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Embedded sensors in cutting tools, a state of art review

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The usage of sensor-based technology in the turning cutting process is a relatively unexplored area of improving the machining process. Most of the found examples have been done in research and only a few examples of sensor technology can be found in the industry. This thesis reviews six different kinds of embedded sensors for cutting tools studied in research and discusses some possibilities and disadvantages of them. The used sources in this thesis are scientific articles, research papers and books.

An adaptive feedback system is also defined, and examples are presented. The possible advantages of using sensors and adaptive feedback systems are explored and results are presented from example studies. Using these technologies showed good potential for future use. The benefits of this technology are presented, and problems with transferring older machines into this new technology and future ideas are also discussed.

Sensoripohjaisen teknologian käyttö sorvaamisprosessissa on suhteellisen vähän tutkittu aihealue prosessin parantamiseksi. Useimmat esimerkit on tehty tutkimuspohjaisessa työssä ja ainoastaan muutama esimerkki sensoriteknologiasta löytyy teollisuudesta. Tämä tutkielma käy läpi kuusi erilaista leikkaustyökaluun upotettua sensoria, joista on tehty tutkimuksia, jonka jälkeen niiden mahdollisuuksista ja haittapuolista keskustellaan. Tässä tutkielmassa käytetyt lähteet ovat tieteellisiä artikkeleita, tutkimuspapereita ja kirjoja.

Adaptiivinen takaisinkytkentäjärjestelmä määritetään myös, ja siitä annetaan esimerkkejä. Sensoreiden ja adaptiivisten takaisinkytkentäjärjestelmien käytön mahdollisuuksia tutkitaan, ja tuloksia esitetään tehtyihin tutkimuksiin perustuen. Näiden teknologioiden hyödyntäminen osoitti hyvää potentiaalia tulevaisuuden käytölle. Tämän teknologian hyödyt esitellään, ja uuden teknologian sovittamisesta vanhoihin laitteisiin sekä tulevaisuuden ideoista keskustellaan.

Key words: adaptive feedback system, embedded sensors, cutting tools.

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1 Introduction

1.1 Brief introduction to machining and cutting tools

Machining is the process of removing materials using a machine, equipped with different kinds of tools. Over the years, machining has evolved from hand-operated machines, to Computer Numerical Controlled (CNC) -machines. There are multiple types of CNC machines, including turning, drilling, and milling machines. This thesis focuses on the possibilities to improve the turning process, by implementing embedded sensors into cutting tools. Turning is done by using lathes, where material is removed by holding the work piece in the lathe’s chuck and then rotated. The material is removed by using a cutting tool held by a tool post and moved against the workpiece. [1]

Cutting tools are divided into plenty of categories. In this thesis they are all grouped together as just cutting tools, because case by case it doesn’t affect the premise. Some examples are roughing, and finishing tools.[2] These tools also have a lot of variances, coming in different shapes and sizes, and a basic introduction will be presented. The tools are chosen depending on the needs of manufacturing. Some of the biggest contributors to choosing a cutting tool are the type of production at hand, specified needs like roughness, precision and size of work piece, and the machine used [3]. The wearing down of cutting tools known as tool wear, and the tool wear rate are constantly kept in mind when choosing cutting tools. Some crucial reasons for tool wear are cutting speed, temperature and feed rate , however only higher feeds tend to create unwanted vibrations [4]. Tool wear is important to mention, because it has an effect on the quality on the surface of the finished product [5]. Temperature has also been proven to affect a machine tools efficiency [6]. These could all be potentially monitored by receiving signals from embedded sensors.

The machining process can be monitored and controlled with certain kinds of feedback systems. These feedback systems use the signals picked up by sensors and adjust the machines accordingly. In chapter 4, different kinds of feedback systems will be presented, and their possibilities will be expanded on.

AI was used in this thesis for the following reasons: coming up with ideas for the table of contents, creating useful questions about topics to help with searching, and searching through longer articles.

1.2 Foreword about sensors

The interest in improving the machines performance and to lower the needed costs have appeared in the industry and in research. Both branches have shown interest in equipping cutting tools with embedded sensors to improve the machining process.[7] In this thesis there will be insert sensors and tool holder sensors. They are both an important part of a cutting tool, and their sensors have some differences in design. The sensor types will be case relative and expanded upon on case-by-case basis.

2 Cutting tools in the industry

There are countless amounts of cutting tools that are used in the industry today. They have different usages, different kinds of holders and overall, a lot of variances. In this chapter, the most important features of cutting tools are explained. Information is presented to give an understanding of these cutting tools and what type of things affect the cutting process.

2.1 Cutting tool parameters and geometries

When turning, the most important parameters used are cutting speed, feed rate and cutting depth. Cutting speed refers to speed of the spindle in the lathe, feed rate is the rate at which a tool is moved along the workpiece, and the cutting depth the thickness of a cut done along the workpiece. [8] In addition to cutting parameters, the placement and the shape of the cutting tool plays a role on how the cutting forces are distributed. Some of the most important geometries to consider are the nose radius, rake angle, flank (relief) angle, and the cutting-edge angle. The rake angle is between the rake face and a reference normal imagined against the workpiece, where the cutting tool meets it. The flank (relief) angle is the angle formed between the flank face of the tool, and the workpiece. The cutting-edge angle is the angle between the rake face and the workpiece, and the nose radius can be defined as the radius at the tip of the cutting tool. [9]

A model of a cutting tool on a workpiece can be seen in figure 1.

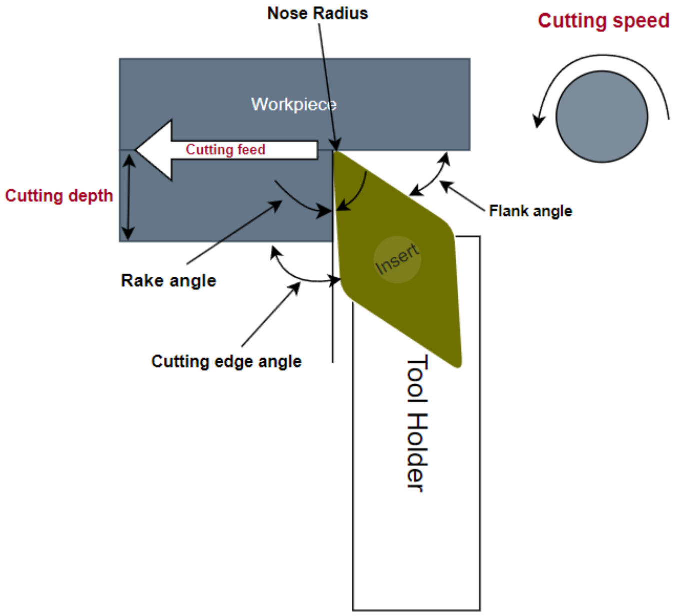

Figure 1 Model of geometries of a cutting tool on a workpiece

Cutting angles are important aspects to acknowledge, because of their effects on the cutting process. The cutting angle defines the width of the cut and the thickness of the chip, which correspondingly affects the tool life. A decrease in cutting angle widens the resulting chip and improves heat removal, resulting in increased tool life. However, this increases the bending force which can lower the accuracy of the process. The parameters of an uncut chip are very important to control, because they determine things like cutting force, plastic deformation, and acceptable feed. Cutting edge angle and flank angle also impact the surface finish of the product, which should be considered when choosing geometries. The rake angle has been shown to impact the magnitude of plastic deformation, although the effects are more noticeable at lower cutting speeds. [9]

The parameters feed rate, cutting speed and cutting depth have been shown to decrease the lifetime of a cutting tool. However, by reducing the nose radius, tool life can be increased. This comes with a downside. When nose radius is decreased, the tool is more sensitive to changes in the cutting parameters. Meaning that, if the conditions are not optimal all the time, the tool life will most likely decrease. [10] This is good to keep in mind when considering the adaptive feedback systems addressed later in this thesis, which could help keep these optimal cutting parameters throughout the process.

