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THE USE OF ACTIVE MATERIALS FOR MACHINING PROCESSES: A REVIEW

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ABSTRACT

This paper provides a review of active materials in the context of applications to manufacturing machining processes. The important concepts and background of active materials are briefly introduced. After which, the applications of these materials are discussed as applied to relevant themes in machining processes. A brief overview of research work on experimental and theoretical studies on various process monitoring and control is considered, and several research papers on these topics are cited. This paper concludes with a discussion of future research areas and a suggested path forward.

1. INTRODUCTION

Given the importance of machining for most industries, there exists a wealth of research focusing on improving the performance of the machining process. In particular, some of this literature can be categorized into the area of process monitoring and control, which is well-summarized by Schellekens and Rosielle (1997) and Liang et al. (2004). In general, the implementation of any methodology for process monitoring and control requires some form of measurement. These measurements are usually mechanical in nature (e.g., strain, acceleration, and acoustic emission), but they can include other sensing techniques, such as optical, magnetic, thermal, and pressure. Accordingly, a wide range of sensing technologies has been used in the research and practice of process monitoring and control of machining processes.

New sensing techniques are also being implemented because of recent developments in machining technology and machine tool design. A critical element to achieving manufacturing automation with high productivity and improved precision and control is the ability to measure and estimate the process variables that impact the product's quality with reliable sensing techniques and associated signal processing and analysis technology. Furthermore, innovative actuation technology is required in machining process control due to the following constraints that are imposed upon the process: (1) fast dynamic response, (2) relatively high force with fine resolution, (3) high stiffness and frequency bandwidths, and (4) space restriction.

This paper is intended to provide an overview of recent research that adapts and implements active materials technology into manufacturing machinery for process monitoring and control. *Active* (or *smart*) *materials* is the name given to a class of materials that exhibit the ability to change mechanical force and motion into other forms of energy. Unlike a simple transducer, many of these materials are able to transform energy into motion and mechanical motion into energy, which can provide many new and creative sensing and actuation possibilities.

The conventional use of instrumentation is often obtrusive and cumbersome and therefore interferes with the normal operation of the structure or machine under study. These measurements may further require multiple instrumented locations to ensure robust and repeatable sensing capabilities. Active materials improve these situations by allowing actuation and sensing to become fully integrated into a structure or machine tool in an unobtrusive manner. Examples of such materials are those that exhibit piezoelectric effects, magnetostrictive effects, as well as materials such as shape memory alloys, magnetorheological and electrorheological fluids, and ionic polymers. Some advantages of these devices are their compactness, light-weight, low-power consumption, ease of integration into critical structural areas, ease of activation through electrical signals, higher operating frequency, and low cost. Initially, a limited number of researchers looked at the engineering application of a small set of active materials and devices to provide performance payoffs. In the last several years, dozens of materials and devices have been invented with unbounded potential for engineering applications. Accordingly, the use of smart materials in structures and machines remains active because of the ability of these materials to create highly integrated sensing, actuation, and control functions into engineering systems. There are many well-documented examples in the open literature on the use of active materials in structural dynamics problems, including structural health monitoring, active and passive vibration control, energy harvesting, and shape control (Srinivasan and McFarland 2001, Chopra 2002, Inman 2003, Sodano et al 2004, Hurlebaus and Gaul 2006). However, the applications of active materials with respect to machining processes have not been summarized. As a result, this literature survey attempts to fill this much needed gap.

This paper reviews several research areas that have utilized active materials for sensing and actuation devices to improve the performance of various manufacturing processes. The majority of the literature summarized in this paper will be concerned with the use of piezoelectric materials applied to machining processes (and in particular turning operations). However, applications of magnetostrictive materials and mageneto-, electro-rheological fluids relevant to machining processes will also be summarized. Finally, future research topics will be proposed in order to help transition the current state-of-the-art to full-scale industrial adoption.

2. PIEZOELECTRIC MATERIALS

Piezoelectric materials produce an electric charge when mechanically stressed and a strain when an electric field is applied across them. This electromechanically coupling property is extremely useful in mechanical systems because they can serve both as a sensor and as an actuator. An important characteristic of active materials is that they provide an unobtrusive, integrated, and distributed way to add actuation and sensing to a structure or machine. This characteristic is a perfect match for use in manufacturing machinery where space constraints are critical. In this section, we will describe the applications of piezoelectric materials in the area of machining processes.

Piezoelectric materials acting in the direct manner produce an electrical charge when stressed mechanically. The direct piezoelectric effect has been most commonly used in sensors such as a piezoelectric accelerometer. Conversely, a mechanical strain is produced when an electric field is applied to this material. With the converse effect, piezoelectric materials apply localized strains and directly influence the dynamic response of the structural elements when either embedded or surface bonded into a structure.

Piezoelectric materials have been widely used in structural dynamics applications because they are lightweight, robust, inexpensive, and come in a variety of forms ranging from thin rectangular patches to complex shapes being used in MEMS fabrications. A full description of the piezoelectric effect and the methods used to model the behavior of these materials is beyond the scope of this paper; however, a significant number of journal papers and conference proceedings have focused on the development of accurate models and discussed the fundamentals of these materials in great detail (Crawley and de Luis 1987, Crawley and Anderson 1990, Hagood et al 1990, Smits and Choi 1991, Sirohi and Chopra 2000a, 2000b, Niezrecki et al 2001). There are also numerous books published on this topic (Gandhi and Thompson 1994, Ikeda 1996, Banks et al 1996, Culshaw 1996, Clark et al 1998, Srinivasan and McFarland 2001). Furthermore, the applications of piezoelectric materials in structural dynamics are too numerous to mention and readers are advised to refer to the aforementioned references. In machining processes, piezoelectric materials are usually used in the form of a stack configuration acting as an actuator for the implementation of a fast tool servo (for reducing unwanted vibrations in manufacturing machinery) and in ultrasonic assisted machining. However, the use of piezoelectric patches and polymers has been also reported as sensors for measuring dynamic responses from the process or as vibration absorbers in chatter suppression. Each of these areas will be discussed in further detail in the following sections.

Fast Tool Servos for Diamond Turning

The development of piezoelectric actuator-based fast tool servos (FTSs) for precision machining has been studied extensively by many researchers. FTSs refer to auxiliary servos that are specially adopted to control a fast-acting tool holder with high resolution and fast dynamic response for ultra-precision turning or facing operations. Piezoelectric materials, in the form of a stack configuration, are very suitable for FTSs because of their high frequency bandwidth (up to kHz ranges), high dynamic stiffness (greater than 100 N/μm), compact size, and the capability of producing relatively high force (greater than 10 kN ranges). The piezoelectric actuator-based FTS has been successfully used for active vibration reduction, dynamic machine error compensation, and axis-asymmetric machining. The primary benefits include improved surface integrity and increased geometrical accuracy. Consequently, these FTSs have seen increasing use in micro-machining applications and are considered a fairly mature technology with some commercial realization. A review of some of the more noteworthy efforts follows.

In the mid-1980s, Patterson and Magrab (1985) proposed a design scheme of FTS using a piezoelectric stack actuator (6 mm in diameter, 12.5 mm long, 1.27 µm free stroke) with a cylindrical shell supported by two diaphragm flexures fixed to a cylindrical support. The FTS was tested for both static and dynamic repeatability. While its peak displacement distortion was found to be less than 0.71 µm over a 0-100 Hz frequency range, the results with respect to machining applications were not reported. Kohno et al. (1989) proposed the concept of a "Workpiece-Referred Form Accuracy Control System," in which the system performs direct control over the machining process based on the use of in-process measurements and a piezo-stack actuator. Although process performance improvement was clearly observed (0.25 µm surface roughness with 0.2 µm spindle turning error), the control system could not compensate for high frequency vibration present in the cutting process due to the lower frequency response bandwidth (50 Hz) of the FTS.

In 1990, Okazaki (1990) reported on the "Piezo Tool Servo" design for diamond turning machines to achieve a surface finish with high resolution. Okazaki's servo employed a 10 mm diameter by 6 mm long actuator that produced a 9 µm free displacement under a maximum applied voltage of 400V. The displacement of the FTS was however reduced to 7 µm because of the stiffness of the flexure. To eliminate the hysteresis in the piezoelectric actuator, two control strategies, including pole-zero cancellation with a notch filter and a proportional-integral-derivative (PID) feedback control with a state observer, were applied to the tool post. The depth-of-cut resolution was reported to be smaller than 25 nm. The frequency bandwidth for this system was 200 Hz, which was limited by the resonance of the tool post.

Research at the North Carolina State University (NCSU) set the foundation for using the piezo-stack actuator for diamond turning of micro-surface applications (Falter 1990, Fornaro et al 1990, Dow et al 1991, Miller et al 1994, Moore et al 1995, Jared et al 1996, Garrard et al 2005). Their FTS design utilized (Dow et al 1991) a piezoelectric ring-type stack actuator (25 mm OD, 18 mm long, 20 µm free stroke) and a pair of high-bandwidth capacitance sensors. The high-bandwidth capacitance sensors were responsible for measuring the motion of the tool relative to the cutting arm and for measuring the relative position of the arm and a reference surface attached to the workpiece. Their unit produced approximately 5 µm of full stroke at 1 kHz with a usable bandwidth of over 2 kHz. The results of the FTS on a parallel axis ultraprecison lathe indicated that it could actively correct thermally induced spindle error motions by 85%, maintain the error of the tool position with respect to the reference signal to within 2% of the input amplitude, and reduce surface roughness by 78%. The system utilized a PI control algorithm, which rejected the disturbances of unmodeled hysteresis (of the actuator) and parasitic vibrations. Their research revealed that the dynamic thrust forces caused by cutting had little effect on the quality of the resulting surface. Follow-on work from this group produced several prototypes of the FTS, shown in Figure 1, which have been used by other researchers as a base design.

Using the FTS developed by NCSU (operation range 100 µm and up to 100 Hz) and illustrated in Figure 2, Cuttino et al.. (1999) optimized the cutting and control parameters to enhance the performance of the FTS. Two independent tests were performed with the goal of (1) improving the control gains and (2) adding a hysteresis compensation module for a piezo-actuator. Improving the controller gain reduced the effects of the actuator hysteretic losses by 51% at an 8 kHz sampling speed. Adding a hysteresis module compensates the error by 43% for full-range travel, and by 80% for a travel range of 70 µm. However, they reported some side effects from these compensations, including sharp anomalies in surface finishing. It was also shown that the performance of the FTS improves with slower spindle speed, while the feedrate seems to have very little effects on the results.

Kim and Kim (2003) and Kim et al (2004a) designed a PI feedback control system for a fast tool servo driven by a piezoelectric stack actuator (18 mm diameter, 45 mm in length). A feedforward controller was implemented based on a simple feedforward predictor to improve tracking performance (up to 0.15 µm peak-to-peak error level). Crudele and Kurfess (2003) published the design of integrating a piezo-based FTS servo with repetitive control for facing applications. In repetitive control, a controller is designed to identify certain periodic patterns in a process. Based on these patterns, the controller's output is a function of the expected pattern coupled with any errors from the previous cycles. This technique is particularly applicable to machining where the material and tool conditions change relatively slowly and the process is relatively repeatable. The benefit of the repetitive controller was the tracking ability of surface waviness. A piezo-actuator with a nominal expansion of 60 µm was used, and a substantial reduction in waviness, up to 62%, was observed. The authors further discovered that traditional polynomial control was somewhat detrimental to the waviness.

Rasmussen et al (1994) designed a piezo-driven cutting tool system capable of dynamically controlling the depth of cut that can be used to machine slightly non-circular workpieces. With an amplification mechanism, the tool was able to produce 52 µm of travel with a bandwidth of 200 Hz. Tool motion error less than 0.5 µm was achieved using a repetitive controller. The authors also proposed that the same device could be used for an active damping element for improving the surface finish. Kim and Nam (1997) and Kim and Kim (1998) developed a piezo-based micro-depth control system that does not rely on an external position sensor. Instead, they utilize the piezoelectric voltage feedback signals from the actuator as an indicator of position. Based on the self-sensing actuation concept (Dosch et al. 1992), the applied voltage to the actuator was subtracted by a reference voltage using a differential subtract circuit to extract the net-sensing voltage. However, details on how to provide an accurate reference voltage to achieve the rigorous self-sensing actuation were not provided. The authors reported improved stability and decreased response time as compared to using an external gap sensor. Gao et al (2003) constructed a FTS using a piezoelectric tube actuator with a bandwidth of 2.5 kHz and a total tool displacement of several nanometers. This FTS was used for machining a sinusoidal grid surface with a wavelength of 10 µm and an amplitude of 100 nm over a diameter of 150 mm area. The effectiveness of the FTS was confirmed, however, the authors noted that the thermal deformation of the workpiece during machining adversely affected the overall accuracy of the surface finish.

