A COMPREHENSIVE METHODOLOGY FOR TESTING HARD LAYERS OF CUTTING TOOL PROPERTIES IN ORTHOGONAL TURNING

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Thin hard layers deposited on cutting tools known as 'coatings' serve as a protective barrier against abrasion and adhesion wear, while also protecting against thermal and chemical processes that deteriorate the cutting performance of the tool. Coating properties including non-zero thickness, surface roughness, and chemical composition affect the cutting process significantly when compared to uncoated tools. The mechanical properties of coatings can be compared using specific, standardized measurement methods that provide indirect information about the behavior of the coating in a given application of the machining. In practice, it is necessary to evaluate the cutting ability by experimental testing of a given combination of cutting tool, workpiece, cutting conditions and cutting environment. This article discusses various experimental procedures that help to recognize the suitability of a coating for a particular application. These procedures can be applied alone, or in combination, as required by the cutting process. Each of these procedures have associated advantages and disadvantages, as described in this paper.

KEYWORDS

Orthogonal turning, testing of cutting tools, experimental methods

1 INTRODUCTION

The thin layer(s) covering the surface of cutting tools, hereafter referred to as *coatings*, can be defined by many different properties. These properties, such as hardness, thickness, tribological behavior, surface roughness of the machined surface, chemical and thermal stability and oxidation resistance [Mrkvica 2015, Badaluddin 2018], only offer an approximate indication of the behavior of the coating in a specific application. All of the properties of the coating are often hidden under the mask of trade secret. However, all properties can be revealed through complex laboratory testing. The real suitability of a coating for a given application can be resolved only after experimental machining. Interesting properties relevant to machining technology, such a cutting tool wear or surface roughness, are related to productivity, cost effectiveness and quality of the machined workpiece. The spectrum of technological tests is relatively wide and this work deals with the most suitable ones. The most important technological tests focus on chip forming, forces from cutting, cutting temperature, cutting tool wear or the geometric and shape accuracy of the workpiece. This article describes all the important methods in orthogonal turning that can answer the question of how suitable the coating is in terms of productivity, economy and quality of the machined workpiece.

1 ORTHOGONAL CUTTING AND PROCESS REQUIREMENTS

Orthogonal machining can be performed with many different technologies, such as shaping, planing, broaching and turning. Orthogonal cutting is an experimental setup that simplifies the process of cutting and shaping chips, because the entire problem is solved in the plane, compared to oblique cutting, where cutting is a three-dimensional issue. This simplification is beneficial when testing the coatings too.

The chip flow is perpendicular to the main cutting movement in the orthogonal arrangement. It can only be achieved if the tool edge inclination angle is 0°, and the main cutting edge angle is 90° for the pipe workpiece and 0° for the disk workpiece. Thus, two basic orthogonal turning options are possible, as shown in Fig. 1 and Fig. 2. For example, orthogonal cutting on thin discs was used by Karpat or Liang [Karpat 2006, Liang 2017] and pipes were used by Wang [Wang 2009] in the case of turning. The thickness of the disc or tube (width of cut) must be lower than the length of the straight part of the cutting edge.

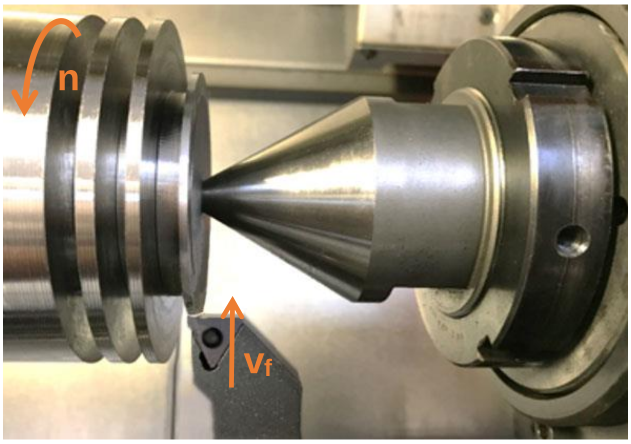

Figure 1. Orthogonal turning of disks.

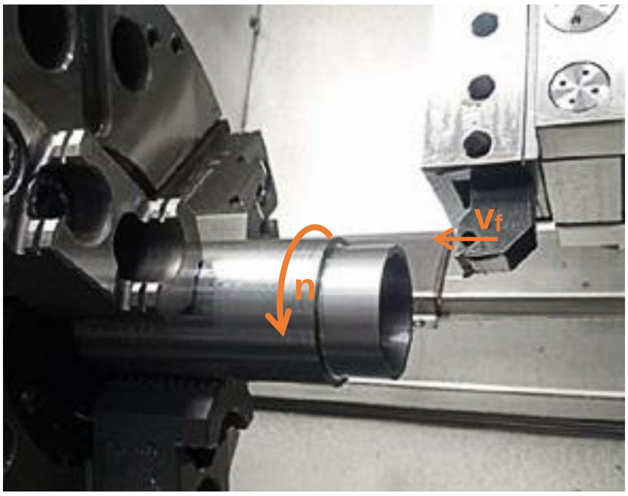

Figure 2. Orthogonal turning of pipe.

