Surface Roughness Statistic Models of Metallized Coatings in Grinding Manufacturing System

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Abstract: - Metallizing process has known a continuous extent, lately, because of the sprayed coatings' intensive application into various industrial fields. Metallized coatings have very important wear or, corrosion resistance characteristics and, when used for repairing worn parts, the prescribed surface quality specifications can be obtained only by grinding, after thermal spraying. Statistic models of grinded surface roughness are useful, specially, for optimizing the machining process. For adequate and, faster measurements, a LabVIEW data acquisition system was used to obtain grinded surface roughness values and, for obtaining statistical models needed, specialized regression soft-ware was considered.

Key-Words: - metallized coating, surface roughness, experiment design, regression analysis, statistic model

1 Introduction

Metallized coating is a lamellar multilayer metallic structure created by a metallizing process. The thermal spray or metallizing process can be described [2] as the process where pure or alloyed metal is melted in a flame and atomized, by a blast of compressed air into fine spray.

The sprayed molten particles, strike [7], at high velocity, a previously prepared surface, of the part, where they flatten out, cool, almost instantly, and build up on one the other. So, a multilayer , slightly porous structure, is generated.

When the sprayed particle strikes the surface, it flattens and cools, and, so it contracts, resulting in residual stresses. By "building" the multilayer coating, these stresses sum up and, so, permanent tensile stresses are there, into the exterior coating layers, while, compressive stresses are into the interior coating layers. That's why, when metallizing and/or machining these structures, caution is necessary, to avoid coating fracture.

As, most of the metallizing processes use air to spray the molten metal and, usually, they take place in normal atmospheric conditions, chemical interactions appear. So, in a metallized coating, there can be noticed, next to sprayed metal particles, oxides and carbides inclusions, outlining the grains of particles' boundary.

The bond of metallized coating particles to the part material is physical – mechanical one, obtained by: "cermeting" the particles into the surrounding oxides; by welding micro-points; by mechanical anchoring onto the roughness of the impact surface.

Materials used in spraying are, as powder or wire and, with various chemical composition, depending on their final use (wear resistance, corrosion resistance, lubricating etc.). Considering the stainless steels, they can be divided into "hard" or "mild" ones and, of course, the more severe wearing conditions in using, the higher coating hardness, needed. Among widely used Romanian materials, wire form, there are 40C130 and MET4 which, metallized, provide hard coatings with very good mechanical characteristics.

The metallographic structures [3] of the thermal sprayed "hard" steels, 40C130 and MET 4, are shown in Figure 1 and, respectively, Figure 2. As observation, it is mentioned the fact that sprayed coatings properties are, completely, different from the initial materials' ones.