While the FTS is traditionally used as an independently operating positioning device, several researchers have attempted to combine the FTS with standard motion systems in order to obtain large motion with high positioning accuracy. In such a way, the advantages of both servos can be fully utilized, while compensating for their drawbacks. Lee and Kim (1997) developed a dual (global and micro) servo stage mechanism. The global stage produced coarse three-dimensional motions using three linear motors, while the micro stage compensated for the position errors of the global stage using three piezoelectric actuators. The dual mechanism employed a PID controller and was capable of a positioning reproducibility to within 20 nm over a working area of 200x200 mm. Ku et al (1998) designed a nano positioner in which a piezo-based FTS and a conventional lead-screw mechanism were combined. A neural network based control algorithm was used to compensate for the large friction in the lead-screw tool, while the FTS was used to further reduce the tracking error by over a factor of 10. Pahk et al (2001) developed a combined ultraprecision positioning system, including a ball screw based servo motor for the global stage and a piezo-actuator for the micro stage. In order to smoothly link the two motions from the global and micro stages, a dual servo loop control algorithm was implemented. In order to reject vibration and noise present in sub-micrometer range, a Chebyshev digital filtering technique was employed to improve the positioning accuracy. An accuracy of 10 nm over the 200 mm stroke was reported.

Kim et al (2001) also proposed the use of a dual-stage servo for precision machining, in which they applied a two-parameter robust repetitive control design to a dual stage FTS. A piezoelectric actuator was installed inside the hollow piston of an electrohydraulic actuator. The error from the first stage electrohydraulic actuator was fed to the second stage piezoelectric actuator as an input. The interaction between the two actuators was assumed to be negligible. A 75% reduction of maximum error in surface finish was observed. In order to achieve even larger error reduction, Krishnamoorthy et al (2004) used a dual-stage FTS consisting of an electromagnetic linear actuator and a piezo-actuator with 20 µm stroke. The feedforward and robust repetitive control for the electromagnetic actuator produced less than 10 µm errors. Their ongoing effort is to further reduce the error by using the piezoelectric actuator. Elfizy et al (2004, 2005) developed a model-based controller for a dual-stage feed drive, which is composed of a linear motor and a piezo-stack actuator. This is illustrated in Figure 3. The model based feedforward controller incorporated both a disturbance observer module and an anti-windup module. They reported significant improvement in the performance of the coarse stage using the linear motor as compared to using PID control. A switching control technique was also investigated to accommodate changes in system dynamics and associated uncertainties relative to the piezo-actuator.

While the traditional application of piezo-based FTS has focused on diamond turning applications which requires relatively small chip loads and small cutting force disturbances, Zhu et al (2001) and Woronko et al (2003) addressed the use of a piezo-based fast tool servo for precision shaft machining in conventional CNC turning machines. They employed an adaptive sliding-mode controller to compensate for uncertainties due to cutting disturbances and hysteresis in the stack actuator. A stack actuator with a maximum displacement of 40 µm was mounted on a flexure frame with 1.5 times of displacement amplification. The author's motivation was to provide rough, semi-finish, and ultra-precision cutting using a conventional CNC machine. The rough and semi-finish operations were performed on a tool with a conventional CNC machine and the ultra-precision cutting was accomplished by the same machine with a piezo-based FTS on the CNC turret. The approach is illustrated in Figure 4. A significant improvement on the surface quality was obtained that cannot be attainable with traditional CNC machine (Zhu et al 2001). Woronko et al (2003) further improved the performance, achieving a cut position accuracy of 20 nm under an average radial cutting force of 6 N. For the piezo-based FTS operation in a conventional CNC machine, the final finishing depth of cut is executed solely by the actuator within the actuator stroke with no change of the CNC radial position. Ultimately, the effects of CNC radial axis backlash and friction were eliminated.

A commercialized solution for a piezo-based FTS is reported by Kinetic Ceramics, Inc (2006) and is illustrated in **Error! Reference source not found.**. Their systems are capable of producing 400, 500, and 600 µm stroke (depending on the design) with a 600 Hz bandwidth. Currently, their systems cannot achieve both the maximum stroke and frequency bandwidth simultaneously. A pair of triangular PZT stacks is used to create push and pull motions, and a T-lever mechanism is used to amplify the mechanical stroke.

As described, piezoelectric stack actuators are widely used in FTS, although the sensing, mechanical design, and control algorithms vary depending on the applications. The majority of sensors used in piezoelectric-based FTS are capacitive gap sensors with nanometer resolution. However, the use of laser interferometers (Miller et al 1994, Ku et al 1998, Pahk et al 2001, Woronko et al 2003), high-resolution strain gauges (Rasmussen et al 1994, Elfizy et al 2004), self-sensing piezoelectric voltage (Kim and Nam 1997) and eddy current probes (Crudele et al 2003) are also reported.

Ultrasonic Assisted Machining

Although it is important to limit vibrations in a machine tool to avoid producing unacceptable surface finish conditions, ultrasonic vibration has been utilized to improve machined surface quality. Ultrasonic-assisted machining is a non-conventional material removal process to promote the improvement of machining quality through the utilization of ultrasonic vibration in the cutting tool at a fixed amplitude and frequency. The approach is founded upon the principle of transforming a conventional turning process into a high frequency vibro-impact process which results in an increase in the dynamic stiffness of the lathe-tool-workpiece system and improves the accuracy of turning (Babitsky et al 2003). Astashev and Babitsky (1998) further explain that the ultrasonic vibration transforms the elasto-plasticity process into visco-plasticity one, and hence, results in the fluidizaton of dry friction. Additional observations include decreased noise, tool wear, and heat radiation, and improved chip breaking capabilities during ultrasonic cutting. Although ultrasonic machining has been widely used for brittle and ductile materials, the surface quality of some conventional materials, including steels and aluminums, were also improved using this technology. Thoe et al (1998) published a literature review of ultrasonic machining in various applications.

Active materials, and in particular piezoelectric or magnetostrictive materials, are suitable for ultrasonic vibration generators because they can easily convert high frequency electrical energy into mechanical vibration, which can provide efficient ultrasonic vibration to the tool assembly.

Consequently, piezoelectric materials have been a popular choice as an ultrasonic generator and numerous books have been published on this topic. Readers are advised to refer to the literature survey by Thoe et al (1998) for more information. This paper will focus only on recent research work performed in the last ten years.

Typically, ultrasonic cutting is applied to small diameter workpieces or slow rotational speeds. This is due to the ultrasonic vibration commonly being applied to the radial or tangential direction with respect to the workpiece orientation which thereby limits the cutting speed to the rotational speed of the workpiece. However, Babitsky et al (2003) applied ultrasonic vibrations along the feed direction in order to improve the cutting speed and to achieve high productivity. The piezo-stack actuator used in this study was able to produce a 20 μm peak-to-peak displacement at 17 kHz. By applying the vibration in the feed direction, the effectiveness of the ultrasonically assisted vibration was extended to high-speed machining processes. Babitsky et al (2004) further utilized the piezo-stack actuator with a self-tuning autoresonant control for ultrasonically-assisted cutting in order to tune the piezoelectric-based ultrasonic system at resonance for maximum vibration effects. This is illustrated in Figure 6. The authors reported significant improvements in surface quality as compared to conventional methods.

Du et al (2004) designed a cutting tool with a piezo-actuator driven ultrasonic vibration system. A matching circuit was used to reduce the piezoelectric capacitive reactance at high frequency ranges. The authors reported improvements in the surface quality and the dimensional tolerance. Zhong and Lin (2005) developed a low-cost ultrasonic vibration device with a piezo-stack actuator that can be mounted onto a conventional CNC machine. The actuator used in this study was capable of a 23 μm displacement under 450 V applied voltage. A significant improvement in the surface quality was also observed. However, they found that varying the depth cut and cutting speed affected the results considerably.

Xu and Han (1999) designed a cutting tool system equipped with both active error compensation (such as those used in FTS) and ultrasonic assisted vibration by integrating two piezoelectric actuators. The actuator used in the error compensation produced a 7 μm stroke with a frequency bandwidth of 50 Hz, while the actuator used in the ultrasonic vibration actuator generated a 10 μm at a fixed frequency of 20 kHz. Using just error compensation during cutting, the authors reported improvement of the roundness of the workpiece by 27% with no improvement in roughness. When both the error compensation and the ultrasonic vibration were activated, the authors reported improvement in both roundness and roughness by 42% and 16%, respectively.

As shown in this section, piezoelectric stack actuators have been effectively used in ultrasonic-assisted vibration. It should be noted that relatively smaller sizes of stack actuators were usually employed in this application in order to relax the power requirement.

Active and Passive Vibration Control

Unwanted vibration in precision manufacturing machinery is a major source of poor surface finish, increased tool wear or failure, and poor dimensional accuracy. There are several sources of vibrations in machining processes, such as self-regenerated vibration within a process (referred to as chatter), rigid body dynamic motions of the machine caused by the internal process including spindle rotations or dynamic cutting process, and externally induced vibration from the foundation or acoustic coupling. These vibrations are usually smaller in magnitude and higher in frequency than those typically found in other mechanical systems. Numerous vibration reduction techniques have been proposed in the past relying on vibration-awareness design, changing machining parameters during operation, or altering structural dynamics via active or passive damping treatments. The use of piezoelectric transducers falls into the last category, as they have been increasingly used to reduce the vibrations in both a passive and an active manner.

Among the several sources of vibration, the suppression of chatter has been extensively investigated by many researchers. Chatter is the self-excited vibrations caused by the modulation of the cutting force to changes in the uncut chip thickness which results in adverse variations in the uncut chip thickness during the next operating cycle. It is also explained by the hysteresis relationship between cutting force and workpiece deflection by the dynamic instability of the process caused by the interaction of the cutting force and vibration. Chatter usually comes with relatively high amplitude of regenerated vibrations compared to other machining vibrations. The mechanism of chatter is relatively well understood (Fabris and D’Souza 1974, Jemielniak and Widota 1989, Marui et al, 1995, Chiou and Liang, 1998). Chatter is considered one of the critical sources of vibration which adversely affects the productivity of high speed manufacturing processes. Chatter can generally be avoided by proper selection of the cutting parameters, including depth of cut and spindle speed in conjunction with an appropriate model, called a chatter stability lobe diagram. However, the selection of such parameters may not be suitable for automated and improved productivity. In addition, many machine tools may not be designed to operate in such modes. Therefore, many researchers have investigated alternative approaches to reducing chatter, namely active or passive vibration suppression techniques, that control the vibration of the cutting tool.

Martinez et al (1996) demonstrated the feasibility of piezoelectric stack actuators in chatter reduction. Their experimental setup employed a surrogate machine tool structure composed of a positive position feedback (PPF) filter and a cantilever solid bar. By combining finite element analyses and experimental results, the authors were able to demonstrate that the stability of cutting process was significantly improved. Eshete and Zhang (1996) used an electrostrictive (Lead-Magnesium-Niobate piezoelectric) stack actuator to actively reduce the tool vibration with a neural network-based control algorithm. Choudhry et al (1997) also proposed an on-line tool vibration control system with a piezoelectric stack actuator mounted on the tool post. The improvement in surface quality was confirmed in both of these studies. Several simulation studies or experiments on machine-representative structures also demonstrated the feasibility of piezoelectric materials in vibration or chatter suppression in various turning or milling operations (Nagaya et al 1997, Mayhan et al 2000, Yan and Al-Jumaily 2002, Chiou et al 2003, Harms et al, 2004, Rashid 2005).

Fung and Yang (2001) used a forecasting compensatory control (FCC) technique with a two-dimensional piezo-actuated tool motion system to compensate for spindle error motion. For FCC, the future errors are estimated using a time-series AR or ARMA model from the past and current response, and the control signal is applied to compensate the estimated errors before the cut is made. The authors reported an improvement of 47% for the roundness error in the taper turning operation. Pan and Su (2001) and Wang and Su (2003) used a piezoelectric actuator mounted on to a tool holder for chatter suppression during turning. The piezoelectric actuator regulates the tool displacement with a robust adaptive controller which accounts for the hysteretic nonlinearity and results in a significant reduction in chatter.

Dohner et al (2004) applied an active control approach for mitigating chatter in milling operations. Unlike turning, implementing sensing and control of a milling process includes additional complexity due to operating in multiple coordinate systems. In particular, the sensors and actuators are typically located in the same stationary coordinate system of the machine tool, while the workpiece remains in the moving coordinate system. Two PMN stack actuators were embedded within the housing of the machine, as illustrated in Figure 7. The actuators were capable of producing lateral motion of the tool. A linear quadratic Gaussian (LQG) control approach was implemented, and strain gauges at the root of the rotating tool were used to sense the bending motion in two lateral directions. The authors reported an increase in the stability of the milling machine by up to an order of magnitude.

Tarng et al (2000) and Lee et al (2001) used a piezoelectric inertia actuator acting as a passive tuned vibration absorber to suppress chatter in turning operations. They demonstrated that the cutting stability is increased six times using this approach. The authors further suggest that, in order to be effective, the resonance of the absorber must be equal to that of the cutting tool. This passive control provides certain advantages, as compared to active control methods, including easy implementation, low-cost, and no need for complicated electronics. Pettersson et al (2001) embedded a miniaturized piezo-stack actuator into a tool holder, forming the concept of an "active tool holder." The bending deformation of the tool holder was actively compensated by the actuator using an adaptive FIR filter. A substantial reduction of the first mode (40 dB reduction at 3.4 kHz) was achieved resulting in a significant improvement in chatter suppression and surface finish.

