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Nanograined surface fabricated on the pure copper by ultrasonic shot peening and an energy-density based criterion for peening intensity quantification

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ABSTRACT

A nanograined (NG) surface layer with the thickness of no less than 70 μm was successfully fabricated on the pure copper by ultrasonic shot peening (USP) and the mechanical performance of the fabricated NG surface was measured by a nanoindenter. The nanohardness of the NG surface at the peened surface is 1.526 GPa, which was increased by 30% compared to that of the coarse-grained pure copper. In addition, the thickness of the strengthened surface is approximately 400 μm, which will potentially enhance the mechanical performances of the entire copper components. To control the surface nanocrystallization of pure copper during USP, an energy-density based criterion was proposed and formulated. High-speed camera was used to capture the motion behavior of a shot experimentally and the Lagrange description method was used to modelling the motion behavior of the shot mathematically. Coefficient of the restitution of the shot was calibrated based on the experimental data and embodied into the mathematical model. Research results indicated that the grain size and mechanical performance of the pure copper could be refined into nano-scaled regime and mechanical strengthened by means of USP efficiently. And the proposed energy-density based criterion for peening intensity quantification provided a reliable reference for the selection of the process parameters during the surface nanocrystallization of the metallic materials during USP.

1. Introduction

Pure copper and copper alloys play important roles in the industry applications. One of the limitations of the copper materials and/or components is their poor mechanical properties. Strain hardening and grain refinement are the two mechanisms for the mechanical enhancement of the metallic materials [1]. For example, Fang et al. developed a gradient nanograined surface layer on the pure copper by using the surface mechanical grinding treatment (SMGT). They found that tensile plasticity can be achieved in the nanograined surface layer where strain localization was suppressed when the nanograined surface layer was confined by a coarse-grained substrate with a gradient grain-size transition. Their experimental results also indicated that the gradient nanograined surface layer exhibits a 10 times higher yield strength and a tensile plasticity comparable to that of the coarse-grained substrate and can sustain a tensile true strain exceeding 100% without cracking [2]. Thus, surface nanocrystallization of the metallic materials provides an effective method to strengthen the mechanical performances of the entire components without changing the chemical components of the materials [3]. Currently, surface nanocrystallization has been realized on varies metallic materials such like stainless steel [4,5], copper [6–8], aluminum [9,10] and nickel [11–13] et al. As one of the severe plastic deformation methods, ultrasonic shot peening (USP) is acknowledged as an effective surface treatment method to increase the mechanical performances of the materials/components by compressive residual stress introduction and/or grain refinement [14,15]. Differing from the conventional shot peening, USP uses high frequency ultrasonic signal, typically 20 kHz or even higher, to accelerate steel shots. The high-speed shots will impact the target surface repeatedly in an enclosed chamber [16].

In spite of surface nanocrystallization of the pure copper and other metallic materials was realized by means of USP, the relationship between the process parameters and the thickness of the nanograined surface layer is still unknown and a proper process parameters selection reference is still not clear [17]. This situation results from the lack of a criterion to quantify the peening intensity for USP. For the conventional

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shot peening, Almen intensity was defined as a standard to quantify and classify the peening intensity. Differing from the conventional shot peening, USP deforms the entire peening area simultaneously and uniformly in an enclosed chamber in most cases. The peened area is also limited by the shape of the vibrating surface and chamber. It is difficult to apply Almen intensity in determining the peening intensity during USP. Hence, a new criterion and standard should be defined and formulated to quantify and classify the peening intensity during USP.

One of the straightforward ways is the energy-based method. However, there are some challenges when the authors want to do this work. The first challenge is the variation of the impact velocity during USP. Differing from the conventional shot peening, impact velocity of the USP is not a constant. The majority of the previously published literatures treated the shot velocity during USP as a constant to simply the calculation model [18]. Our recent findings indicated that the variation of the shot velocity during USP is remarkable and observable [19]. Secondly, the coefficient of restitution (COR) of the shot is a critical factor that could quantify the amount of energy that will be transferred into the plastic deformation of the target materials. It is the plastic deformation energy that contributing to the strain hardening and grain refinement of the metallic materials. Unfortunately, the COR is not a constant during USP and is affected by the impact velocity and the properties of the target materials as well.

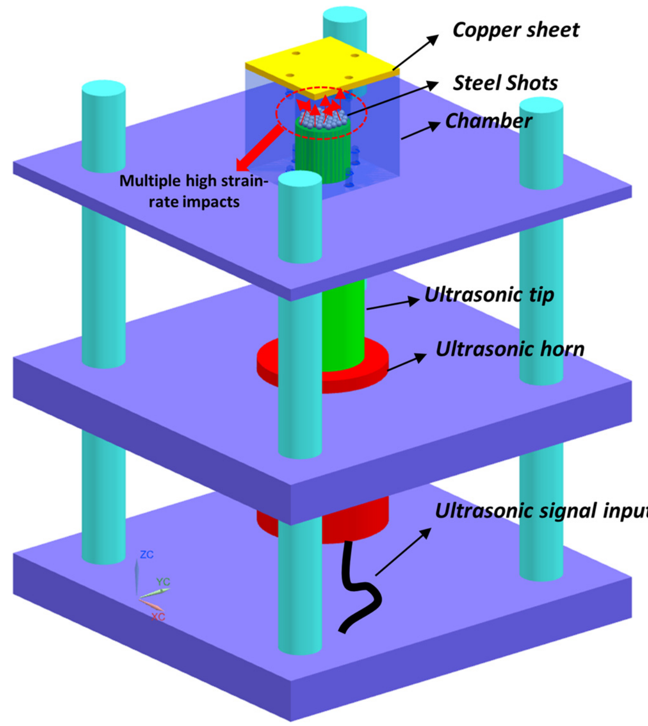

Fig. 1. The scheme of the ultrasonic shot peening utilized in this study.

