Concurrent Measurement of the Tool Co-ordinate and Tool Wear in Turning

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Abstract There has been developed an original method of direct measurement of turning tool wear at the tip of the cutting edge. The measurement is made automatically on an NC lathe by a special probe, which at the same time, enables to determine the X co-ordinate of the edge. In the first original solution the measurement was conducted using a probe with two sensors. The improved probe, patented by one of the authors, has only one displacement sensor. The improvement has not only simplified the probe but also made tool wear measurement more accurate. The results of laboratory tests show great promise in a number of industrial applications.

Keywords: Monitoring, Turning, Tool Probe, Tool Wear Measurement

1 INTRODUCTION

Needs for monitoring and automatic supervision in machining are growing due to high demand for quality and economy in modern manufacturing as well as much higher speeds of movements in manufacturing equipment. Possibilities of fulfilling the needs are also growing thanks to improvements in sensors, signal processing and control technology. A lot of research has been carried out and the CIRP has been active in the field for years. A train of periodic conferences under the CIRP supervision started in 1980. The nearest one is planned for 2004 [1].

Automatic supervision may be needed for every element of a machining system [2], but tools are usually the first choice. Monitoring is the first, and usually the most difficult, step in the implementation of any automatic supervision. Monitoring of tool wear is especially difficult but vital for every machining process. A cutting edge of the tool is the element of the system, which has the shortest time of life. It should be frequently replaced – in many cases of turning after about ten minutes of cutting. The review of research in the field of tool monitoring has been presented in a CIRP keynote paper [3] and a long list of publications has been set [4]. Some tool monitoring systems have been produced and implemented in industry by specialized companies [5].

In tool wear two cases must be distinguished: a sudden destruction of the cutting edge, called catastrophic tool failure, CTF, or natural tool wear, NTW. The automatic supervision in the case of CTF is based on detecting the failure as quickly as possible and the immediate interruption of cutting. So far the prediction of CTF is not possible. A delay in interrupting the cutting process may cause a serious damage and a costly interruption in production. A lot of research has been carried out on CTF detection and there are several monitoring systems for the purpose based mostly on characteristic changes of cutting forces or stress waves, frequently called acoustic emission, AE.

In the case of NTW, the geometry of the cutting edge changes progressively diminishing both effectiveness and accuracy of machining up to the state when the edge is dull and should be replaced by a sharp one. Since the beginning of cutting research, many years ago, some geometric parameters of the edge have been chosen for the evaluation of NTW. The mean length of flank wear land, $VB_{B,}$ or the length of nose wear land, $VB_{C,}$ are frequently used for the purpose. Unfortunately, it seems to be impossible to measure the geometric parameters of the tool edge during turning and that is why it was impossible to monitor NTW directly. There were attempts to use electric resistance of a special pattern of a foil laid on the flank surface of the cutting edge for the evaluation of VB during cutting by measurement of the changes in the resistance of the foil [6]. Another attempt was to measure pneumatically the change in the distance between the unworn part of tool flank surface and the just emerging new surface of the workpiece [7]. Unfortunately, such monitoring systems turned out to be too complicated and not reliable enough for industrial use.

There are many indirect methods of tool condition monitoring. In these methods, tool wear is monitored by measurement of different physical quantities somehow correlated with the geometric parameters of wear: cutting forces, vibrations, stress waves... A lot of sensors have been developed for indirect monitoring of tool wear [7]. Alas, in all methods of indirect monitoring there are two sources of uncertainty. Apart from errors in measurement itself, there are always additional errors, because the models connecting measured quantities with tool wear are not fully reliable. They are usually influenced by the current conditions of cutting.

Another solution to monitoring NTW is to use direct measurement of geometric parameters characteristic of tool wear not during cutting but during interruptions in the cutting process. In contrast to CTF, time delay in establishing the value of natural tool wear is not critical. The actual NTW value is needed for predicting the remaining part of tool life and planning the proper timing of the tool exchange. For contact measurement of the length of flank wear land, VB, multiple needle sensors were used [7]. For non-contact measurement, optical sensors were used. In the first attempts, it was a fiber optic sensor [8] and later CCD cameras. There is no information about the use of the systems in workshop practice.

