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TABLE OF CONTENTS
(С О Д Р Ж И Н А)

PRODUCTION ENGINEERING
(Производно инженерство)

ADDITIVE MANUFACTURING
(Адитивно производство)

INDUSTRIAL DESIGN
(Индустриски дизајн)

SOIL MONITORING
(Мониторинг на почва)

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Original scientific paper

EVALUATION OF THE UNCERTAINTY CONTRIBUTION OF THE NATURAL THERMOCOUPLE CHARACTERISTICS IN THE EMPIRICAL MODELLING OF TEMPERATURE DURING METAL CUTTING PROCESS

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A b s t r a c t: This paper gives a recommendation of including the measurements uncertainty contribution of the natural thermocouple characteristics in the process of empirical modelling of the average temperature during machining process by turning. It is proposed that the calculated uncertainty value of this source should be a part of the overall uncertainty budget of the coefficients/degrees of the resulting power empirical model. The paper includes results of an example where thermo-voltage vs. temperature recordings of the natural thermocouple were analyzed by the proposed approach.

Key words: measuring; natural thermocouple; thermo-voltage; uncertainty; modelling

ПРОЦЕНА НА ПРИДОНЕСОТ НА МЕРНАТА НЕОДРЕДЕНОСТ ОД КАРАКТЕРИСТИКАТА НА ПРИРОДНИОТ ТЕРМОПАР ПРИ ЕМПИРИСКО МОДЕЛИРАЊЕ НА ТЕМПЕРАТУРАТА ВО ПРОЦЕСОТ НА РЕЖЕЊЕ МЕТАЛ

А п с т р а к т: Овој труд дава препорака за вклучување на придонесот на мерната неодреденост што произлегува од карактеристиката на природниот термопар во процесот на емпириско моделирање на средната температура во процесот на обработка со стружење. Се предлага пресметаната вредност на неодреденоста на овој извор да биде дел од вкупниот буџет за неодреденоста на коефициентите/степените на добиениот степенест емпириски модел. Во трудот се прикажани резултати од пример каде добиените вредности за термонапонот во однос на температурата на природниот термопар се анализирани со предложениот пристап.

Клучни зборови: мерење; природен термопар; термонапон; неодреденост; моделирање

1. INTRODUCTION

This paper presents results and conclusions from wider research in the turning operations, which have steady mechanical loads and cutting geometries. Phenomena of interest in this paper that occur in the cutting process by turning due to interaction of the cutting tool with the workpiece is the average cutting temperature. In general, understanding and controlling this and similar phenomena, and the machining conditions under which they occur (e.g. tool geometry, tool materials, processing parameters like cutting depth, feed rate, cutting speed, etc.), is crucial to achieve concurrent manufacturing [1, 2]. Cutting temperature generation as one significant phenomenon that occurs in the cutting process has been described theoretically, as well as, by empirical researches [3, 4]. The empirical researches typically result in power mathematical models, e.g. (1), where T is the cutting temperature, v and f are cutting parameters, cutting speed and feed rate, and C_i (i = 0, 1, 2), are constants:

$$T = C_0 \cdot v^{C_1} \cdot f^{C_2}. \tag{1}$$

These empirical models are qualitatively correct, but quantitatively, they overestimate cutting temperatures and they are unable to estimate cutting temperatures in some operations. [4, 5]. Significant breakthrough in this field, by explaining the model reliability by addition of an uncertainty parameter is given in [6] and [7]. Our investigations which are presented in [7] propose that such uncertainty parameter should accompany all empirically determined coefficients of the mathematical model (2), thus identifying their accuracy.

$$T_C = (C \pm U_C) \cdot v^{p_1+U_{p_1}} \cdot f^{p_2+U_{p_2}} \cdot a^{p_3+U_{p_3}} \cdot r^{p_4+U_{p_1}} \quad (2)$$

This paper gives more detailed insight in the particular study of one source of the measurement uncertainty which is identified as the most significant. That is the measurement uncertainty which arises from modelling of the thermoelectric characteristics of the natural thermocouple.