2. Materials and experimental procedures

2.1. Materials and ultrasonic shot peening

Pure copper sheet with the thickness of 3 mm was purchased from the OnlineMetals. Surface nanocrystallization of the pure copper was performed according to the process parameters as shown in the Table 1. The diameter of the shot used in this study is 5 mm. The shots are placed on the surface of the tip and accelerated by the ultrasonic vibration with the frequency of 20 kHz and amplitude of 50 μm. The working distance during the USP is 12 mm. And the peening duration in this study is 10 min. Fig. 1 shows the scheme of the USP process. The detailed experimental set-up of the USP can be found in our previously published literatures [16,18–24].

2.2. Materials characterizations

Materials characterizations were performed on a FEI Nova 200 Dural-Beam system. The nanograined surface layer of the USPed materials was characterized by the focus ion beam (FIB) channeling contrast image with the operating voltage of 20 KV and the current of 4 pA. FIB channeling contrast imaging method guarantees the large cross-sectional area characterizations. However, one of the limitations of the FIB channeling contrast imaging is the damage caused by the ion beam. So, a proper selection of the current and voltage is needed to get high quality materials characterizations images. In addition, large area with perfect surface quality is another challenge for the FIB channeling contrast imaging. To get a perfect surface quality of such large area, an ion beam with the current of 0.1 nA was used for the final polish of the sample. The smaller ion beam current, the better surface quality and the longer milling time. The entire time cost for the milling and characterizations of the nanograined copper surface layer is about five hours.

Table 1
Selection of the process parameters for the nanograined surface fabrication on the pure copper.

Process parameters	Selection
Diameter of the shots (mm)	5
Number of the shot	21
Working distance (mm)	12
Peening duration (s)	600
Diameter of the probe (mm)	25
Ultrasonic frequency (KHz)	20
Ultrasonic amplitude (μm)	50

2.3. Nanohardness

Nanohardness measurements were performed on the USPed copper by using the Agilent Technologies Nanoindenter G200 with a standard Berkovich diamond indenter. The loading time and the hold period at maximum displacement was 20 s and 5 s, respectively. Mechanical properties including nanohardness and elastic modulus were directly obtained from force–displacement curves by standard Oliver and Pharr method [25]. A cross-sectional sample was prepared and the nanohardness along the cross-sectional direction was measured. Before the nanohardness measurements, the specimen was mounted and polished to get a mirror-like surface.

2.4. High speed camera

High speed camera was used to capture the motion behavior of a shot during USP. A shot was placed on the surface of the ultrasonic tip and a chamber made from the transparent plastic tube was used. The process parameters during this experiment were lists in the Table 1. For the high-speed camera observation, the number of the shot is one and the peening duration is 5 s. The high-speed camera could capture a peening duration of 2 s with frequency of 4000 frame/s.

3. Energy-density based criterion for peening intensity quantification during ultrasonic shot peening

3.1. Description of the energy-density based criterion

During the impact process, the kinetic energy of the shot will dissipate by two mechanisms, e.g. Stress wave propagation and plastic deformation. When impact occurs between a rigid-shot and the elastic-plastic metallic target, plastic deformation initiates if the initial kinetic

