Fig. 1: Machining processes can be monitored accurately with special sensors. However, the level of detail for the data depends on the specific application and the measuring principle that is used.



## A comparison of piezoelectric sensors and strain gauges

# The right technology to monitor machining processes

**There are many application areas where a close watch needs to be kept on machining processes. Special sensors that measure the forces during the machining process have long played an essential part in research and development work on cutting tools. And as Industry 4.0 becomes a reality, this technology is now making inroads into the manufacturing process itself. Sensors that can be installed directly in the machine supply the data needed to adjust the process parameters with utmost precision. Sensors may often appear to be very similar to one another, but there can be fundamental differences in the technology that makes them function. Over the last ten years, two different technologies have become established for the sensory tool holders used in the standard interfaces of machine tool spindles. Making the right choice between these measurement systems ultimately depends on knowing the differences and understanding which measuring principle is suitable for each application.**

More accurate, more stable, faster and more efficient: users want to see their processes improving all the time – so there is growing demand for reliable data as the basis for assessing the processes. Tool design and development, machining strategy and choice of parameters are the aspects where this potential for improvement can generally be found. Cutting force is one suitable measurand that can be used to assess these influencing factors and optimize processes. It provides information about whether a process is running stably. Appropriate and specially designed sensor technology can be used to measure cutting forces. Two different technologies are used in sensory tool holders, and both of them can be expected to deliver accurate results: piezoelectric technology has been established for several decades as a measurement method for use in machining processes, whereas sensor technology based on strain gauges has only begun to gain ground here in the last few years. Both systems supply data about the forces and moments acting on the tools, but their operating principles are fundamentally different.

**A crystal provides insights into cutting forces**
The centerpiece of a piezoelectric sensor is a special quartz crystal. When a force acts on the rather ordinary-looking crystal disk, it generates an electrical charge that is directly related to the force. A charge amplifier can be used to convert these charges into measurable signals as the basis for obtaining accurate data. The advantage of quartz is its enormous rigidity, which gives it a very high natural frequency. This allows highly dynamic processes to be captured in the quasi-linear range of the measuring system. The result is that measured values from different frequency ranges (due to different tooth passing frequencies, for example) can also be compared with one another. Because the quartz crystals are installed in the force flux of the tool holder, the forces can be measured directly in the three directions – x, y and z – and the torque (Mz) can also be measured directly. Another advantage is electronic adjustment of the measurement ranges, which can be set individually depending on the particular measuring task. All these features mean that this sensor technology is very flexible, and it can be used without increased background noise caused by the electronics.

**Measuring force via strain: strain gauges**

An alternative to the use of quartz in sensory tool holders has been available for about ten years: this is the strain gauge, which uses the deformation of the tool holder to obtain measurements. We can imagine it like this: every force that acts on a tool's cutting edge produces minimal deformations in the tool and the holder. These deformations can be measured by strain gauges affixed to the tool holder's surface. In this case, the operating principle is based on measuring the resistance of conductor paths that change their resistivity due to extension and deflection. Unlike a quartz, which has to be installed in the force flux, these sensors are relatively easy to mount on the surface of the tool holders; their pricing is also substantially lower than the acquisition costs for quartz-based measuring equipment. However, the position where the strain gauge is installed results in another major difference regarding measurements in the x and y directions: the deflection of the tool holder measured by strain gauges is not directly dependent on the forces, but on the bending moments. To draw conclusions about the forces in these directions, the user must therefore have exact knowledge of the distance between the center of pressure (COP) and the point where the strain is measured. To determine the absolute forces, or to compare measurements with different tool lengths, this distance must be taken into account in the evaluation. Another drawback is that the measuring range is determined on the basis of the tool holder's specific elasticity, and it cannot be changed. Also, the rigidity – and, consequently, the natural frequency – of a system of this sort is lower due to the strain-based measurement principle. This means that measurement signals in the higher-frequency measuring range tend not to be shown with the correct scaling, and details in the signal may be filtered out unintentionally.

