Tool Probe for Measuring Dimensional Wear and X Co-ordinate of Turning Edge

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An original method of direct measurement of turning tool wear at the tip of the cutting edge, made automatically on an NC lathe by a probe, which at the same time allows for determining the X co-ordinate of the cutting edge. In the initial solution, this measurement, patented by one of the authors, was carried out using a special probe with two touch-trigger sensors or one touch-trigger sensor and a displacement sensor. The improved probe has only one displacement sensor. The new solution has not only simplified the probe but also made tool wear measurement more accurate.

Keywords: *direct measurement of tool wear, tool monitoring, tool probe for turning*

1 Introduction

Automatic supervision of tool wear is vital for any machining process. The cutting edge of a tool is an element of the machining system which should be frequently replaced – in most cases of turning after about ten minutes of work. In the event of a sudden destruction of the cutting edge, called catastrophic tool failure, CTF, serious damage and costly interruption in production may happen. Natural tool wear, NTW, changes progressively the geometry of the cutting edge diminishing both effectiveness and accuracy of machining. Some kind of NTW "virtual monitoring", mostly used in industrial practice, is based on summing up (in an NC controller) the cutting time intervals of every tool and signalling when accumulative time is approaching the expected tool life. But the tool life may vary considerably, especially when cutting with changeable parameters, and this kind of situation is typical in flexible production. To be on the safe side, the shorter tool life is assumed and the tool in most cases is changed too early, diminishing efficiency and increasing the cost of machining. Many research institutes and R&D departments in industry have tried to solve the problem by building a reliable and inexpensive system for tool wear monitoring accommodated to industrial environment, but so far without full success.

Most of research work has been aimed at monitoring catastrophic tool failure [1,2,3], and some success has been achieved. CTF monitoring systems are usually based on measurement of cutting forces or stress waves (called acoustic emission, AE) generated by the cutting process. Existing monitoring systems allow for signalling CTF when it occurs. The process may be stopped at once, diminishing damage. So far they do not allow for predicting CTF and are not useful for monitoring natural tool wear growing during cutting.

For fully automatic machining of workpieces, a system of tool wear monitoring should be able to:

1. to signal any dangerous state of tool edge wear in which the cutting process should be stopped,
2. to evaluate the actual state of tool wear and assess how much of tool life is still left,
3. to measure the geometric parameters of tool wear which influence dimensions of the workpiece generated during machining.

Task 1 is important from the safety point of view and in the most cases is dealing with catastrophic tool failures.

Task 2 is important for proper on-line planning of the tool exploitation and changing the tool, just in time, for a new one, of the same kind but sharp one.

Task 3 allows for proper correction of the NC program and elimination of inaccuracies of the workpiece, which would be caused by the change of the tool geometry.

Task 1 should be fulfilled as soon as possible. Any delay may be dangerous.

Tasks 2 and 3 may be fulfilled with some delay. In the cases of rather short machining cycles, when comparing to the tool life, they can be even fulfilled during interruptions between the machining of consecutive workpieces.

1.1 Direct methods of identifying the state of wear of a turning tool [4]

The tool wear process generally occurs in a mode dependent upon: the cutting conditions, workpiece and tool materials and the tool edge geometry. Different forms of tool wear during metal cutting are observed i.e.: rake face wear, flank face wear, nose wear, edge rounding. Geometric parameters of particular wear forms are standardized and called tool wear features.