Some machine tool producers claim that tool probes with touch trigger sensors, commonly used in NC lathes for automatic determination of the cutting edge actual position in an NC co-ordinate system, can be useful for tool wear evaluation. It is because the length of the nose wear land, $VB_{C,}$ is easily connected with the withdrawal of the tool nose in the direction of axis X, KE, as it is shown in Figure 1a. For the given tool, KE is proportional to VB_C with the coefficient dependent on the angles of the edge. Typically, the KE value is about one tenth of the VB_C value. The value XN of the X co-ordinate, which determines the tool position, is registered when the tool nose activates the touch-trigger sensor, TTS, Figure 1b. The change in the values measured when the tool is sharp XN_0 and after a certain period of cutting XN_i is believed to be equal KE. The practice shows that there are other influences on the value of XN much stronger than KE. First of all, it is the influence of thermal deformations of the lathe and of other elements of the machining system. The procedure is then not good for monitoring tool wear.

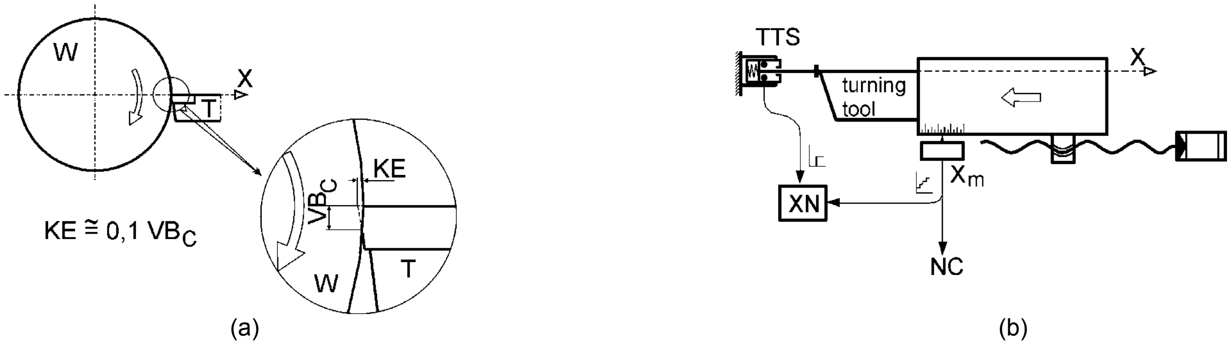


Figure 1: Geometric parameters of tool wear a) and use of a touch-trigger sensor in NC turning b)

In industrial practice, the only system used for some kind of tool wear supervising could be called “virtual monitoring” because it is based on a model of tool wear and not on real wear. It uses automatic summing up of the cutting times of the edge by the NC controller and compares the result with the predicted tool life.

2 AN IDEA OF TOOL WEAR MEASUREMENT

The idea of the proposed tool wear monitoring system is also based on KE measurement by a tool probe, but by a special tool probe. The special probe apart from sending a signal which allows determining the value of the tool nose X co-ordinate is also measuring KE relative to a chosen point on the flank surface used as a basis for measurement. Because the basis of measurement is situated on the same tool and close to the cutting edge all disturbances, including thermal deformations, are minimised. The idea of the proposed tool wear monitoring system is also based on KE measurement by a tool probe, but by a special tool probe. The special probe apart from sending a signal which allows determining the value of the tool nose X co-ordinate is also measuring KE relative to a chosen point on the flank surface used as a basis for the measurement. Because the basis of measurement is situated on the same tool and close to the cutting edge all disturbances, including thermal deformations, are minimized.

In the first solutions, two sensors were built into special probes. They were either both touch trigger sensors, TTS, or one TTS and one linear variable displacement transducer, LVDT. The example of a system with such a probe is shown in Figure 2. The on-off signal send by the TTS is used not only for the registration of the tool nose co-ordinate value, XN, but also for the registration of the X’N value measured by a LVDT. In our probe, LVDT was an inductive sensor. The sharp tip of the LVDT touches the flank surface of the tool outside its worn zone. The KE value is calculated as a difference between $X'N_0$ (registered when the tool was sharp) and $X'N_i$ (measured at the time of monitoring, after some time of cutting).

