Machining Force Regression Models and Real Time Control when Turning MET 4 Metallized Coating

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Abstract: - Due to their wide range of application, metallized coatings are widely used in industry, both for wear resistance or corrosion protection. In order to obtain the required geometric precision, machining these coatings is many times required. As their hardness is of high values, and the turning process is often used, regression models of machining forces, so that to have "an image" of the influencing factors are worth to be determined. A system for real time control of theses forces' values, enabling to monitor the machining process and to stop it when something gets wrong, is also presented by this paper.

Key-Words: - metallized coating, turning, force, regression, experiments design, real time, control system

1 Introduction

A thermal sprayed or, metallized coating does represent a lamellar multilayered metallic structure generated by a complex process. The process, named thermal spraying is the one where pure or alloyed metal is melted in a flame and atomized, by a blast of compressed air into fine spray [1, 2].

Sprayed molten particles do strike, at high velocity, a previously prepared surface of the part, where they flatten out, cool, almost instantly, and build up on one the other [3]. This process of building the multilayered coating is schematically shown in figure 1. When the sprayed particle strikes the surface, it flattens and cools, and, so it contracts, resulting in residual stresses. So, the multilayered coating is characterised by permanent tensile stresses into the exterior layers, and compressive stresses into the interior layers.

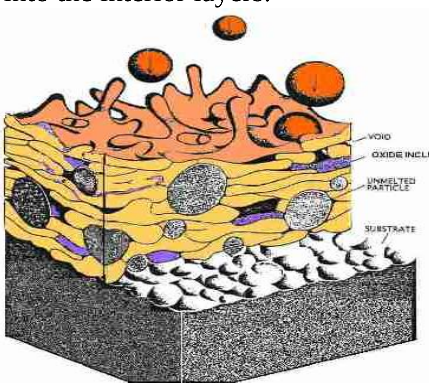

Fig. 1 Schematic representation of the process of generating metallized coating [3]

Depending on the "heat" source used, there are two main categories of metallizing processes, meaning:

- combustion – when a combination of hydro-carbides (acetylene, propane, kerosene, etc) and oxygen (air) is burned and so, the energy required for melting and propelling material particles is generated;
- electric power – by an electric arc or, plasma discharge, the energy required for getting material into molten state and, then, spraying particles onto the surface is obtained.

When considering material's initial state, there are two possibilities, like:

- powder form materials;
- wire form materials

the option of which to be used depends on the energy source available and the properties required for the metallized coating.

In many of the thermal sprayed processes there is used air to spray the molten material particles. That is why, the coating structure is made of oxides and carbides inclusions, outlining the grains of metal particles' boundary.

This is why, the metallized coating hardness is, usually, of high values and, when machining, special attention to the process forces' values should be given. This is because there are many factors influencing them and how they do interact is important for the desired results to be obtained.

There are some qualitative and / or quantitative data mentioned by the specific references.

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The problem is that they can be used for “orientation” purposes and, specially, they are not dealing with the studied Romanian thermal sprayed materials – widely used in Romanian industry.

2 Experimenting

Experiments and results presented by this paper refer to Romanian hard steel MET 4 material.

Some of its characteristics are shown in table 1 and the metallographic structure can be noticed in figure 2.

The samples used in experiments were cylindrical ones, obtained by thermal spraying of MET 4 onto the base material (OLC 45 steel). The coating thickness resulted in, about, 3 mm. An image of the metallizing process – when preparing the samples is shown in figure 3.

Table 1

Chemical structure and mechanical properties

Material	Chemical Structure	HV 0.05	Porosity [% vol]	Wire Diameter [mm]
MET 4	(14 ÷ 15) % Cr, (0,4 ÷ 0,5) % C	370	7 ÷ 9	ϕ 1,8 $^{\pm 0,04}$

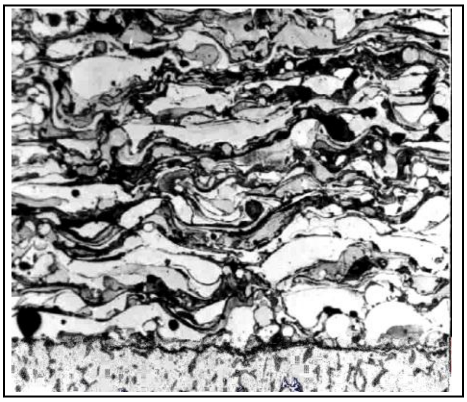

Fig. 2 Metallographic structure of MET4 metallized coating

Fig. 3 Metallizing process for obtaining the experimental samples

When turning, machining force’s components had to be measured and, that is why a special dynamometric device was used [4].

