# Computer Aided Engineering of the Surface Layer in the Machining Process by Material Removal

**Mikolaj Kuzinovski*, Piotr Cichosz**, Neven Trajčevski***, Mite Tomov***

Presented is a computer-oriented methodology designed for complete engineering of the surface layer that is created in machining process by material removal. Computer support enables: projecting of surface layer characteristics related to exploitation requirements; monitoring of influential factors involved in the process of surface layer constitution; complete investigation of the characteristics of the newly created surface, especially the surface layer. In this paper special emphasis is placed on non-standard original approach to the creation of an integrated computer system, and applies: the methodology, hardware and software of the equipment, analysis and processing of data obtained from measurements. The creation of the integrated computer system is a result of the multi-research activities undertaken in cooperation between the Faculty of Mechanical Engineering at the Ss. Cyril and Methodius University in Skopje, and the Institute of Production Engineering and Automation of the Wroclaw University of Technology, Wroclaw.

## Introduction

The condition of the surface layer can be analyzed through its geometrical structure and through the physical and chemical characteristics of the zones that the surface layer is composed of. Geometric structure can be defined on macro-level by way of deviation from the dimensions, shape and position; on meso-level as waviness; and on micro-level as roughness. The physical and chemical characteristics of the zones from the surface layer are defined by their meso-hardness and the depth of the strengthened layer, distribution by depth, type and size of the residual stresses. During exploitation, and because of the mutual contact of coupled surfaces, the surface layer changes, and this is largely due to the emergence of abrasive wear (accounting for about 90%) and fatigue wear (with a share of about 8%). The surface layer where the change occurs as a result of exploitation is called technological surface layer [1]. Characteristics of the technological surface layer have a decisive influence on the behavior of the coupled surface layers in exploitation. This is a reason enough technological processes to be designed and implemented in a way that different methods and processing techniques

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result in surface layer with predefined characteristics that are optimal from the standpoint of functional properties of the product.

Constituting the surface layer with desirable characteristics can be achieved by creating computer-aided systems to perform profound analytical and experimental-analytical research on physical phenomena in the machining processes by material removal. Further more, determination of physical phenomena impact on the mechanism of creating micro-stereometry and residual stresses in the surface layer, and through the development and application of adequate methods for computer-aided management of their design processes. This means constituting the surface layer with previously known characteristics is only possible when considering all the factors involved in the stages of creating the surface characteristics, including: surface projecting methods, relation to production techniques, identification and research methods, and linkage to exploitation conditions, which, according to the definition by Prof. T. Burakovski constitutes surface layer engineering [2].

## Computer Integrated System for Complete Engineering o the Surface Layer

A computer system for engineering of a surface layer created during machining processes by material removal is shown in Figure 1. It integrates several modules that enable projecting of characteristics of the surface layer related to exploitation requirements, monitoring of all influential factors involved in the process of constitution of the surface layer, and complete investigation of the characteristics of the newly created surface, especially the surface layer. This complex system is developed as a result of years of fruitful research work by the authors of this paper and institutional cooperation between the Faculty of Mechanical Engineering at the Ss. Cyril and Methodius University in Skopje, and the Institute of Production Engineering and Automation of the Wroclaw University of Technology. The following presents the characteristics, features and benefits of creating such a complex integrated computer system.

### Projecting characteristics of geometric structure on the surface of the surface layer

For the purpose of projecting the geometric structure of the surface of the surface layer, seen through its characteristics on a micro level, two methods are commonly used. One method is based on kinematic-geometrical reflection of cutting tool edge on the machined surface [3, 4, 5]. The other method is based on mathematical modeling of virtual surfaces by way of using mathematical functions and certain operations with these functions, and it is a purely theoretical aspect [6, 7, 8, 9, 10].

Machining processes with defined geometry of the cutting tool shape generate deterministic (periodic) roughness profile, whereas processes with undefined geometry of the cutting tool generate stochastic (non-periodical) roughness profile. According to [11] the geometry of the cutting tool that is used for the longitudinal turning participates in forming the roughness profile in many ways. Respectively, if the cutting tool nose radius is very small and therefore is disregarded, then the roughness profile is formed only with the tool front cutting edge and the tool side cutting edge (triangular segment). If the tool nose radius is taken in consideration, then the roughness profile can be formed only from the kinematic-geometry reflection of the tool nose radius or as a combination of the tool nose radius and the tool front and side cutting edge. The mathematical models for all of these cases are different and include different number of variables [11].

