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Improving tool wear and surface covering in polishing via toolpath optimization

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ABSTRACT

Polishing operations are commonly carried out manually, thus inducing variability on the surface quality. The aim of this paper is to automate the polishing of free-form surfaces in order to obtain high quality surfaces. Tool wear and toolpath surface covering have a great impact on surface properties. The current work proposes therefore a toolpath which optimizes both tool wear and surface covering. This toolpath is composed of an optimized elementary pattern repeated along a 5-axis carrier trajectory. Usually, trochoid patterns are used. Non uniform wear of the tool and uneven probability density function of the surface covering are the main inconvenients of such pattern. So, this paper proposes two optimized patterns: *Spade* and *Triangular*. Both of them lead to uniform tool wear. Our paper also demonstrates that the second solution provides a uniform probability density function. All presented computations are validated experimentally.

1. Introduction

Biomedical implants need a high finishing quality, in particular for the roughness of friction surfaces. Femoral parts of knee prostheses hold these problems. Manufacturing of such workpiece attracts the interest of different research teams in the world. Hilerio et al. (2004) present the Product Life Management of knee prostheses and a study of the polishing stages. The manufacturing process of this biomedical part is presented in Fig. 1. First, the kinematic and functional requirements are specified in the Computer Aided Design (CAD) model. Next, due to the fact that implants are commonly realized in cobalt-chrome alloy, difficult to machine, lost-wax casting is generally selected to obtain the rough of geometry. Sometimes, before starting polishing, a rough-machined is also realized. Following, the prosthesis is polished with a succession of abrasive tools. After manufacturing, the implant undergoes many cleanings and sterilizations.

In the implant process planning, polishing operations are critical and correspond to the longest phases of the finish process. This stage needs accurate positioning of the prosthesis to the abrasive tool. For that reason it remains commonly still manual. This problem is recurrent for a great number of types of parts like molds, die sets, flow components (impellers, inducers, etc.), biomedical implants (knee, hip, etc.), etc. Polishing operations are however needed to obtain the required finish quality. These stages are labor intense and dangerous to health of the operator. Indeed, small metal airborne particles are produced by this process and may be inspired by the operator. Lison et al. (1996) present a study to understand the pathogenesis of lung disease produced by cobalt airborne particles (standard alloy used for prostheses). Furthermore, the geometrical result is greatly depending on the skill of the operator. Therefore, many works try to automate the polishing operation to stabilize the implant quality and reduce the production costs. The first problem is to find a machine able to emulate hand movements. Some special machines have been designed by numerous research teams. For example, Lee et al. (2001) developed a 2-axis robot designed to be mounted on a 3-axis CNC machine. For polishing assistance, Hocheng and Kuo (2002) propose a specific machine using ultrasonic axial vibrations of the tool. Wu et al. (2007) used a grinding center with an elastic ball end tool to polish free-form surfaces. Charlton and Blunt (2008) designed an industrial 7-axis machine dedicated to polishing operations. Liao et al. (2008) present a compliant toolhead for polishing and deburring operations. The presented head is mounted on a robotized tripod. Hung et al. (2011) suggest the use of a ‘rock-and-roll’ polishing toolpath strategy to get homogeneous tool wear. The presented method uses a ball-tool in rotation around the tool-axis. Furthermore, an additional rotation around the center of the ball-tool is applied to homogenize the tool wear along the spherical surface.

These machines are however only dedicated to polishing operations. In the same way, the use of 5 and 6-axis common industrial robots has been proposed. The advantage of this solution is its low cost. Moreover, the degrees of freedom of the robot offer a great accessibility to any free form surface. However, the accuracy of such

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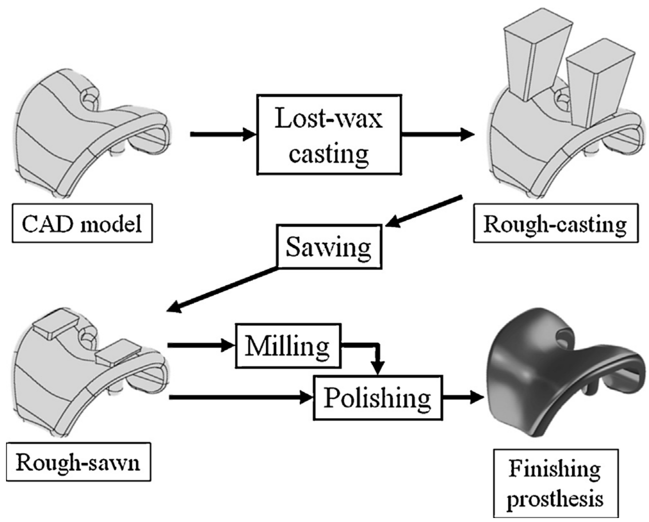

Fig. 1. Process planning of a knee prosthesis femoral part.

machine is limited to about 0.1 mm. The use of a machine dedicated to polishing imposes preparing the surfaces with 5-axis milling. In such process planning, polishing problems may then appear due to the loss of reference frame of the workpiece during its dismounting and next mounting. Thus, Denkena et al. (2010) suggest the use of one single CNC machine for both rough milling and polishing. In fact, such process planning is the most accurate way to know the localization of the real geometry before polishing.

