FLEXIBLE ROBOTIC CELL FOR OPTIMIZATION OF GRINDING PROCESS FOR 40C130 METALLIZED COATING

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ABSTRACT: Metalizing, or thermal spraying technique, was invented almost 100 years ago, but due to its important benefits has been continuously developed since then. This paper is aimed at presenting aspects of optimization the grinding process of 40C130 thermal spayed coatings. Research goals involve applied statistic methods, such as design of experiments and regression analysis joint with the virtual projection method, known as Vladareanu-Munteanu method, for design and develop a real-time control system. Thus, flexible robotic cell with distributed control is presented. As result, required surface roughness, R_a parameter, would be efficiently achieved with optimized grinding process parameters values.
KEY WORDS: thermal spray, grinding, optimization, control system.

1 INTRODUCTION

It was in 1910 when Max Ulrich Schoop invented the thermal spraying technique, in Swiss. Due to its high importance in repairing and reconditioning worn parts, this technique was imported in USA in 1920. Special attention was given in 1950's to the study of phenomena occurring and to the improvement of conditions for thermal spraying. One can notice that there are more than 100 years since this technique has been invented, but still it is in attention of specialists.

Nowadays focus is on the development of new thermal spraying techniques environmental friendly and of new materials for challenging applications, as well as on the design of new high performance equipments. Still, complex studies on process phenomena are the bases for all the above mentioned. The thermal spraying is defined as "a group of coating processes in which metallic and non-metallic materials are deposited in a molten or semi-molten condition to form a coating" (http://www.progressivesurface.com/, 2015). Added to the substrate, it results in a "system" that is better suited for engineering application than just the substrate alone. Schematic representation of the thermal spraying process (with powder material) and of how the multilayer coating is built can be noticed in Figure 1 (velocity oxygen fuel (HVOF) spraying, All these processes are also called "metallizing" or "metal spraying".

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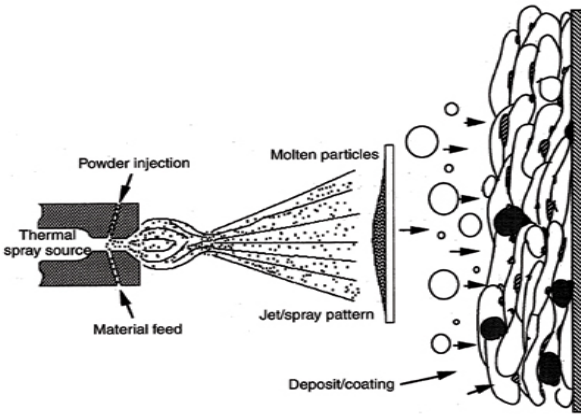


Figure 1. Schematic representation of the thermal spray process flow and layer build-up

Coating materials are either in wire, or powder form, and include metals, alloys, carbides, ceramics, plastics, cermets, composites and blended materials. There are so many applications of thermal sprayed coating, such as: wear resistant coatings, hard chrome replacement coatings, corrosion protection coatings, dielectric coatings, etc. Example of the use of metallised carbide coatings on landing gear for aircraft is shown in Figure 2 (http://www.tstcoatings.com/, 2015).

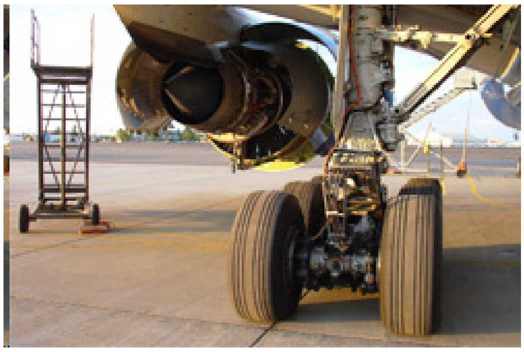


Figure 2. Thermal spray coated landing gear struts -replace hard chromium plating

When wear resistant and hard coatings are required, one material to be used (Romanian produced) is 40C130, wire form. Most of the times, the geometrical precision prescribed for the surface of the part to be coated, is obtained by post thermal spraying processing. Due to high hardness, grinding (flat or, cylindrical) is frequently used and, thus, special attention would be given to surface roughness values. The smaller the values, the better coated parts performances after grinding.