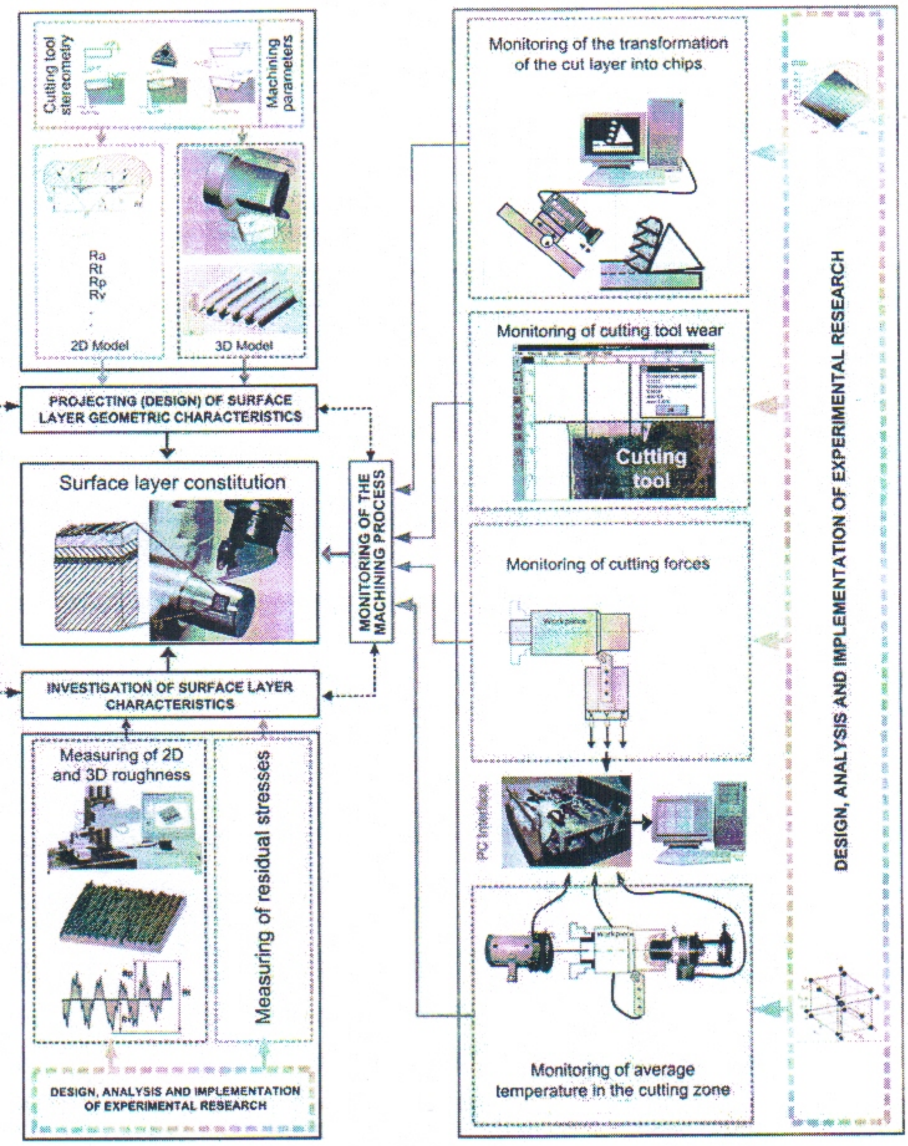
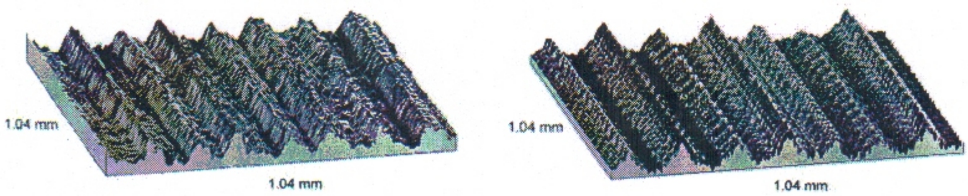



Fig. 1. Computer integrated systems for surface layer engineering in the machining process by material removal

In theoretical roughness modeling by using the principle of kinematic-geometric reflection of the cutting tool, besides geometry of the tool, the machining feed rate is a parameter that defines the resulting roughness profile. To overcome the differences in markings and defining certain terms related to the geometry of the cutting tool, it is suggested to use ISO 3002-1: 1982 [12]. Cutting speed and cutting depth have no influence on the shape of the roughness profile in the mathematical models presented in [3, 4, 5].

Mathematical modeling of virtual surfaces involves the creation of theoretical surfaces by applying purely mathematical functions and operations with no direct correlation with the shape of the surfaces that can be obtained by some kind of machining. In most cases, however, one can get a relatively good approximation to the expected shapes of the surfaces, especially when it comes to complex or specific forms of surface topography.

