Influence of Ultrasonic Rolling Process Parameters on Residual Stress of Tooth Root

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Abstract. The finite element model of ultrasonic rolling of 12Cr2Ni4A gear was established by ANSYS software, and the distribution law of residual stress field of tooth root after ultrasonic rolling was analyzed. A 12Cr2Ni4A gear ultrasonic rolling test platform was built to study the effect of process parameters on the residual stress of ultrasonic rolling tooth roots, and the finite element model was verified at the same time.

Keywords: Ultrasonic Rolling; 12Cr2Ni4A; Tooth Root; Process Parameters; Residual Stress.

1. Overview

12Cr2Ni4A gear steel is an excellent low-alloy martensitic stainless steel with high hardenability, high surface hardness and high matrix strength, and is widely used in the field of high-performance gear processing. High-performance gear manufacturing often requires finishing the tooth flanks to obtain a high surface quality. However, in the process of part processing, especially grinding, residual tensile stress is usually generated, which shortens the service life of the part to a certain extent [1,2]. In order to improve the service life of the gear, it is necessary to strengthen the gear, and the usual practice is to introduce a certain degree of residual compressive stress. At present, the commonly used methods for introducing residual compressive stress include surface quenching, shot peening, laser strengthening, and supersonic particle bombardment. Although these strengthening methods can change the surface stress state of the material to a certain extent, they will also increase the surface roughness of the gear and increase the stress concentration [3]. With the development of ultrasonic machining technology, ultrasonic vibration machining has become a new direction for the development of material strengthening technology. References [4-7] pointed out that while maintaining the precision of pre-processing, ultrasonic rolling can greatly improve the surface finish of the workpiece, the surface hardness can be increased by about 25%, a certain residual compressive stress layer is formed, and the surface microscopic morphology can be further improved. The improvement of the surface layer of the workpiece makes the metal structure of the workpiece fibrillated and nanosized, thereby increasing the service life of the material.

Related scholars [8, 9] have studied the influence of process parameters on the residual stress on the surface of the workpiece, and the process parameters when obtaining the ideal residual compressive stress are large rolling force, low spindle speed and low feed speed. This parameter combination affects the machining efficiency and surface roughness of the workpiece to a certain extent. In this paper, the gear steel 12Cr2Ni4A material is selected to analyze the residual stress field of the gear tooth root after ultrasonic rolling strengthening. Firstly, the finite element model of ultrasonic rolling of 12Cr2Ni4A gears is established by ANSYS software; then a test platform for ultrasonic rolling of 12Cr2Ni4A gears is built to verify the finite element model; finally, the influence of process parameters on the residual stress of ultrasonic rolling is analyzed.

2. The Principle of Ultrasonic Rolling

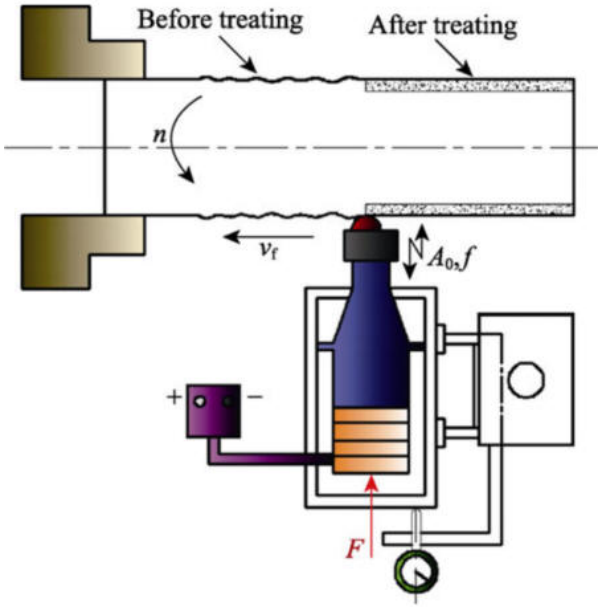


Fig 1. Schematic diagram of ultrasonic rolling

The principle of ultrasonic rolling is shown in Figure 1, The ultrasonic rolling tool head moves linearly along the axis of the workpiece at a certain feed speed v , and acts on the surface of the workpiece rotating at the speed n through the static pressure F and ultrasonic impact force. [10]. During the ultrasonic rolling process, the transducer converts the electrical energy of the ultrasonic generator into mechanical energy, and amplifies it through the horn. The ultrasonic tool head acts on the workpiece with an amplitude A_0 along the vertical direction of the workpiece surface. The surface layer causes a large amount of elastic-plastic deformation on the surface of the workpiece, and the microscopic wave peaks of the surface material are pressed into the valleys, and the surface layer of the workpiece and its subsurface structure produce a certain hardened layer, which prevents the internal elastic recovery of the material and causes a certain depth of residual pressure on the surface of the material. stress layer.