Zhang and Sims (2004) used piezoceramic patches as a sensor and as an actuator for milling chatter suppression. The piezoelectric transducers were surface-mounted on the back side of the flat workpiece. A PPF filter was used to provide an active damping to the workpiece during the milling operation with these transducers. Sims et al (2005) proposed the use of surface-mounted piezoelectric transducers for the prediction of milling tool stability lobes. Two piezoelectric patches were mounted on the surface of the tool in which one patch provides an excitation as an actuator and the other patch measures the dynamic response of the tool as a transducer. The experimental results showed good agreement with traditional stability tests, which require an impact hammer and an accelerometer. This method is particularly suitable for miniaturized milling tools which impose difficulties in performing traditional modal testing. Furthermore, the method has a potential for automated chatter testing requiring little user involvement.

As described in this section, piezoelectric materials have been successfully employed in providing vibration suppression at frequency ranges that are often outside of the effective range of traditional damping materials. Furthermore, compared to traditional passive damping treatments such as viscoelastic dampers, which introduce an appreciable weight penalty and offer limited frequency ranges, the results indicate that piezoelectric-based dampers provide superior performance resulting in improved machining quality.

Boring Applications

Traditional boring operations create cylindrical grooves and enlarge holes or cavities made by a previous process. In order to produce cylindrical surfaces of high aspect ratios or deep holes, longer boring bars are increasingly demanded. However, boring bars are subjected to various loadings, including spindle motions and machine tool and workpiece vibrations. Reducing these vibrations in boring bars with high length-to-diameter (L/D) ratios is critical to avoiding chatter and preventing a deviation from the desired surface accuracy. Several active vibration control techniques have been implemented for boring operations with piezoelectric actuators. Compact piezoelectric-stack actuators are very suitable because the compactness and sufficient actuation authority of the materials does not interfere with the bar's clearance requirement.

Barney et al (1997) utilized a piezo-stack's self-sensing actuation capability for active vibration control of a model of a boring bar. They used a traditional bridge network circuit to achieve a self-sensing signal. The damping of the bar was increased by up to 20 times in the first and second mode using the self-sensing actuator with a PPF filter. However, in order to compensate for the hysteresis of the actuator and the imbalance of the bridge circuit caused by environmental condition changes, the implementation of more advanced nonlinear, frequency-dependent control techniques was suggested. Browning et al (1997) designed an active clamp system that houses four piezoelectric stack actuators with a resulting geometry of 5 cm in diameter and 3 cm long. The actuators were paired on opposite sides so that the actuation could be performed independently in two directions. The active clamp with an adaptive vibration controller enabled a boring bar with L/D ratio of 11 to operate free of chatter.

Chiu and Chan (1997) published the design of a piezoelectric controlled boring bar. The forced displacement of the boring bar was actively corrected by piezoelectric actuation acting on the bar holder. A PID controller was used, and the maximum compensation movement of the actuator was equivalent to 6 μm of tool deflection. Chiu et al (2002) and Gao et al (2002) further enhanced the performance of the original design by implementing an AR-model based FCC. The corrective action of a piezo-actuator is schematically described in Figure 8. The deflection of the boring bar was suppressed through the corrective action of the piezoelectric actuator with an improvement of 40% in roundness errors. Hanson and Tsao (1998) developed a piezoelectric boring bar servo capable of on-line compensation of cylindrical errors by rapidly varying the depth of cut. By using a flexure hinge, a maximum tool travel of 120 μm was achieved. Katsuki et al (2000) developed a laser-guided, deep-hole boring tool using a piezoelectric actuator to prevent axial hole deviation. A boring bar with reduced bending and torsional rigidity was used for better controllability of the tool motion. Controlled boring was possible up to a depth of 700 mm, which was the maximum machinable length of the machine tool.

A new boring bar, referred to as a “smart tool” and shown in Figure 9, utilizing a piezoelectric actuator to isolate the tool vibration and actively reject cutting tool disturbances was developed and substantially investigated by O’Neal et al (1998), Koren et al (1999), O’Neal et al (2001), and Min et al (2002). The smart tool is composed of two position optical detectors, a compact electronics package of controllers, a piezoelectric stack actuator with a lever to amplify the displacement, and a power and data transmitter. This system represents a truly self-contained boring system. The tool is also equipped with two cutting inserts, a rough cutter and a finish cutter. The rough cutter is directly mounted to the boring bar, while the finish cutter is attached to the end of the lever enabling its motion relative to the tool body. An integrated mechatronic and optimal structural and control methodology was implemented, and the smart tool successfully demonstrated positional errors less than 1 μm.

Other Applications

Piezo-driven precision position tables are now considered a mature technology and tables with nanometer resolution can be implemented using commercial off-the-shelf products. The characteristics of fast dynamic response with high resolution, compact size, and high conversion efficiency make piezoelectric materials an ideal candidate for use in high precision positioning tables. In order to amplify the small displacement of piezoelectric actuators, several mechanisms including mechanical, hydraulic, or other novel kinematic designs have been implemented. The simplest way to increase the displacement of an actuator is to use a mechanical lever arm with a flexure-hinged mechanism (Change et al 1999, Koratkar and Chopra 1999), although increases in displacements result in decreases in force outputs. A double lever arm amplification mechanism was also created by Lee and Chopra (1999). The flextensional amplification mechanism, which converts the longitudinal output of the actuator into motion of transverse direction, is also used in micropositioning (Le Letty et al. 1997, Pokines and Garcia 1998). Several other amplification mechanisms, including the use of both flexural hinges and slider-crank mechanism (Chang and Du 1998), linear piezo-motor techniques (Moriwaki and Shamoto 1996, Ni and Zhu 2000), and a "walking drive" mechanism utilizing six piezoelectric elements (Shamoto and Moriwaki 1997) were also implemented. As in the FTS design, there have been several efforts focused on integrating piezoelectric actuators with other mechanical driving systems to overcome the small piezoelectric displacement. These efforts have investigated combining piezoelectric actuators with servo motors (Moriyama et al, 1985), piezo-hydraulic actuators (Kallio et al 1998, Nasser and Leo 2000), piezo-pneumatic actuators (Liu and Higuchi 2001), and piezo-stepping mechanisms (Versteyhe et al 1999). Liu et al (2004) provided substantial details on the use of piezoelectric actuators in precision positioning tables.

Holterman and de Vries (2004a, 2004b) proposed the concept of a "smart disc", which is composed of a piezoelectric stack actuator and a collocated piezoelectric sensor, to provide robust active damping in a microlithography machine. Properly installed, the smart disc-based damping system can reduce the amplitude of the dominant vibration mode by 86% and greatly enhances the line-width precision of circuit patterns for integrated circuit manufacturing. Unno et al (2001) also used a pair of piezoelectric tube-type stack actuators to construct a high-resolution driving system for a semi-conductive diamond probe used in nano-scale machining. This driving system demonstrated a resolution of approximately 20 nm.

Research at Los Alamos National Laboratory utilized a thin-film, piezoelectric sensor from Measurement Specialties, Inc. to monitor tool vibration dynamics during turning (Hartman, et al. 2003). The flexible, thin-film sensor was made from a 28 mm thick piezoelectric polyvinylidene fluoride (PVDF) polymer film that is laminated between a 0.125 mm polyester substrate. The film was screen-printed with Ag-ink electrodes that pass voltage up to 70 V due to strains induced within the piezopolymer film. The motivation behind using an inexpensive thin-film sensor over a traditional accelerometer was due to the radiological environment that the turning process operated in and, hence, the requirement for a "disposable" sensor. The sensor was affixed to the tool holder using 3M's double-sided Poster Tape 109. Figure 10 illustrates this setup (an accelerometer was also attached to the tool for verification and validation of the thin-film's response). Unlike traditional commercial accelerometers that provide vibration data from either single or multiple axes, the thin-film sensor provides a complex vibration signal that is a superposition of several strain components (uniaxial extension and compression) plus multiple bending modes. Placement of the sensor was validated through modeling of the boring bar assembly (see Figure 11). The modeling ensured that the sensor was placed in a location in which the amount of strain during cutting was maximized. Through extensive data analysis techniques, the authors were able to demonstrate how an inexpensive sensing technique could provide a robust and effective method of interrogating tool vibration, monitoring process performance, and inferring product quality (Hartman, et al. 2004, 2005). The prototype system was capable of (1) detecting adverse cutting conditions that could potentially lead to non-conformance part conditions, (2) detecting material property variability, and (3) indicating real-time cutting conditions (i.e., "acceptable", "suspect", and "unacceptable" cutting conditions) for operator feedback and intervention (Hartman, et al., 2007).

In this section, the use of piezoelectric materials in various machining processes has been described. Among all other active materials, this material is the most widely used and has led to several successful commercial products in manufacturing machinery. The advantages of using piezoelectric materials in machining processes include the following: i) they are a relatively small in size and are easy to control, ii) they can produce relatively large forces and achieve high stiffness, iii) they have a relatively large frequency bandwidth (depending on the design), iv) they do not have backlash or friction typically found in conventional actuators, and v) they are capable of nanometer resolution positioning. However, there are also some disadvantages. They include: i) nonlinear hysteresis behavior, ii) temperature dependence, iii) heat generation when operated at high frequencies, which often requires external cooling systems, iv) relatively small displacements (in the micron range), v) the need for a specialized (usually custom-designed) amplifier for operation.

3. MAGNETOSTRICTIVE MATERIALS

In contrast to piezoelectric materials, which exhibit a coupling between the mechanical and the electrical domain, magnetostrictive materials respond with strain to an applied magnetic field (Butler et al 1990, Carman and Mitrovic 1995, Dapino et al 2000, Quandt and Claeyssen 2000, Chopra 2002). The effects can be reversible. Therefore, magnetostrictive materials can serve both as a sensor and as an actuator. Formally, this material is defined by the Joule and Villari effects. The application of a magnetic field across magnetostrictive materials causes longitudinal extension strains accompanied by transverse-compressive strains, referred to as the Joule effect. Conversely, an application of stress results in a change in its magnetic field, referred to as the Villari effects. The magnetic field can be applied by using either permanent magnets (for a steady bias field) or magnet coils surrounding the materials (for time-varying dynamic magnetic field). A popular commercial magnetostrictive material is Terfenol-D (Terbium-Ferrous-Naval Ordnance Laboratory-Dysprosium) and comes in the form of rods, thin films, and powder. Clark and his research group at Naval Ordnance Lab discovered Terfenol-D in the early 1970s. Similar in characteristics, magnetostrictive actuators have been used in some of the same application areas as piezoelectric materials, including ultrasonic assisted machining, FTS design, and machine tool vibration suppression. It should be noted that mechanical hysteresis is also intrinsic to magnetostrictive materials, which causes certain issues in precision control of machining processes.

Michler et al (1993) presented a design of a magnetostrictive-based micropositioner for use in turning operations. Their original design was further developed by Liu et al (1998) with the implementation of control algorithms and is illustrated in Figure 12. A velocity feedback controller was used to augment damping, and a PID controller was implemented to machine non-circular mechanical parts. The Terfenol-D actuator used in the study generated a 25 μm stroke and a maximum output force of 490 N. A substantial improvement in surface texture quality was observed. Eda et al (1992) also proposed the use of a magnetostrictive actuator with a stroke of 2 μm for precise machine tool positioning. The design was improved by compensating for the thermal expansion caused by the heat generation of the actuator (Yamamoto et al 1999) and by implementing a hybrid actuator consisting of piezoelectric and magnetostrictive actuators. The magnetostrictive actuator covered the lower frequency range while the piezoelectric actuator was used at much higher frequency ranges (Eda et al 1999).

Rojas et al (1996) used a Terfonol-D actuator for active vibration control of a boring bar. A PI and a least-mean-squares (LMS) bandwidth controller were simultaneously applied to suppress the vibration present in the boring bar during machining. Furthermore, they implemented an electrorheological elastomer damping device for vibration reduction in high frequency ranges and for improvement of surface quality. Tang et al (2004) published the design and implementation of a micropostioner based on the use of a magnetostrictive actuator (80 mm in diameter and 220 mm long). With a variable structural controller, tool positioning precision of 2 μm could be achieved. In this study, however, the actuator was used at lower frequency ranges and at limited output strok to avoid the hystereric nonlinearity of the actuator. In order to overcome hysteresis, Panusittikorn and Ro (2004) implemented a sliding-mode controller with a switching gain. The experimental results were compared to those using a PID controller. While PID could not overcome the influences of hysteresis resulting in significant output delay, the sliding mode controller yielded better tracking and robust performance.