2 CHIP FORMATION STUDY

2.1 Chip shape, curvature radius and length

Chips are waste material from the machining process. That said, the way they are created contains a lot of information about the machining process itself. The chip can be evaluated according to ISO 3685-1977 [ISO3685 1993]. The shape and length of the chip are affected by cutting conditions, cutting fluids, wear, as well as the macro and micro geometry of the cutting tool. The micro geometry of the cutting tool influences the formation of chips significantly, but thermal and physical properties also contribute to chip formation, and together affect the tribological interaction between the cutting tool and the chip. The main assumption is that the difference between the compared tools is only in the coating and its properties, because the attributes of macro geometry and cutting conditions have a more significant effect on the shape and dimensions of the formed chip. The surface roughness of the coating and its chemical composition affect the formation of chips. Abrasion and adhesion are dominant in affecting the evacuated chips through both friction and microscopic welds, mainly at low cutting temperatures. As the temperature increases in the cutting zone, diffusion and chemical reactions became more important between chips and the cutting tool (and also the machined surface and the cutting environment). The coating directly affects the thermal balance in the cutting zone and thus changes the shape and size of the chips. Rech's study showed a strong effect between the type of coating and the thickness of the chips, as well as the size of the secondary shear zone. The measurement was performed on a polished and etched specimen of the chip [Rech 2006].

A comparison of the shape and length of the chip can be achieved using standard photographic methods and graph paper (Fig. 3). Regarding chip shape, the suitability of a particular coating on a cutting tool can also be assessed on the basis of the length, thickness or radius of a chip curl. A diagram of suitable cutting conditions should be created for each coating. The chip should be as small as possible in order to make the chip management easier and cheaper; long chips take up more volume (with the same amount of material removed) than short chips. Thus, it is important to know the appropriate cutting conditions that make short chips. The dimensions of the chip (Fig. 4) are usually measured by standard microscopy, but it is possible to use standard length gauges unless high accuracy is required.

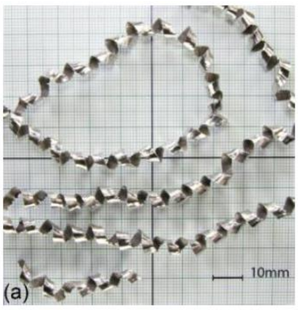

Figure 3. Evaluation of chip shape [Alagan 2021].

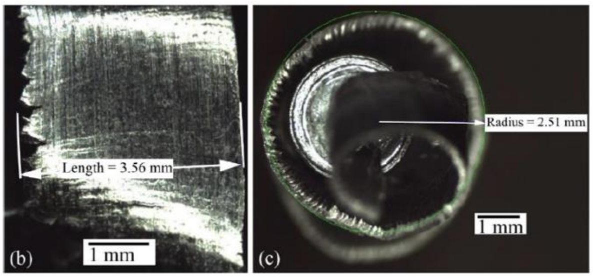

Figure 4. Measurement of chip dimensions [Alagan 2021].

2.2 Chip root

Tribological properties change with the chemical composition of the coating (heat conduction) and micro geometry, and can affect deformation zones in the chip and machined surface. Three deformation zones are known: *primary deformation zone* around the shear plane, *secondary deformation zone* on the back side of the chip, and *third deformation zone* on the newly created surface on the workpiece. The position and size of the primary, secondary and third deformation zones differ depending on the cutting coating used and its micro geometry. This change can be measured using specific parameters such as segment orientation, segment width, chip thickness ratio or segmentation ratio. The chip root is the part of the chip attached to the workpiece material, and its measurement can provide data for the evaluation of the above factors (Fig. 5). The chip root expands information on how the cutting tool affects the workpiece in the shear zone.

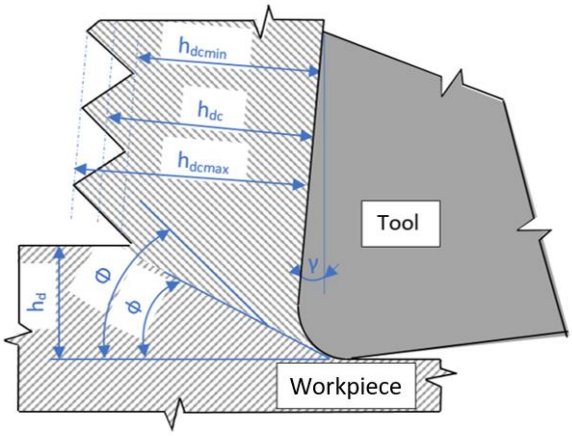

Figure 5. Chip root evaluation.

The chip root sample should be polished for easier metallographic analysis of the position, shape and size of the primary and secondary zones of plastic deformation and related parameters. Polishing of the chip root must be machined without excessive mechanical and thermal load. A suitable polishing technology is electrolytic polishing. The etched root of the chip is shown on Fig. 6.

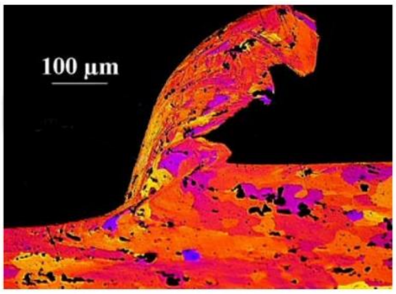

Figure 6. Etched root of a chip [Zeman 2005].

The shrinkage factor, K, is the ratio of deformed, h_{dc}, to undeformed, h_d, chip thickness. Higher deformations can be observed when machining workpiece material under high force loads.

$$K = \frac{h_{dc}}{h_d} = \frac{\sin\phi}{\cos(\phi-\gamma)} [1] \tag{1}$$

Where ϕ is the shear angle and γ is the rake angle of a cutting tool. Another parameter that can reveal the difference between the cutting ability of the coating is the segmentation ratio, Gs, which can be calculated as:

$$G_s = \frac{h_{dcmax} + h_{dcmin}}{h_{dcmax}} [1] \tag{2}$$

Where h_{dcmax} is the maximum of deformed chip and h_{dcmin} is the minimum of deformed chip.