As the cutting itself is done by the cutting insert it’s a very important part of the cutting tool. However, the tool holder is just as important as the same cutting insert can have completely different angles, depending on the holder. This is why calculating proper parameters for cutting tools can sometimes be challenging, as both the insert and holder affect it a great amount. [9]

2.2 Cutting tool materials and coating

Materials used in cutting tools should resist deformation and be tough, have good thermal resistance and be chemically stable. Some of the most common used materials are diamond, ceramic, cemented carbide, high speed steel (HSS), and cermets. However, most of the cutting tools used in practice are made of HSS and cemented carbides. Let’s take cemented carbide as an example. The cutting tool can be either coated or uncoated, which changes some of the features of the material. Carbide tools are often used because of their hardness and resistance to wear. Many tools are often coated by using either Chemical Vapor Deposition

(CVD) or Physical Vapor Deposition (PVD). This is because coating a cutting tool gives it a longer tool life by reducing tool wear. [1]

PVD and CVD are the most common coating methods used for cutting inserts. When creating a PVD coating, the insert is put into a chamber and the material is evaporated. The vapor is made up of ions of the material in question. The coating is created when the vapor is deposited onto the substrate where it condenses to a physical form. Some advantages of PVD are allowing alloys, multilayering and specified structures of coatings. [11]

In CVD coatings the coating is created by using different gases. The inserts are placed into a chamber where gases are released. The chemical reaction in this kind of setup results in the formation of a coating on the inserts. CVD has the advantages of creating dense materials with good adhesion. [12]

2.3 A word about industry used cutting tools

With the knowledge of materials, geometries, and parameters, a choice for the right cutting tool can be made. Although interest in equipping cutting tools with sensors has been high, there aren’t many implementations available. Possibly the most notable implementation of some sort of technology inserted into a cutting tool is Sandvik Cormorant’s Silent Tools™. The Silent Tools are designed with a damping system implemented into the body of a cutting tool, and it supposedly results in gains in productivity, better surface finishing, and better security during the process. The damping system has a bigger mass surrounded by rubbery elements to absorb vibrations created during a cutting process. [13]

3 Cutting tools in research

In the field or research, there have been many experimentations with embedded sensors in cutting tools. This has given good insight into the possibilities they have, and what could be improved. In this thesis there are 2 main types of sensors, which are temperature and force sensors. This is because they are parameters that both affect the cutting process greatly and can be recorded with sensors embedded in cutting tools. This chapter is divided into sub-chapters, where different ways to measure these parameters will be shown and reviewed. A basic understanding of the structure of an embedded sensor, and the potentials of it will be shown. The sub-chapters follow the order shown in figure 2. Afterwards, these sensors will be grouped together in chapter 6 as table 1, where information and properties are listed for each sensor.

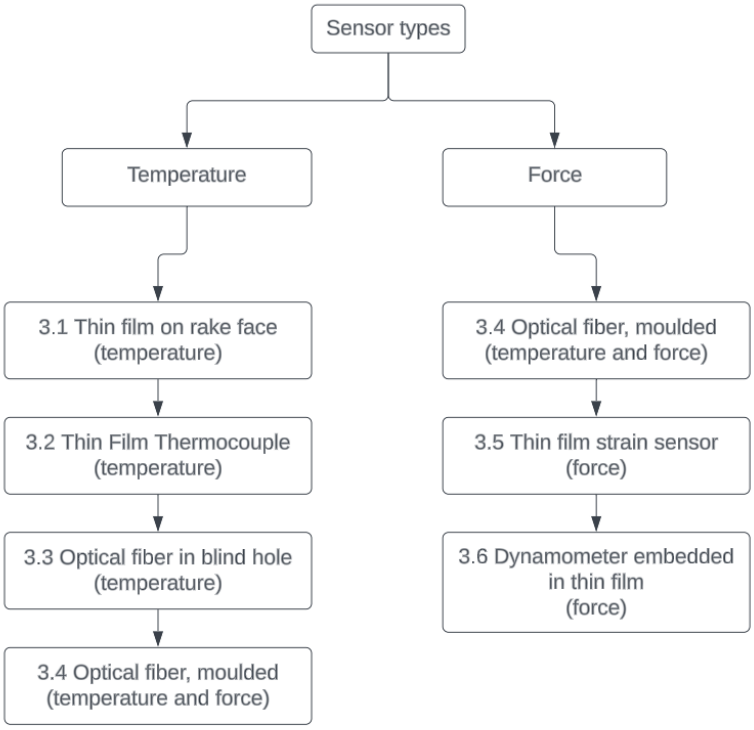

Figure 2 The order of sub-chapters for embedded sensors in thesis

Study environments differ from normal working environments as they are designed with a specific setup and goal in mind, so this should be kept in mind while looking at sensors used for research purposes. Sometimes the sensors are tested in more industry like settings, but this is not the case for most of the sensors.

It’s important to note that another common way of recording data during a machining process is by using so called machine embedded sensors. An example of this could be an audio sensor, like a microphone setup inside the machine [14]. These types of sensors could also be beneficial for the process, but in this thesis the focus is on sensors attached to the cutting tools so machine embedded sensors will be left out of the research.

3.1 Thin film sensor applied on rake face of cutting tool

A study done by Plogmeyer et al. (2021) [15] studied thin films embedded onto cutting tools, to measure temperatures during a cutting process. This experiment used thin films applied to the cutting tools rake face. The thin films are applied with protective layers of Al2O3 coating for insulation and temperature management. Two 20 µm sensors were placed next to each other with a 30 µm gap to implement four-terminal sensing, and the sensors measure their integral temperatures along their length. This allows for better resolution for the vertical measurement, but not for the horizontal. A picture of this applied thin film can be seen in figure 3.