El-Sinawi and Kashani (2005) designed an active tool holder utilizing a Tefenol-D actuator. A Kalman estimator-based, feed-forward control scheme was employed to suppress the vibration of the tool. The results showed that their active tool holder improves the surface roughness of the workpiece by an average of 25% over a conventional tool holder. Al-Zaharnah (2006) used two identical Tefenol-D actuators orthogonally located in both radial and feed directions in order to apply forces on the cutting tool in both directions independently. With the implementation of a Kalman estimator-based controller, vibration suppression of up to 30% was achieved.

Magnetostrictive actuators have been also used in ultrasonically-assisted machining as an ultrasonic vibration generator, which is well summarized in Thoe et al (1998). These materials provide vibration over a wide frequency bandwidth, accommodate tool wear, and demonstrate relatively good repeatability over an extended period of time. However, their performance falls behind that achieved by piezoelectric devices due to their low energy efficiencies, bulky sizes, and high electrical loss resulting in heat generation (Thoe et al 1998).

There are some advantages to magnetostrictive materials in machining processes compared to piezoelectric materials, including i) larger strain generation, ii) higher Curie temperature, iii) resistant to fatigue failure, iv) low-voltage drives, and v) greater stiffness. However, the performance of this material does not seem to be as promising as that achieved by piezoelectric devices mainly because of its high price, heat generation, bulky size, and the lack of a detailed database and reliable modeling of magnetostrictive materials for a wide range of applications, in particular, for machining processes.

4. MAGNETORHEOLOGICAL AND ELECTRORHEOLOGICAL FLUIDS

Magnetorheological (MR) or electrorheological (ER) fluids are another class of smart materials that have been used in manufacturing machinery systems. MR and ER fluids are fluids whose rheological behavior can be externally controlled through the use of either a magnetic or an electric field, respectively. The application of either an electric or a magnetic field results in a change in the effective viscosity and hence, the yield strength of the fluids.

MR fluids are usually composed of oil (usually mineral or silicone based) and ferrous particles that are on the order of 0.05 - 10 µm in diameter. Jacob Rabinow at the US National Bureau of Standards developed this fluid in the late 1940s (Jolly et al 1998, Wang and Meng, 2001). When it is not activated, a MR fluid behaves like a free flowing liquid, with a consistency similar to that of motor oil. In the presence of an applied magnetic field, the ferrous particles become magnetic dipoles, which connect to each other along the lines of the magnetic flux, forming linear chains parallel to the field. This phenomenon effectively "solidifies" the suspension oil and restricts the fluid's movement, developing yield strength. The degree of change is related to the magnitude of the applied magnetic field, and can occur in less than a few milliseconds. As a dual to MR fluids, ER fluids utilize electrically polarized particles to change its viscosity under an applied electric field. Under an applied electric field, an ER fluid can "stiffen" into a semi-solid, and back, with response times on the order of milliseconds.

In their non-activated or "off" state, both MR and ER fluids typically have similar viscosity. However, MR fluids are capable of achieving much higher yield strengths, greater than 60 kPa (Gamota and Filisko 1991, Stanway et al 1996, Goncalves et al 2006), than ER fluids. Furthermore, ER fluids require high voltage and low current, while MR fluids require low voltage and high current. Table 1 summarizes the more salient features of MR and ER fluids (Ashour et al. 1996).

Table 1: Comparisons between MR and ER fluids

Property	MR Fluid	ER Fluid
Yield Strength (field)	50-100 kPa (150-250 kA/m)*	2-5 kPA (3-5 kV/mm)**
Viscosity (no field)	0.2-0.3 Pa-s @ 25 ^{o}C	0.2-0.3 Pa-s @ 25 ^{o}C
Operating Temperature	-40 – 150 ^{o}C	10 - 90 ^{o}C, ionic, DC -25 – 125 ^{o}C, non-ionic, AC
Current Density	N/a. Can energize with permanent magnets.	2-15 mA/cm^2 (4 kV/mm @ 25 ^{o}C)

* Field limimted by saturation.

** Field limited by breakdown.

Because the elastic modulus and loss modulus of the fluids can be changed drastically by applying a magnetic or electric field, these fluids have been extensively used in electrically-controlled active or semi-active viscous dampers. ER fluids have been used in chatter suppression by designing tunable-stiffness boring bars, while MR fluids have been utilized for high precision polishing.

Lei (1995) first proposed the concept of utilizing ER fluids for chatter control. Two different design schemes were proposed including a cutting tool filled with ER fluids that can directly change the stiffness or damping of the tool and a flexible machine tool spindle with an ER squeeze film damper. No experimental results were presented. Segalman and Redmond (1996) utilized ER fluids to actively control the impedance of boring bars to suppress chatter. This approach is similar to a conventional chatter avoidance method, which adjusts the spindle speed so that the cutting process stays inside the stability region. However, instead of changing the spindle speed, the resonance frequency of the cutting tool was varied through the use of ER fluids by applying an electric field. The ER fluid was inserted between the tool sleeve and the cutting tool. A step variation in the electric field showed moderate success in reducing chatter vibrations. However, improved results were obtained through a sinusoidal varying field with the half-period of oscillation equal to the time interval between the cutting passes. The application of ER fluids in boring bars for chatter suppression has been substantially investigated by Wang and Fei (1999a, 1999b, 2001) and a schematic is illustrated in Figure 13. The stiffness and damping characteristics of a bar with L/D ratio of 5 were varied through the application of an electric field to the sleeve filled with ER fluid. Changes of 20 - 30 Hz in the first resonance frequency were achieved by applying an electric field with a strength of 2 kV/mm. At the lower applied electric field (lower than 1.2 V/mm), an increase in the damping of the bar was first observed, while, at a higher electric field, changes in the resonance frequency were clearly observed. Both lower and upper electric field ranges were utilized for chatter suppression. The need for an on-line adjustment of the electric-field strength applied to the ER fluid was suggested to achieve optimal performance. For the detection of chatter, an artificial neural network-based pattern recognition method was employed (Wang and Fei 2001). It should be pointed out that the experiments with ER fluids in chatter suppression have been only performed under laboratory settings. The performance in actual manufacturing environments with higher cutting speeds and larger cut depths still needs to be validated.

The use of MR or ER fluids in high precision grinding or polishing for mechanical parts, including lens, mirrors, and optics has been investigated by many researchers. The principle behind these techniques is that the ER or MR fluids are mixed with ultra-fine abrasive particles and the acting force and resulting motion of abrasive particles can be controlled by an electric or magnetic filed, resulting in ultra-precision polishing. Because the literature concerning this area is too broad, this section only provides a concise introductory survey on this topic as an example of the successful application of active materials in grinding or polishing.

In MR fluid-based finishing processes, a rotating wheel is used to direct the MR fluid against a small portion of the part surface. Material removal takes place in a narrow region between the part and the rotating wheel through the shearing action of the abrasives in the fluid against the part. Sometimes, hydrodynamic pressure is applied to improve the material removal rate. Various research and platforms in the area of MR finishing have been reported (Kordonski and Golini 1999, 2002, Golini et al 2001, Shorey et al 2001, 2004, Kim et al 2004b, Cheng et al 2005, Schinhaerl et al 2005).

Akagami et al (1998) and Kuriyagawa et al (1999, 2002) were the first to propose the use of ER fluids for the creation and polishing of small three-dimensional components. Kim et al (2003) further investigated the fundamentals of ER fluid polishing. Zhang et al (2005) published an optimized design for maximum material removal and surface roughness based on multi-variable linear regression for evaluating the effect of process parameters. Because traditional approaches to polishing processes could not offer a flexible, cost-effective option for micromachining in advanced optics or micro-mesoscale elements, the use of MR or ER assisted polishing has gained increased attention and remains a very active research topic.

ER and MR fluids have certain advantages in machining processes, including wide operating frequency ranges, quick response time, and reversibility. Compared to ER fluids, MR fluids have a higher yield stress (50-100 kPa vs. 2-5 kPa) and can be controlled with conventional power sources, such as car batteries. MR fluids can operate in a temperature range of 40 - 150 °C, while the usable range for ER fluids is limited to 15 - 90 °C. MR fluids require bulky magnet coils, while ER fluids can rely upon a pair of electrodes to establish an electric field. ER fluids, on the other hand, require much higher electric fields (> kV/mm) for operation.

One of the major issues of using either ER or MR smart fluids is that, after a long period at rest, the fluids can become sedimented, leading to degradation in performance and replacement. Another drawback to fully embracing these fluids is due to the difficulties in modeling of these fluids and their devices. The rheological properties depend on many independent variables, including the characteristics of suspended particles, properties of the carrier fluids, additional additives, applied electric/magnetic fields, and many others. Empirical modeling techniques have been typically employed in the smart material community, but the overall difficulty in modeling imposes a serious limitation in optimizing the performance of the smart fluids for machining processes.

5. DISCUSSION

The applications and benefits of active materials are slowly coming into full view of the manufacturing community because of their capability in providing highly integrated sensing and actuation. With continual advances in active sensor/actuator technology, signal processing techniques, and control algorithms, active materials will continue to attract the attention of researchers and field engineers. In this section, future issues of active materials in machining processes are summarized.

The use of active materials in machining processes encompasses a wide range of the multidisciplinary fields and requires experts from different research communities including sensors, controls, active materials, and manufacturing. However, the research to-date has been pursued in a very disjointed manner from different communities, with results published in their respective journals, which has led to significant overlaps in effort. A more integrated and multidisciplinary approach will be necessary in order to fully to utilize the potential of active materials in machining processes. In such a way, the efficiencies and capabilities of active materials-assisted manufacturing systems can be maximized.

Another shortcoming in this field seems to be the lack of theories and a database for integrating active materials into manufacturing systems. The analytical modeling techniques established in the last few decades by the active material community do not appear to be fully utilized in the machining industry. Only fairly simple 1-D or 2-D models have been used, making it difficult to identify key parameters necessary to design such active components for machining processes. The implementation of improved modeling techniques is also necessary. These techniques should incorporate some of the more important machining variables, such as the cutting tool's deflection or the thermal conditions, to help understand the overall effects of active components on manufacturing processes and to produce a useful procedure to select sizes, locations, and materials of the active components. Through advanced modeling and extensive mechanical testing, the issues of matching the force, stroke, and time constant of active materials can be thoroughly investigated. The data would provide a guideline for selecting the size and capacity of the active components for different configurations and operating conditions. The successful outcome of this approach would greatly facilitate active material system design for machining processes for practical and efficient implementation into manufacturing facilities.

In order to transition the technology into practice, engineers must have a set of design rules and data, as they do for conventional sensors and actuators. However, because of the current disjointed research effort, designs incorporating active materials in machining processes are usually realized in an ad-hoc fashion. Considerable efforts are therefore required to design, install, and calibrate an active device for manufacturing machinery. One potential remedy for this problem would be the creation of a pre-packaged "design module" that incorporates active sensors, actuators, and control strategies with the associated electronics that could be embedded into the machining system from the initial design stage. In such a way, one can fully capitalize on the integrated sensing and actuation capability of active material systems. Developing such modules demands substantial research efforts in defining the key parameters and predictive models in designing efficient active devices components. Optimization studies are also necessary, as this is the field that has received the least attention to-date. The literature still contains numerous papers suggesting unrealistic schemes with somewhat impractical energy requirements. The development of a design module would provide a rapid diffusion of active material systems to practicing engineers. In particular, attention should also be paid to the use of new active materials as they are developed, as this has been a fast moving area in recent years.

6. CONCLUSION

This paper has reviewed the development and applications of active materials in machining processes. A key feature in prompting the utility of active materials in process monitoring and control of machining processes is the unobtrusive and integrated nature of active materials that allows actuation and sensing to become fully integrated into the machine tools. The availability of a variety of new sensing and actuation capabilities and the advent of new active multifunctional materials will have a large impact on the types of algorithms and schemes for improved performance in machining process monitoring and control.

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8. REFERENCES

1. Akagami, Y., Asari, K., Jeyadevan, B., Fujita, T. (1999) "Characterization of Particle Motion for Polishing and Texturing under AC Field by Using Particle Dispersion Type ER Fluid," *Journal of Intelligent Material Systems and Structures*, **9**, pp. 672-675
2. Al-Zaharnah, I.T. (2006) "Suppressing Vibrations of Machining Processes in both Feed and Radial Directions using an Optimal Control Strategy: The case of Interrupted Cutting," *Journal of Materials Processing Technology*, **172**, pp. 305-310.
3. Ashour, O., Rogers, C.A., Kordonsky, W. (1996) "Magnetorheological fluids: materials, characterizations, and devices," *Journal of Intelligent Material Systems and Structures*, **7**, pp. 123-130.
4. Astashev, V.K., Babitsky, V.I. (1998) "Ultrasonic Cutting as a Nonlinear (vibro-impact) process," *Ultrsonics*, **36**, pp. 89-96.

