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The Influence of Tool Path Strategies on Surface Roughness and Machining Time in the CNC Milling of UHMWPE

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Abstract: The right choice of tool path strategies in the CNC milling of UHMWPE can lead to significant reduction in machining time, improvement of workpiece surface quality and tool life, thereby, leading to overall cost reduction and higher productivity. In the study, the effects of toolpath strategies on the surface roughness and machining time during CNC milling of UHMWPE materials as acetabular liners of artificial hip joints were examined. The machining experiments were performed using 3-axis CNC milling and three toolpath strategies such as raster, step and shallow and optimize constant Z machining were investigated. The cutting parameters for machining UHMWPE was set-up using the toolpath strategy with step and shallow machining, at a spindle speed of 7000 rpm, step over 0.01 mm and feed rate of 1500 mm/rev. The surface Roughness (Ra) of the outer and inner acetabular liner generated by this CNC machine is 1.195 μm. The results meet the ASTM standard for the Ra value of the acetabular liner for the artificial hip joint which requires a maximum Ra value of 2.0 μm.

Key words: Toolpath strategies, surface roughness, machining time, acetabular liner, maximum, standard

INTRODUCTION

Surface roughness is one of the evaluation criteria to establish the quality of the product and a factor that critically influences manufacturing cost. This is because surface roughness may affect the tribological and mechanical properties of the product such as friction, wear and fatigue. Many machining factors contributed to surface roughness during material machining may be related to cutting parameters, machinability of the workpiece and cutting tools, lubrication fluids. For minimizing the surface roughness, the proper selection of cutting toolpath strategies is needed in particular to cutting in a milling machine.

In the modern industry, the main goal of the manufacturing process is how to produce high-quality products in a short time and at low processing cost. Currently, automatic and compliant manufacturing systems are employed for that purpose along with Computerized Numerical Control (CNC) machines that can produce a product with high dimensional accuracy and low processing time. Here, CNC milling is the common method for machining parts with complex surface geometry. In the context of milling operations, the toolpath strategy has a substantial impact on the surface quality. This means that, for the removal of the same amount of material, the type of tool motion selection will produce significantly different results of surface roughness. Importantly, process planning for CNC milling operations of polymers needs an understanding of the technological parameters (toolpath strategy, spindle speed, step over and feed rate) for machining. Also, the machinability of typical thermoplastic and thermosetting polymers including their viscous properties will influence the surface integrity, chip formation and cutting forces during machining (Xiao and Zhang, 2002).

Further, the tool path generation of surfaces with high curvature variations is the main issue in the machining of materials. It is a challenging task and has been concerned by a number of researchers. Toh (2006) investigated high-speed finish milling of an inclined workpiece surface with a view using an extreme cutting angle inclination. To simulate the effect of different tool path orientations when milling for hardened molds and dies was performed through its machinability assessments in order to detect the best tool path orientation. The results indicate that the use of a vertically downward orientation provided the longest tool life. In terms of

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workpiece surface roughness, however, vertical upward orientation is mostly desired. Furthermore, the tool path strategy has a significant effect on the cycle time for high-speed milling operation focused on pocketing operations with a zig-zag tool path (Monreal and Rodriguez, 2003). In particular, when milling with high feed rates, the zigzag tool path orientation has a significant influence on the machining cycle time. Additionally, the optimum cutting characteristics of DIN 1.2738 mold steel could be related to the tool path strategies when milling pocket using high-speed steel end mills (Gologlu and Sakarya, 2008). The most influential effects within the range of specified cutting conditions are corresponding to the feed rate for one direction and the spiral toolpath strategies and depth of cut for back and forth toolpath strategy.

With respect to the workpiece alignment, the best toolpath strategies and the optimum angular orientation of a tool path have been subjected to study analytically (Wang *et al*., 1987; Prabhu *et al*., 1990; Lakkaraju and Raman, 1990; Jamil, 1998). Most previous studies performed the analysis on the plane surfaces without internal islands of material. Moreover, the different toolpath strategies have been proposed for finishing milling of a complex geometry part containing concave and convex surfaces (Ramos *et al*., 2003). The 3D offset could be the most suitable toolpath strategy of CNC milling because, it can provide the best surface finishing, the more uniform texture and the best dimensional control performance. Therefore, it is essential to determine the toolpath strategy that can help for minimizing the machining time and cost.

