

**Investigation of surface roughness in machining  
by single and multi-point tools**

Dissertation

zur Erlangung des akademischen Grades

**Doktoringenieur**

**(Dr.-Ing.)**

von MSc. Csaba Felhő

geb am 26.07.1977 in Tiszaölök

genehmigt durch die Fakultät für Maschinenbau

der Otto-von-Guericke-Universität Magdeburg

Gutachter: Prof. Dr.-Ing habil. Prof h.c. Bernhard Karpuschewski  
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Promotionskolloquium am Juni 17 2014.



Berichte aus dem Institut für Fertigungstechnik und  
Qualitätssicherung Magdeburg

Band 33

**Csaba Felhö**

**Investigation of surface roughness in machining  
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Shaker Verlag  
Aachen 2014

**Bibliographic information published by the Deutsche Nationalbibliothek**

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at <http://dnb.d-nb.de>.

Zugl.: Magdeburg, Univ., Diss., 2014

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Printed in Germany.

ISBN 978-3-8440-2922-2

ISSN 1863-0936

Shaker Verlag GmbH • P.O. BOX 101818 • D-52018 Aachen

Phone: 0049/2407/9596-0 • Telefax: 0049/2407/9596-9

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## Acknowledgement

This dissertation is a result of a joint research work between the Institute of Manufacturing Technology and Quality Management at the Otto-von-Guericke University Magdeburg (IFQ) and the Institute of Manufacturing Science at the University of Miskolc (IMS). I would like to express my thanks to the staff members of both institutes. First of all, I would like to express my profound thanks to Prof. János Kundrák, director of the IMS. He was the one who started me to work on this topic, and I would not be able to finish my work without his help. His professional and personal assistance helped me a lot, and he always had time for me to discuss the results and the further tasks.

Furthermore I would like to express my appreciation to Prof. Bernhard Karpuschewski, managing director of the IFQ, who made it possible for me to work several months in his Institute at the Otto-von-Guericke University, where I have received all of the needed support from the smallest thing to the everyday life to the very specific questions of my professional career. Furthermore, I would like to thank him for helping me in the finalization of my PhD thesis and in the arrangement of my defending.

I would like to highlight some more people by name from both Institutes who helped me in some ways during my work: Dr. Zsolt Maros, Dr. István Deszpoh and Dr. Gyula Varga from the IMS for their valuable professional remarks and suggestions, and István Pásztor, Gergely Szabó, István Sztankovics and Kálmán Korpás for their help.

From the IFQ staff members I would like to thank the help of Dr. Thomas Emmer and Dr. Konrad Schmidt who have supported me from my very first steps in Magdeburg till this day both personally and professionally, I strongly believe, that they have the greatest influence on me to finish my dissertation. I would like to express my thanks to Dr. Limara Dübner, Dr. Olga Zechiel, Dr. Daniel Mourek, Dr. Oleksiy Klymov, Mathias Petzel, Konstantin Risse, Sybille Faust and Katharina Lanatowitz for helping me during my stays in Magdeburg, and/or for their help in my experiments.

Finally, I would like to express my appreciation to my family: to my mother who allowed me to start a scientific career, to my father for his support and suggestions, to my brother, who always believes me, and to my girlfriend, Zsuzsa for her empowering love.

## Abstract

The goal of the dissertation is to determine the expected roughness of surfaces cut by tools with various geometry; the description of the differences of the necessarily existing unevenness on a given surface, and the determination of the minimal and maximal value of the surface roughness.