The root of the chip can be obtained using a quick-stop device (Fig. 7). There are two basic designs of the quick-stop device. The first interrupts the cut on the side of the cutting tool. The cutting tool must leave the cut as soon as possible, where the external shock energy is directed against the cutting tool or clamping of the cutting tool. A functional concept of a mechanical quick-stop device was introduced by e.g Gwo-Lianq Chern [Chern 2005]. The second type of quick-stop device is on the workpiece side. It needs a specific additional modification of the round blank. A thin disk is prepared from the blank by grooving. Part of this disk is removed by milling, and holes are drilled at a defined distance from the edge. These holes are connected to the milled part by a groove. A small piece of sheet metal is then inserted into the groove and a pin of the same diameter as the hole is inserted into the drilled hole to prevent radial deformation of the workpiece during turning. The chip root (Fig. 8) breaks when the cutting force is higher than the ultimate strength of the material near the drilled hole.

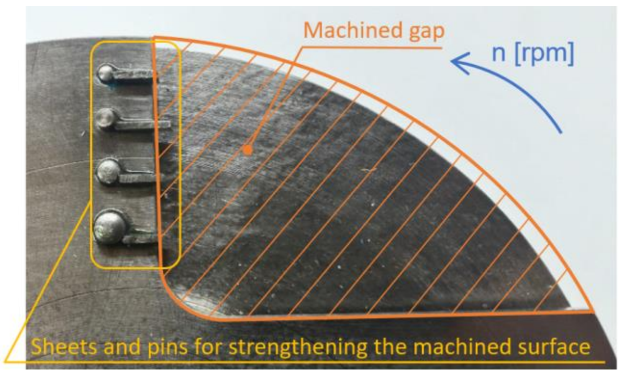

Figure 7. Quick-stop device prepared for four chip roots.

Figure 8. An example of a chip root obtained using a quick-stop device.

2.3 Chip formation

The previously mentioned methods describe the formation of a chip indirectly via the measurement and evaluation of relevant parameters after machining. The formation of the chip can be observed directly during machining, such as the direction of chip evacuation. Nevertheless, a high-speed camera allows us to observe chip formation as a continuous process in greater detail. The chip formation process can be recorded and then reviewed at a reduced playback speed, in order to evaluate the interaction between the tool and the workpiece (e.g. chip breakage or built-up edge formation and its stability in a special setup).

The required chip formation is in the direction from the cutting tool and away from the workpiece. Some basic information about chip flow and chip breakage can be recorded with today's conventional cameras. However, chip creation is a very fast process and requires a special recording device with a high frame rate for observation. In addition, very good lighting, stabilization of cameras to avoid vibration, and correct adjustment of the depth of field is important to solve before using this method. Low-focus cameras are needed where chip creation details are required. The equipment needed to observe chip formation is not recommended for hazardous areas, such as the machining area where chips fly and they threaten the equipment for measuring. Only specific process conditions can be used to record chip formation, for example without coolant.

The experimental design must be modified to achieve a good machining record (Fig. 9). It is then possible to obtain information about the flow direction of the chip and its formation. For some special arrangements, chip formation, segmentation and shaping of the new surface, as well as the formation and breakup of the build-up, can be observed. The chip formation recording should be provided from a parallel and perpendicular direction to the chip flow evaluation direction.

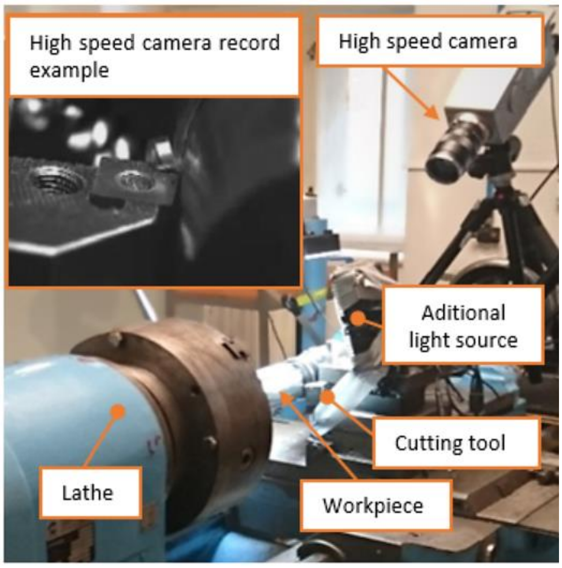

Figure 9. Test of the high speed camera during turning on the lathe.

A high speed camera was used by Pujana for evaluation of shear angles, chip thickness, tool vibration amplitude, deformation rate, and chip topology. Firstly he used a printed gird on the workpiece and then he evaluated a high speed camera record [Pujana 2008].

The direction of chip flow, as well as chip forming, can be evaluated according to ISO 3685 -1993 [ISO3685 1993] (Fig. 10).

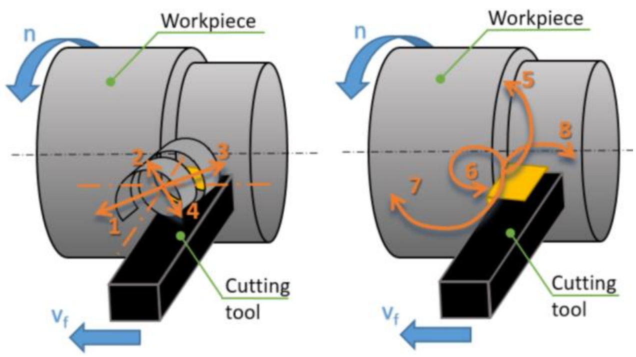

Figure 10. Direction of the chip flow is characterized by the third number bond to the chip designation [ISO3685 1993]
1 – from the workpiece in the feed direction
2 – to the workpiece in the feed direction
3 – to the workpiece against the feed direction
4 – from the workpiece against the feed direction
5 – broken by the main plane of the cut
6 – broken by the flank surface of the cutting tool
7 – broken by the unmachined surface
8 – broken by the machined surface.

