Research on Residual Stress for Plastic Forming Micro-pit on Titanium Alloy Implant

Jinping Shi*, Ying Xu, Yong Jiang

School of Mechanical Engineering, University of Jinan, Jinan, Shandong, 250022, China

bemail: 805354596@qq.com, cemail: 827565691@qq.com,
*Corresponding author: aemail: me_shijp@ujn.edu.cn

Abstract: Titanium alloy is a kind of typical medical implant material because of its excellent mechanical properties, corrosion resistance and good biocompatibility. The most important facts to the success of implanting operation are the combination reactions between the implant and living cells as well as tissues which include cell growth, adhesion, proliferation and differentiation. The combination ability of implant and living body depends on the surface microstructure and morphology of the implant to a certain extent. The bionics research results show that the surface microstructure of biological bone is of the micro-pit geometric characteristics with 10-100μm depth. The residual stress of plastic forming micro-pit were analyzed with finite element simulation software ABAQUS. The correctness of the simulation results has been verified by experiments.

1. Introduction
The development of society promotes people's pursuit of high-quality life. So that medical and health care industry develops rapidly. Market of medical implants such as artificial joints and artificial bones keeps stable increasing. Titanium alloys have been used as medical biological implant materials due to their good mechanical properties, corrosion resistance, low elastic modulus and good biocompatibility. So far, the research on titanium alloy implants mainly focuses on the development of new implant materials with properties closer to human tissues and better biocompatibility, surface modification of titanium alloy implants in order to improve the biocompatibility, bone integrity, antibacterial and infection resistance of the implants [1, 2]. The bionics research results show that the surface microstructure of biological bone is of the micro-pit geometric characteristics with 10-100μm depth [3]. The manufacturing methods for the microstructure on surface of implant materials can be divided into three types i.e. additive manufacturing, reduction manufacturing and plastic forming method. The micro topologies produced by these three method are different in shape and regularity, and have different effects on the adhesion, proliferation and differentiation of human tissue cells. The surface microstructure manufacturing method based on additive principle is to coat hydroxyapatite layer [4, 5] or form TiO2 nanotube sequence [6] on medical implant surface. Additive manufacturing can be carried out by chemical, physical and mechanical methods. Chemical methods include anodic oxidation [7-9], micro arc oxidation [10] and chemical vapor deposition [11]. Physical methods include sol-gel [12], physical vapor deposition, micro molding [13]. Plasma spraying is mechanical method [14]. S. Y. Ding, et al. modified the surface of pure titanium by micro arc oxidation, and found that the surface of pure titanium after micro arc oxidation formed porous composite morphological
characteristics, which can promote the proliferation and differentiation of osteoblasts, and significantly improve the expression level of osteoblast related proteins [15]. There are mainly mechanical and physical methods for manufacturing surface microstructure based on material reduction principle, including micro milling [16], micro grinding [17] and laser machining [3]. Micro machining is to cut regular micro topological structure on the surface of implant material. In laser processing, high-power laser irradiates the implant to melt and vaporize its surface materials, and get craters finally. Microstructure plastic forming is a kind of method to manufacture microstructure with dimension scale less than 1 mm in two directions on part surface by means of plastic deformation. It is of high processing efficiency, simple process, excellent performance and high precision of formed parts [18]. B. Jia, et al. characterized the compression mechanical behavior of TC18 alloy, and derived a microscopic constitutive model which can link the microscopic physical mechanism with the macroscopic experimental results [19]. Fu, et al. introduced the micro plastic deformation mechanism of titanium alloy, analyzed the micro compression deformation behavior and microstructure evolution law [20].

Our research focused on the simulation analysis for the plastic forming process of microstructure on the surface of titanium alloy workpiece. Correctness verification for simulation results has been done by means of test. Research results provide theoretical basis for the plan and implementation of plastic forming process of microstructure on titanium alloy surface.

2. Simulation of residual stress for plastic forming micro-pit
The plastic forming of micro-pit on the surface of titanium alloy Ti6Al4V was simulated by means of finite element analysis software ABAQUS.

2.1. Geometric model and Its meshing
The simplified geometric model for plastic forming simulation is shown in Figure 1. Workpiece is a block of Titanium alloy with 5mm long, 5mm wide and 5mm high. The diameter of spherical carbide indenter is 1.588mm.

![Figure 1. Simplified geometric model for simulation](image)

C3D8R element is used to mesh the grids of indenter and workpiece manually. In order to ensure the accuracy of the simulation, the mesh of the contact zone between the indenter and the workpiece is refined. The geometric model meshing is shown in Figure 2.

![Figure 2. Geometric model meshing](image)
2.2. Parameters setting
The workpiece material is Ti6Al4V, and the material of spherical indenter is cemented carbide.

As setting in the simulation software ABAQUS, a force load with perpendicular direction to workpiece surface is applied to the center of the spherical indenter. In the actual forming process of micro-pit, the strain rate of the workpiece material is so small as within static range. The location of workpiece is constrained to be completely fixed at the bottom as shown in Figure 3. In the process of loading, the indenter gradually presses into the workpiece surface at the speed of $10^{-4}$m/s along the normal of the workpiece surface until the load reaches the setting value. Then, the indenter returns along the original path and leaves the workpiece surface.

