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Surface characterization in ultra-precision machining of Al/SiC metal matrix composites using data dependent systems analysis

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Abstract

This paper presents a data dependent systems (DDSs) method for the analysis of surface generation in ultra-precision machining of Al/SiC metal matrix composites (MMCs). The DDS analysis provides a component by component wavelength decomposition of the surface roughness profile of the machined surface. A series of face cutting experiments was done on Al6061/15SiC$_p$ MMCs under different cutting conditions. The cutting results indicate that the characteristics of the wavelength components analyzed by the DDS analysis method are correlated well with the surface generation mechanisms. Since the relative powers of the wavelength components are used to measure the contributions of the cutting mechanisms to the total roughness, this resolves the shortcomings of the conventional spectrum analysis method in characterizing the surface properties such as pits and cracks in ultra-precision machining of MMCs.

Keywords: Cutting dynamics; Data dependent systems analysis; Metal matrix composites; Surface generation; Wavelength decomposition; Ultra-precision machining

1. Introduction

Over the past decades, the machinability of silicon carbide reinforced aluminum alloy (Al/SiC) composites has attracted much scientific and public attention. The Al/SiC composites are promising as structural materials because of their high specific modules and specific strength, good wear resistance and high temperature resistance [1]. However, it is well known that the metal matrix composites (MMCs) are difficult to machine to a good surface finish. This is due to the fact that the hard SiC reinforcement in the Al/SiC MMC is embedded in the soft ductile aluminum matrix. The mechanism in the cutting of SiC reinforcement depends largely on the deformation of the Al matrix during cutting [2].

Some research work has been reported on the surface characteristics of machined Al/SiC MMCs. In the study of Looney et al. [3], the influence of tool materials on surface finish has been reported. El-Gallab and Sklad [4] have further examined the microstructures of chips, and observed the formation of shear bands, where reinforcement particles align themselves. By developing an improved quick-stop device, Lin et al. [5] are able to examine the cutting mechanisms more effectively. Although extensive studies can be found in literature on the machinability of MMCs, most of these studies focus only on the conventional turning process, relatively little research work has been done on studying the surface generation in ultra-precision machining of MMCs, such as single-point diamond turning (SPDT). In SPDT, the cutting edge radius of the diamond tool is usually in the same order as the average size of the reinforcement in the Al/SiC MMC. There is a significantly thick layer of undeformed chip (i.e. with the same order as the average size of the SiC reinforcement) at which complicated plastic and elastic deformation are taking place. The current understanding on the cutting mechanics, deformation behavior and its relation to the surface generation mechanisms is still limited.

In this paper, the mechanisms of surface generation in ultra-precision machining of an Al/SiC MMC are analyzed based on a data dependent systems (DDS) analysis [6]. The DDS analysis provides a component by component wavelength decomposition of the surface roughness profiles of the machined surfaces. The characteristics of these wavelength components are correlated with different surface generation mechanisms. Their relative powers are used to measure the contributions of the mechanisms to the total roughness.

2. Surface characterization using DDSs analysis

Although the methodology for the characterization of surface generation in ultra-precision machining has been

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the subject of many theoretical and practical studies, most of the methods focus on static measures of surface roughness parameters. Relatively, little research was found in correlating the surface roughness parameters with the surface generation mechanisms. The surface roughness profile of a machined surface provides a faithful signature of the cutting process and the variation of material properties. Moreover, an imprint of all the static as well as dynamic factors such as forces, stress, strains and materials swelling during cutting are left in the surface roughness profile. The stylus measurement method has been proven to be the most useful method owing to its convenience in output, ease of use and robustness. In many cases, a single-profile is sufficient to give an adequate idea of the surface.

Spectrum analysis method has been proven to be useful to the characterization of the influence of process factors, vibration, interference of tool and material swelling upon the surface generation. However, the spectrum analysis method is incapable of determining the exact contribution of individual factors upon the overall surface roughness. A DDSs analysis is used by the authors to provide a parsimonious mathematical model for correlating the metal cutting dynamics with their respective contributions to the total roughness of a machined surface. In the present study, the DDSs analysis is proposed to overcome the shortcoming of spectrum analysis.