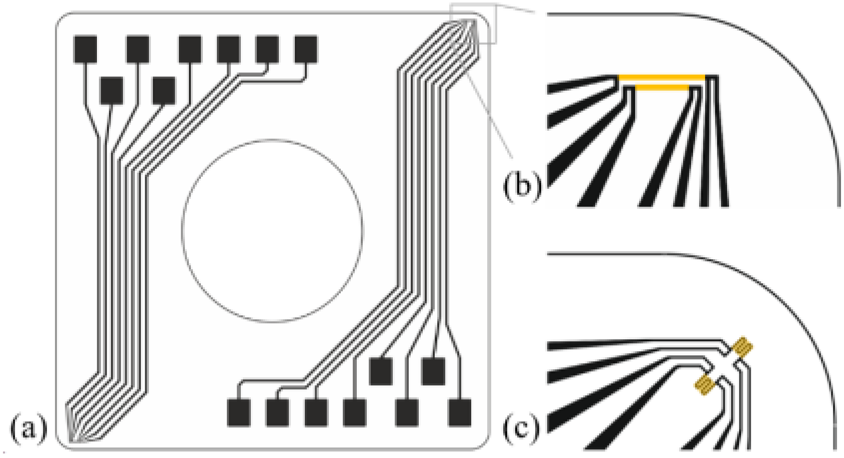

Figure 3 An applied thin film sensor on cutting tool insert [15]

For the measurements, the sensors were first calibrated to receive their thermoresistive characteristic, which can then be used to calculate temperatures during the process from measured resistances. However, there was a slight problem with recording temperature. The sensor is 800 µm away from the contact zone of the tool, and so the recorded temperatures don’t represent the actual temperature of the tool. It can be noted that the sensors were responding fast having a good repeatability of plus/minus 5%. The tool wear was recorded as recognizable. Although the sensors worked fine after the tests, tool wear caused interruptions for the conduction of the sensors which was noted from the signals. With a microscope, some separation into layers could already be noted at the cutting edge.

It was shown that thin films have good potential to be integrated into cutting tools because of their fast response times and good repeatability. However, more improvements would need to be made to measure temperature closer to the edge and have better durability.

3.2 Thin film Thermocouple sensor for temperature measurement

Li et al. (2019) [16] conducted a study experimenting with thin film thermocouples (TFTC) embedded into a commercial cutting insert (TPGN160304H13A, Sandvik), using a CTCPN2514M16, Kennametal tool holder. In this study, six TFTCs were implanted into the cutting insert, to collect data during a cutting process. The purpose of the experiment was to find an alternative to surface-mounted sensors previously used, because of their sensitiveness to higher temperatures and higher stresses.

A TFTC is a pairing of chromel and alumel combined in a groove and coated with different layers of thin film, forming a hot junction at the crossing in the groove. In the study these TFTCs were implanted vertically on the cutting edge towards the rake face. Wires were attached to the TFTCs to collect the received force data.[16] A picture of this embedded sensor is shown in figure 4.

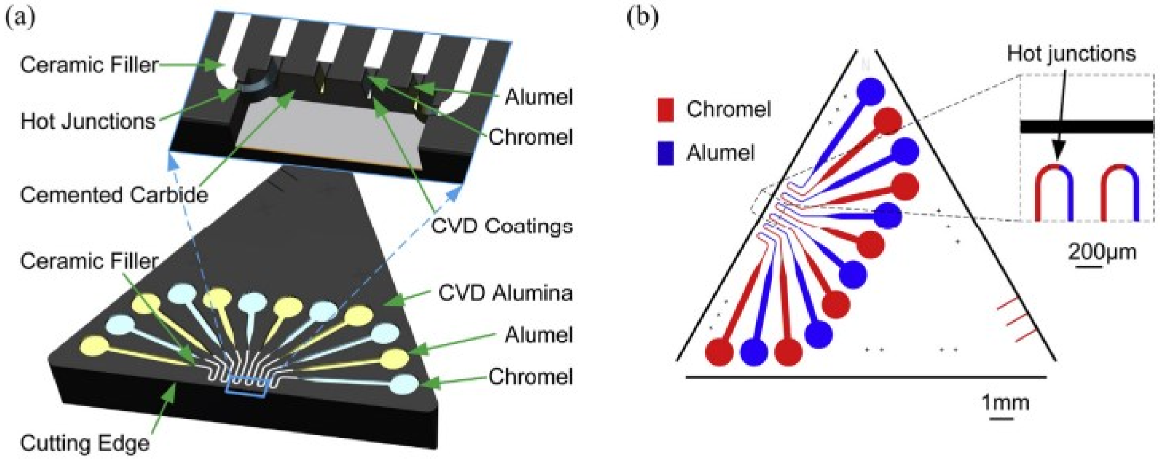

Figure 4 An embedded thermocouple on rake face [16]

During the cutting process the TFTCs detect changes in temperature around their hot junctions. In the experiment concluded by Li et al. [16], the tool was tested on titanium alloy.

At a smaller cutting speed, most of the sensors weren’t in contact with the work piece, and the changes in temperature were small. During higher feed experiments, bigger changes were accomplished, and more reliable data was acquired. According to the results, the sensors were found to have fast response times and their data seemed to coincide with the data collected of used force. After the tests, the cutting insert was examined. The results showed that the wear depth was around 40 to 50µm, and it survived without breakage. Severe wear was noted around the middle TFTCs, but they survived without breakage. According to the study, improved reliability was achieved by using these sensors instead of surface-deposited ones. They allowed accurate temperature measurements without breaking, unlike other types.

Although done earlier, this study shows a good comparison to the thin film sensors studied by Plogmeyer et al. (2021) [15]. Both sensors collected information about cutting temperatures, but the thin film thermocouples could be a better option for some of the shortcomings of the surface deposited thin film sensors, like durability.

3.3 Optical fiber for temperature measurement

Han et al. (2022) [17] did an experiment with an embedded optical sensor in the cutting tool for temperature and tool wear monitoring. According to the study, previously introduced TFTCs aren’t consumer friendly, because of the challenges in fabrication and lower reliability compared to optical fibers. They are also said to be able to measure only the sensors temperature and not the tools. The optical fiber is said to be a better choice, because of its ability to measure small chip areas precisely.

In the setup, a sensor probe is inserted into a blind hole in the cutting insert. The probe is then connected to a NIR spectrometer via optical fiber cable. Lastly the spectrometer is connected to a computer via USB to record values during the cutting process. The sensor works by using thermal radiation picked up with the sensor probe, which has good transmittance. This radiation is sent to the optical fiber cable, which analyses the spectrum and gives good data for temperature measurement. [17] This setup is shown in figure 5.

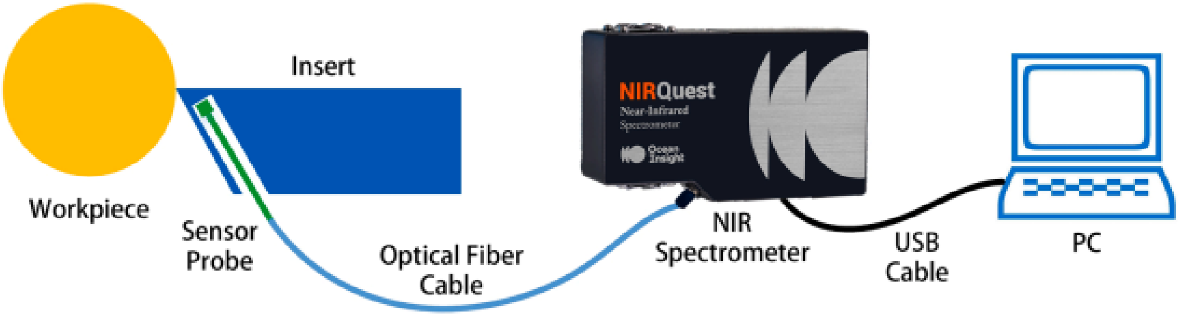

Figure 5 Setup of optical fiber for temperature measurement [17]

The results showed that an optical fibers relative error stabilizes at temperature above 250ºC to less than 0.5%. This shows very good accuracy for measuring temperature. Railway wheelset turning was tested to show compatibility with machines used in the industry. In these tests the forces and feeds used are larger, giving the sensors more of a challenge. It was shown that the optical fibers can be used in these scenarios as well. Lastly the tests showed good tool wear monitoring. The sensor lasted throughout the entire tool life and had an accuracy of 97.3%, showing the stability of the sensor.

