Investigation on Thermal Effect Induced by Ultrasonic Vibration on Surface Deformation Behavior During Micro-forging

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Abstract. In order to investigate the relationship between ultrasonic energy and thermal energy in micro-forming processes, as well as the effects of the resulting heat on the surface deformation. A novel ultrasonic-assisted micro-forging test system is designed, which can offer 60 kHz frequency to the pure copper specimens, face-centered cubic, and proper melting point under amplitude from 0–3.5 µm. A piezoelectric transducer was also used to provide vertical vibration at a lower frequency of about 21 kHz and 1 kHz under the same amplitude for comparison. Furthermore, a technique for directly measuring the surface temperature of the specimen was proposed. A thermoelectric couple with a diameter of 0.1 mm was put into the machined dimple in the specimen surface with a depth of 0.2 mm and width of 1 mm. The entire process was monitored by a high-sensitivity dynamic force sensing system to ensure correct frequency and to distinguish between acoustic softening and impact effects. The experimental results indicate that the increase in surface temperature caused by acoustic softening is very limited, even at high frequencies. The significant increase in temperature is mainly due to the impact effect, which results in high deformation rates. However, as the amplitude continues to increase, the thermal expansion effect caused by the continuous increase in surface temperature will enhance the surface deformation resistance, but this indirectly enhances the impact effect, resulting in more reduction of surface roughness.

Keywords: Thermal effect · Ultrasonic Vibration · Micro forming · Micro-forging · Surface deformation

1 Introduction

Since Blaha effect was reported in 1955 [1], Ultrasonic energy, as a kind of high-density energy, has been considered a more efficient and lower-cost method to assist in various machining and forming processes, such as welding [2], grinding [3], bending [4], and milling [5]. In the last decade, ultrasonic-assisted micro-forming processes have gained significant attention in both academic and industrial fields. The size effect is a critical factor in micro-forming, leading to increased forming stress [6], higher friction factors,

and a lower forming limit [7] as the geometry size of the metal part decreases. Compared to other high-energy density approaches, such as resistance heating [8] and laser [4]. Chunju Wang [9] has indicated that the effect of ultrasonic vibration in overcoming the size effect is performance, the flow stress reduction caused by ultrasonic vibration is inversely proportional to the geometry size of the specimens in micro-forming. The reduction ratio increased from 4.5% to 22.8% as the thickness of the specimens scaled-down from 0.32 mm to 0.04 mm under an ultrasonic-assisted tension test.

In the current study, two significant effects of ultrasonic energy were considered when applied to assist micro-forming processing: acoustic softening and impact effect. Acoustic softening is believed that could enhance the dislocation motion and decrease the real flowing stress by reducing the lattice resistance of dislocations [10]. Under low deformation strain, grain shape transforms from elongated to equiaxed, and dislocation density significantly decreases due to dynamic recovery by acoustic softening compared to non-ultrasonic assistance [11]. Meanwhile, the ultrasonic impact effect is another crucial factor created by vibrated punch detaching from the specimen's surface periodically, as reported by Wojciech Presz [12]. Furthermore, the impact effect was proved more efficient in improving the surface micro-plastic deformation in micro-forming with increasing amplitude [13]. Benefiting from these two effects, some problems caused by the size effect, such as increased surface friction between punch and specimens and higher deformation resistance, can be overcome.

However, the underlying mechanisms of these two effects are still unclarified. Some previous study shows that when ultrasonic energy works, acoustic energy will transmit to cause heating efficiently because of the drastic elasticity, which leads to the decrease of thermal value in dry creep feed grinding [14]. With the increase in amplitude, the impact effect becomes more significant, and this will cause more plastic deformation under the high strain rate. It could probably increase the local temperature on the sample's top side [15] or change the microstructure very close to the surface crystal to improve the deformation behavior [16]. Nevertheless, because of lacking an appropriate method to obtain the surface temperature value during micro-forming processing, studying the relationship between the surface thermal and ultrasonic energy is insufficient. To better understand the mechanism of ultrasonic energy, investigating the temperature history during the micro-forming process is reasonably necessary.