3 FORCE INTERACTION ANALYSIS

The forces in cutting oscillate around their average value, largely due to material inhomogeneity and chip and surface formation. Micro geometry and chemical composition of a coating affect friction and adhesion, as well as deformation processes, in the chip and in the newly formed surface layer. This influences the magnitude and variation of the forces. Rech found a relationship between shear plane tangential force and coating type, but he found only a slight effect on the cutting force during orthogonal pipe turning [Rech 2006]. Aurich described a similar effect. He found the increasing cutting edge radius influenced the process forces with rising cutting length [Aurich 2012]. A different coating leads to a different speed of the cutting tool wear. Wear on the cutting tool changes both the micro and macro geometry of the cutting edge, and influences the chip formation process. One indication of this change may be the measurement of forces. Both the magnitude of the force and the time for the force to change due to wear can be an important factor in deciding the suitability of the coating of the tested cutting tool for a given application [Gheith 2008]. The effect of the cutting tool coating on the cutting forces was also studied by Kumar [Kumar, et al., 2020]

Different types of coatings applied to the same shape cutting tool will provide different tribological properties. These properties have a significant effect on the magnitude of the frictional forces. Friction arises from the chip flowing over the rake face and from the contact of the workpiece and the flank face of the cutting tool. The face tangential force (F_γ), also known as friction force, can be calculated from the measured forces F_c (cutting force) and F_f (feed force) in the orthogonal plane. The tool face perpendicular force ($F_{\gamma N}$) force is calculated similarly (Fig. 11).

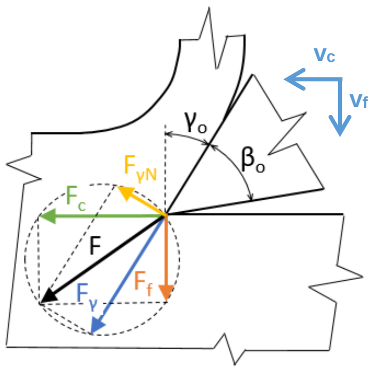

Figure 11. Cutting forces decomposition in orthogonal machining.

$$F_\gamma = F_f \cdot \cos\gamma_o + F_c \cdot \sin\gamma_o \text{ [N]} \quad (3)$$

$$F_{\gamma N} = F_C \cdot \cos\gamma_o - F_f \cdot \sin\gamma_o \text{ [N]} \quad (4)$$

The coefficient of friction is expressed as the ratio between F_γ and $F_{\gamma N}$. [Melkote 2017].

$$\mu = \frac{F_\gamma}{F_{\gamma N}} \text{ [1]} \quad (5)$$

A sudden change in force can be an indicator of cutting edge damage; forces also reflect changes of the tool geometry due to the wear. These phenomena place demands on the measuring equipment. Forces can be measured indirectly form the power input or torque, and with dynamometers. Indirect methods are insufficiently sensitive, yielding results with reduced accuracy due to the estimation of the efficiency. Dynamometers must have high toughness, sensitivity and low inertia. There are several types of dynamometers which are based on various physical principles (e.g. mechanical, hydraulic and electrical). Only electrical dynamometers are sufficiently sensitive for use in machining. Electrical dynamometers use resistors, magnetic induction, capacitators or piezoelectric crystals. Piezoelectric dynamometers are a suitable type of dynamometer that meets all main requirements for detecting the small changes in the cutting process.

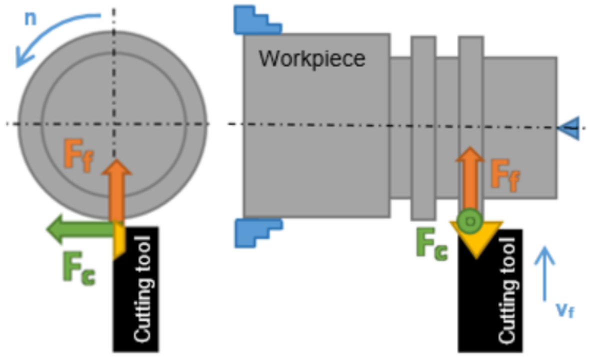

Figure 12. Force interaction at orthogonal turning of disks.

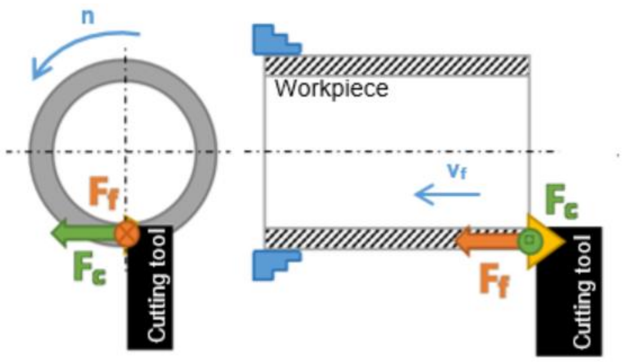

Figure 13. Force interaction at orthogonal turning of pipe.

In orthogonal turning, two components of the resulting force can be identified (the passive force is theoretically equal to zero). The cutting force acts in the direction of the main cutting movement (workpiece rotation and cutting speed). The feed force acts on the center of the workpiece when machining the discs (Fig. 12) and parallel to the workpiece axis when machining pipes (Fig. 13). The workpiece is subjected to a bending force in the case of disc turning and may impair the shape accuracy in the case of small diameter workpieces.

