Integrated Machining Process Modelling and Research System

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Abstract **This paper presents own developed research system for modeling of the metal machining process. The research system integrates measuring sensors and systems, computer interfacing devices, software and investigation methodologies in order to develop machining process models. Our own developed hardware and software solutions are part of the applied strategy for full control over the research measuring chain. The resulting machining empirical models are accompanied with uncertainty parameters in order to fit the criteria of application in Smart Machining Systems (SMS) and new manufacturing optimization techniques.**

Keywords integration, modelling, machining, uncertainty, smart systems.

I. INTRODUCTION

The fight for better quality products and lower production cost never stops in the production industry. If we make an outlook of what is now on the workshop floors, we can see that even with state-of-the-art computer numerical control (CNC) machine tools equipped with the newest control elements, the process of making new products is long and based on many trials and errors. On the other hand, from the market perspective, the demand for new products grows by an exponential trend. Another important characteristic of the market is the growth of the variety of products that are expected to support the developing technology in all fields. In the field of machining, the development of a system to catch up with the production demands refers to the development of smart machining systems (SMS), which are featured to be capable of self-monitoring and optimizing of the operations, self-assessing their own work, self-learning and improving performance over time [1]. The smart machining systems are intended to be aware of what they produce and how well. In the work of Dashayes [1], the SMS components are presented. We can see that the main input in SMS is from the conceptual process plan (CPP) which is directly correlated to the life cycle engineering (LCE). From the point of view of the machining processes, the dynamic process optimization (DPO) uses machining models (MM) to build and achieve the objectives within the design given frames like the dimensional and geometrical tolerances, the surface integrity and quality. The SMS is expected to optimize the machining process before and during its realization. The machining process uses MMs which are approximations and always contain certain amount of uncertainty. This uncertainty will cause machining errors, and the process monitor and control (PMC) will return the process to the desired conditions. The SMS is envisioned to recognize the limitations of certain MMs, or methods in general by knowing their uncertainty, and eventually to make the right selection between them. The main elements in this concept are the optimization tools and the MMs. The MMs are based on large knowledge bases and they should be correlated. It is unlikely that this concept can be achieved without interoperability and cooperation between the research institutions and the manufacturing industry. However, there is new information highways between the products, manufacturing industry and the research institutions enabled by the new age of the Industrial Internet of Things (IIoT). The IIoT can be considered like the infrastructure for the smart manufacturing which is under development by the automation suppliers in the last two decades and it will drive the evolution of the industry. The final goal is to make the integrated systems to "talk" between themself and to deliver meaningful and intelligent results by using the scientific knowledge.

The work in this paper is mainly focused on a comprehensive approach in generating knowledge base in the part of experimental models of the machining process. As we

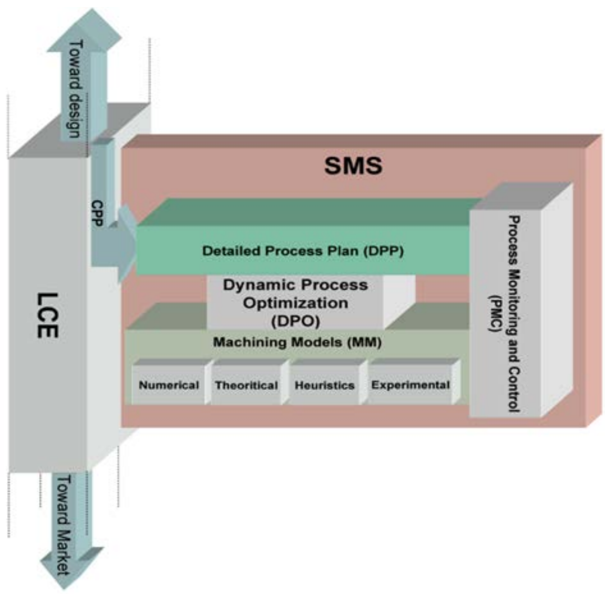


Figure 1. SMS components [1]

