RIGA TECHNICAL UNIVERSITY

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TECHNOLOGICAL ASSURANCE OF MICRO-GEOMETRY SPATIAL PARAMETERS OF MACHINE PARTS

Summary of doctoral dissertation

Field: Mechanical Engineering

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RIGA TECHNICAL UNIVERSITY
Faculty of Transport and Mechanical Engineering
Institute of Technology of Mechanical Engineering

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TECHNOLOGICAL ASSURANCE OF MICRO-GEOMETRY SPATIAL PARAMETERS OF MACHINE PARTS

Summary of doctoral thesis

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PROMOCIJAS DARBS
IZVIRZĪTS INŽENIERZINĀTŅU DOKTORA GRĀDA IEGŪŠANAI
RĪGAS TEHNISKAJĀ UNIVERSITĀTĒ

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I confirm that promotion work is developed by myself and is filed for examination in Riga Technical University for obtaining engineering doctor degree. Promotion work is not filed in any other university for obtaining a scientific degree.

Artis Kromanis ……………………………. (Signature)

Date: 25.10.2011

The dissertation is written in Latvian. It contains an introduction, 6 chapters, conclusions, bibliography, 3 attachments, 88 pictures, 30 tables, 143 pages. The bibliography has 124 titles.

CONTENTS

GENERAL DESCRIPTION OF DISERTATION

Topicality of the subject

Nowadays, more and more new quality standards are developed for manufactured components. One of these quality standards is surface roughness of manufactured component. To a large extent the further life of component is defined by the surface roughness. In manufacturing of parts, the manufacturer must strictly follow to the assigned surface roughness values. It makes manufacturing complicate and imposes additional control to the components. For this reason, it is necessary to develop a technique or methodology that facilitate the control of surface roughness in production and give an opportunity to predict surface roughness according to the technological parameters.

In dissertation surface is described using 3D surface roughness parameters. Advantage of using 3D parameters instead of 2D roughness parameters is a possibility to describe processed surface roughness more accurately, because in real life environment every component is working in three dimensions (3D). As a result it is possible to develop more precise mathematical models, which define surface roughness according to the technological parameters.

Topicality of the subject is defined by the need of development more precise surface roughness, especially 3D surface roughness, prediction models and develop an adaptive control system for manufacturing based on such 3D surface roughness prediction models.

Aim of the work and given tasks

Aim of doctoral thesis is to research and develop technological means for surface spatial parameters, which include creation of 3D surface roughness prediction models, using regression analysis and fuzzy logic, and development of adaptive control system for manufacturing.

To achieve given aims the following tasks have to be performed:

1. Theoretical analysis of state of the art and research of present situation;
2. Study of 3D surface roughness parameters;
3. Experimental development of 3D surface roughness prediction models in milling and turning using regression analysis;
4. Evaluation of possibility to use fuzzy logic in development of prediction models;
5. Experimental development of 3D surface roughness prediction models using fuzzy logic;
6. Comparative analysis of regression and fuzzy logic prediction models;
7. Design of concept of adaptive control system;
8. Simulation of experimental adaptive control system.

Methods of research

To achieve given objectives and carry out given tasks the following methods of research are used: Mathematical Statistics (regression analysis), comparative, analytical and graphical methods, and fuzzy logic. To conduct the experimental part, milling and turning machines, and profilometer *Taylor Hobson Form Talysurf Intra 50* are used. To perform regression analysis statistical analysis program *MiniTab* is used. Program *FuzzyTECH* is used to do the necessary tasks of fuzzy logic. To provide graphical representation of data tables, charts and pictures are used.

Scientific novelty

Scientific novelties of dissertation are as follows:

1. Surface roughness prediction models are developed by implementation of 3D surface roughness parameters;
2. Fuzzy logic is introduced into development of 3D surface roughness prediction models;
3. Methodology of a design of 3D surface roughness fuzzy logic prediction models is developed.
4. For theoretical modelling and for practical applications useful adaptive control system of machining is developed.

The following research results are defended

1. 3D surface roughness prediction models for milling and turning are developed using regression analysis and fuzzy logic.
2. Relevancies between 3D surface roughness parameters and technological parameters are obtained;
3. Accuracy of regression analysis and fuzzy logic prediction methodologies is evaluated.
4. Adaptive control system for machining is developed using fuzzy logic. On a given system Latvian patent No. 14015(B) is obtained – "Device and method for adaptive control of machining".

Given results are new contributions to manufacturing technologies, especially to the technological assurance of surface micro-geometry spatial parameters of machine parts.

Practical application

Developed methodology can be used to obtain 3D surface roughness prediction models using regression analysis or fuzzy logic. Data obtained in experiments can be used, to set up necessary technological parameters according to the desired surface roughness without loosing a valuable time and without performing time-consuming pre-machining. The use of fuzzy logic provides more accurate 3D surface roughness prediction models than regression analysis.

Developed adaptive control concept shows the possibility to implement adaptive control system of machining into the CNC. Such a system makes it possible to automate the control of technological parameters during machining, increasing work efficiency.

The author of the work defends following:

1) Method for 3D surface roughness prediction according to technological parameters, introducing fuzzy logic;
2) Practical application of said method:
   a) 3D surface roughness prediction models in milling and turning;
   b) The assessment of patterns;
3) Development of adaptive control system, using fuzzy logic.

Approbation of dissertation

Main findings and results are reported in following conferences and seminars:

- 6th International Conference of DAAAM Baltic Industrial Engineering, Tallinn, 24-26 April 2008.
- The 2nd Manufacturing Engineering Society International Conference CISIF'07 – MESIC'07, Madrid, 9-11 July 2007.
- RTU 47. International scientific conference, Riga. 12.-14. October 2006.
- 10th International Research/Expert Conference „Trends in the Development of machinery and Associated Technology", Barcelona-Lloret de Mar, 11-15 September 2006.
- 5th International DAAAM Baltic Conference „Industrial Engineering – adding innovation capacity of labour force and entrepreneurs", Tallinn, 20-22 April 2006.
- Seminar of Latvian Mechanical Engineers. Riga technical University, Riga, 16 May 2006.

Results been published in seven scientific papers and in one patent:

1. Kromanis A., Krizbergs J. Prediction of surface roughness in end-milling using fuzzy logic and it comparison to regression analysis. Annals of DAAAM for 2009 & Proceedings of the 20th International DAAAM Symposium, Vienna, Austria, 2009, pp. 803 – 804.
2. Kromanis A., Krizbergs J. Prediction of surface roughness in milling using fuzzy logic and regression. RTU Scientific publications. Mechanical engineering and Transportation – Volume 6 – Edition 31 – Riga: Publisher: RTU, 2009. pp. 75.-78.
3. Kromanis A., Krizbergs J. 3D surface roughness prediction technique in end-milling using regression analysis. 6th International Conference of DAAAM Baltic Industrial Engineering –DAAAM Conference Proceedings, Tallinn, 2008, pp. 257. – 261.
4. Kromanis A., Krizbergs J. Application of 3D surface roughness prediction technique in milling. The 2nd Manufacturing Engineering Society International Conference CISIF'07 – MESIC'07, Madrid, 2007.
5. Kromanis A., Krizbergs J. Development of 3D surface roughness prediction technique in fine turning. 10th International Research/Expert Conference „Trends in the Development of machinery and Associated Technology" TMT 2006 Conference Proceedings, Barcelona-Lloret de Mar, 2006, pp. 109. – 112.
6. Kromanis A., Krizbergs J. Methods for prediction of the surface roughness 3D parameters according to technological parameters. 5th International DAAAM Baltic Conference „Industrial Engineering – adding innovation capacity of labour force and entrepreneurs" DAAAM Conference Proceedings, Tallinn, 2006, pp. 145. – 149.
7. Rudzitis J., Torims T., Kromanis A. Three dimensional roughness effects on rough surface contact. 9th International Research/Expert Conference. „Trends in the development of Machinery and Associated technology". TMT 2005, Antalya, Turkey, 26-30 September, 2005, pp. 57. – 60.

Inventions:

1. Kromanis A., Krizbergs J. Device and method for adaptive control of blank machining. Latvian Patent No. 14015. Owner – Riga Technical University, published on 20.01.2010.

Volume of the dissertation and description of structure

The dissertation is written in Latvian. It contains an introduction, 6 chapters, conclusions, bibliography, 96 figures, 36 tables, all together 143 pages and 3 attachments. The bibliography has 124 titles.

CONTENT OF THE DISSERTATION

Terms and abbreviations used in the works

Terms and abbreviations used in the work are as follows:
a_e – radial depth of cut;
a_p – axial depth of cut;
d – depth of cut;
D – mill diameter;
f – feed;
f_t – feed per revolution of cutter;
f_z – feed per tooth;
FCL – Fuzzy Control Language;
MMR – Material Removal Rate;
n – rotation speed;
r – radius of cutting tip;
R – radius of mill;
Ra – Arithmetical mean deviation of surface profile;
Rq – Quadratic mean deviation of surface profile;
R_{max} – Maximal height of surface profile;
R_{zt} – Theoretical height of surface profile;
t – depth of grinding;
Sa – Arithmetical mean deviation of surface roughness from the mean plane;
Sq – Quadratic mean deviation of surface roughness from the mean plane;
S_{rad} – radial feed;
u – Variable of output;
U – result of fuzzification;
z – number of teeth of cutter;
φ – main cutting angle;
φ – auxiliary cutting angle;
γ – rake angle.

1. REVIEW OF RELATED LITERATURE

This section examines prior art associated with the surface roughness parameters prediction according to technological parameters. The doctoral thesis focuses on two types of metalworking processes: milling and turning, but achieved work results can be used as well as in other manufacturing processes.

Nowadays, grinding, which is relative expensive machining option, is replaced by fine turning (rotating workpieces) or fine milling (rotating tool). During fine machining process, particular importance is given to the surface roughness of machined workpiece and to the technological parameters, which are set in cutting machine providing necessary surface roughness. In practice, to find necessary technological parameters for desired surface roughness, it is necessary to provide experimental machining which increase costs and consume a valuable time. To address this shortcoming, the new 3D surface roughness prediction models are developed using different techniques. This chapter analyses already existing solutions to predict a surface roughness.

