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Automatic dimension measurement on CNC lathes using the cutting tool

Svetlana Koleva[a], Milko Enchev[a], Tamas Szecsi[b,*]

[a]*University of Rousse, Department of Manufacturing Engineering, 7000 Rousse, Bulgaria*
[b]*Dublin City University, School of Mechanical and Manufacturing Engineering, Dublin 9, Ireland*
* Corresponding author. Tel.: +353-1-7008300; fax: +353-1-7007148.*E-mail address*: tamas.szecsi@dcu.ie.

Abstract

In the paper the possibilities of measuring the dimensions of parts using the cutting tool that had machined the surfaces of the part are investigated. Described are the principal scheme of the measuring device and its application for dimensional measurements. The method leads to more efficient machining on CNC lathes. The application of the method results in automatic dimensional control, which otherwise would require specialised measuring equipment or would lead to increased idle time of the machine tool, automatic dynamic setup of the cutting tool, and automatic tolerance assurance using check-up datum surfaces. Reported are the theoretical analysis of the measurement errors and the method of predicting the accuracy of the measurements using the cutting tool itself. Presented are experimental results of applying the system for direct dimensional measurements using the cutting tool on CNC lathes.

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Keywords: Dimension measurement;CNC control

1. Introduction

In order to ensure the machining accuracy of workpieces, a large number of inspection operations that require various measuring equipment both in terms of type an range are required. Some of the inspections are performed on the machine tool itself due to the higher accuracy of the dimensions. This leads to increased idle time of the machine tool which results in decreased productivity and increased unit cost of the operation. The aim of modern machine tool building is to reduce the time necessary to inspect the machined parts on the machine tool using conventional measuring equipment, and automation of measuring procedures during machining [1,2]. Automatic quality control of the machining operations on CNC lathes is mainly performed by using electro-contact coordinate measuring equipment. Using such equipment allows for measuring the dimensions of the workpiece or the cutting tool [2,3,4,8,9].

One of the methods for decreasing the time for measuring procedures directly on the CNC machine tool is the usage of the cutting tool itself as a measuring tool. The principle is based on the fact that machining and measuring are both performed by the same point of the cutting tool, so the two points are the same (Fig 1).

Two independent measuring systems are used. The first one (marked as 1 in Fig 1) is for the periodic definition of the actual position of the dimension defining point of the cutting tool. This is used for the compensation of the systematic errors. The second system is for measuring the surface of the workpiece (marked as 3) using the cutting tool (marked as 2) through the registration of the contact between them. This happens after machining of the surface; the cutting tool slowly approaches the machined surface and at the moment they contact each other a signal is sent to the CNC system of the machine tool for registering the current position of the cutting tool relative to the rotation axis of the spindle [8]. Its principle is based on the existence of an electrical circuit at the moment of the

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contact. Its advantage is that the spindle unit does not have to be electrically insulated [6,7,10]. Since the position of the tip of the tool is measured relative to the spindle rotation axis, coordinate A corresponds to the diameter of the machined surface. Measuring the axial dimensions is performed in a similar manner, but the positions are registered relative to the datum surface of the workpiece or relative to the origin of the coordinate system of the machine tool.

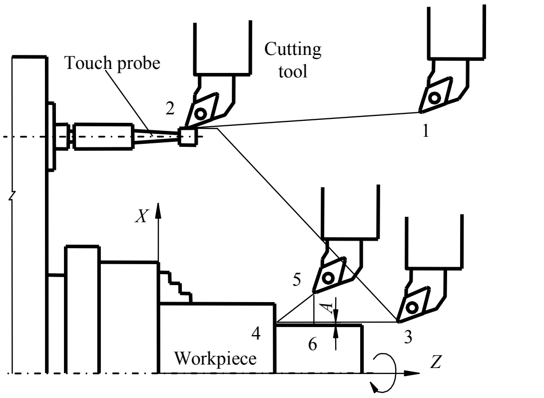

Fig. 1. Measuring the dimension of the workpiece using the cutting tool

2. Capabilities of the Method

Measuring operations outside the machine tool using general purpose and special devices in principle can be performed with a higher accuracy than on the machine tool itself. It is, therefore, necessary to define the cases when measuring on the machine tool itself is justified:

- Measuring operations that require specialised measuring equipment;
- Performing simultaneous automation of the measurements and statistical analysis of the measured data in order to increase the efficiency of quality control;
- Partial or total relief of the operator of the machine tool of the inspection procedures in order to control multiple machine tools or during the so-called "unmanned technologies";
- Quality control using automatic inspection before machining.