3. Finite Element Simulation of Tooth Root Ultrasonic Rolling

3.1 Establishment of Finite Element Model

In order to study the distribution state of the ultrasonic rolling stress field of the tooth root, the impact dynamics LS-DYNA module in the ANSYS software is used to establish a finite element model of ultrasonic rolling, as shown in Figure 2 . In order to improve the operation efficiency of the program, the model is simplified, and the gear tooth root is extracted for simulation calculation.

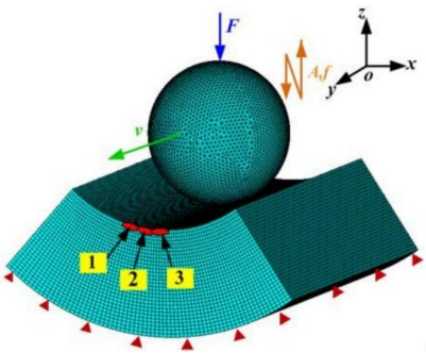


Fig 2. Finite element model of tooth root by ultrasonic rolling

In the modeling process, the ultrasonic rolling ball is set as a sphere with a diameter of 6mm, a tooth root inner diameter of 3.5mm, an outer diameter of 7mm, a length of 20mm , and a part of a hollow cylinder with a central angle of 38° . The element type of tooth root and ultrasonic rolling ball is SOLID164.

12Cr2Ni4A gear steel undergoes ultrasonic impact, the surface material undergoes severe elastic-plastic deformation, and the material anisotropy effect becomes more and more significant. In order to describe this highly nonlinear relationship well, according to the literature, a multi-linear elastic-plastic material model is selected, and its specific expression is:

$$\sigma = \left[1 + \left(\frac{\varepsilon'}{C}\right)^{1/P}\right]\left(\sigma_0 + f_n\left(\varepsilon_{eff}^{P}\right)\right) \tag{1}$$

where ε' is the strain rate, C and P are the corresponding parameters, σ_0 is the yield stress, and $f_n\left(\varepsilon_{eff}^{P}\right)$ is the hardening function.

The material of ultrasonic rolling tool head is YG8 cemented carbide, and the reinforced material is 12Cr2Ni4A gear steel. The hardness of YG8 cemented carbide and 12Cr2Ni4A gear steel is about 1600 and 603HV respectively. Since the hardness of YG8 cemented carbide is higher than that of 12Cr2Ni4A gear steel, the ultrasonic rolling tool head can be defined as a rigid body in ultrasonic rolling. The mechanical properties of the two are shown in Table 1.

Table 1. Mechanical performance parameters of material

Material	Density /(kg·m−3)	Modulus /GPa	Poisson ratio	Tangent modulus /MPa	Yield stress /MPa
YG8	14500	600	0.21		
12Cr2Ni4A	7850	211	0.30	230	785

By applying the initial static pressure and the amplitude of periodic longitudinal vibration to the ultrasonic rolling tool head, this continuous loading mode can be discretized into adjacent ultrasonic shocks plus the rolling process from one point to another [11]. In the finite element simulation, two load forces and displacement conflicts are simultaneously loaded on one degree of freedom. In reference [12], the dynamic impact force is simplified to be loaded according to the law of sine function changes. The specific expression is as follows:

$$F(t) = A_0 + \sum_{n=1}^{\infty}\left(a_n \cos nwt + b_n \sin nwt\right) \tag{2}$$

In the formula, A_0 is the initial amplitude; n is the simple harmonic number; a_n , b_n is the simple harmonic amplitude; w is the ultrasonic circular frequency.

