Surface Nanocrystallization and Numerical Modeling of 316L Stainless Steel during Ultrasonic Shot Peening Process

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Abstract: Surface nanocrystallization of metals and alloys via high-frequency ultrasonic shot peening (USP) can significantly increase the mechanical properties of the materials. However, the relationship between the external process parameters and the internal microstructure of the materials is still unclear and an accurate numerical model to simulate the USP process is urgently required for better control of the grain refinement process. In this study, we successfully realized surface nanocrystallization of 316L stainless steel using USP with an ultrasonic frequency and amplitude of 20 kHz and 50 µm, respectively. The microstructure evaluation of 316L stainless steel during USP was revealed. We established a finite element numerical model to simulate the high-frequency USP process and calculated the plastic strain and stress distribution of 316L stainless steel during the grain refinement process. We investigated the effects of the ultrasonic frequency, working distance, and ultrasonic amplitude on the plastic strain and stress distribution on the materials using the finite element simulation method. The dynamic behavior of the shot during the USP process was studied using a high-speed camera, and the FE simulation results agreed well with the experimental results. We also investigated the impact of multiple shots during the USP process by the high-speed camera observation and FE simulation. Research results indicate that high-frequency USP is an effective method to obtain large-scale bulk nanocrystalline materials and the finite element simulation can help materials scientists and engineers to better understand the relationship between the process parameters and microstructure evaluation of 316L stainless steel.

Keywords: surface nanocrystallization; severe plastic deformation; numerical modeling; 316L stainless steel; ultrasonic shot peening

1. Introduction

Stainless steel type 316L is a kind of material widely used in structural engineering. It has the properties of low cost [1], good corrosion resistance [2], and good formability [3,4]. However, the strength of 316L stainless steel is low (150–300 MPa in the annealed state), which significantly hinders its industrial applications [5,6]. Studies on the strengthening of 316L stainless steel have drawn attention from researchers worldwide [7,8]. One approach is to strengthen 316L stainless steel using grain refinement or surface nanocrystallization, which can be realized by severe plastic deformation (SPD) methods such as surface mechanical attrition treatment (SMAT) [9–11], equal-channel angular pressing (ECAP) [12,13], high-pressure torsion (HPT) [14,15], and ultrasonic shot peening (USP) [16–18]. Nanograined metals and alloys possess extraordinary mechanical properties compared to their coarse-grained counterparts [19,20]. For example, Chen et al. fabricated a nanocrystalline 316L stainless steel with a grain size of ~40 nm by using surface mechanical attrition treatment (SMAT) with yield strength as high as 1450 MPa [5]. Yan et al. synthesized a bulk nanosstructured 316L stainless steel consisting of nanosized grains embedded with bundles of...
nanometer-thick deformation twins using dynamic plastic deformation. The nanostructured samples exhibit a high tensile strength of ~1400 MPa with poor ductility. For instance, a combination of 1 GPa tensile strength with an elongation-to-failure of ~27% is achieved in the annealed as-fabricated nanostructured 316L stainless steel samples [6]. Yin et al. developed a thick gradient nanograined 316L stainless steel with the finest grain size of ~5 nm using ultrasonic shot peening. They conducted micropillar compression tests and nanoindentation to study the strengthening mechanisms of the nano-grained 316L stainless steel. Research results indicated that the yield strength of the nano-grained 316L stainless steel can reach as high as 2 GPa, which is almost 10 times higher than its coarse-grained counterpart [21].