The study given in [7] is empirical modelling of average cutting temperature in turning – T_C, by implementing the new proposed approach of introducing the uncertainty of the mathematical model. The natural thermocouple during the machining process by turning is consisted of a cutting tool plate (Figure 1, marked by A) and a workpiece (Figure 1, marked by B). The generated thermo-voltage is conducted towards the measuring system by a special slip rings assembly (Figure 1, marked by C), from the workpiece side and by conductors implanted in the reconstructed cutting tool insert holder (Figure 2), from the tool side.

On Figure 3, the stages of the research process, which can be divided in two parts, are presented. The first part represents measuring of a single quantity value during one cut. The second part is using a single measurement as one point of the Design of Experiments (DOE) experimental research plan, which further results in the fitted empirical model. The final result is a power mathematical model, where the gained degrees of the model are showing the degree of influence of certain cutting parameters (v – cutting speed, a – depth of cut, f – feed rate, r_e – cutting tool radius, etc.) on the investigated phenomenon (average temperature in the cutting process). Such a model can directly be used as a recommendation for optimization of the cutting process.

As we mentioned within the DOE methodology there is an estimation of the adequacy of the fitted empirical model by the Fisher's test and the experimental error. However, this approach might not consider systematic errors, and can underestimate the real measuring error.

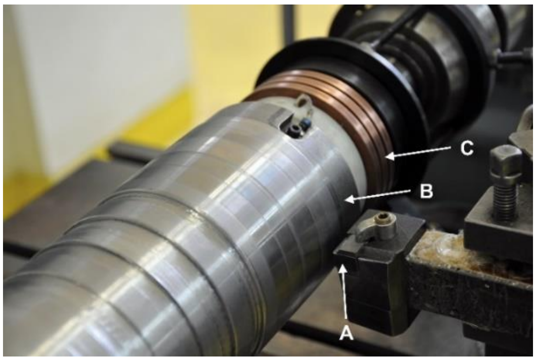

Fig. 1. Thermo-voltage source in the metal machining process [7]

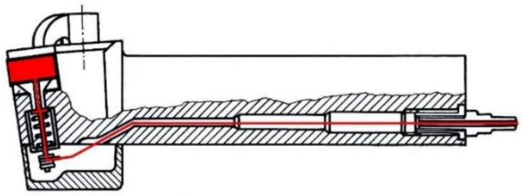

Fig. 2. Conduction of the generated thermo-voltage through the reconstructed cutting tool insert holder

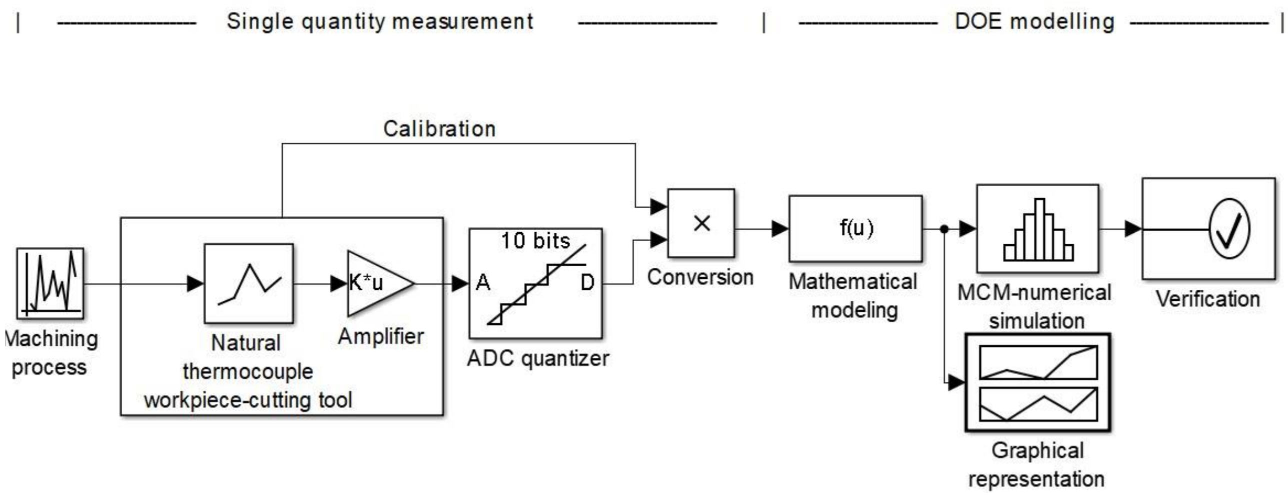

Fig. 3. Average cutting temperature research process chain [7]

Therefore, the research [7] is dedicated on proposing a final power empirical model that includes degrees/coefficients uncertainty parameters (U_p / U_C), as given by the mathematical model (2). This have been done by using type B uncertainty evaluation for every degree/coefficient of the model, while the uncertainty budget is showing the reliability of the gained mathematical model and will identify significant sources of errors.