In mathematical modeling of virtual machined surfaces, and with the purpose of approximation to the actual conditions of kinematic-geometric shaping of surface, [10] outlines several principles that should be taken into account during modeling, such as: reflection of the shape of the cutting edge nose by using an ellipse, forming a stochastic distorted profile with the shape of the cutting edge (furrowing), modeling of stochastic vibration of the cutting tool in three axes, and modeling of harmonic vibration of the cutting tool in three axes. It is proposed to include other distorting influences, simulating other random factors that appear during the real machining (e.g. non-homogeneity of the workpiece material). As a result of this kind of mathematical modeling we obtain virtual machined surfaces that are very similar to real ones, Figure 2.




a) real surface
Sa = 1,19 μm, Sq = 1,4 μm Sp = 5,11 μm,
Sv = 3,44μm, St = 8,55 μm, Ssk = 0,46, Sku = 2,45

b) model surface
Sa = 1,52 μm, Sq = 1,88 μm, Sp = 6,9 μm,
Sv = 3,17 μm St = 10,07 μm, Ssk = 0,67, Sku = 2,98

Fig. 2. Comparison of real machined surface and model surface [10]

During mathematical modeling of virtual stochastic surfaces we should take into account: size of grains, which is different for individual crossings, stochastic choice of grain impact, introduction of random influences ("furrowing") on surfaces of modeled abrasive grains, stochastic impact depth of individual grains, and stochastic size of the active grain at each crossing.

For modeling of surfaces in [9, 10], the software package Modelowanie_skr that runs in the MATLAB environment was used, while for obtaining the roughness profile in [5], the software program SolidWorks was used.

## Monitoring of the transformation of the cut layer into chips

The need for monitoring the process of transformation of cut layer into chips in experimental research outcomes primarily from a few requirements: observing of unwanted phenomenon in the process of transformation (e.g. built-up-edge which can significantly affect the process, Figure 3); analysis of the structure, type and shape of created chips; determination of the shear angle and calculation of the deformation coefficient of chips (Figure 3); determination of the mechanism of de-cohesion which strongly affects the wear of the cutting tool; determination of meso-hardness of constituted surface layer and chip (Figure 4) etc. The equipment that enables the studies mentioned above is shown in Figure 5.

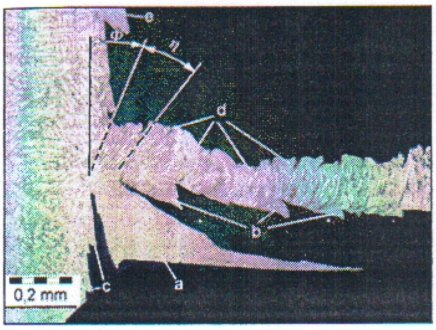



Fig. 3. Creating built-up-edge and determining the shear angle [13]

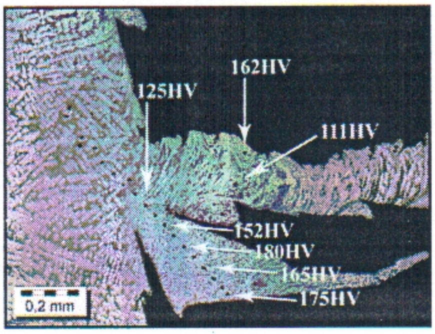



Fig. 4. Meso-hardness of built-up-edge and chip [13]

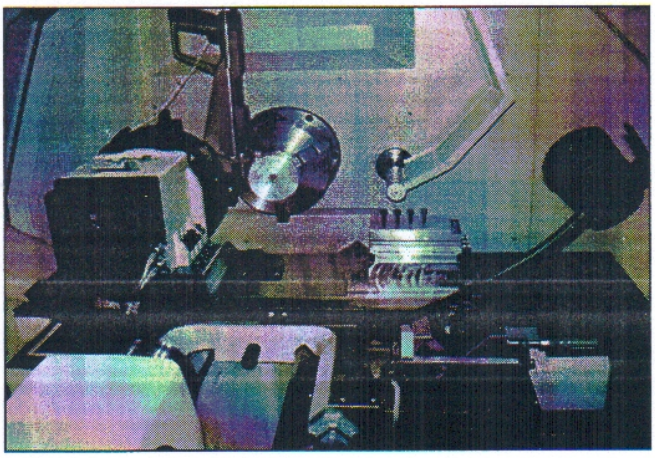


Fig. 5. Experimental set-up with a device for impact-type interrupting of the cutting process [13]

## Monitoring cutting tool wear

The use of cutting tools with unknown degree of wear can significantly affect the geometric characteristics of the surface on macro-, meso- and micro-levels, the physical phenomena in the machining process, or the characteristics of the surface layer generally. The process of cutting tool wear is very complex, as it occurs in conditions of high temperatures and surface pressures, and the total wear is a result of superimposed and mutual influences of a series of basic mechanisms of wear. These mechanisms appear with different intensity, depending on the cutting parameters (especially the cutting speed), the material characteristics of the cutting edge, workpiece material, and many other factors. Simultaneous occurrence of more of those processes can be observed in certain thermal conditions. The known and currently adopted methods for recording and analyzing the cutting tool wear are based on observation and research by microscopic measurements, supplemented by photographs of the research object. These methods are somewhat subjective due to: setting the cutting tool for observation under microscope, lightening of the observed surface, as well as interpretation when determining the boundaries of the wear traces. With these methods it is very difficult to monitor the ongoing changes of progressive wear and to compare one to another the traces of wear on the same cutting edge after different intervals of operation of cutting tool.

To overcome subjectivism when measuring the degree of cutting tool wear, a system for measuring and analyzing the degree of cutting edge wear is developed, Figure 6 [14].