Before using it into experimental machining stand, the device had to be calibrated – meaning submitted to various loading similar to that occurring in real turning, and measuring the induced deformation (along each of the system axes – OX, OY and OZ) – see figure 4.

. Thus, the calibrating equation could be determined and, further used while the turning process is on, as mentioned by relation {1}.

$$\cdot \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = \begin{bmatrix} 2{,}14301\cdot 10^{-4} & -9{,}60789\cdot 10^{-6} & 1{,}66578\cdot 10^{-7} \\ 1{,}13014\cdot 10^{-6} & 2{,}56515\cdot 10^{-4} & -3{,}26354\cdot 10^{-5} \\ -1{,}22414\cdot 10^{-5} & -5{,}98197\cdot 10^{-5} & 2{,}28258\cdot 10^{-4} \end{bmatrix} \cdot \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \end{bmatrix} \quad (1)$$

where:

F_x, F_y, Fz are the turning force’s components;

ε_x, ε_y, ε_z – deformation of dynamometer strain gauges

Further step, was that of turning and, meanwhile, measuring each of machining force’s components values – see figure 5.

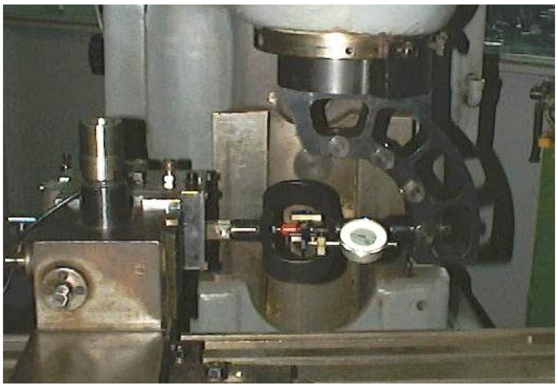

Fig. 4 Calibrating the dynamometric device – F_y loading

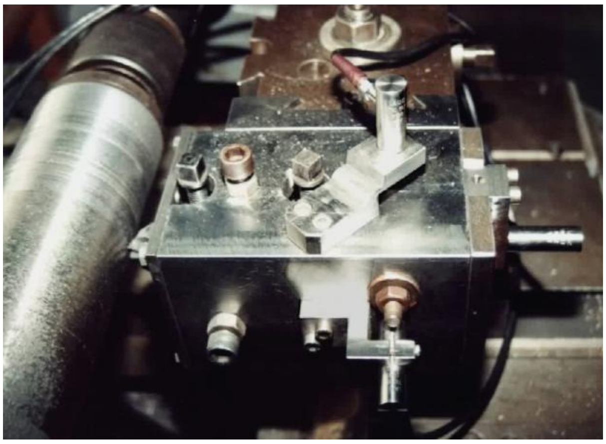

Fig. 5 Measuring machining force’s components values, while turning

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3 Regression Analysis

This paper presents some engineering applied statistics aspects, meaning design of experiments and regression analysis - done in order to determine the dependence of machining force's component on some turning process specific parameters.

It can be considered that a process developing within a certain technological system, can defined by dependence relations like (2):

$$Y = \Gamma\left(x_1, x_2, ..., x_j, ..., x_n\right) \quad (2)$$

called process function; where:

x_j , j = 1, 2, …., k represents the independent process variables (controllable inputs);

Y – the dependent process variable (output);

Γ - the type of dependence relation.

Determining optimum Γ function by regression analysis is possible if, first, there are set the values and variation field of each input.

Then, the appropriate experiments design must be chosen [5], [6].

So, there were studied the variables that follow [7]:

→ *controllable inputs*, x_j:

- rotational speed, v [m/min];
- feed speed, a_f [mm/rot];
- cutting depth, f [mm];
- cutting tool wear, VB [mm]

→ *output*, Y, meaning machining force's component, F_z [daN];

→ *constant inputs* - were considered to be environment characteristics (temperature, humidity);

→ u*ncontrollable (noise) inputs* - were assumed to be *Vickers micro-toughness* ($HV_{0,05}$) of the metallized MET4 and *vibrations of the technological system* - in exterior cylindrical turning..