Using the cutting tool as a measuring tool has several advantages [3,4,5]; the most important ones are:

- During measurements there are no limitations in terms of the workpiece clamping method;
- There is no need to install any additional measuring equipment into the turret of the machine tool;
- There is no need to use specialised measuring equipment for surfaces with special configuration or limited access to them;
- It is possible to automate the processes of machine tool setup and re-setup;
- It is possible to measure the blank material in advance in order to distribute the machining allowances evenly or to optimise the number of cutting paths;
- It is possible to set the coordinate system of the workpiece automatically;
- It allows for setting up the machine tool using test cuts;
- It allows for automatic compensation of cutting tool wear and thermal deformations;
- It is possible to compensate the permanent and regular errors caused by mechanical deformations.

3. Analysis of the errors during measuring the workpiece using the cutting tool

The aim of measuring the workpiece using the cutting tool is to define the coordinates of the dimension-defining point M of the tool. It is a point belonging to the cutting edge of the tool which defines the dimension and shape of the surface in a given direction. The measured coordinates of point M are used for defining the coordinates of the programmed point P. The latter is an artificial point linked to a part of the cutting tool (cutting edge, centre of the tool nose, datum points of the tool, etc.); its trajectory is programmed in the CNC programme (Fig 2).

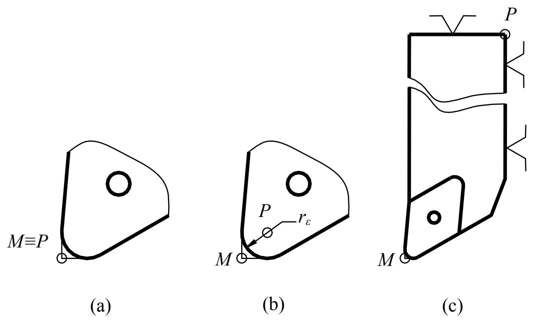

Fig. 2. Position of the dimension-defining (M) and programmed (P) points; (a) M and P coincide; (b) P is in the centre of the tool nose; (c) P is at the tool datum

During programming it is assumed that M is located at a certain position relative to P. In reality this is achieved after the initial cutting tool setup and is maintained by periodic re-setups. The definition of P is performed by introducing the absolute coordinate system of the workpiece; it is linked to datum surfaces of the workpiece. Therefore, the accuracy of defining M has a direct effect on the accuracy of the definition of P relative to the absolute coordinate system. If $P \equiv M$ (Fig 2(a)), the trajectories of the dimension-defining point and the programme point are the same. If P is in the centre of the tool nose radius (Fig 2(b), its trajectory is equidistant to the trajectory of M. During moving the slides of the machine tool the trajectory of P is calculated by the CNC system.

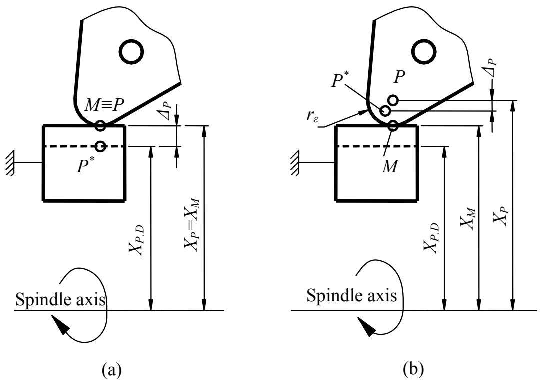

Fig. 3. Error caused by the lack of coordination between the dimension-defining and programmed points; (a) M and P coincide; (b) P is in the centre of the tool nose

Due to the fact that P is defined through M, the error of defining M is directly reflected on the error of defining P. Fig 3 shows the graphical model of the error of defining M in the cases where $P \equiv M$ (Fig 3(a)) and when P is in the centre of the tool nose (Fig 3(b)) so its displacement a relative to M equals the tool nose radius r_ε ($a = r_\varepsilon$).