![Figure 3. Loading and constraint condition](image)

2.3. Simulation of residual stress
Figure 4 illustrates the residual stress nephogram obtained by simulation when the set value of plastic forming force load is 907N, and the maximum residual stress value is -168.8MPa.

![Figure 4. Residual stress of plastic forming micro-pit](image)

Table 1 shows the simulation values of the maximum residual stress of micro-pit plastic forming corresponding to different load settings. The fitting curve shown in Figure 5 results from the processing of data in Table 1 by means of the software SPSS. It describes the relationship between the load set value and the maximum residual stress on the surface of plastic forming micro-pit.
Table 1. Data of maximum residual stress

| Load setting/N | 667 | 752 | 837 | 907 | 967 | 1021 |
|----------------|-----|-----|-----|-----|-----|------|
| Max. residual stress/MPa | -154.5 | -160.3 | -163.7 | -168.8 | -170.3 | -175.8 |
| Load setting/N | 1102 | 1139 | 1162 | 1295 | 1381 | 1447 |
| Max. residual stress/MPa | -179.2 | -181.5 | -182.4 | -187.2 | -188.9 | -190.9 |
| Load setting/N | 1593 | 1669 | 1768 | 1772 | 1799 |
| Max. residual stress/MPa | -194.1 | -197.1 | -200.6 | -201.6 | -201.7 |

Figure 5. Relationship between maximum residual stress and load setting

3. Experiment verification

3.1. Experimental preparation

The experiment for micro-pit plastic forming has been carried out on vertical machining center TK1100. The loading force was measured by means of dynamic dynamometer Kistler 9257B. The diameter of the ball at the front end of spherical carbide indenter is 1.588mm. The specimen is a titanium alloy rectangular block of 30mm×30mm×10mm.

The kistler9257B dynamometer was fixed on the table of TK1100 vertical machining center, the medical titanium alloy Ti6Al4V specimen was fixed at the top of dynamometer, and the carbide spherical indenter was installed with machining center spindle together. The table of the machining center can move along the X and Y direction to locate the position of micro-pit to be formed. With the spindle feeding along Z direction, the indenter gradually presses into the test piece, and the plastic forming loading force will increase gradually. When the loading force reaches the load setting value, the spindle stop feeding immediately and returned, so a micro-pit plastic forming work cycle is
completed. The iXRD stress analyzer produced by Proto Company of Canada as shown in Figure 6 was used to measure the residual stress for plastic forming micro-pit.

3.2. Results and discussion
Table 2 shows the load setting values used in the experiment and the measured micro-pit depth and maximum residual stress value. According to the data in Table 2, the curve about the maximum residual stress and the setting value is shown in Figure 7.

Table 2. Simulation and Experiment Data

| Load setting value/N | Maximum residual stress in simulation/MPa | Maximum residual stress in experiment/MPa | Difference rate/% |
|----------------------|------------------------------------------|------------------------------------------|------------------|
| 667                  | -154.5                                   | -140.7                                   | 8.93             |
| 752                  | -160.3                                   | -142.8                                   | 10.91            |
| 837                  | -163.7                                   | -145.5                                   | 11.12            |
| 907                  | -168.8                                   | -149.2                                   | 11.61            |
| 967                  | -170.3                                   | -150.8                                   | 11.45            |
| 1021                 | -175.8                                   | -155.7                                   | 11.43            |
| 1102                 | -179.2                                   | -164.4                                   | 8.26             |
| 1139                 | -181.5                                   | -166.6                                   | 8.21             |
| 1162                 | -182.4                                   | -168.0                                   | 7.89             |
| 1295                 | -187.2                                   | -168.5                                   | 9.99             |
| 1381                 | -188.9                                   | -170.2                                   | 9.90             |
| 1447                 | -190.9                                   | -171.5                                   | 10.16            |
| 1593                 | -194.1                                   | -174.7                                   | 9.99             |
| 1669                 | -197.1                                   | -176.2                                   | 10.60            |
| 1768                 | -200.6                                   | -180.6                                   | 9.97             |
| 1772                 | -201.6                                   | -186.4                                   | 7.54             |
| 1799                 | -201.7                                   | -190.6                                   | 5.50             |

It follows from Table 2 and Figure 7 that the residual stress of the plastic forming micro-pit is compressive stress, and the absolute value of the residual stress of the plastic forming micro-pit increases with the increase of the load setting value. The absolute value of maximum residual stress obtained by simulation is larger than that of experiment. The difference between the maximum absolute value of simulation residual stress and that tested in experiment is within 11.61%.
4. Conclusion
Titanium alloy is a typical medical implant material because of its excellent mechanical properties, corrosion resistance and good biocompatibility. The research focused on the micro-pit forming on the surface of titanium alloy by means of material plastic deformation. Simulation and experimental results show that the residual stress of the plastic forming micro-pit is compressive stress. The absolute value of the residual stress of the plastic forming micro-pit increases with the increase of the load setting value. The absolute value of maximum residual stress obtained by simulation is larger than that of experiment. The difference between simulation maximum residual stress and tested maximum residual stress is within 11.61%.