The experimental values for each inputs, x_j, are presented in table 2. There should be mentioned that these values have been established based on some "guidance" from specific references but, mostly, based on authors experience and preliminary trials.

The experiments design structure considered is shown in table 3. It should be pointed out that, for regression analysis there were used two specific software, meaning:

– REGS, with P 2.1 design of experiments type, and four controllable inputs, x_j:

- DOE KISS, with CCD (central composite design) design type and two controllable inputs, x_j:.

Table 2

Controllable inputs values

<table>
<tr><td rowspan="3">v [m/min]</td><td rowspan="12">Coded values</td><td>-1</td><td rowspan="12">Real values, for P2.1 design</td><td>10</td><td rowspan="12">Real values, for CCD design</td><td rowspan="3">17.3</td></tr>
<tr><td>0</td><td>17.3</td></tr>
<tr><td>+1</td><td>30</td></tr>
<tr><td rowspan="3">a_f [mm/rot]</td><td>-1</td><td>0.10</td><td>0.10</td></tr>
<tr><td>0</td><td>0.14</td><td>0.15</td></tr>
<tr><td>+1</td><td>0.20</td><td>0.20</td></tr>
<tr><td rowspan="3">f [mm]</td><td>-1</td><td>0.30</td><td>0.30</td></tr>
<tr><td>0</td><td>0.42</td><td>0.45</td></tr>
<tr><td>+1</td><td>0.60</td><td>0.60</td></tr>
<tr><td rowspan="3">VB [mm]</td><td>-1</td><td>0</td><td rowspan="3">0.20</td></tr>
<tr><td>0</td><td>0.20</td></tr>
<tr><td>+1</td><td>0.40</td></tr>
</table>

Once determined, by REGS software, the regression model and, thus, the variables that do highly influence the output (f and a_f), a thorough analysis has been considered worth to be done.

Table 3

Experiment Designs

<table>
<tr><td rowspan="13">Fractional Factorial Design (P 2.1)</td><td>Run</td><td>x₁</td><td>x₂</td><td>x₃</td><td>x₄</td></tr>
<tr><td>1</td><td>-1</td><td>-1</td><td>-1</td><td>-1</td></tr>
<tr><td>2</td><td>+1</td><td>-1</td><td>-1</td><td>+1</td></tr>
<tr><td>3</td><td>-1</td><td>+1</td><td>-1</td><td>+1</td></tr>
<tr><td>4</td><td>+1</td><td>+1</td><td>-1</td><td>-1</td></tr>
<tr><td>5</td><td>-1</td><td>-1</td><td>+1</td><td>+1</td></tr>
<tr><td>6</td><td>+1</td><td>-1</td><td>+1</td><td>-1</td></tr>
<tr><td>7</td><td>-1</td><td>+1</td><td>+1</td><td>-1</td></tr>
<tr><td>8</td><td>+1</td><td>+1</td><td>+1</td><td>+1</td></tr>
<tr><td>9</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>10</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>11</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>12</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td rowspan="11">Central Composite Design (CCD)</td><td>Run</td><td>x₁</td><td>x₂</td><td rowspan="11"></td><td rowspan="11"></td></tr>
<tr><td>1.</td><td>-1</td><td>-1</td></tr>
<tr><td>2.</td><td>-1</td><td>+1</td></tr>
<tr><td>3.</td><td>+1</td><td>-1</td></tr>
<tr><td>4.</td><td>+1</td><td>+1</td></tr>
<tr><td>5.</td><td>0</td><td>0</td></tr>
<tr><td>6.</td><td>0</td><td>0</td></tr>
<tr><td>7.</td><td>-1</td><td>0</td></tr>
<tr><td>8.</td><td>+1</td><td>0</td></tr>
<tr><td>9.</td><td>0</td><td>-1</td></tr>
<tr><td>10.</td><td>0</td><td>+1</td></tr>
</table>

So, it was used the DOE KISS software – that enabled a polynomial regression model type to be determined (even if limited to two inputs study, due to license rights).

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4 Real Time Control System

Present world's trend is of full automatic driving of the complex technological processes by means of programmable logic controllers (PLC).

They are based on automation systems in decentralized and distributed structures in the framework of processes interconnected to superior hierarchical structures of "pyramidal" type. This kind of structures allow system interconnection for central driving of processes from factories, plants or industrial platforms. For improving performances and the quality of the products which result from the process, as well as for obtaining some superior technical and economical performances the need for process modeling and optimization, adaptive driving of processes using optimized mathematical models arises [8].