The errors in the measuring scheme lead to the difference between the position of activation registered by the system X_P (coordinate point followed by the system) and the pre-defined position of activation of the coordinate device $X_{P.D}$. This difference is introduced as correction Δ_P and it leads to the displacement of P into the position shown as P^* in Fig 3. Its value can be defined as:

$$\Delta_P = X_P - X_{P^*} = X_M - X_{P.D} \qquad (1)$$

$$\Delta_P = X_P - X_{P^*} = X_P - (X_{P.D} + a) = (X_P - a) - X_{P.D} = X_M - X_{P.D} \qquad 2)$$

where a defines the position of P relative to M ($a = 0$ when $P \equiv M$, and $a = r_\varepsilon$ when $P \neq M$). (1) is based on Fig 3(a), and (2) - according to Fig 3(b).

The total error of defining the position of M is:

$$\Delta_M = X_M - X_{P.D} \qquad (3)$$

This error has been investigated in [3] and is formed by the following elementary errors:

- Error $\Delta_P = \Delta_M$ in the definition of P that leads to the lack of correspondence between P and M, which displaces P and the trajectory of M and causes machining errors;
- Errors from the preliminary setup of the cutting tool, its wear, and thermal deformations in the technological system change the position of M and in order to compensate these errors is necessary to apply periodic re-setup for coordinate the positions of M and P.

The dimensional error is the difference between the average diameter of the nominal profile and the diameter obtained through actual measurements. The specific elementary errors, connected to this type of dimensional measurements, can be grouped into the following:

- The error resulted form the lack or variation of the conductivity between the cutting tool and workpiece;
- The error which is the effect of the shape of the machined profile on the measured dimension;
- The error caused by the displacement of the axis of the coordinate system of the machined surface relative to the spindle rotation axis;
- The error caused by the cutting tool entering the roots of the unevenness of the machined surface.

The theoretical and experimental investigations show [4,5] that the dominant error during dimensional measurements using the cutting tool is caused by the difference between the trajectories of the spindle rotation axis during machining and during dimensional measurements.

Depending on the angular position of the machined workpiece the position of the points lying on the surface will have a varying distance from the rotation axis. They are the function of the difference between the two trajectories and can be described using polyharmonics positioned symmetrically to the average diameter D_{av} relative to the rotation axis (Fig 4).

Dimensional measurements using the cutting tool can be performed either by a single impulse or a series of impulses as the result from the contacts between the cutting tool and workpiece during a single revolution.

3.1. Measuring the dimension using a single signal (Fig 4(a))

When using a single impulse, besides the difference in the trajectories of the spindle the measurements will also be affected by the deviations of the shape of the machined surface in its cross sectional direction which are not caused by displacement of the axis of the spindle relative to the rotational axis. The measuring accuracy depends on the ratio between the peripheral speed of the workpiece and radial feed rate of the cutting tool.

There are two possible limiting situations when measuring with radial feed motion. The first one is by using low radial feed-per-revolution rate at which contact between the cutting tool and workpiece is formed by the outmost radius relative to the rotational axis (D_{max} in Fig 4). If the radial feed rate f_r is 0.001mm/rev, the outermost point of the surface is registered with a 0,001mm step. This variant results in a measuring error of:

$$\Delta_1 = e + \Delta\phi \tag{4}$$

where e is the displacement of the spindle axis during the measurements and $\Delta\varphi$ is the profile error. Insufficient accuracy and high idle time due to low feed rates are the two main disadvantages of this method. Also, a step $\Delta f = 0.001$ mm can only be achieved under certain conditions. With a minimum available feed rate $f_r = 0.01$ mm/rev, for example, such steps can not be achieved. Achieving such small steps is only possible using table feed (mm/min feed rates) and certain spindle speeds where the step value can be calculated as:

$$\Delta f = k\frac{f_{r,\min}}{n} \quad (k = 1\ldots6) \tag{5}$$

where $f_{r,min}$ is the minimum available radial feed rate and n is the spindle speed in rpm.

With the minimum available value of the minute feed $f_{\min} = 1$ mm/min and $k = 1$, the spindle has to rotate with 1000rpm.