The present study was undertaken to evaluate the effects of toolpath strategy in the CNC milling of UHMWPE (Ultra-High-Molecular-Weight polyethylene) material as the acetabular liner for bearing on the artificial hip joint. The main objective of the study was to improve the surface integrity and reduce machining time during CNC machining of the product. The result is expected to help engineer and machinist in the development of machining program for fabricating the bearing component.

MATERIALS AND METHODS

Workpiece material and cutting tool: UHMWPE was selected as the workpiece material in the present study. This material is commonly found in the biomedical application such as hip and knee joint. The physical and mechanical properties of UHMWPE selected are presented in Table 1. The CAD Model of the bearing components to be machined is shown in Fig. 1. The cutting parameters in this experimental test were set-up at the spindle speed of 7000 rpm, feed rate of 1500 mm/rev., step over of 0.05 mm while milling process was simulated under dry coolant. The cutting tool materials used in the study are carbide end mill (SECO-93060F) and ballnose cutter milling (JS533060D1B0Z3-NXT).

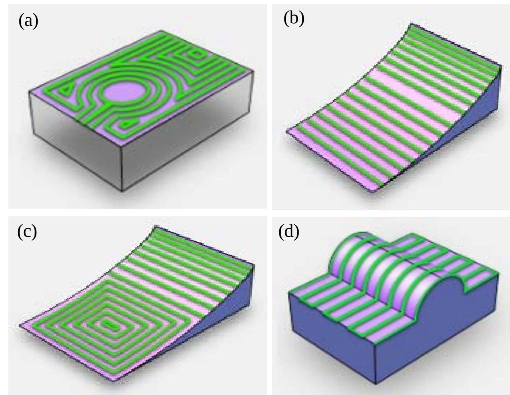

Fig. 1: Toolpath strategy: a) Model area clearance; b) Optimize constant Z finishing; c) Step and shalow finishing and d) Raster finishing

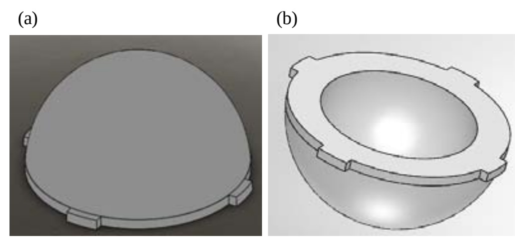

Fig. 2: The CAD Model of the acetabular liner with UHMWPE material

Table 1: The physical and mechanical properties of UHMWPE

Properties	Values
Density	0.930-0.945 g/mL
Elastic modulus	0.8-1.5 GPa
Tensile yield strength	19.3-23 MPa
Elongation at fracture	200-350%
Ultimate stress	30.4-48.6 MPa

Toolpath generation in the CNC milling of UHMWPE: Toolpath strategies for machining UHMWPE were generated using CAM (Computer Aided Manufacturing PowerMill Software in 2016. These machining strategies could be examined through examining the movement of cutter in milling process of workpiece automatically. The strategies were deemed appropriate for this research including model area clearance, optimize constant Z finishing, step and shalow finishing and raster finishing (Fig. 2).

