Surface Quality for Cryogenic Milling Mg-1.6Ca-2.0Zn Medical Magnesium Alloy

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Abstract—As an absorbable and implantable biomedical material, magnesium alloy has made great progress in the application of biomaterials in recent years because of its excellent biocompatibility and biomechanics. At the same time, the disadvantages of magnesium alloy materials are more obvious. Because of the large linear expansion coefficient of magnesium alloy, the high temperature during dry cutting will lead to the degradation of machined surface quality. In addition, due to the active chemical properties of magnesium, cutting fluid is easy to cause corrosion of machined surface, and it is easy to react with water in cutting fluid to release hydrogen, causing accidents. In this paper, the effect of cryogenic milling with liquid nitrogen on the surface quality of magnesium alloy was studied by comparing the prepared magnesium alloy in different cooling environments, and the surface roughness model was established for prediction and verification. The results show that the roughness value of the surface machined by liquid nitrogen cryogenic milling is smaller than that of dry cutting, and the hardness value is larger than that of dry cutting, which is very beneficial to improve the surface quality of workpiece. This paper aims to improve the low-temperature machining process of magnesium alloy, and provide theoretical and practical guidance for the preparation, processing and application of high-performance medical magnesium alloy.

1. Introduction
Magnesium is a macroelement in human body, and the excess magnesium in the body will be excreted through the system\textsuperscript{[1]}. The magnesium alloy formed by adding calcium and zinc to pure magnesium in a certain proportion is a high-quality medical implant, because both calcium and magnesium are metal elements that promote cell growth. The Young's modulus of magnesium alloy is similar to that of human bone, so it does not produce a sense of weight bearing. Its biodegradability avoids the pain of second operation, and its good biocompatibility promotes the growth of cells. Therefore, magnesium alloy has great potential as a medical metal material, but at the same time, it also requires high quality of machined surface. Better surface integrity can significantly improve the corrosion resistance, wear and fatigue resistance of magnesium alloy. On the other hand, the linear expansion coefficient of magnesium alloy during cutting is large, which easily leads to chip combustion, and cryogenic milling can solve this problem well. When the low-temperature medium is used for cooling in the cutting process, the adhesive wear can be reduced, the accumulated chips can be reduced, and thus the surface roughness can be reduced\textsuperscript{[2,3]}. Qi\textsuperscript{[4]} et al. conducted a cryogenic milling test on AZ31 magnesium alloy in liquid nitrogen, which obviously reduced the surface roughness. Dinesh\textsuperscript{[5]} et al. conducted a cryogenic milling test on ZK60 magnesium alloy, and the results showed that the surface hardness obtained by cryogenic milling
was higher than that obtained by dry cutting. Pu \cite{6,7} et al. have studied the effects of low-temperature machining environment and cutting edge radius on the surface integrity of AZ31 magnesium alloy. The experimental results show that the increase of cutting edge and the application of cryogenic milling can effectively improve the surface hardness of AZ31 magnesium alloy.

In this paper, the surface properties of the prepared magnesium alloy are tested and analyzed, and the surface roughness model is established for prediction and verification. The results show that with the increase of cutting speed, the surface roughness decreases and the surface hardness decreases. With the increase of cutting depth and feed per tooth, the surface roughness has been increasing, and the surface hardness has increased. Because liquid nitrogen has always played a good role in lubrication and cooling in the cutting process, the roughness value of cryogenic milling surface is smaller than that of dry cutting, and the hardness value is larger than that of dry cutting, which is very beneficial to improve the surface quality of workpiece.

2. Experimental method

2.1. Material preparation

Feng \cite{8} et al. shows that adding a certain amount of zinc to magnesium alloys can slow down the corrosion rate of the alloys. Wang \cite{9} et al. have prepared magnesium alloys with different ratios by powder metallurgy, and conducted mechanical properties and corrosion tests. The results show that when the calcium content is 1.6\% and the zinc content is 2.0\%, the alloys with other ratios show the best mechanical properties and the slowest corrosion rate. Therefore, the test material is prepared magnesium-calcium-zinc alloy, in which the content of calcium is 1.6\%, the content of zinc is 2.0\%, and the rest are magnesium. The element content of the prepared Mg-1.6Ca-2.0Zn alloy was tested by X-ray energy dispersive spectrometer (EDS), and the results showed that the ratio of calcium to zinc met the expectation.

2.2. Magnesium alloy cutting

As a medical implant material, magnesium alloy has been studied in the fields of bone support and cardiovascular stent, and its shape and structure have higher requirements \cite{10}. In the production process, milling has high efficiency, high precision and is widely used in actual production, so this cutting test adopts milling. The machining center used in the test is YCM-V116B vertical machining center. Considering that some medical implant materials need to be machined with keyways, in order to be close to the actual production process, the cutter selected in this experiment is a coated solid carbide keyway milling cutter produced by Zhuzhou Diamond Cutting Tools Co., Ltd., and its model is GM-2E-D20.0.