1.1. Technological assurance of surface roughness in milling

The first studies of the surface roughness and its technological assurance in milling were carried out using purely geometric correlations – geometry of cutter and its movement along the workpiece to be machined. The theoretical surface roughness can be described by the following equation [11]:

$$Ra = \frac{f_t^2}{32(R \pm f_t n_t / \pi)}, \tag{1.1}$$

where Ra – surface roughness;
n_t – number of teeth in milling cutter;
R – radius of milling cutter;
f_t – feed per revolution of milling cutter („+” in a case of up milling and „–” in case of down milling).

In addition there are know such typical equations describing the surface roughness profile (Ra, R_{zt}) according to the technological parameters (f, R) [1]:

$$Rz = \frac{f_z^2}{8R} \text{ or} \tag{1.2}$$

$$Ra = \frac{0{,}0321 f_z^2}{R}, \tag{1.3}$$

where f_z – feed per tooth of milling cutter (mm).

In the given equations such factors as system vibrations and built-up formation are not taken into account, so that only geometric relationships between workpiece and cutting tool are taken into account. In practice typical known relationships between surface profile roughness and technological parameters has been developed (Fig. 1.1.), which include different factors of influence like build-up edge formation, change of heat flow in the cutting area, tool wear, vibration, wear of a cutter, etc. [18].

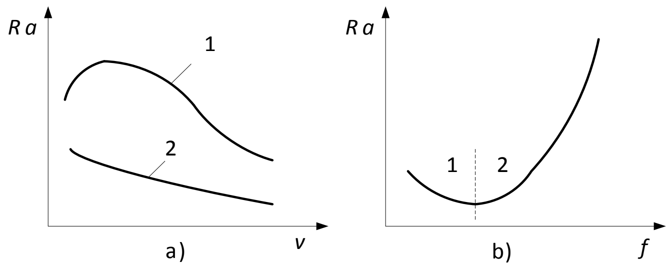


Fig.1.1. Typical relationships a) $Ra = f(v)$ and b) $Ra = f(f)$: 1–materials with tendency to the built-up edge; 2–materials without tendency to the built-up edge.

In the figure 1.2. is shown a theoretical model of formation of surface roughness, when the surface has been machined by the end or face mill having six cutting inserts [1]. This model works only if it is assumed that after machining surface profile roughness will be relatively large. In addition, the experimental results concluded that the roughness was made predominantly by the deviation of cutting inserts in axial direction. Such a model does not work when it is necessary to predict a formation of surface roughness on the relatively smooth surfaces.

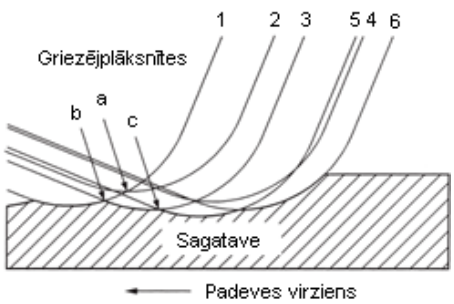


Fig. 1.2. surface profile made by milling cutter in one revolution [1]

Additionally to the geometrical relationships, surface roughness prediction is studied, using mathematical statistics. One of such methods of mathematical statistics is regression analysis. Objective of the regression analysis is to reveal relationships between several variables. In this case, prediction of surface profile roughness (dependent variable) according to the technological parameters (related independent variables). In the work of Kadirgama et. al. [8] the study of profile roughness prediction in milling of Aluminium (AA6061-T6) have been performed. Experimental machining was performed in the range of chosen parameters, which are shown in the table 1.1.

Table 1.1.

Data of Kadirgama experiment in milling AA6061-T6 [8]

Parameters	**1**	**2**	**3**
Cutting speed (m/min) x_1	100	140	180
Feed (mm/rev.) x_2	0,1	0,15	0,2
Axial depth of cut (mm) x_3	0,1	0,15	0,2
Radial depth of cut (mm) x_4	2	3,5	5

Performing regression analysis the following first order linear equation was obtained [34]:

$$Y = 0{,}5764 + 0{,}0049\,x_1 + 3{,}5850\,x_2 + 1{,}5383\,x_3 - 0{,}016\,x_4, \quad (1.4)$$

where Y – surface profile roughness (Ra – mean profile height);
x_1, x_2, x_3 un x_4 – cutting speed, feed, axial and radial depth of cut, respectively.

1.2. Technological assurance of surface roughness in turning

Turning is one of the most common metal processing operations. Lathes can occupy about 50% of the entire machine park [10]. One of the simplest ways to calculate the potential surface profile roughness depending on the technological parameters is the use of geometric patterns, resulting from interaction of the tool with the workpiece. In the turning maximal surface profile roughness R_{max} can be determined using following equation [3]:

$$R_{max} = \frac{f^2}{8r}, \quad (1.5)$$

where R_{max} – maximal surface profile roughness;
f – feed;
r – radius of a cutter tip.

A sketch of machining process (turning), when the radius of cutter tip r and feed f are taken into account for obtaining surface profile roughness is shown in figure 1.3.

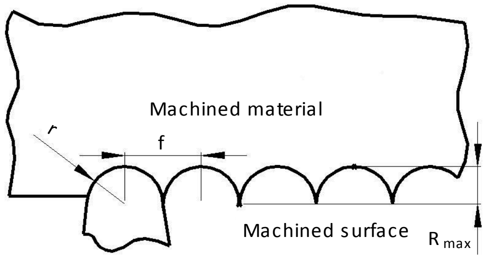


Fig. 1.3. Sketch for machining a surface, taking into account the radius of cutter tip r

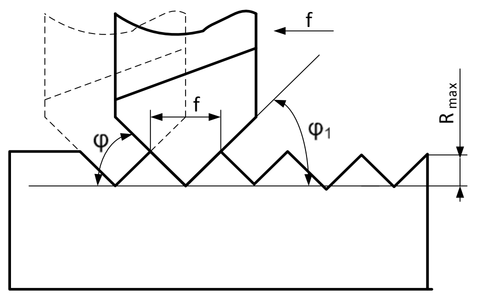


Fig. 1.4. Sketch for machining a surface, not taking into account the radius of cutter tip r

In figure 1.4. a sketch of machining process (turning) is shown, when for a given surface profile roughness cutting edge angles (φ; φ_1) are taken into considerations, ignoring radius of the cutter tip r. In this case, the maximal surface profile roughness Ra_{max} is expressed by the following equation [9]:

$$R_{max} = \frac{f}{4(ctg\varphi + ctg\varphi_1)}, \quad (1.6)$$

where φ – major cutting edge angle;
φ_1 – minor cutting edge angle.

This relationship works only when large feeds f and/or large cutting depths d are used.

Similar as it is mentioned in section 1.1., mathematical statistic methods are used for prediction of surface roughness in turning. For example, in the publication of Nalbanta [15] the study is performed on how profile roughness parameter *Ra* changes according to the changes of radius of cutting tip r, feed f and depth of cut d. Conducting experimental machining and using regression the following first order regression model is obtained [12]:

$$Ra = 0{,}998 + 0{,}376d + 0{,}033f - 4{,}86r. \quad (1.7)$$

1.3. Adaptive control of machining a workpiece

In previous section surface profile roughness prediction according to the technological parameters was reviewed. One of the options, where such models could be used, is its implementation in control of CNC machines, providing automatic control of technological parameters according to the necessary surface roughness.

Fully conceptual approach to said problem is described in US patent application No. US2004/0098147 – „ Artificial intelligence device and corresponding methods for selecting machinability" [14]. Patent application is published in 2004 and generally describes basics of adaptive control not giving any particular technical solutions. An idea of adaptive control with its system blocks, which provide adaptive control, is shown in figure 1.5.

Issues concerning machining adaptive control are very topical, so in this field work such companies as *Ford Motor Company*, which adaptive control system is described in US patent No. 4,926,309, „Artificial intelligence for adaptive machining control of surface finish" [15], and *Toyoda Koki Kabushiki Kaisha*, which adaptive control system is described in US patent No. 5,679,053, „Method and apparatus for grinding a workpiece" [16].

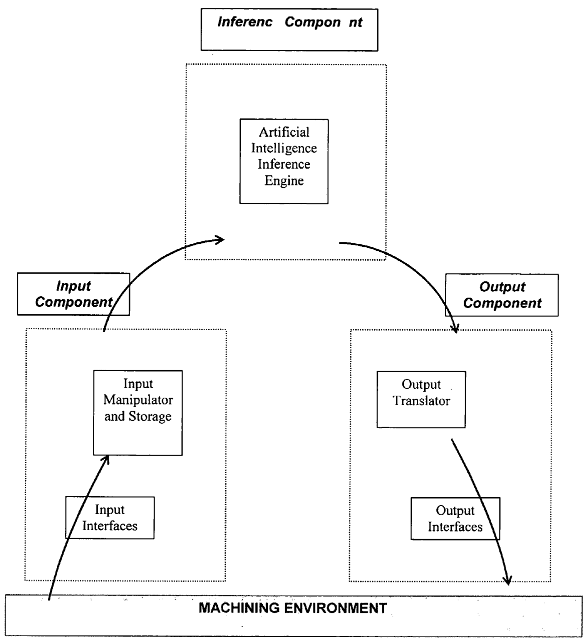


Fig. 1.5. Block diagram of concept of adaptive control machining described in US patent application No. US2004/0098147 [14]

2. 3D SURFACE ROUGHNESS

2.1. 3D surface roughness parameters

Surface profile roughness parameters are determined by ISO standard ISO 4287:1997. Standardization of 3D surface roughness parameters is still in development stage, but it already has an official standard number ISO 25178 [5, 6, 13]. Some parts of standard are already officially approved, but some parts are still in process. The development of the standard points to the fact that the industry has accepted the changes in the field of surface measurement and 3D surface roughness parameters can be considered as a wholesome parameters describing surface texture. Within the standard ISO 25178 the basics of surface texture are reworked by basing them on the fact that the world around us is three dimensional [2]. 3D surface roughness parameters define a surface texture with sufficient precision to determine the nature and performance of measured surface [5]. An extract from a table of 3D surface roughness parameters written in the standard ISO 25178 is shown in table 2.1.