Ultrasonic shot peening (USP) is an effective surface treatment technology that can introduce severe plastic deformation (SPD) onto the target surface repeatedly within seconds. This technology can be used as the final surface treatment/strengthening during a manufacturing process. The accumulated severe plastic deformation can increase the dislocation density and decrease the grain size of the materials. We have successfully fabricated a gradient nano-grained surface layer on 316L stainless steel [21,22], pure copper [23], low-carbon steel [18,24], high-entropy alloys [25,26], and bearing steel [27,28] in the last few years. We also studied the mechanical behaviors of nano-grained metal alloys at the nanoscale and investigated their strengthening mechanism. However, the correlation between the ultrasonic shot peening processing parameters and the microstructure of the materials is still unclear and an accurate simulation model to simulate the USP process is also urgently required for better control of the grain refinement process of the metal and alloys. Bagherifard et al. established a 3D finite element model to investigate the surface topography alterations as a function of peening parameters and processing time. A numerical simulation is implanted to study the surface roughness change by shot peening. The numerical simulation consists in a finite element simulation and elaboration of the obtained data [29]. Chen et al. reviewed the numerical simulation of the conventional shot peening process [30]. They concluded that the developed numerical models coupling finite elements with discrete elements became increasingly mature and showed their advantages incorporating flow behavior and randomness of shots. Mylonas et al. studied the effects of controlled shot peening process parameters on the treated materials. They developed a three-dimensional numerical model with the target plate and a number of shot impacts. The numerical model can be used to predict the effect of shot velocity, impinging angle and shot size on the induced residual stress profile for the specific aluminum alloys through a parametric study [31]. Hu et al. used a modified 3D random representative volume finite element model to study the effects of model dimensions, model shapes and peening-induced thermal softening on resultant critical quantities, such as residual stress, Almen intensity, coverage and arc height of the sample [32]. Pham et al. developed a new method to estimate the full coverage for simulation of the shot peening process. The numerical results show that the coverage, shot velocity and radius significantly affect the residual stress distribution of the target materials [33]. However, there are few studies on simulating the ultrasonic shot peening process. Currently, investigations on the numerical modeling of the ultrasonic shot peening set the impact velocity as a constant for simplification purposes [18,34]. Unfortunately, the impact velocity is not constant according to our observation and the motion behavior of the shots during the USP is unclear because of the complicated physical interaction between the shots and the target materials. Understanding the motion behavior of the shot and the energy transformation from the ultrasonic vibration to the plastic deformation of the materials is critical for materials scientists and engineers to control the surface nanocrystallization of the metal and alloys via USP.

We successfully realized the surface nanocrystallization of 316L stainless steel via high-frequency USP. The average grain size of 316L stainless steel processed by USP is ~30 nm. Extremely fine nanograin with a grain size of less than 10 nm are fabricated via USP as well. Additionally, we establish a finite element simulation model to simulate the strain and stress distribution of 316L stainless steel during the USP process. The plastic strain
is attributed to the main factor for the surface nanocrystallization of the materials. The vibration of the surface with a frequency of 20 kHz and amplitude of 50 µm is simulated in the model. The interaction between the vibrating surface with the steel shots is defined as well. Additionally, a high-speed camera is employed to capture the motion behavior of the shot during the USP for the validation of the FE simulation model. The effects of the processing parameters of the USP, such as the frequency of the ultrasonic signal, amplitude, and working distance on the plastic strain of the materials, are studied and can be referred to for processing routine designs.

2. Materials and Methods

We use ultrasonic shot peening (USP) to realize the surface nanocrystallization of 316L stainless steel. This technology has been successfully used to get nano-grained copper [23], low-carbon steel [24], and aluminum alloys [17]. The frequency and amplitude of the ultrasonic shot peening process are 20 kHz and 50 µm, respectively. The diameter of the ultrasonic tip is 25 mm. Steel shots with the diameter of 3 mm are placed on the surface of the tip and the area coverage of the tip is 100%. High-velocity shots accelerated by high-frequency ultrasonic signals impact the target surface repeatedly, as illustrated in Figure 1a. The inset of Figure 1a illustrates the severe plastic deformation (SPD) introduced into the target materials after USP treatment, and the intense SPD can result in grain refinement of the target materials. It is expected that a gradient nano-grained surface can be generated on the target material along the cross-sectional direction, as illustrated in Figure 1a, due to the gradient severe plastic deformation during the USP process. Figure 1b illustrates the SEM characterization of the as-received coarse-grained (CG) 316L stainless steel and Figure 1c illustrates the statistical analysis of the grain size distribution of the CG 316L stainless steel. The average grain size of coarse-grained 316L stainless steel is ~32 µm.

