CONCEPTUAL DESIGN OF A RECONFIGURABLE Fixture FOR MESO-MILLING

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ABSTRACT

Fixture design is critical to the development of a meso-scale machining system capable of yielding micro-size features with high accuracies. A reconfigurable, intelligent fixturing system with embedded sensors is required (i) to fixture a large group of similar workpieces with minimal set-up changes, (ii) to sense the location of the workpieces placed on the fixture, (iii) monitor clamping forces, etc. In this paper, the conceptual design for such a fixturing system is presented. The proposed design is based on conventional macro-scale modular fixturing principles with innovative features for meso-scale fixturing.

Keywords: Meso-milling reconfigurable modular fixture

INTRODUCTION

During the past decade, global demand for meso-scale systems in applications such as in-vivo biomedical devices, portable electronics, precision tools and components in the aerospace industry has been increasing [1]. Meso-scale parts are expected to have sub-micron accuracies. A fixturing system for meso-milling would require an accuracy level of one order of magnitude better than that of the machine itself.

Currently, most commercially available meso-milling systems either use simple locating/clamping systems or standard dedicated fixturing devices. This approach can satisfy the basic functional requirements of a meso-milling machine. However, using dedicated fixtures would lead to several limitations, including cost of fixturing and long lead-times, especially for one-of-a-kind and small batch-sized parts, and lack of intelligence in terms of sensing. The main motivation behind this research is, thus, to design a reconfigurable fixture with embedded sensors that improves the adaptability and efficiency of meso-milling machines.

This paper describes the conceptual design of an intelligent reconfigurable modular fixture for meso-milling. In Section II, the different available intelligent and reconfigurable modular fixture concepts are reviewed. In Section III, the current state-of-the-art in fixture design for meso-milling is described. In Section IV, our proposed innovative conceptual design and its challenges for meso-milling are presented.

MODULAR FIXTURES

With the rapid growth and evolution of the manufacturing industry, reducing production costs has become a high-priority objective. One approach to cost reduction has been to use a modular reconfigurable fixture rather than dedicated fixturing systems. In the 1960s, modular fixtures were developed in Germany for the machine-tool manufacturing industry. A modular fixturing system consists of locators, clamps and V-blocks which can be assembled on a baseplate [2]. The two conventional concepts for modular fixtures have been dowel-pin (hole) based and T-slot based fixtures. There are some pros and cons for each of these systems. For example, a dowel-pin-based fixture is more accurate and its components are easier to be mounted on the baseplate than the T-slot approach. The drawback is that dowel-pin-based fixture is less flexible. On the other hand, the T-slot fixtures can easily satisfy a wide range of workpiece geometries. Consequently, the locating accuracy is more problematic to control.
Despite the above two conventional modular fixture concepts, magnetic based fixtures (for grinding), vacuum based fixtures (for thin, small parts) and ice based fixtures (for irregular parts that require fine surface finishing that could damaged by conventional method) have also been developed [3].

Increasing complexity of workpieces has resulted in high demand to develop more economical fixtures. Flexible fixtures have been developed to achieve further improvements in adaptability and flexibility of the machining processes. In 1982, Cutkowsky et al. [4] developed a programmable conformable clamping system. The clamping system is specifically designed for the machining of turbine blades, which further allows the possibility of fixturing a non-uniform curved workpiece. Youcef-Toumi et al. [5] also developed a set of clamps consisting of array of fingers that are made by shape-memory alloy to exert motive force. As presented in their paper, shape-memory alloy fingers can be actuated by current and locked by springs when they are not in use, so that they can be applied for parts with different geometries.

Further advancements in flexible manufacturing inspired the creation of fixtures with embedded sensors. In 1990, Chan et al. [6] developed fixtures with embedded optical-fiber-based sensors. A locator and a clamp were successfully prototyped and tested. The embedded sensors can detect the proper location of the workpiece when pushed against the fixturing components.

**FIXTURES FOR MESO-MILLING**

Although meso-milling machines focus on much smaller scale components compared to conventional milling machines, their fixturing needs are similar [7]. As abovementioned, commercialized micro-milling systems such as Makino [8], Microlution[9] integrated the standard kinematic coupling base with tool chuck as workholding system to their micro-milling machines. This approach was also adopted by other meso-milling academic researchers. Honegger et al. in [10] describe a fixture system used in the microfactory developed in UIUC as a pallet system that is incorporated with a kinematic coupling base. The fixturing system accepts separate mounting of interface plate for workpieces. Sensors are placed underneath the base, to perform direct measuring during operations.

Subrahmanian and Ehman in [11] presented the first microfactory prototype developed in Japan, where a conventional dowel based fixture was used. In addition, the same paper reviews the micromachining system developed in Northwestern University. A tombstone with kinematic mount is integrated for workholding. Similar works which integrate conventional hole-based fixture concepts (a tombstone) to meso-milling are presented in [12].

Even though reconfigurable modular-fixture concepts are employed in the aforementioned fixtures, none can achieve the true reconfigurability as in the conventional scale. Often, the fixture does not fix onto the micro-part directly. In this case, the millimeter sized products are first machined from a relatively large working material (stalk) and, then, released from the base.

Another novel workholding principle is fixturing via ice. This technique has been used in fine jewelry and watch making industries, where the end products are often small in size and containing fine, precise details. Mentioned in the work of Yukitatsu et al. [13], an ice-based fixture system was developed for thin-walled, irregular and low rigidity parts.

In summary, current systems noted in the literature for meso-milling are capable to fixture workpieces with sizes greater than millimeters with fixed simple geometries (i.e., block, or cylinder). Thus, there exists a clear need for a modular fixturing system for 5-axis meso-scale milling.