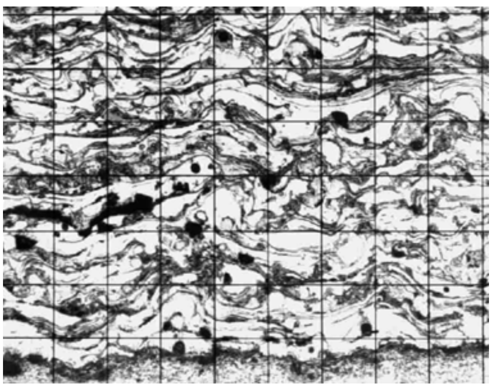


Fig. 1 Metallographic structure of 40C130 metallized coating

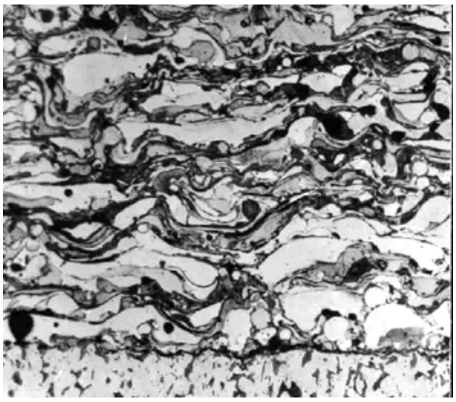


Fig. 2 Metallographic structure of MET 4 metallized coating

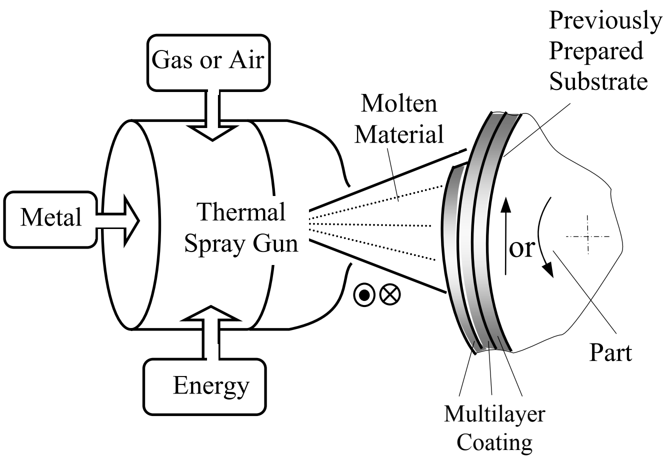


Fig. 3 Metallizing process scheme

A scheme of the metallizing process is presented in Figure 3. One can notice that for a metallizing process there must be *an energy source* (combustion flame, electric arc, plasma) for heating powder or wire form material to a molten or near-molten state and *a gas* (usually, compressed air) to propel the material toward the target substrate.

Most of the times, specially when wear resistance or, lubricating characteristics are required, in order to obtain prescribed geometric precision of the part, machining of the metallized coating is necessary. These multilayer structures, adherent to the base material, are porous, with high hardness and require special machining conditions [*].

As, both 40C130 and Met 4, are "hard" steels, grinding is often used, either after initial turning or, as one and only machining procedure (conditioned by the restriction that the sprayed coating does not differ much from the final prescribed shape, dimensions etc. of the part).

One important geometrical precision parameter, is the surface roughness and, specially when lubricants are used, plays a very important role in functional characteristics of the product which metallized part belongs to.

The specific Reference [2], [7] present only general information on grinding procedures – meaning grinding type wheels, some values of the machining parameters and of possible obtainable surface roughness. There are poor quantitative data of surface roughness' dependence on any, of the grinding parameters and, rarely includes Romanian made stainless steels.

2 Statistical Modeling

Considering all the above mentioned, the research *objective* was to determine statistical models of surface roughness dependence on grinding parameters - for 40C130 and MET4 metallized coatings.

The mentioned objective was reached by "following" the *research directions*:

- establishing the appropriate research methods;
- determining the regression functions;
- pointing out the influence of grinding parameters;
- recommendations for an appropriate active control grinding manufacturing system.

Research methodology [1], [4] is vast but, for the proposed objective, was based on the fact that a process that is on within a certain technological system, can defined by variables connected through relation as:

$$Y = \Gamma(x_1, x_2, ..., x_j, ..., x_n) \quad (1)$$

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.

Before determining optimum Γ type function, there must be established the dependent and, most of all, the independent variables studied, their values and variation fields and, not the least, the experiments' structure (design of experiments) that fits best.

Based on the above mentioned, research was carried on the *controllable inputs*, x_j:

- *part rotational speed,* v_p [m/min];
- *longitudinal feed speed,* s_l [mm/min];
- *transversal speed,* s_t [mm/d.c.], where d.c. refers to double course of the grinding machine plateau;
- *micro-hardness*, HV 0.05.

Constant inputs were considered to be ;
- *environment characteristics* (temperature, humidity)
- *grinding wheel characteristics* (material, dimensions) and *cooling fluid properties*.

Uncontrollable (noise) inputs:
- *vibrations of the technological system* - for exterior cylindrical grinding.

The *output*, Y, was surface roughness, evaluated by R_a [μm] parameter.

For the regression analysis to be carried out, the controllable inputs values had be considered both, real ones, x_j, as well as the coded ones, z_j – see Table 1.

There were considered two three levels experiments designs, one, a fractional factorial - with 6 runs, called P 1.2 and, the other, a central composite- with 8 runs, called [6] CCD, both dealing with three independent variables, x_j . There was, also, applied another fractional factorial design, with 12 runs, dealing with four independent variables, called [3] P 2.1. Their structure is presented in table 2.

The software used for regression analysis were REGS [3] with 3 replicates – for Fractional Factorial Designs, and DOE KISS [1], [5] with 5 replicates – for Central Composite Design.