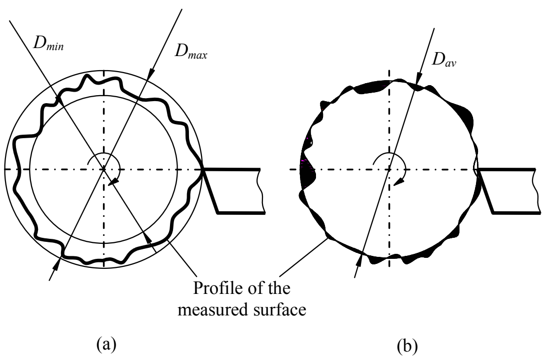

Fig. 4. Measurements using a single impulse (a) and a series of impulses (b)

The second limiting condition is achieved with high feed-per-revolution rates which may result in a contact between the cutting tool and the innermost point of the macro profile of the machined surface (D_{min} in Fig 4). The value of the feed rate is defined theoretically from the condition that during 1/2p part of a revolution of the workpiece the cutting tool should reach the innermost point of the profile of the workpiece defined by the p^{th} harmonic. This can be expressed mathematically:

$$\frac{1}{2pn} = \frac{u}{f_r} \tag{6}$$

where n is the spindle speed in rpm and u is the length the cutting tool travels during the measurement. From here:

$$f_r = 2pnu \tag{7}$$

The described factors form the measurement error:

$$\Delta_2 = e + \frac{\omega_{\Delta\phi}}{\sqrt{m}} \tag{8}$$

where $\omega_{\Delta\varphi}$ is the scatter of the deviation of the shape of the profile and m is the number of repeated experiments.

This variant is with a higher accuracy with multiple measurements (m>1). Also, as a non-systematic error during its addition with the other non-systematic errors its weight becomes much lower. The main disadvantage of this method is the increased measurement time due to multiple measurements, and plunging with high speed into the machined surface. The advantage of measuring the dimension using a simple impulse in both cases is that it only requires a simple control device of the measurement cycle.

3.2. Measuring the dimension using a series of signals during one revolution (Fig 4(b))

The last impulse of the series that gives the command to register the dimension is defined from the condition:

$$\sum t_p \approx 0.5t_{rev} \tag{9}$$

where t_p is the time of action of the p^{th} harmonic and t_{rev} is the time of one spindle revolution.

The major factor that defines the measurement accuracy is the scatter of the position of the spindle in each revolution which forms from the harmonics with a period T larger than 2π. The maximum measurement error Δ_M equals the value of the resultant deviation caused by these harmonics:

$$\Delta_M = e_\Sigma(T > 2\pi) \tag{10}$$

Fig 5 shows the real life measurement of the position of the points of the machined profile relative to the axis of the average diameter of the profile, and the sequence of the contacts at a radial feed rate of 0.001mm/rev. During the approach of the workpiece by the cutting tool, depending on the trajectory of the spindle, there will be a varied number contact points (sectors) between the tool and workpiece and their number changes with each subsequent revolution. It has to be noted that it is of importance at which periods and phases of the polyharmonic signal that describes the trajectory of the spindle axis does the first contact happen as the trajectory may be different in each revolution. Fig 5 shows five revolutions (one revolution corresponds to 300 arbitrary points along the abscissa), and the contact points between the tool and workpiece are marked with different colours depending on the feed rate. Regardless of when the first contact is made, it reaches around 50% of the contacts during one revolution at the same position, so the system would issue the signal registering the achieved coordinates at the same place every time.