For example, mean arithmetical deviation from a plane *Sa* is defined by the following equation:

$$Sa = \sqrt{\frac{1}{\mathrm{A}}\iint_A Z(x, y)dxdy}\,. \quad (2.1)$$

Table 2.1.

Frequently used 3D surface roughness parameters according to the standard ISO 25178

No.	Symbol and name of the parameter
1.	*Sa* – Mean arithmetical deviation from the mean plane (µm).
2.	*Sq* –Root mean square deviation from mean plane (µm). Calculates effective value of surface amplitude.
4.	*Sp* – maximum peak height (µm). Height between mean plane and the highest peak.

In promotion work 3D surface roughness parameter *Sa* is being used as it is one of the most used surface roughness parameters, similar to a 2D surface roughness parameter *Ra*, which is one of the most used surface roughness characterized parameters in mechanical engineering.

2.2. Measurements of 3D surface roughness

In 3D surface roughness measurements *Taylor Hobson Form Talysurf Intra 50* form measurement device was used. This device has touch probe or needle which is in contact with measured surface during measurement. Data acquired during surface roughness measurement are processed in the *TalySurf Intra* computer program showing data of measured surface. A graphical representation of machined (turning) part is shown in Fig. 2.1. A graphical representation of a surface before and after form removal is shown in Fig. 2.2. Form removal must be done to eliminate waviness and other geometrical irregularities from 3D surface. One of the advantages of a system is that each measurement data file stores information about the surface into digital form. Therefore, it is possible to retrieve any information needed in any time, due to the fact that each program file includes original or raw data of the measured surface.

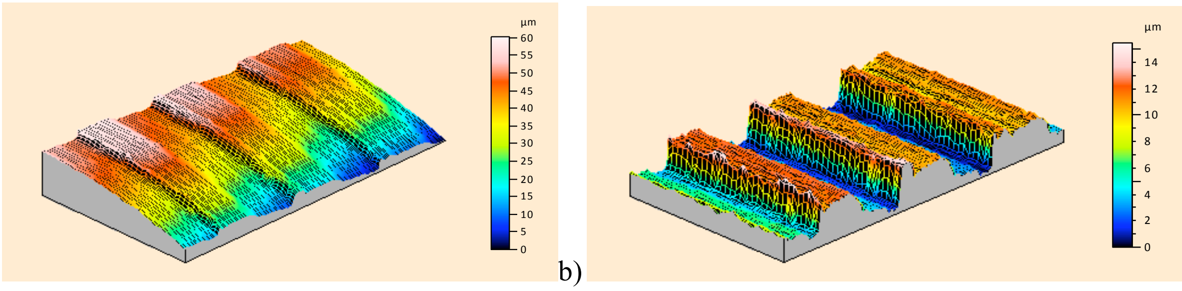


Fig. 2.1. 3D surface roughness representation of measured sample in axonometric view:
a) sample before form removal; b) sample after form removal

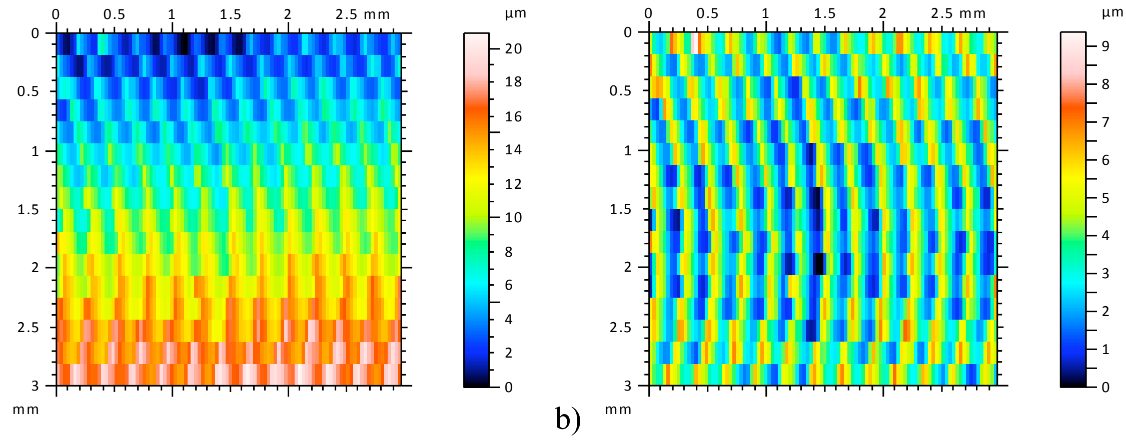


Fig. 2.2. Graphical representation of surface roughness of measured sample:
a) sample before form removal; b) after form removal

3. DEVELOPMENT OF 3D SURFACE ROUGHNESS PREDICTION METHODOLOGY USING REGRESSION ANALYSIS

3.1. Development of methodology in milling

The regression analysis begins with the defining of dependent variables and independent variables. Initially, an equation, which represents functional relationship between dependent variable and independent variables, is made:

$$Sa = \mathrm{C} \cdot f^{a_1} \cdot H^{a_2} \cdot v^{a_3} \cdot d^{a_4}, \tag{3.1}$$

where dependent variable is *Sa* – 3D surface roughness parameter or surface mean deviation, but independent variables are

f – feed (mm/rev. or mm/tooth);
H – hardness of blank material;
v – cutting speed (m/min);
d – cutting depth (mm);
C – coefficient of regression equation.

The next step (3.1) is transformation from nonlinear form to following linear mathematical form using logarithmical transformation:

$$\ln Sa = \ln C + a_1 \ln f + a_2 \ln h + a_3 \ln v + a_4 \ln d \, . \tag{3.2}$$

Further equation (3.2) can be written in a simplified form:

$$y = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_4, \tag{3.3}$$

where y – to be calculated/measured surface roughness parameter after logarithmic transformation;
b_0, b_1, b_2, b_3 un b_4 – estimates of parameters or regression coefficients;
x_1, x_2, x_3 un x_4 – logarithmic transformations of technological parameters.

Next, using statistical analysis program MiniTab and regression analysis tool therein, values b_0, b_1, b_2, b_3 and b_4 are acquired. By inserting the values into equation (3.3), process characterized mathematical model is acquired. Continuing the analysis it is possible to acquire second order equation including cross multiplication of technological parameters. In this case from the equation (3.3) it is possible to acquire the following second order equation:

$$\begin{aligned} y = {} & b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_4 + b_5 x_5 + b_6 x_1 x_2 + b_7 x_1 x_3 + b_8 x_1 x_4 + b_9 x_1 x_5 + b_{10} x_2 x_3 + b_{11} x_2 x_4 \\ & + b_{12} x_2 x_5 + b_{13} x_3 x_4 + b_{14} x_3 x_5 + b_{17} x_4 x_5 + b_{18} x_1 x_1 + b_{19} x_2 x_2 + b_{20} x_3 x_3 + b_{21} x_4 x_4 + b_{22} x_5 x_5 \end{aligned}. \tag{3.4}$$

In this work the equations are made entirely of the technological parameters that are adjustable during the machining process. Such parameters are: cutting speed v, depth of cut d and feed f. Thus, from acquired machining models it is possible to develop adaptive machining control system, which allows changing the technological parameters in on-line mode, obtaining the desired surface roughness.

3.2. Experimental development of prediction model in milling

Aim of the experiment is to find relationships between surface roughness *Ra* of machined surface and technological parameters used to machine the surface (cutting speed v (m/min); feed f (mm/rev. or mm/tooth); depth of cut d (mm)). Initially a surface of the workpiece is machined by end mill and at defined technological parameters. After the machining of the workpiece its surface is measured and surface roughness *Sa* values are acquired following by empirical determination of surface roughness parameters according to the technological parameters, which at the end give 3D surface roughness prediction model.

In the experiment a stainless steel plate (Stainless steel EN 1.4301 – X5CrNi18-10) is machined. Machining is done with four-tooth carbide end mill with a diameter of 10 mm.

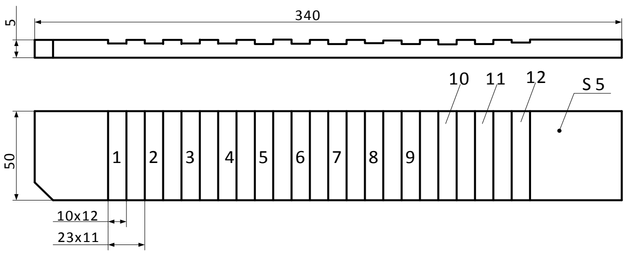


Fig. 3.1. Sketch of the workpiece with marked milling grooves

Table 3.1.