In order to achieve the above mentioned goals, one part of the work was to develop models and computer programs for the prediction of the surface roughness indexes for turning and face milling operations. The main basis for the calculations is the general mathematical model of the single-point cutting tools. Three different methods are introduced in the dissertation based on this model: one which is based on pure analytical calculations, one which uses numerical methods, and one which is based on CAD modelling. In-depth description of the methods is provided together with the introduction of the developed software. The main emphasis is placed on the determination of theoretical roughness on surfaces machined by face milling. The worked-out method allows taking the run-outs of the multi-point cutting tools into consideration, and the application of various insert geometries is also possible. After that, the developed CAD-based modelling is introduced which allows the calculation of 3D theoretical roughness indexes in face milling. Cutting experiments were performed for dual purpose: in one hand to show the differences between the calculated theoretical values and measurement data, and on the other hand to formulate the relations between these two datasets. Thus the expected value of the roughness can be calculated with the given cutting conditions. The experimental conditions are introduced and then the results of the practical investigations are presented. The comparisons of the obtained results have proven that the modelled and the measured surfaces are in good correlation with each other. Finally the calculated regression constants and coefficients are presented which allows the prediction of the expected value of the surface roughness.

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## Nomenclature

Symbol	Name	Unit
$a_e$	Radial depth of cut	[mm]
$a_h$	Semi-major axis of the hyperbola	[mm]
$a_p$	Axial depth of cut	[mm]
$b$	Intersection of the major edge section $l'$ with the y-axis	[mm]
$b_1$	Intersection of the major edge section $l''$ with the y-axis	[mm]
$b_2$	Intersection of the minor edge section $l_1'$ with the y-axis	[mm]
$b_3$	Intersection of the minor edge section $l_1''$ with the y-axis	[mm]
$b_h$	Semi-minor axis of the hyperbola	[mm]
$C_1, C_2$	Regression coefficients	-
$D_e$	Effective cutter diameter	[mm]
$d_f$	Depth of concavity	[mm]
$D_m$	Milling head diameter	[mm]
$e_{rad}$	Radial run-out error of the milling insert	[mm]
$e_{ax}$	Axial run-out error of the milling insert	[mm]
$F_i$	Profile elements which are limited by the x axis and the cutting edges	-
$f$	Feed per revolution	[mm/rev.]
$f_t$	Feed per tooth	[mm/tooth]
$h_1$	X size of the major cutting edge	[mm]
$h_2$	X size of the minor cutting edge	[mm]
$h_3$	Y size of the major cutting edge	[mm]
$h_4$	Y size of the minor cutting edge	[mm]
$h_h$	x coordinate of the centre of the hyperbola	[mm]
$h_s$	x coordinate of the centre of the torus	[mm]
$iC$	Inscribed circle size of the cutting insert	[mm]
$k_h$	Y coordinate of the centre of the hyperbola	[mm]
$k_s$	Y coordinate of the centre of the torus	[mm]
$L$	Cut length	[mm]
$l, l', l''$	Sections of the major edge of the cutting tool	-
$l_1, l_1', l_1''$	Sections of the minor edge of the cutting tool	-

<b>Symbol</b>	<b>Name</b>	<b>Unit</b>
$l_r$	Sampling length	[mm]
$m$	Mean line of the roughness profile	[mm]
$m_h$	Height of the theoretical cone	[mm]
$n$	Rotational speed	[rotation/min]
$N$	Intervals of the abscissa values in which the cutting edge sections are located	[mm]
$P(x_p, y_p)$	Intersection point(s) of the major and minor edges	-
$P_{end}$	End point of the theoretical profile	[mm]
$P_f$	Assumed working plane	-
$P_r$	Tool reference plane	-
$P_{st}$	Start point of the theoretical profile	[mm]
$R, r_\epsilon$	Insert nose radius	[mm]
$R^2$	Coefficient of determination	-
$R_a$	Arithmetical mean deviation of the profile	[ $\mu m$ ]
$r_i$	Rotational radius of the cutting insert	[mm]
$r_g$	Rolling circle radius of the curtate cycloid	[mm]
$r_n$	Edge rounding of cutting tool	[mm]
$RMR(p)$	Relative material ratio at sectioning level $p$	[%]
$R_p$	Maximum peak height of the profile above the mean line within the sampling length	[ $\mu m$ ]
$R_z$	Ten-point height of the profile	[ $\mu m$ ]
$R_t$	Maximum peak to valley height of the profile	[ $\mu m$ ]
$R_v$	Maximum valley depth of the profile below the mean line within the sampling length	[ $\mu m$ ]
$S_a$	Arithmetical mean height of the surface	[ $\mu m$ ]
$S_p$	Highest peak of the surface from the mean plane	[ $\mu m$ ]
$S_v$	Lowest valley of the surface from the mean plane	[ $\mu m$ ]
$S_z$	Maximum height of the surface	[ $\mu m$ ]
$T_1$	Area below the mean line and under the major edges	[mm <sup>2</sup> ]
$T_2$	Area below the mean line and under the minor edges	[mm <sup>2</sup> ]
$T_3$	Area above the mean line and above the major edges	[mm <sup>2</sup> ]
$T_4$	Area above the mean line and above the minor edges	[mm <sup>2</sup> ]

