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The Application of Piezoelectric Materials in Machining Processes

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1. Introduction

In 1880, Jacques and Pierre Curie discovered that pressure generates electrical charges in a number of crystals such as Quartz and Tourmaline, calling this phenomenon the "piezoelectric effect". Later, they noticed that electrical fields can also deform piezoelectric materials, showing an inverse effect comparing to their first observation. Nowadays, the effect has gained considerable practical attractions in miscellaneous industrial applications including machining processes as a broad range within manufacturing methods in our competitively global technologies.

This chapter focuses mainly on the usages of piezoelectric materials in two differently common practiced machining operations adopted by both manufacturers and research scholars.

The first study pays attention to the role of piezoelectric transducers as the core system in producing ultrasonic waves in ultrasonic machines. Ultrasonic machining (USM) process, as one of the popular nontraditional machining processes, is capable of chip removal from every brittle material, whether conductive or nonconductive, susceptible to failure under mechanical loads in conventional machining processes of whatsoever hardness, such as ceramics, glass, porcelains, etc. The viability and effectiveness of piezoelectric transformers with high rate of electro-mechanical conversion compared to their old magnetostrictive counterparts are described and analyzed. The USM process capabilities and applications are also succinctly introduced.

The second is the application of quartz as a piezoelectric material in dynamometers used to measure forces and torques during conventional machining processes, like turning, milling, drilling, and so on. The basic principles and features of how a piezoelectric-based dynamometer works are discussed along with the need to measure forces and torques through dynamometry.

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2. Ultrasonic machining (USM) of materials

Ultrasonic machining is an economically viable operation by which a hole or a cavity can be pierced in hard and brittle materials, whether electric conductive or not, using an axially oscillating tool. The tool oscillates with small amplitude of 10-15 μm at high frequencies of 18-40 KHz to avoid unnecessary noise and being above the upper frequency limit of the human ear, justifying the tem "ultrasonic" [1, 2].

During tool oscillation, abrasive slurry (B4C and SiC) is continuously fed into the working gap between the oscillating tool and the stationary WP. The abrasive particles are, therefore, hammered by the tool into the WP surface, and consequently abrading the WP into a conjugate image of the tool form. Moreover, the tool imposes a static pressure ranging from 1N to some kilograms depending on the size of the tool tip, see Fig. 1. This static pressure is necessary to sustain the tool feed during machining. Owing to the fact that the tool oscillates and moves axially, USM is not limited to the production of circular holes. The tool can be made to the shape required, and hence extremely complicated shapes can be produced in hard materials. Beside machining domain, US techniques are applied in nondestructive testing (NDT), welding, and surface cleaning, as well as diagnostic and medical applications.

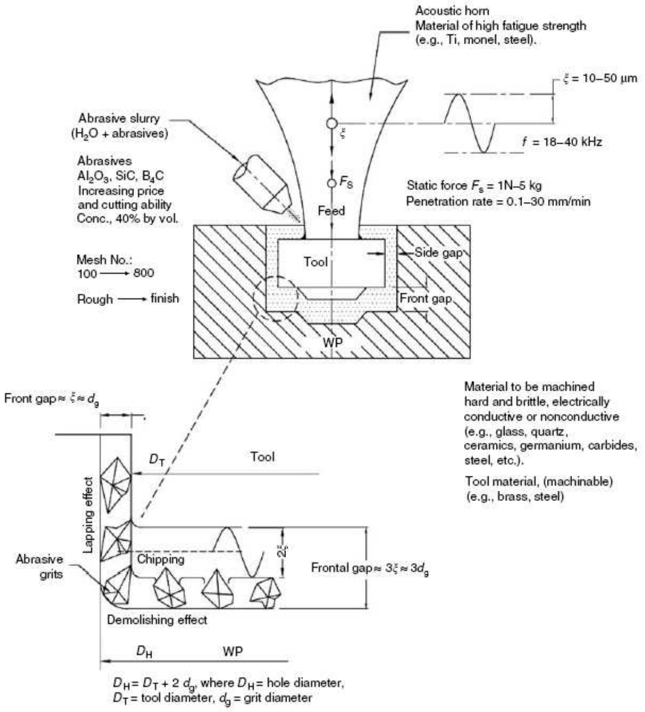

Figure 1. Characteristics of the USM process [1]

2.1. Elements of process

The USM equipment shown in Fig. 2 has a table capable of orthogonal displacement in X and Y directions, and a tool spindle and carrying the oscillating system moving in direction Z

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perpendicular to the X-Y plane. The machine is equipped with a HF generator of a rating power of 600 W, and a two-channel recording facility to monitor important machining variables (tool displacement Z and oscillation amplitude ξ). A centrifugal pump is used to supplement the abrasive slurry into the working zone. Fig. 3 shows schematically the main elements of the equipment, which consist of the oscillating system, the tool feeding mechanism, and the slurry system.