5. Babitsky, V.I., Kalashnikov, A.N., Meadows, A., Wijesundara, A.A.H.P. (2003) "Ultrasonically Assisted Turning of Aviation Materials," *Journal of Materials Processing Technology*, **132**, pp. 157-167
6. Babitsky, V.I., Kalashnikov, A.N., Molodtsov, F.V., (2004) "Autoresonant Control of Ultrasonically Assisted Cutting," Mechatronics, **14**, pp. 91-114.
7. Banks, H.T., Smith R.C., and Wang, Y. (1996), *Smart Materials and Structures: Modeling, Estimation and Control*, Wiley, Chichester.
8. Barney, P., Redmond, J., Smith, D. (1997) "Characteristics of Self-sensing Actuation for Active Control," *Proceedings of the International Modal Analysis conference*, pp.739-744.
9. Browning, D.R., Golioto, I., Thompson, N.B. (1997) "Active Chatter Control System for Long-overhang Boring Bars," *Proceedings of the SPIE - The International Society for Optical Engineering*, **3044**, pp.270-280
10. Butler, J.L., Butler, S.C., and Clark, A.E. (1990) "Unidirectional Magnetostrictive Piezoelectric Hybrid Transducer," *Journal of the Acoustical Society of America*, **88**, pp. 7-11.
11. Carman, G. P., and Mitrovic,M. (1995) "Nonlinear Constitutive Relations for Magnetostrictive Materials with Applications to 1-D Problems," *Journal of Intelligent Material Systems and Structures*, **6**, pp.673-683.
12. Chang, S.H., Du, B.C. (1998) "A precision piezodriven micropositioner mechanism with large travel range," *Review of Scientific Instruments*, **69** (4), pp.1785-1791.
13. Chang, S.H., Li, S.C. (1999) "A High Resolution Long Travel Friction-Drive Micropositioner with Programmable Step Size," *Review of Scientific Instruments*, **70** (6), pp.1-7.
14. Cheng, H.B., Feng, Z.J., Wang, Y.W. (2005) "Optimizing parameters for magnetorheological finishing supersmooth surface," *Proceedings of SPIE - The International Society for Optical Engineering*, **5638**, pp.758-765
15. Chiou, C.H., Hong, M.S., Ehmann, K.F. (2003) "The Feasibility of Eigenstructure Assignment for Machining Chatter Control," *International Journal of Machine Tools & Manufacture*, **43**, pp. 1603-1620.
16. Chiou, R.Y., and Liang, S.Y. (1998) "Chatter Stability of a Slender cutting Tool in Turning with Tool Wear Effect," *International Journal of Machine Tools & Manufacture*, **38**, pp. 315-327.

17. Chiu, W.M., Chan, K.W. (1997) "Design and Testing of Piezoelectric Actuator-Controlled Boring Bar for Active Compensation of Cutting Force Induced Errors," *International Journal of Production Economics*, **51**, pp. 135-148.
18. Chiu, W.M., Lam, F.W., Gao, D. (2002) "An Overhung Boring Bar Servo System for On-line Correction of Machining Error," *Journal of Materials Processing Technology*, **122**, pp. 286-292.
19. Chopra, I. (2002) "Review of State of Art of Smart Structures and Integrated Systems," *AIAA Journal*, **40** (11), pp. 2145-2187.
20. Choudhury, S.K., Goudimenko, N.N., Kudinov, V.A. (1997) "On-line Control of Machine Tool Vibration in Turning," *International Journal of Machine Tools & Manufacture*, **37**, pp. 801-811.
21. Clark, R.L., Saunders W.R., and Gibbs, G.P. (1998) *Adaptive Structures: Dynamics and Control*, Wiley.
22. Crawley, E., and Anderson, E. (1990) "Detailed Models of Piezoceramic Actuation of Beams," *Journal of Intelligent Materials and Structures*, **1** (1), pp. 4-25.
23. Crawley, E.F. and de Luis, J. (1987) "Use of Piezoelectric Actuators as Elements of Intelligent Structures," *AIAA Journal*, **25** (10), pp. 1373-1385.
24. Crudele, M., and Kurfess, T.R. (2003) "Implementation of a Fast Tool Servo with Repetitive Control For Diamond Turning," *Mechatronics*, **13**, pp. 243-257
25. Culshaw, B. (1996), *Smart structures and Materials*, Artech House.
26. Cuttino, J.F., Miller, A.C., Schinstock, D.E. (1999) "Performance Optimization of a Fast Tool Servo for Single-Point Diamond Turning Machines," *IEEE/ASME Transactions on Mechatronics*, **4** (2), pp.169-179.
27. Dapino, M.J., Smith, R., Faidley, L.E., and Flatau, A.B., (2000) "A Coupled Structural Magnetic Strain and Stress Model for Magnetostrictive Transducers," *Journal of Intelligent Material Systems and Structures*, **11**, pp. 135–152.
28. Dohner, J.L., Lauffer, J.P., Hinnerichs, T.D., Shankar, N., Regelbrugge, M., Kwan, C.M., Xu, R., Winterbaur, B., Bridger, K. "Mitigation of Chatter Instabilities in Milling by Active Structural Control," *Journal of Sound and Vibrations*, **269**, pp. 197-211.
29. Dosch, J.J., Inman, D.J., and Garcia, E. (1992) "A Self Sensing Piezoelectric Actuator for Collocated Control," *Journal of Intelligent Material Systems and Structures*, **3**, pp. 166-185.

30. Dow, T.A., Miller, M.H., and Falter P.J. (1991) “Application of a fast tool servo for diamond turning of nonrotationally symmetric surfaces,” *Precision Engineering*, **13** (4), pp. 243-250.
31. Du, Z.C., Yang, J.G., Yan, J.P. (2004) “Vibration Characteristics of Piezoelectric Micro Displacement Actuator Driven Directly for Ultrasonic Machining,” *Key Engineering Materials*, **259-260**, pp. 609-614.
32. Eda, H., Ohmura, E., Sahashi, M., Kobayashi, T., (1992) “Ultra-precise Machine Tool Equipped with a giant Magnetostrictive Actuator,” *Annals of the CIRP*, **41**, pp. 421-424.
33. Eda, H., Shimizu, J., Zhou, L. (1999) “Study on Ultra-Precision Machining of Ceramics for Optical Components,” *Proceedings of the SPIE - The International Society for Optical Engineering*, **3740**, pp. 420-423.
34. El-Sinawi, A.H., Kashani, R. (2005) “Improving Surface Roughness in Turning using Optimal Control of Tool’s Radial Position,” *Journal of Materials Processing Technology*, **167**, pp. 54-61.
35. Elfizy A.T., Bone, G.M., Elbestawi, M.A. (2004) “Design and Control of a Dual-stage Feed Drive,” *International Journal of Machine Tools & Manufacture*, **45**, pp. 153-165.
36. Elfizy A.T., Bone, G.M., Elbestawi, M.A. (2004) “Model-based Controller Design for Machine Tool Direct Feed Drives,” *International Journal of Machine Tools & Manufacture*, **44**, pp. 465-477.
37. Eshete, Z., Zhang, G., (1996) “In-Process Machine Tool Vibration cancellation using PMN actuators,” *Proceedings of the SPIE - The International Society for Optical Engineering*, **2911**, pp.63-70
38. Fabris, N.S., and D’Souza, A.F. (1974) “Nonlinear Stability Analysis of Chatter in Metal Cutting,” *Transaction of ASME Journal of Engineering for Industry*, **96**, pp. 670-675.
39. Falter, P.J. (1990), *Diamond Turning of Nonrotationally Symmetric Surfaces*, Ph.D. dissertation, North Carolina State University.
40. Fung, E.H.K., Yang, S.M. (2001) “A new Method for Roundness Control in Taper Turning using FCC Techniques,” *Journal of Manufacturing Science and Engineering*, **123**, pp. 567-575.
41. Gamota D.R., Filisko, F.E. (1991) “Dynamic Mechanical Studied of Electrorheological Materials: Moderate Frequencies,” *Journal of Rheology*, **35**, 399-425

42. Gandhi M.V., and Thompson B.S., 1994, *Smart Materials and Structures,* Chapman and Hall.
43. Gao W., Araki, T., Kiyono, S., Okazaki, Y., Yamanaka, M. (2003) "Precision Nano-Fabrication and Evaluation of a large Area Sinusoidal Grid Surface for a Surface Encoder," *Precision Engineering*, **27**, pp. 289-298.
44. Gao, D., Yao, Y.X., Chiu, W.M., Lam, F.W. (2002) "Accuracy Enhancement of a Small Overhung Boring Bar Servo System by Real-time Error Compensation," *Precision Engineering*, **26**, pp. 456-459
45. Garrard, K., Bruegge, T., Hoffman, J., Dow, T., Sohn, A. (2005) "Design Tools for Freeform Opitcs," *Proceedings of SPIE - The International Society for Optical Engineering*, **5874**, pp. 1-11.
46. Golini, D., Schneider, G., Flug, P., DeMarco, M. (2001) "Magnetorheological Finishing**,"** *Optics & Photonics News*, **12** (10), pp.20-24
47. Goncalves, F.D., Koo, J.H., Ahmadian, M. (2006) "A review of the State of the Art in Magnetorheological Fluid Technologies – Part I: MR fluid and MR fluid Models," *The Shock and Vibration Digest*, **38**, pp. 203-219.
48. Hagood, N.W., Chung, W.H., von Flotow, A. (1990) "Modeling of Piezoelectric Actuator Dynamics for Active Structural Control," *Journal of Intelligent Materials Systems and Structures*, **1**, pp. 327-354.
49. Hanson, R.D., Tsao T.C. (1998) "Reducing Cutting Force Induced Bore Cylindricity Errors by Learning Control and Variable Depth of Cut Machining," *Journal of Manufacturing Science and Engineering*, **120**, pp. 547-554.
50. Harms, A., Denkena, B., Lhermet, N. (2004) "Tool Adaptor for Active Vibration Control in Turning Operation," *Proceedings of 9th International Conference on New Actuators*, Bremen, Germany, pp. 694-697
51. Hartman, D.A., Brazil, I.E., Talkington, J.E., Salazar, D.R., Neal, G.E., Valdez, R.C., Arellano, G.J., Duncan, W.S., Cola, M.J., Dave, V.R., (2003) "In-Process Surface Roughness Prediction during Turning: Preliminary Findings using a New Sensing Technique," *Proceedings of Small Lots Intelligent Manufacturing Workshop*, Santa Fe, NM.
52. Hartman, D.A., Dave, V.R., Cola, M.J. (2004) "Real-Time Manufacturing Performance Assessment," *Proceedings of NNSA future Technologies Conference*, Washington DC.

LA-UR-06-7063, International Journal of Machine Tool and Manufacture,Vol. 47 (15), 2189-2206, 2007.

53. Hartman, D.A., Bement, M.T., Cola, M.J., Dave, V.R., King, W.H. (2005) "In-Process Monitoring: A Strategy for Small Lot Production," *Proceedings of Small Lots Intelligent Manufacturing Workshop*, Santa Fe, NM.
54. Hartman, D.A., Dave, V.R., Cola, M.J., Bement, M.T., Tolk, N.R., Gubernatis, D.C., Hartman, I.P., Salazar, D.R., Brazil, I.E. (2007) "In-Process Quality Assurance during Near-Dry machining of Plutonium," Los Alamos National Laboratory Report, in press.
55. Holterman, J., de Vries T.J.A. (2004a) "Active Damping within an Advanced Microlithography System using Piezoelectric Smart Discs," *Mechatronics*, **14**, pp. 15-34.
56. Holterman, J., de Vries T.J.A. (2004b) "Prediction of the Applicability of Active Damping Elements in High-Precision Machines," *Proceedings of SPIE - The International Society for Optical Engineering*, **5383**, pp. 211-220.
57. Hurlebaus, S., and Gaul, L. (2006) "Smart Structure Dynamics," *Mechanical Systems and Signal Processing*, **20**, pp. 255-281.
58. Ikeda, T., (1996) *Fundamentals of Piezoelectricity*, Oxford Press.
59. Inman, D.J. (2003). "Smart Materials in Damage Detection and Prognosis," *Proceedings of the 5th International Conference on Damage Assessment of Structures*, Southampton, UK, pp. 3-16.
60. Jared, B.H., Dow, T.A., Garrard, K.P., Moorefield, G.M., Barnes, C., Day, R.D., Hatch, D.J., Salzer, L.J., and Rivera, G. (1997) "Fabrication of Hydrodynamic Instability Targets," *Fusion Technology*, **31**, pp. 501-503.
61. Jemielniak, K., and Widota, A. (1989) "Numerical Simulation of Nonlinear Chatter Vibration in Turning," *International Journal of Machine Tools & Manufacture*, **29**, pp. 239-247.
62. Jolly, M.R., Bendar, J.W., and Carlson, J.D., (1999), "Properties and Applications of Commercial Magnetorheological Fluids," *Journal of Intelligent Material Systems and Structures*, **10** (1), pp. 5-13.
63. Kallio, P. Zhou, Q., Lind, M., Koivo, H.N. (1998) "Position Control of a 3 DOF Piezohydraulic Parallel Micromanipulator," *Proceedings of 1998 IEEE/RSJ International Conference on Intelligent Robots and Systems*, **2**, pp. 770-775.
64. Katsuki, A., Onikura, H., Sajima, T., Takei, T., Thiele, D. (2000) "Development of High-Performance Laser-Guided Deep-Hole Boring Tool: Optimal Determination of Reference Origin for Precise Guiding," *Precision Engineering*, **24**, pp. 9-14.