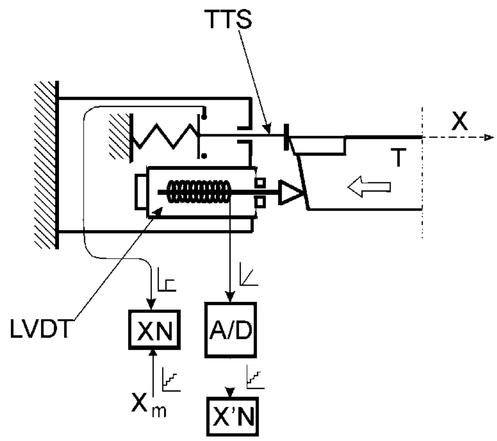


Figure 2: A tool probe with a touch-trigger sensor, TTS, and a linear variable displacement transducer, LVDT, used for the proposed method of tool wear measurement

Laboratory tests of such probes were promising. The values of VB_c calculated on the basis of KE obtained from the probe measurements were close enough to the VB_c measured on a microscope [9]. The probe could be used during an interruption in cutting either as a "standing alone" monitoring system of tool wear or for checking and calibrating of an additional, indirect monitoring system used during the cutting process.

3 A NEW IDEA OF TOOL PROBE

As a result of the research a new tool probe has been developed and patented. In the new probe only one LVDT with the flat tipped finger has been used. Another finger with a sharp tip has been attached to the body of the LVDT. The idea of the probe is presented in Figure 3. The whole LVDT sensor may be moved inside the probe, against the force of a spring. During measurement, the tool T moves toward the probe. The nose of the tool is pressing on a flat tip of the LVDT finger. When a signal from the LVDT reaches a certain value, established in advance (e.g. 1000 μm), the value of the X co-ordinate, measured by the NC system, is registered as a position of the tool edge XN. The tool moves farther by an established distance, e.g. 2 mm. During this movement the sharp tip of the finger attached to the LVDT body is pressing on a distinctive point of the not worn flank surface of the tool used as a basis for measurement. It makes the whole LVDT slide inside the probe against the spring force. When the tool stops, the signal of the LVDT is registered as X'N. The KE value is again calculated as a difference between $X'N_0$ (when the tool was sharp) and $X'N_i$ (measured during monitoring).

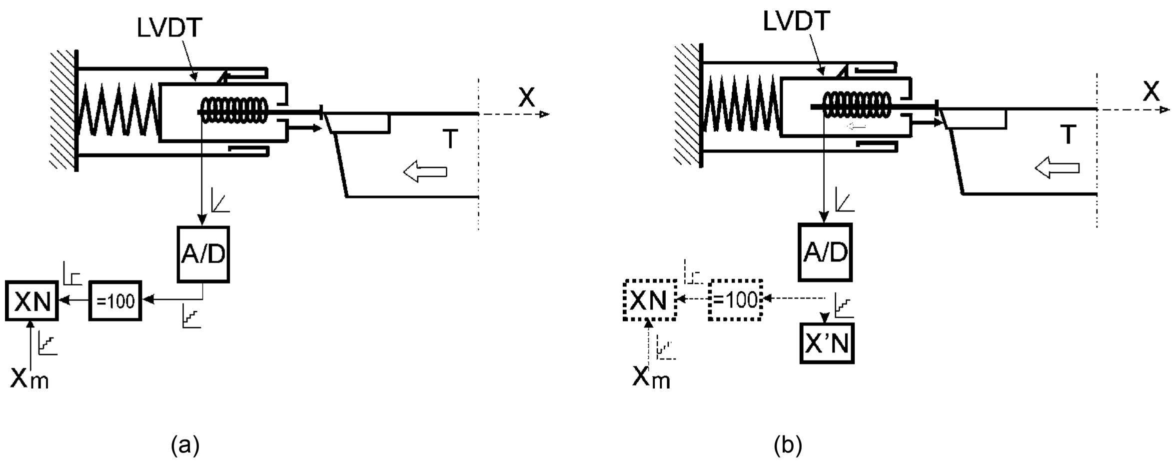


Figure 3: A probe with one LVDT: a) registration of XN, b) registration of X'N

The new probe is relatively simple. Even more important is the fact that with this kind of design of the probe, the distance between the fingers may be smaller. The basis of measurement may be then located closer to the tool nose, in most cases on the cutting insert itself. The X'N measurements may be more accurate.