In this study, a novel ultrasonic-assisted micro-forging system is used to offer ultrasonic energy to the commercial copper surface during the micro-forging process under different conditions. A technique for directly measuring the surface temperature of the specimen is proposed so that the surface temperature change induced by acoustics softening and impact effect can be recorded. Additionally, in order to investigate the influence of thermal energy on the material surface, an AMF (atomic force microscopy) is used to observe the deformation behavior of surface asperities.

2   Experiment Setup

2.1   Design of the Micro-Forging Device

Ultrasonic-assisted micro-forging test system. A novel test system for ultrasonic-assisted micro-forging has been established, which consists of an upper die assembly, a lower die, and an ultrasonic vibrator, as demonstrated in Fig. 1a. To ensure experimental requirements, two sets of ultrasonic-assisted punches will be utilized to achieve different frequencies. As illustrated in Fig. 1b, a micro-forging punch capable of producing high-frequency vibrations will be utilized in the experiment.
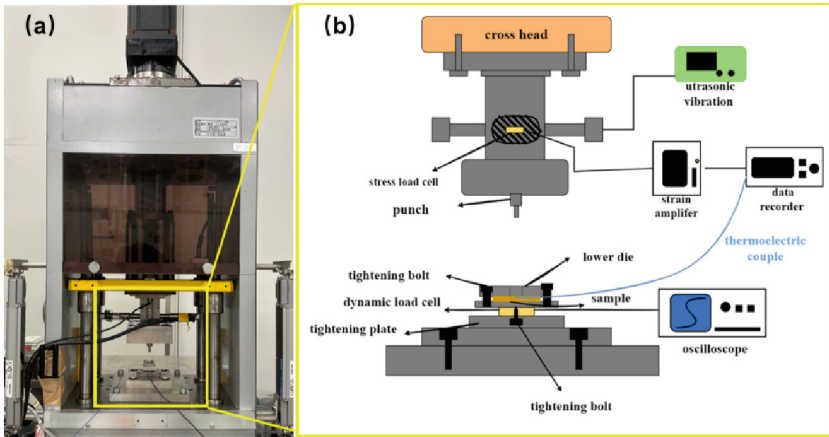
Fig. 1. Configuration of the ultrasonic-assisted micro-forging system, (a) Appearance of miniature desktop servo press machine, and (b) Schematic illustration of the micro-forging system of high-frequency.

Figure 2 shows the integrated structure of the ultrasonic vibrator. Two horizontal transducers generated ultrasonic vibration, originally in the same phase. Then, the punch received the vibration, which was amplified and transformed in a vertical direction by a specially designed horn. Finally, the maximum amplitude of 6 μm (peak-peak) on the punch tip was measured by a laser displacement meter (LC-2400, KEYENCE, Tokyo, Japan). The input electrical signal for the ultrasonic transducers was a sine wave, with a frequency of 60 kHz, from an ultrasonic signal generator.

To conduct the experiment on low-frequency vibrations, the micro-forging punch shown in Fig. 3a can be used by replacing the high-frequency vibration generator. The punch includes a vibration generator, an amplifier, and a piezoelectric transducer (PZT) driver. Two PZT drivers with different models have been prepared to achieve different frequencies. As illustrated in Fig. 3b, The preload was obtained by the load cell located at the end of the punch.