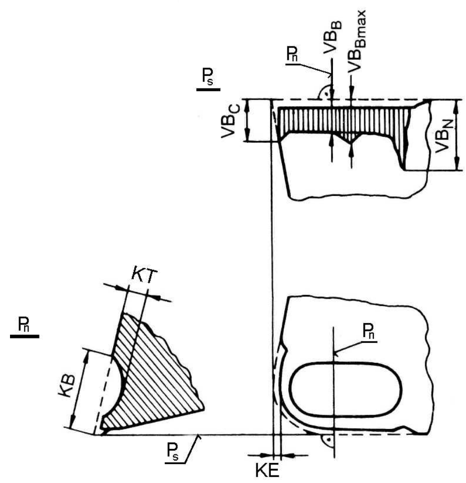

Fig. 1. Typical features of turning tool wear

VB_B – flank wear land length, mm
VB_C – nose wear land length, mm
VB_N – notch wear, mm
KB – distance between primary cutting edge and the most distant crater
KE – tip wear, mm
KT – crater depth, mm

The tool wear features described above, although standardised, are not the only ones used in research work. Investigating tool wear, one must accept these features, which best determine the end of tool work. It can be i.e. auxiliary flank face wear, not mentioned above.

1.2 Methods of tool wear measurement.

The tool edge, when in the cutting zone, is inaccessible to direct observation and its wear measurement is not possible. Besides, the tool wear can be of various forms. It is the reason why the tool wear diagnostics is faced with great difficulties not only from the measurement-technical point of view but also from the interpretation point of view. That is why despite much research work, we still have not a satisfying diagnostic and supervisory system of the natural wear of cutting tools.

Modern manufacturing systems, with their more and more sophisticated demand for the quality of products and production precision, require the application of systems monitoring the tool condition. Systems which are pointed not only at catastrophic wear but also at changes in tool dimensions caused by natural wear. The requirements that such diagnosing systems should meet may be formulated as follows:

- about 1μm accuracy and repeatability of the measurement along the direction of X axis,
- flexibility of the system (measurement of various kinds of tools),
- machine tool working ability not diminished,
- speed of operation (tool measurement and correction calculation should not prolong the machining cycle significantly),
- low cost of buying and installation on a machine tool,
- low sensitivity to disturbances arising during machining.

Tool wear measurements are divided into direct and indirect methods [5].

The direct methods are based on the changes of tool geometry. It means that they are based on geometrical features of the cutting edge. The indirect methods use the effects caused by tool edge wear and not the wear parameters themselves.

The direct methods are more reliable but are difficult to implement. The indirect methods are simpler to implement but their results are burdened with uncertainty resulting from inaccuracy of the model connecting wear with the measured quantity.

Indirect methods

The indirect methods, i.e. the ones based on the measurement of the wear effects, despite their uncertainty are applied in idustrial practice to estimate both natural tool wear and catastrophic tool wear. In comparison with the direct ones they need two-stage actions:

- measurement of the chosen physical quantity,

- use of a model making it possible to assess the tool state on the measurement bases.

To estimate tool wear by an indirect method the following physical quantities can be measured:

- cutting forces [6] and derivative quantities (moment, driving motor current [7], tool elastic strain);
- change in surface roughness or geometric dimensions of the workpiece [8];
- vibrations or noise [9];
- stress waves, so-called acoustic emission, AE [10,11];
- cutting temperature…

There is a lot of literature describing the solutions and tests of tool monitoring systems based on the indirect measurement. It indicates that many research centres are working on such measurement methods.

Most commercial diagnostic systems for industrial application are based on the measurement of one physical quantity (mostly cutting force) and are useful only during mass production in simple one-cut operations at the fixed cutting conditions. Sometimes wear identification is based on two measured quantities (the most often on acoustic emission and cutting forces) [12,13]. In the future, probably several various physical quantities will be measured simultaneously (multiple sensor systems) [14] and the appropriately elaborated strategy of the tool wear recognition will be used [15,16,17].

In practice, with different cutting parameters during tool life, at least one tool edge should be worn out for assessment of the tool wear strategy in this particular case. Such methods are not appropriate for the tool wear monitoring in the case of flexible manufacturing when only a few workpieces are going to be machined.