Data sheet of experiment for milling X5CrNi18-10

No.	f (mm/rev.)	d (mm)	v (m/min)	Sa_{measur} (µm)	Sa_{calc} (µm)	ΔSa	$\Delta Sa\%$
1	2	3	4	5	6	7	8
1.	0,25	1,5	190	1,370	1,325	0,045	3,284
2.	0,25	0,5	190	0,631	0,879	0,248	39,303
3.	0,1	0,5	190	0,388	0,419	0,031	7,990
4.	0,1	1,5	190	0,988	0,825	0,163	16,498
5.	0,1	1,5	120	0,635	0,767	0,132	20,787
6.	0,25	1,5	120	1,370	1,267	0,103	7,518
7.	0,25	0,5	120	1,090	0,821	0,269	24,679
8.	0,1	0,5	120	0,472	0,321	0,151	31,992
9.	0,21	1	210	1,020	1,036	0,016	1,569
10.	0,13	1	210	0,871	0,770	0,101	11,596
11.	0,21	1	100	0,805	0,882	0,077	9,565
12.	0,13	1	100	0,407	0,616	0,209	51,351

After the machining of material, measurements of 3D surface roughness are conducted and *Sa* (Fig. 3.2.) values are retrieved. Data of table 3.1. are entered into program MiniTab and following the established regression analysis methodology, developed in 3.1. chapter, the following mathematical model or equation of milling process was acquired:

$$Sa = -0{,}403 + 3{,}33f + 0{,}446d + 0{,}00140v\ . \qquad (3.5)$$

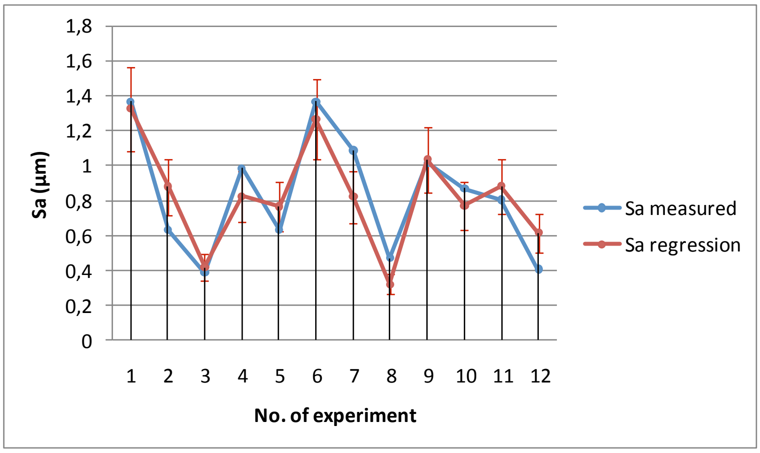


Fig. 3.2. Measured and calculated 3D surface roughness values in milling X5CrNi18-10

After regression analysis it is very important to ascertain the reliability of the regression analysis model. Results of data are shown in figure 3.2., showing values of calculated and measured *Sa* and its prediction error 19% (18.84%).

3.3. Development of prediction methodology in turning

Similarly to developed prediction methodology in milling using regression analysis (3.1. chapter), a methodology for turning was also developed. To confirm the accuracy and usefulness of the methodology experiments were performed, which are described in more detail in 3.4. chapter.

3.4. Experimental development of prediction model in turning

For machining at different cutting modes a calibrated rod material (11SMnPb30) was used. At the same time with choice of material a table of technological regimes was created (table 3.2.). The following technological parameters were used: v – cutting speed ($130 \leq v \leq 200$ m/min.); f – feed ($0{,}1 \leq f \leq 0{,}4$ mm/rev.); d – depth of cut ($0{,}5 \leq d \leq 1{,}5$ mm).

Table 3.2

Data sheet of experiment for turning 11SMnPb30

No.	***v* (m/min)**	***f* (mm/rev.)**	***d* (mm)**	***Sa*(µm)**	Sa_{apr_1}	Sa_{apr_2}
1	**2**	**3**	**4**	**5**	**6**	**7**
1.	130	0,1	0,5	0,36	0,54	0,40
2.	130	0,1	1,5	0,92	0,73	0,82
3.	130	0,4	1,5	3,68	3,57	3,75
4.	130	0,4	0,5	3,36	3,38	3,36
5.	170	0,1	0,5	0,61	0,63	0,60
6.	170	0,1	1,5	0,65	0,83	0,79
7.	170	0,4	0,5	3,53	3,47	3,45
8.	170	0,4	1,5	3,66	3,67	3,62
9.	200	0,1	0,5	0,90	0,70	0,86
10.	200	0,1	1,5	0,92	0,90	0,89
11.	200	0,4	0,5	3,54	3,54	3,63
12.	200	0,4	1,5	3,64	3,74	3,63

Carrying out the steps of methodology described in 3.1. chapter and taking into account table 3.2. values the following regression model or equation is obtained:

$$Sa_1 = -0{,}806 + 0{,}00234v + 9{,}47f + 0{,}195d \quad (3.6)$$

and the second order equation is:

$$Sa_2 = -0{,}71 - 0{,}0076v + 11{,}0f + 1{,}15d - 0{,}00863vf - 0{,}00561vd - 0{,}078fd + 0{,}000054vv \quad (3.7)$$

Results are shown in figure 3.3. Analysis of data showed that prediction error of the first order equation is 11% (11.21%), but the prediction error of the second order equation is 5% (5.17%).

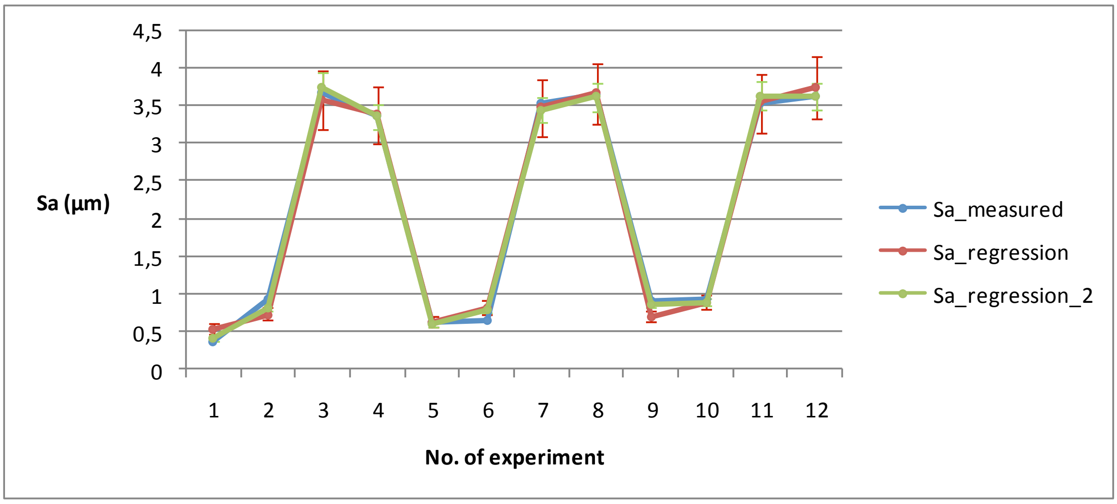


Fig. 3.3. Measured and calculated 3D surface roughness values in turning 11SMnPb30

As the second machined material a stainless steel (X8CrNi18 – 9) was chosen and the following technological parameters: v – cutting speed ($70 \leq v \leq 90$ m/min); f – feed ($0{,}05 \leq f \leq 0{,}1$ mm/rev.); d – depth of cut ($0{,}5 \leq d \leq 1{,}5$mm).

Table 3.3

Data sheet of experiment for turning X8CrNi18 – 9

No.	*v* (m/min)	*f* (mm/rev.)	*d* (mm)	*Sa* (µm)	$Sa_{apr\ 1}$	$Sa_{apr\ 2}$
1	**2**	**3**	**4**	**5**	**6**	**7**
1	80	0,05	0,5	0,78	0,710	0,810
2	80	0,05	1,5	0,82	0,792	0,848
3	80	0,10	1,5	0,92	0,903	0,969
4	80	0,10	0,5	0,87	0,821	0,908
5	90	0,05	0,5	0,81	0,901	0,877
6	90	0,05	1,5	0,90	0,983	0,947
7	90	0,10	0,5	0,95	1,012	0,977
8	90	0,10	1,5	1,04	1,094	1,070
9	100	0,05	0,5	1,14	1,092	1,172
10	100	0,05	1,5	1,22	1,174	1,274
11	100	0,10	0,5	1,21	1,203	1,274
12	100	0,10	1,5	1,35	1,285	1,400

Carrying out methodological steps described in 3.1. chapter the following regression model or equation is obtained:

$$Sa_1 = -0{,}970 + 0{,}0191v + 2{,}23f + 0{,}0817d \quad (3.8)$$

As well as the second order equation is developed:

$$Sa_2 = 8{,}53 - 0{,}189v + 1{,}32f - 0{,}246d + 0{,}0050vf + 0{,}00325vd + 0{,}467fd + 0{,}00114vv\ . \quad (3.9)$$

Results are shown in figure 3.4. Analysis of data showed that prediction error of the first order equation is 5% (5.43%), but the prediction error of the second order equation is 5% (5.21%).

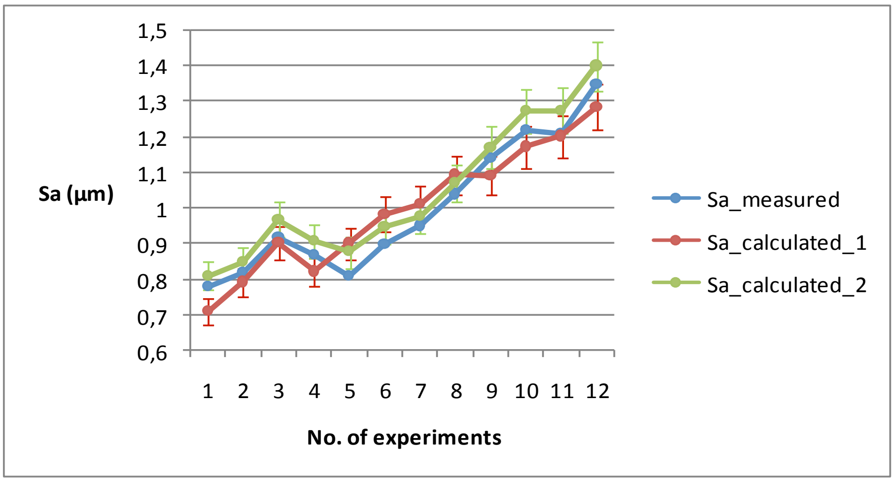


Fig. 3.4. Measured and calculated 3D surface roughness values in turning X8CrNi18 – 9

4. DEVELOPMENT OF METHODOLOGY FOR PREDICTION OF 3D SURFACE ROUGHNESS USING FUZZY LOGIC

4.1. Fuzzy logic, the concept of fuzzy logic, its history and development

In 1965 professor of the electronics and computer science L.A. Zadeh from Berkley University published his work „Fuzzy Sets“, where he described a math of uncertain sets and fuzzy logic [17]. From this work logic of uncertainty got its name – fuzzy logic. Fuzzy logic is considered as a complement to traditional logic giving a possibility to process partly true values – between „completely true“ and „completely false“. This theory proposes use of membership functions, which operate in the range of 0 (false) to 1 (true).