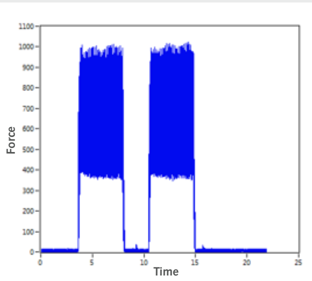
**Comparative testing of piezo sensors and strain gauges**

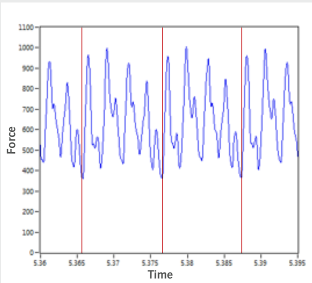
Testing under real practical conditions can identify the precise strengths and weaknesses of the two systems. Both of them are used to determine the forces acting during a milling process. The tests are carried out using a tool with a diameter of ten millimeters on the one hand, and with a six-millimeter milling cutter on the other. The charts show the results in each case, so differences in measurement can be seen directly.

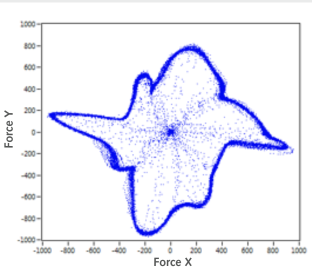
**Measurement results**

**Tool Ø 6/z = 4 – vc 175 – fz 0.03 – ap 6 – ae 3**

## XY-forces/piezo

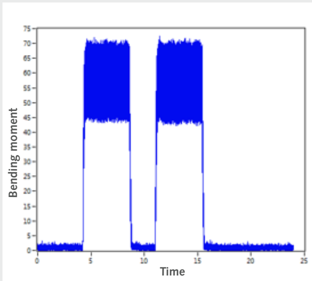


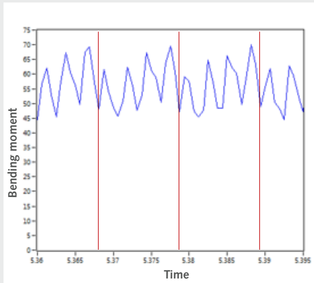



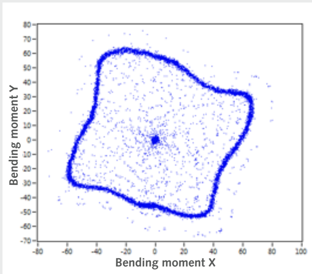




- Graph with clear signal
- Individual tool rotations (marked in red) are easily recognizable, high level of detail
- Polar plot shows clear results

## Bending moment/strain gauge




- Graph with clear signal
- Individual tool rotations (marked in red) are easily recognizable, reduced level of detail
- Polar plot shows clear results

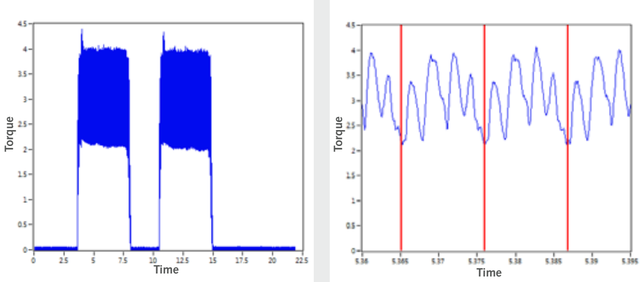
Fig. 2: Comparative values for the action of forces in the x/y directions and bending moment, with a tool diameter of 10 mm

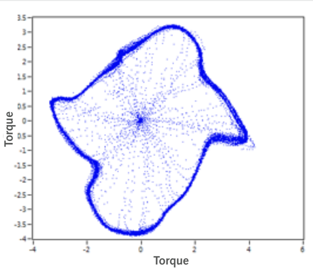
Both systems perform best in the comparison of measurements in the x and y directions with a tool diameter of ten millimeters (Figure 2). Due to the higher sampling rate, the data from the piezoelectric sensor is more accurate in detail, but both systems provide a reliable presentation of the process profile. The individual rotations of the tool (marked with red lines) can be reproduced in both cases.