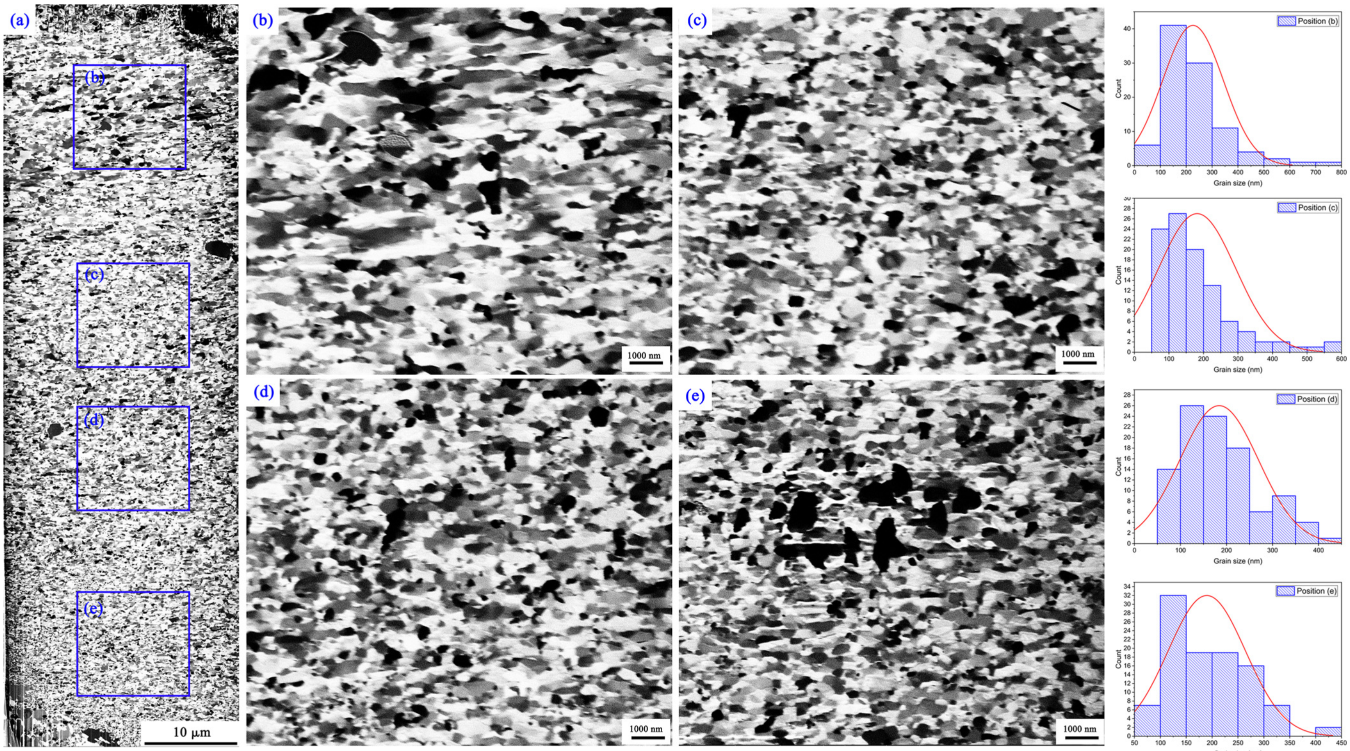

Fig. 2. (a) FIB channeling image of the ultrasonic shot peened copper from the cross-sectional direction; the magnified FIB channeling images of the materials at the location of (b) 10 μm, (c) 20 μm, (d) 40 μm, and (e) 60 μm depth from the peened surface and the corresponded grain size distributions.

energy of the shot is high enough. The initial kinetic energy converts into (a) elastic strain energy stored in the contacting bodies, (b) plastic strain energy to deform the materials and (c) energy for elastic waves to propagate [26]. Eq. (1) shows the energy conservation for an impact period:

$$\frac{1}{2}mv_1^2 = \frac{1}{2}mv_2^2 + \Delta E^p + \Delta E^{wave} \tag{1}$$

Where, v_1 and v_2 is the shot velocity before and after impact, respectively; ΔE^p is the plastic strain energy dissipation and was calculated as $\int \sigma_{ij} d\varepsilon_{ij}^p$. ΔE^{wave} is the stress wave energy dissipated during the impact process. Comparing to the plastic strain energy dissipation, the stress wave energy dissipation is only a small fraction of the kinetic energy and can be ignored. In addition, the relationship between the shot velocity v_1 and v_2 can be formulated as follows:

$$v_2 = C_1 v_1 \tag{2}$$

Where, C_1 is the COR between the shot and the target materials.

During USP, plastic strain energy is the energy that contribute to the grain refinement and mechanical strengthening of the target materials. The plastic strain energy can be easily calculated by ignoring the plastic wave energy dissipation shown as follows:

$$\Delta E = \frac{1}{2}mv_1^2 - \frac{1}{2}mv_2^2 = \frac{1}{2}mv_1^2(1 - C_1{}^2) \tag{3}$$

Thus, the entire kinetic energy transformation during USP can be formulated in the Eq. (4):

$$E = \sum_{j=1}^{M}\sum_{i=1}^{N} \Delta E_i^j \tag{4}$$

Where, M is the number of the shot used during USP; N is the impact time for each shot during USP and ΔE_i^j represents the kinetic energy transformation of the j^{th} shot during the i^{th} impact.

Hence, the energy-density based criterion for quantification of the peening intensity during USP can be formulated as follows:

$$E_\rho = \sum_{j=1}^{M}\sum_{i=1}^{N} \Delta E_i^j / A \tag{5}$$

Where, A is the peening area. The number of the shot M and the impact times N are relating to the selection of the process parameters.

3.2. Calculation algorithm

Using high-speed camera to observe the motion behavior of the shot during USP is proved to be an effective way to obtain the impact velocity, rebound velocity and COR of the shot. However, high speed camera was limited to its working duration and it is a heavy duty to process a large number of the frames. Hence, a reasonable numerical algorithm should be developed to describe the motion behavior of the shot during USP. According to the analysis of an impact period as illustrated in the Fig. 4 as shown in the following Section 4.3, the entire impact period can be classified into four states and they can be described via the mathematical language shown as follows:

State 1: $dU \le r$; Impact between the shot and vibrating surface occurs;

State 2: $r < dU < H - r - A * \sin(2 * pi * f * t)$; The shot velocity is in the positive direction; Gravity slows down the velocity of the shot;

State 3: $dU \ge H - r - A * \sin(2 * pi * f * t)$; Impact between the shot and workpiece occurs; The coefficient of restitution will be calculated according to Eq. (7);

State 4: $r < dU < H - r - A * \sin(2 * pi * f * t)$. The shot velocity is in the negative direction. Gravity accelerates the velocity of the shot;

Where, dU is the distance between the shot and the vibrating surface; r is the radius of the shot; H is the working distance of the ultrasonic shot peening; A is the amplitude of the ultrasonic signal; f is the frequency of the ultrasonic signal; t is the time.

Lagrange description method was used to trace the motion behavior of a shot and a dynamic system was established on the MATLAB platform to calculate the velocity of the shot during USP. A program was coded on the MATLAB platform to simulate the motion behavior of the shot during USP. And the program was tested with a peening duration of 2 s to compare with the experimental data captured by the high-speed camera.

4. Results

4.1. Characterization of the ultrathick nanograined surface

Fig. 2 shows the FIB channelling contrast images of the USPed pure copper. The entire microstructure of the polished area from the peened surface to the depth of 70 μm can be seen in Fig. 2(a). It can be seen in Fig. 2(a) that nano-sized grains were successfully fabricated on the surface of the ultrasonic shot peened copper and the thickness of this nanograined surface layer is 70 μm. Fig. 2(b)–(e) shows the magnified observations of the ultrasonic shot peened copper at the depth of 10 μm, 20 μm, 40 μm and 60 μm, respectively. It can be seen in the Fig. 2(b) that the nanograins at the topmost surface were elongated in a direction that perpendicular to the impact direction. There is no preferred orientation of the nanograins in the depth of 20 μm, 40 μm and 60 μm as shown in Fig. 2(c)–(e). The grain size distributions at the area (b)–(e) were analyzed as shown in the Fig. 2. There is no significant increment of the average grain size with increasing of the depth from the peened surface. The average grain size at these four areas is around 180 nm. And the developed ultrathick nanograined surface layer will significantly improve the mechanical performance of the copper components. The nanohardness and modulus tests will be demonstrated in the following sections.