The vibration is provided by two different PTZs, one with a maximum amplitude of 9 μm and a maximum frequency of 140 kHz is used to offer 21 kHz frequency, as shown in Fig. 4a. And the other with an amplitude of 17 μm and a maximum frequency
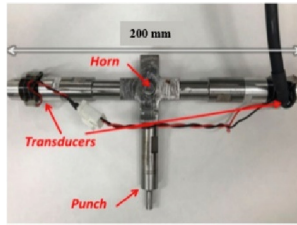
Fig. 2. (a) Integrated structure of ultrasonic vibrator
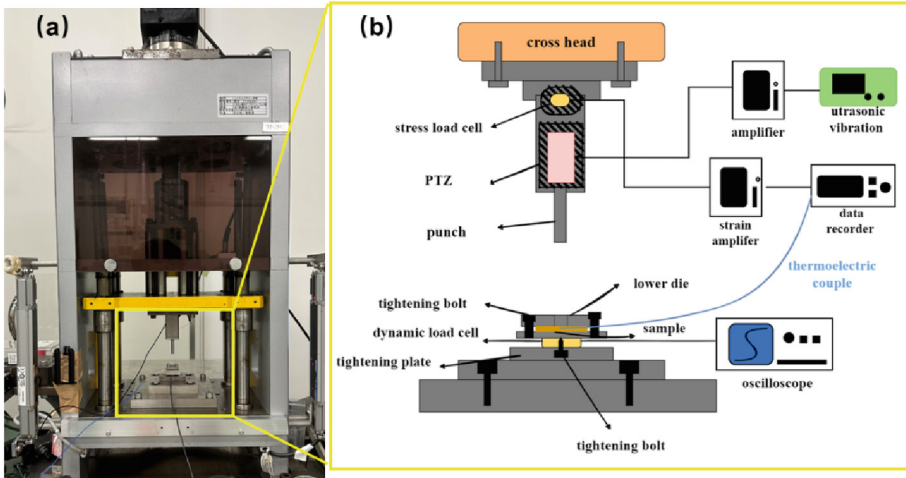

Fig. 3. Configuration of the ultrasonic-assisted micro-forging system, (a) Appearance of minia-
ture desktop servo press machine, and (b) Schematic illustration of the micro-forging system of
low-frequency.

of 7 kHz is used to offer 1 kHz frequency, as shown in Fig. 4b. The maximum output
force of both PTZs is 850 N.

Dynamic force test system. A dynamic load cell (Kistler 9132B), oscilloscope (Tek-
tronix, DPO2014), and data recorder (OMRON ZR-RX70) is made up of a data collection
module to measure the dynamic force, as shown in Fig. 5. Because of the high rigidity
of the dynamic load cell (Kistler 9132B) is suitable for measuring rapidly changing
force, so the tiny force change during the processing would be detected, which means
that if the impact effect happened, the punch would detach with the specimens surface
transitorily so the wave on the oscilloscope would distort form sin wave to non-sin wave.
Otherwise, there is only acoustic softening work, and the wave in the oscilloscope would
keep the sin wave always during the whole micro-forging processing. Its reliability has
been proved in the previous study [15] and performed well in the later experiment.

Surface temperature monitoring system and the specimen. The specimen material
used in the investigation is pure copper plates with an initial thickness of 2 mm. All
the specimens were cut into 10 mm × 10 mm from one sheet for use, as shown in
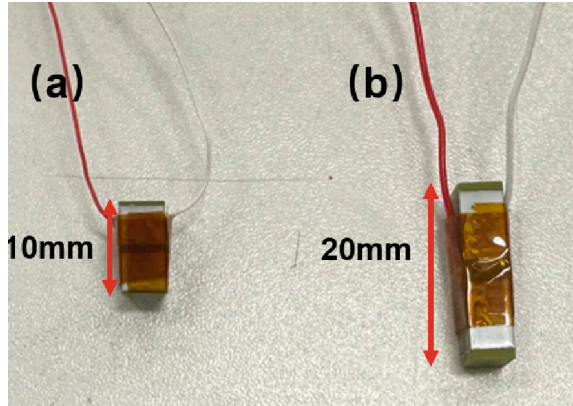
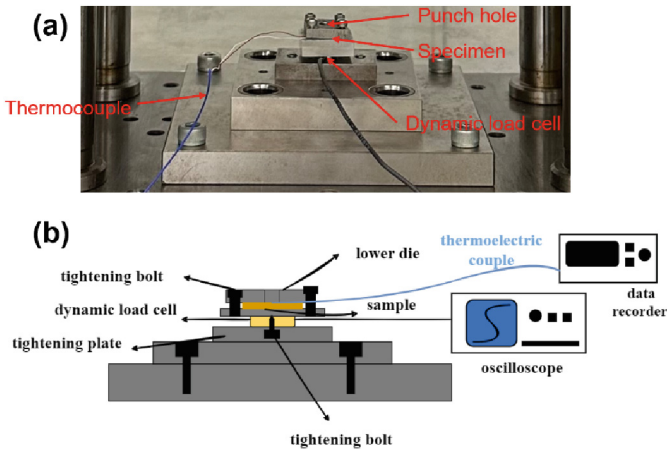**Fig. 4.** Piezoelectric transducer (PZT) driver (a) 21 kHz (b) 1 kHz.