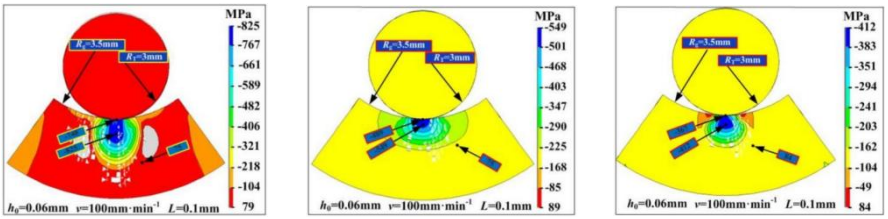
Since ultrasonic vibration is sinusoidal intermittent vibration, take $n=1$, $a_n=0$. The static pressure is converted into the initial amplitude A_0 and directly defined. At this time, the dynamic impact force is converted into a function of simple harmonic amplitude b_1 and ultrasonic circular frequency w . The specific expression is as follows:

$$F(t) = A_0 + b_1 \sin(wt) \tag{3}$$

According to the clamping method of the machine tool, the freedom of the two end faces of the workpiece is constrained, and only the rotation of the workpiece along the axis is retained, and the ultrasonic rolling tool head moves axially along the outer surface of the workpiece at the feed speed v .

3.2 Simulation Results and Analysis

Constrain the bottom surface of the tooth root, and the rolling head moves along the Y- axis direction. In order to describe the change of the step distance *L*, three load steps of the rolling ball are set in the simulation, and the second load step is taken as the simulation result.



(a) in the Z direction (b) in the Y direction (c) in the X direction

Fig 3. Stress distributions

Figure 3 shows the stress contours along the Z - axis, Y - axis and X- axis of tooth root ultrasonic rolling. The maximum residual compressive stress along the Z - axis, Y - axis and X- axis is on the subsurface at a certain depth from the workpiece surface. The residual compressive stress increases first and then decrease from the surface to the inside, and the elliptical plastic deformation core area is gradually uniform. is transformed into an elastic deformation zone around it.

4. Experimental Design and Analysis

4.1 Experimental Design

Table 2. Working parameters of X-ray diffraction-meter

Tube voltage	25~30kV	Tube current	25mA
Target and radiation type	target K- Alpha	Radiation filter material	V
Aperture specification	1*5mm Rectangular aperture	Diffraction crystal plane and Bragg angle	211,156°
Beta Angle range	±19°	Normal inclination angle range	±42°
X-ray elastic constant	1/2*S2=18879*10^{-6}	S_1=2.97*10	

In order to verify the rationality of the finite element simulation model of ultrasonic rolling tooth root residual stress, a gear tooth root ultrasonic rolling test device was developed. The experimental platform is built on a CA6140 lathe, as shown in Figure 4. Under the same rolling parameters, two groups of gears with the same size and material properties were ultrasonically rolled at the same time. Afterwards, one pair of gears was cut off by wire cutting method to detect the surface characteristics; the other pair of gears was used for bending fatigue test.

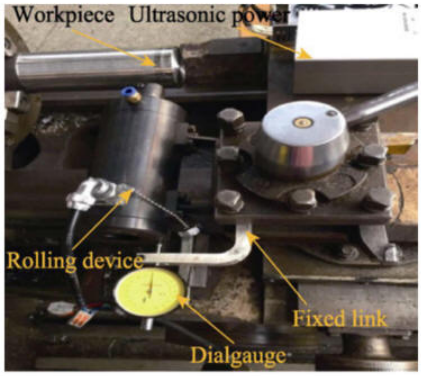


Fig 4. Ultrasonic rolling experiment

In order to ensure that the detection of the subsequent surface characteristics of the gear is not affected, the residual stress of the tooth root is detected by the X -ray method. Table 2 gives the working parameters of the X -ray diffractometer when measuring residual stress.

The cut gear tooth root was cleaned with acetone solution to measure the residual stress on the surface. Then, the tooth root surface was polished layer by layer with 5% perchloric acid alcohol solution, put into acetone solution for ultrasonic cleaning, rinsed with alcohol, blown dry, measured the size, and tested the residual stress. This is repeated until the residual stress distribution field of the matrix is obtained.

4.2 Analysis of Test Results

According to the above test parameters, the gear tooth root was subjected to ultrasonic rolling strengthening orthogonal test, and the test results are shown in Table 3 shown.