Complex automation installations were produced worldwide for the adaptive driving of processes. These installations also take over the decision role from the human factor, the previous ones having the job of just supervising the installation [7, 9].

Some aspects of building an interactive automation system with data acquisition in industrial processes based on programmable logic controllers (PLC) in distributed and decentralized structure with supervisor system (PC) which achieves graphical interface regarding process parameters monitoring are presented below.

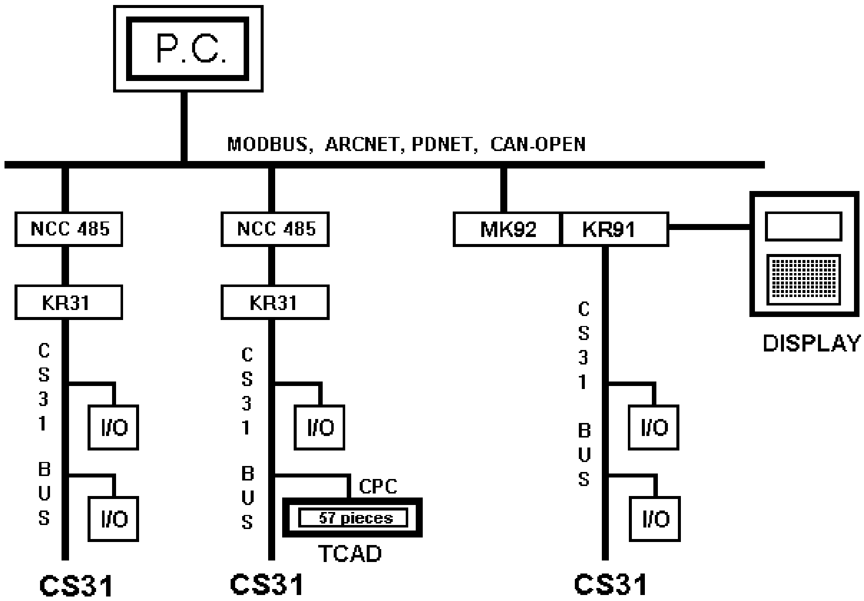

Fig. 6 Decentralized intelligence system for complex processing

An example of complex processing with decentralized intelligence system is presented by figure 6. It enables: freely expandable network from CS31 BUS, which is a PLC network, to MODBUS, ARCNET, PDNET, CAN-OPEN power communication networks, using coupler modules: NCC485, MK92; additional configurable I/O (input-output) units that can be connected whilst the installation is operational with extensive diagnosis functions. All of the remote units KR31, KR91 contain a microprocessor which is dedicated to the management of the PLC input/output and diagnostic facilities in order to reduction of wiring cost and a simple transparent programming.

The remote I/O channels are handled by the central units; programmable serial communications (RS232) can be connected to modem, printer, operator's display, etc.

For non-standard communications, a C-programmable communication coupler (CPC) allows rapid solutions. By twisted-pair serial connection of a panel display (TCAD) to the central unit, a man/machine interface (Display module) may be provided. This allows visualizing the parameters of an interactive process. Decentralized display ensures an ergonomic installation and transmission of the right message to the right person at the right moment.

For connection to other completely different communication systems, that are closed systems (e.g. bar code reader), it is mandatory to use specific protocols. By using a communication processor and the development software one can program using the C language and communicate using a given protocol.

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5 Results

In order to validate the experimental results, there has been conceived a real time control scheme for the measurement error – see figure 7. So, the results obtained in real experiments are compared to the ones obtained by regression models.

This is possible as, one measuring channel stands for "classical" method as it enables measuring deformations caused by machining process (with experimental module, ME) and correcting the "received" information from a measuring "bridge" (with a modelling-reading module, MRM). This is how, there are real time generated the machining force's components values, $F_{x, y, z}$ as $C_i(\delta_i)$.