The research given in [7] includes identification and determination of many uncertainty contributors, which derive from the measuring system and the machining process itself.

The scope of this paper is to analyze, calculate, and present the uncertainty that arises from the thermoelectric characteristics of the natural thermocouple workpiece-cutting tool, which is a non-standard thermoelectric material, as part of the overall procedure of modelling the average cutting temperature and determining the uncertainty parameters of all degrees/coefficients of the generated power mathematical model.

2. METHODOLOGY AND RESULTS

In order to determine the thermoelectric characteristics of the natural thermocouple, a special experimental stand has been developed as showed on Figure 4 [8]. The natural thermocouple, consisted of a piece of the workpiece material EN C55 and cutting tool inserts from mixed ceramics MC2, has been placed in the middle of the furnace. Efforts for lowering oxidation on the joint are made by applying an inert gas in the furnace. The temperature has been measured by thermocouple PtRh6-PtRh30, and the thermo-voltage generated by the natural thermocouple has been measured by a voltmeter. For the thermocouple PtRh6-PtRh30, it has been used thermoelectric characteristics with cold junction with reference point of 20ºC:

$$T = 0.1711 \cdot u_T^4 - 4.9428 \cdot u_T^3 + 44.737 \cdot u_T^2 - 42.494 \cdot u_T + 104.13. \quad (3)$$

The results of the measuring are presented in Table 1, and the fitted mathematical representation has been showed on Figure 5, and by the mathematical model (3), [8].

During the experimental investigation and mathematical interpretation of the data, it was concluded that the curve has two inflection points, rather than being interpreted as linear, exponential, logarithmic or other type of regression function. Consequently, a biquadratic (quartic) function was selected (4th order polynomial function), which can have two inflection points to fit the data points, as the most suitable mathematical representation. This mathematical model is a result of the anisotropic electric properties of the cutting inserts, as well as the complexity of the heating process.

The published papers in the field [9, 10, 11], use similar mathematical models or thermoelectric characteristics' curves, while the error which arises by using this equation in order to make a conversion from the measured voltage to temperature units is not accounted and presented.

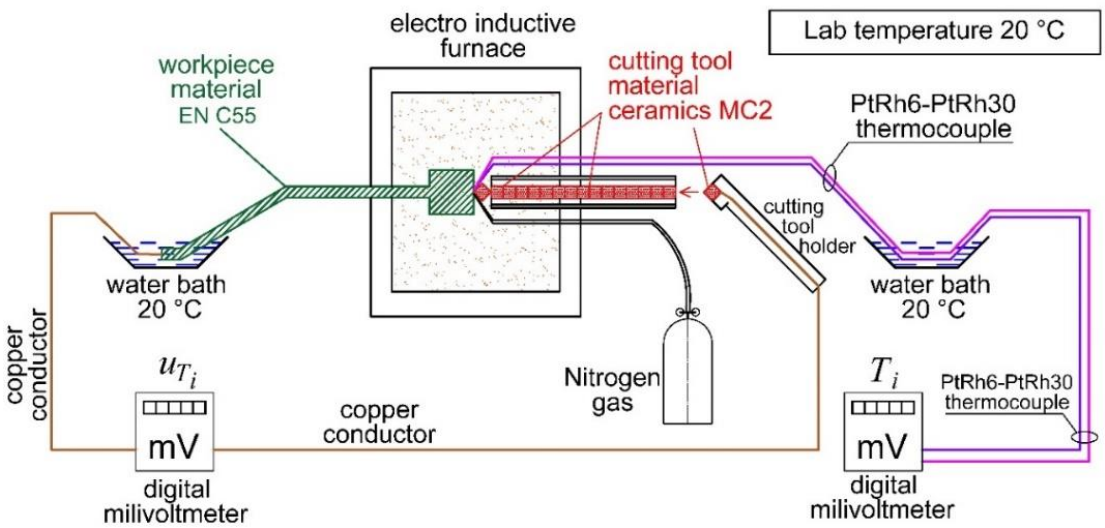

Fig. 4. Experimental setup for determining the thermoelectric characteristics of the natural thermocouple EN C55-MC2 [8]