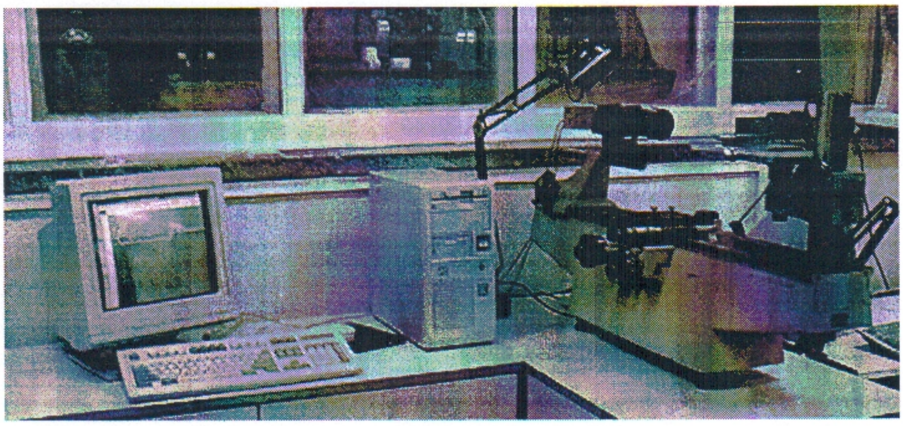


Fig. 6. Measuring system for computer analysis of the degree of cutting edge wear [14]

The measuring system consists of a personal computer coupled with a CCD camera with a resolution of 512×512 and CFG PC card, which transforms TV signals into a computer format. To avoid vibration, the camera-researched object system is placed on a rigid base of horizontal measuring machine, ensuring stability of the measurement system. The camera, along with additional equipment, adjustable distance and lens, are mounted on a slider on the base. The adjustable distance and lens make it possible to change the magnification and set the image sharpness. The research carried out with a monitoring system designed in this way allows to conclude that a 300-times increase produces an image with a very good stability and sharpness, and the researched object, with an area of several millimeters, is within the screen boundaries.

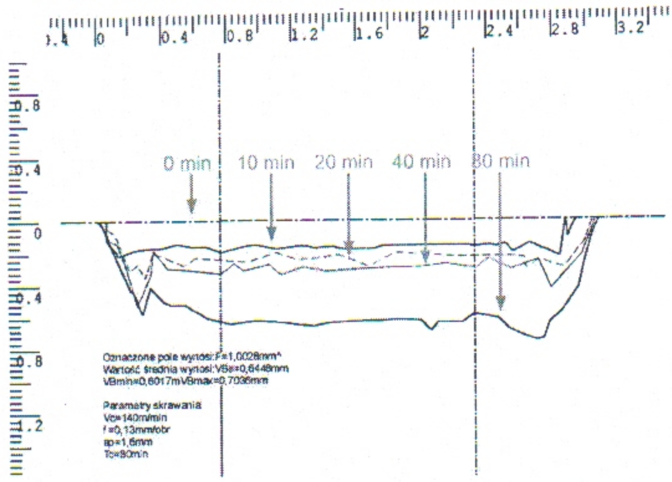



Fig. 7. Example of recording traces of cutting edge wear in successive intervals of operation of the cutting tool [14]

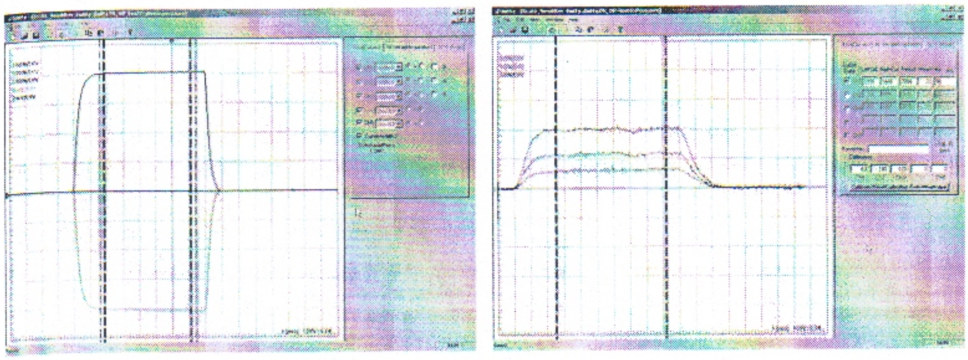
On the table of the measuring machine, which can move in a vertical, longitudinal and transverse direction, special holders are installed to fix the inserts of the cutting tool. Mobility of the holder along with the mobility of the table of the machine, allow for the tool inserts to be set in the most adequate position in relation to the lens of the camera. The recording and measuring system of the value of the cutting edge wear is based on specially developed software VB-measure. VB-measure software carries out the measurements in accordance with international standards [15]. One of the particularities and advantages of the developed measuring system is that it allows recording of the traces of cutting edge wear in successive intervals of operation of the tool, Figure 7. According to particular needs, the measuring system with a camera can be applied to control and document various types of surface errors, even control the accuracy of dimensions and shape of the manufactured parts. It should be emphasized that none of the additional capabilities requires any change in the software of the measuring system.