Direct methods

The direct methods of the tool edge state identification can be divided according to the measurement method in the following way:

- optical methods – based on the tool edge image analysis [18],
- touch methods – the most often by use of a tool probe [19],

- inductive methods – on a similar principle as the touch methods but they use the contact-less methods of measurement,
- contact resistance methods – estimating the wear land by the measurement of electric resistance.
- radioactive methods – based on the estimation of the tool edge mass decrease by the measurement of radiation.

Research on direct methods of tool wear identification took place mostly on the turn of the 1970's and 1980's, but without industrial application. Later scientists focused their research on the indirect methods. It was caused probably by difficulties of direct measurement and dynamic growth of electronics, as well as improvement in measuring transducers and progress in computers used for signal processing.

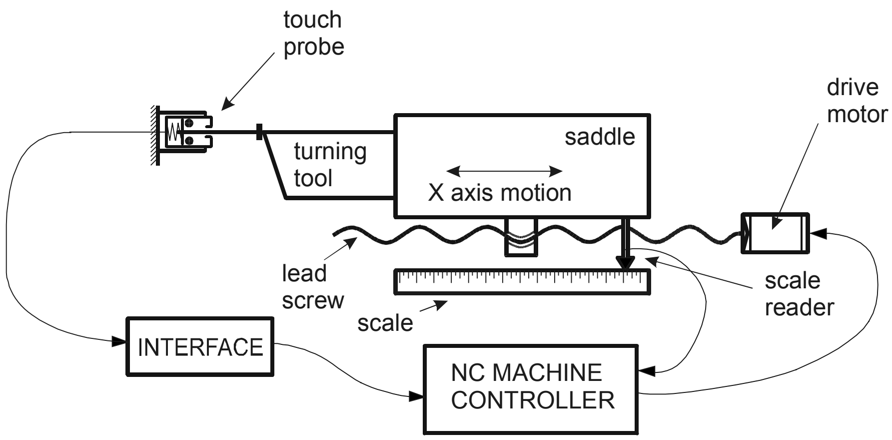

Fig. 2. The use of a standard touch trigger probe system for determination of X co-ordinate of the tool edge.

The solution of direct tool wear measurement advised most frequently for industrial use is based on the use of a tool probe, Fig. 2 . The tool probe is used as a standard for orientation of the tool tip in the co-ordinate system of the NC lathe. However, the application of the tool probes for the measurement of natural tool wear is not efficient, because of too great influence of other factors than the tool wear on the results of X co-ordinate measurement.

The method of direct measurement of natural tool wear proposed in the paper is based on measurement of relative displacement – when the reference point and the tip of the tool edge are on the same element - cutting insert. That is why the result of measurement is not affected by the errors of the machine tool nor thermal distortions. The probe described in the article can be fixed on a standard arm, the same way as typical tool probes. Besides wear measurement, our probe can be used for setting up the tool co-ordinate, the same way as a typical probe used so far.

2 Direct measurement of natural wear

2.1 Idea of measurement

Determination of the value of tool wear by measuring the wear index VB_C on a workshop microscope has been the method often used for the cutting edge wear identification. It permitted also to determine the value of the cutting edge retraction KE and to determine the needed correction of X co-ordinates in the NC controller of machine tool. The correction of co-ordinates is needed because natural wear of a cutting tool affects dimensional accuracy of the workpiece. In particular it is important during turning, since the wear in X direction KE expresses itself as double in deviation from the workpiece diameter. The direct influence of the cutting edge retraction on the accuracy of the turned diameter may be expressed as $\Delta\varnothing = 2KE$. Wear influences also cutting forces and through forces, indirectly, dimensional accuracy.

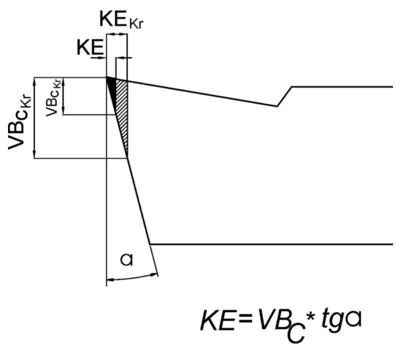

Fig. 3. Relation between VBc and KE.