## Measurement results

**Tool Ø 6/z = 4 – vc 175 – fz 0.03 – ap 6 – ae 3**

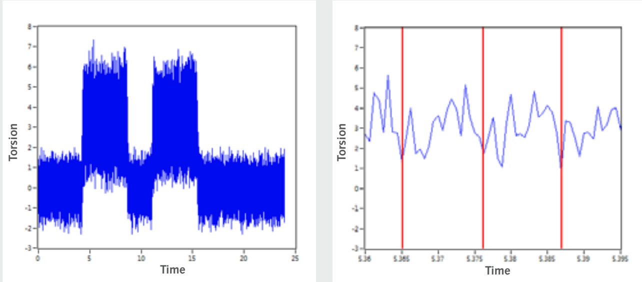
### Torque Mz/piezo

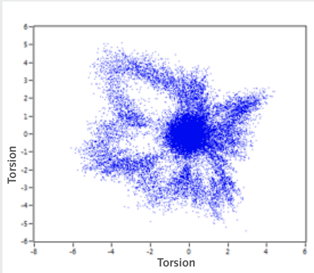



- Graph with clear signal
- Individual tool rotations (marked in red) are easily recognizable, high level of detail
- Polar plot shows clear results

### Torque Mz/strain gauge




- High noise level
- Individual tool rotations (marked in red) are not easily recognizable, lower level of detail
- Polar plot is unusable

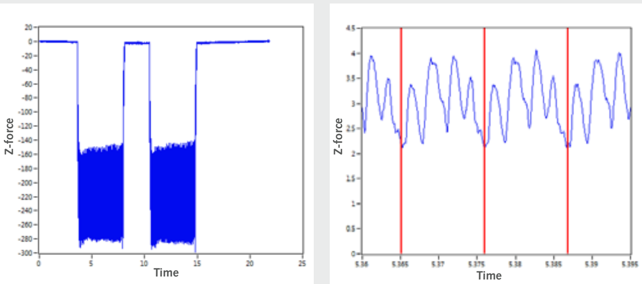
Fig. 3: Comparative values from the torque measurement with a tool diameter of 10 mm

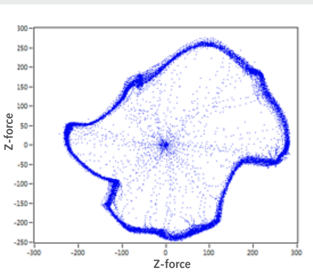
When it comes to torque, however, the weaknesses of strain gauge technology become apparent (Figure 3). The piezoelectric measurement still shows a clearly reproducible pattern for each rotation of the tool, but no further details are recognizable with the strain gauge technology. The sampling rate and signal strength are too low to obtain a reproducible pattern. The signal from the strain gauge sensor has to be greatly amplified because the low forces only have a very small effect on the torsion of the tool. However, this results in substantial noise and a significant loss of measurement accuracy. As opposed to the measurements with quartz sensor technology, it is no longer possible to distinguish the individual rotations of the tool with the strain gauge method.

## Measurement results

**Tool Ø 6/z = 4 – vc 175 – fz 0.03 – ap 6 – ae 3**

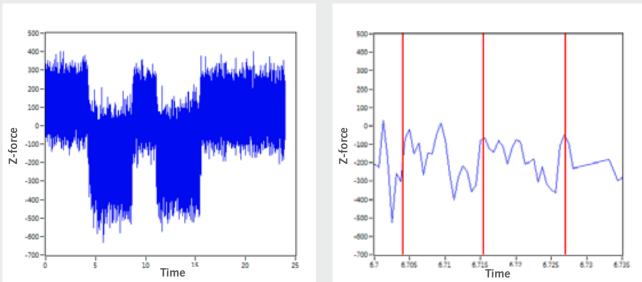
### Z-force/piezo

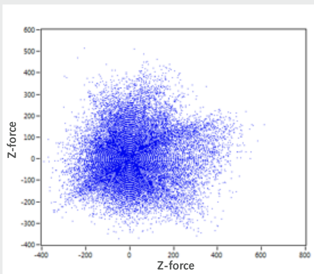



- Graph with clear signal
- Individual tool rotations (marked in red) are easily recognizable, many details are recognizable
- Polar plot shows clear results

### Z-force/strain gauge




- High noise level
- Individual tool rotations (marked in red) are not recognizable, no details recognizable
- Polar plot is unusable

Fig. 4: Comparative values for the action of forces in the z direction with a tool diameter of 10 mm



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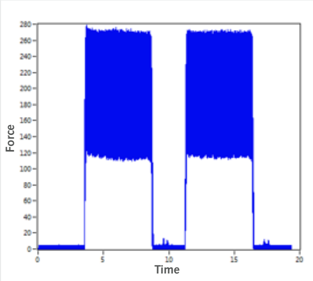
The measurement results for the z-force are equally unflattering to the cheaper sensor (Figure 4). The quartz generates a distinct signal with clearly reproducible forces for the individual rotations of the tool, but the data from the strain gauge sensors is lost amid the interference signals. We can see this problem very clearly if we look at the polar coordinates: all that now remains of the signal is a point cloud.