### Monitoring system for cutting forces and temperature during machining process by material removal

It is known that during the transformation of workpiece cut layer into chips, and because of energy transformations in the cutting zone, significant quantities of heat are released. The heat created during the cutting process directly depends on the applied processing parameters (*v*, *f*, *a*, ...), on the condition of the workpiece material, and on the cutting tool stereometry. The heat, represented by way of maximum temperature, is an important factor which exerts dominant influence on: the mechanism of transformation of the workpiece cut layer into chip; the phenomena that occur in the process of cutting tool wear (abrasive, adhesive, diffusive, heat, oxidative); the magnitude of the cutting force components that are in close correlation with the force and thermal model of creating residual stresses; and thus on the creation of the resultant characteristics of the newly constituted technological surface layer [16, 17, 18, 19]. Therefore, in the course of the machining process by material removal it is very important to know the magnitudes of the temperature and of the cutting forces that occur in the cutting zone, especially on the working surfaces of the cutting edge. Determination of the magnitude of the average temperature and of the cutting forces that emerge in the cutting zone during machining by turning is made by way of a computerized system, with capabilities and characteristics presented in [20, 21, 22, 23, 24, 25].

The computer system integrates analog dynamometer model "Fisher messtechnik typ EF2D3 NR24570", which has cutting tool holder with inductive measuring cells for converting forces into electric signal. To measure the temperature, the method of natural thermocouple workpiece-cutting tool is used. It enables the generated thermo-voltage from the natural thermocouple to be transmitted along two paths. Along the first path for signal transmission from the workpiece, a special device [26] is used, which can be applied in a case when the signal cannot be transmitted from the side of the clamping head through the main spindle. Along the other path for signal transmission from the workpiece, the Hottinger's device is used and applied in a case when there is tube-shaped main spindle.

PC computer interface that is used in the measuring system has been developed within [27]. It is composed of 5-channel signal amplifier and data acquisition card. The signal amplifier performs triple role as part of the interface. It amplifies thermo-voltage generated from the natural thermocouple and the signals from the dynamometer to the required level. The second role of the amplifier is to provide galvanic separation of the electric circuits with the thermocouples, from the electric circuits consisting of data acquisition card and PC. The role of this galvanic separation is to protect against any possible electric shocks that can damage this part of the measuring system. The third role is to remove the influence of the electric circuit consisting of data acquisition card and PC on the electrical circuit with thermocouples and the dynamometer. The data acquisition card integrates Microchip microcontroller type PIC 16F877 and electrical components that support its work. The microcontroller integrates 10-bit A/D converter and operates at generator frequency of 20 MHz. The microcontroller also contains a built-in module for serial synchronous and asynchronous communication in both directions with ability to easily adjust communication speed. For communication with PC, a speed of 115200 bps is used. The sampling frequency is 1 kHz for each channel separately.



a) Measuring of the temperature b) Measuring of the cutting forces

Fig. 8. Screenshot of the monitoring system software FORTMON [27]

The software package for monitoring system support has the abbreviated code FORTMON (FORce & Temperature MONitoring). There is a section for graphic interpretation of forces and the thermo-voltage depending on time, and a section containing dialogue window with many controls (Fig. 8). It provides: real-time monitoring, software calibration, acquisition management, multitasking, resolution adjusting, simultaneous analysis, operations over curves, open source code, data recording, saving of the settings, export of the graphics, selection of axes grid value and so on.

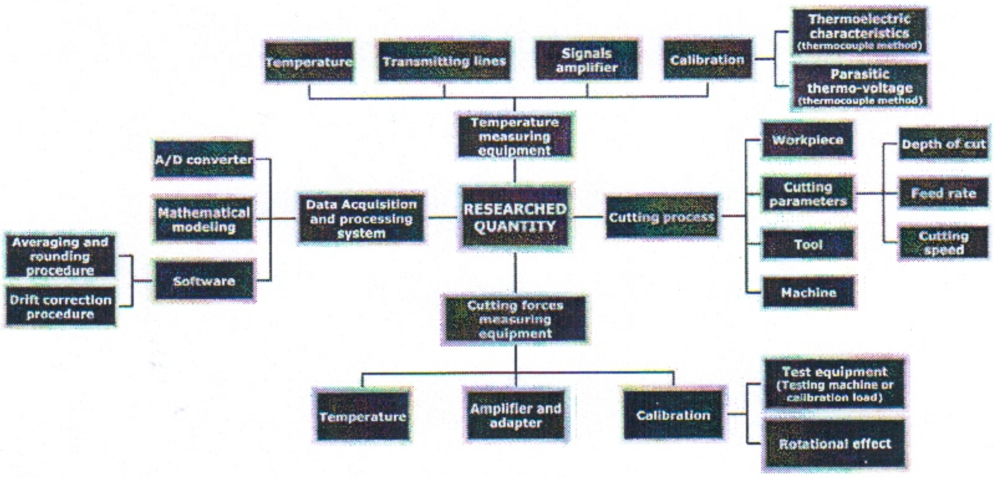



Fig. 9. Possible error sources during experimental research of physical phenomena in the cutting process [28]

Calibration of the monitoring system for forces measurement is performed by way of applying load on the dynamometer in the direction of the specified component of the force. After each load change, the value indicated by the monitoring system was recorded. In this way, tables with corresponding values were generated. They are graphically analyzed and model that represents a relation between monitoring system reading and force was created. By using this model into the software package, readings of the monitoring system can be expressed in force measurement units.