4.2. Mechanical performance of the ultrasonic shot peened copper

Fig. 3, shows the variation of Young's Modulus and nanohardness of the ultrasonic shot peened copper along the cross-sectional direction. From Fig. 3(a), there is no change in the modulus between the nanograined surface layer and matrix material with the coarse grains. Fig. 3(b) shows the variation of nanohardness of the ultrasonic shot peened copper along the cross-sectional direction. The maximum nanohardness of the gradient nanograined copper is 1.526 GPa. And the average nanohardness of the coarse-grained copper is 1.182 GPa. Fig. 3(b) shows that the nanohardness decreases gradually with increase in the distance from the peened surface. That's because grain size increases gradually with increase in the distance from the peened surface, the presence of finer grains in metallic materials will result in better mechanical properties including higher hardness and better wear resistance. The thickness of the surface layer with enhanced mechanical properties is approximately 400 μm and can significantly increase the wear resistance and prolong the fatigue life of the material or components. This ultrathick nanograined surface layer will potentially breakthrough the mechanical limitations of the copper's applications in the related fields.

4.3. Motion behavior of the shot during USP

Fig. 4 shows a period of motion behavior of a shot during ultrasonic shot peening captured by the high-speed camera. Fig. 4(a) shows the initial position of the shot that seating on the vibrating surface. In the Fig. 4(b), the shot moves upward to the target surface. The kinetic energy was transferred from the vibrating surface to the shot. The gravity works on the moving shot and slows down the impact velocity of the shot in the Fig. 4(b). In the Fig. 4(c), the shot was impacting to the target surface. During the impact process, part of the initial kinetic energy will be transferred into the plastic deformation energy of the target materials. In the Fig. 4(d), the shot changed direction of the velocity and moved downward to the vibrating surface. In the Fig. 4(e), the shot was impacting to the vibrating surface and the direction of the velocity was changed after impact as shown in the Fig. 4(f). It can be seen in Fig. 4 that, the entire impact period of the shot during ultrasonic shot peening can be clearly recorded by a high-speed camera. The impact velocity and the rebound velocity can be calculated according to the observed results. In this case, the impact velocity of the shot is 3.1 m/s and the rebound velocity is 1.56 m/s. The coefficient of restitution of the shot during this impact is 0.5.

Fig. 5 shows the statistically analyzed experimental data obtained from the high-speed camera. The entire high-speed camera observation period is 2 s and the total impact time is 206. It can be seen in Fig. 5 that the shot velocity during ultrasonic shot peening is not a constant and it varied with the peening time. The rebound velocity and the coefficient of restitution were calculated and demonstrated in the Fig. 5 as well.

4.4. Coefficient of restitution calibration

Based on the experimental data, variation of the coefficient of restitution with the impact velocity during ultrasonic shot peening was investigated in this section. Table 2 listed the statistical analysis of the experimental data during the ultrasonic shot peening of pure copper. In the Table 2, the impact velocity, the corresponding coefficient restitution, the frequency of the impact velocity and the standard deviation of the coefficient of restitution with the same impact velocity were demonstrated.

To get the mathematical relationship between the coefficient of restitution and the impact velocity, a second order exponential function as shown in Eq. (6) was used to fit the experimental data:

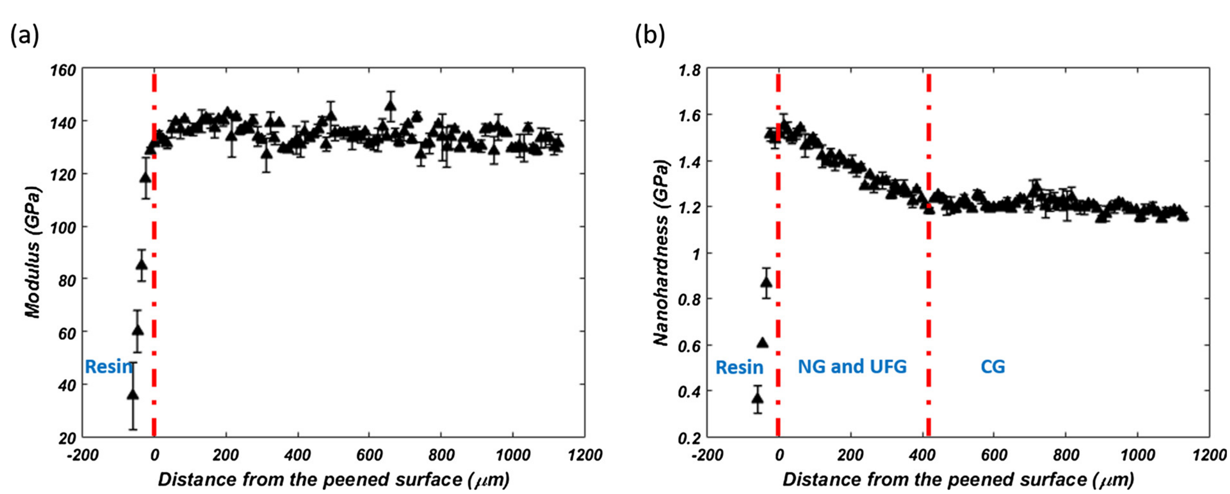

Fig. 3. (a) Young's modulus and (b) Nanohardness of the ultrasonic shot peened copper sample along the cross-sectional direction.