Table 1

Controllable inputs values

v_p [m/min]			s_l [mm/min]			s_t [mm/d.c.]		
Coded values								
(-1)	(0)	(1)	(-1)	(0)	(1)	(-1)	(0)	(1)
Real values, for P1.2 design								
11,5	14,43	18,1	12	17	24	0,013	0,02	0,03
Real values, for CCD design								
11,5	14,8	18,1	12	18	24	-	0,0215	-
Added independent variable, for P2.1 design								

(-1)	(0)	(1)	- coded values
370	540	780	- real values

Table 2

Experiment Designs

Design	Run	x_1	x_2	x_3	x_4
Fractional Factorial Design (P1.2)	1.	+1	-1	-1	
	2.	-1	+1	-1	
	3.	-1	-1	+1	
	4.	+1	+1	+1	
	5.	0	0	0	
	6.	0	0	0	
Central Composite Design (CCD)	1.	-1	-1		
	2.	-1	+1		
	3.	+1	-1		
	4.	+1	+1		
	5.	0	0		
	6.	0	0		
	7.	-1	0		
	8.	+1	0		
	9.	0	-1		
	10.	0	+1		
Fractional Factorial Design (P2.1)	1.	-1	-1	-1	-1
	2.	+1	-1	-1	+1
	3.	-1	+1	-1	+1
	4.	+1	+1	-1	-1
	5.	-1	-1	+1	+1
	6.	+1	-1	+1	-1
	7.	-1	+1	+1	-1
	8.	+1	+1	+1	+1
	9.	0	0	0	0
	10.	0	0	0	0
	11.	0	0	0	0
	12.	0	0	0	0

The regression analysis, carried out with REGS program, provides function of type:

$$Y = a_0 x_1^{a_1} x_2^{a_2} x_3^{a_3} \quad (2)$$

or

$$Y = a_0 x_1^{a_1} x_2^{a_2} x_3^{a_3} x_4^{a_4} \quad (3)$$

The regression function [5] determined with DOE KISS is polynomial type:

$$Y = a_0 + \sum_{i=1}^{k} a_i z_i + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} a_{ij} z_i z_j + \sum_{i=1}^{k} a_{ii} z_i^2 \quad (4)$$

Obs.

Relations (2) and (3), by logarithm, are similar to relation (4) except for the fact that there are, only, first order polynomial factors, with no interactions or second order ones included.

3 Experimental research

Research has been done and, the experimentally obtained results were used in order to determine required statistical models.

3.1 Experiments

Experiments were carried out on electric arc thermal sprayed "hard" steels, 40C130 and MET 4, whose initial (wire form) chemical structures is presented in Table 3 and the electric arc metallizing process parameters are shown in Table 4.

Table 3

Chemical structure and mechanical properties

Material	Chemical Structure	HV 0.05	Porosity [% vol]	Wire Diameter [mm]
40C130	0,4 % C, (13 ÷ 13,2) % Cr	750 ÷ 810	8 ÷ 9	$\phi\, 2^{\pm\, 0,04}$
MET 4	(14 ÷ 15) % Cr, (0,4 ÷ 0,5) % C	370	7 ÷ 9	$\phi\, 1,8^{\pm\, 0,04}$

Table 4

Metallizing process parameters

Material	Electric Arc Voltage [V]	Electric Current Intensity [A]	Metallizing Distance [mm]	Compressed Air Pressure [bar]
40C130	29	200	170	5.2
MET 4	25	200	170	5.0

The thermal sprayed coatings were sprayed on the exterior cylindrical surface of a previously prepared sample. Figure 4 presents an image taken while the metallizing process was on. One can see that the part to be sprayed is clamped onto a lathe, having a rotational movement and, the longitudinal movement is that of the spraying gun.

Additional preparation of samples was necessary, meaning the zones submitted to various grinding parameters, were separated to one another by rough turning, to allow the access of the grinding wheel.

Fig. 4 Metallizing process

Fig. 5 Prepared sample for grinding experiments

A sample, prepared for required experiments is shown by Figure 4.

Once grinding experiments over, in concordance with the required experimental program, there were measured roughness values of the generated surfaces. The measuring apparatus was a Rugomas type one and, for faster and more precise measurements, a LabVIEW data acquisition system was, also used.

