Ratcheting induced cyclic softening behaviour of 42CrMo4 steel

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Abstract. Ratcheting is an important field of fatigue deformation which happens under stress controlled cyclic loading of materials. The aim of this investigation is to study the uniaxial ratcheting behavior of 42CrMo4 steel in annealed condition, under various applied stresses. In view of this, stress controlled fatigue tests were carried out at room temperature up to 200 cycles using a servo-hydraulic universal testing machine. The results indicate that accumulation of ratcheting strain increases monotonically with increasing maximum applied stress however; the rate of strain accumulation attains a saturation plateau after few cycles. The investigated steel shows cyclic softening behaviour under the applied stress conditions. The nature of strain accumulation and cyclic softening has been discussed in terms of dislocation distribution and plastic damage incurred in the material.

1. Introduction

The continually increasing safety and quality levels for engineering and automotive industry, foreseen by global regulations, make compulsory the design and implementation of quality administration scheme to the entire supply series for failure prevention and continuous improvement. The performance and reliability of an engineering structure or assembly is a function of the quality of the various components [1]. It is understood that critical engineering structures and machine components often subject to various kinds of load transients, which may be static as well as fluctuating in nature; thus prone to fatigue failure [2, 3]. Situation becomes more critical when these load transients become asymmetric in nature. It is well established that the conventional low cycle fatigue life of engineering components are predicted by Coffin – Manson relationship [4], but application of load transients of asymmetric nature leads to increased damage accumulation in components which leads to reduced fatigue life of the component [5]. The phenomenon of strain accumulation in a material under the influence of positive and/or negative mean stress is known as ratcheting. Investigations on ratcheting behaviour of materials were started during 1911 when Bairstow did some experiments on carbon steel [6]; it was extensively studied in the last few decades as reviewed by Ohno [7] and Yoshida [8]. The ratcheting–fatigue interaction was experimentally investigated by Rider et al. [9], Xia et al. [5], and Kang et al. [10]. Investigators have studied the ratcheting behaviour of various materials like stainless steel [11, 12], aluminum [13], and aluminum alloys [14], copper alloys [13], composites as well as polymers [15, 16]. Kang et al. studied uniaxial ratcheting and fatigue behaviour of tempered 42CrMo
steel on constitutive modeling [17]. But limited works have been directed to understand the ratcheting behaviour of 42CrMo4 steel as per the knowledge of current investigation.

In the present study, ratcheting behaviour of 42CrMo4 steel is investigated under different applied stresses. These tests were carried out up to 200 cycles with different maximum applied stress. Experimental observation, which shows influence of material behaviour on cyclic stress strain response as well as effect of maximum applied stress of investigated steel also, has been discussed.

2. Experimental Procedures

2.1. Material and Heat Treatment

The selected 42CrMo4 steel was available in the form of solid cylindrical bars of diameter 16 mm. The chemical composition of the steel was assessed using optical emission spectrometer (Model: ARL 3460 Metals Analyzer, Thermo Electron Corporation Limited, Switzerland) and it is given in Table 1. To remove any pre-existing anomalies of material properties, all samples were subjected to annealing. This is done by heating the steel up to a temperature of 900°C followed by soaking for 60 mins and ultimately cooled inside the furnace.

| Table 1: Chemical composition of the investigated 42CrMo4 steel |
|-----------------|---|---|---|---|---|---|---|
| Element | C | Cr | Mo | Mn | Si | Al | Fe |
| Wt% | 0.384 | 0.926 | 0.222 | 0.678 | 0.210 | 0.035 | 0.020 | Balance |

2.2. Tensile and Fatigue Test

Heat treated samples were mechanically tested for tensile and fatigue properties. Round bar fatigue properties. Round bar specimens, for tensile and fatigue tests having a gauge lengths of 25 mm and 13 mm with diameters of 6 mm and 7 mm respectively were fabricated as per ASTM standards E 8M and E 606 respectively [18]. These tests were done on servo-hydraulic universal testing machine. All tensile tests were carried out at a crosshead speed of 1mm/min. Samples for ratcheting tests were with very well surface finish. All these tests were done at a constant stress rate of 50 MPa/s. Whole tests carried on varying maximum applied stress ($\sigma_{\text{max}}$). A summary of the test conditions is shown in Table 2. All fatigue tests were done up to 200 cycles.

Table 2: Selected $\sigma_{\text{max}}$ values for ratcheting tests

| Sl. No. | $\sigma_{\text{max}}$ /MPa |
|---------|-----------------|
| 1       | 400             |
| 2       | 430             |
| 3       | 460             |
| 4       | 490             |
| 5       | 520             |

3. Results and Discussion

As described above, samples were subjected to annealing heat treatment. Nature of microstructure, tensile and ratcheting behaviors of 42CrMo4 steel after this heat treatment is presented below in detail. All mechanical tests were performed at room temperature.