LA-UR-06-7063, International Journal of Machine Tool and Manufacture,Vol. 47 (15), 2189-2206, 2007.

65. Kim, B.S., Li, J., and Tsao, T.C., (2001) "Control of a Dual Stage Actuator System for Noncircular Cam Turning Process," *Proceedings of the American Control Conference*, Arlington, VA, pp. 2549-2554.
66. Kim H.S., Kim, E.J. (2003) "Feed-forward Control of Fast Tool Servo for Real-time Correction of Spindle Error in Diamond Turning of Flat Surfaces," *International Journal of Machine Tools & Manufacture,* **43**, pp. 1177-1183.
67. Kim H.S., Kim, E.J. and Song, B.S. (2004a) "Diamond Turning of Large Off-axis Aspheric Mirrors using a Fast Tool Servo with On-machine Measurement," *Journal of Materials Processing Technology*, **146**, pp. 349-355.
68. Kim, W.B., Lee, S.J., Kim, Y.J., Lee, E.S., (2003) "The electromechanical Principle of Electrorheological Fluid-assisted Polishing," *International Journal of Machine Tools & Manufacture,* **43**, pp. 81-88.
69. Kim, W.B., Lee, S.H., Min, B.K. (2004b) "Surface Finishing and Evaluation of Three-Dimnsional Silicon Microchannel using Magnetorheological Fluid," *Journal of Manufacturing Science and Engineering*, 126, p.772-778
70. Kim, J.D., Kim D.S. (1998) "Development of a Micro-depth Control Ssytem for an Ultra-Precision Lathe using a Piezoelectric Actuator," *International Journal of Machine Tools & Manufacture*, **38**, pp. 1305-1322.
71. Kim, J.D., Nam, S.R. (1997) "Development of a Micro-depth Control Ssytem for an Ultra-Precision Lathe using a Piezoelectric Actuator," *International Journal of Machine Tools & Manufacture,* **37**(4), pp. 495-509.
72. Kohno, T., Okazaki, Y., Ozawa, N., Mitui, K., Omoda, M. (1989). "In-Process Measurment and a Workpiece-referred Form Accuracy Control System (WORFAC): Concept of the Method and Preliminary Experiment," *Precision Engineering,* 11 (1), pp. 9-14.
73. Kordonski, W; Golini, D (1999) "Fundamentals of magnetorheological fluid utilization in high precision finishing," *Journal of Intelligent Material Systems and Structures,* **10**, pp.683-689
74. Kordonski, W; Golini, D (2002), "Multiple Application of Magnetorheological Effect in High Precision Finishing," *Journal of Intelligent Material Systems and Structures,* **13**, pp. 401-404.

75. Koren, Y., Pasek, Z., and Szuba, P. (1999) "Design of a Precision, Agile Line Boring Station," *CIRP Annals – Manufacturing Technology*, **48** (1), pp. 313-316.
76. Koratkar, N.A., Chopra, I. (1999) "Design, Fabrication and Testing of a Mach Scaled Rotor Model with Trailing-Edge Flaps," *Annual Forum Proceedings—American Helicopter Society*, **1**, 558-578.
77. Krishnamoorthy, R., Lin C.Y., and Tsao, T.C. (2004) "design and control of a dual stage fast tool servo for precision machining," *Proceedings of the 2004 IEEE International Conference on Control Applications*, pp. 742-747.
78. Ku, S.S., Larsen, G., Cetinkunt, S. (1998) "Fast Tool Servo control for Ultra-Precision Machining at Extremely Low Feed Rates," *Mechatornics*, **8**, pp. 381-393.
79. Kuriyagawa, T., Saeki, M. (1999) "Development of Electrorheological Fluid-assisted Machining for Small Three-Dimensional Parts," *Journal of Japanese Society in Precision Engineering*, **65**, pp. 145-149.
80. Kuriyagawa, T., Saeki, M., Syoji, K. (2002) "Electrorheological fluid-assisted Ultra-Precision Polishing for Small Three-Dimensional Parts," *Precision Engineering*, **26**, pp. 370-380.
81. Le Letty, R., Claeyssen, F., Lhermet, N., and Bouchilloux, P. (1997) "A New Amplified Piezoelectric Actuator for Precise Positioning and Active Damping," *Proceedings of the SPIE—The International Society for Optical Engineering*, **3041**, pp. 496-504.
82. Lee C.W., Kim S.W. (1997) "An Ultraprecision Stage for Alignment of Wafers in Advanced Microlithography," *Precision Engineering*, **21**, pp. 113-122.
83. Lee, E.C., Nian, C.Y., Tarng, Y.S. (2001) "Design of a Dynamic Vibration Absorber against Vibrations in Turning Operation," *Journal of Materials Processing Technology*, **108**, pp. 278-285.
84. Lee, T., and Chopra, I. (1999) "Development and Validation of a Refined Piezostack-Actuated Trailing Edge Flap Actuator for a Helicopter Rotor," *Proceedings of the SPIE—The International Society for Optical Engineering*, **3668**, pp. 22-36.
85. Lei, Y.Z, (1995) "Use of the electrorheological technique (ERT) for chatter control," *Proceedings of SPIE - The International Society for Optical Engineering*, **2620**, pp.762-766.

86. Liang, S.Y., Hecker, R.L., and Landers, R.G. (2004). "Machining Process Monitoring and Control: The State-of-the-Art," *ASME Journal of Manufacturing Science and Engineering*, **126** (5), pp. 297-310.
87. Liu D., Sutherland, J.W., Moon, K.S., Sturos, T.J., Kanizar, W.L., (1998) "Surface Texture Improvement in the Turning Process via Application of Magnetostrictive Actuated Tool Holder," *Journal of Dynamic Systems Measurement and Control*, **120**, pp. 193-199.
88. Liu, Y.T., Higuchi, T. (2001) "Precision Positioning Device Utilizing Impact Force of Combined Piezo-Pneumatic Actuator," *Mechatronics*, **6** (4), pp. 467-473
89. Liu, Y.T., Fung, R.F., Huang, T.K. (2004) "Dynamic Responses of a Precision Positioning Table Impacted by a Soft-Mounted Piezoelectric Actuator," *Precision Engineering*, **28**, pp. 252-260.
90. Martinez, D.R., Hinnerichs, T.D., Redmond, J.M. (1996) "Vibration control for Precision Manufacturing using Piezoelectric Actuators," *Journal of Intelligent Material Systems and Structures*, **7**, 182-191.
91. Marui, E., Hashimoto, M., and Kato, S. (1995) "Regenerative Chatter Vibration Occurring in Turning with Different Side Cutting Edge Angles," *Journal of Engineering for Industry*, **117**, pp. 551-558.
92. Mayhan, P., Srinivasan, K., Watechagit, S., Washington, G. (2000) "Dynamic Modeling and Controller Design for a Piezoelectric Actuation system Used for Machine Tool Control," *Journal of Intelligent Material Systems and Structures*, **11**, pp. 771-780.
93. Michler J.R., Moon, K.S., Sutherland, J.W., Kashani, A.R. (1993) "Development of a Magnetostriction based Cutting Tool Positioner," *Transactions of the North American Manufacturing Research Institute of SME*, pp. 421-427.
94. Miller, M.H., Garrard, K.P., Dow, T.A., Taylor, L.W. (1994), "A Controller Architecture for Integrating a Fast Tool Servo into a Diamond Turning Machine," *Precision Engineering*, **16** (1), pp. 42-48.
95. Min, B.K., O'Neal G.P., Koran, Y., Pasek, Z. (2002), "A Smart Boring Tool for Process Control," *Mechatronics*, **12**, pp. 1097-1114.
96. Moorefield, G.M., Garrard, K.P., Falter, K.J., Taylor, L.W., Dow, T.A., (1994) "Generation of Rotationally Asymmetric Optical Surfaces using a Fast Tool Servo," *Proceedings of the Ninth Annual ASPE Meeting*, **10**, pp. 45-48.

97. Moriwaki T. Shamoto, T. (1996) “Ultraprecision Feed System Based on Walking Drive,” *Annals of the CIRP*, **45**(1), 505–508.

98. Moriyama, S., Harasa, T., Takanashi, A., “Precision X-Y stage with a Piezo-driven Fine Table,” *Journal of Japanese Society in Precision Engineering*, **50**, pp. 718-723.

99. Nagaya, K., Yamazaki, H., Kashimoto, H. (1997) “Control of Micro-vibrations of a Machine Head by using Piezoelectric Actuators,” *International Journal of Applied Electromagenetics and Mechanics*, **8**, pp. 315-328

100. Nasser, K., Leo, D. J., (2000) “Efficiency of Frequency-rectified Piezohydraulic and Piezopneumatic actuation,” *Journal of Intelligent Material Systems and Structures*, **11**(10), pp.798-810.

101. Ni, J., Zhu, Z. (2000) “Design of a Linear Piezomoter with Ultra-High Stiffness and Nanopreciosn,” *IEEE/ASME Transactions on Mechatronics*, **5** (4), pp. 441-443.

102. Niezrecki, C., Brei, D., Balakrishnan, S., Moskalik, A. (2001) “Piezoelectric Actuation: State of the Art,” *The Shock and Vibration Digest*, **33** (4), pp. 269-280.

103. Okazaki, Y. (1990) “A Micro-Positioning Tool Post using a Piezoelectric Actuator for Diamond Turning Machines,” *Precision Engineering*, **12** (3), pp.151-156.

104. O’neal, G.P., Min, B.K, Li, C.J., Pasek, Z.J., Korean, Y., and Szuba, P. (1998) “Precision Piezoelectric Micro-Positioner for Line Boring Bar Tool Insert,” *Proceedings of ASME International Mechanical Engineering Congress and Exposition, Vibration and Noise Control*, **DSC 65**, pp. 99-106

105. O’neal, G.P., Min, B.K, Pasek, Z.J., and Korean, Y. (2001) “Integrated Structural/Control Deign of Micro-Positioner for Boring Bar Tool Insert,” *Journal of Intelligent Material Systems and Structures*, **12**, pp. 617-627

106. Pahk, H.J., Lee, S.D., Park, J.H. (2001) “Ultra Precision Positioning System for Servo Motor-Piezo Actuator using the dual Servo Loop and Digital Filter Implementation,” *International Journal of Machine Tools & Manufacture,* **41**, pp. 51-63.

107. Pan, J.C., Su, C.Y. (2001) “Chatter Suppression with Adaptive control in turning Metal via Application of Piezoactuator,” *Proceedings of the 40th IEEE Conference on Decision and Control*, Orlando, FL, pp. 2436-2441.

108. Panusittikorn, W., Ro, P.I. (2004) “Modeling and Control of a Magnetostrictive Tool Servo System,” *Proceedings of the 2004 American Control conference*, pp. 3770-3775.

109. Patterson, S.R., Magrab, E.B. (1985) "The design and testing of a fast tool servo for diamond turning," *Precision Engineering*, **7** (3), pp123-128.

110. Petersson, L., Hakansson, L., Claesson, I., Olsson, S., (2001) "Active Control of Machine-tool Vibration in a CNC Lathe Based on an Active Tool Holder Shank with Embedded Piezoceramic Actuators, *Proceedings of 8th International Congress on Sound and Vibrations*, HongKong, pp. 301-308.

111. Pokines, B.J., Garcia, E., (1998) "A Smart Material Microamplification Mechanism Fabricated Using LIGA," *Smart Materials and Structures*, **7**, 105-112.

112. Quandt, E., Claeyssen, F. (2000) "Magnetostrictive Materials and Actuators (Review)," *Proceedings of 7th International Conference on New Actuators*, pp. 100-105.

113. Rashid M.K. (2005) "Smart Actuator Stiffness and Switching Frequency in Suppression of Vibration of a Cutting Tool," *Smart Materials and Structures*, **13**, pp. 478-486.

114. Rasmussen, J.D., Tsao, T.C., Hanson, R.D., Kapoor, S.G. (1994) "Dynamic Variable Depth of Cut Machining using Piezoelectric Actuators," *International Journal of Machine Tools and Manufacture*, **34** (3), pp. 379-392.

115. Rojas, J., Liang, C., Geng, Z.J. (1996) "Experimental Investigation of Active Machine Tool Vibration Control," *Proceedings of SPIE - The International Society for Optical Engineering*, **2721**, 373-384

116. Schellekens, P., Rosielle, N., Vermeulen, H., Vermeulen, M., Wetzels, S., Pril, W. (1997) "Design for Precision: Current Status and Trends," *Annals of the CIRP*, **47** (2), pp. 557-586.

117. Schinhaerl, M., Pitschke, E., Geiss, A., Rascher, Rolf., Sperber, P., Stamp, R., Smith, L., Smith, G., (2005) "Comparison of different magnetorheological polishing fluids," *Proceedings of SPIE - The International Society for Optical Engineering*, **5965**.

118. Segalman, D., Redmond, J. (1996) "Chatter Suppression Through Variable Impedance and Smart Fluids," *Proceedings of the SPIE - The International Society for Optical Engineering*, **2721**, pp.353-363.