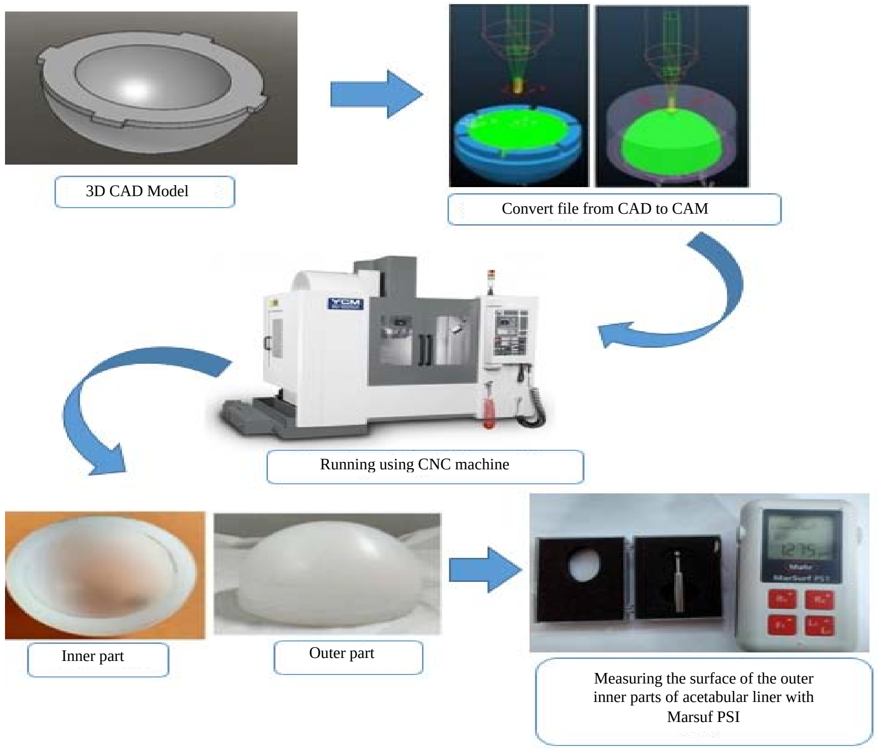

Fig. 3: The CAM process stages for the outer and inner parts of the acetabular liner selected during the experimental tests

Model area clearance can be selected in the roughing process which could remove UHMWPE material quickly with a large depth of cut, ranging from 1-5 mm depending on the shape of the component being machined. In this study, about 1-1.5 mm for depth of cut was proposed. Subsequently, the cutter movement followed the pattern of the area to be machined. This toolpath movement pattern is suitable for saving time and speeding up machining time because the cutter moved only in the required area (Fig. 2a). Moreover, optimize constant Z finishing is suitable for use in a less complicated and detailed modeling machining process. The cutter motion pattern in the toolpath is proposed for moving around the model from the top end of the model to the bottom end of the model bit by bit following to the model product to be created. Consequently, this toolpath cutter movement is robust and reliable, thereby producing smooth finishing (Fig. 2b). On the other hand, step and shallow finishing could be an alternative generation of toolpath strategy. Furthermore, the optimized constant Z, that combines the threshold angle of 3D offset and constant Z, could be an alternative for cutting on the slices of corners that can't be done by constant Z but 3D offset provides the toolpath perfectly (Fig. 2c). This strategy is particularly suitable for the area profiles that have a working radius as in the acetabular cup wherein the profile near the top of the outer and the inner base of the worked part will form a radius. Finally, the raster finishing is a toolpath that can be used to process semi-finishing and finishing work. Similar to another toolpath, the raster finishing has a movement tool pattern to feed into all areas of the material while the movement of the cutter is from the left and right to form a model. The downside of the toolpath taster requires a process with quite long time when the tool feed into any material area (Fig. 2d).

Equipment and experimental procedure: The experimental tests were carried out on the vertical 3-axis CNC milling machine (YCM 1020 EV 20). This machine can be run at a maximum spindle speed equal to 10000 rpm, maximum power 15 HP/11 kW, feed rate equal to 24-36 m/min, whereas the cutting speed can be set equal to 1-10000 m/min. All experiments were performed under dry conditions. The surface roughness was measured at three-point around the circumference of the inner and outer sphere of the workpiece using surface roughness tester (Mark Surf PS1). The cut off distance was specified as 2.5 mm.

Figure 3 presents experimental steps of machining process of UHMWPE material for the acetabular liner. In view of machining UHMWPE, a commercial CAM Software was employed for the realization of the tool path strategies which in turn allows the management of various modes of tool path according to the geometry of the surface to be machined. Nevertheless, the choice of a machining strategy remains difficult task (Quinsat and Sabourin, 2007). In this study, the obtained tool path strategies from CAM Software was used for NC to generate code files in the CNC machine controller prior to the machining process.

RESULTS AND DISCUSSION

Surface roughness of the product: The effect of employing various toolpath strategies on average workpiece surface roughness was investigated. Figure 4 and 5 shows the average of surface roughness for the outer and inner acetabular liner as a result of the selected toolpath strategy. The range bars indicate maximum and minimum values. It is evident that the surface quality of both the inner and outer acetabular liner can be improved by selection strategy of steep and shallow. Obviously, the product of acetabular cup based on this toolpath strategy can meet ASTM standard of surface roughness (<2 µm) for the acetabular liner (Fig. 6). Accordingly, the use of the strategy of steep and shallow is promising for the development of milling strategy for the medical component. Nevertheless, from the economy of the point of view, the cost for machining should be relatively lower than that for high-temperature injection molding. Moreover, work remains to be carried out to optimize the machining parameters during CNC milling of UHMWPE.