This system allowed 1,000 measurements/sec., for 6 seconds each, and measurements were taken in 5 different points of the generated surface, so that every experience results were checked out. The structure of this acquisition system, allows the calculus of medium surface roughness' value – see Figure 6

An image of, thus obtained, surface roughness profile is presented in Figure 7. It can be the "cut off" values (marked by an arrow). These values refer to the moments (points) when Rugomas measuring ball point got into the existing surface's pores. The data acquisition program structure automatically removes these values from the ones considered fit to determine arithmetic media.

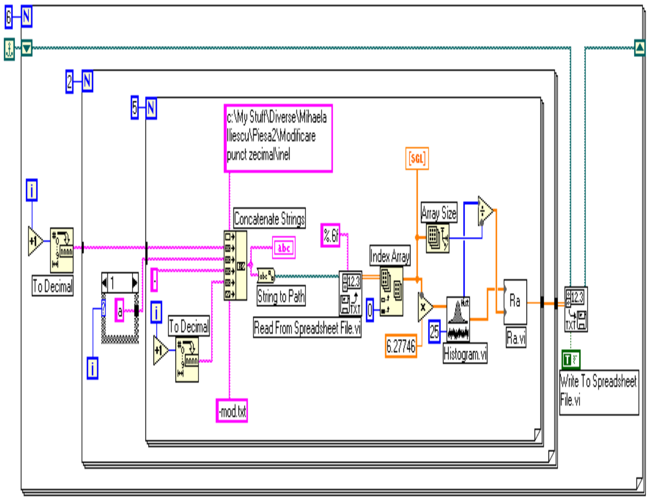


Fig. 6 LabVIEW program for obtaining medium values of surface roughness measurements