Fig. 5. (a) the lower die (b) schematic of a dynamic force test system.

Fig. 6a. In order to obtain the surface temperature change during the process correctly, a thermoelectric couple with a 0.1 mm diameter was used. It was placed into the sample surface where was machined a tiny dimple with a depth of 0.2 mm and a width of 1 mm while processing. And to keep sure the vibration would not be disturbed by a thermoelectric couple during processing, it would be fixed in the bottom of the dimple by conductive adhesive, as shown in Fig. 6b.

Temperature check by infrared thermometer. To ensure the reliability of the temperature monitoring system, non-contact infrared thermometers were used to check the temperature measured by the thermocouples, as shown in Fig. 7. However, due to the infrared thermometer cannot directly measure the area where the punch and the specimen contact, which is also the reason why thermocouples were selected for the formal
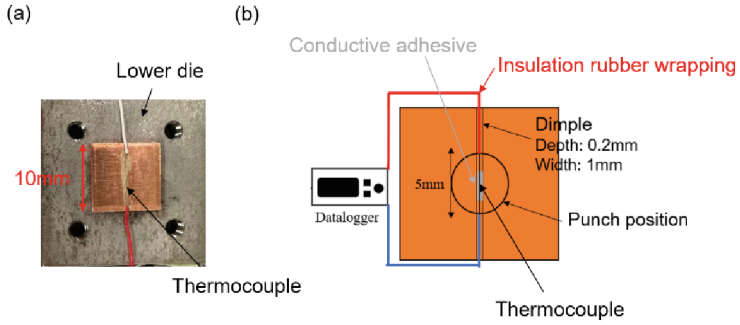
Fig. 6. (a) specimen on the lower die (b) schematic of surface temperature monitoring system.

experiment, the measurement point can only close to contact area as well as possible. The temperature change curves measured by the two methods are presented in Fig. 8.
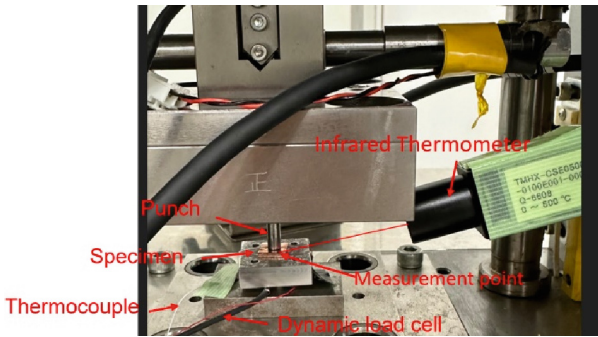

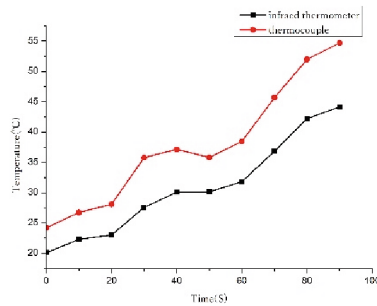**Fig. 7.** Calibration of temperature by Infrared Thermometer.

Fig. 8. Temperature change curves by the two methods.

2.2   Forging Test Condition

Both of the punches are made from tool steel (SKD11), and the surfaces are fine-grinded with the heat treatment, keeping the surface roughness on Ra = 0.1 µm. Since all the small pieces of chips are cut from a big one, the initial surface roughness can be Rs = 0.3 µm.

The impact effect is more difficult to observe under larger preloads, so the Preload is set to 30 N. Vibration would keep the 60 s in every process to observe a temperature-changing history easier. According to the theory of wave energy [14], the ultrasonic energy density (I) depends on the vibration amplitude (A) and frequency (f). Equation (1) defines the ultrasonic energy density (I):

$$ I = \frac{\overline{P}}{S} = \frac{1}{2}\rho A^2 \omega^2 u \tag{1} $$

where P is the average energy flow (output power) through area S during a period of time, ρ the density of the material in which the ultrasonic can travel (ρ = 7.8 × 103 kg/m³ in steel), ω the angular frequency (ω = 2πf), and u the wave velocity in the media (u = 5200 m/s in steel).