![Figure 1](image-url)

**Figure 1.** Principle of the ultrasonic shot peening process and the initial condition of the as-received matrix materials: (a) scheme of the surface nanocrystallization of 316L stainless steel by ultrasonic shot peening; (b) SEM characterization of the as-received coarse-grained 316L stainless steel; (c) statistical analysis of the grain size distribution of the coarse-grained 316L stainless steel.
A scanning electron microscope (SEM) (Thermo Fisher Scientific, Waltham, MA, USA) is used to characterize the microstructure of 316L stainless steel on an FEI Quanta 3D FEG dual-beam system. The 316L stainless steel samples are polished according to the protocol with sandpaper and diamond paste and etched using a mixture of nitric acid, hydrochloric acid, and distilled water with a volume ratio of 1:1:1. A focused ion beam (FIB) is used for a transmission electron microscope (TEM) sample of the ultrasonic shot peened 316L stainless sample with the FEI Quanta 3D FEG dual-beam system. The treated sample is cut from the cross-sectional direction and loaded into the SEM. A TEM lamellar with the width and length of 6 µm and 10 µm, respectively, is cut from the sample and lifted out using the Oxford OmniProbe 200 (Oxford Instruments, Abingdon, United Kingdom) and welded on a FIB lift-out TEM grid. TEM characterization of the nanosized grains is conducted by the FEI Talos F200X (Thermo Fisher Scientific, Waltham, MA, USA) with an accelerating voltage of 200 kV. We use a Fastcam Nova S12 (Photron, Tokyo, Japan) to study the impact behavior of the shot during the USP process. We place a shot with a diameter of 3 mm on the surface of the tip and use a transparent chamber made from organic glass for observation. We set the camera to observe the USP process with fps of 40,000 and acquire a time duration of 1 s for data analysis. We establish a finite element (FE) model to simulate the high-frequency ultrasonic shot peening process on the Abaqus platform. The geometry of the FE simulation model can be seen in Figure 2. Firstly, we establish an FE simulation model to simulate the USP process with one steel shot and verify this simulation model experimentally. Then, we simulate the USP process using 100% coverage of the impact area. Nine steel shots with a diameter of 3 mm are placed on the vibrating surface. The interaction between the shots is considered and defined in the FE model during the simulation. The gravity field is applied to the whole FE model during the simulation. An ultrasonic vibration with a frequency of 20 kHz is applied on the vibrating surface. A materials model for 316L stainless steel reported by Chou et al. [35] is used in this FE simulation model. Table 1 summarizes the detailed key parameters used in the FE simulation model. We observed the motion behavior of the multiple shots via the high-speed camera as well.

![316L stainless steel target](image)

![High-strength steel shots](image)

![Ultrasonic vibration f=20KHz](image)

**Figure 2.** The finite element model to simulate the high-frequency ultrasonic shot peening process with a single shot.
Table 1. The key parameters for the FE simulation of the ultrasonic shot peening process with a single shot.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value/Set</th>
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<td>Yield strength (MPa)</td>
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<tr>
<td>Young’s modulus (GPa)</td>
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<tr>
<td>Poisson ratio</td>
<td>0.3</td>
</tr>
<tr>
<td>Density (g/cm$^3$)</td>
<td>7.8</td>
</tr>
<tr>
<td>Gravity field (m/s$^2$)</td>
<td>9.8</td>
</tr>
<tr>
<td>Vibrating frequency (kHz)</td>
<td>20</td>
</tr>
<tr>
<td>Vibrating amplitude (µm)</td>
<td>50</td>
</tr>
<tr>
<td>Working distance (mm)</td>
<td>5</td>
</tr>
<tr>
<td>Simulation duration (s)</td>
<td>$5.00 \times 10^{-4}$</td>
</tr>
<tr>
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</tr>
<tr>
<td>Steel shots</td>
<td>Rigid body</td>
</tr>
<tr>
<td>Vibrating surface</td>
<td>Deformable</td>
</tr>
</tbody>
</table>

