Materials Research Proceedings 44 (2024) 297-304 https://doi.org/10.21741/9781644903254-32

Reduction of springback of Ti6Al4V alloy in ultrasonic vibration assisted deformation: Numerical simulation and experimental study

GAO Meng[1,a], WEN Dongxu[1,b,*], LI Jianjun[1,c] and HUANG Liang[1,d]

[1]State Key Laboratory of Materials Processing and Die & Mould Technology, School of Materials Science and Engineering, Huazhong University of Science and Technology, 1037 Luoyu Road, Wuhan, China

[a]gaomeng@hust.edu.cn, [b]dxwen@hust.edu.cn, [c]jianjun@hust.edu.cn, [d]huangliang@hust.edu.cn

Keywords: Ultrasonic Vibration, Titanium Alloys, Forming Process, Numerical Simulation

Abstract. The ultrasonic vibration assisted bending tests of Ti6Al4V are conducted under different forming temperatures and vibration amplitudes. The effects of forming temperature and vibration amplitude are investigated. Moreover, based on ABAQUS software and explicit solver, the ultrasonic vibration-assisted bending deformation process is simulated to explore the influence of temperature and amplitude on the springback of the plate. The results show that the springback of the plate decreases with the increase of vibration amplitude. Increasing the temperature can also reduce the springback of the plate. At 1000°C, increasing the amplitude shows the best effect on reducing the springback of the plate. The finite element simulation results show that increasing the amplitude can reduce the stress in the central deformation area and makes the stress distribution uniform. The increase of temperature reduces the overall deformation stress of the plate, thereby reducing the springback of the plate.

Introduction

Titanium alloys have been widely used in aerospace and aviation applications due to their attractive comprehensive properties such as high specific strength, excellent fracture toughness, and good heat resistance [1]. However, due to the poor formability of titanium alloys, it is difficult to form complex parts at room temperature. And the important reason for the poor formability of titanium alloy at room temperature is springback. Springback is one of the most serious defects in metal forming industry, because the shape of stamping parts after springback is related to the whole forming process [2]. Effective springback control is a key requirement for zero-defect metal forming and intelligent manufacturing.

Hot forming process is a traditional method to improve the formability of titanium alloy thin-walled plate [3]. However, this process has the disadvantages of surface oxidation, short mold life, complex microstructure evolution and high energy consumption [4]. As a new multi-energy field forming technology, ultrasonic vibration assisted forming has the advantages of green, energy saving and high efficiency [5]. During the deformation process, ultrasonic vibration assisted forming can effectively reduce the deformation resistance and improve the elongation and surface quality [6]. Therefore, it is expected to be an effective way to improve the forming ability of thin-walled plate of titanium alloy.

However, the mechanism of ultrasonic softening during plastic deformation is still unclear. The effect of ultrasonic vibration on the forming process is different for different materials such as copper, steel, aluminum alloys and titanium alloys. Liu et al. [7] investigated the effect of ultrasonic vibration compression on pure titanium, and found that ultrasonic vibration could reduce the yield and flow stresses in the plastic stage and the material showed residual softening after stopping the vibration. Kang et al. [8] studied the plastic deformation behavior of pure copper in ultrasonic-assisted micro-tensile experiments, and found that ultrasonic vibration promoted the reorientation of preferred grains and reduced the misorientation inside the grains. From the above studies, it can be concluded that the effect and inner mechanism of ultrasonic vibration on the forming process of alloys need be carefully studied.

Usually, the combination of finite element simulation and experiment is very important to study deformation. Sun et al. [9] combined simulation and experiment to study the ultrasonic vibration-assisted milling process of GH4169 superalloy, and the results show that increasing the ultrasonic amplitude can reduce the machining stress and improve the chipbreaking effect. Li et al. [10] investigated the principle of ultrasonic vibration assisted shear thickening polishing, and studied the influence of ultrasonic amplitude and ultrasonic frequency on polishing speed and polishing pressure based on simulation. However, the effect of ultrasonic vibration on the deformation process of Ti6Al4V alloy is rarely known.