It bears special notice that the present research by the authors is aimed at determining the reliability of results obtained by measuring the mean (average) temperature and cutting forces that occur in the cutting zone. In line with this, [28] gives an overview of possible sources of errors that affect the value of the final results of the measurement, schematically illustrated in Figure 9. Such investigations are provided as a result of knowing the characteristics of the built-in elements in the monitoring system, which is a feature only in self-developed open systems.

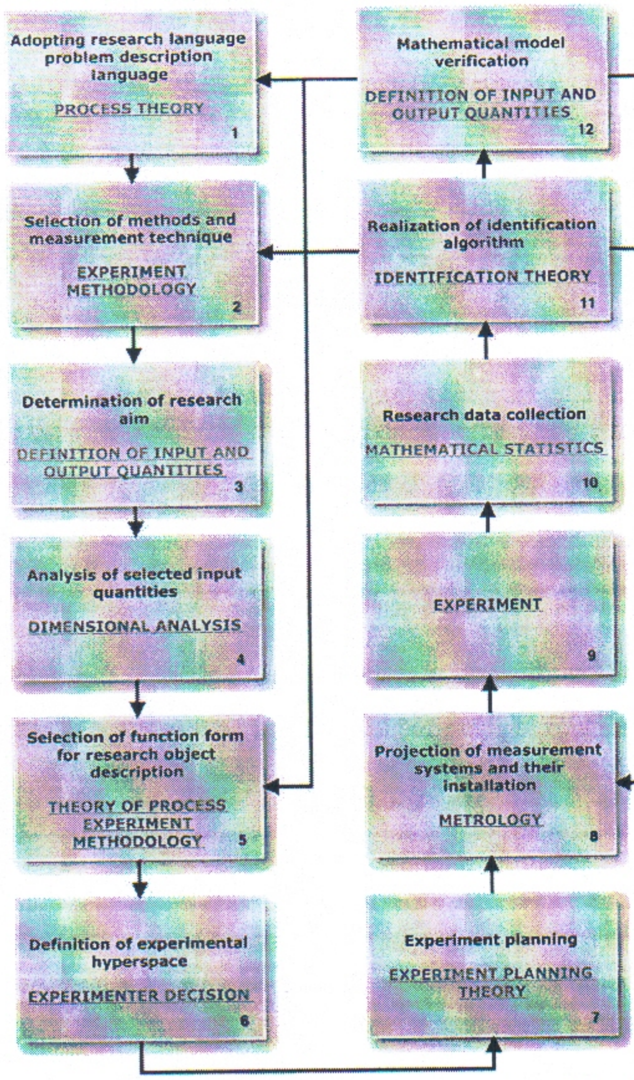



Figure 10. Experimenter activities when planning and analyzing experimental scientific researches [29]

### Design, analysis and implementation of experimental research

In the stages of projecting the characteristics of the surface layer, that is, when defining the mathematical models that describe dependencies and influences between the required characteristics of the surface layer and the adopted technical condition for its realization with machining by material removal, it is required to apply an appropriate methodology.

The computer-aided systems for engineering of the surface layer in the machining process by material removal, shown in Figure 1, includes many activities (experimental research) that are performed stepwise and in particular order. Detailed preview of the set of activities that need to be planned by experimenter during implementation of experimental scientific research is given in [29], algorithmic represented by Figure 10.

The introduced automation in the computer system, shown in Figure 1, implies certain stages, given in Figure 11, that the experimenter needs to go through when projecting and implementing the experimental research.

### Measurement and analysis of the characteristics of the geometric structure on the surface of the surface layer

Consideration of the geometric structure of the surface of a surface layer as deviation from form, waviness and roughness is widely accepted and standardized [31, 32, 33, 34, 35, 36]. Such approach is illustrated in Figure 12.

The idea for such approach during surface analysis comes out of the fact that roughness, waviness and form have various effects upon functionality of parts from several aspects and therefore such classification is considered an important segment of surface texture analysis, according to [37].

