Fatigue life extension of 42CrMo high-strength steel and its micro strengthening mechanism under laser shock peening

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Abstract. Laser shock peening is an advanced surface treatment technique in improving the fatigue properties of metallic components. In this study, the effects of different laser shock peening regions on the high cycle fatigue of 42CrMo high-strength steel were investigated. Surface deformation, residual stress, and microhardness were analyzed, and microstructural evolution including grain size, boundary distribution, and misorientation was examined. Results show that peening the specimen with both surfaces and sides resulted in a better fatigue life than only peening the surface. The compressive residual stress introduced in both the surfaces and sides provided a higher resistance for fatigue initiation. In addition, the increase of low angle grain boundary accounted for the micro strengthening mechanism for the fatigue life extension.

1. Introduction
High cycle fatigue features the fatigue cracking under the low-amplitude cycling loads, in which case, the material deforms primarily elastically till a sudden collapse occurs [1, 2]. This unexpected fatigue has become the dominant failure process in a variety of engineering applications, and has become an important issue that hinders the service safety and reliability of components. In the past several decades, a number of techniques have been developed to deal with the problem of fatigue failure [3-5]. Among these techniques, laser shock peening (LSP) applies a high power nanosecond pulse laser onto the material surface to introduce large-depth and high-value compressive residual stress, which is known to be beneficial for enhancing the fatigue properties [6-8]. Therefore, LSP has been widely utilized for fatigue life extension of key components of high-end equipment.

In spite of its growing applications, the effectiveness of LSP on the fatigue life extension is still difficult to be determined, since the fatigue life is not only affected by laser parameters, but also factors such as the specimen design, peening process control. Correa et al. found that the specimen peened with the laser advancing direction parallel to the direction of the external load exhibited a higher fatigue strength [9]. Cuellar et al. pointed out that the LSP pattern with multiple concentric rings of spots around the circumference of the hole provided the best fatigue performance [10]. Our previous study also discovered that the sequence between hole drilling and peening had an influence on the fatigue life [11]. Hence, a better understanding of the peening region or pattern is still of great necessity to fulfill the effectiveness of LSP in fatigue life extension.
This study seeks to understand the fatigue life extension by employing two different peening patterns. Thus, the surface deformation, residual stress, and microhardness were analyzed. The micro strengthening mechanism was further discussed. This study aims to enrich the fundamental understanding of LSP induced fatigue life extension and to expand its applications in scientific and engineering sectors.

2. Materials and methods

2.1. Material and specimens preparations

42CrMo steel is widely utilized in manufacturing larger and heavy load-carrying components, such as gear, connecting rod, spring clamp, etc., due to its high strength, excellent toughness and hardenability [12]. In this study, an oil quenched and high temperature tempered 42CrMo high-strength steel plate, was employed with its chemical compositions (wt. %) of C 0.43, Si 0.21, Mo 0.18, Mn 0.83, Cr 0.91, and Fe balance. The physical and mechanical properties of this steel are given in Table 1. The plate was machined into different types of specimens for high cycle fatigue tests, electron backscatter diffraction (EBSD) observations, surface deformation observations, residual stress measurements, and microhardness measurements.

Table 1. The physical and mechanical properties of the 42CrMo steel employed in this study.

| Density (Kg/m³) | Young’s modulus (GPa) | Poisson’s ratio | Yield strength (MPa) | Ultimate tensile strength (MPa) |
|----------------|-----------------------|----------------|----------------------|-------------------------------|
| 7850           | 212                   | 0.28           | ≥ 930                | ≥ 1080                        |

The fatigue specimen was designed according to the Chinese standard GB/T 3075-2008 with an overall length of 180 mm, a uniform thickness of 4 mm and a width of 15 mm at the minimum section (see Figure 1). The fatigue specimens had a total number of twelve and were divided into three types: unpeened, LSPed (only the top and bottom surfaces were peened) and LSPwSed (both the surfaces and sides were peened). In each type, three specimens were prepared for the fatigue tests and the last one was prepared for the EBSD observation, residual stress, and microhardness measurements. The EBSD specimen was initially cut into a sheet of around 500 μm from the peened surface and mechanically ground to about 100 μm in thickness. This ultra-thin sheet was then polished by argon iron. The specimen for surface deformation observation was cut into a size of 20 mm × 15 mm × 4 mm (length × width × thickness) and peened with only one laser spot in the geometry center.