3.4 Embedded optical fiber for temperature and force measurement

In a research done by Alemohammad et al. (2007) [18], the usage of optical fibers embedded in cutting tools created via moulding and LSFF (Laser Solid Freeform Fabrication) was tested. The purpose for this experiment was to figure out the capabilities of optical fibers moulded into work pieces, and to test their advantages to other sensors. Optical fibers are lightweight, small sized and durable in the long term, which makes them a good choice as a sensor.

To embed the optical fiber, laser solid freeform fabrication was used. Since optical fibers are sensitive to high temperatures, the fiber was combined with Sn-Pb alloy in a moulding process to provide a low temperature, good adhesion having coating to the fiber. After moulding, the LSFF process begun. During the process, layers of WC-Co were deposited onto mild steel, creating a block ready to be machined. After the LSFF, the block was then machined to represent a desired cutting tool with the correct geometries. A picture of the experimental setup in the study is shown in figure 6.

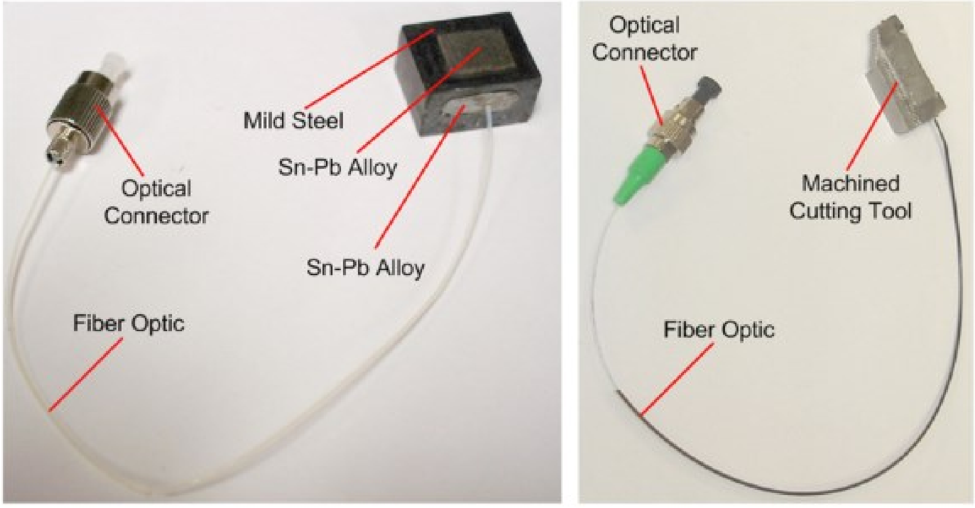

Figure 6 The embedded optical fiber before and after machining [18]

For results, the values for the embedded optical fiber were compared to the values before being embedded. In both setups, the fiber was connected to a light source and a photodetector cell. No damage was caused, but 21% of light was lost at the most. This is a noticeable drop, but it shows that the fiber could still pass waves and was working. The fiber kept the same behaviour, and it was concluded that it could monitor the tool well.

Another test was conducted to test the parameters of the embedded fiber under different loads of stress. The tool was put under compression, so that the sensor was fully loaded at a maximum 7000N of force. Multiple test runs were completed, to show repeatability of the procedure. As a result, failures were mostly spotted at the interface, and the tool was analysed to withstand pressure well. Although this is an older study, it is still a good example of possible configurations for tool monitoring.

3.5 Thin film strain sensor

Cheng et al. (2022) [19] experimented with thin film strain sensors to measure forces during a cutting process. The study showed three ways to attach the sensor to a tool holder which will be shown here. The sensor material selection is important for the properties of the product. In the study it was reported that for the best chance to improve adhesion, the insulating layer should be composed of silicon nitride, and the transition layer should be aluminum oxide and titanium nitride.

A thin film sensor measures forces based on the bending of the sensor. Forces applied on the cutting tool cause the thin film to bend, and by deforming the resistance grid, it will also change the output voltage of the sensor. The data is then processed through electrical components to measure the forces.

The first way to connect a sensor consisted of a sleeve type setup, where a cutter bar is fixed in place with screws into a circular sleeve with thin film strain sensors. Forces applied during a cutting process will be processed through the sleeve. which allows synchronized data collection and improves the range of measurements. A picture of the setup can be seen in figure 7.

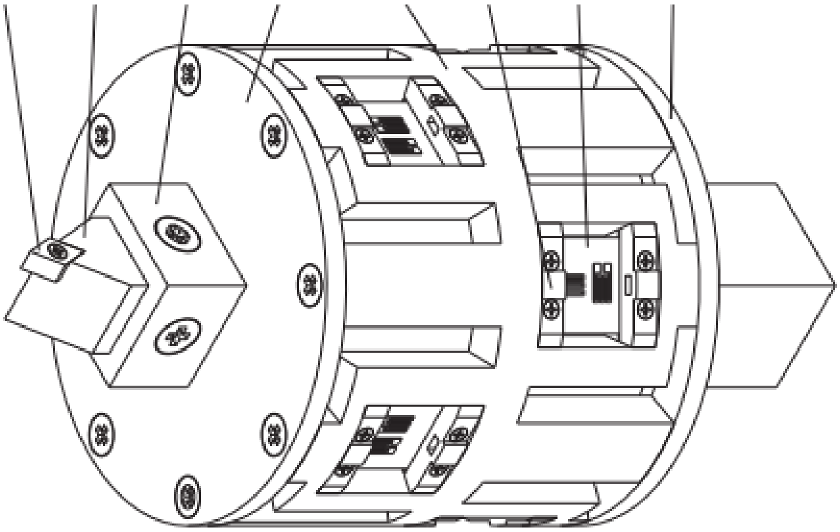

Figure 7 Circular sleeve type setup for thin film strain sensor [19]

In the second setup, four thin film strain sensors were clamped in place on a cutting tool. The setup was described as a plug method, where there are grooves on the side of the cutting tool for the sensors. The setup was said to be good for production reasons, as it’s quick to use. Setup of the thin film strain sensor can be seen in figure 8.