4 THE NEW PROBE AND THE TEST BED

The design of the new probe is presented in figure 4. A professional inductive transducer, with the measuring ranges ±2 mm and linearity 0.3%, has been used as a LVDT.

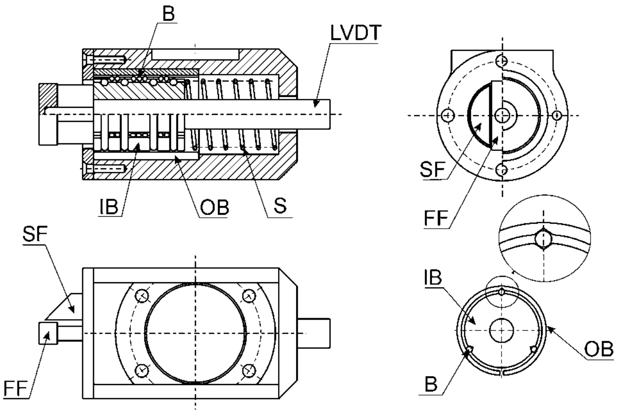


Figure 4: Design of the new probe

The LVDT body is connected to a cylindrical bush IB. They may be moved together inside an outer bush OB and are pressed to a lid of the probe by a spring S. The spring S is attempting to move them outside the probe. The inner bush IB is guided in the outer bush OB by three rows of balls B. The LVDT has a flat topped finger FF and the inner bush IB has a sharp finger SF. During orientation of the tool in X axis of the co-ordinate system of the NC lathe the tip of the cutting insert is pressing on the flat topped finger of LVDT, FF. During measurement of the tool wear the sharp finger SF is pressing on the unworn part of insert flank surface. The inner bush together with the LVDT is then moved further inside the probe.
The probe was tested on an NC lathe. For convenience reason, the probe was fixed to the tailstock spindle as it is shown in figure 5.

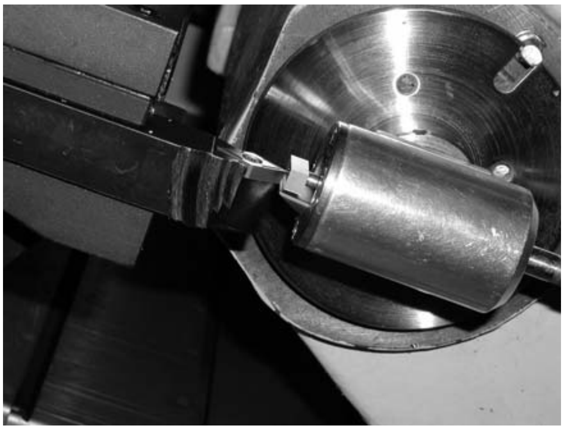


Figure 5: The probe mounted on the tailstok of the lathe

The tool wear measurements by the probe were carried out automatically. For checking purposes the cutting inserts were unfasten and taken of the toolholder for tool wear measurements under a microscope. The fact that an insert was taken of the toolholder did not influence accuracy of later measurement by the probe because the basis of the measurement was at the insert itself. The figure 6 shows an insert under the microscope.

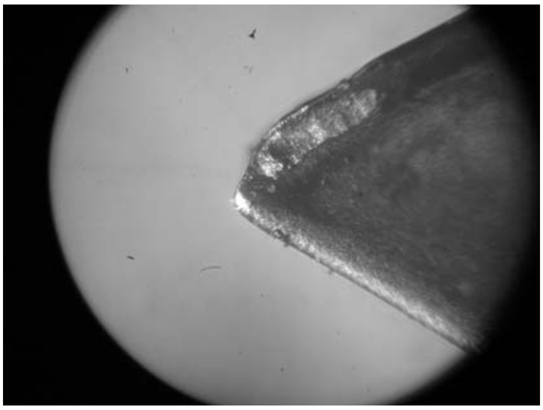


Figure 6: A cutting insert under the microscope after 33.07 min of cutting with v_c=100 m/min and 150 m/min. KE=0.054 mm (VB_c=.46 mm)

As an alternative, the pictures of the cutting inserts have been taken by a digital camera. In this case the inserts were not removed from the toolholder. An example of the picture after computer processing is shown in figure 7. The known dimension of the insert was also measured for the purpose of calculation of the actual scale of the picture.