The direct touch-method measuring the retraction of the tool tip due to wear was used in research. For typical values of the critical coefficient VB_{CKr}=0.4 mm and at the clearance angle α=7°, the limiting retraction of the cutting edge KE_{Kr} is 0.049 mm. It determines the required accuracy when the cutting-edge retraction is measured.

The developed methods of direct determination of natural turning tool wear, not burdened with the errors of the machine itself, are described below. They seemed to be simple and rigid enough for industrial application and may be useful for advanced automation of turning. The devices for direct measurement of turning tool wear were based on the concept patented by M.Szafarczyk and A.Winiarski [20].

2.2 Two sensors probe.

As the initial solution was the measurement by a probe with a two touch-trigger sensors [21]. Figure 4 presents the principle of the measurement.

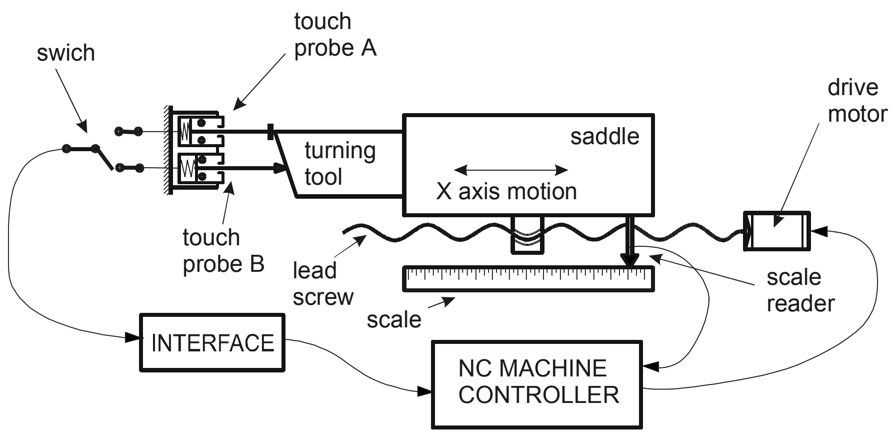

Fig. 4. The principle of measurement by a probe with two touch-trigger sensors

The measurement of the value of dimensional tool wear is performed in such a way that the touch-trigger sensor A with a flat tip is in contact with the tool tip and the sensor B with a sharp tip is in contact with the tool datum surface. The tool approaching the probe presses with the tip of the cutting edge on the sensor A and opens its switch. The signal from the probe is sent to the control unit, which registers the A-value of the co-ordinate read from the NC controller. The move of the turning tool continues till the switch of the sensor B opens. Then the B-value of the co-ordinate is registered and the movement stops. The difference between the co-ordinate values A and B may be used for the measurement of tool-wear. A new tool is measured for obtaining a reference difference and then the tool is measured after the machining process. The value of wear may be received by subtracting the tool dimension (the difference between co-ordinate values A and B) after machining from the reference dimension. Such method of measurement of wear enables to eliminate the errors of the measurement that can appear in the case of using a standard tool probe (recommended by some producers of machine tools).

The method makes it possible to orient concurrently the tool edge in the NC co-ordinate system with the same probe and at the same time as the tool wear measurement. The A-value of the X co-ordinate may be used for the purpose.

Another concept of the two-sensor tool probe was based on the installation of a linear variable displacement transducer (LVDT) of a small measuring range instead of a second touch sensor. The remaining touch sensor orients the tool within the working space of the NC machine tool and LVDT carries out the measurement of tool wear (KE) in relation to the tool datum surface, Fig. 5.