Figure 1. Schematic of the fatigue specimens with the shadow area showing the LSPed region and the cuboid illustrating the LSPed surfaces and sides.
2.2. LSP experiments
The LSP experiments were conducted by a Q switched Nd: YAG high power pulse laser with a wavelength of 1064 nm and a pulse duration of 15 ns. The employed laser parameters were 25 J pulse energy, 4 mm square spot, 1 impact time and 50% overlapping rate. The zigzag laser path was realized by a six-joint robot manipulator. Prior to LSP, a 3M manufactured aluminum foil was attached to avoid possible damage or roughening of the peening surface. During LSP, a running deionized water layer was sprayed onto the peened surface, forming a transparent constrained layer to increase the peak pressure of the laser-induced shock wave.

2.3. Material tests and characterizations
Three specimens in each type were tested on a high-frequency fatigue machine (QBG-100, Qianbang) with a stress level of 400 MPa (a sinusoidal cycling load), a frequency of about 100 Hz and a stress ratio of 0.1. Shortly after the breaking of the fatigue specimens, the fracture surfaces were observed by a scanning electron microscope (SEM, Gemini 500, Carl Zeiss). Surface deformation after one spot peening was observed by a large depth-of-field digital microscope (VHX-5000, Keyence). Residual stresses in depth direction were measured based on the incremental hole drilling method (PRISM, StressTech). Microhardness of the unpeened and LSPed specimens was measured by a microhardness tester (FM-800, Future-Tech) with a load of 200 g and dwelling time of 10 s. It was repeated for three times and the averaged values were presented. The auger electron spectroscopy (PHI710, ULVAC-PHI), in which an EBSD detector was integrated, was employed to study the grain refinement, boundary distribution and misorientation of the unpeened and LSPed specimens with a detection area of 100 μm × 100 μm and a step size of 1 μm.

3. Results and discussion
3.1. Fatigue life and fracture analysis
Figure 2 shows the fatigue lives of the unpeened, LSPed and LSPwSed specimens. The fatigue life of every single specimen in each type is presented in Figure 2a. It can be clearly seen that both LSPed and LSPwSed specimens showed dramatic improvements in the fatigue life compared with the unpeened specimens. Moreover, it is noticed that the fatigue life scatter became higher after peening, which can be attributed that the peening of each specimen can hardly be the same, i.e., the thickness of the running water layer, the quality of the aluminum foil adhesion. Figure 2b exhibits that the average fatigue lives of LSPed specimens and LSPwSed specimens were 115,033 and 145,000 cycles, respectively. Compared with 71,033 cycles for the unpeened specimens, the average fatigue lives of LSPed specimens and LSPwSed specimens showed a significant increase by 62% and 104%, respectively. Thus, the average fatigue lives of LSPwSed specimens were 1.3 times higher than that of the LSPed specimens, which indicates that the side surface is also of great importance in the LSP. Spadaro et al. peened both the sides and surfaces of 253 MA steel, and found the fatigue life was increased as well [13].

Figure 2. Fatigue lives of the unpeened, LSPed and LSPwSed specimens with (a) presenting the fatigue life of every single specimen and (b) illustrating the averaged fatigue lives.
Figure 3 depicts the SEM images observed on the fresh fracture surface of the above three different types of specimens. As can be clearly seen, the fracture can be typically divided into three zones: fatigue initiation (FI) zone, fatigue stable propagation (FSP) zone and final fracture (FF) zone according to their different morphology features [14]. Moreover, their difference was also associated with the propagation rate of the fatigue. The faster the propagation rate is, the closer to final breaking the fatigue propagation is. It is evidently seen from Figure 3(a), 3(c) and (e) that the FI sides were all located at the corner of the surface edge. It is worth noting that LSP did not cause any shift of the FI sites, which indicates that the improvement of the fatigue life after peening does not result from FI site shifting, but from other reasons. Considering that the residual stress LSP introduced into the surface layer, it should be an important factor needing to be further analyzed (see Section 3.2). Figure 3(b), 3(d) and (f) illustrate the typical fracture morphology of the FSP zone, which were taken from the yellow dotted rectangles. The observation was carried out in the area which was about 800 μm to the initiation site in each specimen. A large number of fatigue striations can be clearly found in all types of specimens. These striations were the trace of the blunting and re-sharpening of the crack tip during crack propagating [1]. According to the Paris law, the width of each striation is proportional to the fatigue propagation rate [15]. Apart from the striations, the small secondary cracks and tearing ridges can be observed as well. Their occurrence indicates the instability of the propagation process and the fatigue would soon come to the FF zone and the specimen would break shortly.