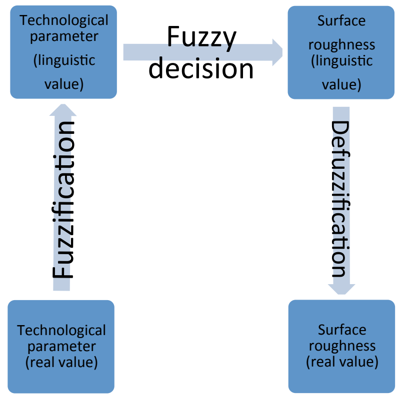


Fig. 4.1. Operational phases of fuzzy logic system

Fuzzy logic – logic, which is developed to specially display knowledge and processes of human thinking. Fuzzy logic is widely used in artificial intelligence and expert systems. Unlike the binary logic, which uses values „false“ and „true“, fuzzy logic operates with logical variables, which can adopt to a number of different values, such as “correct”, ”incorrect”, ”not quite right”, ”more or less correct”, “quite correctly”, “false”, “not too wrong”, ”quite wrong”, ”highly inaccurate”, which makes it closer to a human thinking [21]. Some fuzzy logic solutions are implemented in the automatic gearboxes of cars, automatic washing machines and helicopters, which obey to voice commands [9].

4.2. Fuzzy logic expert system

In recent years new and upgraded CNC (Computer Numerical Control) has been developed for machining centres, but operation without human–operator has not yet been imagined. In setting and adjustment of cutting modes high credits are given directly to the experience and deductive abilities (the logic) of the operators, decreasing level of automatization. Such problems could be solved using fuzzy logic expert systems [15].

Setup of technological parameters for machining depends on the technologist or CNC operator, which often in vague (fuzzy) and intuitive way sets up the necessary technological parameters in order to achieve the desired surface roughness, based on their experience and knowledge. In such cases fuzzy logic expert system is very useful, because it combines linguistic thinking of humans and accuracy and speed of computer. From the point of IT Fuzzy control is rule-based expert system, but looking on it from the point of view of control system technology, it is mostly a controller of non-linear characteristics [19].

4.3. Operational phases of fuzzy logic expert system

To create a prediction system, steps of fuzzy logic system have to be obeyed. Fuzzy logic system can be divided in 3 phases (Fig. 4.1.). The first phase is fuzzification, during which real values, for example cutting speed *v*, using membership functions are transformed into linguistic terms – very fast, fast, medium, slow and very slow, and so on. The second phase is fuzzy decision, which using linguistic terms obtained in previous phase and fuzzy rules, evaluates situation resulting in linguistic terms. The third phase includes defuzzification, where acquired result, using membership functions of output value, is expressed in numerical value (for example, in μm). At the beginning, system interconnections have to be defined – what will be input and output data. In promotion work fuzzy logic system is adapted for the needs of surface roughness prediction (Fig. 4.2.).

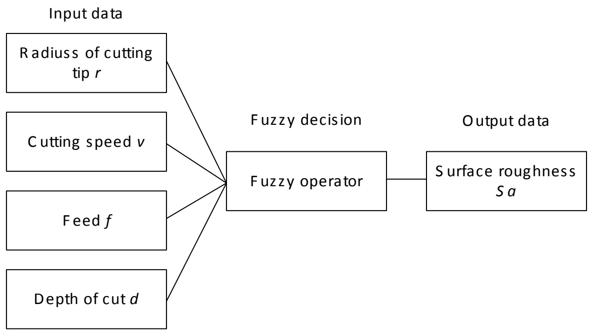


Fig. 4.2. Defining task in fuzzy logic system

4.3.1. Fuzzification

For selected parameters, which will be used as input and output values such as cutting speed v, feed f, depth of cut d and 3D surface roughness Sa, membership functions have to be made. Such a process (fuzzification) can be considered as a transfer of operator knowledge into fuzzy logic system. Each input value has its own fuzzy logic set with membership functions therein, where its values are in range from 0 (completely false) to 1 (completely true) (Fig. 4.3.).

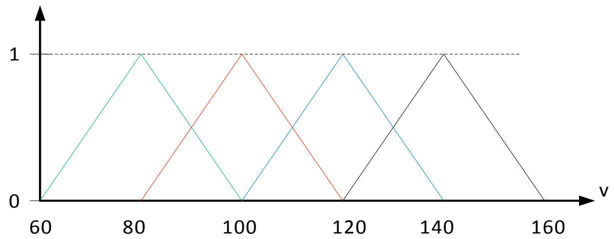
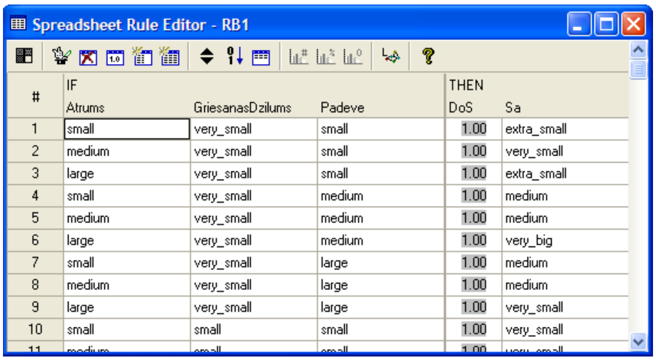


Fig. 4.3. Set of cutting speed (*v*) with 4 membership functions

4.3.2. Defining of fuzzy rules

After fuzzification, the next step in the development of fuzzy logic system is defining of judgment mechanism or rules. A window for input of rules into FuzzyTECH system is shown in figure 4.4.

Unlike conventional systems, where exact values of variables and precise result would be provided, in this case membership functions of variables and results are shown. In case of fuzzy logic empirical knowledge is defined by rules which have the following form: IF condition is **a** THEN judgment is **b**. IF and THEN serves as the logical operators. Linguistic rules display a knowledge inserted into the system.



#	IF Atrums	GriesanasDzilums	Padeve	THEN DoS	Sa
1	small	very_small	small	1.00	extra_small
2	medium	very_small	small	1.00	very_small
3	large	very_small	small	1.00	extra_small
4	small	very_small	medium	1.00	medium
5	medium	very_small	medium	1.00	medium
6	large	very_small	medium	1.00	very_big
7	small	very_small	large	1.00	medium
8	medium	very_small	large	1.00	medium
9	large	very_small	large	1.00	very_small
10	small	small	small	1.00	very_small

Fig. 4.4. Fuzzy decision making mechanism or rules editor

4.3.3. Defuzzification

Defuzzification essentially is the reverse process of fuzzification. If by use of fuzzification numerical values are transformed into linguistic values then in defuzzification linguistic vales are transformed into numerical values. At this stage, output data of fuzzy logic system are derived. Defuzzification can be performed by different means. One of the means of defuzzification is Centre of Gravity method or Centre of Area method, expressed as follows:

$$U = \frac{\int_{Min}^{Max} u\mu(u)du}{\int_{Min}^{Max} \mu(u)du} \qquad (4.1)$$

or

$$U = \int_{u'}^{Max'} \mu(u)du \ , \qquad (4.2)$$

where U – result of defuzzification;
u – output variable;
μ – membership function after accumulation.

These two methods are the most popular defuzzification methods to acquire output values. Output set and it defuzzification using Centre of Gravity method is shown in figure 4.5.

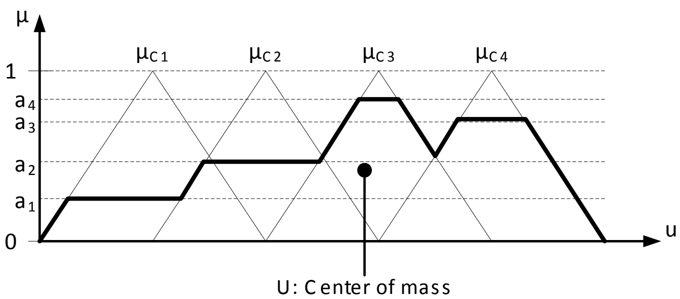


Fig. 4.5. Graphical representation of defuzzification using centre of mass method

4.4. Development of fuzzy logic prediction methodology using FuzzyTECH

FuzzyTECH computer program was used to develop a fuzzy logic prediction model. Said program includes graphical tools, which let to obtain results in graphical mode as well as provide a possibility to change the output values interactively changing input values.

4.5. Experimental development of 3D surface roughness prediction model in milling

One of the aims of the research is to develop methodology of 3D surface roughness prediction by using fuzzy logic. For realization of said goal experiments were made which resulted in fuzzy logic prediction models. Developed methodology would let to implement given surface roughness prediction technique in the workshops or in the work of technologists. Data for experiments taken from the data described in the 3. chapter, including regression prediction models.

The functional relationship in fuzzy sets is defined as follows: $f(f; v; d) = Sa$, where f defines nonlinear relationship between surface roughness Sa (fuzzy output value) and feed f, cutting speed v and depth of cut d (fuzzy input values). At the beginning the input values are defined, then said input values undergo fuzzification or defined a language understandable to fuzzy logic. Next phase is generation of output values by means of fuzzy interface according to the previously inserted fuzzy rules into the database. Finally, interface of defuzzification defines output value, which in said case is 3D surface roughness parameter Sa. To develop a prediction methodology based on fuzzy logic a computer program (FuzzyTECH 5.54) was used. FuzzyTECH is made to help solving fuzzy logic problems.

4.5.1. Fuzzification of data and defining its functions of memberships

At the beginning, data fuzzification is done or membership functions for input values are defined. It should be noted that experience and expertise of system's developer plays a big role in evaluation of values of membership functions. Developer of the system has to know the cutting process and its resulting effects of surface roughness. Partly this work has been made easier by experimental data and conclusions obtained in the third chapter, which can be considered as a preliminary information database. Unlike regression, development of fuzzy logic prediction model requires skilled work force, which has full understanding about machining processes and has the knowledge about the main factors that influence surface roughness. Technologist by himself can serve as a knowledge database or it can be made on conclusions of previously done machining processes, which in this case are results of 3. chapter.

