



Technical Paper

Assessment of micro turning machine stiffness response and material characteristics by fuzzy rule based pattern matching of cutting force plots

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ABSTRACT

In micro-nano systems technology (MNST), application of mechanical based machining operations such as micro turning, micro milling, micro EDM have shown promising trends to produce micro parts in batch scale. In order to ensure reproducibility better understanding on micro cutting process dynamics and sensitivity of machine stiffness and material characteristics becomes critical. In this paper, a methodology has been developed to assess machine stiffness and material dependent characteristics and demonstrated for micro turning operations conducted on DT-110 micro machining center. In this method, authors incorporate pattern matching algorithm to compare run data image of cutting force plots with that of reference plot. The reference plots of cutting forces v/s time were drawn from simulation run data computed from the micro turning process models. The run data plots of cutting force v/s time were drawn from the processed signal data obtained from the dynamometer during machining operation. The plots were fragmented into patterns and Euclidean distance computed between pair patterns of reference and measured cutting forces v/s time plot image represents the changes happened in machining conditions. This has been used to perform backward calculation to assess the machine stiffness response and material characteristic constants variations over machining time. In order to perform these comparative pattern error adjustments between reference and measured cutting force plots a fuzzy rule based algorithm has been developed.

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1. Introduction

The growing interest in applications of micro-nano scale devices in many applications has diversified the market demand toward batch production of multi material micro parts. Therefore, innovative integration and development of knowledge base for scaling up of production by precision manufacturing technologies to ensure effective industrial utilization has become the primary focused area of micro-nano scale manufacturing research. The successful adaptation of material removal processes such as milling and turning that uses cutting tools having geometrically defined cutting edges, have shown significant potential for producing accurate simple holes to a complex 3D features.

Micro metal cutting research sees the creative results in understanding process physics, and modeling. In the view of the issues associated with tool breakage, and instability of micro machine

tools dynamics, process control is getting much importance. Tool breakage, instability and machine chattering occur due to improper machine stiffness and material constants. These parameters are not fixed but vary with operation and aging. This paper presents a systematic methodology for assessing the machine stiffness and material constants during run time of machine using image pattern matching approach. This work is an essential element of intelligent controllers being developed for micro factory test bed by the authors. The proposed fuzzy rule base driven comparative pattern error adjustment algorithm is generic, and it can be adapted to several micro machining process. In this paper, authors demonstrate the assessment of machine stiffness and material constants to use in micro turning operations. In order to establish the better context to this multidisciplinary study a brief overview of micro turning process and methodologies of pattern matching of reference and measured images are reviewed next, before discussing the proposed algorithm, its implementation and evaluation.

2. Micro turning process modeling: an overview

Micro turning is the precision machining process, used to produce cylindrical shaped micro parts varying from few hundred microns to 1 mm in diameter. In this process, normally single point

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tool (diamond tip brazed on to miniaturized HSS tool shank) is fed against the rotating work piece. The elastic deflection of micro-scale work piece by induced cutting and feed forces becomes the primary concern for process control. This elastic deflection changes the process kinematics; hence prediction of real feed rate and real depth of cut, which are important parameters in preserving surface integrity of machined work piece, becomes approximate. This prediction becomes further unrealistic, because of a complex dynamics contributing to changes in machine stiffness, changes in tool positioning and orientation. Therefore, dynamic representation of micro-turning process conditions is the current demand. Many researchers including Hwang et al. [1], Aris and Cheng [2], Luo et al. [3] and Budak and Ozlu [4] have investigated on dynamic modeling and simulation of surface generation for conventional macro scale turning process conditions. They have investigated a single or multiple aspects of dynamic machine tool structural response, cutting process variables, tool geometry and dynamic cutting force modeling. Some of these dynamic modeling approaches have been adapted for other micro machining processes such as micro-drilling by Gong and Ehmann [5], micro-milling by Piotrowska-Kurczewski and Jost [6] and micro scale grinding by Park and Liang [7].