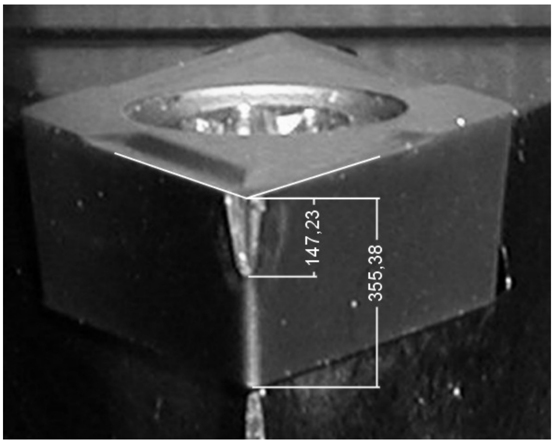
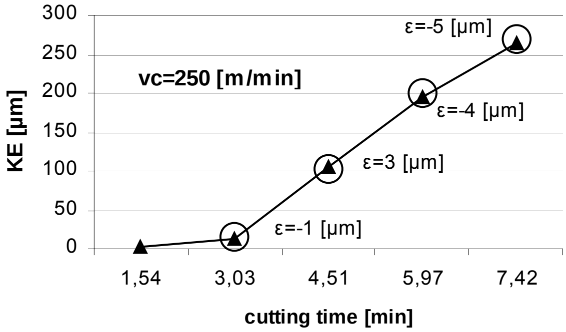


Figure 7: A picture of the insert after 5.97 min of cutting with v_c=250 m/min. VB_c=1.64 mm (KE=0.196 mm)

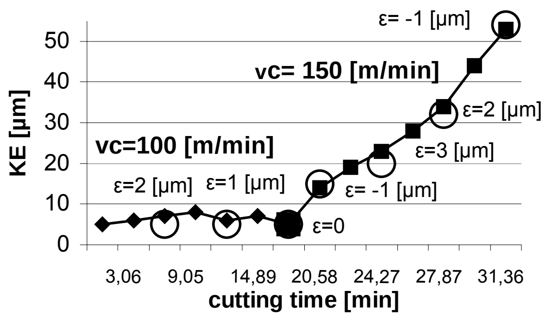
5 RESULTS OF THE TESTS

The results of tests when the developed probe was used to determine the X value of the cutting edge in the co-ordinate system of the NC lathe were about the same as with a Renishaw touch-trigger probe. Stiffness of an arm supporting the new probe had to be higher because of a slightly bigger force applied by a tool to the probe.

During measurement of tool wear, cutting tests were conducted. As the tools, ISCAR cutting inserts DCMT 11T303 IC 8025 in a toolholder SDNCN 2020K-11 were used. Steel NC6 (1.4% C, 0.6% Mn, 0.3 Si, 1.4% Cr) was machined with the depth of cut a=0.5 mm, feed f=0.1 mm/rev and different cutting speeds.



(a)



(b)

Figure 8. KE values during a test with cutting speed v_c=250 [m/min] (a);
when the cutting speed was changed from v_c=100 [m/min] to v_c=150 [m/min] (b)

Two examples of the test results are presented in figure 8. Triangles on the plots represent the results of the measurements by the probe. Circles represent the results obtained during measurements under a tool microscope. When both measurements were made, at the same state of wear, the difference between the measurement by the probe and the KE value measured under the microscope is written by the plot as ε.
The test presented in figure 8b was interrupted after about 32 minutes of cutting because of a very small rate of tool wear. The KE obtained the value of only 50 μm.

6 CONCLUSIONS

The laboratory tests of the proposed method for natural tool wear monitoring show that the method is good enough for industrial applications. The developed tool probe may be used at the same time for tool edge orientation and for automatic tool wear measurement. Installation of the tool wear monitoring system does not require changes in the lathe design. The typical tool probe should be replaced by a new probe. The machine tool controller should be adapted to the new functions. It may be necessary to increase stiffness of the probe arm.
The new probe makes it possible to monitor directly natural tool wear at the tip of the edge during any interruption in the turning process. Because the cutting insert wear, KE, is measured relative to unworn part of the same cutting insert, the measurement is practically insensitive to all disturbances. The measured value of KE may be also used directly for correction of the error of the workpiece diameter caused by tool wear.

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