Study on the generative design method and error budget of a novel desktop multi-axis laser machine for micro tool fabrications

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Abstract Micro end mills made of hard or ultra-hard materials are mainly fabricated by grinding or by wire electrical discharge machining (WEDM). However, with the advances of new tool materials from ultra-hard to super-hard together with lower or no electrical conductivity such as the material of nano-polycrystalline diamond, the grinding or the WEDM method cannot be used for machining due to their ultra-low process efficiencies for such materials. Laser machining has been tested an effective method. Accordingly, multi-axis laser machines need to be designed for micro tool fabrications. In the paper, a typical micro ball end mill with relatively complex features has been analyzed by the generative design method to generate the number and properties of needed motion axes. Based on the analysis, a novel five-axis laser machine has been designed. Aiming at high-quality micro tool fabrications, the kinematics model has been derived for this five-axis laser machine and error budge has been studied for the subsequently optimum selection of key motion components.

Keywords Micro tool · Generative design method · Error budget · Laser machine

1 Introduction

Mechanical micro/nano machining is gaining more and more importance due to the miniaturization tendency of products throughout the world. However, micro/nano machining process is performed under lower feed rates and smaller depths of cut comparing with conventional machining, which results in comparatively longer micromachining time. Consequently, longer tool life is needed. Ultra-hard materials such as cubic boron nitride (CBN) and polycrystalline diamond (PCD) are usually selected as tool materials to fulfill this requirement. To fabricate micro tools made of CBN or PCD, the grinding method is usually applied commercially and the wire electrical discharge machining (WEDM) method is also successfully applied in custom micro tooling [1, 2].

With the advances of new technologies, NPD is a new material made directly from graphite by direct conversion under high temperature and high pressure. It has the Knoop hardness of 120–145 GPa, which is higher than those of natural single crystal diamond [3, 4]. Therefore, it is an ideal material for micro tooling. Recently, micro ball end mills have been created [4]. However, by the grinding method using the soft materials to grind the hard materials, the machining efficiency is very low.

The WEDM uses a thin single-strand metal wire as the electrode to cut through the workpiece, which is one of the most favorable variants owing to its ability to machine conductive, exotic, and high-strength and temperature-resistant (HSTR) materials with the scope of generating intricate shapes and profiles [5]. Also, spools of wire are...
typically very long. For example, a 5-kg spool of 0.1-mm-diameter wire is just over 20 km long and it can cut for about 60 h, which makes the batch production possible. An appropriate manufacturing process to cover the growing need for accurate small tools is EDM with thin wires [6]. WEDM has been gaining wide acceptance in the machining of the various materials used in modern tooling applications [7]. However, the ultra-hard nano-polycrystalline diamond is electrically nonconductive, which makes it impossible or very difficult to machine the material by WEDM method.

According to literature [8], laser machining techniques seems a good choice. Consequently, laser machine tools are needed for the fabrication of micro tools. There is limited research on the special purpose laser machines made for the fabrication of micro/nano milling tools. Also such kind of special purpose laser machine does not exist in the market yet. Furthermore, desktop or mesoscale machine tools are getting more and more importance for their inherent attributes [9, 10]. This paper attempts to give a basic study from the functional design point of view for a desktop machine tool.

Like any design, it is critical that the best concept is chosen in the early stage of the design process because 80% of the final cost and quality of a product are designed at this phase [11], which can also be applied to machine tool design. A generative design method was introduced in [12] and used for a lathe design, which gave reasonable and intuitionistic answers to machine tool designs. By this method, a six-axis WEDM machine has been functionally analyzed and developed [13, 14].

In this paper, the generative design method is studied and expanded to the function design of the multi-axis laser machine for the fabrication of micro tools. First, the geometry features, namely the generating line and guide line, of the typical ball end mill are defined. Second, the mathematical model to describe the interrelation between the tool blank geometry and the laser focal point is derived. Based on the mathematical model, the required number of the axes and axis motions are obtained. According to the characteristics of specialized laser machine, the schematic three dimensional CAD models are created. In order to acquire a high-accuracy laser machine, the kinematics model is built and consequent error budget has been made to guide the optimum selection of the motion components in the future.

2 Generative kinematics design

2.1 Typical geometric analysis

In mechanical micro/nano machining, micro tools used in micro/nano milling is comparatively more complicated in geometry than that used in micro/nano turning, shaping, etc. Therefore, in this paper, a micro ball end mill is selected for analysis as it has the near freeform geometries. The selected micro ball end mill pictures and CAD models are shown in Fig. 1.

The geometric model of the selected ball end mill is shown in Fig. 2, where the most important geometrical features, namely the cutting edge and rake and clearance faces, are depicted. O is the center of the ball shape, circle ACA is the cross section of the ball at the middle with the center O, arc ABC is the cutting edge, P is an arbitrary point on the cutting edge with the central angle of β, R is the radius of the ball shape, the half circle A1B1C1 is auxiliary for the following analysis, the plane A1B1C1 is parallel to the cutting edge plane ABC with the distance of L, O1 is the center of arc A1B1C1, P1 is the corresponding point on arc A1B1C1 to point P with the same central angle of β, α is the absolute value of the rake angle. To form the cutting edge and the rake and clearance faces, line AA1 moves along the arc ABC and the arc A1B1C1 respectively, which overlaps P1P while the central angle in β, overlaps BB1 while β equals 90° and overlaps CC1 while β equals 180°. The other half rake and clearance faces can be created with the same principle.

2.2 Generative design analysis

The coordinates are built as shown in Fig. 2, where \( \Sigma_{O} \) has the X-axis pointing from O to O1, Y-axis pointing from O to A, and Z-axis is at the center line of the rotational axis of the ball end mill. \( \Sigma_{P} \) has the X-axis pointing from P to P1, Y-axis pointing from O to P, and Z-axis is tangent to arc ABC at point P. Based on the generative design method as discussed in [13], line PP1 is selected as the generating line, and arc ABC is selected as the guide line. Point P1 represents the arbitrary point on the ball end mill geometry to be machined and overlaps P while L equals 0. According to the coordinates built above, the transformation matrix for the generating line can be written as,

\[
O_{T_{P1}} = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & C_{\beta} & S_{\beta} & 0 \\
0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0
\end{bmatrix} \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & R \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
1 & 0 & 0 & \frac{L}{R} \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

(1)

namely,

\[
O_{T_{P1}} = \begin{bmatrix}
1 & 0 & 0 & \frac{L}{R} \\
0 & C_{\beta} & -S_{\beta} & RC_{\beta} \\
0 & S_{\beta} & C_{\beta} & RS_{\beta} \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

where, \( C \) and \( S \) means the cosine function and sine function, respectively.