Input values of the experiment are taken from the table 3.1. and their ranges are as follows: $f = 0.1 ... 0.25$ mm/rev.; $v = 100 ... 210$ m/min; $d = 0.5 ... 1.5$ mm.

For the feed three membership functions were chosen. Series vector of feed is $f^T = \{M, V, L\}$, where: $M =$ *small* (0.1 mm/rev.); $V =$ *medium* (0.175 mm/rev.); $L =$ *large* (0.25 mm/rev.). At the given values degree of support (DoS) is 1 (one). For example, if Degree of Support for membership function is 1 (one) then *medium* value is 0.175, but 0 is at 0.1 and 0.25. Given relationship can be displayed with the following membership functions (Fig. 4.6.):

$$A_s(f) = \begin{cases} 1, when\ f \leq 0.1 \\ (0.1 - f)/0.075, when\ 0.1 < f < 0.175; \\ 0, when\ f \geq 0.175 \end{cases} \qquad (4.3)$$

$$A_m(f) = \begin{cases} 0, when\ f \leq 0.1 or \geq 0.25 \\ (f-0.1)/0.075, when\ 0.1 < f < 0.175 \\ (0.25-f)/0.075, when\ 0.175 < f < 0.25 \\ 1, when\ f = 0.175 \end{cases}; \quad (4.4)$$

$$A_l(f) = \begin{cases} 0, when\ f \leq 0.175 \\ (f-0.175)/0.075, when\ 0.175 < f < 0.25 \\ 1, when\ f \geq 0.25 \end{cases}. \quad (4.5)$$

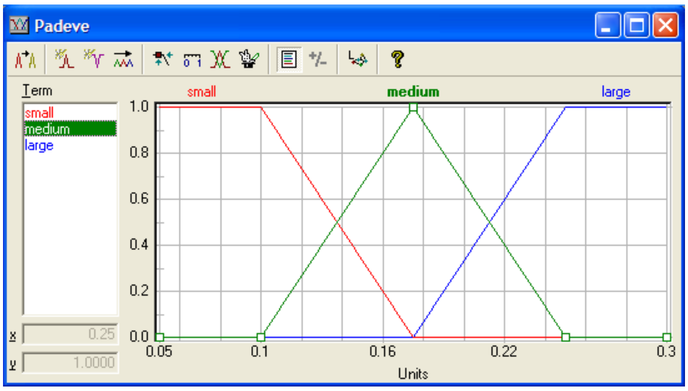


Fig. 4.6. Three feed *f* membership functions in milling X5CrNi18-10

Similar fuzzification procedure was done to the cutting speed *v* choosing three membership functions. Series vector of cutting speed is $v^T = \{M, V, L\}$, where: *M* = *small* (120 m/min); *V* = *medium* (150 m/min); *L* = *large* (190 m/min). For the depth of cut *d* five membership functions were chosen taking into account conclusions obtained in the 3. chapter. Series vector of depth of cut is $d^T = \{LM, M, V, L, LL\}$, where: *LM* = *very_small* (0.5 mm); *M* = *small* (0.75 mm); *V* = *medium* (1 mm); *L* = *large* (1.25 mm); *LL* = *very_large* (1.5 mm).

For the surface roughness *Sa*, which fuzzy logic output value, six membership functions were chosen. Series vector of surface roughness is $d^T = \{PM, LM, M, V, L, LL\}$, where *PM* = *extra_small* (0.4 μm); *LM* = *very_small* (0.6 μm); *M* = *small* (0.8 μm); *V* = *medium* (1 μm); *L* = *big* (1.2 μm); *LL* = *very_big* (1.4 μm). In figure 4.7. membership functions of surface roughness are shown.

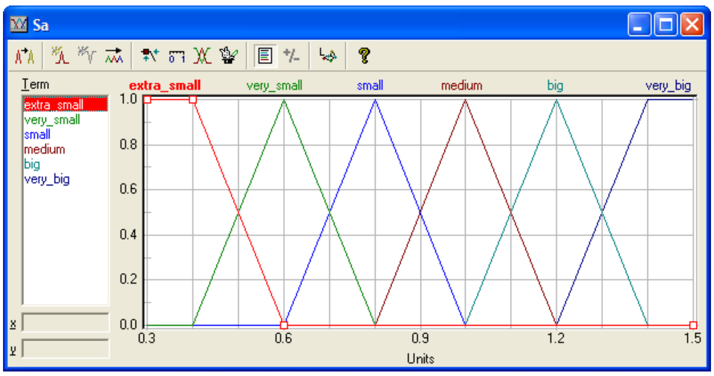


Fig. 4.7. Six surface roughness membership functions in milling X5CrNi18-10

For each parameter it is possible to create membership functions as much as necessary. However, in some cases, too much membership functions will not give a desired result and system will become unnecessary complicated and there will not be any sufficient improvement in the accuracy of the whole system.

4.5.2. Development of fuzzy rule database

After development of membership function of fuzzy logic it is necessary to create a database of fuzzy rules. Said database consists of rules, which should be followed by the system and on basis of which output values are obtained. The given fuzzy rules dictate interaction between input and output variables, allowing appropriate control procedures for the system to work with the desired result, in this case, how cutting parameters should be changed to obtain the desired surface roughness. In table 4.1. is shown a data base of fuzzy rules in form of matrix, where given fuzzy rules determine a work of the fuzzy logic system. Said rules are designed according to the conclusion obtained in the 3. chapter. For example, **if** cutting speed *v* is small and **if** depth of cut *d* is very large, and **if** feed *f* is large, **then** 3D surface roughness *Sa* is very large.

Table 4.1.

Matrix for fuzzy rules

***v* →**	**small**			**medium**			**large**		
***f* →**	**small**	**medium**	**large**	**small**	**medium**	**large**	**small**	**medium**	**large**
***d* ↓**									
very small	*PM*	*M*	*V*	*LM*	*M*	*M*	*PM*	*LM*	*LM*
small	*LM*	*M*	*V*	*LM*	*M*	*M*	*M*	*M*	*M*
medium	*PM*	*LM*	*M*	*LM*	*M*	*V*	*M*	*V*	*V*
large	*LM*	*V*	*L*	*M*	*L*	*L*	*V*	*L*	*LL*
very large	*LM*	*V*	*LL*	*M*	*V*	*L*	*V*	*L*	*LL*

After development of membership functions and database of fuzzy rules, it can be said that the surface roughness prediction model using tools of fuzzy logic has been developed. The next step is defuzzification of data to verify predictability or confidence of model.

4.5.3. Defuzzification of data and acquisition of prediction model

Data defuzzification is a step in which linguistic values are transferred into numerical values. The fuzzy model with opened windows of defuzzification is shown in figure 4.8. In the window named „*watch: interactive debug mode*" it is possible to change input values interactively, which then are processed according to the fuzzy rules, resulting in output value, which in this case is a value of surface roughness. In window shown in figure 4.8., "Sa" is shown as an output value or surface roughness value, as well as process of defuzzification, where the output value is determined by the above mentioned Centre of Area method.

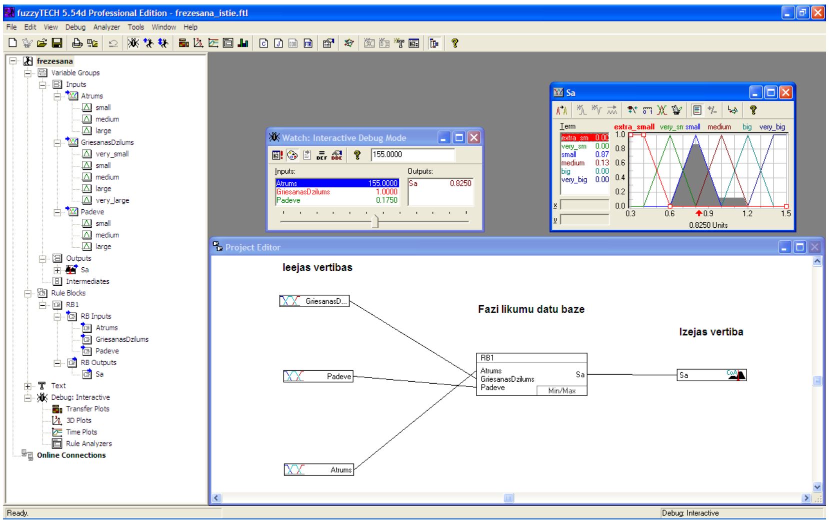


Fig. 4.8. Fuzzy model with defuzzification for milling X5CrNi18-10

In further analysis it is possible to retrieve graphs showing the relationship between input values (horizontal axis) and output value (vertical axis). The surface roughness *Sa* dependence on technological parameters (cutting speed *v* and feed *f*) is demonstrated in figure 4.9.

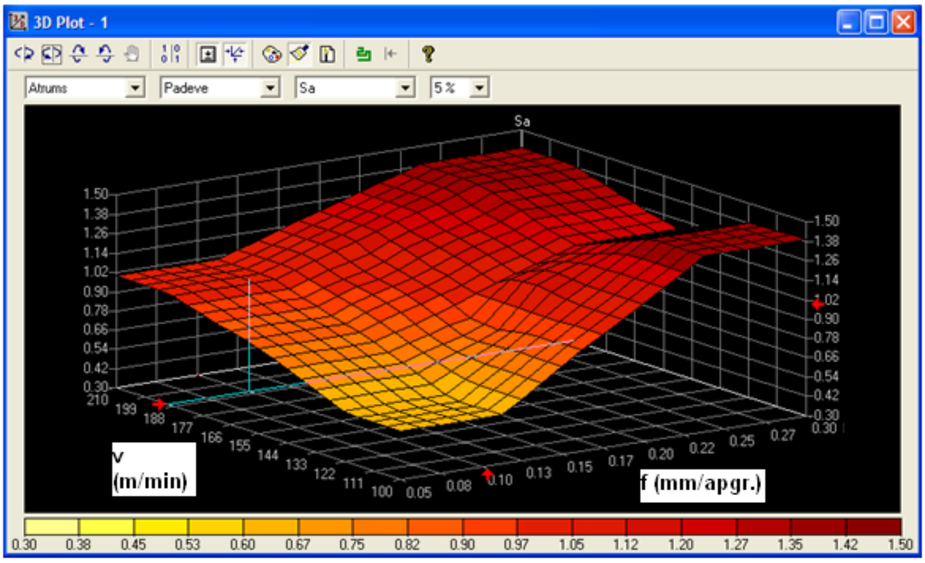


Fig. 4.9. 3D plot of 3D surface roughness *Sa* according to
the cutting speed *v* and feed *f* in case of milling X5CrNi18-10

4.6. Experimental development of 3D surface roughness prediction model in turning

Similarly, as described in 4.5. chapter, a fuzzy logic prediction model in turning was made (data for experiment were taken from 4.4. chapter). As a workpiece cylindrical stainless steel (X8CrNi18 – 9) was used. First of all, a block diagram showing correlation between parameters was made, as shown in figure 4.10.