3. Results

3.1. Gradient Nano-Grained 316L Stainless Steel

Figure 3a illustrates the bright-field TEM characterization of the gradient nano-grained 316L stainless steel fabricated via high-frequency USP with a processing time of 600 s. The average grain size of the materials increases gradually with the increase in depth from the topmost surface. This gradient characteristic of the treated sample is due to the gradient severe plastic strain of the sample along the cross-sectional direction during the USP process. Figure 3b illustrates the statistical analysis of the grain size distribution of the as-fabricated 316L stainless steel at the peened surface. The average grain size of the materials at area 1 is 33 nm. Extremely fined nanograins with a grain size of less than 10 nm are indicated by the red arrows. The extremely fined nanograins can benefit the mechanical strength and thermal stability of the gradient NC 316L stainless steel at the nanoscale. Figure 3c–e illustrates the statistical analysis of the grain size distribution of the materials at area 2, area 3, and area 4, respectively. The average grain size of the NC 316L stainless steel at area 2, area 3, and area 4 is 42 nm, 56 nm, and 77 nm, respectively. The portion of the extremely fine nanograins of the as-fabricated 316L stainless steel decreases with the increase of the depth from the peened surface according to the data analysis. Elongated nanograins indicated by the red arrows are characterized at area 4. The inset of Figure 3a is the selected area diffraction pattern (SADP) of the area circled by the red dashed line. The continuous diffraction rings indicate the formation of the nanosized grains. The stronger signals on the diffraction ring pointed at by the red arrows imply the formation of the orientated/elongated nanograins. Some of our publications have verified that the gradient nano-grained surface layer can improve the strength of 316L stainless steel. Herein, we pay more attention to the FE modeling for the surface nanocrystallization of 316L stainless steel during the USP process, because it is a challenge to establish accurate FE simulation for the USP process and it is important for materials scientists and engineers to understand the relationship between the process parameter and microstructure evaluation of the metal and alloys during the USP process.
Figure 3. Characterizations of the gradient nanograined 316L stainless steel subjected to the ultrasonic shot peening process: (a) Bright-field transmission electron microscope (TEM) characterization of the as-fabricated gradient nano-grained 316L stainless steel. The inset is the diffraction pattern for the area circled by the red dashed line. The average grain size of the gradient nano-grained structure at different locations can be seen in (b–e).

3.2. Simulation Results

Figure 4a illustrates the plane view and cross-sectional view of the calculated effective plastic strain of 316L stainless steel with a USP period of 0.01 s. Gradient plastic strain has been generated into the target materials and multiple impacts are predicted. Figure 4b illustrates the calculated von Mises stress of 316L stainless steel after a peening period of 0.01 s. One of the features of USP is that accumulated plastic strain can be introduced into the materials effectively. Four black points illustrated in the inset of Figure 4a on 316L stainless steel sample are selected and analyzed. Figure 4c illustrates the effective strain of the points with the peening time. There are nine impacts during this period for a single shot and effective plastic strain of the materials accumulates after each impact. The number of the impacts is determined by counting the number of the peak in Figure 4e. Figure 4d illustrates the calculated shot velocity. The peaks mean the change in impact direction, which suggest that the shot rebounds after impact with the target sample. Figure 4d illustrates the stress of the materials during the peening period. It can be seen in Figure 4e that stress peaks occur during each impact and the stress peak agrees well with the effective plastic strain increment, as illustrated in Figure 4c. The calculated velocity of the vibration surface is illustrated in Figure 4f. The input load of the vibration surface is an ultrasonic signal with a frequency of 20 kHz and an amplitude of 50 μm. The maximum velocity of the vibrating surface is 5.5 m/s. Shots will be accelerated by the vibrating surface and Figure 4e shows the velocity distribution of the shot during the USP process. It can be seen in Figure 4e that the velocity of the shot is not constant and the maximum velocity of the shot can reach 15 m/s. In general, the numerical results illustrated in Figure 4 indicate that the plastic strain, stress, and velocity of the shot have been successfully calculated and the established finite element simulation model can be used to simulate the USP process. However, typically dozens of seconds are needed for the surface nanocrystallization of the metal and alloys during the USP process. The time consumption for the simulation with a peening period of 0.01 s is half an hour using an Intel Core i5-8265U CUP @1.6GHz. A robust numerical method combined with the finite element simulation model can be used...
for simulating the USP with a longer peening period. We reported a numerical method to simulate the surface topography of the materials during the USP by combing the finite element method and numerical analysis [18,19]. In that case, the impact velocity and material properties are assumed to be constant. However, according to Figure 4e, the impact velocity of the shot is not constant, and it can be calculated by the finite element method or directly observed via a high-speed camera. We believe a more accurate and complicated method can be proposed based on this robust FE model to simulate the USP for a longer period.