As most of specific References offer only general information on thermal sprayed coatings grinding process parameters values (http://www.gordonengland.co.uk/ 2015), Heuermann, 2007) and the data are rather quantitative, the study presented by this paper – regression model of surface roughness, R_a parameter and real-time control system, will contribute to the real optimization of this type of grinding process.

2 STATISTIC RESEARCH METHOD

The applied statistic method used in this study involves design of experiments and regression analysis (Iliescu, 2008). Thus, it was required identification and set-up of grinding process variables as follows.

2.1 Material / coating

The coating material studied is 40C130, Romanian produced. It has a percentage of 4% C and (13 ÷ 13,2) % Cr and it is wire form, of $\phi\ 2^{\pm 0,04}$ mm in diameter (Iliescu, 2000). The metallographic structure of this thermal spray coating is shown in Figure 3.

There can be noticed the flat type shape of particles and lamellar multilayer aspect, as well as the voids and inclusions.

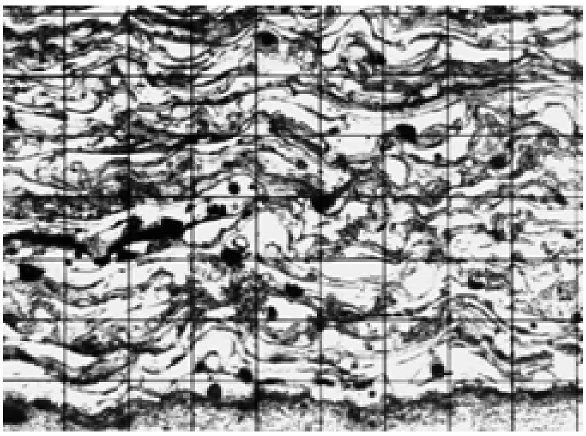


Figure 3. Metallographic structure of 40C130 coating

2.2 Grinding process parameters

This study is done for cylindrical exterior grinding of thermal spay 40C130 coatings, the metallizing process being electric-arc spray.

Grinding process parameters, considered independent variable for the process (inputs), are mentioned next:

- peripheral speed (of the grinded part), v_p, $v_p \in [11.5,\quad 18.1]$ [m/min];
- longitudinal feed speed, s_l, $s_l \in [12,\quad 24]$ [mm/min];
- traverse feed, s_t, $s_t \in [0.013,\quad 0.03]$ [mm/d.c.],

where d.c. means double course.

There was used special cooling fluid for grinding.

2.3 Process output

As the studied process is grinding, and surface roughness does represent an important output of this process, the dependent variable considered is R_a (arithmetic average of the absolute surface roughness values).

Based on the above mentioned, the general type of process function is the one in Equation (1):

$$R_a = \Gamma(v_p, s_l, s_t) \tag{1}$$

where:

R_a is the surface roughness parameter, dependent process variable (output) in [μm]

Γ - the type of dependence relation, regression function.

2.4 Regression analysis

The applied statistic methods used for research involve design of experiments – by Central Composite Design, CCD, with five replicates, and regression analysis – by DOE KISS software (Schmidt, 2005). DOE Kiss software is used for determining regression functions of polynomial type.

In regression there are used, both real and coded values for inputs. The independent variables, are noted by z_j $(j = 1,2,3)$ and, the coded variables are noted by x_j $(j = 1,2,3)$, the corresponding relationship being evidenced by Equation (2):

$$x_j = \frac{z_j - \frac{z_{\min} + z_{\max}}{2}}{\frac{z_{\max} - z_{\min}}{2}}, \quad (j = 1,2,3) \tag{2}$$

where:

z_{min} is the minimum value for the independent variable, z_j, - in fact it represents the minimum experimental value;

z_{max} is the maximum value for the independent variable, z_j, - in fact it represents the maximum experimental value;

$j = 1,2,3$ - the number of independent variables considered

($v_p = z_1$; $s_l = z_2$; $s_t = z_3$)

3. EXPERIMENTS AND RESULTS

The samples were prepared by electric-arc thermal spraying with coating thickness about 2.5 mm. Grinding process experiments were performed on universal cylindrical grinding machine and the grinding wheel made of electro-corundum abrasive and ceramic binder.