Figure 3. Typical SEM images of unpeened, LSPed and LSPwSed specimens. (a) Macroscopic fracture morphology indicated the FI sites, FSP zone, and FF zone; (b) Micro-features in the FSP zone.

3.2. Surface morphology, residual stress and microhardness

Figure 4 shows the surface morphology of the specimen peened with only one laser spot. It can be seen from the deformation map in Figure 4(a) that the peened area remained a high flatness. This is different from the results obtained from the round laser spot, because the laser energy spatial distribution of square spot exhibits a top flat distribution, while the round spot displays a quasi-Gaussian distribution [16]. Figure 4(b) shows the surface profile detected from the red horizontal line in Figure 4(a). It can be seen that the size of the deformed region was 3.94 mm, which is slightly smaller than the laser spot (4 mm × 4 mm) employed. The narrowing can result from the attenuation of the laser energy near the edge [17]. The plastic deformation in regions [A] and [B] were 7.46 μm and 7.61 μm, respectively, while the deformation in [C] was 6.25 μm. This might be associated with the boundary generated rarefaction wave converging, and resulting in permanent reverse plastic
deformation at the center. Hu et al. observed a similar drop in the residual stress at the laser spot center using finite element simulation [18].

![Surface morphology of the specimen peened with a single laser spot.](image)

**Figure 4.** Surface morphology of the specimen peened with a single laser spot. (a) Surface deformation map and (b) surface profile obtained from the red line.

Figure 5 shows the residual stress distribution in the unpeened, LSPed and LSPwSed fatigue specimens. As illustrated by the black line, the near-surface residual stress in the unpeened specimen was slightly lower than zero, which can be resulted from the stress brought in by machining. Then, the stress fluctuated around zero with the increasing of the depth. While in the LSPed specimen, the maximum compressive residual stress increased to nearly 300 MPa with an affected depth of around 1.0 mm. Note that the maximum stress value did not locate at the very top surface but at a depth of around 0.1 mm, which can be related to the stress hole effect, as reported by Hu et al. [18]. Thus, the residual stress on the side was also in compressive with its maximum value of around 20 MPa, which can be due to the stress penetration during the peening of top and bottom surfaces. Differently, when both the surfaces and sides were peened, the residual stress measured from the surface was at the same level as the LSPed specimen, while the residual stress measured from the side was increased to about 200 MPa. However, the compressive stress penetrated shallower than that from the LSPed specimen. Because the mid-section was in tensile state after peening the surface, which further neutralized the compressive residual stress induced by peening the side. After the residual stress was imparted, it can actually minimize the local load at the FI sites, and further delayed its initiation [19], contributing to the fatigue life extension. As a higher value of residual stress was introduced into the side surface of the LSPwSed specimen, the fatigue crack initiated slower than that in the LSPed specimen, and hence, resulted in a higher fatigue life of the LSPwSed specimen.

Figure 6 shows the microhardness distribution in the depth direction in the unpeened and LSPed specimens. The microhardness was originally fluctuated around 320 HV. Then, a large enhancement of microhardness was achieved after the peening. The surface microhardness increased to around 360 HV and it gradually decreased to around 320 HV, which corresponded to a depth of around 1.0 mm. Such depth is in good agreement with the thickness of the residual stress affected layer. As indicated by the Hall-Petch theory [20], the improvement in microhardness is proportional to dislocation density. Hence, the microhardness was increased accordingly.