Separation of roughness, waviness and form profiles, shown in Figure 12, from the measured total (raw) profile is performed by means of a filtration process. In measurement technique development, two filtration methods are presented, known as E-filtration system and M-filtration system [37, 38, 39]. The E-filtration system uses the envelope method (rolling or sliding a ball with certain diameter against surface) and is a mechanical filtration system used in oldest measuring instruments. The M-filtration system includes the use of a profile filter. Profile filter could be analogue or digital. The subsequence of use of profile filters and the procedure for gaining profiles of roughness, waviness and form is standardized with ISO 4287:1997 [35]. This international standard defines three types of profile filters $\lambda_s$, $\lambda_c$ and $\lambda_f$. $\lambda_s$-profile filter removes components with very short wave length (noise, deformation of the stylus and the like) from the total profile. $\lambda_c$-profile filter separates roughness profile, while $\lambda_f$-profile filter separates waviness from the form. This filtration process which uses the $\lambda_s$, $\lambda_c$ and $\lambda_f$ profile filters for contact (stylus) measuring systems is presented in Figure 13. The primary profile is described by P-parameters, waviness profile by using W-parameters, and roughness profile by R-parameters.

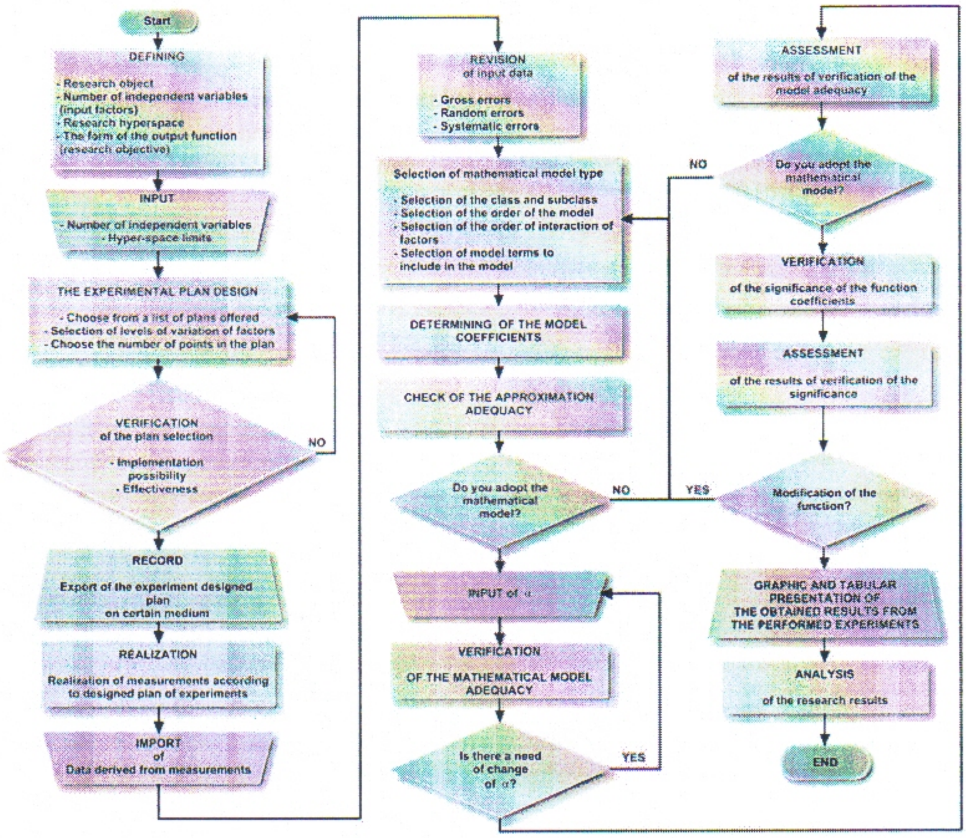



Fig. 11. Stages in projecting and implementation of computer-aided experimental scientific research [29, 30]

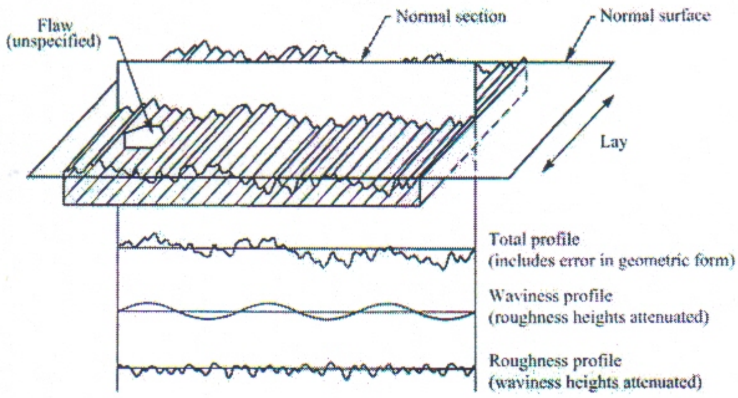



Fig. 12. Graphic interpretation of the characteristics of surface [31]

Again, the ongoing research activities by the authors are in aiming at a more reliable determination of the parameters that characterize the roughness profile, and thus the geometric structure of the surface of the surface layer. The need for such research derives from the presented conclusions in [2], which allow us to find large differences in results when measuring roughness, and ambiguity when evaluating the roughness parameters.