mentioned, these mathematical models are approximations and their quality is very important in order to be used in the SMS concept, and other similar concepts. The quality of the experimental models is an issue by itself, which is often neglected due to its complexity. The quality of the experimental models can be described by the uncertainty parameter of the model. The uncertainty parameter of the generated experimental models is based on the propagation of the uncertainties of the single measurements upon which the model is fitted. A lack of such comprehensive approaches is evident in the papers published in this field. This also leads to differences in the results between laboratories. However, the new trends have already determined that new researches and new experimental models should be accompanied by the uncertainty parameter, as recommended in [2-6]. Now, if we go deeply in the analysis of the experimental research of the machining processes and the experimental modeling, we come to the point that this is also a wide system. The experimental research system, in order to provide models as described, should integrate many components. The main components in this chain are the methodology, the measuring system, the hardware and the software solutions, and the machining process itself. Our *directions* into the design of these components, and their subcomponents that we adopted, in order to follow the SMS concept are:

- open platform of hardware and software
- good metrological practice
- all measurements are accompanied by an uncertainty parameter
- interoperability between laboratories and experts

These elements are in function of the investigation (measuring) and the reproducing (modeling) of the machining process or the physical phenomena of interest. Furthermore, we describe the integration and the features of the elements of such developed research system on the Faculty of Mechanical Engineering in Skopje in cooperation with the Wroclaw University of Technology from Poland [7].

II. RESEARCH SYSTEM

On Fig. 2, the path of identification and modeling of the cutting forces is presented, as well as the average temperature in the machining by turning. These physical quantities are representative of the set of physical quantities that can be the object of research, and other can be the tool wear, the residual stresses, 3D temperature, etc. In order to present a certain approach in the design and application of the components, we can break the description of the research system down in:

- Identification methodology
- Measuring and computer interfacing components
- Software
- Calibration
- Modeling and representation

Herein, we will present only a brief summary of the main features of the research system in order to fit within the paper size given criteria, and we will stress some features which are of significant importance.

A. Identification methodology

After selecting the phenomena of interest and research, the question arises of what the most appropriate measuring instrument to apply is. Here, balance should be achieved between the available technology, methods and the given concept by the SMS.

For the measuring of the cutting forces, and by following the adopted directions in the previous section, we modernized an analog dynamometer, due to the accessibility of its electrical diagrams, based on a bridge circuit, Fig. 2.a. Modernization is justified as it is budget oriented, and investment in new equipment can bring difficulties in the integration with other parts of the system, not to mention the risk of not having the available documentation of the processing of the measured signals regarding investigation of the measurement uncertainty. The process of modernization is done by the design of the amplifier circuit, providing additional benefit by expanding the knowledge of the researchers with the possible sources of errors from this part.

For the measuring of the average temperature, there is a wide palette of identification methods given by [8]. This measuring system integrates the method of nature thermocouple workpiece-cutting tool. Although this method is considered to be under the influence of many sources of errors, our approach can benefit from determination and quantification of these errors by the adopted system of uncertainty budget determination, and consequently dealing with them. As many as two paths for the signal conduction from the workpiece side are designed in order to detect any deviations and errors, Fig. 2.b. Conduction of the signal from the workpiece is done by slip-ring assemblies, Fig. 3, and reconstructed cutting tool with built-in conductors.

B. Measuring and computer interfacing components

This research system consists of our own developed interface between the sources of the signal and the personal computer. As we mentioned before, the benefits of developing our own system are significant regarding the open access of signal manipulation and errors identification. Excluding any influence of the measuring equipment to the source of the signals was of special concern. It has been done by application of voltage followers by high input impedance, galvanic separated power supplies of the amplifiers and optically amplifier insolation, by using the integrated circuit ISO100. Acquisition of the signals is done by our own developed data acquisition card, by our own software design which controls the measuring process, provides customization, provides uncertainty determination, and connects with our own developed personal computer application designed for conduction of a large number of experiments in a short time, Fig. 2.c.

C. Software

Our own developed software for conducting of the measurements is developed in C++, and provides the benefits of the open access, customization and uncertainty determination as in the case with the PC interface, Fig. 2.d. The most important consideration, like decimal places in the rounding and calculating procedure, biasing, etc., regarding the uncertainty is available for moderation and estimation.