In summary, the effect of ultrasonic vibration on springback during plastic deformation of titanium alloy is rarely known. Few researchers have studied the ultrasonic vibration assisted forming process by finite element simulation. Therefore, in this paper, the effect of ultrasonic vibration on the springback of plates of Ti6Al4V alloy after hot bending test is investigated. In addition, the whole process of ultrasonic vibration-assisted hot bending of Ti6Al4V alloy plates was constructed by finite element simulation model. The results illustrate the influence of forming temperature and vibration amplitude on the springback of Ti6Al4V alloy plate.

Material and experiments

The composition of Ti6Al4V alloy is shown in Table 1. The length of the plate is 110 mm, the width is 40 mm and the thickness is 1 mm. The principle diagram of ultrasonic vibration assisted bending is shown in Fig. 1. Firstly, the plate is heated by electricity, then the ultrasonic vibration equipment is turned on, and finally stamping is carried out. The stamping speed is set to 2mm / s. The holding time after stamping is 30 s. Then the plate is taken out and the springback of the plate is measured. Ultrasonic vibration equipment, mobile fixture and die are all equipped with insulation design. The time of energizing heating is set to about 8s, and the temperature of the plate can be adjusted by controlling the voltage. The forming temperature is set to 800°C, 900°C and 1000°C. The ultrasonic vibration frequency is set to 20khz, and the vibration amplitude (λ) is set to 0-16 μm.

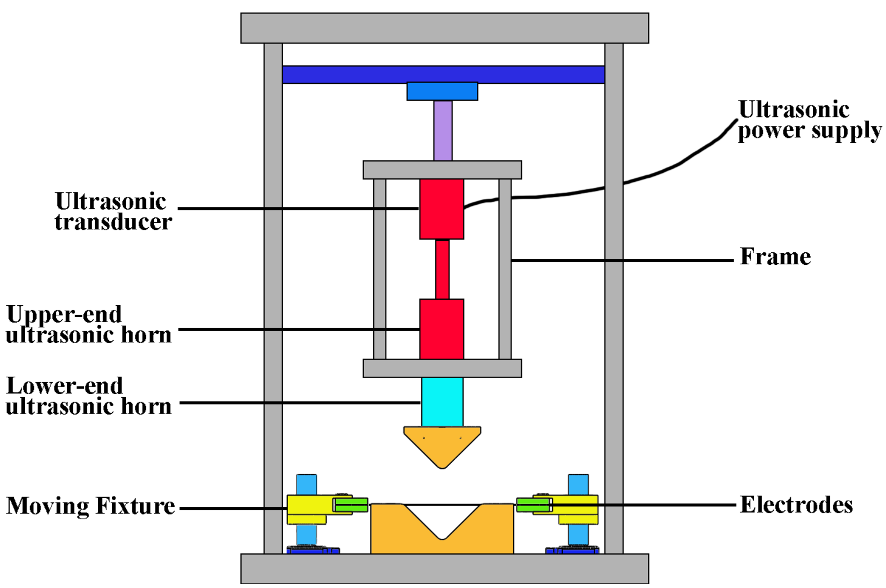


Fig. 1. Schematic diagram of ultrasonic vibration-assisted bending equipment.

Table 1. Chemical composition of Ti6Al4V alloy (wt.%).

Element	Al	V	Fe	Cu	Ni	Ti
wt.%	6.36	2.57	0.18	0.02	0.01	Bal.