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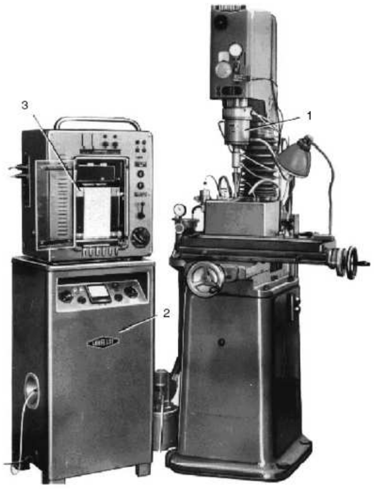

Figure 2. USM equipment [1]

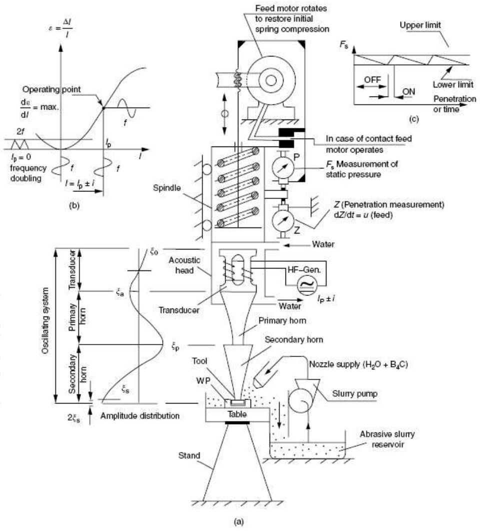

Figure 3. The schematic of complete vertical USM equipment [1]

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2.1.1. Oscillating system and magnetostriction effect

The core element of each US machine, the oscillating system, includes a transducer in the acoustic head, a primary horn, and a secondary acoustic horn (see Fig. 4).

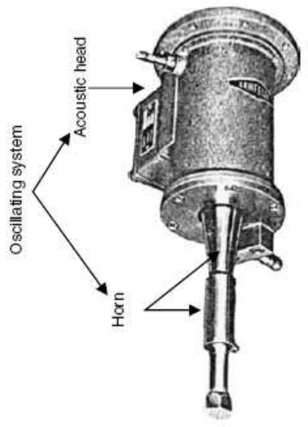

Figure 4. The oscillating system of USM equipment [1]

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2.1.2. Acoustic transducer

This transforms electrical energy to mechanical energy in the form of oscillations. Magnetostrictive transducers are generally employed in USM, but piezoelectric ones may also be used.

The magnetostriction effect was first discovered by Joule in 1874. According to this effect, in the presence of an applied magnetic field, ferromagnetic metals and alloys change in length. The deformation can be positive or negative, depending on the ferromagnetic material. An electric signal of US-frequency f_r is fed in to a coil that is wrapped around a stack made of magnetostrictive material (iron-nickel alloy). This stack is made of laminates to minimize eddy current and hysteresis losses; moreover, it must be cooled to dissipate the generated heat (Fig. 3a). The alternating magnetic field produced by the HF-ac generator causes the stack to expand and contract at the same frequency.

To achieve the maximum magnetostriction effect, the HF-ac current i must be superimposed on an appropriate dc premagnetizing current I_p that must be exactly adjusted to attain an optimum or working point. This point corresponds to the inflection point ($d^2\varepsilon/dl^2=0$) of the magnetostriction curve, (Fig 3b). Without the application of premagnetizing direct current I_p, it is evident that the magnetostriction effect occurs in the same direction for a given ferromagnetic material irrespective of the field polarity, and hence the deformation will vary at twice the frequency $2f_r$ of the oscillating current providing the magnetic field (Fig. 3b). Therefore, the premagnetizing direct current I_p has the following functions:

- When precisely adjusted, it provides the maximum magnetostriction effect (maximum oscillating amplitude)
- It prevents the frequency doubling phenomenon

If the frequency of the ac signal, and hence that of the magnetic field, is tuned to be the same as the natural frequency of the transducer (and the whole oscillating system), so that it will be at mechanical resonance, then the resulting oscillation amplitude becomes quite large and the exciting power attains its maximum value.