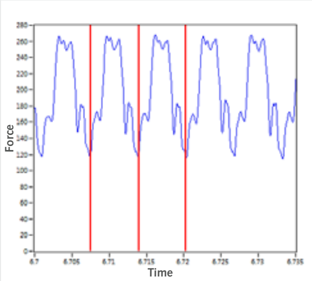
As the size of the tool decreases, the advantages of piezoelectric measurement technology stand out even more. The differences in quality for measurements with a six-millimeter tool are striking (Figures 5-7). The quality of measurements from the piezoelectronic sensor remain unchanged even with a tool diameter of six millimeters, whereas the weaknesses of the strain gauge regarding torque and z-force are even more clearly visible with the smaller milling cutter.

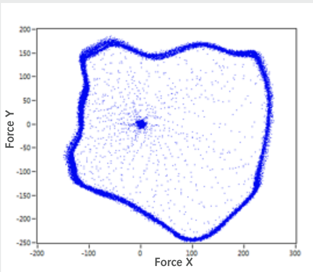
**Measurement results**

**Tool Ø 6/z = 4 – vc 175 – fz 0.03 – ap 6 – ae 1.5**

## XY-forces/piezo

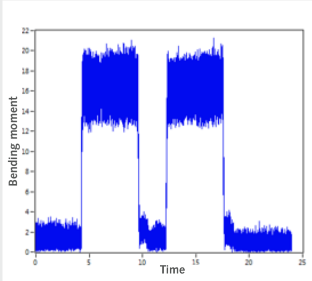


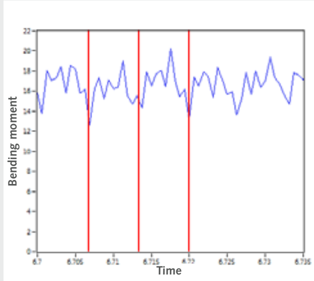



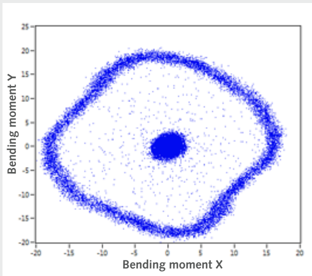




- Clear signal in graph
- Individual tool rotations (marked in red) are easily recognizable with many details
- Polar plot shows clear results

## Bending moment/strain gauge



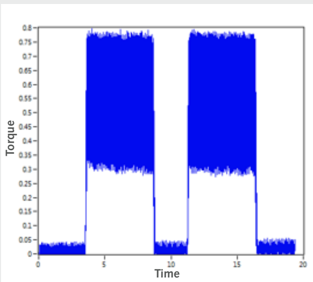

- Clear signal in graph
- Individual tool rotations (marked in red) are recognizable, lower level of detail
- Results in polar plot are recognizable, but the low flexibility of the bandwith acts like a low-pass filter

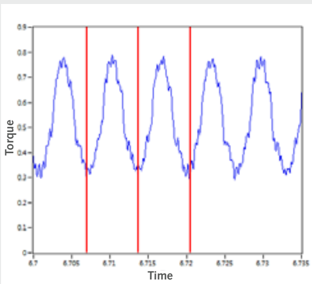
Fig. 5: Comparative values for the action of forces in the x/y directions and bending moment, with a tool diameter of 6 mm

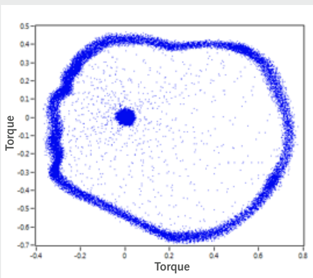
**Measurement results**

**Tool Ø 6/z = 4 – vc 175 – fz 0.03 – ap 6 – ae 1.5**

## Torque Mz/piezo

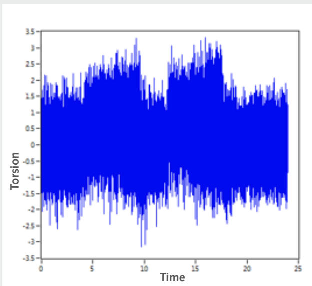


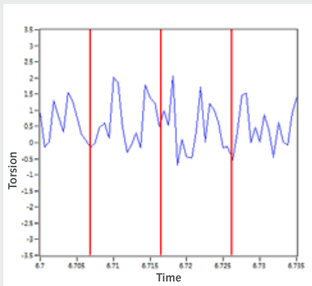



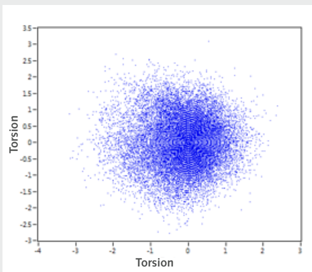




- Clear signal in graph
- Individual tool rotations (marked in red) are easily recognizable with many details
- Polar plot shows clear results