The springback angle is shown in Fig. 2, and the change of the forming zone angle $\Delta\alpha$ is mainly studied. The angle to be measured after forming is δ, and α is the tool design angle. The following equation can be obtained:

$$\Delta\alpha = \frac{(\delta - \alpha)}{2} \quad (1)$$

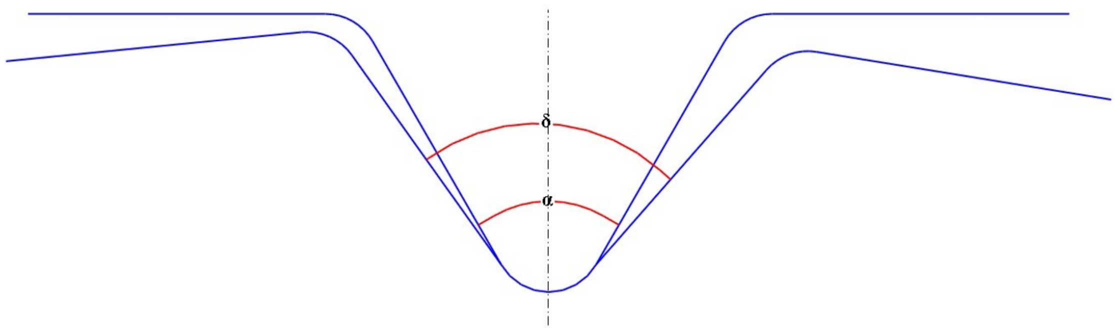


Fig. 2. Definition diagram of springback angle in the bending test.

Numerical modeling

In this study, ABAQUS software and explicit solver were used to simulate the ultrasonic vibration assisted bending process. The geometric model is shown in Fig. 3. Among them, the upper mold, the lower mold and the electrode are set as discrete rigid bodies, and the R3D4 element is used to divide the grid. The Ti6Al4V alloy plate is set as a deformable shell, and the S4RT element is used to divide the grid. The forming process is carried out by the display dynamics module, and the contact relationship of each component in the model is set by universal contact. The normal contact property is described by penalty function, and the friction coefficient is set to 0.15. The tangential contact property is defined as hard contact.

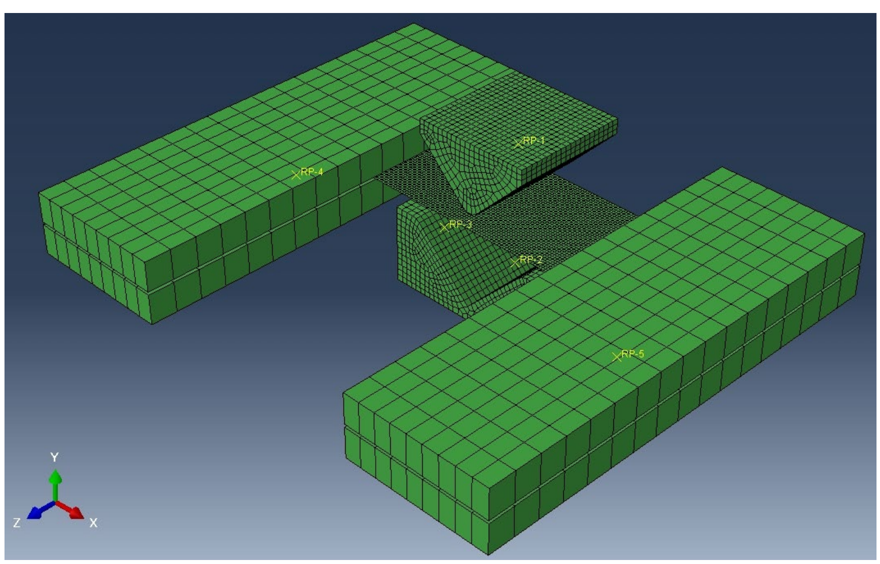


Fig. 3. Geometric model to simulate the ultrasonic vibration assisted bending test.