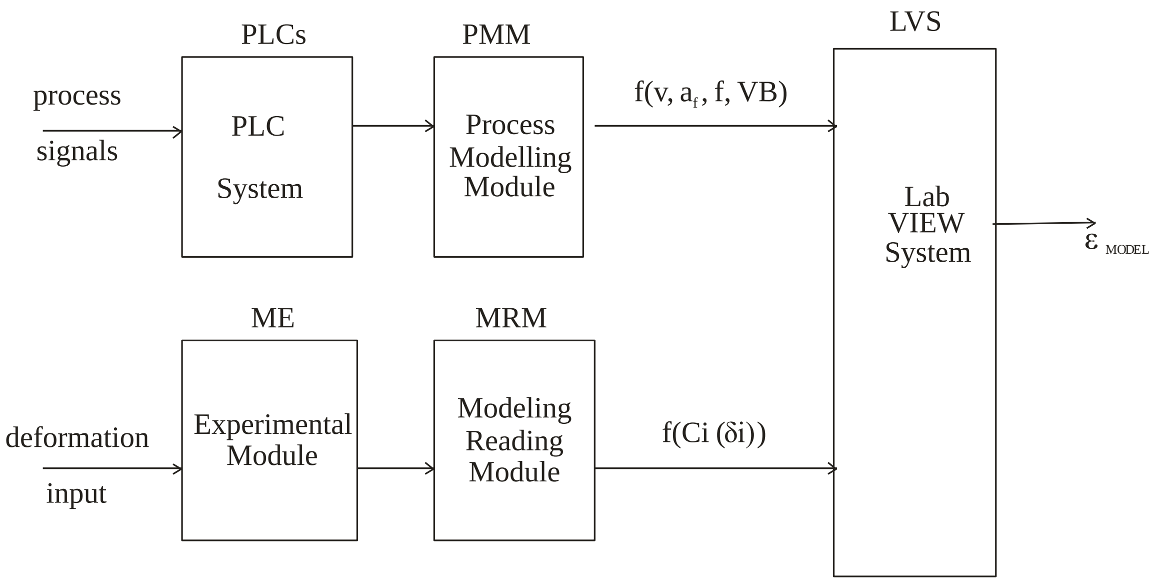

Fig. 7 The real time control system of the measurement errors

The second measuring channel stands for acquiring machining process specific measured signals (v, a_f, f, VB) from a programmable logical controller (PLC) system with real time acquisition. This is done at high sampling rates, by rejecting noise signals and in high processing speed, all of these ensuring an 11 bits minimum measuring accuracy. Further, they are processed according to the regression models obtained (with a machining process modelling module, PMM) and thus, the machining force's components values real time are generated, as function of process specific parameters, $F_{x, y, z}$ (v, a_f, f, VB).

The results obtained in turning experiments are presented in table 4. It should be mentioned that data acquisition while experimenting, was done using a LabVIEW system (LVS) with 1.000 sampling rates / sec, each measurement lasting for 5 seconds. An image of machining force's components values, while turning and measuring, is shown in figure 8.

The regression model obtained by REGS software, for F_z [daN] is:

$$F_z = e^{4,106} \cdot v^{0,259} \cdot a_f^{0.581} \cdot f^{0,842} \cdot (1,169)^{VB} \quad (3)$$

Table 4

Experiments Results

	Run	F_z [daN]	Run	F_z [daN]
P 2.1	1.	10,21	7	28,52
	2.	15,05	8	38,75
	3.	17,21	9	20,64
	4.	20,66	10	20,69
	5.	19,83	11	20,02
	6.	25,76	12	20,22
	Run	F_z [daN]	Run	F_z [daN]
CCD	1.	10,23	6	16,36
	2.	31,15	7	17,02
	3.	17,68	8	33,59
	4.	43,84	9	19,02
	5.	20,43	10	45,04

The q_j coefficient values do point out how strong the influence of each input, on the output, really is.

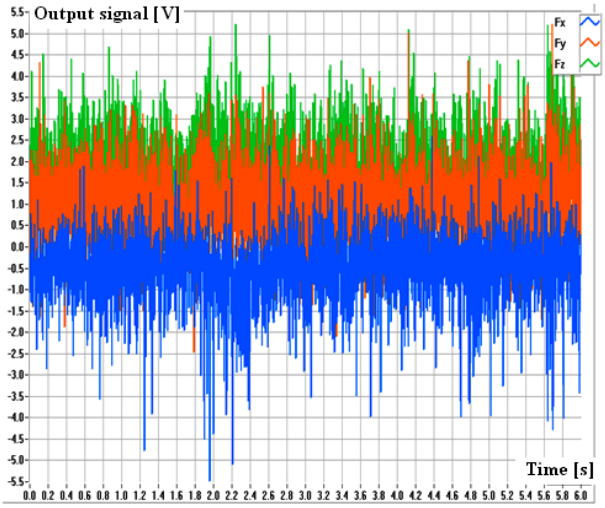

Fig. 8 Turning force's components values – while experimenting

They are evidenced in relation (4):