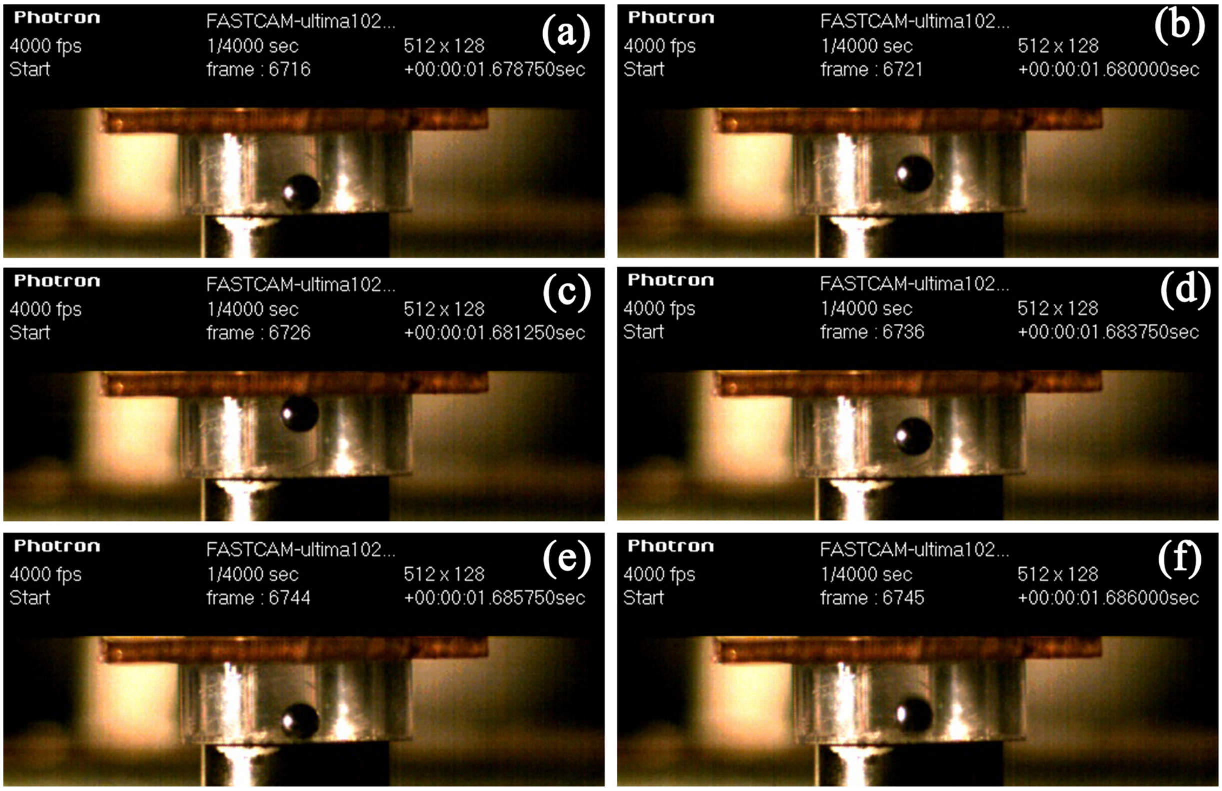

Fig. 4. Motion behavior of a shot during ultrasonic shot peening: (a) shot at the initial position; (b) the shot moves upward to the target surface; (c) the shot started to impact the target surface; (d) the shot move downward to the vibrating surface; (e) the shot started to impact the vibrating surface and (f) the shot move upward to the target surface again.

$$C_1 = a * e^{b*v_1} + c * e^{d*v_1} \quad (6)$$

Where, a, b, c, and d are the coefficients of the function; v_1 is the impact velocity and C_1 is the coefficient of restitution of the shot.

Fig. 6 shows the variation of the coefficient of restitution of the shot with the impact velocity and the line fitted by the MATLAB. After calculation, the mathematical function of the variation of the coefficient of restitution with the impact velocity during the ultrasonic shot peening can be seen as follows:

$$C_1 = 0.6078 * e^{-1.803*v_1} + 0.4794 * e^{-0.02571*v_1} \quad (7)$$

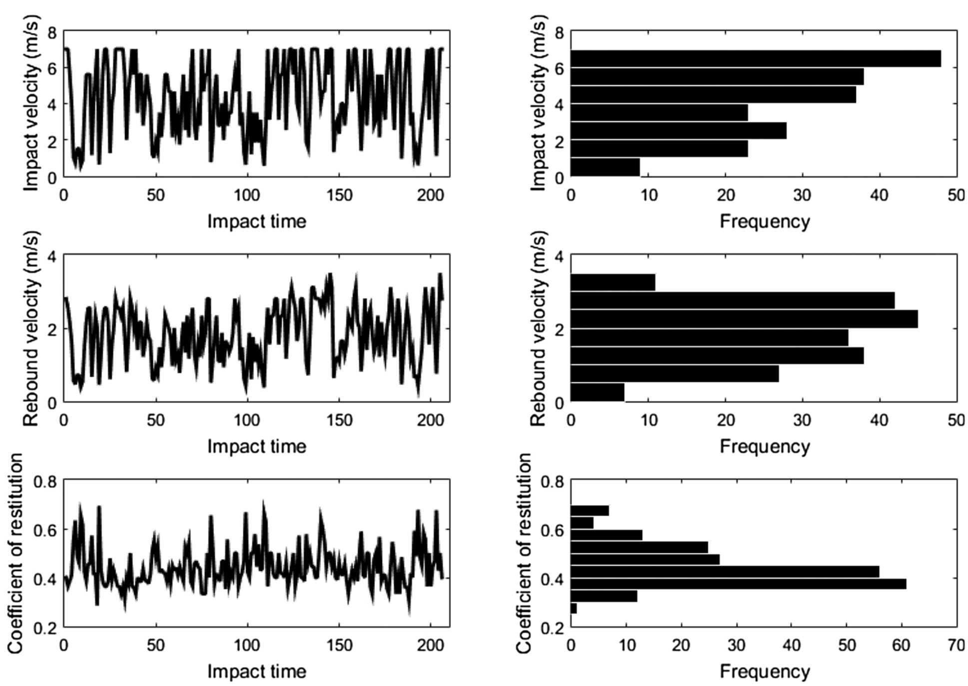

Fig. 5. Statistical analysis of the motion behavior of a shot during ultrasonic shot peening: Variation of the (a) impact velocity, (b) rebound velocity and (c) coefficient of restitution with the impact time and their corresponding distributions.