119. Shamoto, E., Moriwaki, T. (1997) "Development of a "Walking Drive" Ultraprecision Positioner," *Precision Engineering*, **20**, pp. 85-92.

120. Shorey, AB; Kwong, KM; Johnson, KM; Jacobs, SD (2001) "Experiments and observations regarding the mechanisms of glass removal in magnetorheological finishing," *Applied Optics*, **40** (1), pp. 20-33.

121. Shorey, A; Kordonski, W; Tricard, M. (2004) "Magnetorheological finishing of large and lightweight optics," *Proceedings of SPIE - The International Society for Optical Engineering*, **5533**, pp.99-107

122. Sims, N.D., Bayly, P.V., Young, K.A. (2005) "Piezoelectric Sensors and Actuators for Milling Tool Stability Lobes," *Journal of Sound and Vibrations*, **281**, pp. 743-762.

123. Sirohi, J., and Chopra, I. (2000a) "Fundamental Behavior of Piezoceramic Sheet Actuators," *Journal of Intelligent Material Systems and Structures*, **11** (1), pp. 47-61.

124. Sirohi, J., and Chopra, I. (2000b) "Fundamental Understanding of Piezoelectric Strain Sensors," *Journal of Intelligent Material Systems and Structures*, **11** (4), pp. 246-257

125. Smits, J., Choi, W. (1991) "The Constituent Equations of Heterogeneous Bimorphs," *IEEE Transactions on Ultrasonic, Ferroelectrics and Frequency Control*, **38** (3), pp. 256-270.

126. Sodano, H.A., Inman, D.J., Park, G., (2004) "A Review of Power Harvesting from Vibration Using Piezoelectric Materials," *The Shock and Vibration Digest*, **36**, pp. 197-205.

127. Srinivasan, S., and McFarland, M. (2001) *Smart Structures: Analysis and Design*, Cambridge University Press.

128. Stanway R., Sproston J.L., and EI-Wahed ,A.K. (1996) "Applications of Electro-Rheological Fluids in Vibration Control: a Survey," *Smart Materials and Structures*, **5**, pp. 463-482.

129. Tang, Z., Xiang, Z., Lv, F. (2004) "Modeling and Control Method Study of Magnetostrictive Micropositioner and its Application," *Proceedings of 2004 IEEE International Conference on Systems, Man, and Cybernetics*, pp. 4296-4300.

130. Tarng, Y.S., Kao, J.Y., Lee, E.C. (2000) "Chatter Suppression in Turning Operations with a Tuned Vibration Absorber," *Journal of Materials Processing Technology*, **105**, pp. 55-60.

131. Thoe, T.B., Aspinwall, D.K., Wise, M.L.H. (1997) "Review on Ultrasonic Machining," *International Journal of Machine Tools & Manufacture*, **38** (4) pp. 239-255.

132. Unno, K., Kitamoto, Y., Shibata, T., Makino, E. (2001) "Smart Nano-Machining and Measurement System with Semiconductive Diamond Probe," *Smart Materials and Structures*, **10**, 730-735

133. Versteyhe, M., Reynaerts, D., Van Brussel, H. (1999) "Hybrid Force-Position Control of Clamping with a Piezo-Stepper," *IEEE Control Systems Magazine*, **19** (2), pp. 31-39.

134. Wang, J. and Su, C.Y. (2003) "Two Degree-of-Freedom Modeling and robust Chatter control in Metal Cutting by Piezoelectricity," *Proceedings of the American Control Conference*, Denver, CO, pp. 3044 - 3048.

135. Wang, J., Meng, G. (2001) "Magnetorheological fluid devices: principles, characteristics and applications in mechanical engineering," *Proceedings of the Institution of Mechanical Engineers, Part L (Journal of Materials: Design and Applications)*, **215** (3), pp. 165-74.

136. Wang, M., Fei, R.Y., (1999a) "Improvement of Machining Stability using a Tunable-Stiffness Boring Bar Containing an Electrorheological Fluid," *Smart Materials and Structures*, **8**, pp. 511-514.

137. Wang, M., Fei, R.Y., (1999b) "Chatter Suppression based on Nonlinear Vibration Characteristic of Electrorheological Fluids," *International Journal of Machine Tools & manufacture*, **39**, pp. 1925-1934.

138. Wang, M., Fei, R.Y., (2001) "On-line Chatter Detection and control in boring based on an electrorheological fluid," *Mechatronics*, **11** (7), pp. 779-792.

139. Woronko, A., Huang, J., Altintas, Y. (2003) "Piezoelectric Tool Actuator for Precision Machining on Conventional CNC turning Centers," *Precision Engineering*, **27**, 335-345.

140. Xu, W.L., Han, L. (1999) "Piezoelectric Actuator based Active Error Compensation of Precision machining," *Measurement Sciences and Technology*, **10**, pp. 106-111.

141. Yamamoto, Y., Eda, H., Shimizu, J. (1999) "Application of Giant Magnetostrictive Materials to Positioning Actuator," *Proceedings of the 1999 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, pp. 215-220.

142. Yan, W.Y., Al-Jumaily, A.M. (2002) "Feasibility of Using an Active Actuator for Two-Dimensional Vibration Abatement in a Turning Process," *Journal of multi-body dynamics* **216**, pp. 335 -342

143. Zhang, L., Kuriyagawa, T., Kaku, T., Zhao, J. (2005) "Investigation into Electrorheological Fluid-assisted Polishing," *International Journal of Machine Tools & Manufacture*, **45**, 1461-1467.

144. Zhang, Y., and Sims, N.D. (2004) “Milling Workpiece Chatter Avoidance using Piezoelectric Active Damping: A feasibility Study,” *Smart Materials and Structures*, **14**, pp. 65-70.

145. Zhong, Z.W., Lin, G. (2005) “Diamond turning of a Metal Matrix Composite with Ultrasonic Vibration,” *Materials and Manufacturing Processes*, **20**, pp. 727-735.

146. Zhu, W.H., Jun, M.B., Altintas, Y. (2001) “A Fast Tool Servo Design for Precision Turning of Shafts on Conventional CNC Lathes,” *International Journal of Machine Tools & Manufacture*, **41**, 953-965.

List of Figures

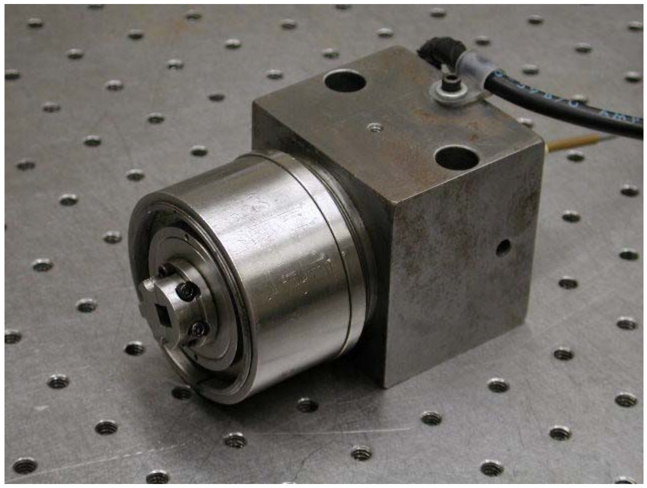


Figure 1: Piezo-based FTS servo developed by NC state researchers (courtesy of NCSU)

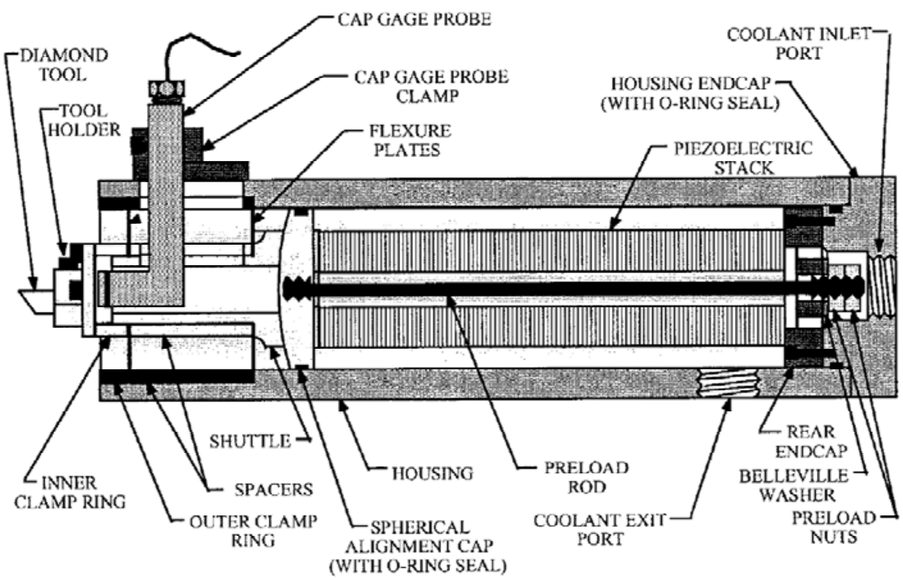

CAP GAGE PROBE
DIAMOND TOOL
TOOL HOLDER
CAP GAGE PROBE CLAMP
FLEXURE PLATES
COOLANT INLET PORT
HOUSING ENDCAP (WITH O-RING SEAL)
PIEZOELECTRIC STACK
SHUTTLE
INNER CLAMP RING
SPACERS
OUTER CLAMP RING
HOUSING
SPHERICAL ALIGNMENT CAP (WITH O-RING SEAL)
PRELOAD ROD
COOLANT EXIT PORT
REAR ENDCAP
BELLEVILLE WASHER
PRELOAD NUTS

Figure 2: Schematic of the FTS used by Cuttino et al (1999) (Cuttino et al 1999)

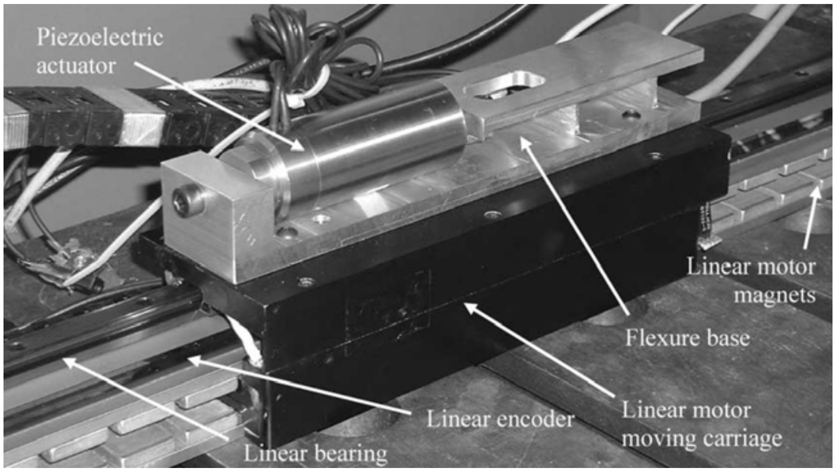


Figure 3: Single axis dual-stage feed drive developed by Elfizy et al 2005 (Elfizy et al 2005)

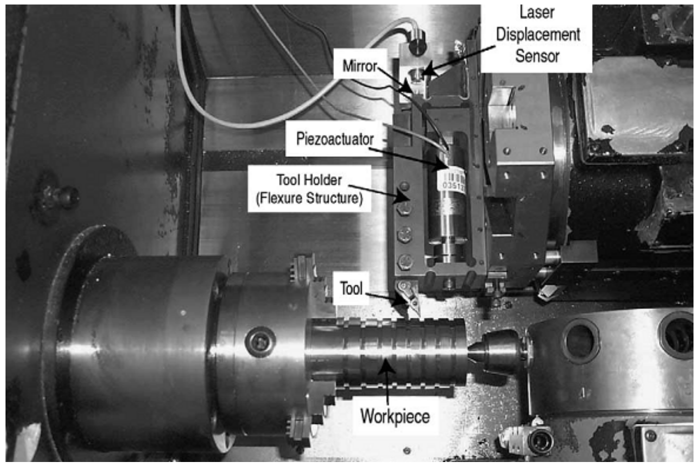


Figure 4: Piezo-based FTS attached to conventional CNC machine (Zhu et al 2001)

