Cyclic deformation behavior of gradient structured austenitic stainless steels

W L Zhou, K K Liu, Y Li and H S Ho

School of Mechanical Engineering, Zhengzhou University, Science Road 100, 450001 Zhengzhou, China.

Email: hsinshen.ho@zzu.edu.cn

Abstract. The cyclic deformation behavior of gradient structured 316L austenitic stainless steels produced by shot-peening is investigated. The experimental results show that for all specimens, the cyclic response exhibits a similar fundamental evolutionary character, i.e., first cyclic hardening then followed by cyclic softening. The presence of a gradient structured surface layer is observed to be capable of accelerating the cyclic hardening process but decelerating the cyclic softening process. It is further suggested that the former can be related to the restricted cyclic hardening ability and the latter to the high plastic deformation uniformity.

1. Introduction

Austenitic stainless steel is one of the most widely used metallic materials in engineering applications. Due to its excellent corrosion resistance and high temperature strength, such material is mostly used in chemical, fertilizer, and other harsh industrial production environments.

With the increasing demand for highly reliable products, the fabrication of a new class of material referred to as gradient structure (GS) with superior dual-property of high strength and high ductility, which is preferable in designing stronger, lighter and tougher components, is expected in engineering machinery [1]. The GS can be processed using a large variety of surface strengthening methods such as shot-peening, surface mechanical attrition treatment, deep rolling, etc. [2-4]. However, the shot-peening remains one of the most important means in industrial production due to its high flexibility, low cost, and environmental friendliness.

In the literature, it has been shown that considerable efforts have been devoted to investigating the influence of peening processes on mechanical properties. These works show that the efficacy of these processes in enhancing GS surface layer properties can contribute to the improvement of not only tensile strength but also fatigue strength and life, especially in the high-cycle fatigue regime [5-7]. Despite extensive research on tensile and high-cycle fatigue strength, little research has been focused on the examination of cyclic deformation behavior of GS in the low-cycle fatigue regime.

Thus, the present work is aimed to investigate the cyclic deformation behavior of gradient structures. Particular focus is given to the evaluation of cyclic hardening/softening behavior and fatigue life. The contributions of the present paper are as follows: firstly, investigate the influence of GS surface layer on cyclic behavior and then, identify the notable cyclic hardening and/or softening characteristics brought by the GS surface layer.
2. Material and Methods

The material used in the present work is 316L austenitic stainless steel, with its chemical composition presented in Table 1. The as-received state has an initial average grain size of 25μm.

| Element | C  | Si  | Mn  | S   | P   | Cr  | Ni  | Cu  | N   | Mo  | Fe   |
|---------|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| Amount (wt.%)    | 0.08 | 0.52 | 1.14 | 0.001 | 0.028 | 16.51 | 10.16 | 0.069 | 0.05 | 2.05 | Balance |

The shot-peening treatment is performed with the air blast shot-peening machine using the impact angle of 90°. The cast steel balls with an average diameter of 0.6mm are selected. The peening intensity of 0.35 mmA is measured by using the arc height of type-A Almen strips. The peening coverage value of 200% is obtained by doubling the treatment based on the basis of the coverage value of 100%. The shot-peening condition used in the present work is summarized in Table 2.

| Variant | Shot diameter (mm) | Coverage value (%) | Almen intensity (mmA) |
|---------|-------------------|--------------------|----------------------|
| NP      | -                 | -                  | -                    |
| SP      | 0.6               | 200                | 0.35                 |

The mechanical tests are carried out using MTS370.25 servo-hydraulic axial control machine. The tensile test is conducted with the strain rate of 5×10^{-4} s^{-1} on the specimens prepared according to ISO 6892-1 (2016) [8]. The tensile-tensile fatigue test is performed with the total strain amplitude of 0.3% under the strain ratio of 0.1 and loading frequency of 0.1 Hz at room temperature on the specimens prepared according to ISO 12106 (2017) [9].

The investigated specimens are first mechanically polished and then chemically etched using a mixture constituted of 2/5 hydrochloric acid, 1/5 nitric acid, and 2/5 ethanol. The cross-section microstructure is observed using optical microscopy. The hardness is measured along the depth of the cross-section using the Vickers hardness tester with a load of 0.1kg and a holding time of 10s. The in-depth profile of residual stress is obtained using the X-ray diffraction with Mn-Kα radiation and austenite {311} crystalline plane, with the interference peaks being evaluated by the sin^2Ψ method with the diffraction angle (2θ) varying from -45° and 45°.