Table 2
Statistical analysis of the experimental data during the ultrasonic shot peening of pure copper.

No.	Impact velocity (m/s)	Average COR	Frequency	Standard Deviation	Probability (%)
1	0.571	0.662	1	–	0.485
2	0.596	0.653	1	–	0.485
3	0.609	0.676	1	–	0.485
4	0.636	0.667	1	–	0.485
5	0.651	0.694	1	–	0.485
6	0.737	0.633	1	–	0.485
7	0.778	0.655	1	–	0.485
8	0.875	0.615	1	–	0.485
9	0.966	0.483	1	–	0.485
10	1.037	0.551	2	0	0.971
11	1.077	0.591	1	–	0.485
12	1.120	0.676	1	–	0.485
13	1.167	0.571	1	–	0.485
14	1.217	0.506	2	0.008	0.971
15	1.273	0.478	1	–	0.485
16	1.333	0.472	2	0.007	0.971
17	1.400	0.557	2	0.044	0.971
18	1.474	0.487	2	0.000	0.971
19	1.556	0.462	2	0.000	0.971
20	1.647	0.436	1	0.000	0.485
21	1.750	0.444	1	–	0.485
22	1.867	0.531	5	0.047	2.427
23	2.000	0.444	3	0.038	1.456
24	2.154	0.502	5	0.058	2.427
25	2.333	0.462	1	–	0.485
26	2.545	0.465	5	0.039	2.427
27	2.800	0.455	14	0.067	6.796
28	3.111	0.450	10	0.046	4.854
29	3.500	0.442	13	0.052	6.311
30	4.000	0.443	17	0.070	8.252
31	4.667	0.441	20	0.073	9.709
32	5.600	0.408	38	0.057	18.447
33	7.000	0.388	48	0.045	23.301

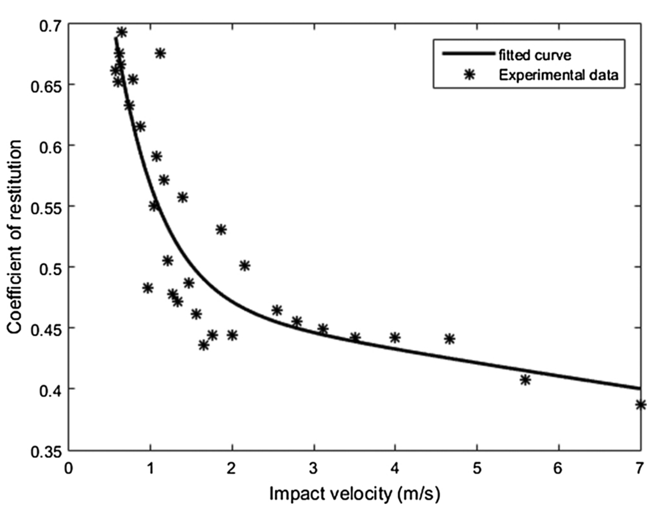

Fig. 6. Variation of the coefficient of restitution with the impact velocity.

It can be seen in the Fig. 6 that the coefficient of restitution decreases with the increment of the impact velocity of the shot. And the mathematical function as shown in the Eq. (7) will be used for the dynamic simulation of the peening process in the following section.

4.5. Numerical calculation

The program for the shot velocity prediction during ultrasonic shot peening was ran on the MATLAB platform and Fig. 7 shows the calculated impact velocity of the shot and the statistical distribution of the impact velocity during ultrasonic shot peening. It can be seen in the Fig. 7 that the number of impacts for two seconds is 217. According to the experimental results as shown in Fig. 5 and Table 2, the number of impacts for two seconds ultrasonic shot peening is 206. The calculated maximum impact velocity of the shot is 6.71 m/s. The observed maximum impact velocity of the shot is 7 m/s. In addition, the plastic energy dissipation was calculated according to the Eq. (4) based on the experimental data and calculated data, respectively. The experimental and calculated plastic energy dissipation is 1.0367 J and 1.244 J, respectively. The comparison between the experimental and calculated results indicated that the developed calculation model can predict the impact velocity of the shot and the plastic energy dissipation during ultrasonic shot peening.

5. Discussion

Nanograined surface was successfully fabricated on the pure copper by ultrasonic shot peeing with a peening duration of 600 s. The thickness of the nanograined surface layer was no less than 70 μm as characterized in Fig. 2 and the thickness of the strengthen surface is 400 μm according the mechanical testing results as illustrated in Fig. 3. It is the first time to use the FIB channeling contrast image technique to characterize such a large area of the pure copper subjected to the ultrasonic shot peening. This method was proved to be an effective method to characterize the nano grains of the metallic materials subjected to the ultrasonic shot peening. Nevertheless, nanograined surface was successfully fabricated on the pure copper by ultrasonic shot peening, one of the barriers that limiting mass production and industrial application of surface nanocrystallization of metallic materials/components via ultrasonic shot peening is the selection of the process parameters. To solve this problem, an energy-density based formula was proposed to quantify the peening intensity and a dynamic system was developed to predict the motion behavior of the shot. The coefficient of restitution of the shot during the dynamic system was calibrated via the experimental data. Variation of the impact velocity of the shot during ultrasonic shot peening was calculated and the distribution of the impact velocity was statistically analyzed.