2.1.3. Transducer length

The resonance condition is realized if the transducer length is l, which is equal to half of the wave length, λ (or positive integer number n of it).

Therefore,

$$l = \frac{n}{2}\lambda = \frac{\lambda}{2}, \; if \;\; n = 1$$

and

$$\lambda = \frac{c}{f_r} = \frac{1}{f_r}\sqrt{\frac{E}{\rho}}$$

where

c = acoustic speed in magnetostrictive materials (m/s)

f_r = resonant frequency (1/s)

E, ρ = Young's modulus (MPa) and density (kg/m^3) of the magnetostrictive material

Hence,

$$l = \frac{c}{2f_r} = \frac{1}{2f_r}\sqrt{\frac{E}{\rho}}$$

2.1.4. Piezoelectric transducers

A main drawback of magnetostriction transducers is the high power loss (η = 55%). The power loss is converted into heat, which necessitates the cooling of the transducer. In contrast, piezoelectric transducers are more efficient (η = 90%), even at higher frequencies (f = 25-40 KHz). Piezoelectric transducers utilize crystals like quartz and lead titanate-zirconate that undergoe dimensional changes proportional to the voltage applied. Similar to magnetostrictors, the length of crystal should be equal to half the wavelength of the sound in the crystal to produce resonant condition. At a frequency of 40 KHz, the resonant length l of the quartz crystal ($E = 5.2 \times 10^4$ MPa, $\varrho = 2.6 \times 10^3$ kg/m^3) is equal to 57 mm. Sometimes a polycrystalline ceramic like barium titanate is used.

Piezoelectric transformers were first introduced into modern ultrasonic machines in the late 1960s. In 1970, Tyrrell [3] has described such a system. In essence, piezoelectric transducers are composed of small particles bound together by sintering; undergoing polarization by heating above the Curie point and placing it in an electric field such that orientation is preserved on cooling. A disc of the piezoelectric material which has a very high electromechanical conversion rating is sandwiched between two thick metal plates to form the ultrasonic horn. When a current of fixed frequency is fed to the horn the whole system is found to vibrate at some resonant frequency along the longitudinal axis; acoustically the motion is equal to one half a wavelength.

2.2. The advantages and disadvantages of USM process [4, 5]

Advantages

Some of the special priorities can be mentioned as follow:

- Intricate and complex shapes and cavities in both electric and nonelectric materials can be readily machined ultrasonically
- As the tool exhibits no rotational movement, the process is not limited to produce circular holes
- High dimensional accuracy and surface quality
- Especially, in the sector of electrically nonconductive materials, the USM process is not in competition with other nontraditional machining processes regarding accuracy and removal rates
- Since there is no temperature rise of the WP, no changes in physical properties or microstructure whatsoever can be expected

However, the USM process has some disadvantages listing below.

Disadvantages:

- The USM is not capable of machining holes and cavities with a lateral extension of more than 25-30 mm with a limited depth of cut
- The tool suffers excessive frontal and side wear when machining conductive materials such as steels and carbides. The side wear destroys the accuracy of holes and cavities, leading to a considerable conicity error.
- Every job needs a special high-cost tool, which adds to the machining cost
- High rate of power consumption
- In case of blind holes, the designer should not allow sharp corners, because these cannot be produced by the USM.

2.3. The applications of USM

It should be understood that the USM is generally applied to machining shallow cavities and forms in hard and brittle materials having a surface area not more than 10 cm^2. Some typical applications of USM are as follow:

- Manufacturing forming dies in hardened steel and sintered carbides
- Manufacturing wire drawing dies, cutting nozzles for jet machining applications in sapphire, and sintered carbides
- Slicing hard brittle materials such as glass, ceramics, and carbides
- Coining and engraving applications

- Boring, sinking, blanking,, and trepanning
- Thread cutting in ceramics by rotating the tool or the WP

Figure 5 illustrates some of the products produced ultrasonically.