2.3. Study on Surface Roughness of Magnesium Alloy

In order to explore the influence of cutting speed on surface roughness, and clearly analyze the influence law of cutting parameters on surface quality, the single factor test method was adopted. Due to the unique machining method of keyway milling cutter, the axial cutting depth \( a_p \) is usually chosen to be fixed in practical application, and here the axial cutting depth is set at 10 mm. As the use of cutting fluid will pollute the environment, which does not meet the requirements of "green manufacturing" and "clean manufacturing", dry cutting and cryogenic milling are adopted here, and then the effects of cutting speed \( v_c \), cutting depth \( a_e \) and feed per tooth \( f_z \) as variables on surface roughness are studied. The test parameters are shown in Table 1. The surface roughness of the cut specimen is measured by Mitutoyo SJ-410 portable surface roughness meter.

| Parameter | cutting speed \( v_c \)(m/min) | cutting depth \( a_e \)(mm) | feed per tooth \( f_z \)(mm/z) | axial cutting depth \( a_p \)(mm) |
|-----------|-------------------------------|-----------------------------|-------------------------------|-------------------------------|
2.4. Study on Surface Hardness of Magnesium Alloy
After machining, the hardness of the machined surface was tested by 402MVD Vickers hardness tester. The hardness tester measures the Vickers hardness of the material surface through the diamond indenter. When measuring, the applied load is 0.49 N and the loading time is 15 s. After the diamond indenter rises, the indentation is measured on the workpiece surface. The contour data of quadrilateral indentation is measured by the software of hardness tester, and the surface Vickers hardness of this point is obtained by comprehensive processing. In order to reduce the measurement error, three points are randomly selected to measure Vickers hardness on the machined surface, and the average value is taken as the final result.

3. Test Results and Discussions

3.1. Cutting surface roughness

3.1.1 Study on Surface Roughness of Cryogenic Milling
First, a single-factor test with speed as the variable was carried out. In order to avoid the chance of the test, the test was repeated three times under each parameter for comparison. The test results are shown in Figure 1. It can be seen from the figure that the roughness value decreases with the increase of cutting speed, whether it is dry cutting or cryogenic milling. With the increase of cutting speed, although the amount of material removed per unit time will increase, the cutting force will increase, but the increase of cutting speed will lead to the reduction of cutting deformation, the chip will be discharged at a high speed, the chip on the machined surface will be greatly reduced, and the roughness value will be reduced. When the cutting speed further increases, the cutting temperature increases, which leads to obvious thermal softening effect of the material, and the friction resistance between the tool and the workpiece decreases, which leads to the decrease of roughness. When the cutting speed reaches 300 m/min, because it is close to the maximum rotation speed of the milling machine spindle, the vibration intensifies, which leads to an insignificant decrease in roughness. Compared with dry cutting, liquid nitrogen plays a lubricating role in cryogenic milling, resulting in a smaller roughness value than dry cutting. The experimental results with radial cutting depth as variable are shown in Figure 2. From the observation results, it can be seen that with the increase of radial cutting depth, the roughness value tends to increase. When the cutting depth just increases, the increase of roughness value is relatively small, because with the increase of cutting depth, the cutting amount of each tooth becomes larger and the cutting force becomes larger. In intermittent cutting, this constantly changing cutting force will cause the vibration of the cutting process. However, magnesium alloy has low density, soft texture and easy cutting, so the increase of machined surface roughness value is relatively small. When the cutting depth continues to increase, the cutting amount of each tooth will further increase, which will lead to a significant increase in cutting force and the vibration of the machine tool, so the increase of roughness value will be larger. The test results with the feed rate per tooth as variable are shown in Figure 3. With the increase of feed per tooth, the roughness value tends to increase, because with the increase of feed per tooth, the material removed per unit time increases, the cutting force increases, and the surface residual area increases after cutting, which leads to the increase of surface roughness value. When the feed rate of each tooth continues to increase, the cutting force keeps increasing, which leads to the intensification of machine tool vibration, the further increase of surface residual area and the substantial increase of roughness value.
3.1.2 Establishment and verification of surface roughness prediction model

Orthogonal test method can be used to systematically study the influence of liquid nitrogen cooling and cutting amount on surface roughness, and the optimal parameter combination within the selected parameter range can be obtained through less test times. Taking cutting speed, feed rate, cutting depth and cooling mode as four factors, orthogonal table L9(3^4) is considered to design the experiment. The cooling mode is two levels of dry cutting and cryogenic milling, and three levels of other factors. In this case, there is no suitable orthogonal table of mixing levels. The better one of the two levels is selected and repeated once as the third level, which is called the virtual level [11]. In the single factor test, it is found that the effect of cryogenic milling is better than that of dry cutting, so the third level of cooling mode is liquid nitrogen. Through orthogonal test, it is found that the feed per tooth has the greatest influence on the surface roughness within the selected parameter range, and it is better to take 0.06 mm/z. Furthermore, it is cutting speed and cooling mode, so it is better to choose a larger cutting speed and liquid nitrogen cooling mode. Cutting depth has the least influence on surface roughness, so it is better to choose a smaller cutting depth.