Fig. 8 shows the calculated impact velocity and statistically distribution of the impact velocity of a shot with the peening duration of 6 s, 60 s and 600 s, respectively. It can be seen in Fig. 8 that the statistically distribution of the impact velocity agree well with the experimental results as illustrated in Fig. 5. The difference may result from the assumptions for the calculation model and will be discussed as follows.

Nanograined surface layer was fabricated on the pure copper according to the process parameters as listed in the Table 1. There are 21 shots in the chamber and the peening duration is 600 s with the peening area of 5.06e-04 m^2. The dynamic system was used to calculate the plastic energy dissipation during the entire ultrasonic shot peening process. There are some assumptions for this calculation: (a) The interaction between the shots will be ignored; (b) The multiple impacts can be treated as a sequence of single impact based on the truth that a materials point cannot impact with more than one shot at the same time; (c) All the impacts are assumed to be normal impact and the incident angle of the shot will be ignored.

Table 3 shows the calculated results of a shot during the surface nanocrystallization of pure copper with different peening duration. It can be seen in Table 3 that with the increment of the peening duration, the number of the impacts, plastic energy dissipation and the energy-density increases linearly. The power-density doesn't change with the change of the peening duration. The power-density is determined by the ultrasonic signal, the number of the shot, the diameter of the shot and working distance.

The experimental results indicated that the plastic energy dissipation of a shot during ultrasonic shot peening with the peening time of 2 s is 1.0367 J, which is 20% smaller than that of calculated plastic

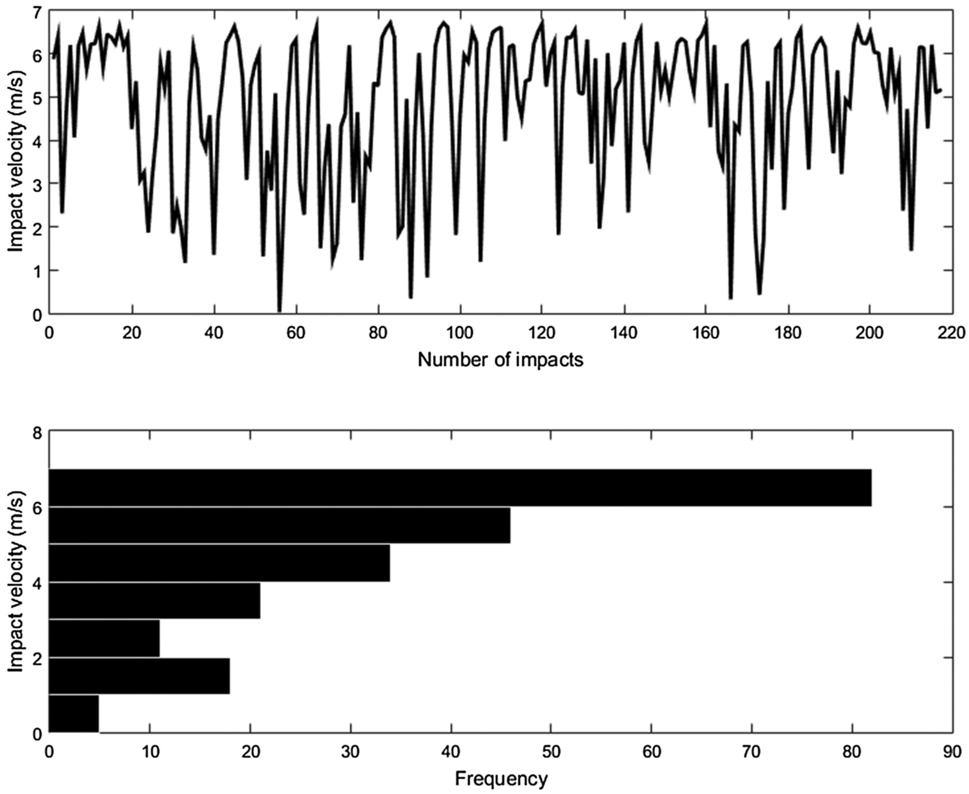

Fig. 7. Calculated impact velocity of the shot during ultrasonic shot peening process with the duration of 2 s and the statistical distribution of the impact velocity.