Figure 4. Simulation results of a shot during the ultrasonic shot peening process: (a) Plane view of the simulation results of the target surface with a duration of $1 \times 10^{-2}$ s; (b) cross-sectional view of the simulation results of the target surface with a duration of $1 \times 10^{-2}$ s. (c) simulated PEEQ of the materials during the ultrasonic shot peening process; (d) simulated von Mises stress of the materials during the ultrasonic shot peening process; (e) simulated velocity of the shot; (f) simulated velocity of the vibrating surface.

4. Discussion

4.1. Grain Refinement

We reported the surface nanocrystallization of 316L stainless steel in our previously published work [16]. However, the grain refinement process of 316L stainless steel during USP was not given. Figure 5a–d illustrates the SEM characterizations of 316L stainless steel subjected to USP with peening periods of 60 s, 120 s, 240 s, and 600 s. Figure 5e–f illustrates the magnified SEM characterizations of the peened 316L stainless steel, as indicated by the
blue rectangles. It can be seen in Figure 5 e–f that with the increment in peening time, the thickness of the SPD layer increases. Figure 5i illustrates the scheme of the microstructure evolution of 316L stainless steel during the USP process. Surface nanocrystallization of 316L stainless steel during USP includes the following stages: (a) formation of the slip bands in the coarse grains; (b) formation of the subgrains due to the severe plastic deformation; (c) annihilation of the initial grain boundaries and the formation of the nanograins; and (d) formation of the extremely fine nanograins and the gradient nanocrystalline structure. According to Figure 5a, severe plastic deformation has been introduced into the target materials after a peening period in 60 s, which will increase the mechanical properties of 316L stainless steel significantly. Nanosized grains can be obtained on 316L stainless steel via USP with a peening period of 120 s, as illustrated in Figure 5b,f. Thicker and thicker nano-grained 316L stainless steel can be obtained with increments in peening period, which will benefit the mechanical properties of all components.

![Increased processing time (s)](image)

**Figure 5.** SEM characterizations of ultrasonic shot peened 316L stainless steel with peening periods of (a) 60 s, (b) 120 s, (c) 240 s, and (d) 600 s; magnified characterizations of the as-fabricated 316L stainless steel indicated by the blue rectangle with peening duration of (e) 60 s, (f) 120, (g) 240 s and (h) 600 s; (i) scheme of the microstructure evaluation of 316L stainless steel subjected to USP with different peening periods.

### 4.2. Validation of the FE Numerical Model

To validate the established finite element simulation experimentally, the movement of the shot during the USP is captured using the high-speed camera, as illustrated in Figure 6. The observed duration is 1 s with frames per second (fps) of 40,000. We capture and analyze the value and distribution of the shot velocity and rebound velocity experimentally. A shot is placed on the surface of the tip, as illustrated in Figure 6a. The vibration of the tip will accelerate the shot and impact the workpiece, as illustrated in Figure 6b,c. The impact velocity and the rebound velocity of the shot can be calculated by the position of the shot and the recorded time. The shot will move towards the vibrating surface after the impact as illustrated in Figure 6d,e. It will impact the vibrating surface again and change...
the direction of the motion as illustrated in Figure 6f. Due to the high frequency of the ultrasonic vibration of the surface, a single shot can impact the target surface more than 900 times in 1 s, as illustrated in Figure 7a.