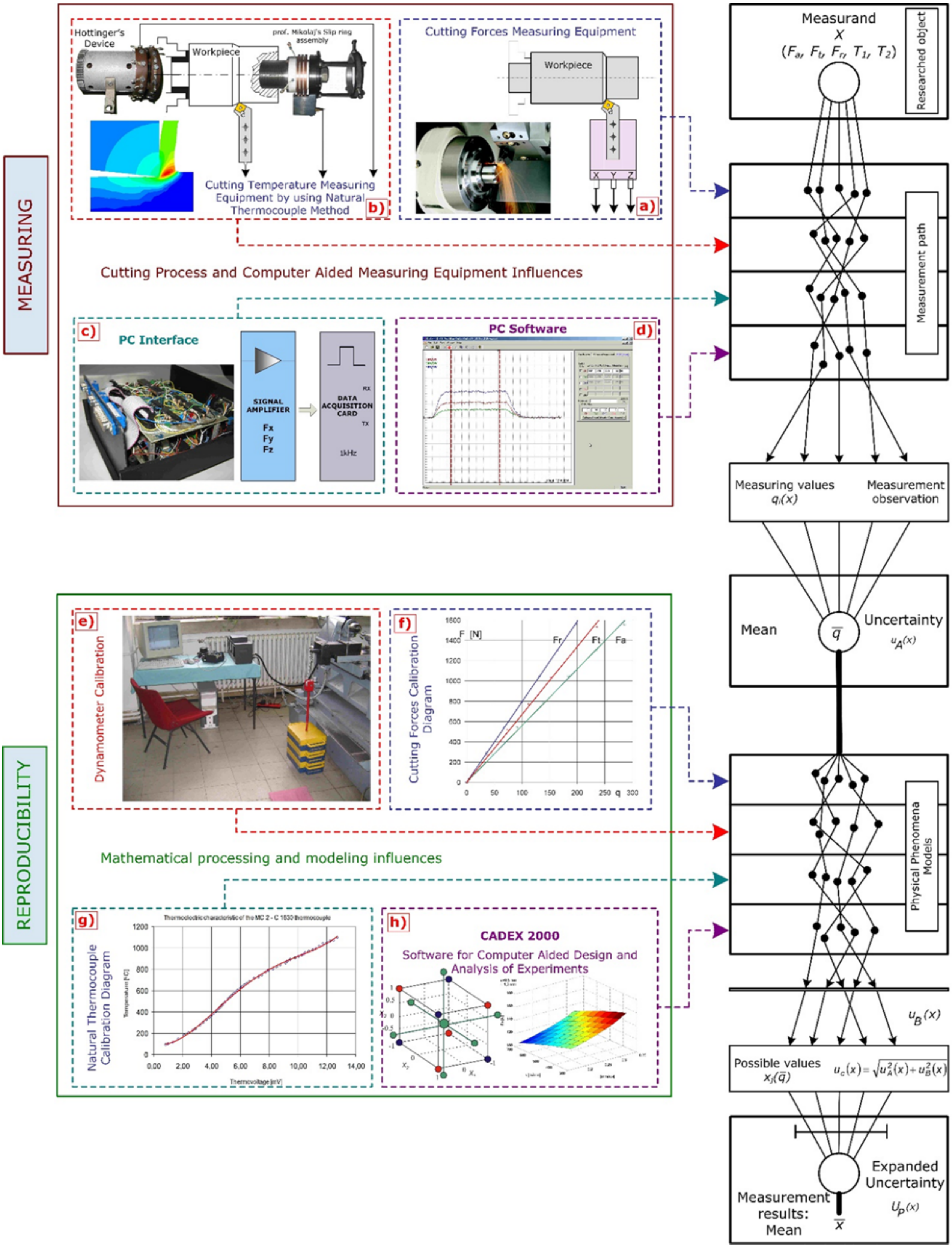


Figure 2. Machining process research system components and their influence on the empirical modeling

D. Calibration

The transformation of the raw generated signals into the measured quantity in the SI system units has been done by applying of the calibration curves. The calibration curves are calculated upon our own experimental data, providing very significant data about the amount of error generated by fitting them. Actually, this is one of the parts of the measuring system which is of high importance as it takes a big piece of the uncertainty budget pie. The thermo-voltage characteristic of the nature thermocouple workpiece-cutting tool has been done by special equipment in a furnace and is given by Fig. 2.g. The calibration of the dynamometer has been done by dead weights that were previously calibrated in the Bureau of Metrology in the Ministry of Economy in Skopje, Fig. 2.e., 2.f. and 4. Calibration by dead weights results in a significantly lower uncertainty rate regarding the force testing machine, which is usually available in the laboratories for testing forces.