Consequently, to compare the temperature changes under different ultrasonic energy densities, three groups of forging tests were conducted at frequencies of 1 kHz, 21 kHz, and 60 kHz. Each group consisted of six specimens processed with six different amplitudes of 0.5, 1, 1.5, 2, 3, and 3.5 µm.

3   Result and Discussion

3.1   Separation of Acoustic Softening and Impact Effect

Based on the Dynamic force test system, the waveform with different ultrasonic amplitudes during processing would be recorded by oscilloscope. According to the changing waveform displayed on the oscilloscope, which kind of effect is at work could be estimated, as shown in Fig. 9, when the waveforms are typical sinewaves, the same as the input electrical signal. It indicates the continuous contact between vibrated punch and specimens as Fig. 9a and only acoustic softening work. Otherwise, the waveform would distort to a non-sin waveform, as shown in Fig. 9b, which indicates the impact effect happened. In this study, sin waveform will occur at the amplitude of 0.5 µm, 1 µm, and 1.5 µm. Then it would be distorted to a non-sin waveform when the amplitude increase to 2 µm, 2.5 µm, and 3.5 µm.

3.2   Influence of Different Ultrasonic Energy on Surface Temperature

The amplitude versus temperature change under different frequencies. The temperature change curves under different amplitudes and frequencies are presented in Fig. 10a. For the low frequencies of 1 kHz and 21 kHz, the temperature change at 21 kHz should be 400 times higher than at 1 kHz for the same amplitude. However, the actual temperature change observed in the experiment was only 5°C. Similarly, although the temperature
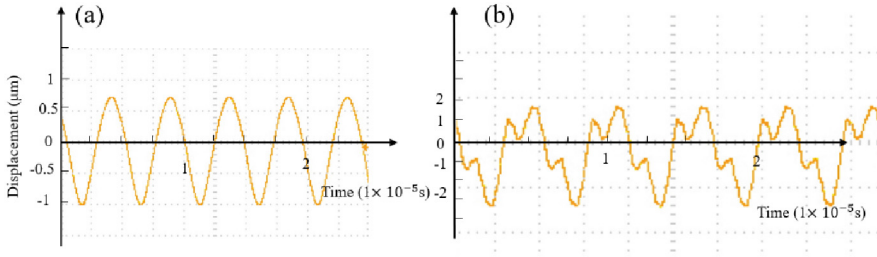
Fig. 9. The waveform of (a) acoustic softening, (b) impact effect.

change should increase 9 times from 21 kHz to 60 kHz for the same amplitude, the actual temperature change observed was 25°C. The difference in temperature change means that under low frequency, the absorption rate of material to ultrasonic energy is relatively higher; most of the ultrasonic energy is absorbed by the material as acoustic softening to reduce the dislocation density in the inner material. As a result, only a small amount of energy is converted to heat, leading to a limited increase in surface temperature.

Moreover, when the vibration happens at low amplitude, the asperities on the surface would absorb much of the ultrasonic energy by elastic deformation. It is used to overcome the lattice resistance for dislocation in the microstructure. So, despite the frequency increase of about sixty times, the temperature increase remains limited until the amplitude reaches 2 µm. However, a significant temperature rise is observed after the impact effect occurs, indicating the occurrence of plastic deformation of the surface asperities, which generates heat. As the amplitude increases, the deformation amount gradually increases, and the higher strain rate under high frequency generates more heat. This is why the temperature change curve under a maximum ultrasonic density of 60 kHz, 3.5 µm in Fig. 10a increases so drastically.
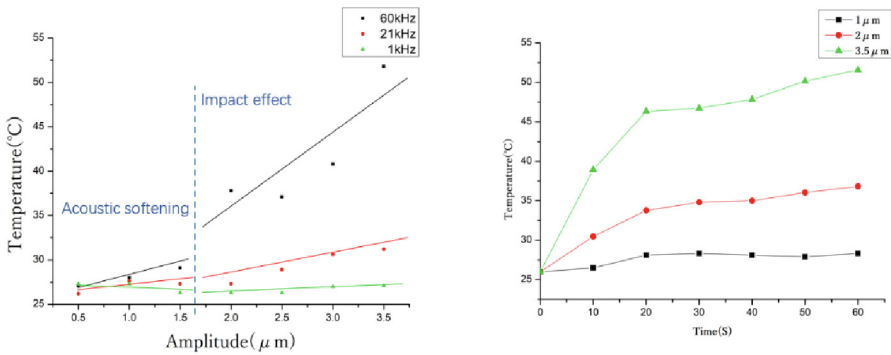