Results and discussion

Effect on springback angle

The relationship between springback angle, forming temperature and vibration amplitude is shown in Fig. 4. On the one hand, increasing the temperature leads to a significant reduction in the springback angle of the plate. When the temperature is 800°C, 900°C and 1000°C, the springback angles are 9.85°, 7.90° and 5.82° respectively without ultrasonic vibration. This is because the high temperature promotes the α-β phase transformation of Ti6Al4V alloy, and β phase with better plasticity improves the formability of Ti6Al4V. At the same time, the energy provided by the high temperature promotes the dislocation motion and promotes the plastic deformation of the plate.

On the other hand, at the same forming temperature, increasing the amplitude can effectively reduce the springback angle of plate. At 800°C, 900°C and 1000°C, the springback angle at the amplitude of 16 μm is respectively reduced by 0.80°, 1.04° and 1.15° compared with the amplitude of 0 μm. After the deformation, the ultrasonic vibration during the pressure holding process effectively eliminates the residual stress of the plate and reduces the springback of the plate.

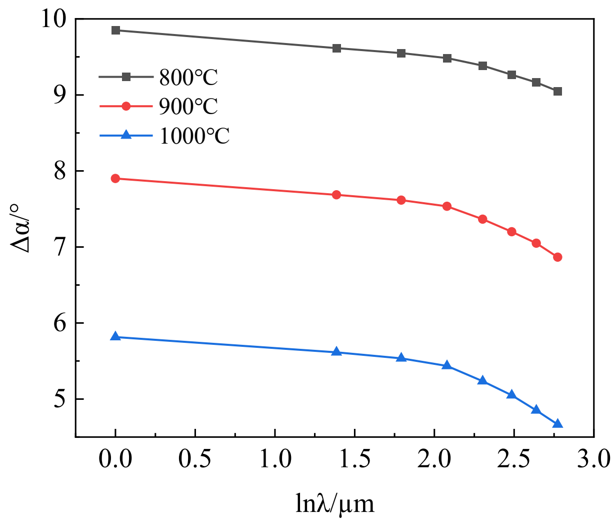
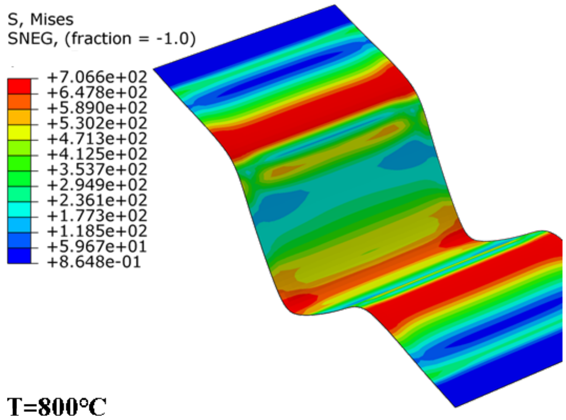


Fig. 4. Springback angle under different forming temperatures and vibration amplitudes.

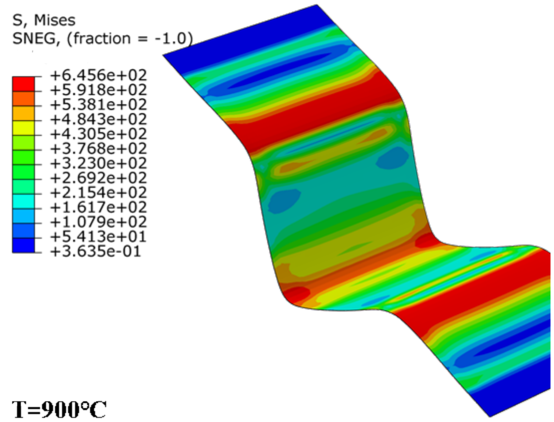
Assessment of ultrasonic vibration assisted bending by FE simulation

Fig. 5 shows the stress distribution cloud diagram of Ti6Al4V alloy plate during bending under different forming temperatures. The central area of the plate and the outer area of the bending area are the areas with the largest deformation stress. Moreover, with the increase of temperature, the deformation stress decreases significantly, which leads to the reduction of springback of the plate.