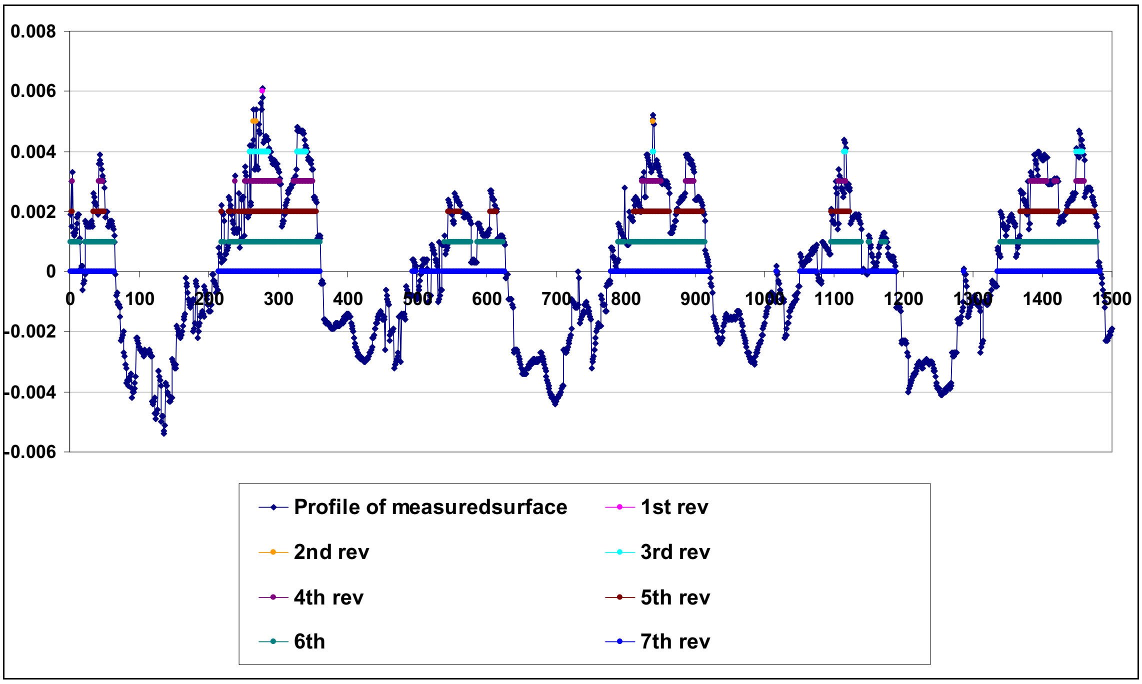

Fig. 5. Contacts between the tool and the machined surface

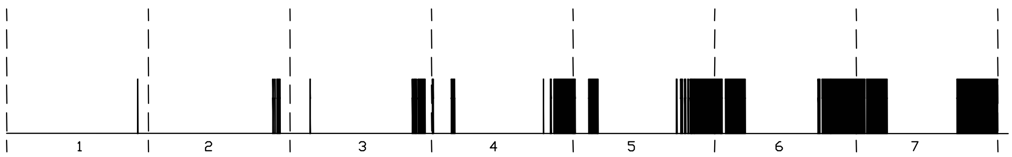

Fig. 6. Output signal from the contact measurement system

Since during each contact between the tool and workpiece there is an electrical loop, during one revolution of the workpiece a series of alternating ‘0’ (no contact) and ‘1’ (contact) is issued by the system for registering the contacts. The sequence depends on the profile of the machined surface and the trajectory of the spindle axis (Fig 6). With the tool successively approaching the workpiece the number of contacts increases with each revolution of the workpiece.

The number of revolutions through which sufficient number of contacts is achieved depends on the profile error of the machined surface, the deviation of the position of the spindle axis during machining and measurement, and the feed rate of the cutting tool.

In order to prove the above statement an experiment is performed with the cutting tool approaching the machined workpiece and making contact with it. The CNC lathe used is a CE063 type machine; the blank is clamped in a three-jaw chuck, and the cutting insert is of type VBMT160408. For registering the contacts a digital oscilloscope was used to which two signals were submitted: one is the single impulse per revolution signal from the photoelectric transducer of the spindle feedback system, and the other is from the system for registering the contacts. The oscilloscope was linked to a computer for recording and analysing the signals. Simultaneous recording of the signals allows for analysing them during each revolution of the workpiece, and also for defining the number of revolutions from the first contact between the tool and the workpiece until the tool reaches the innermost point of the profile of the machined surface. The records of the signals is shown in Fig 7 (the signal from the spindle feedback is in green, and the signal from the contacts is in yellow).

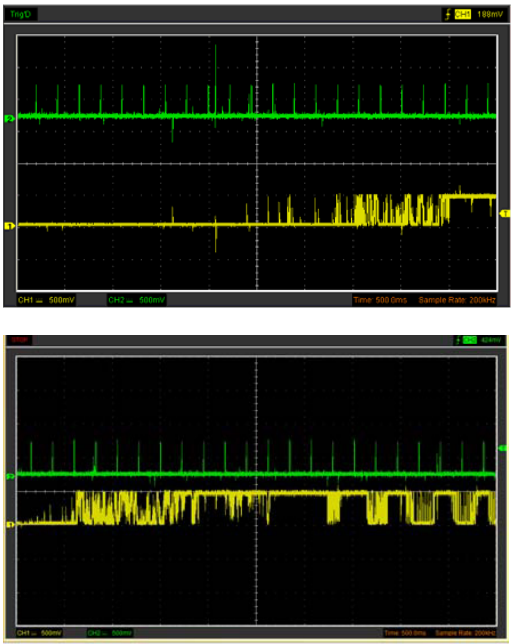

Fig. 7. Recorded signal from the feedback sensor of the spindle (green) and from the contact measurement system (yellow)

From the records it can be seen that after the first moment of contact between the workpiece and cutting tool initially only standalone signals are emitted from the contact recording system. With the advance of revolutions their density increases. The feedback signal from the photoelectric transducer appears as a single impulse at the beginning of each revolution of the spindle. Reaching the innermost (deepest) point of the profile of the machined surface at which the contact signal becomes permanent is reached within 7-11 revolutions after the first contact was made. The feed rate was 0.001mm/rev which means that the radial distance between the contact with the first and last point on the profile was 7-11μm.