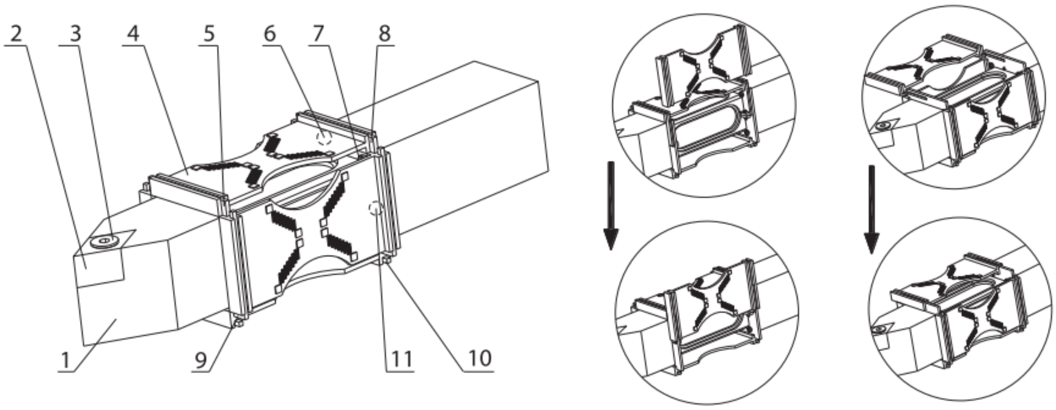

Figure 8 Quick plug version of thin film strain sensor [19]

The third way to connect the thin film sensor was a more insertion-based method where the thin films are screwed to the tool bar which holds them tightly in place. Because the substrate used wasn't as wide, the setup was said to have better elastic properties. It was said to have properties such as high efficiency for strain transmission and a steady way of positioning. A picture of the setup can be seen in figure 9.

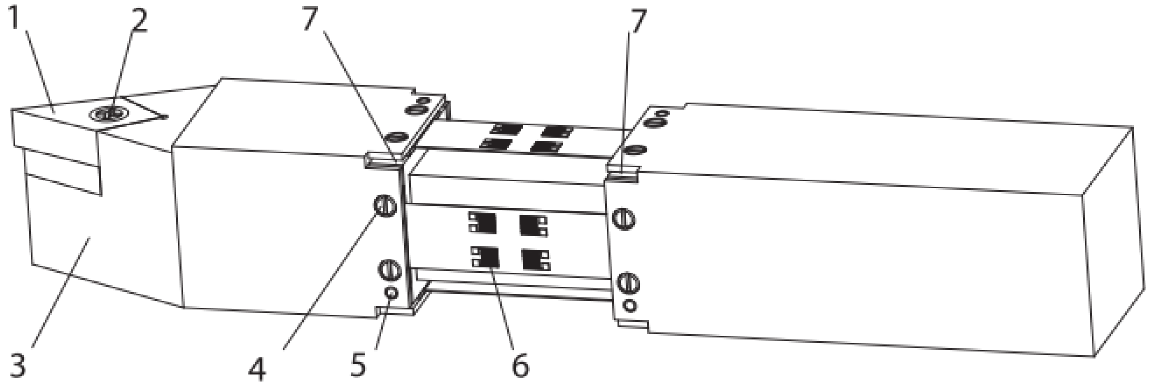

Figure 9 Thin film sensors inserted to the tool bar [19]

During the experiments, a cutting tool with strain sensors setup in a similar way to the second and third setup was connected to a Dynamic Signal Test and Analysis System (DH5929) and a Wheatstone circuit, to collect the received data. A static load was then applied to the cutting tool to demonstrate changes in loads during a machining process. The results showed that as the static load got larger, so did the output voltage of the sensor. This voltage was then compared to the micro strain caused by the load, and there was a clear correlation. According to the test results, the sensors sensitivity was very high, shown by small fluctuations in the strain caused by the load swinging. The choice of materials in the study, showed improved adhesion for the insulation layer and the substrate.

3.6 Dynamometer embedded in thin film

Dynamometers are often used to measure forces in different scenarios. The usage of a dynamometer applied to a cutting tool was tested in a research done by Zhang et al. (2019) [20]. In this experiment a thin film sensor was embedded into a turning dynamometer, which consisted of a cutter head, a tool shank, a flange, an elastomer to collect forces and several parts for connection. A picture of the design can be seen in figure 10. The purpose of the research was to propose a high strain dynamometer with the ability to measure triaxial cutting forces, and to account for the influence the dynamometer had on the strain coefficient.

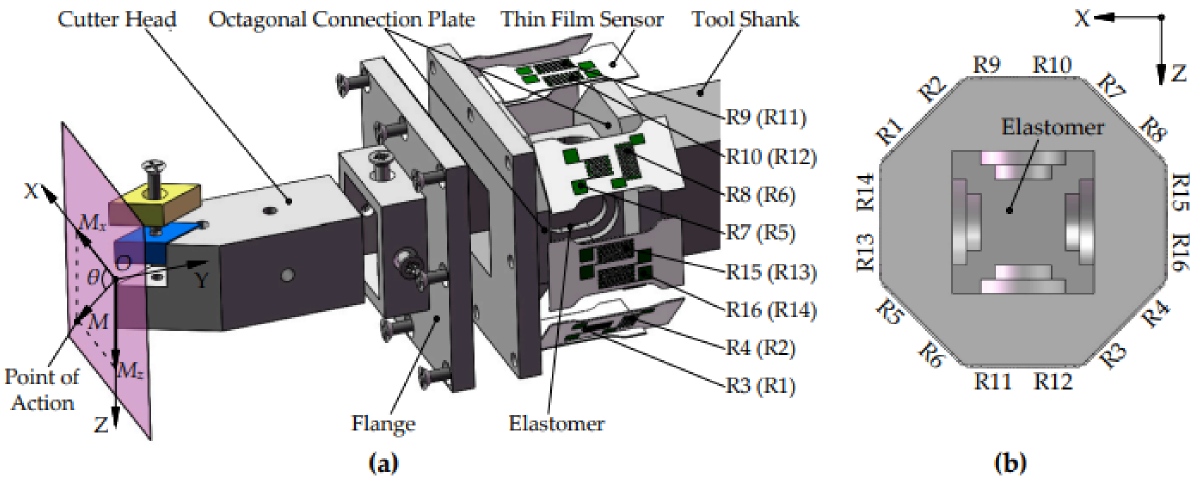

Figure 10 The design of a turning dynamometer with thin film sensor: (a) a view of the whole dynamometer, (b) a visualization of the resistance grids [20]

To measure the cutting forces, the cutting head was inserted into the elastomer. This way the elastomer can transmit the occurring cutting forces to the eight Ni-Cr alloy thin film sensors attached to it, each equipped with a resistance grid pair. These resistance grids are attached to three Wheatstone bridge circuits to allow the measurement of cutting, feeding, and thrust force. During a cutting process, the forces will exert changes to these resistance grids, and the total resistance in the Wheatstone circuits will change. Similarly to the previous research by Cheng et al. [19], this way the output voltages will change and the cutting forces can be measured.

The results showed potential for the usage of this dynamometer in the future. This was concluded because of its ability to avoid fluctuance on the strain transmission caused by the pasting process, which was caused by the film sensors strain coefficient. The sensitivity of the dynamometer was tested to be that of 2.32 times higher than a normal turning tool, which is good for measurements during a cutting process.

4 Adaptive feedback systems of tools and machines

The signals received from embedded sensors can be processed by a feedback or management system. These systems can then adjust the parameters of the operation based on received signals and optimize the working process for better results. There are multiple types of these systems, and this chapter gives insight into these technologies.

4.1 A basic description of a feedback system

Using feedback systems to automatically change cutting parameters is by no means a new concept. In fact this was studied already in the 1980s by Yen and Wright (1983) [21] in their paper about adaptive control in machining. In the study a model for an adaptive control system (AC) was defined as a system that could change the parameters of a system based on changes detected by cutting tools equipped with different kinds of sensors.

To take advantage of signals and use them, the signals need to be processed properly for the machine. The process of signal processing can be done in numerous ways to provide a type of data wanted for the application. Some signal processing types include amplification, normalization, filtering and denoising [22].