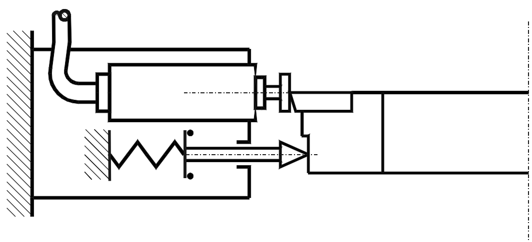

Fig. 5. Tool probe system with a touch sensor and linear variable displacement transducer.

The application of the LVDT sensor was successful. The results obtained during the tests were within the limits determined by the probe repeatability. To simplify the probe design as well as to increase the measurement accuracy of the cutting edge wear a new idea has been developed – to apply only one linear displacement sensor.

2.3 LVDT probe.

Figure 6 presents the idea of direct measurement of tool wear with a linear variable displacement transducer, LVDT. The transducer is built into the probe and may move as a slider in guidelines. The transducer body has a fixed stopper and a stop tooth. A spring tries moving it outside. The movable stylus of the transducer is touching the tip of the tool. The transducer was scaled in such a way that it indicates the "0" value in the position in which the measuring tip of the stylus is aligned with a stop tooth of the transducer. This value is a signal for the lathe NC system and causes that the X value of the tool position is saved to the correction register for the tool tip orientation within the co-ordinate system of the machine.

The Fig. 6A, 6B, 6C present the positions of the turning tool during the measurement.

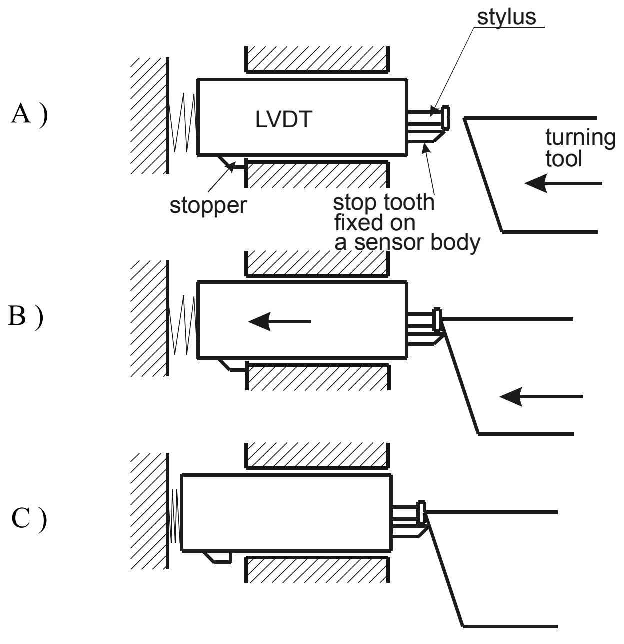

Fig. 6. The concept how a probe with one movable LVDT transducer works

Figure 6A presents the turning tool approaching the probe after starting the measurement procedure. The turning tool advancing in the direction of the probe touches with its tip the measuring stylus tip and then shifts it till it reaches the position in which the turning tool touches the stop tooth of the LVDT body. When, during the movement, the LVDT signal is equal 0 the X co-ordinate value is registered and is used later for tool orientation.

In the case of a typical tool setting by e.g.: a RENISHAW probe, the tool after its orientation is retracted. In the case of this probe the lathe NC system displaces the tool by additional 2 mm. During the movement the turning tool touches the stop tooth. The measurement stylus of the transducer stops moving whereas the transducer body is shifted along the guidelines– Fig. 6B. The displacement value 2 mm was selected to ensure that all kinds of cutting edges will touch the stop tooth and the transducer body will be shifted. Then the transducer signal is used for wear assessment – Fig. 6C. The measurement of the new insert is used as a reference – the same way as with the two-sensor probe. During measurements after machining the obtained values are subtracted from the reference one.

The design of the probe is presented in Fig. 7 and the photography of the probe installed on the tool machine in Fig. 8.