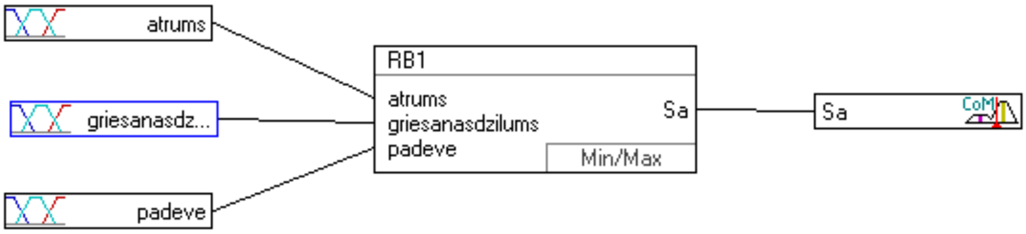


Fig. 4.10. Block diagram showing relationships between process parameters in turning

After the fuzzification of parameters, membership functions are made as shown in figure 4.1.

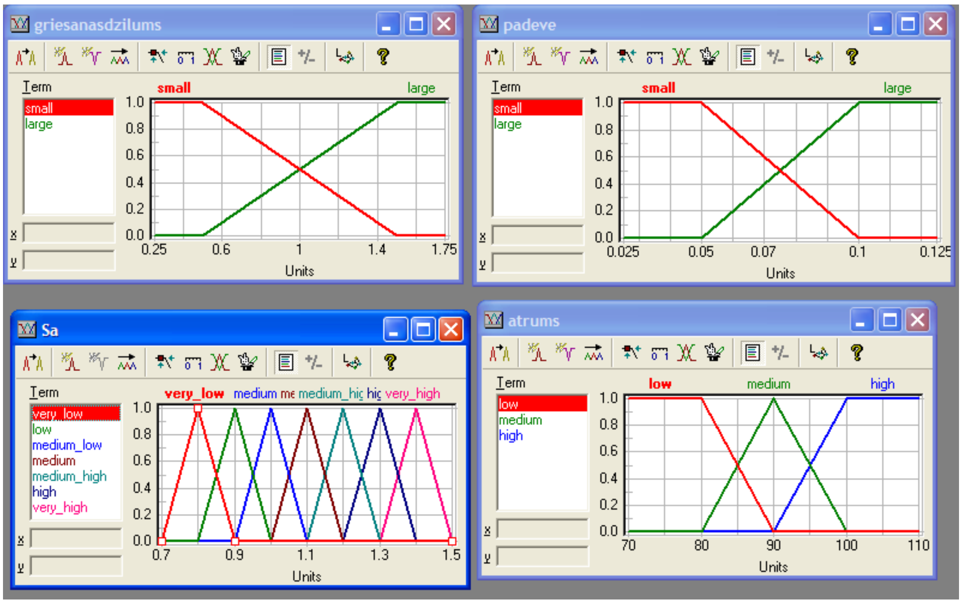


Fig. 4.11. Membership functions for parameters in case of turning X8CrNi18 – 9

The next step is development of fuzzy rule database, after which follows defuzzification of data and finally generation of prediction model is performed. 3D plot for surface roughness *Sa* is shown in figure 4.12. Following a similar methodology a prediction model for turning stainless steel 11SMnPb30 was made. Results are shown in 5. chapter.

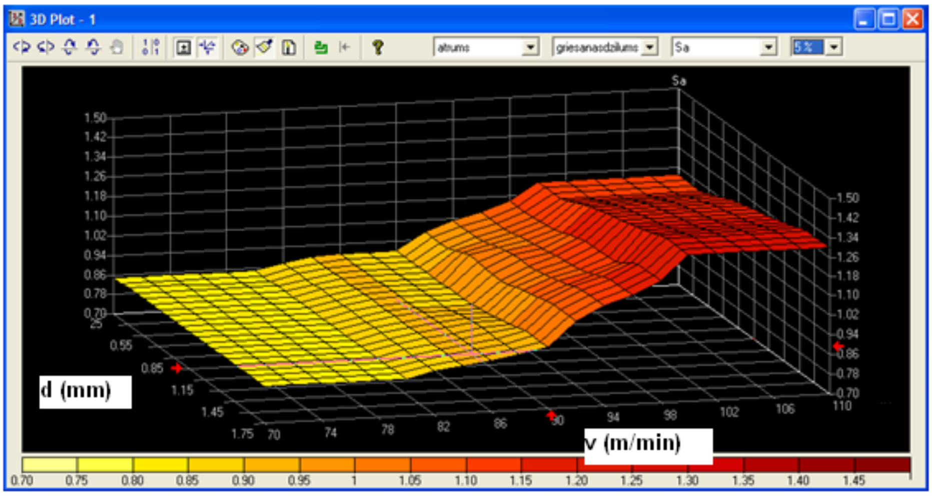


Fig. 4.12. 3D plot for surface roughness *Sa* according to technological parameters (*v* and *d*) in the case of turning X8CrNi18 – 9

4.7. Control programme for fuzzy controller

After the testing of the new fuzzy system it is possible to write a computer program for controller, which can be used in CNC adaptive control systems and controllers. Program code for controlling the controller is written in Fuzzy Control Language (FCL), which is published standard of International Electro Technical Commission (IEC) for programming fuzzy control devices [16]. Taking into account all the experimental data fuzzy control program or programmable surface roughness prediction model has been developed. The full text of the program is given in the 1. Annex of promotion work.

5. COMPARATIVE ANALYSIS OF REGRESSION AND FUZZY LOGIC 3D SURFACE ROUGHNESS PREDICTION METHODOLOGIES

In this section results of obtained prediction models (regression and fuzzy logic) are compared. From results which are summarized in figure 5.1., can be seen that 3D surface roughness prediction model obtained by the use of fuzzy logic having a prediction error 6%, while 3D surface roughness prediction model obtained by the of regression analysis having prediction error 19%. From this experiment can be concluded that by the use of fuzzy logic more accurate 3D surface roughness prediction models can be acquired.

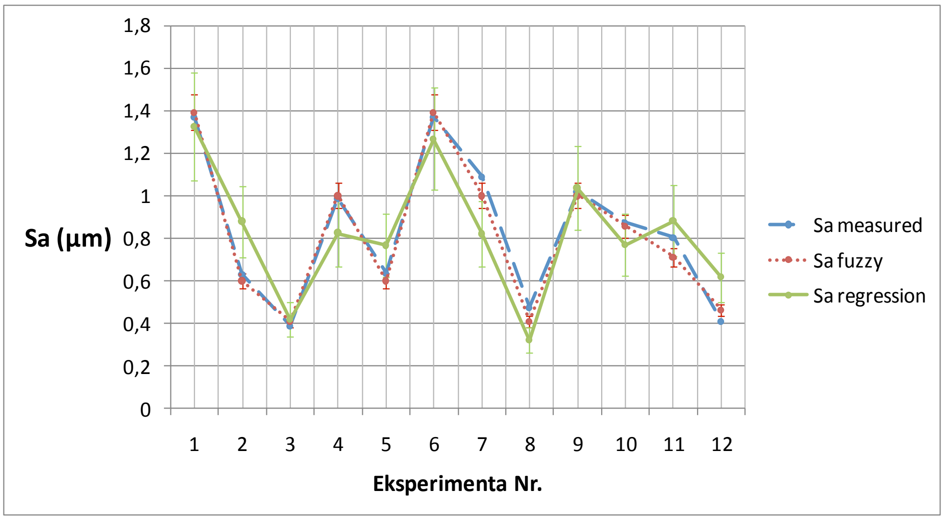


Fig. 5.1. Comparative graphic of 3D surface roughness parameters in milling X5CrNi18-10

From results which are summarized in figure 5.2. it can be seen that 3D surface roughness prediction model obtained by the use of fuzzy logic having prediction error 4%, while the 3D surface roughness prediction model obtained by the of regression analysis having prediction error 6%. From this experiment it can be concluded that by the use of fuzzy logic little more accurate 3D surface roughness prediction models can be acquired.

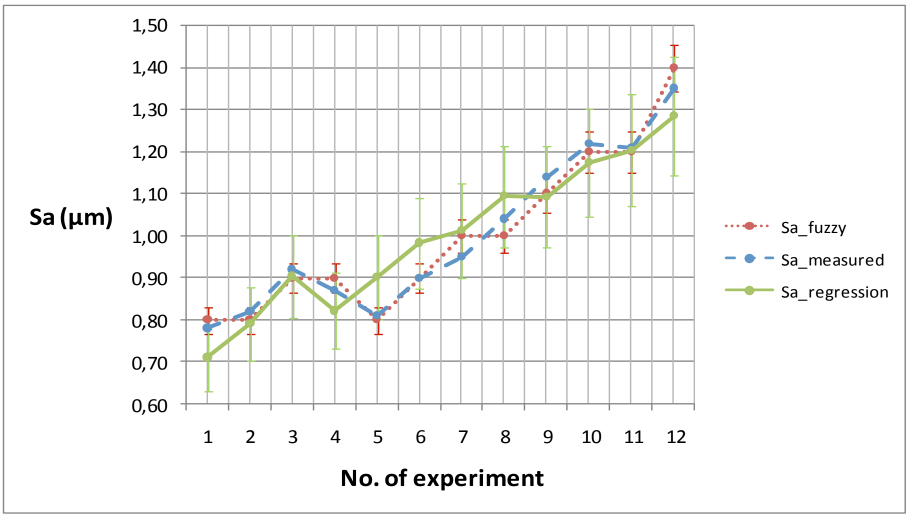


Fig. 5.2. Comparative graphic of 3D surface roughness parameters in turning X8CrNi18 – 9

From results which are summarized in figure 5.3. it can be seen that 3D surface roughness prediction model obtained by the use of fuzzy logic having prediction error 4%, while the 3D surface roughness prediction model obtained by the of regression analysis having prediction error 11%. From this experiment it can be concluded that by the use of fuzzy logic more accurate 3D surface roughness prediction models can be acquired.