E. Modeling and representation

The methodology implemented for the experimental research is by Design of Experiments (DOE) or factorial experiments. The CADEX 2000 software was developed for planning of the experiments. Fig. 2.h. A power mathematical model was adopted for the representation of the physical quantities of the cutting forces and cutting temperature related to the cutting process parameters. The exponents of the power mathematical models depicture the rising or decreasing of trend and rate. After fitting the model, a graphical representation is presented. There is plenty of research in the field of similar experimental setups and mathematical models in order to make comparisons between laboratories with the same or similar machining conditions. Although small changes in the cutting process conditions result with different mathematical models, the importance of empirical research has motivated many laboratories to have such experimental stands and to compare results under the same conditions. The results from different laboratories in general are not comparable, and there is no clear explanation of such discrepancies. Tracing of the reasons for that usually encounters the lack of the measurement uncertainty parameter. As our research system is designed on an open platform and is dedicated to present the uncertainty detailed budget of such complex researches, we have developed and recommended a certain approach for measurement uncertainty determination [9]. The presentation of our experimental results is an ongoing process aimed at making a knowledge base in the field.

III. Measurement uncertainty

Regarding our dedication to achieve distinct results in the field of experimental investigation, an approach for measurement uncertainty parameter of the final mathematical model has been developed and proposed during our researches. Often, only partial approaches for measurement uncertainty evaluation are presented. They usually refer to the measurement uncertainty of the measuring instrument, like the uncertainty of the dynamometer, or at the most the uncertainty of a single measurement. However, our view is that such partial approaches are not depicturing at all the uncertainty of the final product of the research, which is the mathematical model of the investigated quantity. Our proposal is that measurement uncertainty should be presented in a suitable manner same as the final result [10]. The final power mathematical model represents the investigated quantity with the determined exponents and coefficients. Consequently, the proposal is every fitted exponent or coefficient in the mathematical model to be accompanied by the uncertainty parameter. Although the exponents of the power mathematical model are a result of many additive and logarithmic or antilogarithmic mathematical calculations, we propose to propagate the combined measurement uncertainty in the same way in order to find the appropriate parameter. An example of the form of such a power mathematical model is given by (1).

$$\varphi = \left(C \pm U_C\right) \cdot v^{p_1 \pm Up_1} \cdot f^{p_2 \pm Up_2} \cdot a^{p_3 \pm Up_3} \cdot r_\varepsilon^{p_4 \pm Up_4} \qquad (1)$$

where f is the researched quantity (cutting force component,

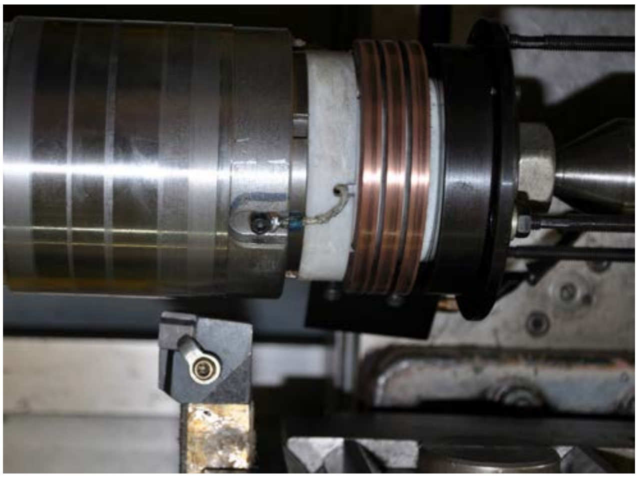


Figure 3. The cutting process and slip-ring assembly for conduction of temperature signals