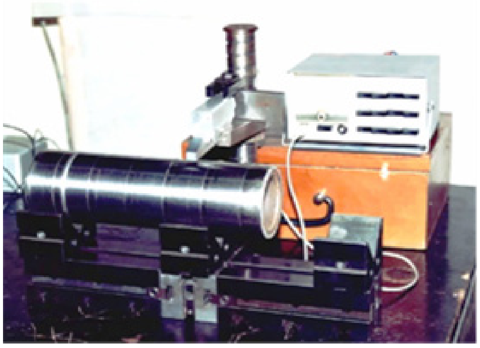
As mentioned above, the experiments design is CCD. The experimental values obtained for R_a parameter are presented in Table 1. For each experiment, these values represent the arithmetic mean of the five replicates values.

Table 1. Experimental results

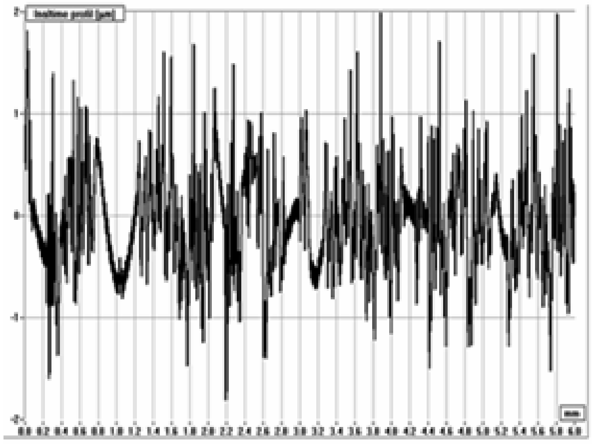
Experiment number	Inputs (x_j) coded values			Output real value
	x_1	x_2	x_3	R_a [μm]
1	-1	-1	-1	0.80
2	-1	-1	1	0.77
3	-1	1	-1	0.40
4	-1	1	1	0.49
5	1	-1	-1	0.51
6	1	-1	1	0.58
7	1	1	-1	0.38
8	1	1	1	0.37

Surface roughness R_a parameter values were measured with RUGOMAS instrument, as shown in Figure 4. There can also be noticed a part of the grinded coating surface profile, more specifically its micro-geometric irregularities

More, for accurate determination of surface roughness, a LabVIEW data acquisition system was used so that 1,000 measurements/sec., for 6 seconds each, were done – see Figure 5. The program was designed so that to enable the determination of medium value of all the measurement taken in a circumferential section.



experimental stand (a.)



grinded surface roughness profile (b.)