Figure 6. Observations of the motion behavior of a shot during the ultrasonic shot peening process using a high-speed camera with 40,000 fps: (a) is the initial state of a shot; (b) shows a shot moving toward the target surface; (c) is an impact between the shot and the target surface; (d) shows the shot rebound back to the surface of the tip after the impact; (e) shows the shot moving toward the vibrating surface; and (f) shows the impact between the shot and the vibrating surface.

Figure 7. Data analysis of the motion behavior of a shot during ultrasonic shot peening process captured via the fast speed camera for 1 s: (a) the impact velocity of the shot; (b) the frequency of the impact velocity; (c) the rebound velocity of the shot; and (d) the frequency of the rebound velocity.
Figure 7 summarizes the data analysis of the captured motion behavior of the shot via the high-speed camera. The impact velocity is not constant and varies from 1 to 12 m/s in this case. A single shot can impact the target surface more than 900 times within 1 s and the distribution of the impact velocity can be seen in Figure 7b. According to the simulated results, the shot makes nine impacts within 0.01 s. Additionally, the simulated impact velocity is not a constant, it varies from 1 to 12 m/s and the distribution of the impact velocity agrees well with the recorded impact velocity as illustrated in Figure 4e, which means the established FE simulation model can accurately simulate the velocity of the shot during the USP process. Figure 7c,d illustrate the rebound velocity and their distribution, respectively. The energy transferred into 316L stainless steel during the USP process can be calculated using the experimental data.

The craters and the displacement of the simulated and experimental samples can be seen in Figure 8. Figure 8a illustrates the displacement distribution of 316L stainless steel surface with a peening duration of 0.01 s. The diameter of the crater is around 1.22 mm as illustrated in Figure 8b. Figure 8c illustrates the optical microscopy observation of two craters on the ultrasonic shot peened 316L stainless steel with a short peening duration. The diameter of the craters is around 1.19 mm, which indicates that the established FE simulation model can accurately simulate the motion behavior of the shot and the deformation of 316L stainless steel.

4.3. Parameter Investigations

4.3.1. Ultrasonic Frequency

The established simulation model in Section 3 is modified and used for parameter investigations. The effect of the ultrasonic frequency on the plastic strain and stress distribution of 316L stainless steel during the USP is studied. The peening period in
the simulated models is 0.05 s. The distribution of the von Mises stress, PEEQ, and maximum principal stress of the ultrasonic shot peened 316L stainless steel with the ultrasonic frequency of 20 kHz, 25 kHz, and 30 kHz is calculated and illustrated in Figure 9. With the increase in ultrasonic frequency, the SPD area, compressive residual stress, and PEEQ of the target surface increase gradually as illustrated in Figure 9. The peening intensity during the ultrasonic shot peening process can be increased by increasing the ultrasonic frequency.

Figure 9. Effect of ultrasonic frequency on von Mises stress, maximum principal stress, and plastic strain of 316L stainless steel during the ultrasonic shot peening process: (a–c) von Mises stress, maximum principal stress, and plastic strain of 316L stainless steel with USP frequency of 20 kHz, respectively; (d–f) von Mises stress, maximum principal stress, and plastic strain of 316L stainless steel with USP frequency of 25 kHz, respectively; (g–i) von Mises stress, maximum principal stress, and plastic strain of 316L stainless steel with USP frequency of 30 kHz, respectively; (j–l) comparison of von Mises stress, maximum principal stress, and plastic strain of 316L stainless steel with USP frequency of 20 kHz, 25 kHz and 30 kHz, respectively.
4.3.2. Working Distance