### 3.3. Microstructure evolution

Figure 7 illustrates the surface EBSD maps of the unpeened and LSPed specimens, which details their inverse pole figure and grain size distribution. [100] was adopted as the reference direction for the inverse pole figure to code the color pattern (red: [001], blue: [111], green: [101]), as indicated by the triangle in the top right corner of Figure 7a and 7b. The original microstructure, displayed in Figure 7a, was consisted of equiaxed grains with an average size of 10.11 μm, while the microstructure was refined in LSPed specimen with an average size of 9.20 μm (see Figure 7b). The grain refinement can be attributed to the microstructure evolution during LSP, as the intense interaction between laser-
induced shock wave and the surface material can generate dislocations or mechanical twins [21]. The dislocations or twins can further interact, forming subgrain boundaries, and finally, the original coarse grains were refined. It is, however, worth noting that the grain refinement effect is not as strong as expected. This can be accounted for several factors as following: the specimen is only peening once, the material has a high yield strength, and the grain size in the original specimen is relatively small, which is hard to provide that much space for the refinement. Figure 7c and 7d present frequency histograms of area fraction versus grain size of the unpeened and LSPed specimens. The majority of grains are smaller than 20 μm in both specimens. 60% of the grains in the unpeened specimen were less than 10 μm, while this number in the LSPed specimen increased to 67%.

**Figure 5.** The in-depth distribution of residual stress.

**Figure 6.** The in-depth distribution of microhardness.

**Figure 7.** Microstructure observed by EBSD, (a) and (b) Inverse pole figure, (c) and (d) Grain size distribution in the unpeened and LSPed specimens.
Figure 8 expounds the surface EBSD maps of grain misorientation in the unpeened and LSPed specimens. The misorientation angle is defined as the minimum rotation angle required for two neighboring crystal lattices to coincide [22]. The misorientation angle, which is less than 15°, is known as the low angle grain boundary. The number fraction of the misorientation angle is defined as the number of pixels along boundaries with the same misorientation angle divided by the total number of pixels in the analysis area. As can be seen from Figure 8a, the length of the low angle grain boundary was increased from 3.04 mm to 4.37 mm after peening, while the boundary length with angles between 15°-45° was decreased from 5.81 mm to 4.81 mm. This might be contributed that the large grain broke into new smaller grains or rotated to coincide with the neighboring grains driven by the laser-induced shock wave. Figure 8b and 8c present the frequency histograms of number fraction versus misorientation angle of the unpeened and LSPed specimens. 23% of grain boundaries in the unpeened specimen were found with low misorientation angles, while the percentage increased to 34% in the LSPed specimen. Our previous study regarding Ti-17 alloy [3], additive manufactured aluminum alloy [23] found a similar increase of the low angle grain boundaries after LSP.

![Figure 8](image-url)

**Figure 8.** Microstructure observed by EBSD, (a) grain boundary length, (b) and (c) grain misorientation of the original and LSPed specimens.

### 4. Conclusion

Two different LSP regions are employed to investigate the effectiveness of LSP on fatigue life extension. Surface deformation, residual stress, and microhardness were analyzed to reveal LSP’s capability in improving surface properties. Microstructural evolution (grain size, boundary distribution, and misorientation) was examined to understand the micro mechanism of the prolonging of fatigue life. The main findings can be summarized as follows:

1. Peening both the surfaces and sides provides a better fatigue life improvement compared with only peening the surfaces. The fatigue life of LSPwSed specimen was 2.04 times and 1.26 times higher than that of the unpeened and LSPed specimens, even though the fatigue still initiated from the corner of the edge.

2. A surface deformation of around 7.5 μm and a compressive residual stresses of nearly 300 MPa were introduced into the surface layer. The surface microhardness was improved from 320 HV to 360 HV, with an affected depth of 1.0 mm.

3. LSP did not bring in significant grain refinement, but generated more amount of low angle grain boundary in the 42CrMo steel, which accounted for the micro mechanism of the fatigue life enhancement.

Our study reveals that the design of the peening region is a significant factor requiring careful consideration to fulfill the advantages of LSP in both scientific and engineering fields.

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