Figure 4. Calibration of dead weight

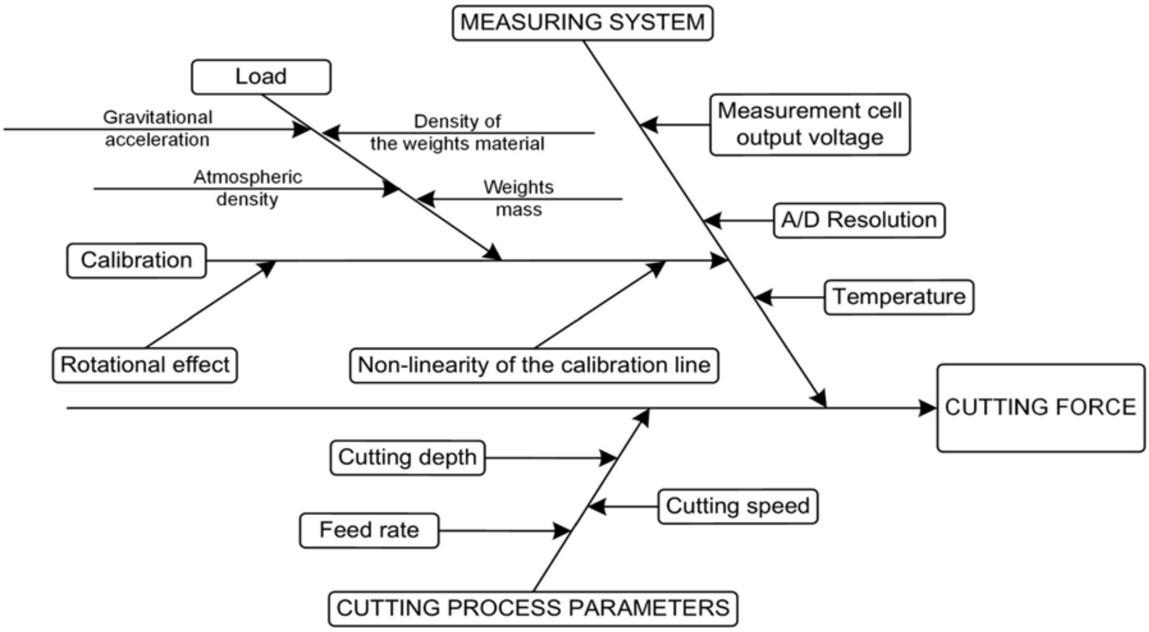


Figure 5. Ishikawa diagram of cutting force component measurement uncertainty contributors

cutting average temperature), v, f, a and r_ε are the cutting process parameters, cutting speed, feed rate, depth of cut and cutting tool nose radius, while C, p_1, p_2, p_3 and p_4 are the exponents and the coefficient of the mathematical model and U_C, Up_1, Up_2, Up_3 and Up_4 are the expanded uncertainty parameters.

Following the path of fitting the mathematical model and the chain of measuring and reproducing the investigated phenomena, Fig. 2, we can group the uncertainty contributors into:

- Measurement system contributors
- Mathematical modeling contributors
- Machining process contributors

On Fig. 5 an example is presented of braking the measurement system and machining process uncertainty contributors of single cutting force component by the Ishikawa diagram. The modeling contribution arises while combining (propagating) all the single measurement uncertainties by the DOE matrix equation, and it depends on the DOE plan size and structure.

While some of the presented uncertainty contributors on Fig. 5 are typical to consider, other must be well thought-out. Such are the contributors from the cutting process, which in the worst case are totally neglected. Even when they are taken in consideration, as in the case of determining the single measurement uncertainty, it is neglected that such measurement is just one point in the experimental hyperspace. For example, the error of the cutting depth is estimated by measuring the deviations from the mean value of many depths of cuts after the single cut. That is the main reason for underestimating the uncertainty from this contributor. We propose that this contribution should be calculated upon the deviations from the assumed mean (planned and programed value according to the DOE plan matrix). The assumed mean should be also considered for the other cutting process parameters.