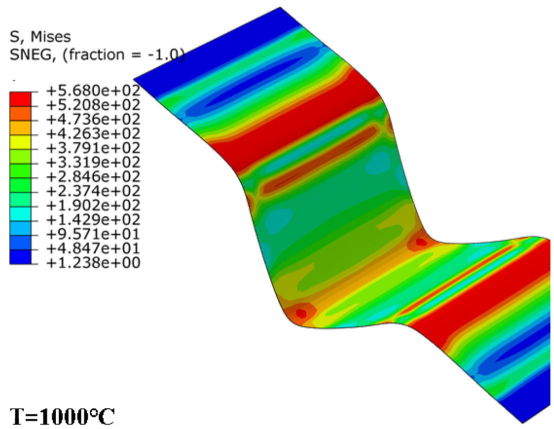
Fig. 6 shows the stress cloud diagram of the plate under 800°C and different vibration amplitudes. It can be seen that as the amplitude increases, the stress in the deformation area gradually decreases and the stress distribution is more uniform. Therefore, the decrease of stress and the uniform distribution of stress caused by the increase of amplitude are the important reasons for the reduction of springback.



(a)



(b)



(c)

Fig. 5. Stress distribution cloud diagram under different forming temperatures: (a) 800℃, (b) 900℃, (c) 1000℃.

A path along the length direction is established at the midpoint of the plate to extract the stress distribution, and the equivalent stress distribution of the Ti6Al4V alloy plate along the length direction under different amplitudes is obtained. The results are shown in Fig. 7. The maximum stress in the middle of the plate reaches 635 MPa without ultrasonic vibration, and the maximum stress in the middle of the plate decreases to 554 MPa after ultrasonic vibration with amplitude of 10 μm is applied. When the applied ultrasonic vibration amplitude is increased to 16 μm, the maximum stress in the middle of the plate decreases to 488 MPa, and the stress distribution is more uniform.

Based on the deformed plate model, the springback angle of the plate after unloading can be derived. The results are shown in Table 2. The predicted springback angle is basically consistent with the experimental springback angle after comparison. The maximum relative error is 5.48%, indicating that the finite element simulation method is reasonable.