Table 1

Measurements of the thermoelectric characteristics of the natural thermocouple EN C55 - MC2 [11].

i	u_T mV	T_i ºC	$\hat{T}_i$ ºC	i	u_T mV	T_i ºC	$\hat{T}_i$ ºC
1	0.80	93	96	29	6.27	653	643
2	0.97	100	101	30	6.43	666	659
3	1.30	113	114	31	6.62	684	678
4	1.69	146	138	32	6.96	715	711
5	2.10	180	170	33	7.26	731	738
6	2.38	203	195	34	7.48	749	756
7	2.68	226	225	35	7.73	772	777
8	2.87	242	245	36	7.93	790	792
9	3.20	277	282	37	8.26	804	816
10	3.41	301	307	38	8.51	825	834
11	3.65	328	335	39	8.77	841	850
12	3.83	348	357	40	9.15	860	874
13	3.98	366	375	41	9.24	875	879
14	4.13	384	393	42	9.45	893	891
15	4.28	403	412	43	9.80	908	910
16	4.42	423	429	44	10.04	921	923
17	4.54	438	443	45	10.27	933	936
18	4.67	455	459	46	10.41	944	943
19	4.80	474	475	47	10.52	955	949
20	4.94	494	492	48	10.76	969	962
21	5.14	522	516	49	11.03	981	978
22	5.28	537	532	50	11.24	995	990
23	5.42	556	549	51	11.48	1016	1006
24	5.54	571	563	52	11.75	1041	1024
25	5.68	588	578	53	12.02	1050	1045
26	5.82	604	594	54	12.24	1064	1063
27	6.00	625	614	55	12.47	1073	1084
28	6.12	638	627	56	12.73	1100	1110

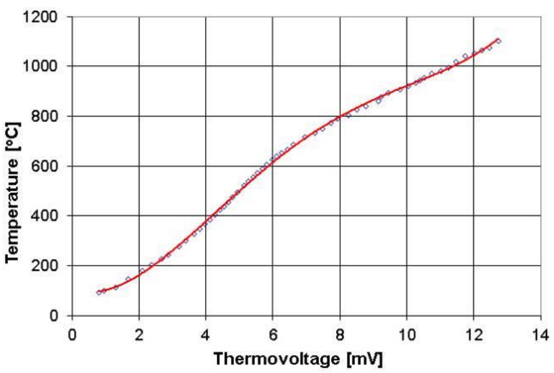

Fig. 5. Thermoelectric characteristics of the natural thermocouple EN C55 - MC2 [8]

After an analysis of the possible sources of uncertainty from the thermoelectric characteristics, we propose that three error contributors should be included in the uncertainty budget: the error of the least square method upon which the thermoelectric characteristics are fitted, the error which arises from the artificial thermocouple PtRh6-PtRh30 and the error which arises from the voltmeter used to record the thermo-voltage of the natural thermocouple during the calibration.

A. *Contribution from the least square method*

Error contribution of the least square method, upon which the thermoelectric characteristics have been fitted, has been estimated by using the recommendations ("Least-squares fitting") given in [12], section H.3.2, by equation (4), where T_i is the measured value and $\hat{T}_i$ is the predicted value by the fitted curve, and df is the degrees of freedom. Standard uncertainty of 7.67 ºK was found:

$$u(\delta c) = \sqrt{\frac{\sum_{i=1}^{n}(T_i - \hat{T}_i)^2}{df}}. \qquad (4)$$

B. *Contribution of the artificial thermocouple in measuring temperature in the calibration process*

The standard uncertainty of the artificial thermocouple has been calculated using manufacturer's data in the amount of 0.86 ºK.

C. *Contribution of the voltmeter in measuring the generated thermo-voltage of the natural thermocouple*

The standard uncertainty due to resolution of the voltmeter of 10 μV, has been estimated in the amount of 0.25 ºK (conversion of the units from μV to ºK has been done by using the same thermoelectric characteristics in the measuring example point u_T = 7.38213 mV).