Fig. 10. (a) temperature amplitude under different frequencies. (b) temperature-time under different amplitude and 60 kHz.

The times versus temperature change under different amplitudes. To better understand the role of the acoustic softening and the impact effect on the temperature

increase, the temperature change of 1 μm, 2 μm, and 3.5 μm under 60 kHz in the 60 s is converted to time-temperature curves in Fig. 10b. In the case of 1 μm amplitude, the temperature change curve fluctuated within 60 s but remained relatively flat overall. This indicates that acoustic softening had little effect on increasing the material temperature, even if it was only the surface temperature. In contrast, when the impact effect occurred at 2 μm and 3.5 μm amplitudes, the overall increasing trend of surface temperature became more evident, with a rapid temperature increase observed in the first 20 s. This rapid increase is most likely due to the heat generated by the plastic deformation of surface asperities caused by the impact effect. The heat then accumulated rapidly in the initial time and gradually diffused from the surface to the entire material, resulting in a tendency for the rate of surface temperature increase to flatten over time.

Effect of Heat Effect on Surface Deformation.
The surface roughness change is also investigated in this study to learn deformation behavior under different temperatures. As shown in Fig. 11, before the impact effect happens at 1 μm amplitude, although the temperature increase is not significant under any frequency, the enhancement of acoustic softening with increasing frequency has a more substantial influence on reducing surface roughness. At the 2 μm amplitude, that impact effect just happened, the temperature increase at 60 kHz is significantly higher than that at low frequency, but the reduction of surface roughness decreases. When the amplitude continues to increase to 3.5 μm, the temperature increase at 60 kHz is the most significant compared to 20 kHz and 1 kHz, and the reduction of surface roughness also increases again.
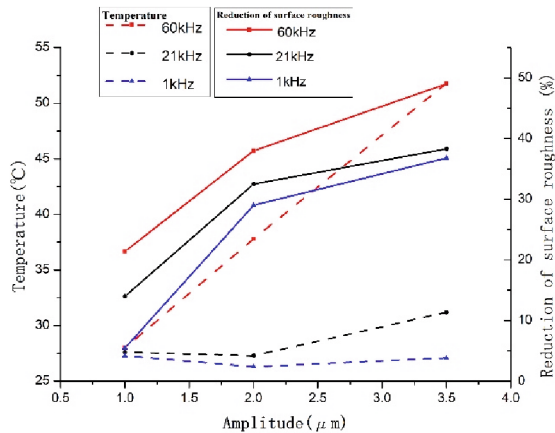

Fig. 11. Temperature and surface roughness reduction with different amplitude.

Figure 12 presents the stress and temperature variation curves at different amplitudes within 60 s under a frequency of 60 kHz. Figure 12a shows that the punch load gradually decreases after the vibration starts with 1 μm amplitude, it suggests a stress reduction brought about by acoustic softening. When the amplitude increase to 2μm, the punch load also increases with the temperature rise, as shown in Fig. 12b, which is likely