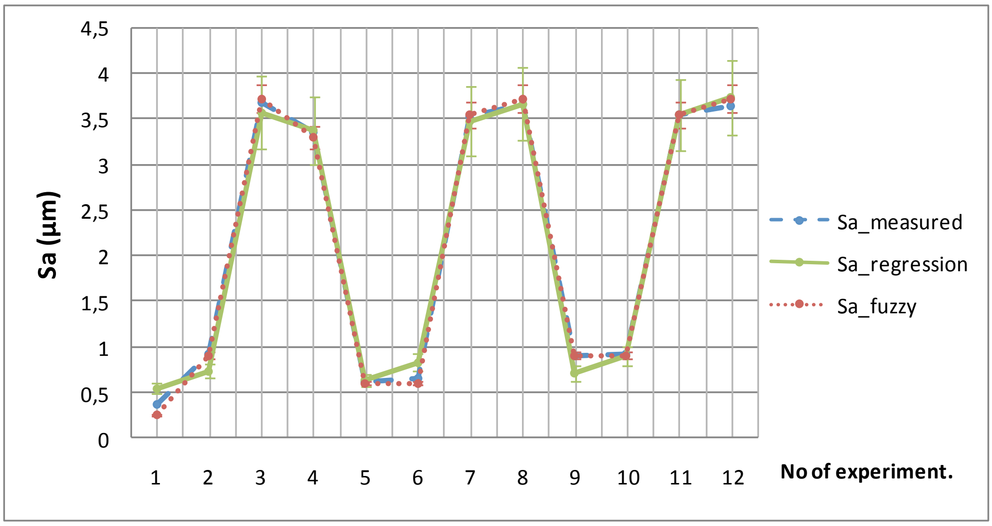


Fig. 5.3. Comparative graphic of 3D surface roughness parameters in turning 11SMnPb30

From the experimental results can be concluded that the fuzzy logic prediction models are more accurate than the regression prediction models.

6. DEVICE AND METHOD FOR ADAPTIVE CONTROL OF MACHINING

In this section is described a development of system and method for adaptive control of machining workpiece. The block diagram of developed system is shown in figure 6.1., where are shown known CNC control system elements (prior art) and developed elements showed by the green colour. System for adaptive control of cutting parameters is designed, which controls cutting parameters to obtain set 3D surface roughness parameters. The system is based on the FLC controller, which from processing unit receives data on the 3D surface roughness parameters changes during machining and using fuzzy logic adaptive control model output cutting parameters with new values providing desired 3D surface roughness during machining. The developed system provides technological assurance of surface micro-geometry spatial parameters.

Taking into account novelty of the system, its industrial applicability and inventive step, patent application was filed in Latvian Patent Office on the object of invention „Apparatus and method for adaptive control of machining a workpiece". On the 1st January 2010 on this invention a patent No. 14015B was issued with priority from 2 September 2009. Owner of the patent is Riga Technical University. Inventors are Artis Kromanis and Juris Krizbergs.

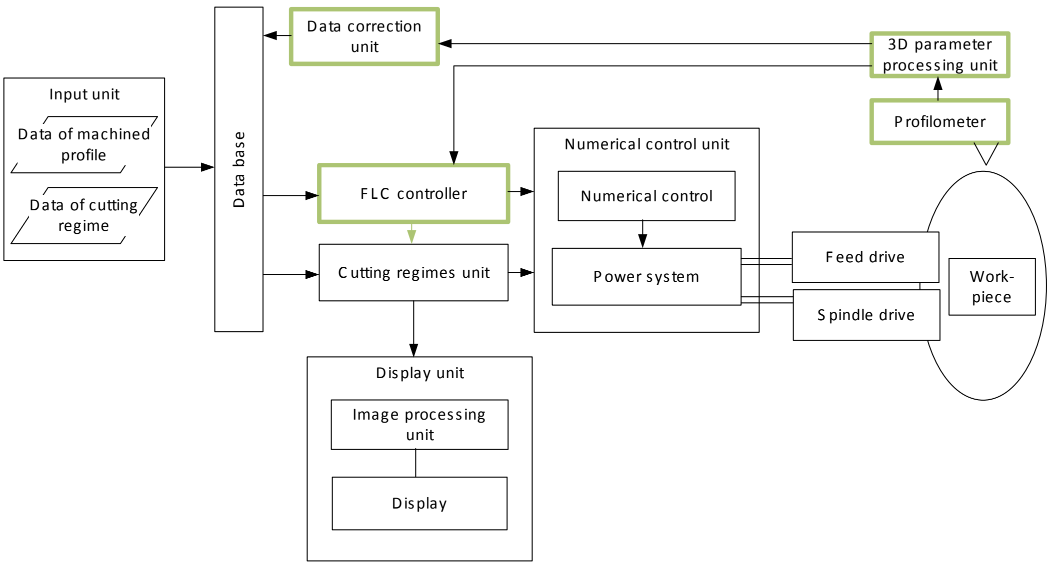


Fig. 6.1. Block diagram of developed adaptive control system

After development of adaptive control system for machining the next step is to conduct simulations for said system to verify its effectiveness and viability. Experiments were conducted, in which the new adaptive control system was used to control cutting speed *v* according to the necessary surface roughness parameters *Sa*. In experiment it was assumed, that the cutting speed *v* will be the parameter which can be controlled adaptively. Said parameter is controlled adaptively trough FLC controller and CNC unit (see Fig. 6.1.). Cutting speed *v* is changed according to the changes of surface roughness of machined work piece *delta_Sa*. Fig. 6.2. illustrates a 3D plot obtained in experiment, where can be seen at which changes of surface roughness delta_Sa cutting speed *delta_atrums* will change. *Iestatītais_Sa* serves as a reference of 3D surface roughness indicating pre-set value of 3D surface roughness.

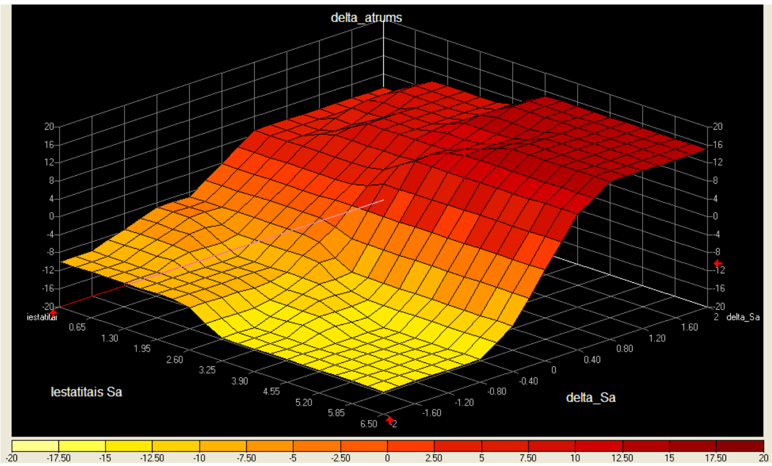


Fig. 6.2. Graphical representation showing relationships between *iestatitais_Sa* (set Sa), *delta_Sa* (Sa changes) and *delta_atrums* (changes of cutting speed)

After creating adaptive control system and making simulations it was concluded that fuzzy logic prediction models are useful for creating adaptive control system for machining, which can be implemented in CNC work table. Developed adaptive control system allows creating automated cutting regimes control system, which depending on the necessary surface roughness controls cutting regimes. A use of fuzzy logic prediction models allows developing adaptive control system, which is useful both for theoretical modelling and practical applications.

CONCLUSIONS AND USE

1. Analysing known technical level, it was concluded that for surface roughness technological assurance exact combination of 3D surface roughness parameters and regression analysis or fuzzy logic were not used.

2. Fuzzy logic can be successfully adapted to solve tasks of 3D surface roughness technological assurance.

3. 3D surface roughness prediction models in milling and turning are developed, giving an opportunity to the manufacturing engineers operatively set-up necessary technological parameters in order to obtain desired 3D surface roughness.

4. Prediction errors are evaluated for developed fuzzy logic and regression models in milling X5CrNi18-10. Regression model prediction error is 19%, while the fuzzy logic model prediction error is 6%. It can be concluded that the developed fuzzy logic prediction model methodology offers considerably more accurate 3D surface roughness prediction model.

5. Regression model prediction error is 6% in turning (11SMnPb30) and 11% (X8CrNi18-9), while the fuzzy logic model prediction error is 4% (11SMnPb30) and 4% (X8CrNi18-9). Although prediction errors for both models of the experiment in turning 11SMnPb30 are similar, trend remains – developed fuzzy logic prediction methodology is able to provide more accurate 3D surface roughness technological assurance.

6. Developed methodology for obtaining fuzzy logic 3D surface roughness prediction models reduces run-in time of machining, respectively, reducing production costs and time. Developed fuzzy logic models can be used by technologist to set up the necessary technological parameters according to the desired 3D surface roughness without additional experiments.

7. Promotional work is based on two types of metal processing: milling and turning – but achieved results can be adapted to other types of metal processing, for example grinding.

8. Fuzzy logic prediction models are useful for development of adaptive control system for CNC, realizing it through the FLC controller, which is operationally linked to the CNC control unit. Developed adaptive control system creates an automated cutting control system, depending on the required 3D surface roughness of workpiece. On given adaptive control system Latvian Patent No. 14015B is issued.

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