3. DISCUSSION

Considering that the measuring uncertainty of a non-standard thermoelectric material is not different from considering the uncertainty and uncertainty sources of standard thermocouples, official standards and guidelines that are based on the most contemporary approaches in the field have been considered in our analysis. The guidelines in [13] propose considering the uncertainty components that arise from the resolution and calibration of the voltmeter, parasitic voltages, reference temperatures, non-uniformity of the furnace, compensation leads, inhomogeneity of the material, etc. Besides the proposed elements of the uncertainty budget, there are other recommendations about potential influences, which we have attempted to reduce or exclude, also given in [13, 14 and 15]. We propose including the most significant uncertainty components (described in section 2. A, B and C), as components which have the highest relative contribution in the uncertainty budget table of the measured single temperature during the cutting process.

The presented results indicate that the amount of uncertainty that arises from using the least square method to fit the thermoelectric characteristics (3) is very significant. If the mathematical function of the thermoelectric characteristics is adopted to be linear, we can expect that the contribution to the uncertainty will be even higher. For comparison, we can make a linear model and calculate the uncertainty contribution using the same data from Table 1, as the most common approach in the research field [11]. Such fitted linear thermoelectric characteristic will be given by (5).

$$T = 88.161 \cdot u_T + 40.247. \qquad (5)$$

In this case, the standard uncertainty of the least square method for the mathematical model (5) will be estimated in the amount of 22.3 ºK.

Mathematical models of thermo-electrical characteristics given in [10, 11, etc.] are considered deterministic by the authors. There is no analysis about the error introduced by their application.

It is important that herein we give an answer to the next two questions. First, can we use the thermoelectric characteristic as deterministic and not consider the error arising from its modelling? Second, should we consider using the polynomial model (3) that has a standard uncertainty of the least square fitting of 7.67 ºK, or can we use the simpler linear model (5) that has a standard uncertainty of the least square fitting of 22.3 ºK? In order to give an answer to this question, we must analyze the data given in the uncertainty budget in [7] according to which, the standard uncertainty in the amount of 7.67 ºK has a relative contribution to the budget of measurement uncertainty of a single temperature measurement by 30–70%, depending on the experimental measurement point. As a result, our new proposal for including the measurement uncertainty of the thermoelectric characteristics (especially contribution that arises from the applied least square method) is essential and should not be neglected in any measurement in this and similar fields.

Additionally, we propose that the standard uncertainty of thermoelectric characteristics should be combined with other important uncertainties which arise from the cutting process itself, the cutting parameters (feed rate, depth of cut, etc.), while measuring a single quantity. Another recommendation is that after making many single measurements which are part of the experimental plan, further to propagate these measurement uncertainties and present them like a parameter of the final mathematical model (relationship) between the researched quantity and the cutting process parameters, which is the final goal of the research.

Using linear form of thermoelectric characteristics, which is simpler and results in bigger uncertainties, like our example (5), with a standard uncertainty which arises from the least square method of 22.3 ºK, should be avoided as it will make a relative contribution of more than 95% during one single measurement and consequently will not give reliable results.

Empirical modelling is a very important part of the research process of the physical phenomena that occur in the metal cutting processes. With the new development of the SMSs (Smart Machining Systems), they are an essential part of the knowledge base, which is needed as the SMSs are limited on the parameters that can be monitored in real time.

Although many of the experimental research methods, like the method of natural thermocouple, are considered insufficiently reliable, herein we have shown that by using the right approach, we can determine if these methods are reliable and accurate, and what the error sources are. In our example we found that the neglected error which arises from the thermoelectric characteristics modelling is actually half of all the measuring uncertainty while using the method of natural thermocouple for determining the average temperature in the cutting process by turning. Having these results and analysis in mind, we can further focus our work on lowering this uncertainty.

4. CONCLUSIONS

This paper proposes an evaluation of the uncertainty contribution that arises from the usage of natural thermocouple characteristics in the empirical modelling in the machining process with turning. Additionally, it raises a question about the most common approaches in the published works in the field of metal cutting processes, which are neglecting or underestimating the error arising from using the thermoelectric characteristics of the natural thermocouple cutting tool – workpiece, resulting in avoiding of this method as unreliable. Through an example based on our own experimental data, the values of the standard uncertainty components arising from the calibration of the natural thermocouple EN C55-MC2 have been presented.