There are some rules for the correct clamping of the cutting tool, which must suit the requirements of the type of dynamometer. The highest force must be caught in the direction of the highest stiffness of the dynamometer. The mass of the clamping device should be as small as possible. More mass decreases the ability of the dynamometer to absorb resonant vibrations from the dynamic loads. On the other hand, the clamping device must be tough and strong enough in order to stabilize the cutting tool. Instability of clamping leads to additive vibrations and faster cutting tool wear or destruction.

4 VIBRATION ANALYSIS

Another parameter that can be used to compare individual coatings is the vibration that occurs during machining. In terms of vibration, we can distinguish two states in machining: stable (chatter free) and unstable machining (chatter). Unstable machining is an undesirable phenomenon that can damage the tool, workpiece and machine. Therefore, we try to avoid chatter during tests. A certain disadvantage of turning is the fact that the cutting force is static and therefore does not excite any vibrations. Therefore, it is appropriate to measure oscillations in non-stationary processes such as approach and exit from the cut. The second possibility is the turning of a special shaped workpiece, the shape of which will be optimized so that the thickness of the cut changes over time and thus a time-varying cutting force is generated.

Piezocrystalline accelerometers are standard sensors for measuring vibrations, and we choose the IEPE standard. Accelerometers can be connected to a wide range of analyzers. The main parameters for their selection should be a 24-bit AD converter and a frequency range above 1 kHz. The optimal location of the accelerometer is the tool edge, which is not feasible. Therefore, we place the accelerometers on the body of the tool as close as possible to the cut (Fig. 14). From a practical point of view, we choose clamping with a sufficiently strong permanent magnet. If possible, we use screw clamping.

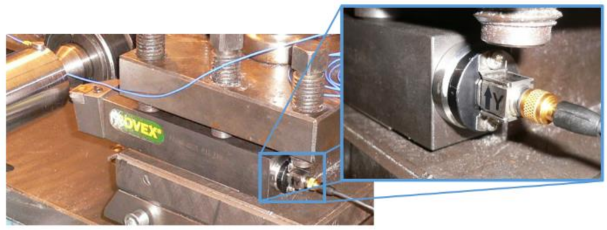

Figure 14. Setup of vibration measurement in longitudinal turning.

The effect of tool wear on the amplitude of vibration has been published by Kumar [Kumar 2018]. The tribological properties of the coating and the surface roughness have an influence on the friction, which in turn affects the generation of vibrations [Weremczuk 2016]. The source of vibration is usually the least rigid part of the machining system chain [Kuljanic 2008]. The influence of different geometries and cutting conditions, and the possibilities of their suppression, were discussed by Falta [Falta 2018]. Another possibility for indirect comparison is the effect of vibrations on the specific cutting force, as demonstrated by Drobilek [Drobilek 2019]. Janota and his team showed an operating method for identifying the tangential coefficient of the specific cutting force [Janota 2019].

5 ACOUSTIC EMISSION MONITORING

Acoustic emission is the fastest way, how to recognize changes in a machining system because acoustic waves spread with the speed of the sound in the given environment. It is an alternative measurement method to vibration analysis. This method could be used for the measurement of tool wear detection. Acoustic waves arise as a result of the dynamic release of mechanical stress within the material, due to contact of adjacent bodies (dry or lubricated - for example rolling bearings) or due to the cutting process during machining. These excitations subsequently act as sources of elastic stress waves. The waves propagate inside the bodies and especially on the surface. These elastic tension waves can be detected by a piezo sensor known as a 'sensor of acoustic emission'. These sensors are mostly broadband sensors, typically with a range of 0.1 to 4 MHz. Their resonant frequency can be above the observed frequency range of acoustic emission, or can be inside of the monitored band. Chiou presented measurable influences of the tool wear and width of cut on the RMS AE signal [Chiou 2000.]

The acoustic sensor should be located on the underside of the turning tool holder (Fig. 15). It is the closest place to cutting zone, but the safety of the sensor must also be ensured. The acoustic wave is detected as soon as possible, without the risk of damaging the sensor during cutting (from chips or liquids). A high sampling rate acquisition device should be used; the reason is the same as for vibration sensors. The problem with measuring acoustic emission is the impossibility of recognizing where an acoustic tension wave arose. Therefore, if a comparison is to be made between different coatings, all variables entering the machining process must be thoroughly excluded.

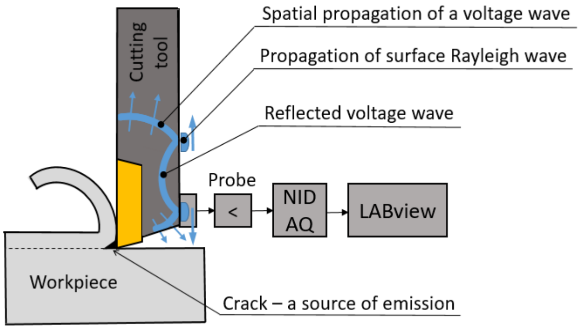

Figure 15. Setup of acoustic emission measurement.

6 CUTTING TEMPERATURE MEASUREMENT

The cutting tool coating also serves as a thermal barrier between the chip and the newly formed workpiece surface and the cutting tool, as mentioned earlier. The energy from the cutting process is for the most part converted into heat. The main heat sources are deformation in the formed chip (primary shear zone), friction in the contact zone between the cutting tool and the chip (secondary shear zone) and deformation of the newly formed surface (tertiary shear zone).