Build a prediction model of cutting surface roughness [12]:

\[ R_a = C \times v_c^{b_1} \times a_e^{b_2} \times f_z^{b_3} \]  \tag{1}

\( R_a \) -- roughness value of machined surface  

\( C \) -- coefficient determined by workpiece material and cutting conditions  

\( v_c \) -- cutting speed  

\( a_e \) -- cutting depth  

\( f_z \) -- feed per tooth  

\( b_1,b_2,b_3 \) -- influence index of cutting parameters on machined surface roughness

The regression coefficient values and corresponding confidence intervals related to the surface roughness prediction model can be obtained by fitting and processing the orthogonal test data with MATLAB software, and the regression effect is remarkable. The numerical value of the calculation result of the regression equation is processed and put into the formula (1) to obtain the prediction model (2) of the surface roughness of cryogenic milling. The F-value statistics of the constructed surface roughness prediction model show that the regression effect is remarkable. Then, the surface roughness prediction model is tested and verified in detail, and six groups of different cutting parameters are randomly selected and substituted to get the predicted values of each model's surface roughness. Comparing the predicted value with the actual measured value, the results are shown in Table 2. The smaller error indicates that the surface roughness prediction model has practical engineering significance and can guide engineering practice.

\[ R_a = 5.17273 \times v_c^{-0.1766} \times a_e^{0.0989} \times f_z^{0.8995} \]  \tag{2}
Table 2 Prediction and Measurement of Surface Roughness in Cryogenic milling

| Cutting speed $v_c$ (m/min) | Cutting depth $a_c$ (mm) | Feed per tooth $f_z$ (mm/z) | Prediction value of surface roughness $Ra$ (μm) | Surface roughness measurement value $Ra$ (μm) | Error magnitude (%)
|-----------------------------|--------------------------|----------------------------|-----------------------------------------------|-----------------------------------------------|------------------|
| 180                         | 1.2                      | 0.10                       | 0.265                                         | 0.238                                         | 11.3             |
| 180                         | 1.8                      | 0.06                       | 0.174                                         | 0.172                                         | 1.2              |
| 180                         | 1.8                      | 0.14                       | 0.374                                         | 0.345                                         | 8.4              |
| 180                         | 2.4                      | 0.10                       | 0.284                                         | 0.290                                         | 2.1              |
| 240                         | 1.8                      | 0.10                       | 0.262                                         | 0.255                                         | 2.7              |
| 300                         | 1.8                      | 0.14                       | 0.342                                         | 0.323                                         | 5.9              |

3.2. Machining surface hardness

The experimental results with cutting speed as variable are shown in Figure 4. Under the condition of dry cutting, with the increase of cutting speed, the microhardness of workpiece surface decreases. The reason is that with the increase of cutting speed, the cutting temperature rises. At this time, the softening effect of high temperature is more obvious than the mechanical effect, which leads to the decrease of work hardening effect and the decrease of material microhardness. When cutting at low temperature, because of the good cooling effect of liquid nitrogen, the microhardness value is higher than that of dry cutting, although the overall trend is decreasing. The test results with the variable of cutting depth are shown in Figure 5, and the test results with the variable of feed per tooth are shown in Figure 6. It is found that with the increase of cutting depth and feed per tooth, the surface microhardness has been increasing. The analysis shows that with the increase of cutting depth and feed per tooth, the cutting force increases, and the extrusion effect of the cutter on the machined surface increases, which leads to the hardening degree of the material.

4. Conclusion

In this paper, the single factor test method is adopted, and the test conclusions are as follows:

1. With the increase of cutting speed, the surface roughness tends to decrease, while with the increase of cutting depth and feed per tooth, the surface roughness tends to increase. Because liquid nitrogen has always played a good role in lubrication and cooling in the cutting process, the roughness value of the machined surface in cryogenic milling is smaller than that in dry cutting.

2. With the increase of cutting speed, the cutting temperature rises, the thermal softening effect of the material is obvious, and the surface hardness of the material decreases. Liquid nitrogen has a good cooling effect during cryogenic milling, so the surface hardness value of cryogenic milling is larger than that of dry cutting. With the increase of cutting depth and feed rate per tooth, the cutting force increases,
and the extrusion effect of the cutter on the machined surface is enhanced, which leads to the hardness of the machined surface, which is very beneficial for prolonging the service life of parts.

(3) Orthogonal experiments were designed with cutting speed, cutting depth, feed per tooth and cooling mode as four factors. The results showed that feed per tooth had the greatest influence on surface roughness, while cooling mode and cutting depth had the least influence. Based on the numerical value of orthogonal test, a prediction model of surface roughness is established, and the prediction model is solved by fitting with MATLAB software. The regression effect of the prediction model is remarkable, which has practical significance in engineering.

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