Acknowledgments
This work was supported by Key R&D Projects of Shandong (No. 2019GGX104096), China.

References
[1] Yang. X. M, Li. M, Lin. X, et al. (2013) Enhanced in vitro biocompatibility/bioactivity of biodegradable Mg-Zn-Zr alloy by micro-arc oxidation coating contained Mg2SiO4[J]. Surface & Coatings Technology, 233:65-73.
[2] Havlíčková, Strasky, J, Vandrovcová, M, et al. (2014) Innovative surface modification of Ti–6Al–4V alloy with a positive effect on osteoblast proliferation and fatigue performance[J]. Mater, Eng C Mater Biol Appl, 39(1):371-379.
[3] Ren, B, Wan, Y, Wang, G. S, et al. (2018) Effects of surface morphology and composition of medical Titanium alloys on biocompatibility[J]. Surface Technology, 47(4):160-171. in Chinese
[4] Mao. D. L, Cao. H. P, Chang. C. K, et al. (2003) Investigation on the bonding behavior of hydroxyapatite coating to hard tissue[J]. Journal of Shanghai Jiaotong University, 37(2): 264-268. in Chinese
[5] Wang. L. P, Zhang. C, Zhang. Y. Q, et al. (2018) Synthetic magnesium-doped hydroxyapatite particles and adsorption characteristics of Cu2+ from aqueous solution[J]. Journal of China University of Mining Technology, 47(6): 1340-1347. in Chinese
[6] Park, J, Bauer, S, Vond. M. K, et al. (2007) Nanosize and vitality: TiO2 nanotube diameter directs cell fate[J]. Nano Letters, 7(6): 1686-1691.
[7] Wang. J. S, Li. D. S, Li. H. Y, et al. (2013) Formation process of TiO2 nanotube arrays prepared by anodic oxidation method[J]. Journal of Nanoscience & Nanotechnology, 13(6): 4110-4116. in Chinese
[8] So. S, Lee. K, Schmuki. P. (2012) Ultrafast Growth of Highly Ordered Anodic TiO2 Nanotubes in Lactic Acid Electrolytes[J]. Journal of the American Chemical Society, 134(28): 11316-11318.
[9] Gong. D, Grimes. C. A, Varghese. O. K, et al. (2011) Titanium oxide nanotube arrays prepared by anodic oxidation[J]. Journal of Materials Research, 16(12): 3331-3334.
[10] Han, Y, Chen, D, Sun, J, et al. (2008) UV-enhanced bioactivity and cell response of micro-arc oxidized titania coatings[J]. Acta Biomaterialia, 4(5): 1518-1529.
[11] Paretta, R, Yang, L, Kothari, A, et al. (2010) Tailoring nanocrystalline diamond coated on titanium for osteoblast adhesion[J]. Journal of Biomedical Materials Research Part A, 95(1): 129-136.
[12] He, G, Hu, J, Wei, S. C, et al. (2008) Surface modification of titanium by nano-TiO2 /HA bioceramic coating[J]. Applied Surface Science, 255(2): 442-445.
[13] Li, D, Lu, X, Lin, H, et al. (2013) Chitosan/bovine serum albumin co-micropatterns on functionalized titanium surfaces and their effects on osteoblasts[J]. Journal of Materials Science: Materials in Medicine, 24(2): 489-502.
[14] Wang, S. P, Li, Z. X, Du, J. H. (2013) Research progress in plasma spray coating materials on the Titanium alloy substrates[J]. Surface Technology, 42(5): 93-97. in Chinese
[15] Ding, S. Xia, Y, L, Chen, N, et al. (2012) Effects of Titanium modified by micro-arc oxidation on protein synthesis of osteoblast [J]. Journal of Oral Science Research, 28(2): 125-128. in Chinese
[16] Yang, Z. K, Dong, W. M, Zhan, Z. H, et al. (2011) Research on precision micro-milling microstructure technology[J]. Aviation Precision Manufacturing Technology, 47(1): 8-10. in Chinese
[17] Xie, J, Li, P, Wu, K, et al. (2013) Micro and precision grinding technique and functional behavior development of micro-structured surfaces[J]. Journal of Mechanical Engineering, 49(23): 182-190. in Chinese
[18] Geiger, M, Kleiner, M, Eckstein. R. Microforming[J]. (2001) CIRP Annals-Manufacturing Technology, 50(2): 445-462.
[19] Jia, B, Song, W, Tang, H, et al. (2014) Hot deformation behavior and constitutive model of TC18 alloy during compression[J]. Rare Metals, 33: 383-389.
[20] Fu, M. W, Chan, W. L. (2013) A review on the state-of-the-art microforming technologies[J]. The International Journal of Advanced Manufacturing Technology, 67(9-12):2411-2437.