The micro geometry of the cutting coating can contribute to the increasing heat generated in the cutting zone. In addition, the chemical composition of the coating has a further effect on the diffusion and oxidation processes at high temperatures of machining, and changes the tribological properties in the cutting zone. The ration of conducted heat varies between chip, workpiece, and cutting tool, with different coatings. In addition, the chemical composition may or may not assist in dissipating heat to the cutting tool.

There are several methods for measuring temperature during machining. Various methods give different values of temperature from separate places in the machining zone and other important chosen places included in the machining process.

Infrared sensors allow for the measurement of temperature and temperature field on the visible parts of the machining system. Embedded thermistors and artificial or semi-artificial thermocouples give the point temperature of any chosen place. The highest temperature is measured only on the cutting edge and it is called the 'cutting temperature'. The cutting temperature is the average temperature of all the contact points and areas between the cutting tool and the workpiece. The cutting temperature can be measured by a tool-work thermocouple [Kaminise 2014, Grzesik 1999].

A tool-work thermocouple is based on the Seebeck phenomenon. The electromotive force (EMF) is a voltage that arises due to a difference between electric potentials of two different metals when one of the junctions is heated and the second one has a stable temperature (e.g. room temperature). The basic requirement is electrical conductivity of the cutting tool and workpiece. Sutter, M'Saoubi and Rech all tried to identify temperature of the tool-chip interface by infrared cameras [Rech 2006, M'Saoubi 2004, Sutter 2003].

The design of a tool-work thermocouple is relatively complicated. The basic issue is how to conduct the electromotive force from the stationary to the rotating part of the thermoelectric circuit without introducing a parasitic temperature that can affect the resulting EMF. A suitable solution to this is to use a mercury bath translation. Another method is to use a contact brush or tips, but they can be a source of the parasitic junction. The second important factor is the insulation of the thermoelectric circuit from the rest of the machining system due to the suppression of the other parasitic EMF signal. The last major problem is the need to calibrate the thermocouple for every pair combination of the tool and workpiece materials. The entire setup of the thermocouple for working with tools is shown in Fig. 16.

The thermocouple can be calibrated, for example, under the flame of a butadiene torch, in a temperature controlled furnace, or in a bath of molten metal.

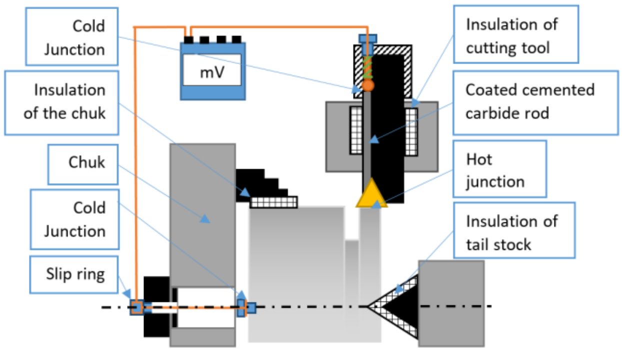

Figure 16. Setup of cutting temperature measurement.

The signal of the EMF flows through the circuit only when the circuit is closed. Therefore, the beginning of the measurement is when the cutting tool is in contact with the workpiece. The response signal of the tool-work thermocouple is in the Fig. 17.

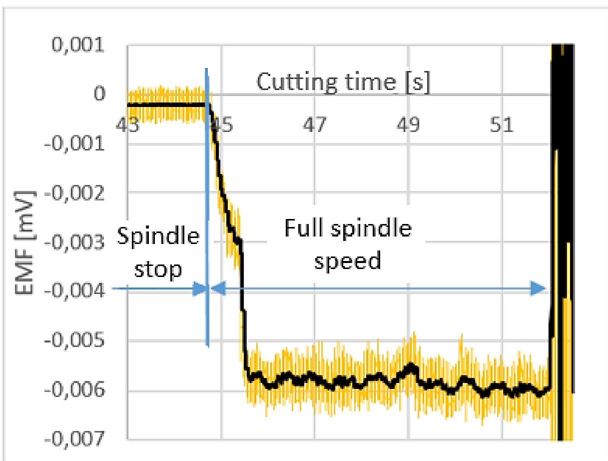

Figure 17. EMF signal from work-tool thermocouple.

7 CUTTING TOOL WEAR ANALYSIS

Different coatings perform during machining different cutting tool wear depending on the machined material. The cutting tool wear varies in the size, intensity or dominant type of wear. Areas of the tool that are in contact with the workpiece are abraded, chipped, deformed, broken or chemically worn, and thus change the cutting tool geometry and micro geometry. In turn, the cutting tool coating is being worn out during machining. This phenomenon has a significant effect on the economy of the machining process, because when the wear of the cutting tool reaches a certain critical value, it should be replaced by another. The wear and its progress are a measurable phenomenon. The main goal is to achieve the smallest intensity of wear under given cutting conditions.

In some cases, the coating is not abraded, but impact and thermal shocks can cause thermal cracks in the coating and expose the carbide substrate. In this particular case, the coating must be able to stop (or slow down) the spread of this crack.

Cutting tool wear assessment is the main and most widely used standardized method for assessing the cutting ability of a cutting tool. Different types of cutting coating provide different protection for the cutting tool. Many studies compare various types of coatings based on the results from tool life analysis, e.g. [Capasso 2019] or [Grzesik 2018].

The size of wear is described in the standard ISO 3685:1993 and due to the comparability of measured values it is necessary to follow the recommendations of this standard. The various wear parameters of the cutting tool can be evaluated for the flank surface (Fig. 18) and rake surface (Fig. 19). In some specific cases, the wear of the cutting tool can be evaluated by the flank wear area method. This method was used by Alagan [Alagan 2019].