3. Results and Discussion

3.1. Surface integrity and tensile property

Figure 1, presenting the cross-sectional surface of the shot-peened specimen obtained by optical microscopy, reveals a gradient microstructure. Two principal distinct regions can be identified: the gradient structured (GS) surface layer and the coarse-grained (CG) interior. In the innermost zone, the undeformed austenitic grains, which represent the initial state of the material, are observed (c.f. Figure 1(b)). At the outermost zone, the so-called work-hardened (c.f. Figure 1(c)) and grain-refined (c.f. Figure 1(d)) layers are formed. The former consists mainly of plastically-deformed austenitic grains, while the latter composely of small-sized grains with the thickness lying between a few ten microns at the top surface.

Figure 2(a) shows the hardness distributions along the depth direction of both NP and SP specimens. For SP specimen, the hardness which is maximal at the near-surface region is found to decrease gradually until reaching a stabilized value of ~200 HV. It is worth noted that the maximum hardness measured in the peening-affected near-surface region (~400 HV) is about twice the hardness measured in the untreated area (~200 HV). In Figure 2(b), the residual stress distributions along the depth direction of investigated specimens are presented. It can be seen that the peened specimen possesses an obvious compressive residual stress distribution as compared to the un-peonned specimen; the compressive...
residual stress first increases to a maximum value of ~760 MPa at a depth of ~50 µm, then decreases gradually and remains constant thereafter at around 400 µm.

![Figure 1](image1.png)

**Figure 1.** The cross-sectional surface of the SP specimen (a): the bulk (b), the work-hardened region (c), and the top surface region (d).

![Figure 2](image2.png)

**Figure 2.** Distributions of in-depth hardness (a) and residual stress, (b) of investigated specimens.

The engineering stress-strain curves of investigated specimens are plotted in Figure 3. It can be noted from Figure 3 that although the SP specimen has deteriorated elongation to fracture properties, it possesses enhanced tensile yield strength and ultimate tensile strength, as compared to the NP specimen. This observation shows that the shot-peening process has resulted in a notable improvement in the strength-ductility relationship.
3.2. Fatigue behavior and properties

As the cyclic stress response can generally be used to examine the cyclic hardening/softening behavior and fatigue life in the low-cycle fatigue regime, we thereby perform the investigation of cyclic stress amplitude ($\sigma_a$) versus the number of cycles ($N$). Figure 4 shows that shot-peening causes an improvement of cyclic stress levels. The observed peening-induced increment of cyclic stress amplitude can, in fact, be a consequence of the combined effects of work hardening and compressive residual stress produced by shot-peening in the near-surface region of peened specimen [10].

In the following, the cyclic hardening and softening behavior of NP and SP specimens is investigated. To quantify the cyclic hardening and softening behavior of the two investigated specimens, a simple expression of cyclic hardening factor ($H_\sigma$) is hereby used [11]:

$$H_\sigma = \frac{\sigma_a - \sigma_a(1)}{\sigma_a(1)} - 1$$

(1)

where $\sigma_a$ and $\sigma_a(1)$ are stress amplitudes corresponding to arbitrary number of cycles and the first cycle, respectively.
Figure 5. Cyclic hardening factor ($H_\sigma$) versus the number of cycles ($N$) (a), and maximum ($H_{\sigma\text{(max)}}$) and minimum ($H_{\sigma\text{(min)}}$) of cyclic hardening factor for NP and SP specimens (b).

In Figure 5(a), the plot of the cyclic hardening factor ($H_\sigma$) versus the number of cycles ($N$) is presented. It is revealed that both the NP and SP specimens experience cyclic hardening in the first few cycles and then cyclic softening upon fatigue failure, i.e., the two investigated specimens are cyclically hardened at the very beginning of life cycle until attaining a peak value then cyclically softened over the rest of the life. Figure 5(a) shows that the $H_\sigma$-values computed for the SP specimen are smaller than that for the NP specimen. To make it clear, the values of the maximum ($H_{\sigma\text{(max)}}$) and minimum ($H_{\sigma\text{(min)}}$) of cyclic hardening factors are estimated, as presented in Figure 5(b). It can be seen from the figure that SP specimen has indeed much smaller values of $H_{\sigma\text{(max)}}$ and $H_{\sigma\text{(min)}}$ than NP specimen. The result implies that the presence of a peening-induced gradient structured surface layer can result in the decrement of the cyclic hardening factor. From Figure 5, two remarks can be given:

Firstly, regarding the cyclic hardening ability: to reflect the cyclic hardening ability, the $H_{\sigma\text{(max)}}$-values estimated for NP and SP specimens in Figure 5(b) are hereby examined. The NP specimen is found to have a higher $H_{\sigma\text{(max)}}$-value than SP specimen, revealing that NP specimen has a much stronger cyclic hardening ability as compared to SP specimen. For the NP specimen, the plastic strain is fully accommodated by the coarse-grained austenite during cyclic loading, and consequently, the austenite is cyclically hardened. As for SP specimen, the plastic strain, which is furnished by the central coarse-grained austenite, is constrained by the two outer high strength GS surface layers due to their restricted plastic deformability, causing thus in an overall reduced cyclic hardening ability.

