta et al. [22] observed that rapid accumulation of ratcheting strain in the initial few cycles followed by attainment of a steady state value in ratcheting rate are the characteristic features of the asymmetric cyclic deformation behavior of IF steel. All these studies indicate that strain accumulation takes a saturation plateau after few cycles of loading. In this study also, the nature of attainment of steady state has been examined. Figure 4 (a) and (b) depict the variations in ratcheting strain rate effect with number of cycles at different stress ratios in both annealed and normalised conditions respectively. From Figure 4, it can be seen that the rate of strain accumulation decreases continuously up to initial few cycles after that it reaches saturation level in both annealed and normalised conditions. It can also be stated that there is no much variation in ratcheting strain rate at different stress ratios. One can note that the saturation level for annealed steel is about 30 cycles while that for normalized steel is about 15 cycles.

![Figure 4: Variation in the rate of accumulation of ratcheting strain with increasing number of cycles for (a) annealed (b) normalised AISI 4340 steel at different stress ratio.](image)
3.4 Post ratcheting tensile

To understand the effect of previous strain accumulation on tensile properties of ratcheted specimens; tensile tests were carried out on a series of specimens after 100 cycles of ratcheting, subjected to varying stress ratio conditions. Mahato et al. [23] observed that post ratcheting yield and ultimate tensile strength of copper increased as compared to unratcheted samples and these are decreased with decreasing stress ratio. Dutta et al. [19, 22] reported that both yield strength and ultimate tensile strength of IF steel and Aluminum alloy increase as compared to unratcheted values. Figure 5 (a) and (b) show the post ratcheting tensile plots for both the heat treated conditions. All the details related to these tests are summarized in Table 4. The results clearly showed that yield strength and ultimate tensile strength increased as also shown in Figure 5. Further, the results indicate that the strength values are higher at stress ratio \( R = -0.4 \) than at \( R = -0.6 \) and \( -0.8 \) in both annealed and normalized samples. The strain hardening exponent values for post ratcheted tensile samples increased compared to unratcheted one in both annealed and normalised conditions. This fact indicates that the strength of the ratcheted steel is governed by increased strain hardening [22]. From the results it can be concluded that post ratcheting yield strength and ultimate tensile strength of selected steel increased as compared to unratched samples and these are decreased with decreasing stress ratio.

![Fig.5: Post ratcheting tensile stress-strain plots for (a) annealed and (b) normalised samples of investigated steel.](image)

| Properties | Stress ratio | Yield strength (MPa) | Ultimate tensile strength (MPa) | Strain hardening exponent (n) |
|------------|--------------|----------------------|-------------------------------|-----------------------------|
| Annealed   | Unratcheted  | 616                  | 906                           | 0.18                        |
|            | -0.4         | 854                  | 1019                          | 0.18                        |
|            | -0.6         | 833                  | 978                           | 0.17                        |
|            | -0.8         | 769                  | 916                           | 0.15                        |
| Normalised | Unratcheted  | 1300                 | 1467                          | 0.10                        |
|            | -0.4         | 1380                 | 1895                          | 0.10                        |
|            | -0.6         | 1621                 | 1737                          | 0.11                        |
|            | -0.8         | 1504                 | 1675                          | 0.13                        |
3.5 Post ratcheting hardness
To assess the extent of deformation during cyclic loading, post-ratcheting hardness tests were also carried out on ratcheted samples. In order to this, Vickers hardness tests were done on a series of specimens after post ratcheting tensile, subjected to varying stress ratio conditions and the results were

Table 5. Post ratcheting hardness values for annealed and normalised samples at different stress ratios

| Stress ratio | Annealed HV | Normalised HV | Average         | Average         |
|--------------|-------------|---------------|-----------------|-----------------|
|              | HV<sub>20</sub> | Average | HV<sub>20</sub> | Average |
| Unratcheted  | 229         | 226         | 228             | 323             |
|              | 329         | 330         | 333             | 321             |
| -0.4         | 329         | 330         | 333             | 462             |
| -0.6         | 301         | 304         | 302             | 447             |
| -0.8         | 252         | 253         | 255             | 427             |

listed in Table 5. It can be noticed that hardness values of the investigated steel specimens increased after ratcheting deformation. Bhattacharyya et al. [24], in their rolling cycle fatigue experiments, have reported hardness increase can be a result of cyclic hardening, which takes place due to continuous plastic strain accumulation (via ratcheting). Hence in this investigation also increase in hardness can be considered as due to effect of strain hardening due to deformation. It is clear from the table that hardness varies with stress ratio i.e., as the stress ratio decreases, hardness increases. From the results it can be concluded that at more negative stress ratio, hardness becomes more in the investigate steel.

4. Conclusions
The obtained results and their pertinent analyses related to fatigue-ratcheting interaction behavior of AISI 4340 steel at room temperature assist to infer:
1. Accumulation of ratcheting strain increased with increasing stress ratio in both annealed and normalised samples of AISI 4340 steel. Maximum accumulation of ratcheting strain (1.16% for annealed and 1.02% for normalised) was observed at R = -0.4.
2. Rate of strain accumulation is decreased from first cycle to last cycle. This indicates clearly that the selected material shows cyclic hardening behavior. The increase in strain accumulation can be explained with increased dislocation densities in the ratcheted samples.
3. Post ratcheting yield strength, tensile strength and hardness of investigated steel increased as compared to unratcheted samples and these increased with increasing stress ratio. The fact can be attributed to the previous cyclic hardening during ratcheting tests.
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