The experiments were carried out with various spindle speeds in the 600-1000rpm range. The number of revolutions required to reach the innermost point on the machined surface did not depend on the spindle speed. Increasing the radial feed rate would proportionally reduce the number of spindle revolutions required.

Permanent contact between the tool and workpiece can be seen as a straight line with high potential. After a couple of extra revolutions, due to the reduction of the elastic deformations in the technological system from the elastic deformations (forming of a small radial groove on the machined surface) the electrical contact between the tool and workpiece started to diminish. The peaks resulting from this effect in the figure should be ignored.

According to the discussion above, in order to submit the signal to the CNC system after having reached a contact between the workpiece and the cutting tool within one revolution it is necessary to develop a device that can register the period during which the contact registration system is activated. Since it is necessary to start counting the impulses after each revolution of the spindle, it is necessary to also have feedback from the rotations of the spindle. It is a good idea to use the signals from the photoelectric transducer of the spindle feedback unit that generates 1024 impulses per each revolution of the spindle. The single impulse from the same system that is issued at the beginning of each revolution can be used for the start of counting the number of contacts.

The device that counts the impulses during one revolution of the spindle during which there is contact between the workpiece and the cutting tool, and which informs the CNC system that the radial position has been reached is presented schematically in Fig 8.

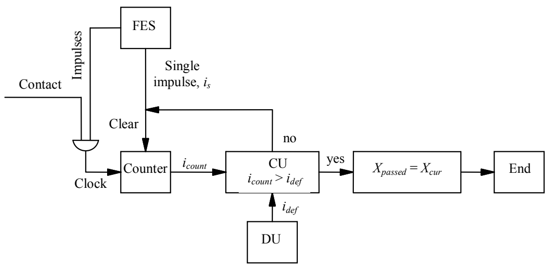

Fig. 8. Principal scheme of the device for counting the impulses

Its principle is that only those impulses from the photoelectric sensor (FES) are counted during which the contact registration system is active. The single impulse i_s starts counting the series of impulses, and the comparing unit (CU) decides if the number of counted impulses i_{count} is larger than the pre-defined number i_{def} defined by the defining unit (DU). If the condition is not met the counter is set to zero by the signal i_s and counting starts again. When i_{count} becomes larger then i_{def}, the device issues a signal to the CNC system that the radial position is reached and the CNC system registers the current position of the cross slide. With this the measurement cycle stops. There could also be a solution where the number of contacts is counted during more than one revolution of the spindle.

The experimental equipment is developed for a CNC lathe CE063 and it contains the following elements (Fig 9): system for registering the contacts between the workpiece and cutting tool; device for analysing the density of the contacts; feedback transducer for measuring the linear position of the movements; personal computer linked to the device for analysing the density of the contacts; personal computer, linked to the feedback transducer.

Workpiece *1* is machined on the CE063 CNC lathe. The workpiece is held in a three jaw chuck with a free-hanging length of 120mm. Its material is mild steel and the machined diameter D_M is 40mm. The spindle speed is 1000rpm, the radial feed rate is 0.12mm/rev, and the depth of cut is 0.25mm. The cutting insert is of type VBMT160404 – 2015. The measurements are performed by cutting tool *2*, the same that has machined the surface. Contact sensor *4* is mounted into a pocket of the turret *3* which upon a contact between the tool and workpiece sends a signal to the system for registering the contacts (CRS, *9*). The aim is to reach a minimum of 50% of contacts between the tool and workpiece during one revolution of the spindle before a signal is sent to register the actual position of the cutting tool, that is to register the dimension of the machined workpiece. The length of the contact is calculated by the device for measuring the density (DMD, *10*) of the contacts. Its principle is based on charging a capacitor during the period of contact and discharging it when there is no contact. When a certain charge is reached a signal is sent to the registering device *6* which registers the position of the feedback positional transducer *5*. This procedure is repeated many times with a step in the axial (*Z*) direction larger than the tool nose radius. The device for analysing the density of the contacts is linked to the personal computer *8* which makes it possible not only to record the whole process but also to investigate the parameters in real time: dimension of the impulses, density of the contacts, signals from noises, number of revolutions before a permanent contact between the workpiece and tool is achieved, etc. The device *6* that registers the position of the cutting tool after reaching the necessary contacts between the workpiece and tool is connected to another computer *7* which stores the data, presents them in a graphical form, and performs statistical analysis from a process engineer's viewpoint.