For micro turning operations, recently, Piotrowska et al. [8] have developed a mathematical model to predict real feed rate, real cutting depth, as well as cutting and feed forces. In this work deflection of tool has been considered. The derivation of the model and further discussion is available in the reference. The final equation sets derived in the paper are as in Eqs. (1)–(7).

$$\dot{d}^a(t) = v_f^a(t) \quad (1)$$

$$\dot{\delta}_x(t) = v_f - v_f^a(t) \quad (2)$$

$$\dot{\delta}_y(t) = \frac{c_y}{c_x} \left[(v_f - v_f^a(t))(r - \int_0^t v_f^a(\tau) d\tau) - \delta_x(t)v_f^a(t) \right] \quad (3)$$

$$\dot{a}_p^a(t) = -\frac{1}{l_h} \left[\delta_x(t)(v_f - v_f^a(t)) + \delta_y(t) \frac{c_y}{c_x} [(v_f - v_f^a(t))r - \int_0^t v_f^a(\tau) d\tau - \delta_x(t)v_f^a(t)] + c_r A_r(t) \right] \quad (4)$$

$$v_f^a(t) = \frac{v_f - v_f^a(t)(1 + c_x a_p^a(t))}{c_x a_p^a(t)} \quad (5)$$

where c_x and c_y are given by Eqs. (6) and (7)

$$c_x = \frac{c_f b_\varepsilon}{K_{ex}} \quad (6)$$

$$c_y = \frac{c_c 2\pi}{K_{ey}} \quad (7)$$

These differential equations are solved with the following initial conditions: $\delta_x(0) = 0$, $\delta_y(0) = 0$, $a_p^a(0) = a_p$, $v_f^a(0) = 0$, $d^a(0) = 0$.

Nomenclature

v_f	feed velocity
a_p	depth of cut
l_h	length of tool holder
K_{ex}	machine stiffness in X-direction
K_{ey}	machine stiffness in Y-direction
δ_x	deflection of tool tip in X-direction
δ_y	deflection of tool tip in Y-direction
r	radius of work piece

b_ε	width of tool in X–Y plane
A_r	frictional area during machining process
d	displacement of turning tool on work piece surface
C_f, C_c, C_r	material related constants affecting the machining dynamics

Note: Symbols bearing superscript ‘a’ denotes its dependence on machining time. For example $a_p^a(t)$ denotes instantaneous depth of cut varying with time.

In the above study, the authors solved these non-linear differential equations by taking two stage input information. The work piece properties, tool specifications and the process parameters of the turning process are used in MATLAB calculations. For numerical calculations nominal system parameters for machine stiffness and material constants have been used at three different values.

However in practice, metal cutting mechanics in micro turning changes with time. This is owing to the elastic deflection of tiny work piece, wear of cutting edge having minimum nose radius. This dynamic change in cutting mechanisms also depends on work-tool combinations, operation cycle, position and orientation of tool and tool holder, and also because of aging effects. Thus assessment of these changes is critical, demanding dynamic process control of micro turning. On the other hand, selection of appropriate instrumentation to monitor this process dynamically is difficult. Because, change in cutting forces resulting from these cutting dynamics is in few fraction of Newton-force and appreciating the deflection of micro parts becomes difficult till the damage is significant. Often this situation leads to breakage work piece and/or tool cutting edge. Further, Kistler dynamometer used widely for micro cutting force measurements are capable of acquiring the force signals in micro-Newtons resolutions at higher frequency. Therefore, in this work, authors have integrated simple image pattern matching techniques, wherein the cutting forces v/s time plots drawn from the run data (acquired from the dynamometer) is being constantly compared with the model (reference) plots which are drawn based on the solutions obtained from the micro turning models proposed by Piotrowska et al. [8]. The methodologies and results on its implementation into practical micro turning experiments have been discussed in later part of this paper. In order to appreciate and for the better understanding, pattern matching techniques and their applications are reviewed next.

3. Previous work on pattern matching methods

Pattern matching algorithms deal with adjustment of image patterns. One of the patterns is essentially theoretical obtained using a model, whereas the other pattern is obtained using a sensor from real time operation of a system known as observed pattern. The job of the algorithm is to match the theoretical and observed patterns as cited in Trochim [9]. The theoretical pattern is governed by a known relationship or more specifically a mathematical equation. Further the equation bears some constant and variable parameters. The observed pattern can also be described using a mathematical equation. In real time operation of a system, generally it becomes impossible to evaluate the exact mathematical relationship for the observed pattern. Pattern matching algorithm allows the user to match the two mentioned patterns. In this process the exact mathematical relationship along with the constants and variables present in the relationship gets evaluated at exact match of the patterns.

In matching patterns between two images, the issue lies with registering of transformation (i.e. rotation, scaling and translational) parameters. It is usually impossible to determine the transformation that maps an arbitrary point coordinates of first image to the corresponding coordinates of the point in the second image, unless they are spare set of points and are unique from their neighbors as in Goshtasby et al. [10]. In image processing

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