3.1. Microstructural and Tensile Properties

Figure 1 reveals the microstructure of annealed steel. It consists of pearlite colonies (dark contrast) and ferrite grains (light contrast). It is evident that the pearlite lamellar colonies are clearly existed. The average grain size was evaluated as 20.66 $\mu$m, using linear intercept method [19]. Typical engineering stress strain plot of the investigated steel was shown in Figure 2. It shows continuous yielding behaviour from elastic to plastic region and therefore, the yield strength has been calculated by offset method (offset = 0.2%) as specified in ASTM standard E8M [20]. The tensile properties of the investigated steel are summarized in Table 3.
3.2. Ratcheting Behaviour

Uniaxial ratcheting experiments were carried out under asymmetrical cyclic loading conditions up to 200 cycles. Figure 3 shows the characteristic evolution of ratcheting strain as a function of number of cycles for different maximum applied stress ($V_{\text{max}}$) values. It can be seen from these graphs that strain accumulation takes place in distinct stages with varying rates. It is reported in earlier investigations that there exists three different stages of strain accumulation during ratcheting; analogous to creep curves [20]. In the primary stage, the ratcheting strain rate decreases until it reaches a steady-state; attainment of steady state represents secondary stage. The strain accumulation curves presented in Figure 3 indicate presence of primary and secondary stages, as cyclic loading was stopped after 200 cycles. It is worthy to mention here that the tertiary stage of strain accumulation starts when the material under investigation accumulates large strain at a high rate and accelerates until the final failure. However, this stage is absent in the current investigation. Moreover, it can be noted from Figure 3 that strain accumulation during ratcheting depends on the maximum applied stress ($V_{\text{max}}$) values, and the evolution of ratcheting is accelerated remarkably by the increase of maximum applied stress. The strain accumulation varies from 0.85% to 7.26% for applied stress of 400 MPa and 520 MPa respectively.

**Table 3:** Tensile properties of the selected 42CrMo4 steel

| Yield Strength (MPa) | Tensile Strength (MPa) | %Uniform Elongation | %Total Elongation |
|----------------------|------------------------|---------------------|-------------------|
| 387                  | 650                    | 15.56               | 26.4              |

**Figure 1:** Typical optical microstructure of the annealed 42CrMo4 steel.

**Figure 2:** Engineering stress-strain plots of the investigated 42CrMo4 steel.

**Figure 3:** Variation of ratcheting strain with number of cycles.
3.3. Analysis of Hysteresis Loops

The nature of hysteresis loops is one of the better ways to explain the ratcheting behavior of materials. The hysteresis loops are the representation of stress-strain response during each cycle. Figure 4 (a) shows the representative stress-strain hysteresis loops (N = 1) obtained in ratcheting tests of investigated steel for different maximum applied stresses. This figure indicates that, the total deformation zone gets increased with increasing maximum applied stress. Moreover, the plastic damage increases with increasing $\sigma_{\text{max}}$. Figure 4 (b) show that hysteresis loop energy increases with increase in $\sigma_{\text{max}}$, indicating increased accumulation of cyclic damage in the specimens. It can be stated that any increase in ratcheting strain would induce higher extent of plastic deformation, consequently strain accumulation increases with increasing maximum stress. However, all the discussion made on strain accumulation is based upon mechanistic aspects of cyclic deformation. The phenomenon can be discussed in terms of materialistic point of view. Dutta et.al and Kang et.al have discussed in their recent report that strain accumulation due to ratcheting in material depends on dislocation formation and their redistribution. In the forward cycle, dislocation gets generated; a few of this dislocations gets annihilated in opposite direction due to asymmetric of loading. Hence, considerable numbers of dislocations remain in the substructure of material in each cycle [21]. Thus, strain accumulates during cyclic loading. The amount of remnant dislocations increases with increasing maximum applied stress of loading. Therefore accumulation of ratcheting strain increases with increasing maximum stress.

3.4. Cyclic Softening Behaviour

Figure 5 shows the stress-strain hysteresis loops generated during asymmetric cyclic loading of the investigated 42CrMo4 steel at constant $\sigma_{\text{max}}$. The 1st, 50th, 100th, 160th and 200th loops are shown here. One can note that widths of the hysteresis loops increase with increasing number of cycles. This is attributed to cyclic softening behaviour of the material. For better understanding of damage accumulated during cyclic loading, a quantitative assessment of hysteresis loop area was done and this
shows that the loop area varies from 24.49 MJ/m$^3$ to 90.740 MJ/m$^3$, as summarized in Table 4. The phenomenon of cyclic softening in the investigated material can be explained following Hussain et al. [22]. According to Hussain et al., in a high strength material, initially the dislocation density is high and cyclic loading cause’s re-arrangement of the dislocations into a new configuration that offers less resistance to deformation and therefore material shows cyclic softening feature.

Table 4: Energy values of the cyclic softening hysteresis loops

| Sl. No | No. of Cycles | Energy /MJ-m$^3$ |
|--------|---------------|-----------------|
| 1      | 1             | 24.49           |
| 2      | 50            | 48.013          |
| 3      | 100           | 66.352          |
| 4      | 160           | 81.576          |
| 5      | 200           | 90.740          |

4. Conclusions

The following conclusions can be drawn from the experimental results and pertinent discussion. The obtained results and their relevant analyses lead to infer that:

1. Accumulation of ratcheting strain increases with increasing maximum applied stress ($\sigma_{\text{max}}$). The strain accumulation varies from 0.85% to 7.26% for applied stress of 400 MPa and 520 MPa respectively. The increase in ratcheting strain is explained in terms of cyclic damage measured as the area under hysteresis loops, which increases with increase in maximum applied stress, indicating increased accumulation of cyclic damage in the specimens. Further, it may be inferred that increase in strain accumulation occurs due to increased remnant dislocation density with increased maximum stress, followed by Dutta et. al [21].

2. The investigated annealed 42CrMo4 steel has shown cyclic softening feature. The phenomenon is explained in terms of dislocation activities during asymmetric cyclic loading; this kind of cyclic loading reduces the resistance to the motion of dislocations in the material and thus material shows cyclic softening.
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