Symbol	Name	Unit
$T_a$	Rectangular area which exists only in case of $a_p < y_p$	[mm <sup>2</sup> ]
$T_{m,up}$	Area above the mean line of the roughness profile	[mm <sup>2</sup> ]
$T_{m,low}$	Area below the mean line of the roughness profile	[mm <sup>2</sup> ]
$v$	Cutting speed	[m/min]
$v_f$	Feed rate	[mm/min]
$w$	Workpiece width	[mm]
$x_{apf}$	Abscissa of the intersection point of the depth of cut with the major edge	[mm]
$x_{apm}$	Abscissa of the intersection point of the depth of cut with the minor edge	[mm]
$y_{ma1},$ $y_{ma2}, y_{ma3}$	Sections of the cutting tool major edge	-
$y_{mi1}, y_{mi2},$ $y_{mi3}$	Sections of the cutting tool minor edge	-
$x_{mm}$	Abscissa of the intersection point of the mean line with the minor edge	[mm]
$x_{mf}$	Abscissa of the intersection point of the mean line with the major edge	[mm]
$x_p$	Abscissa of the intersection point of the major and minor edges	-
$y_p$	Ordinate of the intersection point of the major and minor edges	-
$y_{pmax}$	Y coordinate of the highest peak of roughness profile	[mm]
$y_{vmax}$	Y coordinate of the lowest valley of roughness profile	[mm]
$z_p$	Z coordinate of the intersection point of the $i^{th}$ intersection point between edge sections	[mm]
$\Delta\phi$	Angular rotation	[°]
$\Delta x$	Relocation of the x-points on the tool coordinate system	[mm]
$\Delta y$	Distance from the cutter centreline on the tool coordinate system	[mm]
$\phi$	Half cone angle of the conical surface	[°]
$\phi_i$	Roughness profile inspection angle	[°]

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Symbol	Name	Unit
$\phi_p$	Independent angle parameter of the curtate cycloid	[°]
$\kappa_{r1}, \kappa_{r2}$	Cutting edge angles	[°]
$\kappa_{r1}', \kappa_{r2}'$	Minor cutting edge angles	[°]
$\Theta$	Spindle tilt angle of the milling machine	[°]

## Abbreviations

AI	Artificial Intelligence
ANFIS	Adaptive Network-Based Fuzzy Inference System
ANN	Artificial Neural Network
ANOVA	Analysis of Variance
BUE	Built-up-edge
CAD	Computer Aided Design
CBN	Cubic Boron Nitride
CCD	Charge-Coupled Device
CNC	Computer Numerical Control
CSG	Constructive Solid Geometry
DoE	Taguchi Techniques for Design of Experiments
FFT	Fast Fourier Transform
GA	Genetic Algorithm
GEP	Gene Expression Programming
GUI	Graphical User Interface
HT	Hard Turning
MF	Membership Function (in Fuzzy Logic)
OEM	Original Equipment Manufacturer
RSM	Response Surface Methodology
SA	Simulated Annealing
SLE	Surface Location Error