Figure 4. Measuring surface roughness with RUGOMAS instrument

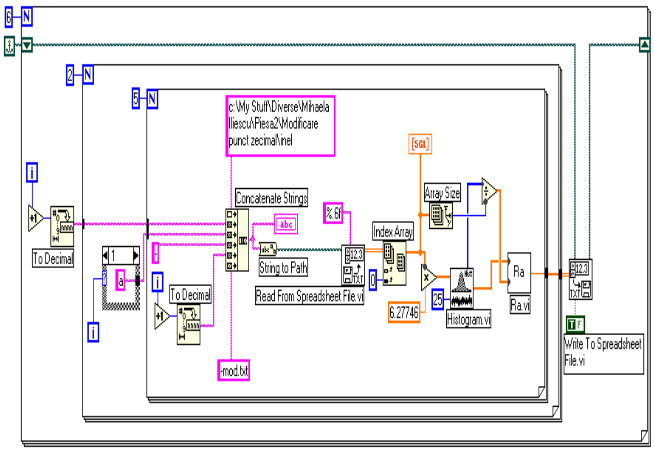
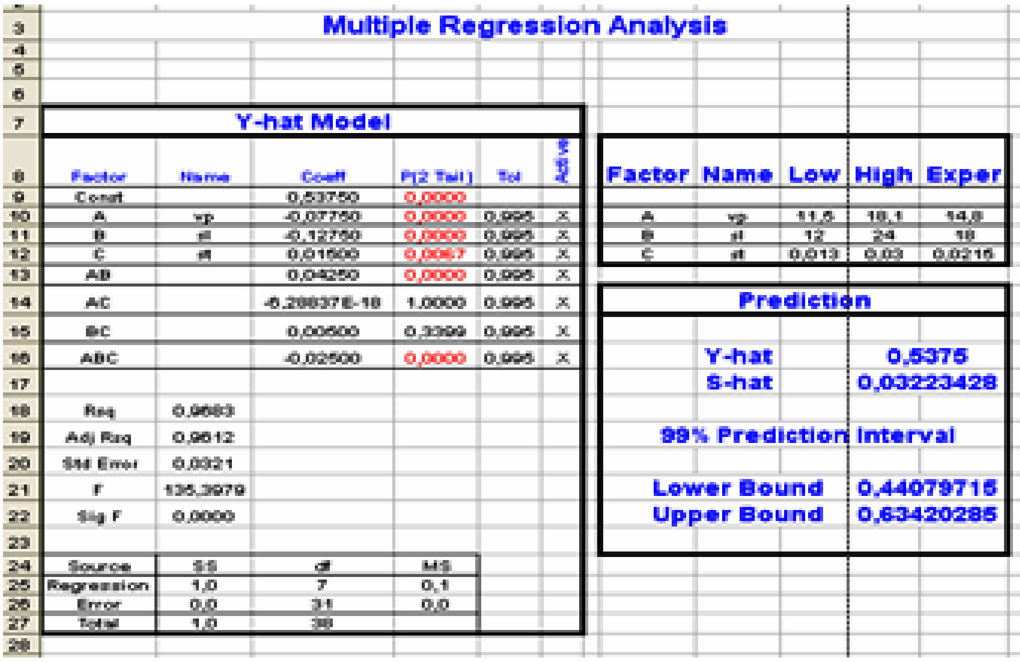


Figure 5. LabVIEW program structure

The regression analysis results, obtained with DOE KISS software (student version) are evidenced in Figure 6.

It is considered that one input significantly influences the output, if the P (2 Tail) value is less. or equals, 0.05.



Multiple Regression Analysis

Y-hat Model

Factor	Name	Coeff	P(2 Tail)	Tol	Active
Const		0,53750	0,0000		
A	vp	-0,07750	0,0000	0,995	X
B	sl	-0,12750	0,0000	0,995	X
C	st	0,01500	0,0067	0,995	X
AB		0,04250	0,0000	0,995	X
AC		-6,28837E-18	1,0000	0,995	X
BC		0,00500	0,3399	0,995	X
ABC		-0,02500	0,0000	0,995	X

Rsq	0,9683
Adj Rsq	0,9612
Std Error	0,0321
F	135,3979
Sig F	0,0000

Source	SS	df	MS
Regression	1,0	7	0,1
Error	0,0	31	0,0
Total	1,0	38	

Factor	Name	Low	High	Exper
A	vp	11,5	18,1	14,8
B	sl	12	24	18
C	st	0,013	0,03	0,0215

Prediction

Y-hat	0,5375
S-hat	0,03223428

99% Prediction Interval

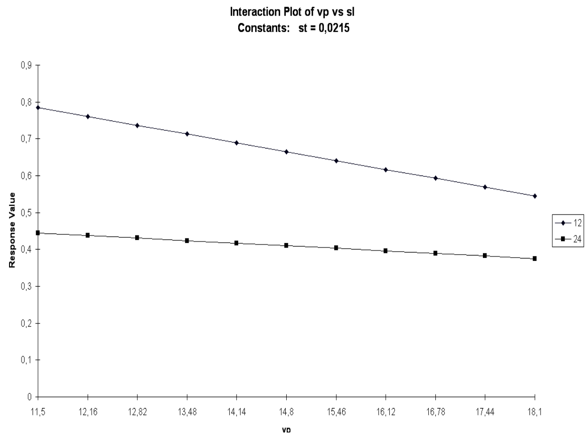
Lower Bound	0,44079715
Upper Bound	0,63420285

Figure 6. DOE KISS regression analysis results

Finally, the resulting regression model for R_a parameter of surface roughness is a third order polynomial one, as evidenced by Equation (3).