Another view is considering the contribution from the feed rate. The indirect approach with length-time readings can be substituted by estimating the real feed rate from the roughness parameter PS_m of the machined surface, Fig. 6. Here, the help of the laboratory of metrology of the geometric characteristics and research of quality is welcome.

The calculation of the measurement uncertainty has been done in the spirit of the Guide to the expression of uncertainty in measurement (GUM) [11]. Furthermore, as the propagation of the measurement uncertainty is based on complex additive models, we adopted the verification of the uncertainty value and distribution to be by the adaptive Monte Carlo numerical method (MCM). We recommend the verification by numerical method as it is ensuring avoiding the disadvantages of the GUM methodology.

Such an in-depth analysis of the possible contributors in the uncertainty budget results in as much as possible true estimation of the uncertainty parameter, which will accompany the exponents and the constants in the final mathematical model.

IV. INTEGRATION

The research system that is subject of this work is live matter of continuous development, growth of experience and expanding the knowledge base in the field. It is already an integral part of a wider system of computer aided engineering of the surface layer during machining process by material removal. This wider system integrates the research setups for: Monitoring system for transformation of the cutting layer into chips in the Wroclaw University of Technology (WUT),

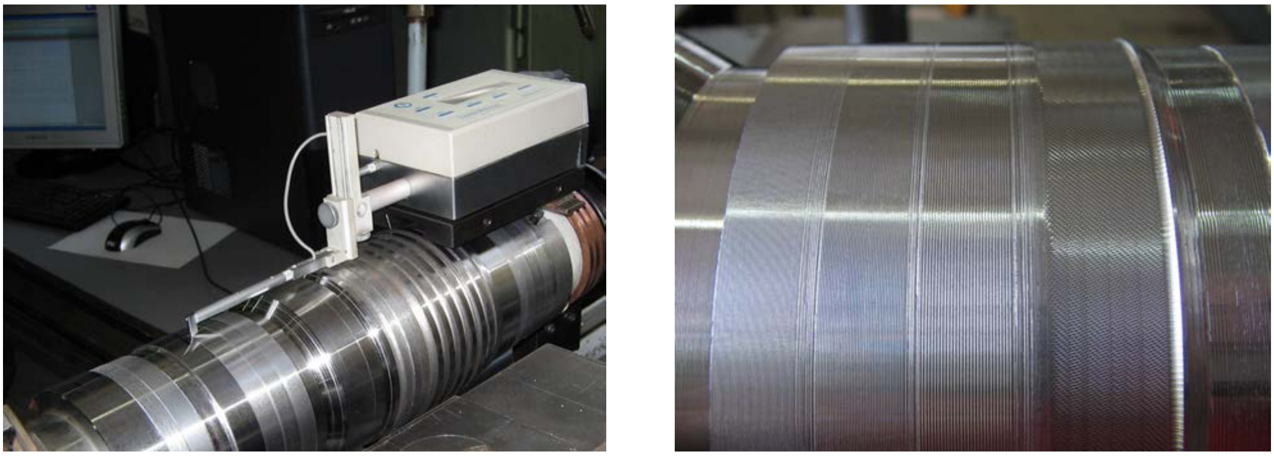


Figure 6. Measuring of the roughness parameter PS_m during experimental research of cutting forces and cutting average temperature

Monitoring system of cutting tool wear in the WUT, System for design of the geometrical characteristics of the surface layer in the WUT and the Faculty of Mechanical Engineering in Skopje (FME) and the System for investigation of the surface layer geometrical characteristics in the FME. The continuous developing knowledge base and the distinctive achievements of the results aim at integration in an SMS as part of the LCE.

V. EXPERIMENTAL RESULTS

The capabilities of the system for research of the machining process by turning are very wide, and some of them are: measuring of the cutting force components, measuring of the average cutting temperature, empirical modeling of the cutting force and average temperature in the cutting process, calculation of the measurement uncertainty of single measurement of force or average temperature, determination of the uncertainty of the empirical models, design of experiments within the DOE methodology, investigation of the influence of the design of the experimental plan on the uncertainty of the empirical results, estimation of the quality of the empirical researches, determining recommendations for lowering of the measurement uncertainty and different simulations.