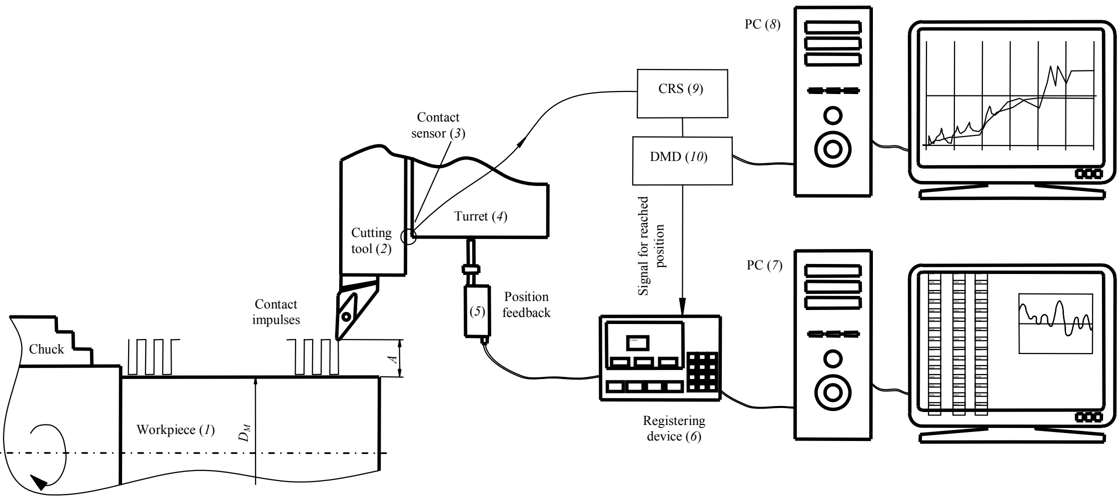

Fig. 9. Scheme of the experimental equipment

The results from the measurements are presented graphically in Fig 10; the deviation of measured dimensions is plotted against the number of repeated experiments *N*. The measurements were repeated after machining the workpiece several times. The scatter of registered by the system position of the cutting tool after achieving a minimum 50% contact between the cutting tool and workpiece was in the range of ±2.2μm.

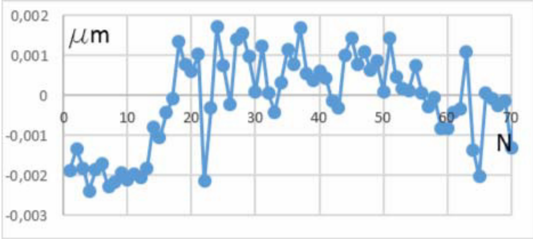

Fig. 10. Dimension measurement of the machined surface using a series of impulses

4. Conclusions

Measuring the dimension of the machined surface with the help of the cutting tool itself is justified when the aim is automation of the inspection during and after machining, during simultaneous quality control and statistical analysis, in order to avoid the use of special measuring devices, and during controlling multiple machine tools.

The level of coordinating the positions of the programmed and dimension-forming points of the cutting tool defines the errors that occur during measuring the dimension of the workpiece with the cutting tool. Measuring the dimension of the workpiece with the cutting tool is possible using a single signal or a series of signals from the contacts between the cutting tool and workpiece during one spindle revolution. In the first case, it is the largest diameter of the surface, and in the second case the average diameter at which 50% contact between the tool and workpiece are achieved is measured.

The number of revolutions necessary to achieve sufficient contact between the tool and workpiece depends on the profile error of the measured surface, on the deviation of the position of the spindle axis during the measurements from its position during machining, and on the feed rate of the cutting tool. It is experimentally defined that at a radial feed rate of 0.001mm/rev the innermost point of the measured profile can be reached within 7-11 spindle revolutions.

The scatter of the measured position of the cutting tool using the developed system is ±2.2μm.

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