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Characterization of tool-workpiece contact during the micromachining of conductive materials

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ABSTRACT

The characterization of dynamic cutting in micro-machining operations is essential for real-time monitoring of tool performance. The analysis of tool-edge/material contact and its electrical resistivity is therefore an interesting avenue of research for monitoring tool-workpiece interaction. This study examines mechanical cutting operations in micromilling operations that remove material to meet the design requirements of conductive parts. It draws from previous research into the theoretical models of cutting mechanisms in milling operations, to present a mathematical characterization of the tool-edge/material contact area. The rationale behind this research is that the contact area between two conductive materials is one of the main factors in determining the magnitude of resistance to the flow of an electric current between both materials. The study also offers a theoretical analysis of tool-edge radial immersion angles on entry and exit and their dynamic behavior. The analysis is mainly centered on cutting operations and cutting-time intervals, where tool-material contact is intermittent. Our theoretical analysis is experimentally corroborated by measuring tool-edge immersion time and tool-edge/material contact time. Promising results are reported that contribute to the development of a technological method for high-precision, real-time monitoring of tool-workpiece interaction and cutting detection in micromachining operations.

1. Introduction

Nowadays, high-precision micro-machining operations for component miniaturization are in great demand, especially in medical instrumentation, aerospace engineering, and computer manufacturing, among other industries [1]. Further challenges arise, due to the smaller-scale of overall part dimensions and cutting-tool diameters that require highly accurate manufactured parts. Indeed, expert operators can no longer monitor micromachining operations by visual inspection or audible signals alone, due to the dimensions of tools, chips, burrs and the amount of lubricant that is used [2,3]. One possible solution is to develop high-precision, real-time monitoring systems for micromachining operations [4,5].

The characterization of dynamic spindle-tool-piece (STP) interaction, for monitoring micro-scale machining processes, such as micromilling operations, is now an active area of research. Theoretical STP models and mathematical characterizations have been proposed to predict cutting forces and other related variables and parameters (chip formation, burrs, etc.) [6–8]. There are, however, far fewer studies when the focus shifts from the macro to the micro-scale.

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Some studies have reported techniques to determine the state of STP interaction from sensors. These works have been widely used for monitoring STP by means of different sensorial principles (i.e., accelerometers, acoustic emission, cutting force, infrared, etc.) [9–13]. In contrast, when the use of sensors to collect information is process intrusive, expensive, and computationally inefficient, some authors predict or estimate the behavior of representative variables (e.g. cutting forces) from mathematical models of tool-workpiece interaction, so that they may subsequently be used for monitoring and controlling machining operations [14–17].

All the above-mentioned methods are valid at laboratory level when there are no restrictions on response time, cost or limitations in the workspace. Therefore, the redesign and implementation of new sensor systems and processing techniques [18] are very necessary to deal with new micro-scale requirements.

This paper is focused on conductive materials commonly used in mechanical machining operations for material removal. The electric contact resistance of the tool edge/conductive material can be obtained, by supplying an AC current through the *STP* impedance system (Z_{STP}). This basic operating principle has been used in a previous work [19], in which various methods were investigated to detect tool breakage. The same principle has been already reported in the context of adjusts to the position reference at the tip of the cutting tool [20,21]. However, any method solely based on this operating principle is insufficient for an appropriate characterization of *STP* contact. Accordingly, decision-making on the status of the micro-scale cutting process depends on the dynamic behavior or temporal transient of *STP* by measuring Z_{STP} in micromachining operations.

The main contribution of this work can be organized into four areas. Firstly, a theoretical analysis of the cutting mechanism is presented, in order to obtain a mathematical characterization of the tool-edge/material contact area. The rationale behind this research is that the contact area between two conductive materials is one of the main factors in determining the magnitude of resistance to the flow of an electric current between both materials. The second contribution relies on a theoretical analysis of the dynamic behavior of the radial immersion angles along the cutting tool edges in relation to the dynamic behavior of the contact area. The theoretical analysis is mainly focused on micromilling operations and cutting time intervals where tool-material contact is intermittent. Moreover, this paper also presents an experimental characterization based on the measurement of two representative variables of the cutting mechanism in micromilling operations, the contact time and the distance contact, that will be defined later. Finally, the experimental results point to the use of this simple principle as a method for experimental characterization of mechanical processes and, specifically, processes for the micromilling of conductive materials.

The paper is organized as follows: Section 2 presents the theoretical foundations of contact resistance and contact area; Section 3 describes the procedure for obtaining real-time values of contact time and distance covered by the tool; Section 4 explains the experimental results and relative errors between the experimental and the theoretical values. Finally, some conclusions from the results are discussed in Section 5.

2. Theoretical foundations. Contact resistance

Electrical resistivity, also known as specific material resistance, is a measure of resistance to the passage of an electric current through a material. Low resistivity implies that an electrical charge passes through a material easily. According to Eq. (1), the static resistivity, ρ (Ω m), of a material and its inverse value or electrical conductivity, σ, are determined by the magnitude of an electric field E (V m^{-1}) that is applied to a material and the current density, J (A m^{-2}), that flows through it.

$$\rho = \frac{E}{J}, \quad \sigma = \rho^{-1} \tag{1}$$

The total electrical resistance R (Ω) of a material to an electric current that passes through it is defined in terms of material resistivity and is affected by the geometry of the material. For example, in the case of a single workpiece formed of a resistive material with a uniform cross-sectional area, a, and a length, ℓ, its electrical resistance, R, and therefore, inversely, its electrical conductance, G, are determined by: (Fig. 1).

$$R = \rho\frac{\ell}{a}, \quad G = R^{-1} \tag{2}$$

2.1. Relationship between contact area and contact resistance

During the machining of conductive material, if an electric field is applied to a tool-piece system, electrical resistance appears at contact points (contact resistance [22]). This resistance is due to the current intensity that is generated when an electric field flows through an extensive section. Resistance in the cutting operations, R_c, depends mainly on both the electrical resistivity of the workpiece material, ρ_p, the resistivity of the tool material, ρ_t, and the contact area, A_c (Eq. (3)):

$$R_c = f(\rho_p, \rho_t, A_c) \tag{3}$$

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