As this work is focused on the description of the research system and its components (equipment and methods), herein, we want to present the results of one simulation of the necessity of implementing the procedure of verification of the uncertainty by numerical method Monte Carlo, as proposed in the penultimate paragraph in the third section of this paper. For that purpose we performed an experimental measurement of the average cutting temperature under the experimental features showed in Table I. The result of the experimental measuring is the value of T_C=748.07^{o} C and the combined standard uncertainty determined by the GUM uncertainty framework (GUF) as presented in the first row in Table II, and by line on Fig.7.b. and 7.d. Verification has been done by adaptive MCM showed in Table II under MCM1, and we can see that the test within the given criteria for stabilization and validation of the adaptive MCM results in positive validation, presented by bars on Fig.7.b.

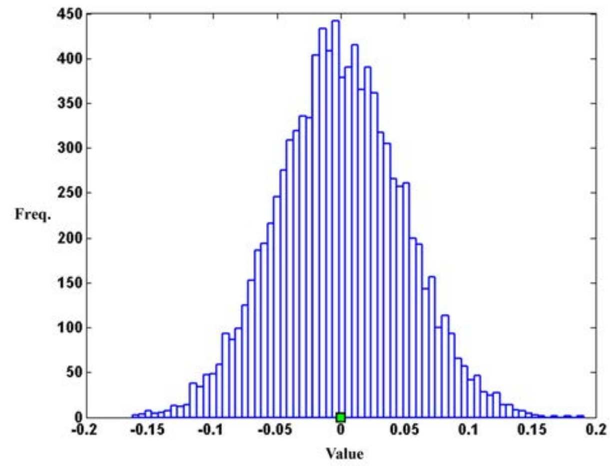
TABLE X. EXPERIMENTAL FEATURES

Workpiece material	*Carbon steel: EN C55*
Workpiece shape	*Cylindrical bar, Diameter 100 mm*
Cutting tool holder	KENNAMETAL, IK.KSZNR-064 25x25
Cutting insert	HERTEL, SNGN 120704, mixed ceramics MC2(Al_2O_3+TiC)
Cutting tool geometry	κ_r=85 $^\circ$, κ_{r1}=5 $^\circ$, $\gamma_0 = -6^\circ$, $\alpha_0 = 6^\circ$, $\lambda_s = -6^\circ$
Cutting process parameters	*v*=92 m/min, *f*=0.16 mm/2πrad, *a*=0.5mm, r_ε=0.4 mm

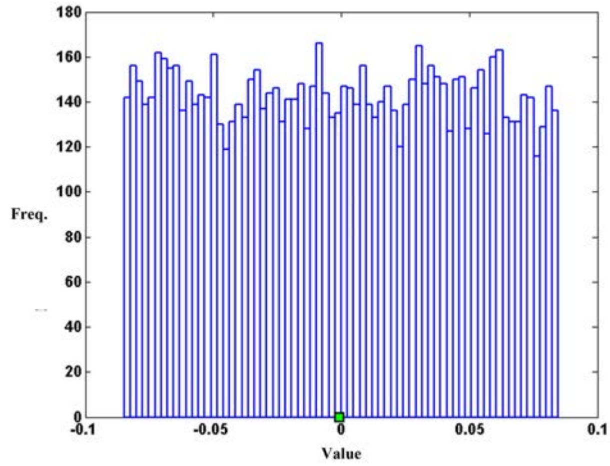
The combined measurement uncertainty is propagated considering the standard uncertainties and sources of errors as described before. For this example, we analyze the influence of only one source, the contribution of the mathematical modeling of the thermoelectric characteristic, Fig 2.g. The standard uncertainty of this parameter is 49μV normal distribution (showed by bars on Fig. 7.a), with a sensitivity coefficient of 85.26 results in the uncertainty contribution of 4.2^{o}C in the budget of the measurement uncertainty. Now, if we make a simulation and we change only the type of the distribution of δc into rectangular as showed on Fig.7.c, then, although the results for the final propagated combined uncertainty by GUF method, stays the same, the MCM validation as presented in the last row of Table II and by bars on Fig.7.d, is negative and GUF results cannot be considered as reliable.