$$q_v = \left(\frac{v_{max}}{v_{min}}\right)^{0.259} = 1.329; \quad q_s = \left(\frac{a_{f\,max}}{a_{f\,min}}\right)^{0.581} = 1.496 \tag{4}$$

$$q_t = \left(\frac{f_{max}}{f_{min}}\right)^{0.842} = 1.793; \quad q_{VB} = (1.169)^{VB_{max} - VB_{min}} = 1.032$$

The regression model obtained by DOE KISS software for F_z [daN] is:

$$F_z = 8.84 - 18.27 \cdot f - 48.57 \cdot a_f + \\ + 20.29 \cdot f^2 + 144.98 \cdot a_f^2 \tag{5}$$

and all the other polynomial factors coefficients resulted to be of no significance.

The coefficients Pareto chart can be noticed in figure 9.

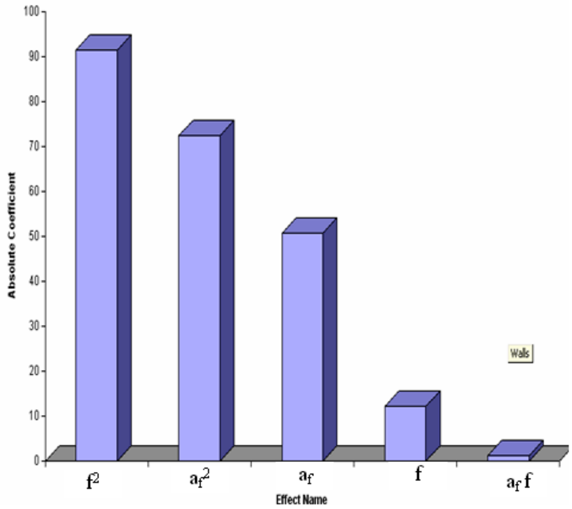

Fig. 9 Pareto chart of coefficients – for polynomial regression model

6 Conclusion

Metallized coatings are widely used in industry, both for wear resistance or corrosion protection.

Turning does represent an important machining procedure of the thermal sprayed coatings. Regression models of machining force's component, F_z, has been considered worth determining, specially for the case of a widely used Romanian hard steel., MET 4. The obtained results proved out the high influence of cutting depth, f, and speed feed, a_f, on machining force's values.

Further research development should involve other machining process specific parameters and, the implementation of the obtained models into the automated active control system.

References:

[1] S. Ingham, A. P. Shepard, *The METCO Metallizing Handbook*, Long Island City 1, New York, 1979.

[2] Iliescu M., Vladareanu L., "Statistic Models of Surface Roughness MET 4 Metallized Coating in Grinding Manufacturing System", 12th WSEAS International Conference on Systems, ISSN 1790-2769, Heraklion, 22-24 July, 2008

[3] www.gordonengland.co.uk, March, 2010.

[4] Iliescu, M., *Research on Quality and Machinability of Thermal Sprayed Coating*, Doctoral Thesis, Bucharest, Romania, 2000.

[5] Noraini A, Zainodin J, Nigel J, *Volumetric Stem Biomass Modeling Using Multiple Regression*, 12th WSEAS International Conference on Applied Mathematics, Cairo, December, 2007,

[6] Schmidt, L., et al., *Understanding Industrial Designed Experiments*, Acad.Press, Colorado, 2005.

[7] Iliescu M, Vladareanu L, Spanu , *Modelling and Controlling of Machining Forces when Milling Polymeric Composites*, Materiale Plastice , pg. 231-235, 2010, WOS:000281051300022, SN 0025-5289

[8] Vladareanu L, Velea LM, Vasile A, Curaj A, *Modular structures in the open architecture systems*, Proceedings of the 9th WSEAS International Conference On Acoustics & Music: Theory & Applications, pg.100-105, 2008, WOS: 000258073500022

[9] Diaconescu E, Vladareanu L, Lefter E, *Signal acquisition for the analyzing and compensation of the rotating shaft oscillations*, Proceedings of the 10th WSEAS International Conference on Mathematical and Computational Methods in Science and Engineering, pg. 444-448,2008, WOS: 000262436800094

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