A feedback system can be defined as a loop consisting of steps repeated during machining. The cutting tool needs to have a sensor of some sort to send out a signal for processing. This signal then needs to be formulated properly so that it can be used, by using amplifiers or filters of some kind. Now a processing unit reads the given input information and by making appropriate calculations, it can send out a signal with the needed correction data. The last step is to adjust the machine by using a control system of some kind. There are multiple ways to control the machining parameters with only these signals, and some of them are presented in this chapter. These steps are then repeated during the cutting process, to adjust the cutting tool and have good finishing quality for the product. The main premise of an adaptive feedback system is to automatically change the cutting conditions so that the production is optimal. [23] A simplified version of this loop is presented in figure 11, where the steps are described broadly, and more specific steps are dependent on the specific system.

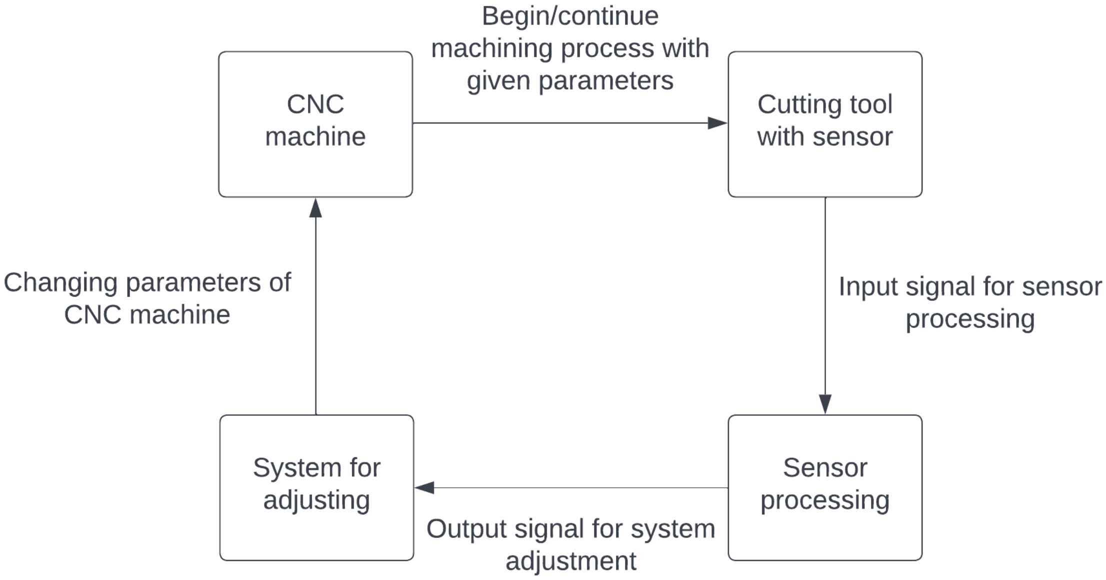

Figure 11 A simplified version of the feedback system loop

4.2 Examples of feedback systems in use

While this definition is good at describing what is done, the methods of how it can be done have been tested over the years. In the following segment, multiple example studies are shown to give insight into possible methods.

4.2.1 A PID Control system

One way to control the machining process for optimization is by using a PID Control system. This was tested in an experiment conducted by Muqeet et al. (2023) [24]. In the experiment a piezoelectric sensor was implanted onto a cutting tool to record vibrations during a cutting process of a CNC lathe. These vibrations would then be used to adapt the cutting depth to allow better surface finishing.

The adaptations were made possible with a PID Control system, which was tuned by using Reinforcement learning (RL) and Sand Cat Swar Optimization (SCSO). SCSO works by iterating through solutions with defined search options, using a so-called fitness function to evaluate results. The RL used a method known as Q-learning where actions are assigned to the machine, and based on the success its values are recorded into a Q-table. In the experiment the two methods were combined to a hybrid version of SCSO known as QSCSO. The PID controller was then adapted by comparing the relationship between armature current and the sum of friction and inertia forces. According to the study, the PID controlled system achieved better surface finishing by optimizing the cutting depth and amplitude of vibrations.

4.2.2 Electro-magneto-rheological damper

Another experimentation for an adaptive control system of a cutting process to reduce vibrations was done in a research by Orra and Choudhury (2021) [25]. In this experiment the feedback system was constructed with the following parts: a piezoelectric accelerometer on a cutting tool for vibrations, an electro-magneto-rheological damper, a data acquisition card (DAQ) for creating a voltage as feedback and an amplifier for signal processing before and after. The dampers' purpose is to create damping forces that are opposite to vibration, reducing the effect. During testing, this feedback system was compared with a process without it. It was reported that the feedback system could reduce the vibrations well, especially at frequencies around 250 Hz. This reportedly resulted in reducing tool wear by 30% and improving surface finishing by 37%.

4.2.3 Chip formation monitoring system

With a good tool monitoring and management system, the size of the chips produced while machining can also be controlled. In an experiment done by Ryynänen et al. (2009) [26], a chip control system was developed to manage chip formation. To detect changes in chip formation, an acoustic emission sensor was implanted onto the tool machine turret. When a chip breaks, it creates a stress wave on the acoustic emission sensor and creates a signal. The signals were then picked up with a PCI-6251 multichannel data acquisition board and sent to National Instruments LabVIEW software.

To adapt the values in the system the control mechanism used an application in Fanuc control known as FOCAS, to change the cutting parameters. Desired values are set in the applications memory, and when the current conditions differ from it, new values are set into the machine's memory. When an unwanted chip occurred, the feed of the machine was paused for a short period of time, and the process continued with a higher feed after that. This is because only increasing the feed doesn't cause chip breakage and can sometimes increase the size of the chip. The study concluded that the chip rate could be monitored at a rate of 95%. The speed of adjustment was noted to be long at a time of 5-10 seconds.

4.2.4 Temperature based control system

The presented feedback systems are good examples of adaptations done based on force feedback (vibration and chip formation), but it's also important to consider an adaptive feedback system based on the temperature of the cutting tool, since temperature was the other main category of sensors presented in this thesis.

A feedback system based on the temperature of the cutting tool was tested in a study done by D'Errico (1998) [6]. The setup consisted of a cutting tool with an embedded standard thermocouple, and a self-tuning regulator (STR) as the control system. A STR can generally be divided in to three parts: an estimator that creates estimates of parameters using inputs and outputs, a controller that creates signals using the estimations and a third block that relates the parameters of the estimation and the controller [27]. In this case, the information for the STR came from the embedded thermocouple. During the cutting process, the temperature is monitored using emf signals sent by the thermocouple. A set point for temperature where tool wear is acceptable is set, and by adjusting the cutting speed the process is kept at that point. The results showed the capability of the system to operate steadily and adapt to changes in temperature.

4.3 The benefits of adaptive feedback systems

From the studies presented above, it's clear that implementing some sort of sensor technology and a feedback system into machining could be highly beneficial for the turning process. The main researchers were Ryynänen et al., Orra and Choudhury and Muqeet et al. The main concerns brought up in the studies were surface finishing, tool wear, and chip formation which as stated before also correspondingly affects the plastic deformation, acceptable cutting speed, and feed rate. The methods presented showed good adaptability and provided improvements in the results of the cutting process. This means that with an adaptive feedback system a machine can have the ability to sustain optimal parameters throughout its cutting process, and thus optimize the whole process better.