Machining time: The machining time was measured for each toolpath strategy in all experiments. Table 2 presents results of the Ra-value and machining time for the outer and inner parts for three selected tool paths. The step and shallow processing time provided the lowest Ra-values but it required the longest time compared to the others. Toolpath of the raster is perhaps the best strategy to provide the lowest machining time, although, the highest Ra-values were obtained during milling. However, the Ra-values for the outer and inner parts were still lower than the ASTM standard value. Correspondingly, to reach good results in terms of surface quality, geometric accuracy of the final components requires a tool path with a variable step depth (depending on the part geometry). Accordingly, in a normal practice, the best final roughness in the acetabular liner production may use tool paths optimized setting corresponding to other machining parameters.

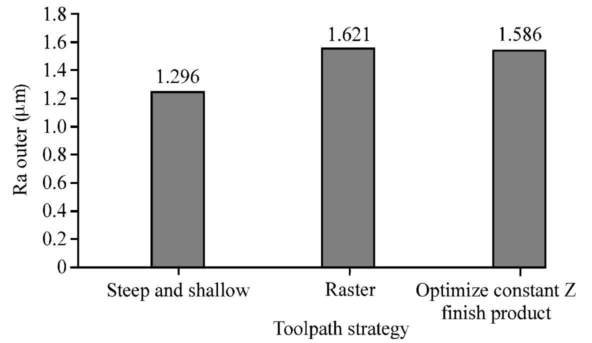

Fig. 4: Toolpath strategy versus surface roughness for the outer acetabular cup

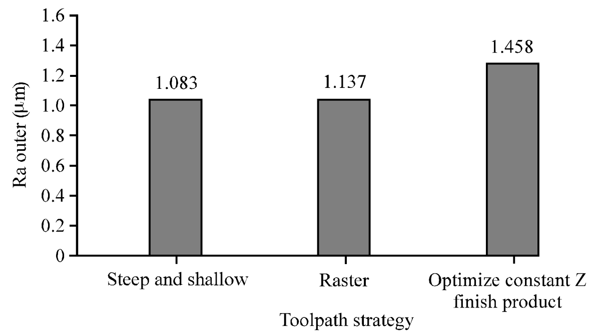

Fig. 5: Toolpath strategy versus surface roughness for the inner acetabular cup

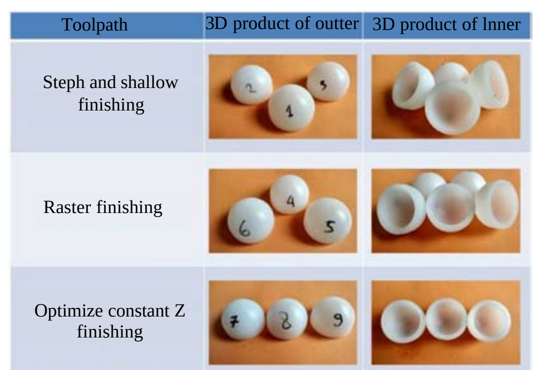

Fig. 6: Product of acetabular cups of hip joint with UHWPE material

Table 2: Experimental data of surface roughness and machining time

	Surface roughness		Machining time	
Toolpath strategy	Outer (µm)	Inner (µm)	Outer (h:min:sec)	Inner (hr:min:sec)
Steep and shallow	1.296	1.083	5:37:45	1:59:55
Raster	1.621	1.137	3:40:59	1:52:31
Optimize constant Z finish product	1.586	1.458	3:51:15	1:56:28

CONCLUSION

The following conclusions can be derived from this researcher: Use of 3-axis CNC machine can produce the acetabular cup of the artificial hip joint with surface Roughness value (Ra≤1.6 μm) for the outer and inner parts which meet the ASTM standard. Step and shallow finishing has the most significant effect on the Ra-values and machining time generated. Finally, milling process can be successfully used either to manufacture or to finish prototypes using the UHMWPE.

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