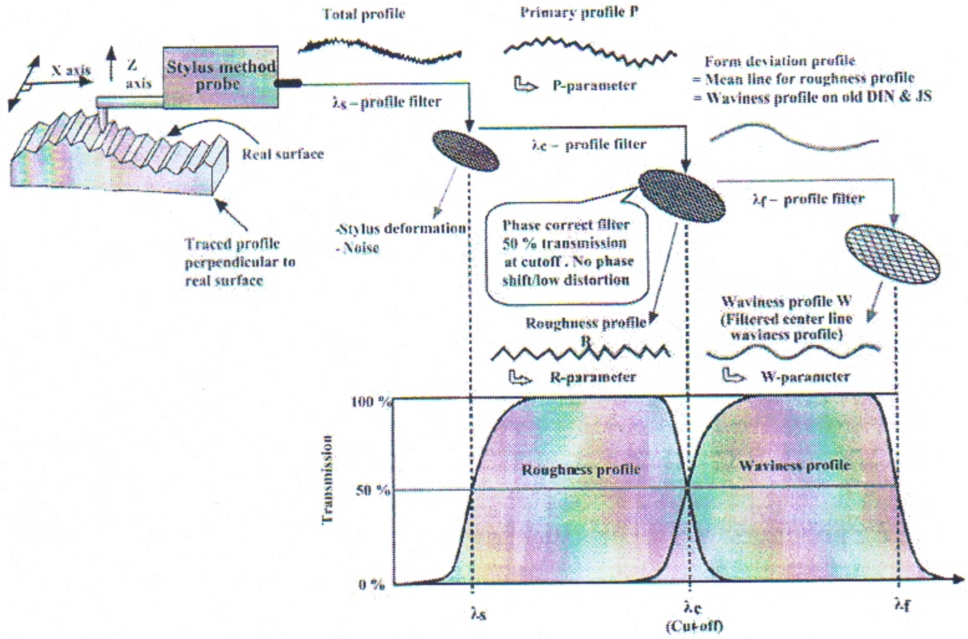



Fig. 13. Filtration process by using $\lambda_s$, $\lambda_c$ and $\lambda_f$ profile filters [36]

A research which aims at a more reliable determination of the roughness parameters must take into consideration all elements involved in the process of gaining roughness profile. Some of the elements which are analyzed include: influence by the sampling length [40, 41, 42], influence by the size of cut-off length [43], and influence by the software filtration on the valuesof the roughness parameters [44, 45, 46].

The above research primarily considers geometric structure of the surface of the surface layer in 2D domain. It is necessary to emphasize that the computer integrated system shown in Figure 1, for the purpose of investigation of the geometric structure, also includes an analysis in the 3D domain, by determination and calculation of the surface parameters.

### Research concerning determination of residual stresses in the surface layer

Drawing on the analyzed literature and performed experimental studies [47, 48] on determination of residual stresses in the surface layer obtained in machining process by material removal, it can be concluded that undoubtedly an advantage is given to the Davydenko destructive method. This method is based on measuring deformations in samples with the form of thin wall rings, caused by release of residual stresses as a result of chemical or electrochemical dissolution of the layers of the analyzed surface. Some believe that the method is characterized by relatively high accuracy, especially when determining residual stresses in simple geometric samples. In that case, during the dissolution of the material layers, the determination of relation between the tension condition and the deformations is simple and accurate. However, we can find large discrepancies in determining the residual stresses, especially when they are determined by the same method and under the same measurement conditions, but performed in different research centers [47, 48]. Big dissipation in results justify the need for analysis of applied research methodology and equipment, with particular attention to: anchorage of measurement samples, operation and concept of the amplifier system for electrochemical dissolution, polarization, level, flow and temperature control of the electrolyte, deformations gauge, etc., and also the mathematical transformations of the deformations in voltage (the influence of roughness, module of elasticity, reading the current deformations of measurement samples, deflection during dissolution, mass of the measuring samples in different stages of the experiment, etc).

This justifies the efforts invested in developing own research equipment which, by way of changing the characteristics of the hardware and software components, makes it possible to reach a conclusion about the influence of the above mentioned issue of accuracy of determination of residual stresses in the surface layer.

## Conclusion

Introduction of computer-aided integrated methodology (engineering of the surface layer) to research the complex physical and chemical processes of constituting the surface layer created during machining process by material removal, in correlation with its characteristics, as well as relating it to the desired exploitation characteristics of the product, create conditions for a more complete control of the process of constituting and forecasting characteristics of the surface layer. The development and possession of own hardware and software equipment for scientific research on physical phenomena in the machining process and technological effects in the surface layer, with open access to hardware and software components, is the main goal of the research centers and is an important pre-condition for achieving distinctive results. Open access to hardware and software solutions enables identification and removal of systematic errors that arise in measurement systems, which is not the case in commercial solutions. In addition it provides conditions for quantitative determination of the effects of individual components and for possibility to determine the uncertainty of measured result, individually for each module of the above mentioned measurement equipment.

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