Secondly, regarding the cyclic hardening and softening rate, for the NP specimen, while the number of cycles to attain the peak state is the largest, the number of cycles to encounter failure is the smallest. As for SP specimen, the number of cycles in achieving the peak state is decreased, while the number of cycles to encounter failure is enhanced, as compared to NP specimen. The result implies that the GS surface layer can, on the one hand, speed up the cyclic hardening process and, on the other hand, slows down the cyclic softening process. The former phenomenon can be related to the decreased cyclic hardening ability. The latter phenomenon can most likely be attributed to the fact that the plastic deformation in the GS surface layer is more uniform, and it can thus better accommodate the cyclic plastic strain during loading [7,12].

3.3. Fatigue lifetime
The number of cycles required to fracture a specimen can be attributed to the ductility level of a specimen, which is in general corresponded to the tensile yield strength ($Y$), i.e., greater the tensile yield strength ($Y$), higher the ductility level and thus, longer the fatigue life ($N_f$). As the total strain amplitude is composed of an elastic component and a plastic strain component, a higher $Y$-value would imply a larger elastic component, which means a higher ductility level and, thus, a smaller plastic strain component. The plastic strain component, generally denoted as the plastic strain amplitude, is well-
recognized to act as the primary contributor to the fatigue damage, ultimately resulting in fatigue failure. Thereby, the plastic strain amplitude is hereby investigated. The plastic strain amplitude ($\Delta \varepsilon_p/2$) versus the number of cycles to failure ($N_f$) is presented in Figure 6 for NP and SP specimens.

![Figure 6. Plastic strain amplitude acquired prior to fatigue testing ($\varepsilon_p$) versus the number of cycles to failure ($N_f$).](image)

In Figure 6, it can be seen that the NP specimen with lower fatigue life has higher plastic strain amplitude than the SP one with higher fatigue life. This implies that the peening-induced GS surface layer is capable of decreasing the plastic strain amplitude. Due to the presence of a very high peening-induced dislocation density in the GS surface layer, the movement of dislocations is restricted, and the plastic deformation ability is thus lowered, leading thereby to a significant improvement in fatigue life.

4. Conclusion
The present work is designed to investigate the cyclic deformation behavior of 316L austenitic steels treated with shot-peening. The results show that shot-peening, though it uses less intense parameters compared to other surface strengthening methods, is capable of producing gradients of microstructure, hardness and residual stress, which can contribute to the synchronous improvement of mechanical properties and fatigue life. It is revealed that both the untreated and peened specimens, possessing a similar trend of cyclic stress responses, exhibit some initial cyclic hardening followed by cyclic softening. Our findings show that the highly deformed gradient structured surface layer can not only speed up the cyclic hardening process but also retard the cyclic softening process. It is further suggested that the former is most to be a consequence of the low plastic deformability of the gradient structured surface layer, while the latter can be attributed to the high plastic deformation uniformity in the gradient structured surface layer.

References
[1] Lu K et al 2004 J. Mater. Sci. Eng. A 375-377 38
[2] Zhou J, Sun Z, Kanoute P and Retraint D 2017 Int. J. Fatigue 103 309
[3] Roland T, Retraint D, Lu K and Lu 2006 J. Scripta Mater 54 1949
[4] Muñoz-Cubillos J, Coronado J J and Rodriguez S A 2017 Int. J. Fatigue 95 120
[5] Yin X N, Fu X S, Chen G Q, Zhou W L, Gai P T and Li ZQ 2016 Heat Treat Met 2016 3 48
[6] Zheng Y, Zhou J Z, Meng X K, Sheng J, Huang S and Wang X 2016 App Laser 3 276
[7] Huang HW, Wans Z B, Lu J and Lu K 2015 Acta Mater. 87 150
[8] ISO 6892-1. 2016 Metallic materials, Tensile testing, Part 1: Method of test at room temperature
[9] ISO 12106. 2017 Metallic materials, Fatigue testing, Axial strain, controlled method
[10] Altenberger I, Scholtes B, Martin U and Oettel H 1999 Mater. Sci. Eng. A 264 1
[11] Paul S K, Stanford N and Hilditch T 2015 Mater. Sci. Eng. A 638 296
[12] Fang T, Li W, Tao N and Lu K 2011 Science 331 1587