**PROPOSED CONCEPTUAL DESIGN**

**Design Requirements**

General specifications for the modular meso-milling fixturing system with embedded sensors include:

- The fixture will be able to fix workpieces with 3D sculpted surfaces
- The workpiece dimensions will be in the range 0.5 mm to 5 mm
- The positioning accuracy will be less than 0.1 micron

**Conceptual Design**

Considering the specifications of this system, the design of a clamp will be excluded from this current work. In order to satisfy the reconfigurability of the desired fixture, the dowel-pin based fixing concept is selected. The system is designed to resemble the form of fixtures used in conventional scale fixturing, and it will consist of locators (dowels), rest buttons and V-blocks that can be assembled onto the hole-based plate (Figure 1). Constrained by the dimensions of the workpieces, different sizes of the fixture components would be required and will range from 0.1 mm to 3 mm in size. Figure 2 shows an example of possible ways to fix a meso-size part using the proposed fixture.

![Figure 1. Basic components of the proposed reconfigurable fixture for meso-milling.](image-url)
In order to obtain a highly accurate product, the fixture shall be resistive to the impact loading, shear and maintain minimal deflection during the machining. Depending on the workpiece material, cutting depth, desired surface finish and tool/spindle settings, the cutting forces can range from 0.1 N to 30 N [14], [15]. Under these cutting force constraints, many groups are working towards an integrated system with bulk, non-reconfigurable components, since as abovementioned the material selection and manufacturing limitations can be eliminated. Therefore, in order to design a reconfigurable fixturing system, material selection, modeling and manufacture process planning of fabricating different fixture components have to be planned carefully. Specifically, the modeling should be focused on the shear and deflection of the locators.

With detailed specifications considered, initial FEA was performed on the locator and the rest button. Then, material selection was made based on the simulation results. In order to satisfy the mechanical constraints of the proposed system, tool steel and silicon are considered as the locator materials. However, a manufacturing technique with desired accuracy in micron-scale to fabricate the described steel tool fixture components could not be found.

Silicon, on the other hand, has widely been used in MEMS devices. Different fabrication techniques can be employed to get nanometer precision of the final fixture components. Nonetheless, silicon is known to be brittle, which raises some issues regarding fracture, durability, and the repeatability of the fixtures. Therefore, more complex mechanical tests and modeling are required in order to proceed with this material selection.

Basically, the fabrication procedures for the previously described pins can be divided in two different categories: additive (e.g., metal deposition and stereolithography) and subtractive process (e.g., traditional machining, meso-milling and Focus-Ion Beam milling).

Although, through additive processes, micron-scale precision can be achieved, the material and fabrication costs are relatively high. However, one of the significant advantages of these methods is that, the force sensor can be embedded within the locator. As mentioned in Varadan et al.’s book [16], metal/polymer microstructure was fabricated by special designed microstereolithography process. A cylindrical object was build that consists of copper element rotating around polymer housing. Similar process can be used in fabricate locators. Thus, the post-assembly process can be removed which makes the fabrication process flow less complicated.

On the other hand, by using a subtractive process, a post-assembly process is required to integrate the sensor with the fabricated pins. This can make the fabrication procedure more complicated. 

Aforementioned, sensors must be embedded in the fixture. Considering the size of the dowel pin (locator), there is not any commercially available sensor that is ready to use and that can be integrated with the locators. Thus, the design of the sensors has to be customized. While trying to maintain the mechanical strength of the design, a possible option would be fabricating the sensors embedded into the individual locators.

There are different available sensors which can be integrated into the described fixturing system, such as fiber optic-based, piezoresistive-based, piezoelectric-based and polymer-based sensors. Although proposed in the literature for conventional scaled fixtures, fiber optic-based sensors would need to be excluded due to the dimensional requirements. Thus, the options left are piezoresistive-based, piezoelectric-based and polymer-based sensors.

Implementation of the piezoresistive and piezoelectric-based sensors into the fixture components at micron-scale would be challenging. Because of the cylindrical shape of the locators, deposition and patterning of the piezoresistive or piezoelectric materials through MEMS fabrication techniques would not be possible. Other concerns regarding the piezoresistive and piezoelectric-based sensors include the durability and repeatability of these sensors under the shear forces and machining conditions of the meso-milling machine.

Polymer-based sensors are force sensitive resistors (FSR) which can convert deflection due to the applied force of the workpiece to resistance change. For example, polyurethane PMC121/30, Polydimethylsiloxane (PDMS), disperse with conductive fillers (such as metal, carbon-black, carbonanotube) as a FSR polymer can be cast around the locator. They can be used to sense the workpiece location. One of the drawbacks of the proposed method is that when the locator is in use, the embedded sensor might experience tearing, by the machining force due to a partial adhesion of the polymer and the workpiece. Sol-gel process involves chemical bonding and can be used to cast polymers as well as improve the adhesion between the polymer and metal [17],[18], and reduce the physical drifting situation.
As shown in Figure 3, the resistance changes of the polymer can be read out by two electrodes that are placed underneath the locator. Engel et al. [19] and Lu et al. [20] showed that FSRs can be implemented in micron-scale and the sensing resolution is in the order of milli-N.

Regarding the signal extraction from the sensors and communication with the main controllers, the fixturing system can be treated as an electronic device. Connection lines would be printed on the individual components and signal would be processed underneath the base plate. A common concern of the smart material-based sensors is drift. This can be monitored by using feedback control as well as adding filters and protective coatings to the sensor surface.

CONCLUSIONS

A conceptual design of an intelligent and reconfigurable fixture system with embedded sensors is presented. The design described includes adoption of principles from macro-scale fixturing system. Issues dealing with modeling, manufacturing and sensory selections of the fixture for meso-milling are also discussed in the paper.

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REFERENCES