It is proposed that special considerations should be given to the selection of the order of the mathematical model, because fitting the calibration curve with high values of standard uncertainty will lead to a high value of uncertainty of the measurement where the thermoelectric characteristic will be used, and further making measurement results unreliable.

Further work should be focused on lowering the error contribution from the calibration of the natural thermocouple, as a main source of errors in the experimental research.

REFERENCES

[1] Landers, R. G., Ulsoy, A. G., Furness, R. J. (2002): Process Monitoring and Control of Machining Operations, In: *The Mechanical Systems Design Handbook, Modeling, Measurement, and Control*, Chapter 6, CRC Press, Boca Raton, USA.

[2] Armarego, E. J. A., Ostafiev, D., Wong, S. W. Y., Verezub, S. (2000): An appraisal of empirical modeling and proprietary software databases for performance prediction of machining operations, *Mach Sci Technol*, **4** (3), pp. 479–510.

[3] Astakhov, V. P., Outeiro, J. (2019): Importance of temperature in metal cutting and its proper measurement/modeling, In: Davim J. (ed.) *Measurement in Machining and Tribology. Materials Forming, Machining and Tribology*, Springer, Cham.

[4] Davies, M. A., Ueda, T., M'Saoubi, R. et al. (2007): On the measurement of temperature in material removal processes, *CIRP Ann*, **56**, pp. 581–604.

[5] Schmitz, T. L., Karandikar, J., Kim, N. H., Abbas, A. (2011): Uncertainty in machining: Workshop summary and contribution, *J. Manuf. Sci. Eng.*, **133** (5), 051009.

[6] Axinte, D. A., Belluco, W., De Chiffre, L. (2001): Evaluation of cutting force uncertainty components in turning, *Int. J. Mach. Tool. Manu*, Vol. **41** (5), pp. 719–730.

[7] Trajchevski, N., Tomov, M., Sarac, V. (2022): An approach of empirical model uncertainty estimation during physical quantities investigation in turning, *Journal of Advanced Manufacturing Systems*, DOI: 10.1142/S0219686722500329.

[8] Kuzinovski, M., Zebrovski, H., Cichosz, P., Rosienkievicz, P. (1993): Determination of the thermoelectric characteristic of the thermocouple carbon steel – mixed ceramics for temperature measurement during cutting process, In: *Proceedings of Faculty of Mechanical Engineering*, Skopje, Vol. **12**, no. 13, pp. 45–48.

[9] Kaminise, A. K., Guimarães, G., Da Silva, M. B. (2014): Development of a tool-work thermocouple calibration system with physical compensation to study the influence of tool-holder material on cutting temperature in machining, *Int. J. Adv. Manuf. Technol.*, **73**, pp. 735–747.

[10] Zhang, X., Lu, Z., Peng, Z., et al. (2018): Development of a tool-workpiece thermocouple system for comparative study of the cutting temperature when high-speed ultrasonic vibration cutting Ti-6Al-4V alloys with and without cutting fluids, *Int. J. Adv. Manuf. Technol.*, **96**, pp. 237–246.

[11] Gostimirović, M., Milikić, D. (1989): Tool-work thermocouple calibration problems during metal cutting and their solution way, *Zbornik radova Instituta za proizvodno mašinstvo*, Novi Sad, Godina **6**, Broj 5, 6, pp. 217–226.

[12] Joint Committee for Guides in Metrology (JCGM) (2008): *Guide to the expression of uncertainty in measurement, GUM 1995 with minor modifications*, JCGM 100:2008 (ISO/IEC Guide 98–3:2008).

[13] EURAMET Calibration Guide No. 8, Version 3.0 (02/2019): *Guidelines on the Calibration of Thermocouples*.

[14] Burns, G. W., Scroger, M. G. (1989): *NIST Measurement Services: The Calibration of Thermocouples and Thermocouples Materials*, NIST, Gaithersburg, MD 20899.

[15] Stephenson, D. A. (1993): Tool-work thermocouple temperature measurements – Theory and implementation issues, *J. Eng. Ind.*, **115** (4), pp. 432–437.