a. Engraving a medal made of agate

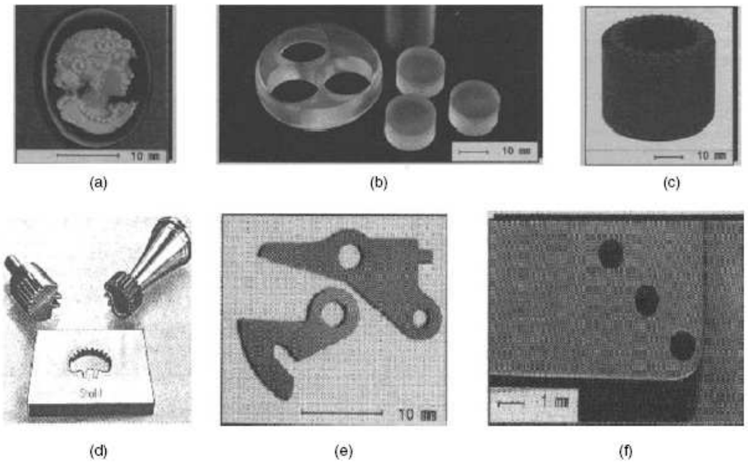
b. Piercing and blanking of glass

c. Producing a fragile graphite electrode for EDM

d. Sinking a shearing die in hardened steel or WC

e. Production of outside contour and holes of master cutters made of zirconium oxide (ZrO_2) of a textile machine

f. Drilling fine holes Φ = 0.4 mm in glass



(a) (b) (c)

(d) (e) (f)

Figure 5. Some typical products by USM [1]

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3. Dynamometry in conventional machining processes

During machining, the cutting tool exerts a force on the WP as it removes the machining allowance in the form of chips. Empirical values for estimating the cutting forces are no longer sufficient to reliably establish the optimum machining conditions. Depth of cut, feed rate, cutting speed, WP materials, tool material and geometry, and cutting fluid are just a few of the machining parameters governing the amplitude and direction of the cutting force.

The optimization of a machining process necessitates accurate measurement of the cutting force by a special device called a machine tool dynamometer, capable of measuring the components of the cutting force in a given coordinate system. It is a useful and powerful tool employed in a variety of applications in engineering research and manufacturing. A few examples of these applications are [1]:

- Investigating into the machinability of materials
- Comparing similar materials from different sources
- Comparing and selecting cutting tools
- Determining optimum machining conditions
- Analyzing causes of tool failure
- Investigating the most suitable cutting fluids
- Determining the conditions that yield the best surface quality
- Establishing the effect og fluctuating cutting forces on tool wear and tool life

The machine tool dynamometer is not standard equipment or a device that can be used on every machine. Rather, it is equipment especially designed to fulfill some desired requirements that adapt a specific machine type operating at a specific range of machining conditions.

3.1. Piezoelectric (Quartz) dynamometers

Of the numerous piezoelectric materials, quartz is by far the most suitable one for force measurement, because it is stable material with constant properties. In its crystalline form, quartz is anisotropic, in that its material properties are not identical in all directions. Depending on the position in which they are cut out of the crystal, disks are obtained that are:

1. Sensitive only to pressure (longitudinal effect), Fig. 6a, which measure the main force component F_z (brown)
2. Sensitive only to shear in one particular direction (shear effect), Fig. 6b, which measures components F_x (blue) and F_y (green), perpendicular to F_z, as well as the torque M_z (red). Figure 6c illustrates the generalized multi-components with reference to a Cartesian coordinate system.

The piezoelectric force measuring principle differs fundamentally from their old traditional counterparts, the strain and displacement based dynamometers, in that it is an active system. When a force acts on a quartz element, a proportional electric charge appears on the loaded surfaces, meaning that it is not necessary to measure the actual deformation.

In piezoelectric dynamometers, the deflection is not more than a few micrometers at full load, whereas with conventional systems, several tenths of a millimeter may be needed. Thus, piezoelectric dynamometers are very stiff systems and their resonant frequency is high, so that even rapid events can be measured satisfactorily. Moreover, the individual components of the cutting force can be measured directly, eliminating any interference between measuring channels. Quartz dynamometers require no zero adjustment or balancing of the bridge circuit. It is just a matter of pressing a button, being ready for duty. The outstanding features of quartz dynamometers are [1, 6]:

- High rigidity, hence high resonant frequency

- Minimal deflections (few micrometers at full load)
- Wide measuring range
- Linear characteristics, free of hysteresis
- Lowest cross talk (typically under 1%)
- Simple in operation and without need for bridge balancing
- Compact design
- Unlimited life expectancy