## Torque Mz/strain gauge



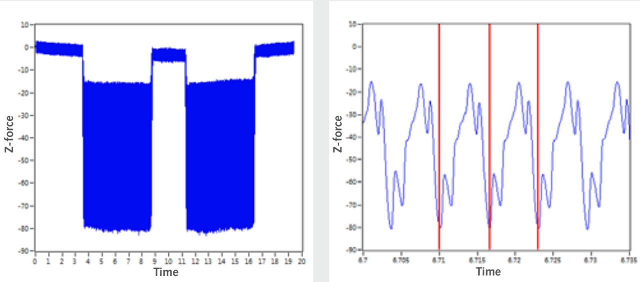

- High noise level – graph is unusable
- Individual tool rotations (marked in red) are not recognizable
- Polar plot is unusable

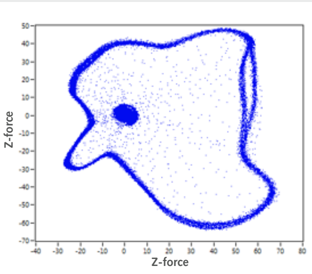
Fig. 6: Comparative values from the torque measurement with a tool diameter of 6 mm

## Measurement results

**Tool Ø 6/z = 4 – vc 175 – fz 0.03 – ap 6 – ae 1.5**

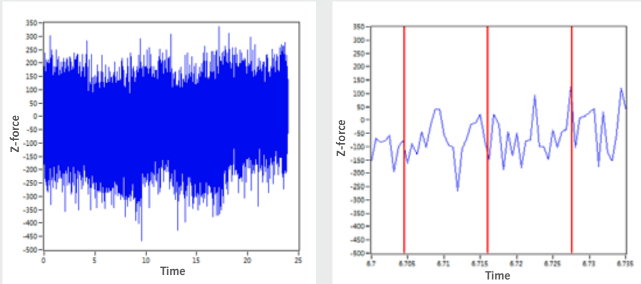
### Z-force/piezo

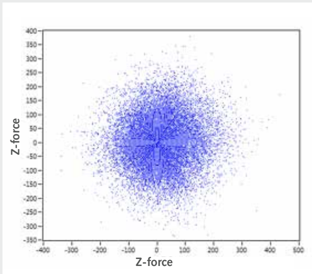



- Clear signal in graph
- Individual tool rotations (marked in red) are easily recognizable with many details
- Polar plot shows clear results

### Z-force/strain gauge




- High noise level, graph is not usable
- Individual tool rotations (marked in red) are not recognizable
- Polar plot is unusable

Fig. 7: Comparative values for the action of forces in the z direction with a tool diameter of 6 mm

**Piezoelectric sensor: definitely the front runner**

When large tools are used, both systems are perfectly suitable for measuring forces in the x/y directions. But strain gauges reach their technical performance limits on measurements of torque and z-force. The lower sampling rate and the high level of background noise after the necessary amplification make their results virtually unusable in these cases. If deformation is the only parameter measured, the measurement characteristics are – to a certain extent – defined by the tool itself. The smaller the tool, the more inaccurate the measurement will be: this is because the surface strains on the tool holder are correspondingly low, and high amplification is required.

In the case of the piezoelectric sensor, sensitivity depends solely on the electronic characteristics – and these can be adjusted via software. But since the quartz reacts sensitively even to very small forces, measurements of torque and z-force present no problems. For all measurement tasks where a high level of detail is essential, the piezoelectric measurement principle is also advisable because its high sampling rate provides precise information about the smallest changes. The force that the cutting edge exerts on the workpiece at different moments is easily recognizable in the graphic presentations. To conclude: the piezoelectric sensor is still the solution of first choice for all users who perform complex and challenging measurements, and for those who prefer a flexible range of applications.



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