TABLE XI. GUF-MCM VALIDATION PROCEDURE PARAMETERS

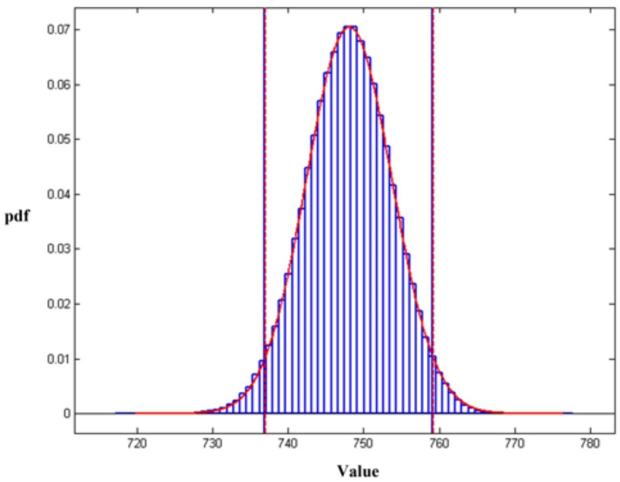
Method	***M***	T_C [^{o}C]	$u(T_C)$	**95% coverage interval**	Δ_{low}	Δ_{high}	δ_{stab} δ_{val}	**Validated**
GUF		748.08	5.662	[736.980 - 759.176]				
MCM1	5.1e5	748.05	5.654	[736.822 - 759.019]	0.158	0.157	0.05 0.25	yes
MCM2	2.7e5	748.03	5.668	[737.143 - 758.755]	0.163	0.421	0.05 0.25	no



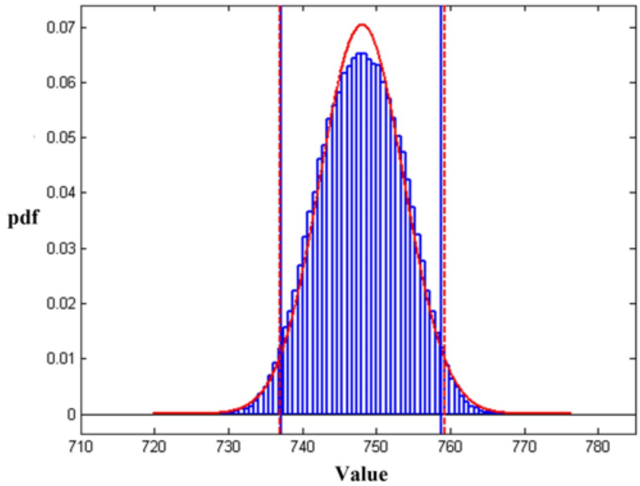
a) $\delta c = 0$, u(δc)=49µV, normal distribution



c) $\delta c = 0$, u(δc)=49µV, rectangular distribution



b) MCM1 T_C [°C]



d) MCM2 T_C [°C]

Figure 7. Monte Carlo Simulations results for the average cutting temperature

This simulation shows that the adopted procedure of MCM verification is sensitive and will be important when determining the uncertainty during the experimental research, because of the complex propagation models and many different types of input uncertainty contributor's distributions.

VI. Conclusions

The research system presented in this paper has been successfully developed, including the measurement equipment, calibration, methodology, the computer interfacing hardware and software. A full factorial experimental plans are designed and executed and mathematical models are developed including the measurement uncertainty for the model. As a result of the performed research, certain scientific conclusions, proposals and recommendations are in the process of publishing. The research system and adopted approach are aimed to meet the criteria of the newest trends in the field as the Smart Machining Systems whose target is achieving optimal machining conditions. We consider that the developed open access architecture of the research systems makes it as an advanced tool for integration into the SMS or similar systems.

Our further efforts are aimed at creating bigger knowledge base of different machining materials and tools in order to demonstrate improvement in the reliability of the gained empirical mathematical models. Additionally, we consider as significant the scientific contribution of the proposed approaches for further experimental researches. As a final phase of all the efforts, we expect more reliable recommendations for the industry.

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