The major problem of automated polishing is the control of the contact pressure between the tool and the workpiece. This pressure is essential in the material removal rate. To monitor this pressure, it is necessary to control the surface geometry and the contact force between the tool and the surface. Using a CNC machine, the workpiece is not dismounted between rough and polishing stages. In consequence, the polished surface geometry is accurately controlled. Two methods are employed to monitor the contact force:

- Using a load cell to control the force applied to the workpiece. The penetration of the tool is then directly linked to the selected force. Tsai and Huang (2006) control the load applied to a compliance tool using a polishing force control loop. Nagata et al. (2007) employ an industrial robot driven in force to polish molds. Huissoon et al. (2002) propose to polish surfaces with a flexible abrasive disk mounted on a load cell. This sensor is used to drive the tool position in force.
- Defining the constitutive law characterizing the relation between the tool displacement and the contact force. This law can be obtained through an experimental approach or theoretical calculations. Tsai and Huang (2006) use a polishing experiment, instrumented with a load cell to determine this law. On the other hand, lots of studies propose a Hertz contact model to determine the constitutive law between the tool displacement and the contact force. For example, Roswell et al. (2006) implement this model to find the stress in the Hertz contact between the tool and the polished surface.

Another problem is to define the polishing toolpath. Its aim is to cover the entire surface. To solve this problem, Tam et al. (1999) propose a linear scanning of the parametric space of the surface. After, the authors optimize the steps between the different scanning toolpath segments to get a uniform covering of the surface. This method reduces the overlapping of the segments, thus lowering their number. To boost the overlapping, Márquez et al. (2005) propose to use an elementary square pattern with two diagonals.

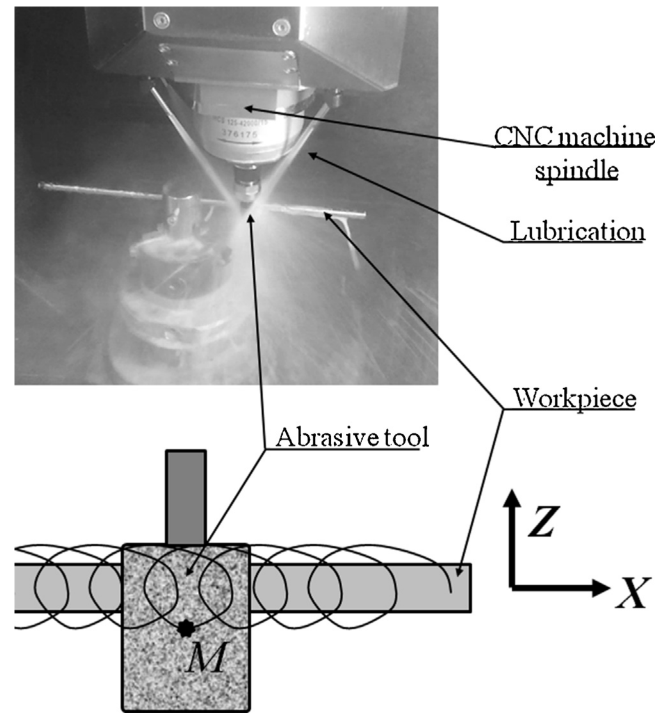

Fig. 2. Polishing process on a 5-axis milling machine.

Furthermore, fractal curves can be employed to cover the entire surface. Commonly Hilbert's curves are therefore taken. Chen et al. (2002) propose a method to compute Hilbert's curves on complex surfaces. In this paper, the authors test this method on a large range of geometries. Pessoles and Tournier (2009) use Hilbert's curves as a carrier to generate polishing toolpaths. The surface covering may be resolved using an elementary pattern repeated along a carrier toolpath. Usually, a trochoid pattern is selected, because the related movement looks like human polishing trajectory. For example, Tsai and Huang (2006) used a trochoid pattern in polishing toolpaths along a linear carrier toolpath. This type of pattern leads to a great number of loops which many times cross the same surface area. The trochoid pattern gives interesting results but its choice is arbitrary.

The aim of current paper is now to propose different toolpaths to automate the polishing operations of workpieces. A mathematical optimization of the polishing toolpath pattern will thus be presented to get homogeneous tool wearing and uniform surface covering. In a first section, the employed polishing process will be detailed. Next, the tool wear induced by trochoid patterns in flank polishing will be analyzed. This study will highlight the non uniform wear of the tool using such pattern. After, a *Spade* pattern will be proposed to correct this problem. Subsequently, a similar approach will be used to get a pattern which leads to a uniform covering of the polished surface. The results of experiments carried out to demonstrate the relevance of the presented developments will finally be presented.

2. Polishing process on CNC

The proposed polishing toolpaths can be used on any 5-axis CNC machine or industrial robot. The defined experimental process is illustrated in Fig. 2. The polishing operation is carried out using the flank of a cylindrical abrasive tool.

The proposed 5-axis polishing toolpath is a repetition of elementary loops with a small feed movement. This movement is presented in Fig. 3. The polishing toolpath is composed of a carrier toolpath and an elementary pattern along the tool axis. First,