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International Journal of Machine Tools & Manufacture 46 (2006) 603–610
INTERNATIONAL JOURNAL OF MACHINE TOOLS & MANUFACTURE DESIGN, RESEARCH AND APPLICATION
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Adaptive support vector regression analysis of closed-loop inspection accuracy

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Received 17 March 2005; accepted 7 July 2005
Available online 19 August 2005

Abstract

This study investigates how closed-loop measurement error in CNC milling relates to two different inspection techniques. The on-line inspection of machining accuracy using a spindle probe has an inherent shortcoming because the same machine that produced the parts is used for inspection. In order to use the spindle probe measurement as a means of correcting deviations in machining, the magnitude of measurement errors needs to be quantified. The empirical verification was made by conducting three sets of cutting experiments at the state-of-the-art Cincinnati Arrow Vertical Machining Center. Three different material types and parameter settings were selected to simulate a diverse cutting condition. During the cutting, the cutting force and spindle vibration sensor signals were collected and a tool wear was recorded using a computer vision system. The bore tolerance was gauged by a spindle probe as well as a coordinate measuring machine. The difference between the two measurements was defined as a closed-loop measurement error and adaptive support vector regression analysis was used to predict these bore difference at various values of the explanatory variables. The results show the potential of improving production efficiency and part quality.

Keywords: CMM; Touch probe; SVR; Statistical learning; On-line inspection

1. Introduction

Discrete part manufacturing using computer numerical controlled (CNC) milling machines is common in modern manufacturing [1]. Depending on the accuracy and surface finish requirements, the machining parameters, which have a significant influence on part quality, need to be set properly [2,3]. Vibration in machining is particularly harmful in this regards [4], yet can be minimized through the use of computer simulation prior to the machining. The simulation can project the optimal range of cutting speeds and feed rates for a chatter-free machining, thereby producing less scrap and enhancing part quality. Since each machine tool exhibits disparate characteristics in stiffness, damping, and natural frequency [5], the importance of pre-machining simulation is applied to each machine, especially when the machine is newly acquired. Equally important in machining is the confidence in the measuring instruments from which part quality characteristics are ascertained. Part dimensional accuracy check has been largely based on the post-process inspection such as a coordinate measuring machine (CMM). CMMs are widely used in the manufacturing industry for precision inspection and quality control [6,7], and recognized as a reliable and flexible gauge suitable for assessing the acceptability of machined parts [8]. The downside of this technique is that non-conforming parts can be produced between inspections since there can be a significant delay between production and completion of inspection [3].

To remedy the problem, a machine mounted touch probe which has similar working principles as CMM [9] has started gaining popularity. The probe enables the measurement of machined parts while they are still fixed on the machine. By providing part size information directly into a CNC controller, a closed-loop process control can be realized in the form of real-time automatic tool offset to correct deviations or prevent defects in machining [10]. This is particularly important for a modern, computer controlled

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doi:10.1016/j.ijmachtools.2005.07.011

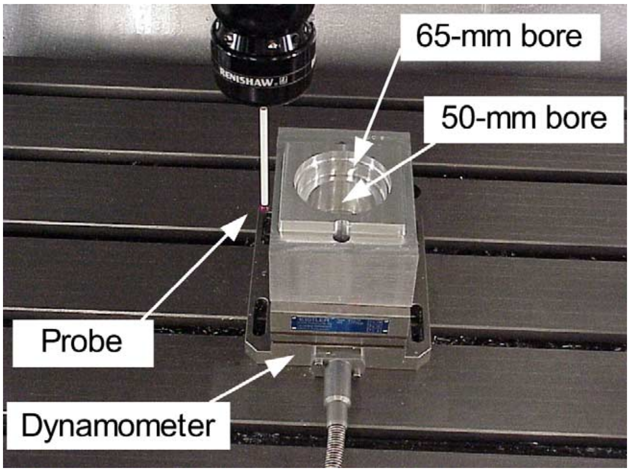

Fig. 1. Spindle touch probe moving to inspect a finished aluminum block mounted on the force dynamometer.

production environment, where very little human intervention is expected during the machining cycle. The accuracy of the probe, however, is affected by the machine tool positional accuracy and positioning system [10,11]. Since the same machine which produced the parts is used for inspection, there is an inherent problem in the accuracy of probe inspection. Therefore, in order for the probe data to be used for real-time control, the capability of probe needs to be analyzed and the factors affecting the probe data need to be ascertained.