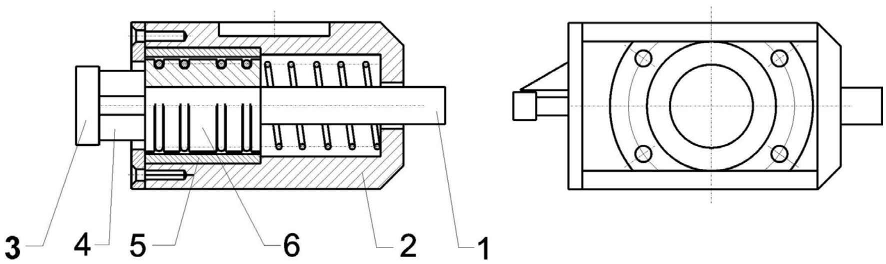

Fig. 7. Design of the probe with LVDT.

The sensor (1) is fixed in the sleeve fitted with linear bearings (6), which shifts itself along the guideline (5) mounted in the probe body (2). The movable tip of the sensor (1) is ended with a flat plate. A stop tooth (4) is fixed to the sleeve (6).

In tests, the wear-measuring device was attached to the body of the lathe tailstock, as it is shown in Fig. 8, and connected to the NC unit of the machine. The tool data were sent to the numerical control unit and utilised for co-ordinate correction during machining. After each use of the wear-measuring device, a program saved the "X" co-ordinate values in a file and the values of the differences between the datum surface co-ordinates and the cutting edge co-ordinates.

Fig. 8. The probe mounted on the tailstock of the lathe

The tool wear measurements by the probe were carried out automatically. For checking purpose, the cutting inserts were unfastened and taken off the toolholder for tool wear measurements under a microscope. The fact that an insert was taken off 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 9 shows an insert under the microscope.

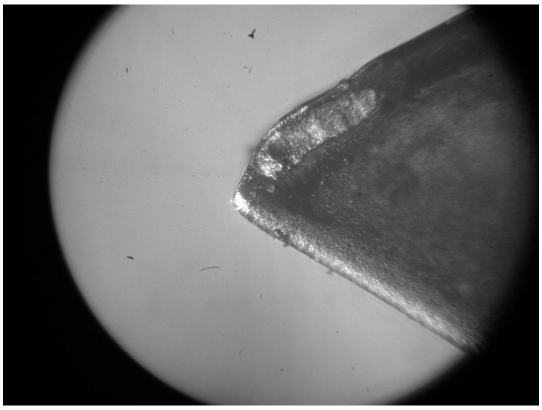

Fig. 9. A cutting insert under the microscope after 33.07 min of cutting with v_c=100 m/min and 150 m/min. KE=0.054 mm (VB_c= 0.46 mm)

As an alternative, the pictures of the cutting inserts were 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 Fig. 10. The known dimension of the insert was also measured for the purpose of calculating the actual scale of the picture.

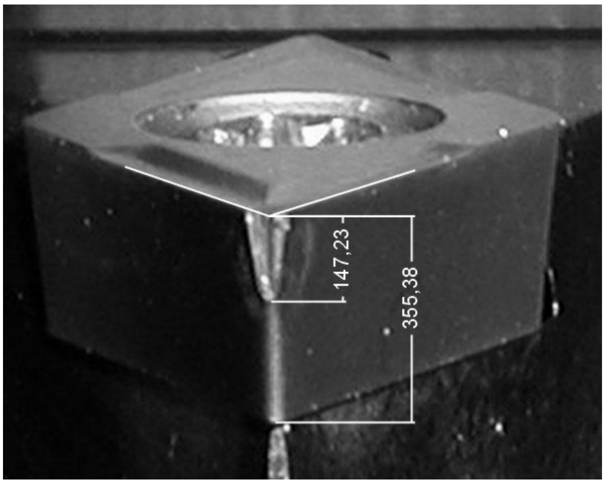

Fig. 10. A picture of the insert after 5.97 min of cutting with v_c=250 m/min. VB_c=1.64 mm (KE=0.196 mm)

3 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.