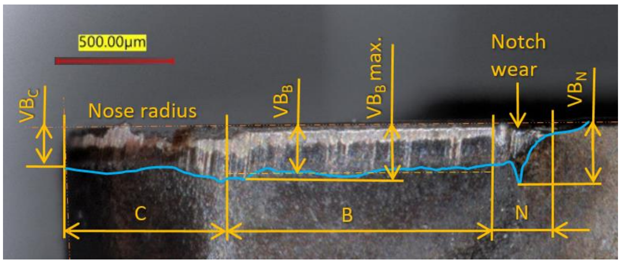

Figure 18. Selected parameters of the flank surface wear measurement.

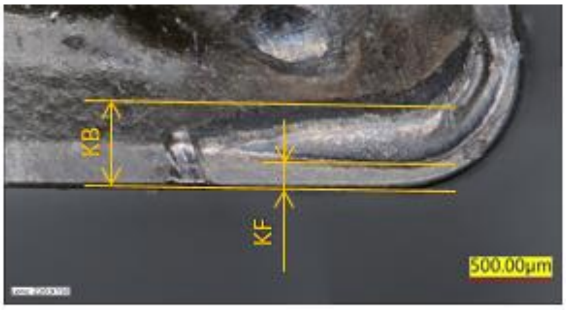

Figure 19. Selected parameters of the rake surface wear measurement.

The wear of the cutting tool depends on many external influences and many of them are considered accidental. The variability of the measured values is relatively high, also under the same cutting conditions. On the other hand, monitoring cutting tool wear is time consuming and costly. It is necessary to find a balance between the number of replications and costs.

Optical microscopes are particularly suitable for measuring tool wear. Digital microscopic cameras, along with automatic movement / zoom along the Z-axis, makes it possible to take photos with an impressive depth of field. In order to be able to select the wear width values correctly, a sharp drawing of the wear edges is necessary. Some microscopes allow the microscope lens to be tilted, enabling viewing of the damaged cutting edge from the flank and rake surface. If the microscope does not allow the lens to be tilted, a special clamp is required for the cutting tool. The surfaces of the cutting tool wedge are not usually perpendicular to each other, and if the direction of view of the lens is not perpendicular, a first-order angular error occurs. The angular error can be corrected mathematically.

8 ANALYSIS OF THE INTEGRITY OF MACHINED SURFACE

Integrity of machined surface covers many different characteristics. Micro geometry and chemical composition of the coating affects surface roughness, hardness and micro hardness, and in certain cases also geometric and dimension accuracy. Under intensive heat loading, the diffusion and chemical interaction can change the chemical structure of the machined surface, which is indirectly measurable by the methods discussed below.

The most preferred characteristics of the surface integrity are geometric accuracy, surface roughness, surface hardness and micro hardness, as well as chemical structure. Coatings affect surface integrity by the micro geometry of the cutting tool and the chemical composition. Most testing methods require additional adjustment of the shape, dimensions, or surface of the workpiece, due to the requirements of the especially precise measurement device or method used.

8.1 Geometric and dimensional accuracy

Roundness and cylindricality are geometric accuracy characteristics used for rotating parts made by turning. The results of these factors reflect a lack of clamping or improper operation of the machine tool. Small deviations in geometric accuracy can be caused by rapid wear of the cutting tool or the formation of a built-up edge. These phenomena are closely related to the coating of the cutting tool.

Measuring the geometric accuracy requires special and precise measuring machines, using the principle of point measurement or a continuous measuring cycle. The most suitable device for this purpose is a roundness tester. A precise measuring device should be used because the influence of the coating on the geometric accuracy is predicted to be relatively small. Coordinate measuring machines (CMM) are usually less accurate than a roundness tester, but are also suitable. It is also possible to use distance amplifying instruments when the workpiece has too large dimensions, but will yield reduced measurement resolution.

8.2 Surface roughness

The workpiece surface roughness is mainly determined by the geometry of the tool and the cutting conditions. The thickness of the coating changes the nose of the cutting tool very slightly and this change affects the surface roughness in combination with the feed. The higher effect of the coating can be observed on the cutting edge micro geometry due to the cutting edge radius and surface roughness. The adhesion of the coating affects the formation of built-up cutting edges, which changes the geometry of the tool wedge. By evaluating the surface roughness of the machined surface, the suitability of the coating for a given application in a given range of cutting conditions can be determined. Gökkaya's study showed that surface roughness measurements are sensitive enough to change the type of coating [Gökkaya 2006]. Surface roughness measurements are described by ISO 4287 [ISO4287 1997] for two-dimensional measurements and ISO 25178-2 [ISO25178-2 2012] for three-dimensional measurements.

Surface roughness is measured using devices based on optical or contact principles. A practical device for workshops is a surface roughness tester with a diamond stylus tip on the swinging rod. The smaller dimensions of these workshop devices allows for using them directly in the machine tool space. There are also more accurate touch roughness gauges for laboratory purposes, but only for a smaller wrokpiece specimen size. Optical devices for measuring surface roughness include precise laboratory microscopes with the capability of surface scanning. These measuring instruments are suitable for the scanning of the surface roughness. Scanning can be done by the focus variation method or laser scanning. However, specimens must have relatively small dimensions for such laboratory devices.

8.3 Hardness

The hardness of the surface after machining should ideally be the same as before machining. If the hardness newly created surface is higher, it could indicate significant plastic deformation of the machined surface or alloying of machined surface with hard particles from the cutting tool coating. Hardness testers can detect a change in hardness after machining.