2. Cutting experiments

To address the aforementioned problem, a newly acquired, state-of-the-art Cincinnati Arrow 750 CNC Vertical Machining Center (0.00254 mm repeatability) was used to conduct the cutting experiments. Three material types that are widely used in both automotive and aerospace industry (6061-T6 Al, 7075-T6 Al, and ANSI-4140 steel) were selected. A 25.4 mm end mill was fixed in the spindle and the hammering on the tool was analyzed to determine the frequency response function of the machine tool structure. The stability lobe graph generated by the CutPro® software provided the combination of depth of cut and cutting speed for minimum chatter in machining. Consequently, the axial and radial depth of cut and cutting speed were tuned for a chatter-free machining.

Each machined block has two stepped bores (65 and 50 mm diameter). The bores were selected as the critical quality characteristics because circularity and cylindricity of machined parts are regarded as the most fundamental geometric features in engineering [12,13]. To ensure the proper functioning of round parts, permissible deviations from the true circle are allowed in the form of tolerance zones bounded by two concentric circles [13], which dictate the desired dimensional and form accuracy [14]. The bores have a tolerance of -0.1 mm, corresponding to an ISO tolerance grade of IT10. Tolerances were measured using a spindle probe as illustrated in Fig. 1 (a Renishaw MP 700 surface sensing wireless probe with 2.54×10^{-4} mm repeatability) and a newly calibrated Mitutoyo B403B CMM. The CNC mill was fitted with multiple sensors and data acquisition systems to collect cutting force measurements and spindle quill vibration/acceleration. Each measurement was further divided: x, y, z cutting force components (F_x, F_y, F_z) and x, y, z spindle quill vibrations (A_x, A_y, A_z). Those components were filtered and processed for both time and frequency domain features. The arithmetic averages, F_v and A_v, were also calculated. All cuttings utilized coolant to minimize friction and overheating. For aluminum parts, a high speed steel (HSS), 2-flute, cobalt end mill cutter was used until the tool wore out. The frequency of tool vibration was monitored throughout the machining; the tool was considered worn out when it started generating excessive chatter and vibration. For 6061-T6 Al, a total of 20 parts were machined; for 7075-T6 Al, tool wore out after 19 parts were cut. For steel, an uncoated, 2-flute, tungsten carbide cutter was used and 17 parts were finished before tool wore out.

After the machining, two randomly selected points along the surface of the blocks were measured for material hardness. The average hardness was 43, 85, 93 HRB for

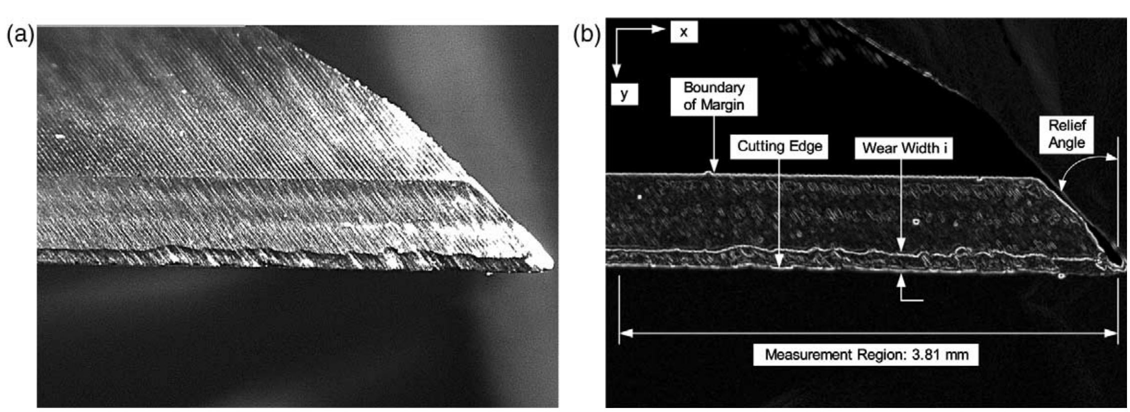

Fig. 2. Preprocessed image of cutting edge (a) and the further processed image showing the wear width and the boundaries (b).