caused by thermal expansion. It also explains why at this point, the decrease in surface roughness rate is not as high as at lower frequencies. If the amplitude increases to 3.5 μm Fig. 12c. In that case, The higher temperature not only causes an increase in the punch load but also leads to more volume expansion due to thermal expansion, resulting in more deformation created by the impact effect, which indirectly enhances the impact effect.
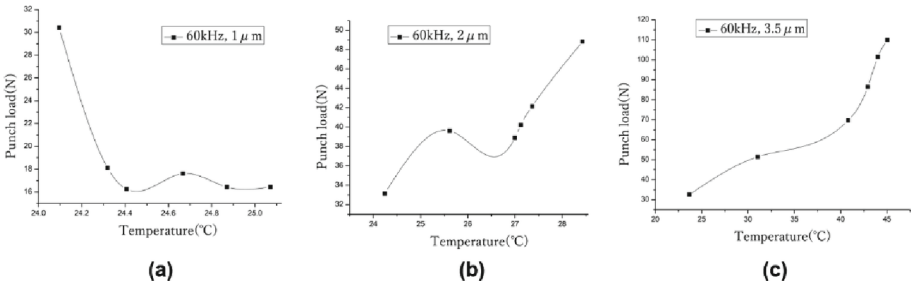

Fig. 12. Stress-temperature curve of 60 kHz within the 60 s (a) 1 μm (b) 2 μm (c) 3.5 μm.

Figure 13 is pictured by AFM, and it shows the sample's surface after processing at different frequencies with an amplitude of 3.5 μm; the surface at the highest frequency is obviously finer. It suggested that only when the ultrasonic energy density is high enough, and the impact effect occurs at the same time, the surface temperature can be raised to a level sufficient to generate more volume expansion, thereby further enhancing the surface deformation produced by the impact effect.
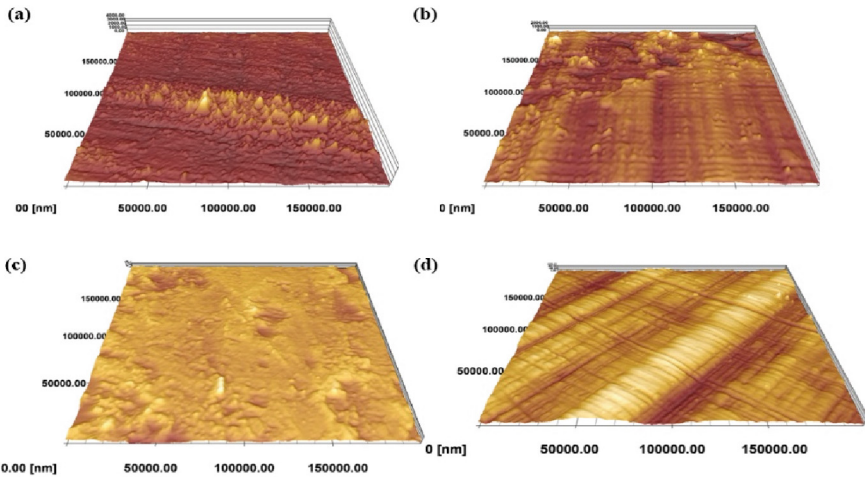

Fig. 13. The topographies of the sample surface under 3.5 μm amplitude (a) original (b) 1 kHz (c) 21 kHz (d) 60 kHz

4   Conclusion

In this study, a novel method of measuring surface temperature is conducted to investigate the temperature change in the material surface induced by acoustic softening and impact effect during the ultrasonic vibration-assisted micro-forging process. A longitudinal ultrasonic-assisted micro-forging test of 60 kHz, 21 kHz, and 1 kHz was carried out at different amplitudes on commercially pure copper specimens. Based on the result of experiments, the relationship between temperature change and various ultrasonic energy densities is discussed, and the measurement of 3D surface topographies also was obtained. It can be concluded as follows:

1. The acoustic softening and impact effect were successfully separated in the ultrasonic-assisted micro-forging experiment through waveform analysis using a specially designed dynamic force test system.
2. Regardless of the frequency, the surface temperature increase caused by acoustic softening is very limited. More heat is generated with the appearance of the impact effect, and in this case, higher ultrasonic energy density leads to a higher conversion rate from ultrasonic energy to heat energy.
3. With an amplitude of 2 μm, the reduction in surface roughness caused by the impact effect is less than that under low-frequency conditions due to the influence of surface temperature. However, with the increase of amplitude, the higher temperature caused by the impact effect under high frequency will cause more surface deformation, resulting in a continuous decrease in surface roughness.

In this paper, qualitative research on surface temperature changes caused by ultrasonic energy has been conducted. However, in order to further quantitatively study, future research needs to improve the accuracy of temperature measurements.

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