There are many methods that can be used to measure the hardness. Some well-known methods, such as Brinnell, Rockwell and Vickers, are usually used for laboratory measurements. They use an exact load of the indenter, and a microscope to measure the size of the imprint. Dynamic methods are more suitable for workshop measurement. They measure the rebound of the impactor and its height or speed of the rebound. These devices are useful for large workpieces.

8.4 Micro hardness

When the hardness is different before and after machining, it is important to know how deep the higher hardness penetrates below the machined surface. In some cases, the measured hardness could be the same on the surface both before and after machining, but under the surface layer the hardness may have changed. Micro hardness testers are used to detect changes in micro hardness. Ordinarily, these are based on the Vickers method at specific loads according to the ISO 4516 [ISO4516 2002] and ISO 6507-1 [ISO6507-1 2018] standard.

On specially modified samples, measurements are made at various depths below the surface. When the value of the micro hardness stays equal for a few consecutive measurements, the maximum depth of micro hardness below the surface is reached. It is necessary to provide a specific section of the sample at a particular small angle, usually 7° to 10°. This angle facilitates micro hardness measurements at very small depths below the machined surface. For cylindrical workpieces, a different type of specimen must be prepared. A round workpiece can be made as a cylindrical sheet [Krolczyk 2014] or as a cylindrical section (Fig. 20), which Vosough used for the identification of the residual stress under the machined surface with an X-ray diffractometer [Vosough 2005], but the principle of specimen preparation is applicable also for micro hardness measurements. The better results of measurement is possible to obtain Better measurement results can be obtained if the surface of specimen was polished before the measurement [Warren 2006]. The indenter imprint is then more clearly visible.

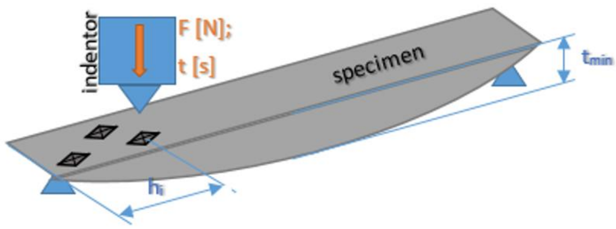

Figure 20. Shape of specimen for the measurement of micro hardness beneath the machined surface.

The micro hardness under the machined surface can be shown as a diagram of the dependence of the micro hardness on the depth below the machined surface (Fig. 21). A comparison between two cutting coatings can reveal a coating that has a less pronounced effect on the hardness below the surface.

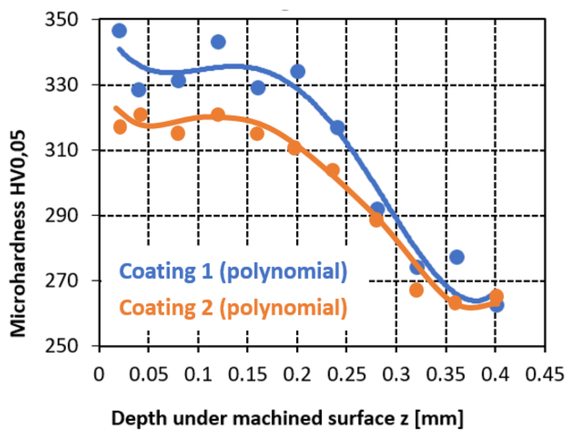

Figure 21. An example of the microhardness variation beneath the machined surface for orthogonal turning of Ti6Al4V without coolant (v_c = 210 m/min; a_p = 2 mm; v_f = 3000 mm/min) for the specific cutting tool geometry and various coatings.

8.5 Residual stress

Uneven plastic deformation or thermal loading of the workpiece surface can cause residual stresses in the surface layer of the machined workpiece surface, depending on its significance. The influence of the coating due to its tribological properties or the influence on the micro geometry of the cutting edge can also be recognized by measuring the residual stresses.

It is possible to use a specimen in the form of the cylindrical segment for measuring residual stresses, see Fig. 20. The surface layer must be electrochemically polished to prevent the formation of residual stresses caused by specimen preparation. Residual stress measurements can be performed non-destructively for example by X-ray diffractometry [Vosough 2005] or by destructive methods such as hole-drilling or layer removal method which uses strain gauges [Rossini 2012].

CONCLUSION

There are many different types of cutting tool coatings that are suitable for a particular workpiece material. These cutting tool coatings are tested by various methods, including tests of hardness, chemical composition, friction properties, etc. The property values obtained from these tests do not provide basic information about the suitability of the cutting tool coating for machining a selected workpiece material. Experimental investigation of the coating properties within the cut is an integral part of improving our knowledge of the behaviour and properties of the coatings. A lot of the parameters is possible to observe during machining as well as many of them are affected by cutting tool coating. This article introduced some key experiments that can help find the most suitable cutting coating for a given application. These technological tests are performed directly during machining or immediately after machining. These experiments also make it possible to find suitable cutting conditions for the tested cutting coatings, or to find the optimal combination of coating and cutting conditions for a given type of workpiece.

Many important quantities can be observed during and after the machining process, which tell us about the real behaviour of the coating within the cut. The most important quantities captured during machining are forces, vibrations, temperature in the cutting zone or chip formation. Cutting tool wear, shape and chip size, or surface integrity parameters, are measured after the machining process. These, and several other measurable quantities, have been described in this article and have been assessed for the coating of the cutting tool. The chemical composition and method of production have an effect on the measured quantities. However, the difference in geometry and cutting conditions must be excluded from technological experiments, otherwise the effect of the cutting coating will remain hidden.

All of the mentioned measurements can contribute to forming the overall picture of the coating function. They can detect small differences between different cutting coatings, and can help identify a suitable coating for a given material alongside suitable working conditions.

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