Table 3. The result of tooth root surface characteristic

No.	Rolling depth /mm	Feed speed /mm·min-1	Step distance / mm	Amplitude /mm	Residual stress /MPa	Hardness /HV	surface roughness /μm
1	0.03	60	0.05	0.002	-407	796	0.49
2	0.03	80	0.10	0.0025	-380	775	0.57
3	0.03	100	0.15	0.003	-365	759	0.61
4	0.03	120	0.20	0.0035	-355	743	0.65
5	0.04	60	0.10	0.003	-493	886	0.49
6	0.04	80	0.05	0.0035	-524	925	0.43
7	0.04	100	0.20	0.002	-406	836	0.60
8	0.04	120	0.15	0.0025	-424	879	0.56
9	0.05	60	0.15	0.0035	-565	1051	0.48
10	0.05	80	0.20	0.003	-518	976	0.52
11	0.05	100	0.05	0.0025	-566	1008	0.41
12	0.05	120	0.10	0.002	-499	961	0.48
13	0.06	60	0.20	0.0025	-591	1065	0.48
14	0.06	80	0.15	0.002	-569	1059	0.46
15	0.06	100	0.10	0.0035	-630	1081	0.42
16	0.06	120	0.05	0.003	-647	1086	0.38
17	\	\	\	\	-176	608	2.84

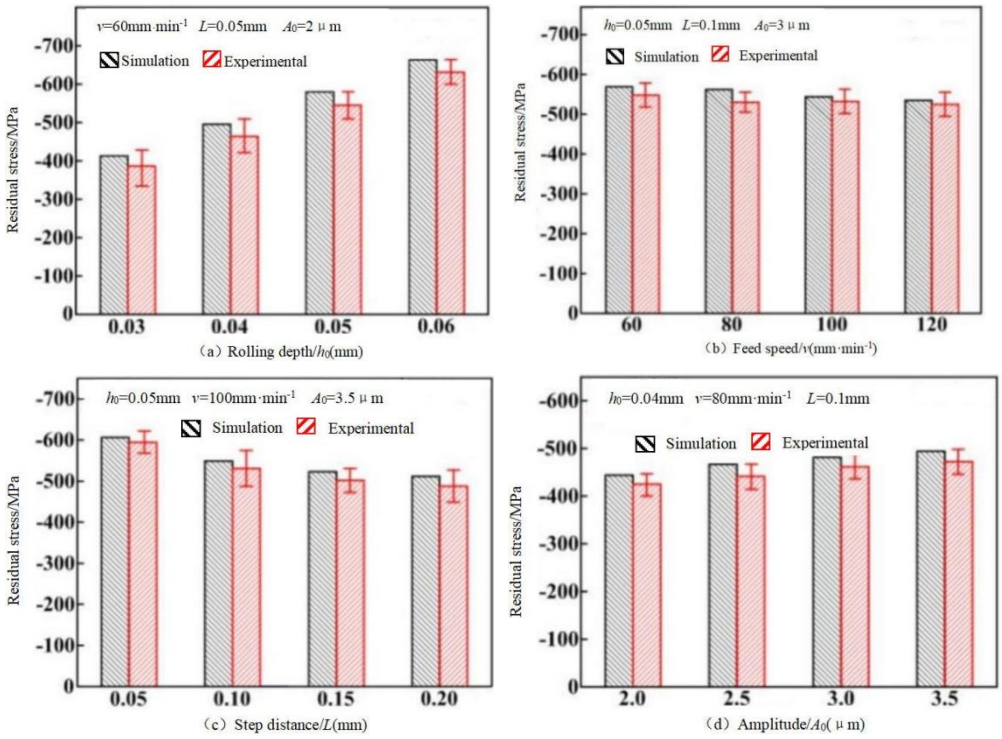


Fig 5. Experimental verification of finite element simulation

The above theoretical simulation model is verified by the ultrasonic rolling residual stress test on the tooth root surface under different process parameters, and the influence of process parameters on the residual stress is studied, as shown in Figure 5. The results show that the most influential parameter is the rolling depth. The residual stress test results are consistent with the simulation calculation results. The simulation value is slightly smaller than the test value, and the maximum error is within 12%. This is mainly because the test value is affected by the rigidity of the vibration system and the surface finish.