Lowering the tool wear of a cutting tool helps the cutting process as it results in longer tool life. A longer tool life in turn allows a manufacturer to use the same tool for longer periods of time. This can then lower the cost of production and also help with the time needed for tool changing and setting up. [28]

In the bigger picture, an adaptive feedback system can bring reliability and consistency to a manufacturer, by implementing automation to CNC machining. When the machine produces quality products reliably and automatically, it gives the company more freedom to relocate the current worker at the station to also work on additional areas of the process, giving flexibility to manufacturing. [29]

5 Results

Some basic information about discussed sensors is presented in Table 1. The table is based on information gathered from the original studies.

Table 1 Different sensor types laid out with explanations of certain properties

	Thin film temperature	TFTC	Optical fiber temperature	Optical fiber temperature and force	Thin film strain	Dynamometer thin film
Short Description	Thin films applied on rake face with coating layers	Embedded thin film thermocouple made of chromel and alumel	A sensor probe is inserted into the blind hole of a cutting tool, and connected to a computer	Optical fiber moulded with Sn-Pb alloy, then laser solid freeform fabrication was used to create a block which was machined to desired shape	Thin film attached to the side of cutting tool holder. Three ways of attaching sensors	Eight thin films embedded into a turning dynamometer connected to tool shank with elastomer
Working principle	Temperature is calculated from measured resistances using thermoresistive characteristics	Measures temperatures at hot junctions of thermocouples	Probe picks up thermal radiation and sends it to the optical fiber cable, which analyses its spectrum	One end of fiber is connected to light source and the other to a photodetector cell. Results compared for fiber before and after embedding.	Based on the bending of the thin film, the resistance grid changes and so does the output voltage of the sensor	Thin films use resistance grids. Dynamometer uses relationship between deflection and strain under external force.
Advantages	Fast response time, good repeatability	Accurate measurement without breaking	Precise measurements of small chip areas,	Withstands pressure well	Improved adhesion, can have high efficiency for strain transmission or be quick to use	High sensitivity, avoids fluctuance on the strain transmission
Disadvantages	Durability, measurements not close to cutting edge	Consumer friendliness, fabrication issues	N/A	Amount of lost light 21% (was still working)	N/A	N/A
Accuracy	OK	Good	Very good	Good	Good	Good

Since Table 1 is based on the original studies, some information wasn’t always available, hence why some cells are marked as N/A (not available).

Six different types of sensor technologies implemented into cutting tools were reviewed in this thesis. Although some of them had some shortcomings, they all showed some potential capabilities to be used in the industry. The two main types of sensors used were force and temperature based. With temperature sensors there were more noticeable disadvantages with some sensors, and it could be noticed that improvements had been constantly made. The force-based sensors presented overall good results for monitoring the forces exerted onto the cutting tool. There were less noticeable differences between the force-based sensors, compared to that of the temperature-based sensors.

After this the concept of an adaptive feedback system was defined and four examples were presented. It was shown that implementing adaptive feedback systems and embedded sensors into a cutting process could have noticeable advantages in the outcome. Some of the advantages of these systems concluded in the examples were:

- Improved surface finishing
- Reduced tool wear
- Good monitoring and adaptation capabilities
- Manufacturing benefits, such as flexibility and cost-effectiveness

6 Conclusions and discussion

6.1 Conclusions

It can be concluded that most of the sensors showed good potential, which hasn’t been delved into in the industry. The untapped potential of the presented technology is clear when considering the small amount of cutting tools that are manufactured with sensor technology. This is also a little bit surprising considering some of the studies were much older. The biggest limitations come from inserting new technology to old machines, and methods to do that should be discussed. When this is achieved, the presented studies show good possibilities.

6.2 Discussion

It can be noticed that most of these promising embedded sensors were only seen in the research part of this review. This raises the question of how these sensors and feedback systems could be brought to use in the industry. The installation process would have to be quick and easy, and the costs can’t outweigh the cost of the product. It’s also important to consider the fact that a lot of the time the same thing is done with a different kind of sensor. This means that it can be hard to determine which type of technology should be prioritized, and it can also lead to the development being pushed forward into the future.

A lot of current sensors are based on mounting techniques, needing a physical connection with the tool. The next step in research could be to develop more advanced sensors based on non-touching technologies like lasers, which was an idea brought forward by Muqeet et al. [24].

Since many of the machines in the industry used for turning might be older than the sensor-based technology presented in this thesis, and since new machines are expensive, it could be more beneficial to integrate this technology straight into the older machines. Doing this is known as retrofitting, and it serves as a good step to bring existing machines towards industry 4.0 [30]. Industry 4.0 is the fourth industrial revolution, where the transformation towards digital technology is the main concern. In manufacturing Industry 4.0 brings interconnectivity between different processes, and in the turning process it could help with better machine learning and optimizations. These so called ‘smart processes’ take advantage of Artificial Intelligence and automation, to estimate data and make predictions. [31] This should be considered in the future when developing the turning process.

References

[1] P. K. Wright and E. M. Trent, *Metal Cutting*. San Diego, UNITED STATES: Elsevier Science & Technology, 2000. Accessed: Feb. 06, 2024. [Online]. Available: http://ebookcentral.proquest.com/lib/kutu/detail.action?docID=296697

[2] A. Lasemi, D. Xue, and P. Gu, ‘Recent development in CNC machining of freeform surfaces: A state-of-the-art review’, *Computer-Aided Design*, vol. 42, no. 7, pp. 641–654, Jul. 2010, doi: 10.1016/j.cad.2010.04.002.

[3] X. G. Ruan, Y. C. Wang, D. F. Zhang, H. X. Cao, M. Sun, and F. Y. Li, ‘Introduction of Characteristics and Choice of CNC Machining Cutter’, *AMR*, vol. 421, pp. 329–333, Dec. 2011, doi: 10.4028/www.scientific.net/AMR.421.329.

[4] J. Ratava, *Modelling Cutting States in Rough Turning of 34CrNiMo6 Steel*. Lappeenranta University of Technology, 2015. Accessed: Feb. 04, 2024. [Online]. Available: https://lutpub.lut.fi/handle/10024/106809

[5] R. Pavel, I. Marinescu, M. Deis, and J. Pillar, ‘Effect of tool wear on surface finish for a case of continuous and interrupted hard turning’, *Journal of Materials Processing Technology*, vol. 170, no. 1–2, pp. 341–349, Dec. 2005, doi: 10.1016/j.jmatprotec.2005.04.119.

[6] G. E. D’Errico, ‘An adaptive system for turning process control based on tool temperature feedback’, *Journal of Materials Processing Technology*, vol. 78, no. 1–3, pp. 43–47, Jun. 1998, doi: 10.1016/S0924-0136(97)00461-5.

[7] X. Chen, ‘A multi-physics-based approach to design of the smart cutting tool and its implementation and application perspectives’, College of Engineering, Design and Physical Science, Brunel University, 2016.

[8] R. Davis, V. Singh, and S. Priyanka, ‘Optimization of Process Parameters of Turning Operation of EN 24 Steel using Taguchi Design of Experiment Method’, *World Congress of Engineering 2014*, vol. II, 2014.