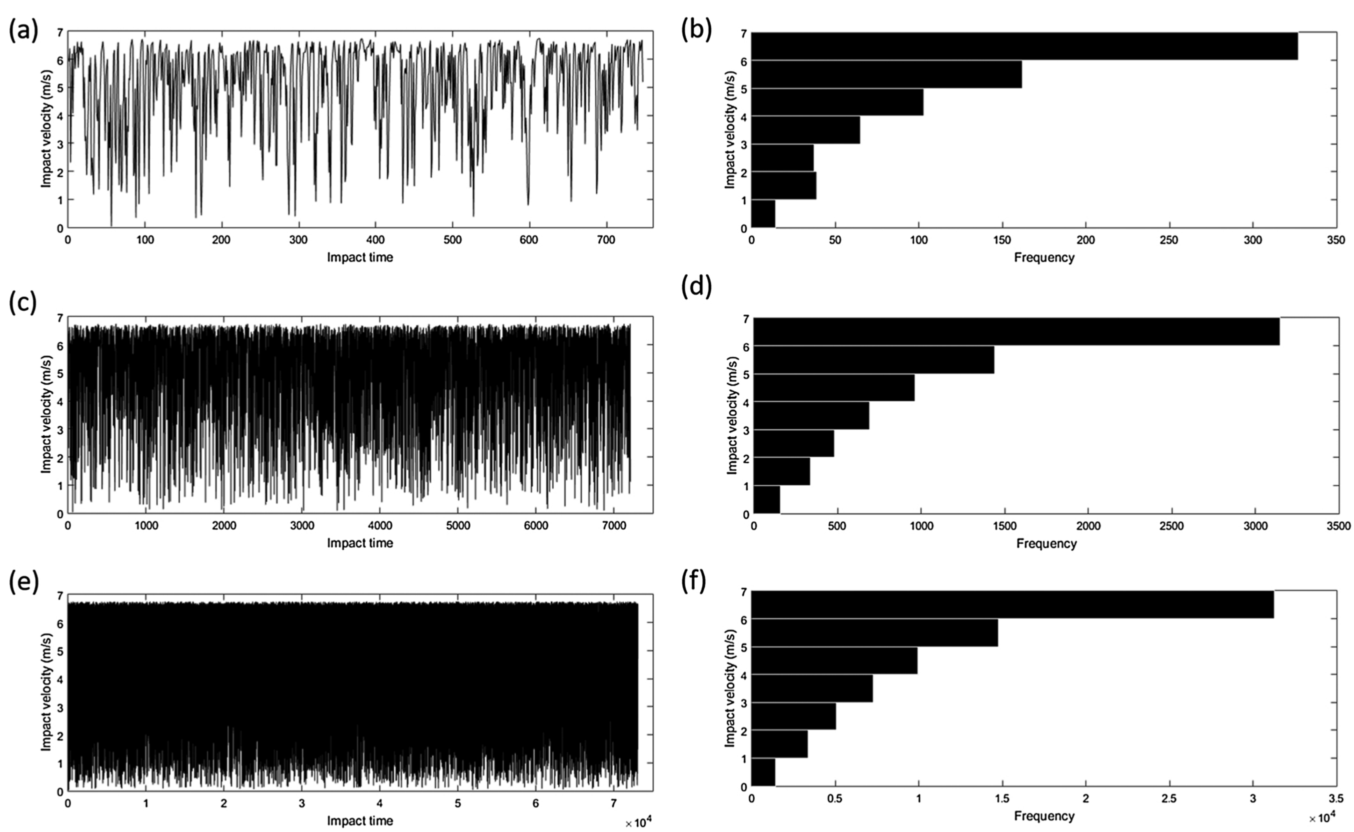

Fig. 8. Variation and statistical distribution of the impact velocity of a shot during surface nanocrystallization of copper with peening duration of (a, b) 6 s, (c, d) 60 s and (e, f) 600 s.

Table 3
The calculated results of the energy criterions of twenty-one shots during surface nanocrystallization of the pure copper with peening durations of 2 s, 6 s, 60 s and 600 s.

Peening duration (s)	Number of impacts	Plastic energy dissipation (J)	Energy-density (J/m^2)	Power-density (w/m^2)
2	4557	26.124	5.16E+04	2.58E+04
6	15687	98.238	1.94E+05	3.24E+04
60	151473	940.359	1.86E+06	3.10E+04
600	1534806	9474.822	1.87E+07	3.12E+04

energy dissipation 1.244 J. That's because the incident angle of the impact velocity was ignored in the calculation model. Ultrasonic shot peening could modify the surface topography of the targeted surface according to our previously research [18]. The rough surface will affect the direction of the impact velocity. For future study, the effect of the surface topography on the incident angle of the shot during ultrasonic shot peening process should be taken into consideration to improve the accuracy of the calculation model.

In addition, the coefficient of restitution of the shot is affected by the properties of the target materials. During the surface nanocrystallization of the pure copper, the mechanical properties and microstructure of the peening surface will be strengthened and refined. In the current calculation model, the coefficient of restitution was calibrated with the coarse-grained surface. For the long-term ultrasonic shot peening calculation, the coefficient of restitution should be calibrated with a rough and strengthened surface as well.

In summary, the proposed energy-density based method provides a quantified reference for the selection of the process parameters during surface nanocrystallization of the pure copper via ultrasonic shot peening. The established dynamic calculation model could predict the impact velocity, impact frequency and plastic energy dissipation during ultrasonic shot peening with an acceptable accurate level. More accurate calculation model could be established by taking into considerations of the incident angle of the shot and strengthen of the materials during the ultrasonic shot peening process.

6. Conclusions

In this paper, ultrasonic shot peening was employed to fabricate nanograined surface on the pure copper and an energy-density based criterion for peening intensity quantification during ultrasonic shot peening process was proposed and verified. Conclusions can be drawn as follows:

(a) Ultrathick nanograined surface with the thickness of no less than 70 μm was successfully fabricated on the pure copper by ultrasonic shot peening with a peening duration of 600 s and the nanohardness of the nanograined surface can be strengthened by 30% compared to the coarse-grained materials; The thickness of the entire strengthened surface layer is around 400 μm, which will potentially increase the mechanical performances of the materials or components;
(b) Shot velocity during surface nanocrystallization of the pure copper was measured and statistically analyzed and the coefficient of restitution during ultrasonic shot peening was calibrated mathematically. Research results indicated that the impact velocity during ultrasonic shot peening obeys statistical distribution and the formula between the coefficient of restitution and impact velocity during surface nanocrystallization of pure copper was given;
(c) An energy-density based criterion for peening intensity quantification during ultrasonic shot peening was proposed and an algorithm to predict the peening intensity during ultrasonic shot peening was programed. The calculated results agreed well with the experimental results, which will provide reliable references for the process parameters selection for the nanograined fabrication on the pure copper and/or metallic materials in future.

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