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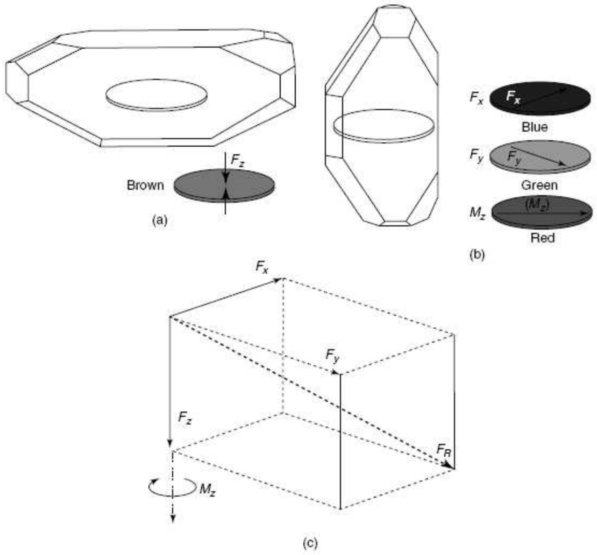

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Figure 6. Disks of quartz crystals. (a) Pressure-sensitive, (b) shear-sensitive, (c) multi-components in reference to a Cartesian coordinate system [6]

3.2. Typical piezoelectric dynamometers

Piezoelectric dynamometers are efficiently used on the majority of machine tools. Three application examples are described below with their corresponding setup.

1. *Two-component piezoelectric drilling dynamometers.*Figure 7 illustrates a two-component drilling dynamometer in which shear-sensitive discs are organized in a circle with their shear-sensitive axes oriented to respond to the torque M_z (red), whereas pressure-sensitive disks are arranged and oriented to measure the trust load F_z (brown). A high

preload is necessary because the shear forces must be transmitted by friction to measure the torque.

The two-component dynamometer, shown in Fig. 7, is suited for operations including drilling, thread cutting, countersinking, reaming, and so on. Torques and forces acting when machining holes from less than 1 mm to over 20 mm diameter can be measured satisfactorily by this dynamometer. A record of M_z and F_z is illustrated in Fig. 7, from which it is clearly seen that F_z rises steeply at the beginning (entry of tool chisel), followed by the gradual rise of the M_z component, as the latter is more affected by the force acting on the two drill lips.

2. *Three-component piezoelectric turning dynamometer.* This model includes several shear-sensitive quartz, with their shear-sensitive axes oriented to measure F_x (blue ring) and F_y (green ring), respectively. Their shear sensitive-axes are inclined to each other at an angle of 90^0, and both are contained in a housing to form a two-component force measurement element for F_x and F_y (Figure 8). Pressure-sensitive quartz disks are contained in a single housing to form a single-component force-measuring element for F_z (brown ring). Another alternative is illustrated in the construction shown in Figure 8, where three separate elements for measuring F_x, F_y, and F_z are sandwiched under high preload between a base plate and a top plate. The dynamometer is mounted on the lathe slide in place of a cross-slide. A record of the three components is shown also in the same figure, from which it is clear that F_x=F_y, meaning that the cut is preferred at an approach angle χ=45^0.
3. *Three-component piezoelectric milling or grinding dynamometer.* Whole quartz rings may be employed. Two-shear-sensitive quartz pairs, for F_x (blue) and F_y (green), and a pressure-sensitive pair for F_z (brown), can be assembled in a common housing to form a three-component force-measuring element (Figure 9). The pressure-sensitive quartz are arranged in the middle so that they lie in the neutral axis under bending. During milling and grinding, the application point of the force varies a great deal. Consequently, dynamometers having four piece three-component force-measuring elements are employed. All the x, y, and z channels respectively are paralleled electrically. This makes the measurement independent of the momentary force application point. For bigger work, two dynamometers paralleled electrically and mechanically may be employed together. This system measures correctly independent of the point of force application. A typical output of the three-component milling dynamometer is shown in Fig. 9. The milling process has been performed under the following conditions:

- Status: Up milling
- Cutter diameter = 63 mm, helix $\beta = 30^0$, n = 90 rpm, Z = 12 teeth
- Feed u = 53 mm/min
- Depth of cut t = 3.5 mm

The severe periodic fluctuation in the measured forces is attributed to an eccentric motion of the cutter shaft. Superimposed are vibrations due to gearing of the machine. It is perfectly clear from the record that the setup shown is far from ideal. The force measure, therefore, sheds light on the machine tool behavior as well, and not just on the actual cutting operation.