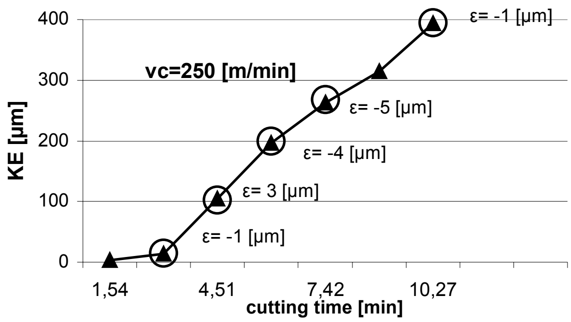

Fig. 11. KE values during a test with cutting speed v_c=250 [m/min] measured by the probe and under a tool microscope

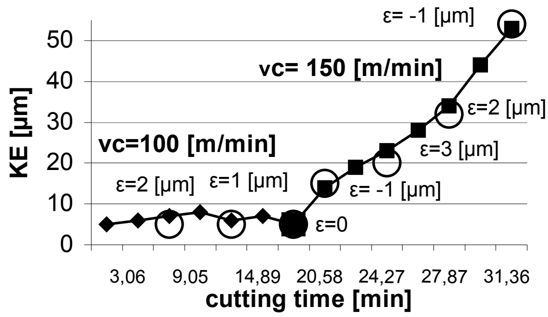

Fig. 12. KE values during a test when the cutting speed was changed from v_c=100 [m/min] to v_c=150 [m/min]

Two examples of the test results are presented in Fig. 11 and Fig.12. 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 tool 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 Fig. 12 was interrupted after about 32 minutes of cutting because of a very small rate of tool wear. The KE obtained then the value of only 50 μm.

In the measurement system, a PC computer with an A/C converter card was used – Fig. 13. The computer is connected with the probe and lathe NC unit via interfaces. Programs were prepared in such a way that one procedure can orient a tool in the NC co-ordinate system and another performs the measurement of the cutting edge natural wear.

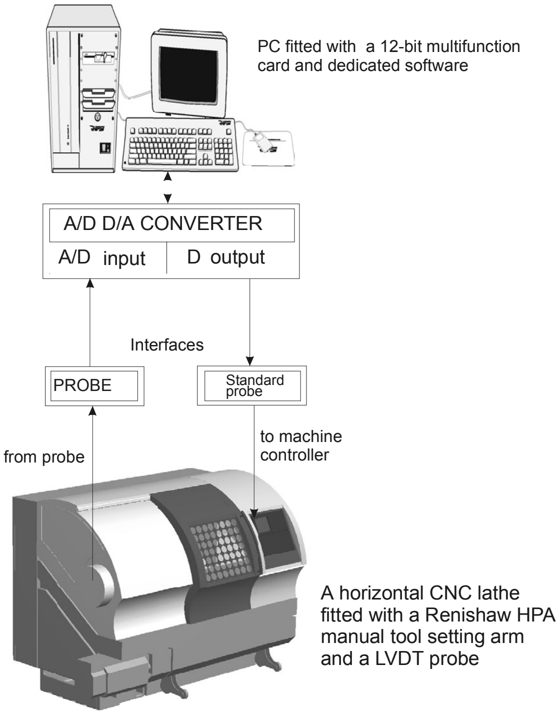

Fig. 13. Measurement system

4 Conclusions

The results of performed tests show that the developed probes are suitable both for the tool orientation and for the measurement of turning tool wear. The probe with only one displacement sensor is even more accurate than the previously tested two-sensor probe. The measurement accuracy is within the repeatability limits of the linear displacement sensor. The smaller distance between the touching elements of the probe is important - the LVDT sensor tip and the stop tooth may touch the cutting insert. It eliminates errors resulting from e.g.: non-uniform thermal expansion of the holder and the insert.

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