The effect of the working distance on the von Mises stress, maximum principal stress, and plastic strain of 316L stainless steel during USP is studied as well. Figure 10 illustrates the distribution of the von Mises stress, maximum principal stress and PEEQ of the ultrasonic shot peened 316L stainless steel with the working distance of 5 mm, 10 mm, and 15 mm, respectively. As illustrated in Figure 10, the compressive stress area and PEEQ of the ultrasonic shot peened 316L stainless steel decrease with the increase of the working distance. That’s because the increased working distance decreases the impact numbers as illustrated in Figure 10I. The shot needs more time and energy to travel from the vibrating surface to the target surface. The peening intensity can be adjusted by the working distance and the peening intensity decreases with the increase of the working distance during the ultrasonic shot peening process.

![Figure 10](image-url)

**Figure 10.** Effect of the working distance on the von Mises stress, maximum principal stress, and plastic strain of 316L stainless steel during the ultrasonic shot peening process: (a–c) von Mises stress, maximum principal stress, and plastic strain of 316L stainless steel with USP working distance of 5 mm, respectively; (d–f) von Mises stress, maximum principal stress, and plastic strain of 316L stainless steel with USP frequency of 10 mm, respectively; (e–i) von Mises stress, maximum principal stress, and plastic strain of 316L stainless steel with USP frequency of 15 mm, respectively; (j–l) comparison of von Mises stress, maximum principal stress, and plastic strain of 316L stainless steel with USP frequency of 5 mm, 10 mm and 15 mm, respectively.
4.3.3. Ultrasonic Amplitude

The effect of ultrasonic amplitude on von Mises stress, maximum principal stress, and plastic strain of 316L stainless steel during USP was studied. Figure 11 illustrates the distribution of von Mises stress, maximum principal stress, and PEEQ of ultrasonic shot peened 316L stainless steel with ultrasonic amplitude of 20 µm, 50 µm, and 80 µm, respectively. The SPD area of the ultrasonic shot peened 316L stainless steel increases with the increase of the ultrasonic amplitude as illustrated in Figure 11a,d,g. The PEEQ of the ultrasonic shot peened 316L stainless steel increases from $1.031 \times 10^{-1}$ to $3.846 \times 10^{-1}$ and decreases to $2.665 \times 10^{-1}$ with increased ultrasonic amplitude of 20 µm, 50 µm, and 80 µm. The maximum PEEQ can be achieved with ultrasonic amplitude of 50 µm as illustrated in Figure 11l.

Figure 11. Effect of ultrasonic amplitude on von Mises stress, maximum principal stress, and plastic strain of 316L stainless steel during ultrasonic shot peening process: (a–c) von Mises stress, maximum principal stress, and plastic strain of 316L stainless steel with USP amplitude of 20 µm, respectively; (d–f) von Mises stress, maximum principal stress, and plastic strain of 316L stainless steel with USP frequency of 50 µm, respectively; (e–i) von Mises stress, maximum principal stress, and plastic strain of 316L stainless steel with USP frequency of 80 µm, respectively; (j–l) comparison of von Mises stress, maximum principal stress, and plastic strain of 316L stainless steel with USP frequency of 20 µm, 50 µm and 80 µm, respectively.
4.4. Multiple Impacts and Verification

We establish an FE simulation model to simulate multiple impact processes for 316L stainless steel during the ultrasonic shot peening process, as illustrated in Figure 12. In this simulation model, nine steel shots are assembled in the model and the interactions between the shots and the chamber are considered. The gravity field is applied to the entire model. A vibrating surface with a frequency of 20 kHz and amplitude of 50 μm is defined in the FE simulation model as well. We run the simulation model on a Dell T7920 workstation for an ultrasonic shot peening duration of 0.1 s. It takes roughly 120 h to run this entire simulation and Figure 13 demonstrates the plastic strain (PEEQ) and von Mises stress distribution of the peened sample. The overlap of the multiple impacts as well as the interaction between the steel shots during the ultrasonic shot peening process can be accurately simulated in this FE simulation model. The ultrasonic shot peening process with multiple shots is modeled and calculated for the first time to the knowledge of the authors. We can accurately simulate the motion behavior of the multiple shots, the plastic deformation, and the displacement of the target surface as illustrated in Figure 13. The increment in PEEQ in the target surface and the residual stress at different locations along its thickness can be calculated as well. One big issue affecting the accuracy of the simulation model is the motion of the multiple shots, which is observed by high-speed camera in the next session.