[9] V. P. Astakhov, *Geometry of Single-point Turning Tools and Drills*. in Springer Series in Advanced Manufacturing. London: Springer London, 2010. doi: 10.1007/978-1-84996-053-3.

[10] W. Li *et al.*, ‘Influence of cutting parameters and tool nose radius on the wear behavior of coated carbide tool when turning austenitic stainless steel’, *Materials Today Communications*, vol. 37, p. 107349, Dec. 2023, doi: 10.1016/j.mtcomm.2023.107349.

[11] A. Baptista, F. J. G. Silva, J. Porteiro, J. L. Míguez, G. Pinto, and L. Fernandes, ‘On the Physical Vapour Deposition (PVD): Evolution of Magnetron Sputtering Processes for Industrial Applications’, *Procedia Manufacturing*, vol. 17, pp. 746–757, 2018, doi: 10.1016/j.promfg.2018.10.125.

[12] K. Choy, ‘Chemical vapour deposition of coatings’, *Progress in Materials Science*, vol. 48, no. 2, pp. 57–170, 2003, doi: 10.1016/S0079-6425(01)00009-3.

[13] Sandvik Coromant, ‘Silent Tools^{TM}– DAMPED TOOLS FROM SANDVIK COROMANT’, 2017. Accessed: Mar. 28, 2024. [Online]. Available: https://cdn.sandvik.coromant.com/publications/b6abecdc-40ef-4e55-a89d-458b4a20cdf0.pdf?sv=2021-08-06&st=2024-03-28T11%3A51%3A15Z&se=2024-03-28T13%3A56%3A15Z&sr=b&sp=r&rscd=inline%3B+filename%3DSilent+Tools.pdf&rsct=application%2Fpdf&sig=dqxkKNfhqHupQ0Bh5z2%2FBOQ2%2FwLMZL6IN1cy0%2B1v2%2BU%3D

[14] C. Salame, R. Rapold, B. Tasdelen, and A. Malakizadi, ‘Sensor-based identification of tool wear in turning’, *Procedia CIRP*, vol. 121, pp. 228–233, 2024, doi: 10.1016/j.procir.2023.09.252.

[15] M. Plogmeyer, G. González, S. Biehl, V. Schulze, and G. Bräuer, ‘Wear-resistive thin-film sensors on cutting tools for in-process temperature measurement’, *Procedia CIRP*, vol. 101, pp. 85–88, 2021, doi: 10.1016/j.procir.2021.02.011.

[16] J. Li, B. Tao, S. Huang, and Z. Yin, ‘Cutting tools embedded with thin film thermocouples vertically to the rake face for temperature measurement’, *Sensors and Actuators A: Physical*, vol. 296, pp. 392–399, Sep. 2019, doi: 10.1016/j.sna.2019.07.043.

[17] J. Han, Z. Liu, K. Cao, L. Xu, T. Shi, and G. Liao, ‘Cutting temperature measurement in turning using fiber-optic multi-spectral radiation thermometry and its application in tool wear status recognition’, *Measurement*, vol. 198, p. 111413, Jul. 2022, doi: 10.1016/j.measurement.2022.111413.

[18] H. Alemohammad, E. Toyserkani, and C. P. Paul, ‘Fabrication of smart cutting tools with embedded optical fiber sensors using combined laser solid freeform fabrication and moulding techniques’, *Optics and Lasers in Engineering*, vol. 45, no. 10, pp. 1010–1017, Oct. 2007, doi: 10.1016/j.optlaseng.2007.04.006.

[19] Y. Cheng, W. Wu, L. Liu, Z. He, and D. Song, ‘Structural design and optimization of a turning tool embedded with thin-film strain sensors for in-process cutting force

measurement’, *AIP Advances*, vol. 12, no. 1, p. 015126, Jan. 2022, doi: 10.1063/5.0079837.

[20] Y. Zhang, W. Wu, Y. Han, H. Wen, Y. Cheng, and L. Liu, ‘Design and Analysis of a Turning Dynamometer Embedded in Thin-Film Sensor’, *Micromachines*, vol. 10, no. 3, p. 210, Mar. 2019, doi: 10.3390/mi10030210.

[21] D. W. Yen and P. K. Wright, ‘Adaptive Control in Machining—A New Approach Based on the Physical Constraints of Tool Wear Mechanisms’, *Journal of Engineering for Industry*, vol. 105, no. 1, pp. 31–38, Feb. 1983, doi: 10.1115/1.3185861.

[22] M. Kuntoğlu, E. Salur, M. K. Gupta, M. Sarıkaya, and D. Yu. Pimenov, ‘A state-of-the-art review on sensors and signal processing systems in mechanical machining processes’, *Int J Adv Manuf Technol*, vol. 116, no. 9–10, pp. 2711–2735, Oct. 2021, doi: 10.1007/s00170-021-07425-4.

[23] Y. Koren, ‘Adaptive Control Systems for Machining’, in *1988 American Control Conference*, Atlanta, GA, USA: IEEE, Jun. 1988, pp. 1161–1167. doi: 10.23919/ACC.1988.4789896.

[24] A. Muqeet, A. Israr, M. H. Zafar, M. Mansoor, and N. Akhtar, ‘A novel optimization algorithm based PID controller design for real-time optimization of cutting depth and surface roughness in finish hard turning processes’, *Results in Engineering*, vol. 18, p. 101142, Jun. 2023, doi: 10.1016/j.rineng.2023.101142.

[25] K. Orra and S. K. Choudhury, ‘Stability analysis in machining process by using adaptive closed-loop feedback control system in turning process’, *Journal of Vibration and Control*, vol. 27, no. 17–18, pp. 2034–2046, Sep. 2021, doi: 10.1177/1077546320952613.

[26] V. Ryynänen *et al.*, ‘Chip control system for monitoring the breaking of chips and elimination of continuous chips in rough turning’, *Mechanika*, vol. 78, pp. 57–62, Jan. 2009.

[27] K. J. Åström, ‘Self-Tuning Regulators’, *Systems Reliability Issues for Future Aircraft*, pp. 51–67, 1975.

[28] M. Narasimha, K. Sridhar, R. R. Kumar, and A. A. Kassie, ‘Improving Cutting Tool Life a Review’, *International Journal of Engineering Research and Development*, vol. 7, no. 1, pp. 67–75, May 2013.

[29] K. Hon and B. H. T. Baharudin, ‘The impact of high speed machining on computing and automation’, *Int J Automat Comput*, vol. 3, no. 1, pp. 63–68, Jan. 2006, doi: 10.1007/s11633-006-0063-3.

[30] J. Herwan, S. Kano, O. Ryabov, H. Sawada, N. Kasashima, and T. Misaka, ‘Retrofitting old CNC turning with an accelerometer at a remote location towards Industry 4.0’, *Manufacturing Letters*, vol. 21, pp. 56–59, Aug. 2019, doi: 10.1016/j.mfglet.2019.08.001.

[31] Md. S. Rahman, T. Ghosh, N. F. Aurna, M. S. Kaiser, M. Anannya, and A. S. M. S. Hosen, ‘Machine learning and internet of things in industry 4.0: A review’, *Measurement: Sensors*, vol. 28, p. 100822, Aug. 2023, doi: 10.1016/j.measen.2023.100822.