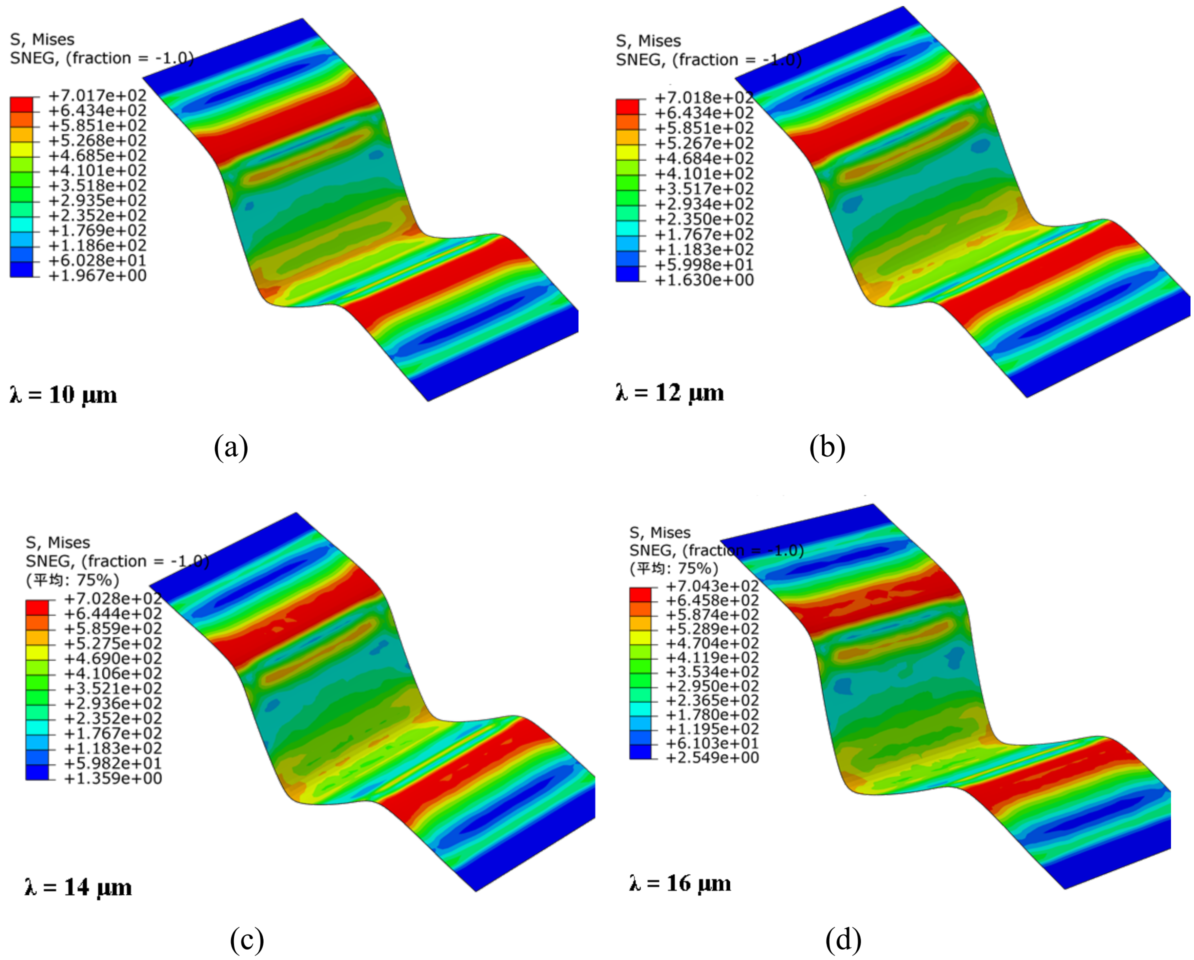


Fig. 6. Stress distribution cloud diagram of the plate under 800°C and different vibration amplitudes: (a) λ=10 μm, (b) λ=12 μm, (C) λ=14 μm, (d) λ=16 μm.

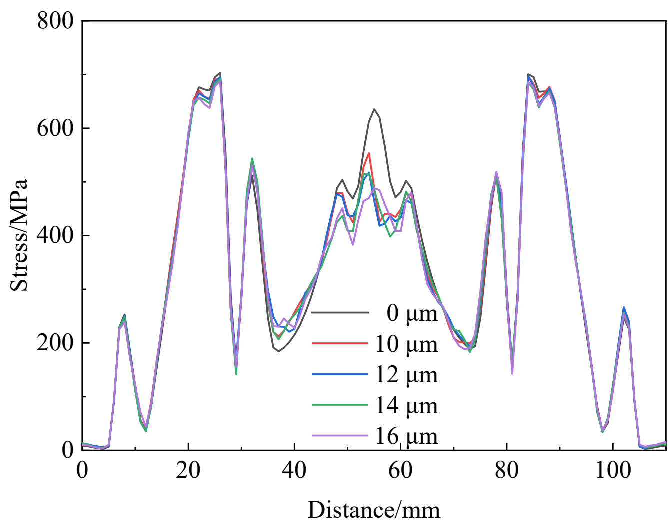


Fig. 7. Stress along the length direction under different vibration amplitudes at 800°C.

Table 2. Comparison of measured and predicted springback angle under different deformation parameters.