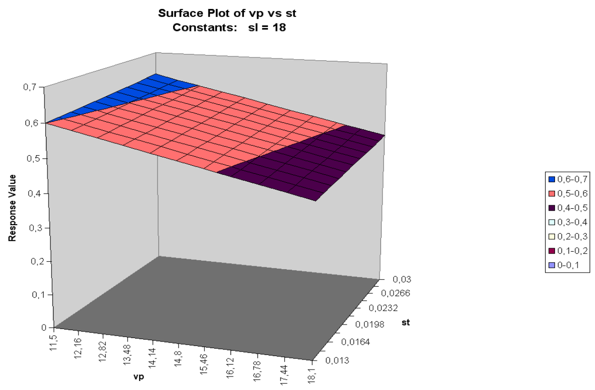
$$\begin{aligned} R_a &= 2.686 - 0.119 v_p - 0.100 s_l + \\ &+ 39.749 s_t + 0.0053 v_p s_l + \\ &+ 2.674 v_p s_t + 2.198 s_l s_t - \\ &- 0.149 v_p s_j s_t \end{aligned} \quad , \ [\mu\text{m}] \qquad (3)$$

The software enables the plot of relevant graphs, such as, for example, the interaction plot (of v_p versus s_l variables) and surface plot (of v_p versus s_t variables), as shown in Figure 7.



interaction plot (a.)

Figure 7: Graphs of variables interaction and dependence



surface plot (b.)

Figure 7: Graphs of variables interaction and dependence (continued)

There is the Pareto chart of coefficients, in Figure 8, to point out how strong is the influence of input variables and their interactions on the output.

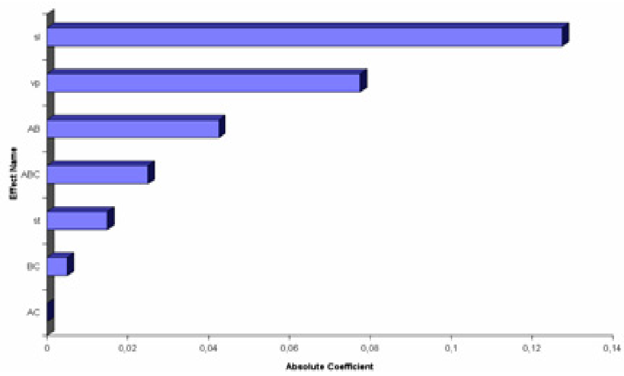


Figure 8. Pareto of coefficients chart

4. WORK SEQUENCE CONTROL OF THE MACHINING PROCESS

The development of real time control system for cylindrical exterior grinding of thermal spray coatings was done by applying the virtual projection method (Vlădăreanu L., 2013), (Vlădăreanu V., 2014). The acting servomotors generate the process parameters – peripheral speed $\mathbf{v_p}$, longitudinal feed speed $\mathbf{s_l}$ and traverse feed $\mathbf{s_t}$, that are transmitted as input signals to the virtual projection graphic interface of the grinding process equipment and to the intelligent control interfaces. By the intelligent virtual projection interface, (Vlădăreanu V., 2013).it is modeled the grinding process referenced to input process parameters (v_p, s_l and s_t) and by regression analysis it is generated the output – surface roughness parameter, $R_a = \Gamma\left(v_p, s_l, s_t\right)$.

The whole process required for thermal spraying of cylindrical exterior parts requires the sequence of next steps: thermal spraying by electric-arc of 40C130, grinding and surface measuring, the output being R_a parameter. A flexible robotic cell (FRC) with distributed control (Spîrleanu, 2014) is presented in Figure 9.

The FRC (Flexible Robotic cell) is made of the components that follow: *M1, the* grinding machine; *M2*, the surface roughness measuring equipment; *R*, the robot. The robot has the function of manipulating the parts from input transport system to the grinding machine and from the surface roughness measuring equipment to the output transport system. This robot could also be used in thermal spraying process, when the clamping device is replaced by special device for holding the spraying gun, required for arc spraying of 40C130 wire material. The coating process, by robot, could be “in collaboration” with the grinding machine.