Figure 5: FTS developed by Kinetic Ceramic Inc

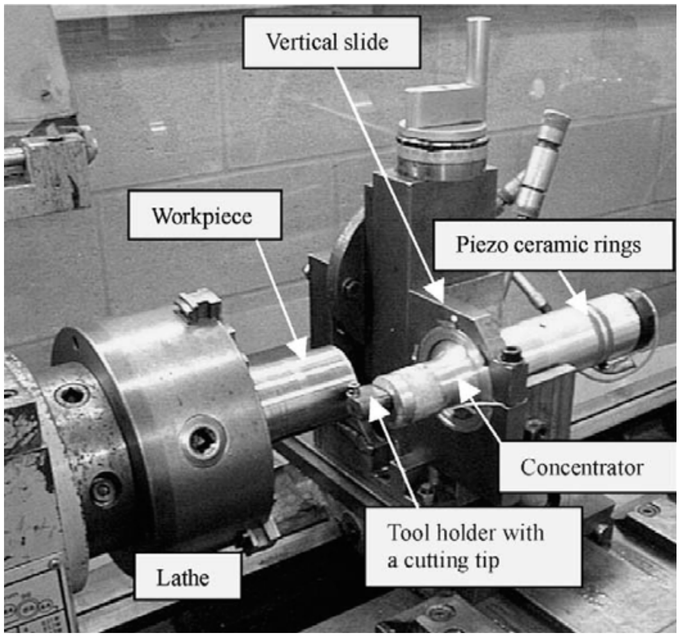


Figure 6: Experimental setup of ultrasonic cutting (Babitsky et al 2004)

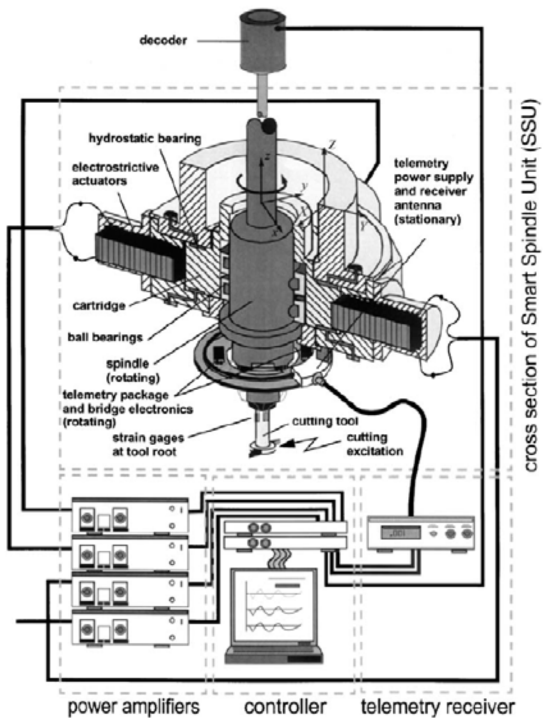


Figure 7: Hardware configuration of smart spindle unit developed by Dohner et al (2004) (Dohner et al 2004)

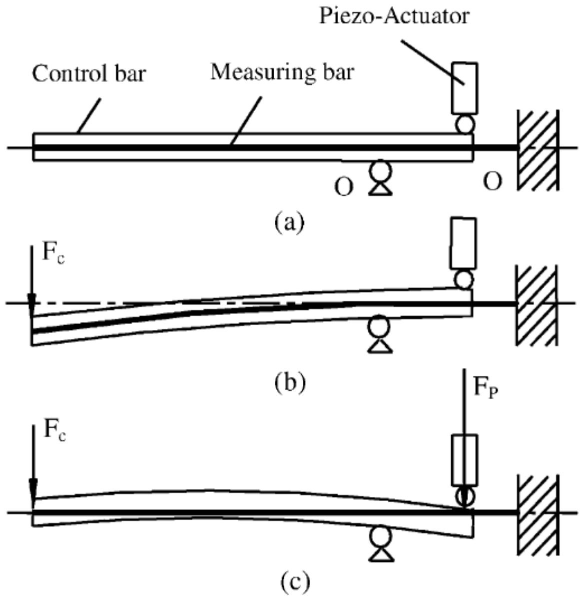


Figure 8: Interaction of a boring bar and piezo-actuator corrective action proposed by Chiu et al (2002) (Chiu et al 2002)

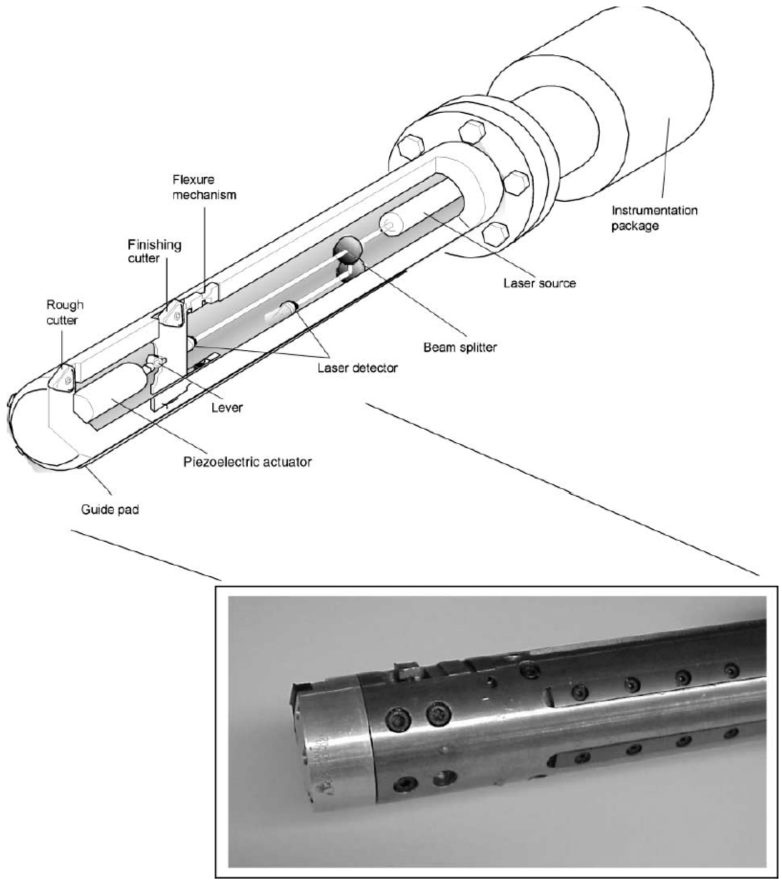
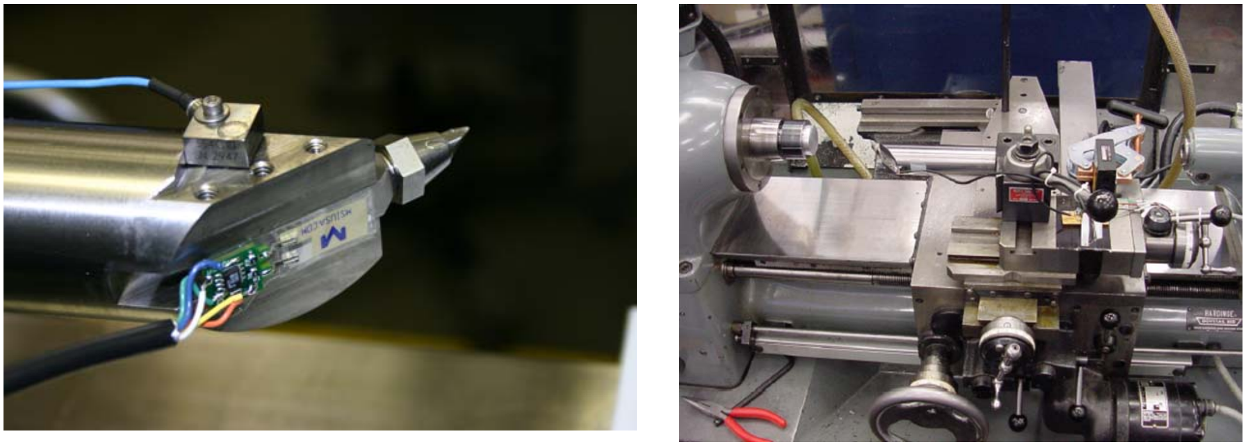


Figure 9: Structure of smart tool proposed by researchers from University of Michigan (O'Neal et al 2001)



(a) A close up of cutting tool and sensor (b) Experimental Set up

Figure 10: Sensor orientation and Experimental Setup (Hartman et al 2007)

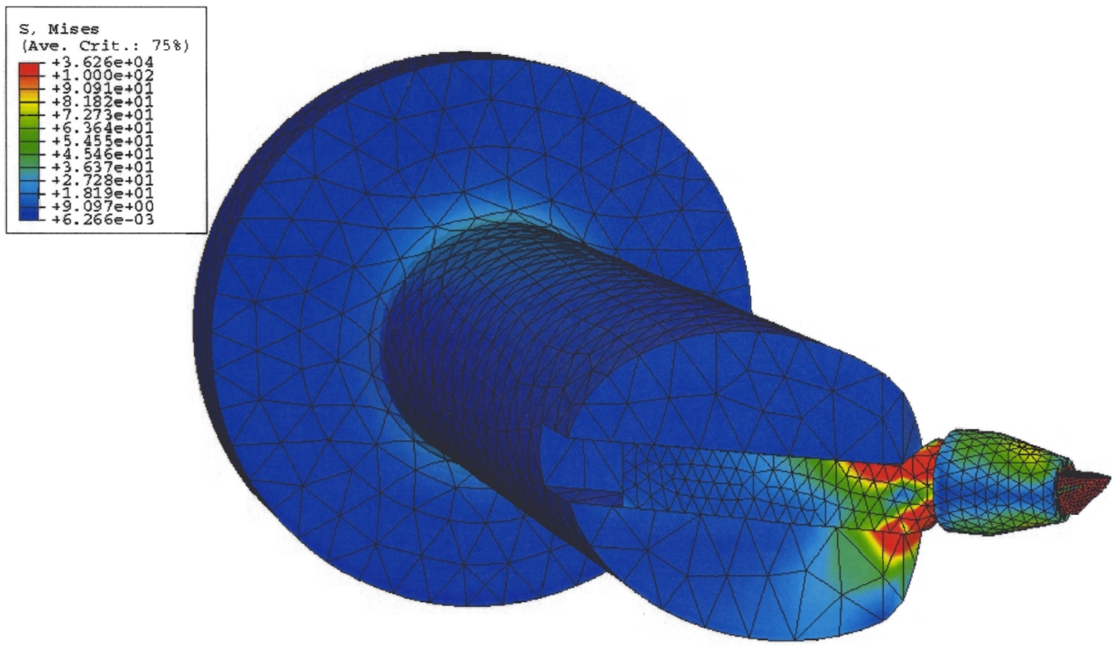


Figure 11: Finite Element analysis of the Boring Bar (Hartman et al 2007)

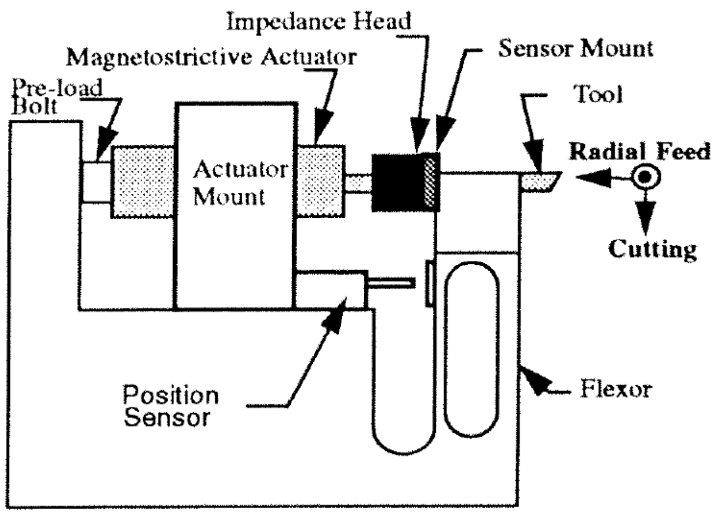


Figure 12: A schematic of magnetostrictive-based FTS proposed by Liu et al (1998) (Liu et al 1998)

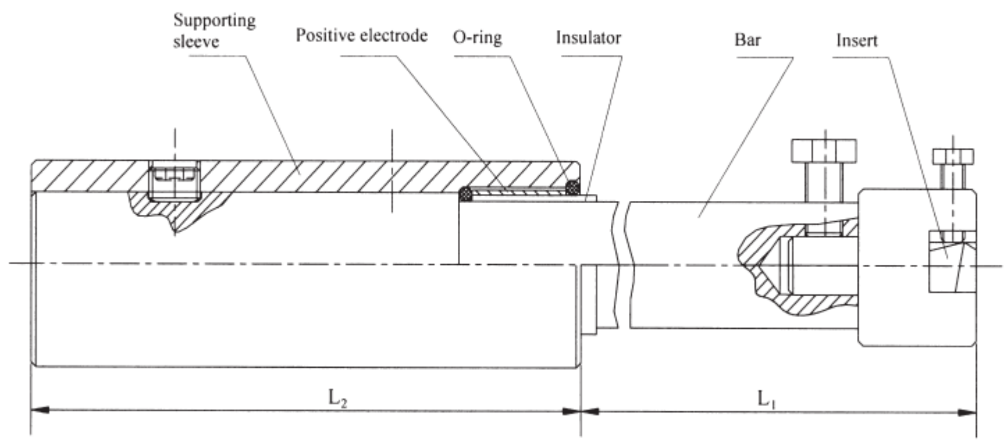


Figure 13: A schematic of tunable stiffness boring bar proposed by Wang and Fei (1999) (Wang and Fei 1999)