Deformation parameter	Measured springback angle	Predicted springback angle	Relative error
800℃/0 μm	9.85	10.39	5.48%
800℃/10 μm	9.39	9.80	4.32%
800℃/12 μm	9.27	9.01	-2.80%
800℃/14 μm	9.17	8.95	-2.37%
800℃/16 μm	9.08	8.86	-2.45%

Conclusion

In this study, the ultrasonic assisted bending test of Ti6Al4V alloy plate was carried out. The effects of temperature and ultrasonic amplitude on the springback of the plate after deformation were analyzed by finite element simulation. The conclusions are summarized as follows:

1. The springback of titanium alloy plate is significantly reduced due to the effect of ultrasonic vibration. As the amplitude increases, the springback angle further decreases.
2. Increasing the forming temperature can also reduce the springback. Increasing the amplitude can better reduce the springback of the plate at higher temperature.
3. The finite element simulation can well reflect the ultrasonic vibration assisted bending process. Increasing the temperature leads to a decrease in the overall deformation stress of the plate, thereby reducing springback. Increasing the vibration amplitude leads to a decrease in the stress in the central deformation area and a uniform stress distribution, thereby reducing springback.

References

[1] P.A. Grün, E.H. Uheida, L. Lachmann, D. Dimitrov, G.A. Oosthuizen, Formability of titanium alloy sheets by friction stir incremental forming, Int. J. Adv. Manuf. Technol. 99 (2018) 1993-2003. https://doi.org/10.1007/s00170-018-2541-5

[2] X.M. Yang, L.M. Dang, Y.Q. Wang, J. Zhou, B.Y. Wang, Springback prediction of TC4 titanium alloy V-bending under hot stamping condition, J. Cent. South Univ. 27 (2020) 2578-2591. https://doi.org/10.1007/s11771-020-4483-y

[3] G.D. Shao, H.W. Li, X. Zhang, M. Zhan, Z.Y. Xiang, Characteristics and mechanism in ultrasonic vibration-assisted deformation of Ni-based superalloy thin-walled sheet by quasi-in-situ EBSD, J. Alloys Compd. 908 (2022) 164591. https://doi.org/10.1016/j.jallcom.2022.164591

[4] S. Kumar, C.S. Wu, G.K. Padhy, W. Ding, Application of ultrasonic vibrations in welding and metal processing: a status review, J. Manuf. Process. 26 (2017) 295-322. https://doi.org/10.1016/j.jmapro.2017.02.027

[5] G. Shao, H. Li, M. Zhan, A review on ultrasonic-assisted forming: mechanism, model, and process, Chin. J. Mech. Eng. 34(1) (2021) 99. https://doi.org/10.1186/s10033-021-00612-0

[6] E. Malekipour, E. Sharifi, N.S. Majd, H. Heidary, Observation on the behavior of ultrasonic micro-hammer and its effects on the deep drawing process: numerical simulation and experimental study, Ultrasonics. 119 (2022) 106566. https://doi.org/10.1016/j.ultras.2021.106566

[7] T. Liu, J. Lin, Y. Guan, Z. Xie, L. Zhu, J. Zhai, Effects of ultrasonic vibration on the compression of pure titanium, Ultrasonics. 89 (2018) 26-33. https://doi.org/10.1016/j.ultras.2018.04.006

[8] J. Kang, X. Liu, M. Xu, Plastic deformation of pure copper in ultrasonic assisted micro-tensile test, Mater. Sci. Eng.: A. 785 (2020) 139364. https://doi.org/10.1016/j.msea.2020.139364

[9] J. Sun, P.Y. Li, S. Zhang, Y.S. Chen, H. Lu, G.Q. Chen, D. Shao, Simulation and experimental study of ultrasonic vibration-assisted milling of GH4169 high-temperature alloy, Alex. Eng. J. 73 (2023) 403-413. https://doi.org/10.1016/j.aej.2023.04.065

[10] X.H. Li, Z.H. Hu, Y. Tu, S.C. Wu, H. Zou, X.G. Chen, C.J. Qin, Y. Wang, Simulation and experimental study of ultrasonic-assisted shear thickening polishing of cemented carbide, J. Manuf. Process. 102 (2023) 106-118. https://doi.org/10.1016/j.jmapro.2023.07.042