5. Influence of Process Parameters on Residual Stress

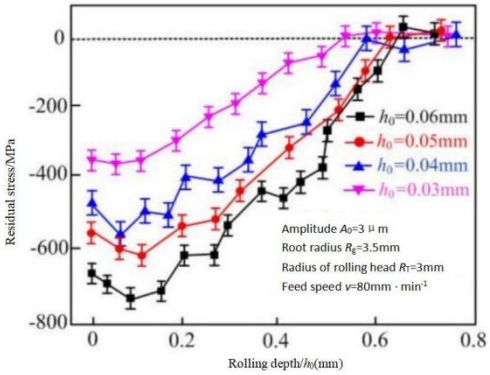


Fig 6. Residual stress profile with different rolling depth

Figure 6 shows the distribution characteristics of the residual stress field along the depth direction of the tooth root under different rolling depths. It can be seen from the figure that, as the rolling depth increases, the number of impacts per unit area of the tooth root increases, the plastic deformation energy in the contact arc area increases, and the residual compressive stress formed inside the tooth root increases. And with the increase of depth, the residual compressive stress shows a trend of increasing first and then decreasing. When the rolling depth is 0.06mm, the maximum residual compressive stress reaches -650MPa. From the distribution state of residual compressive stress, when the rolling depth h_0 is 0.06, 0.05, 0.04 and 0.03mm respectively, the maximum residual compressive stress peak is 0.11 , 0.09 , 0.08 and 0.06mm away from the workpiece surface, respectively. The vertical coverage is 0.65, 0.60, 0.54 and 0.47mm respectively. And the maximum residual compressive stress in all samples is located on the subsurface of the tooth root. With the increase of rolling depth, the peak value of the maximum residual compressive stress further moves to the inside of the tooth root, and the coverage of residual compressive stress increases linearly and gradually.

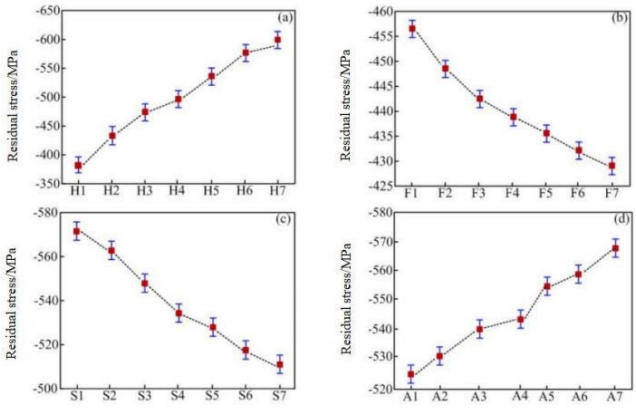


Fig 7. Effects of process parameters on residual stress

Figure 7 shows the relationship between the process parameters and the residual stress on the tooth root surface. It can be seen from the figure that with the increase of rolling depth h_0 and amplitude A

$_0$, the residual compressive stress on the tooth root surface gradually increases; the residual compressive stress decreases with the increase of feed speed v and step distance L trend.

The rolling depth has the most significant effect on the residual compressive stress. The main reasons for the analysis are as follows: (1) The increase of the rolling depth makes the elastic-plastic index of the contact arc area of the tooth root surface increase, and the plastic deformation becomes more severe; (2) The increase of the rolling depth effectively improves the rolling depth. The number of impacts between the indenter and the tooth root surface is 1.27 times when the rolling depth h_0 =0.06mm is 1.27 times that when h_0 =0.03mm, and the overlapping area of the indentation pits increases from 35% to 67% . The increase of the overlapping area results in repeated "tempering" in the unit area of the tooth root surface, and the plastic core area increases greatly, which increases the residual compressive stress; when the rolling depth increases to 0.06mm, the entire processing system is in the rolling force Vibration occurs under the action, causing the rolling head to "vibrate the knife". At the same time, repeated impacts cause uneven dimples on the surface of the tooth root, resulting in a fish-scale surface. (3) The number of impacts when the feed speed v = 60mm·min-1 is 23% of that when v = 120mm·min-1, the number of impacts per unit area decreases, and the surface of the tooth root cannot be sufficiently plastically deformed. When the feed speed is increased by 2 times, the residual compressive stress is reduced by 16%, and the processing efficiency is effectively improved; (4) The step distance mainly determines the circumferential contact state of the gear. When the contact radius *a in the* YOZ plane is constant, the with the increase of the step distance, the overlapping area of the circumferential indentation decreases, and the overlapping area of the plasticity decreases, so that the residual compressive stress decreases. When the step distance is increased from 0.1mm to 0.2mm, although the residual compressive stress is reduced by 12% , the processing efficiency is increased by 2 times. Therefore, it is necessary to comprehensively evaluate the residual compressive stress and processing efficiency to determine the appropriate step size; (5) When the amplitude A_0 increases from 2 μm to 3.5 μm, the residual compressive stress only increases by 7.6% . The reason for this is the increase of the amplitude, on the one hand, the increased rolling depth, and the number of axial and circumferential impacts along the tooth root surface is increased. On the other hand, under high-frequency impact, increasing the amplitude increases the impact energy of the rolling head on the surface of the tooth root, the plastic deformation of the surface material increases, and the strengthening effect is enhanced. Therefore, increasing the rolling depth and amplitude, and reducing the feed speed and step distance can effectively increase the residual compressive stress on the surface of the tooth root.