The FRC control performs with robotic controllers DMQX, real time operating system for the interface with components M1, M2 and R. For the grinding machine, M1, there are used functions implemented into the functions library of language extension DMQX (Iliescu, 2015), such as the reading function of encoders for X and Z axes. For the surface roughness measuring equipment, M2, the robotic controller enables the data acquisition for surface roughness measurements, or the configuration of measuring instrument by digital signals, I/O.

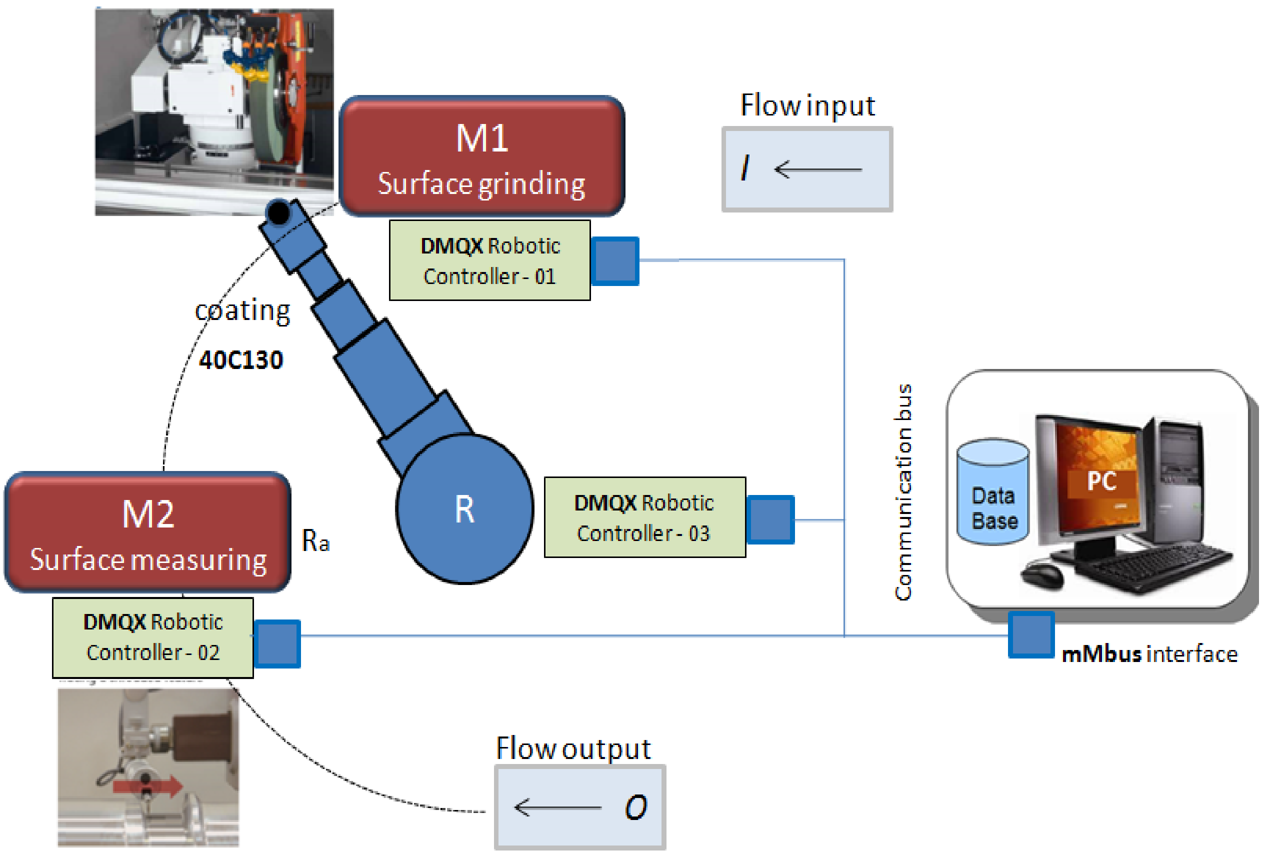


Figure 9. The flexible robotic cell for grinding process optimization

The relationship $R_a = \Gamma(v_p, s_l, s_t)$ involve setting of inputs (process parameters) v_p, s_l, s_t, prior to grinding and that is why, a computer, PC, is used for reading the optimum values to be further used as grinding process parameters values. Usually, the configuration of grinding process parameters, for machine M1, is at higher values but, still, limited to the values for a safe process correlated to required geometrical precision, specially, surface roughness values.