2.1. Theoretical background of DDSs modeling

The DDSs modeling [6] is based on two theorems called Fundamental Theorem and Uniform Sampling Theorem [7]. It consists of fitting autoregressive moving average (ARMA) $(n, n-1)$ models by a non-linear least squares errors searching algorithm until the sum of squares of the prediction error cannot be significantly reduced as judged by the F-test [6]. The advantage of the DDS approach over FFT is not merely in providing the parsimonious mathematical models of physical significance, but also in quantifying the power and damping ratios of all modes [7]. It provides statistically adequate models in the form of difference equations, directly from the measured surface roughness data as shown in Eq. (1).

$$\begin{aligned} &X_t - \phi_1 X_{t-1} - \cdots - \phi_n X_{1-n} \\ &\quad = a_t - \theta_1 a_{t-1} - \cdots - \theta_{n-1} a_{t-n+1} \end{aligned} \tag{1}$$

where X_t is the measured height of the surface roughness profile, a_t's the independent series with variance σ_a^2, i.e. the white noise; $\phi_1, \phi_2, \ldots, \phi_n$ are the autoregressive coefficients and $\theta_1, \theta_2, \ldots, \theta_{n-1}$ are the moving average coefficients.

The left-hand side of Eq. (1) is the autoregressive (AR) part of the model which can be expressed by:

$$\begin{aligned} &(1 - \phi_1 B - \phi_2 B^2 - \cdots - \phi_n B^n) \\ &\quad \equiv (1 - \lambda_1 B)(1 - \lambda_2 B) \cdots (1 - \lambda_n B) \end{aligned} \tag{2}$$

where B is the backward shift operator defined by $BX_t = X_{t-1}$. Eq. (2) represents a nth order differential equation with characteristic roots $\mu_1, \mu_2, \ldots, \mu_n$ which are related to $\lambda_1, \lambda_2, \ldots, \lambda_n$ of the difference equation (1) by:

$$\lambda_i = \mathrm{e}^{\mu_i \Delta} \quad \text{for } i = 1, 2, \ldots, n \tag{3}$$

where Δ is the sampling interval.

The ARMA $(n, n-1)$ model in Eq. (1) can be rewritten in the transfer function form by using the backward shift operator as

$$\begin{aligned} X_t &= \frac{1 - \theta_1 B - \theta_2 B^2 - \cdots - \theta_{n-1} B^{n-1}}{1 - \phi_1 B - \phi_2 B^2 - \cdots - \phi_n B^n} a_t \\ &= \sum_{j=0}^{\infty} G_j a_{t-j} \quad \text{for } i = 1, 2, \ldots, n \end{aligned} \tag{4}$$

G_j is the Green's function which can be determined by applying partial fractions to Eq. (4) as

$$G_j = g_1 \lambda_1^j + g_2 \lambda_2^j + \cdots + g_n \lambda_n^j \tag{5}$$

where

$$g_i = \frac{\lambda_i^{n-1} - \theta_1 \lambda_i^{n-2} - \cdots - \theta_{n-1}}{\prod_{j=1, j \neq i}^{n} (\lambda_i - \lambda_j)} \tag{6}$$

$$d_i = \left(\frac{g_i g_1}{1 - \lambda_i \lambda_1} + \frac{g_i g_2}{1 - \lambda_i \lambda_2} + \cdots + \frac{g_i g_n}{1 - \lambda_i \lambda_n} \right) \sigma_a^2 \tag{7}$$

for $i = 1, 2, \ldots, n$.

For the diamond turning process, the components g_i of the Green's function G_j are the results of inherent periodicity interacting with various process elements. Thus, the Green's function may represent a characteristic shape of the random profile and together with a_t provides a complete physically characterization of the cutting dynamics.

The variance or total power of the roughness profile is given by:

$$\gamma_0 = d_1 + d_2 + \cdots + d_n \tag{8}$$

For a pair of complex conjugate roots, λ_i, λ_{i+1}, this percentage is

$$P = \frac{100(d_i + d_{i+1})}{\gamma_0} \tag{9}$$

For a real root λ_i, this percentage is given as

$$P = \frac{100 d_i}{\gamma_0} \tag{10}$$

The order of the model is usually increased in even number of step size since an odd number step size of order increment will force a root of the system to be real, not allowing for complex conjugate pairs. The statistical significance of the reduction in the sum of squares after increasing the order of the model is checked by a F-test [6] at 5% level of significance as follows:

$$F = \frac{(E_1 - E_0)/S}{E_0/(N - r)} \sim F(S, N - r) \tag{11}$$