The motion of the multiple shots is captured by the high-speed camera with fps of 10,000, as illustrated in Figure 14. Due to the interaction between the multiple shots, we identified a “relay” effect of the impact during the ultrasonic shot peening process. The collision between the shots with high velocity can shorten the working distance to increase the impact times during the USP process. For example, a shot moves downward after impact with the target surface. The shot can change move direction and impact upward to the target surface by making a collision with another shot with an upper velocity. This phenomenon is observed many times by high-speed cameras as illustrated in Figure 14 and we named it the relay effect during the USP process. The relay effect will significantly increase the peening/impact times of the USP by shortening the working distance.
Figure 12. Finite element simulation model for ultrasonic shot peening process with multiple steel shots: (a) entire meshed simulation model; (b) view of established FE model without steel chamber.

Figure 13. FE simulation of ultrasonic shot peening process of 316L stainless steel with multiple shots for a duration of 0.1 s: (a) plane view of PEEQ distribution of 316L stainless sample; (b) cross-sectional view of PEEQ distribution of 316L stainless sample; (c) plane view of von Mises stress distribution of 316L stainless sample; (d) cross-sectional view of von Mises stress distribution of 316L stainless sample; (e) accumulated PEEQ with time during the peening process for the four points marked in (a); and (f) the residual stress distribution of the peened 316L stainless steel along the four paths marked in (d).
An accurate finite element numerical model to simulate the USP process with multiple impact processes is established and verified experimentally for the first time to the authors’ knowledge. It is still challenging to simulate long-period multiple impacts during the USP process. Firstly, the time consumption of USP simulation for a long period is huge. In this case, the time consumed to simulate the USP process for 0.1 s with a Dell workstation is roughly 1 week. The surface nanocrystallization of 316L stainless steel needs a peening duration of no less than 120 s. Secondly, with the increase in peening duration, the microstructure and constitutive equation of 316L stainless steel will change. The strengthening of the material’s property during USP was not taken into consideration during the currently established FE simulation. With the established FE simulation, the effect of the process parameter of the USP can be revealed and can help materials scientists and engineers select reasonable process parameters for surface nanocrystallization of metal and alloys via USP in the future.
5. Conclusions

In this study, we successfully developed a nano-grained surface layer on 316L stainless steel using ultrasonic shot peening technology. We established a finite element simulation model to simulate the ultrasonic shot peening process and validated the numerical model with experimental results. Conclusions can be summarized as follows:

(a) Ultrasonic shot peening technology is an effective method for surface nanocrystalization of 316L stainless steel and the thickness of the nano-grained surface layer increases gradually with the increment of the processing time;

(b) The finite element simulation model can be used to simulate the impact behavior of the shot, stress, and strain distribution of the materials during the ultrasonic shot peening process. The multiple impacts of the shot with a short duration can be simulated using the established FE simulation model; however, it is still a challenge for a long-period simulation;

(c) According to the simulation results, the intensity of the impact during the ultrasonic shot peening process can be significantly improved by increasing the amplitude of the ultrasonic tip and frequency of the ultrasonic signal, as well as by decreasing the working distance from the target surface to the ultrasonic tip;

(d) The motion behavior of the multiple shots cannot be simplified by a series of single-shot impacts according to the observation of the high-speed camera during the ultrasonic shot peening process. We identified a relay effect for multiple impacts during the ultrasonic shot peening process experimentally. This relay effect can increase the efficiency of the ultrasonic shot peening process.

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References