This is why, grinding machines, usually operate above their maximum capability and machining times are higher than normal. The machining operator does not have the ability to cope and recalculate the many values of variables specific for the process. Running the PC software application enables the values of grinding process parameters to be changed every time by reading the data base and configuring these values to the level of grinding machine, M1, by the robotic controller, DMQX. Finally, the result is that of a considerable increase in operating efficiency.

5 CONCLUDING REMARKS

Thermal spraying techniques are successfully used in industrial application due to their ability of generating wear resistant coatings, hard coatings, corrosion protection coatings, etc. Many times, the required surface roughness of the coating is obtained by grinding, as post thermal spray coating processing,

This study based on polynomial regression model of surface roughness, R_a parameter and real-time control system does contribute to optimization of the grinding process of thermal spray coatings.

Grinding process parameters were evidenced as significantly influencing the surface roughness values, by the polynomial regression model determined. Also, most of their interactions resulted in being significant, still it can be noticed that the traverse feed parameter, s_t, has real weak influence on the output, R_a surface roughness parameter.

The decentralized and distributed control system allows monitoring of the process parameters - peripheral speed $\boldsymbol{v_p}$, longitudinal feed speed $\boldsymbol{s_l}$ and traverse feed $\boldsymbol{s_t}$, aiming to optimizing through regression analysis the surface roughness. The results presented by this paper are worth to be applied for grinding process optimization of 40C130 thermal spray coating.

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7 REFERENCES

►http://www.progressivesurface.com/thermalspraying_process.php, Accessed: 2015-03-30.

►http://www.glasscanadamag.com/content/view/1124/38/, Accessed: 2015-03-30

►http://www.tstcoatings.com/index.php?page=hard_chrome_replacement.html, Accessed: 2015-04-01

►http://www.gordonengland.co.uk/wear.htm, Accessed: 2015-04-01

►Heuermann, T. (2007), *New Grinding and Finishing Methods for Thermal Spray Coatings*, HCAT/JCAT Meeting

►Iliescu, M., Costoiu, M. (2008) *Surface Roughness Statistic Models of Metallized Coatings in Grinding Manufacturing Systems*, WSEAS Transactions on SYSTEMS, Issue 9, pag. 824-833,

►Iliescu, M. (2000), *Research on Quality and Machinability of Thermal Sprayed Coatings,* Doctoral Thesis, POLITEHNICA University, Bucharest

► Schmidt, L., et al. (2005), *Understanding Industrial Designed Experiments*, Academy Press,

►Vladareanu L., Velea L.M., Munteanu R.I, Curaj A., Cononovici S., Sireteanu T., Capitanu L., Munteanu M.S. (2013), *Real time control method and device for robots in virtual projection*", patent no. EPO-09464001, 18.05.2009, EP2105263. Patent OSIM 123527/30.04.2013

►Vladareanu V. , Şchiopu P., Vladareanu L. (2014), *Theory and Application of Extension Hybrid Force-Position Control in Robotics*, U.P.B. Sci. Bull., Series A, Vol. 76 (3), pg.43-54,

►Vladareanu V., Sandru O.I., Vladareanu ., Yu H.N. (2013), *Extension Dynamical Stability Control Strategy for the Walking Robots*, International Journal of Technology Management, SKIMA 2013, Inderscience Publisher, ISSN online: 1741-5276,

►Spîrleanu,C, Vladareanu,L. E.Diaconescu (2014), *An experimental framework for Multi-Agents using RTOS based robotic controllers*", Applied Mechanics and Materials Vol. 555 pp.269-266,

►Iliescu, M., Spirleanu, C., Pătraşcu, A., and Vladareanu, L., (2015), *Distributed Control System for Machining Process Optimization in Drilling Mineral Composites Reinforced by 3% Glass Fibers*, TEHNOMUS Journal, pag. 426-431. ISSN-1221-029X.