6. Conclusion

After ultrasonic rolling strengthening, the residual compressive stress on the surface of the workpiece increases linearly with the increase of static pressure, and the influence is significant; it gradually decreases with the increase of spindle speed and feed speed, but the influence is small.

The residual stress distribution law obtained by the finite element simulation is basically the same as the experimental value under the same process parameters. Along the rolling depth direction, the residual compressive stress first increases and then decreases. With the increase of static pressure, the residual compressive stress peak value the point gradually moves from the surface layer to the subsurface layer, the thickness of the hardened layer increases linearly and gradually, the maximum residual compressive stress is −654 MPa, and the thickness of the hardened layer is about 0.8 mm.

The process parameters for obtaining large residual compressive stress, low surface roughness and high-efficiency machining are: F =253 N, v =0.4 mm/min, n =197 r/min. Under the same level of surface roughness, the residual compressive stress on the surface is increased by 32.8%, and the processing efficiency is increased by 1.79 times.

Acknowledgments

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References

[1] HE Shao-jie, YANG Wen-yu, GUO Bu-peng, et al. Research progress on evaluation of surface residual stress and fatigue life of machined products[J]. Surface technology, 2015, 44(6): 120-126.

[2] LI You-guo, KANG Guo-zheng, WANG Chang-an, et al. Effect of residual stresses on the crack initiation life for rolling contact fatigue[J]. Journal of Tsinghua University (science and technology), 2005, 45(12): 1664-1667.

[3] SHAW L L, TIAN J W, ORTIZ A L, et al. A direct comparison in the fatigue resistance enhanced by surface severe plastic deformation and shot peening in a C-2000 super alloy[J]. Materials science & engineering, 2010, 527(4-5): 986-994.

[4] MORDYUK B N, IEFIMOV M O, PROKOPENKO G I, et al. Structure, micro-hardness and damping characteristics of Al matrix composite reinforced with AlCuFe or Ti using ultrasonic impact peening[J]. Surface & coatings technology, 2010, 204(9-10): 1590-1598.

[5] MOUSAVI S A A A, FEIZI H, MADOLlAT R. Investigations on the effects of ultrasonic vibrations in the extrusion process[J]. Journal of materials processing technology, 2007, 187-188(12): 657-661.

[6] JIANG J J, ZHENG J X, LIU C S. Research on surface roughness of ultrasonic polishing without abrasive based on orthogonal experiments[J]. Key engineering materials, 2009, 416(8): 133-136.

[7] WANG T, WANG D, LIU G, et al. Investigations on the nano crystallization of 40Cr using ultrasonic surface rolling processing[J]. Applied surface science, 2008, 255(5): 1824-1829.

[8] HUANG Shi-qiao, CAO Guo-bing, PENG Min, et al. Experimental calculating the surface roughness of SUS304 steel produced by the vibratory ball burnishing process[J]. Journal of Sichuan University (science and technology), 1990, 51(3): 1-8.

[9] ZHENG Jian-xin, JIANG Shu-xiang. Residual stress field in the process of 2D ultrasonic rolling 7050 aluminum alloy[J]. Surface technology, 2017, 46(12): 265-269.

[10] JIAO Feng, LAN Shuai-ling, WANG Yi, ZHAO Bo. Residual Stress Characteristics and Parameters Optimization of Ultrasonic Rolling 12Cr2Ni4A Gear Steel[J]. Surface technology, 2020, 49(11): 334-341.

[11] ZHAO Yun-cai, WEN Chun-bin. Simulation of 3D residual stress field of ultrasonic surface rolling by dynamic finite element analysis[J]. Journal of mechanical strength, 2017, 39(4): 875-881.

[12] LIU Y, WANG L, WANG D. Finite element modeling of ultrasonic surface rolling process[J]. Journal of materials processing technology, 2011, 211(12): 2106-2113.