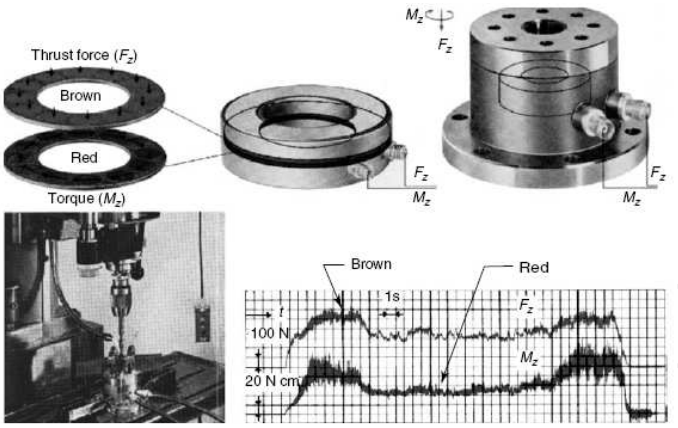

Figure 7. Two-component piezo drilling dynamometer [6]

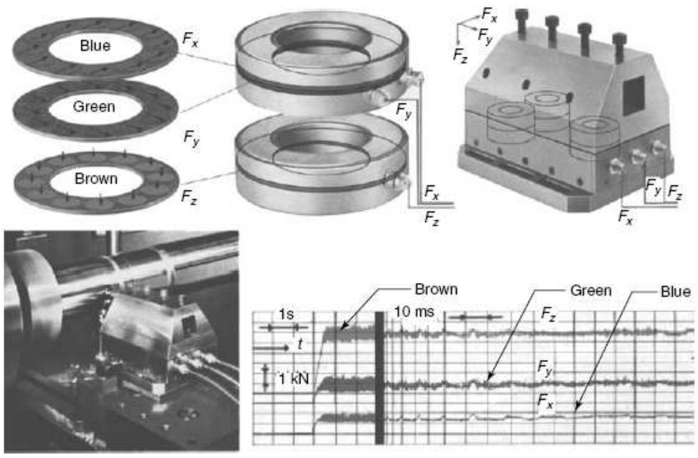

Figure 8. Three-component piezo turning dynamometer [6]

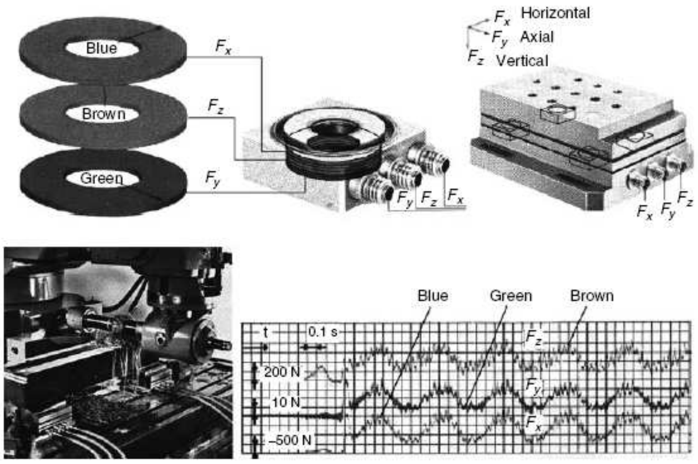

Figure 9. Three-component piezo milling dynamometer [6]

4. Conclusion

In this chapter, attempt has been made to cover the basic details of utilizing piezoelectric materials in two different fields of machining processes. The first focused on the effectiveness of a piezoelectric transducer in producing ultrasonic waves as a cutting tool in ultrasonic machining processes. Compared to their old magnetostriction counterparts, the piezo ones demonstrate higher electro-mechanical efficiency. Besides, they are more compact as well as being simpler in design and operation. The second emphasizes the unique suitability of piezoelectric dynamometers in measuring various components of forces and torques generated during different kinds of conventional machining processes. The importance of measuring forces and torques in an on-line manner during every traditional machining operation for the purposes of modeling and optimization makes the use of a precise piezoelectric dynamometer an inseparable part in manufacturing industries as well as academic domains.

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