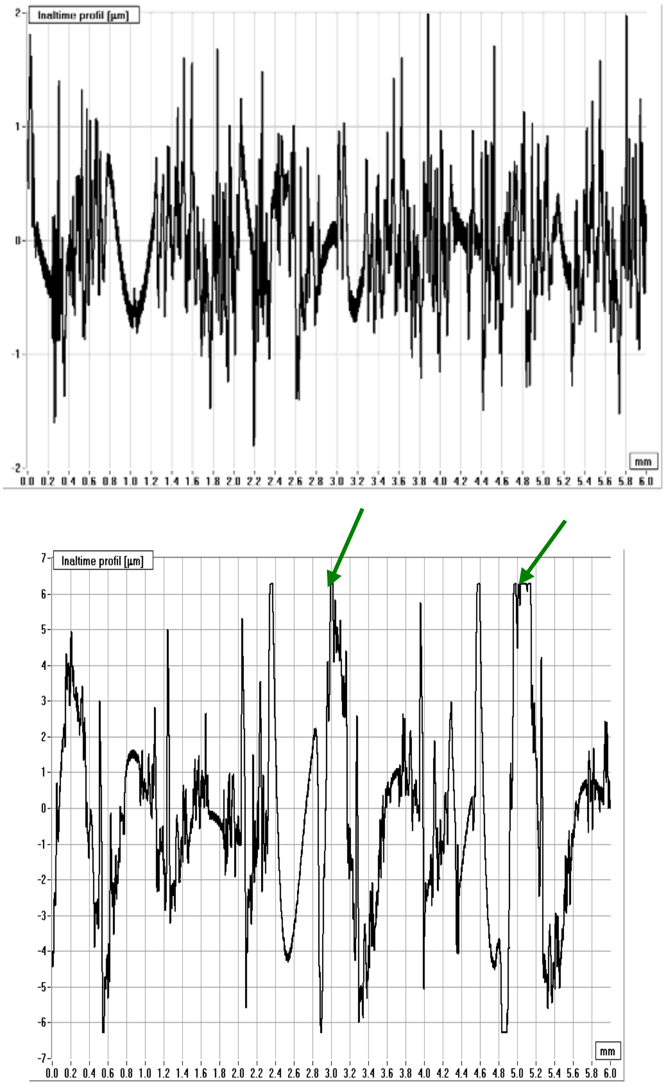


Fig. 7 Surface roughness measured profile

Table 5

Experimental Values

Design	Run	40C130 R_a [µm]	MET 4 R_a [µm]
Fractional Factorial Design (P1.2)	1.	0,51	0,67
	2.	0,40	0,57
	3.	0,77	0,87
	4.	0,37	0,50
	5.	0,48	0,64
	6.	0,52	0,68
Central Composite Design (CCD)	1.	0.78	0.95
	2.	0.46	0.57
	3.	0.55	0.69
	4.	0.36	0.44
	5.	0.53	0.66
	6.	0.55	0.68
	7.	0.53	0.66
	8.	0.50	0.62
	9.	0.66	0.82
	10.	0.44	0.55
Fractional Factorial Design (P 2.1)	Run	40C130; MET 4 R_a [µm]	40C130; MET 4 R_a [µm]
	1.	0.88	0.88
	2.	0.51	0.51
	3.	0.40	0.40
	4.	0.52	0.52
	5.	0.77	0.77
	6.	0.69	0.69
	7.	0.59	0.59
	8.	0.37	0.37
	9.	0.55	0.55
	10.	0.59	0.59
	11.	0.58	0.58
	12.	0.57	0.57

Thus, the experimentally obtained values, the ones that are considered for regression analysis, are shown in Table 5.

3.2 Statistic Modeling

There has been carried out regression analysis and, when using REGS program, the specific calculated parameters were, as follows:

- regression coefficients values;
- significance quantifiers (show if the independent studied variable has significant influence on the output);
- adequacy quantifier (shows if the model is adequate).

All of above mentioned obtained values are presented in Table 6.

So, there were obtained the statistic model, of grinded surface roughness metallized coatings for:

- 40C130 sprayed material

$$R_a = 33.549 \cdot v_p^{-0.540} \cdot s_l^{-0.704} \cdot s_t^{0.200} \text{ [µm]} \quad (5)$$

- MET 4 sprayed material

$$R_a = 11.978 \cdot v_p^{-0.432} \cdot s_l^{-0.516} \cdot s_t^{0.078} \text{ [µm]} \quad (6)$$

For the independent variable, x_j, having significant influence on the dependent variable, y, it is necessary that its significance quantifier, R_j, has a value that, at least, equals 1.00.

As noticed, from Table 6, the significance quantifier for transversal speed, s_t, has value lower than 1.00 which means that this controllable input does not significantly influence the surface roughness values.

Based on the above, it has been considered useful further research on the influence of the other two controllable inputs, part rotational speed, v_p, and longitudinal feed speed, s_l, on the output variable, surface roughness, R_a.

The regression analysis was done with DOE Kiss software, and the obtained results, for both 40C130 and MET 4, are presented in Figure 8.

The statistic models are as follows, for:

- 40C130 sprayed material

$$R_a = 0.536 - 0.060x_1 - 0.122x_2 + 0.033x_1x_2 + - 0.018x_1^2 + 0.017x_2^2 \quad (7)$$

- MET 4 sprayed material

$$R_a = 0.671 - 0.072x_1 - 0.150x_2 + 0.033x_1x_2 + - 0.028x_1^2 + 0.017x_2^2 \quad (8)$$

where: $x_1 = 2\frac{v_p - 14.8}{6.6}$; $x_2 = 2\frac{s_l - 18}{12}$ (9)

Table 6

REGS – regression analysis results

40C130			
Regression Coefficients			
a_0	a_1	a_2	a_3
3.513	-0.540	-0.704	0.200
Significance Quantifiers			
R_0	R_1	R_2	R_3
89.500	1.800	7.130	0.840
Adequacy Quantifier , R^*			
0.973			
q_j Quantifier			
	$q_{v_p} = \left(\frac{v_{p\max}}{v_{p\min}}\right)^{a_1}$	$q_{s_l} = \left(\frac{s_{l\max}}{s_{l\min}}\right)^{a_2}$	$q_{s_t} = \left(\frac{s_{t\max}}{s_{t\min}}\right)^{a_3}$
	0.783	0.614	1.182
MET 4			
Regression Coefficients			
a_0	a_1	a_2	a_3
2.483	-0.432	-0.516	0.078
Significance Quantifiers			
R_0	R_1	R_2	R_3
38.000	1.207	4.230	0.140
Adequacy Quantifier , R^*			
0.968			
q_j Quantifier			
	$q_{v_p} = \left(\frac{v_{p\max}}{v_{p\min}}\right)^{a_1}$	$q_{s_l} = \left(\frac{s_{l\max}}{s_{l\min}}\right)^{a_2}$	$q_{s_t} = \left(\frac{s_{t\max}}{s_{t\min}}\right)^{a_3}$
	0.822	0.699	1.067

Obs.:

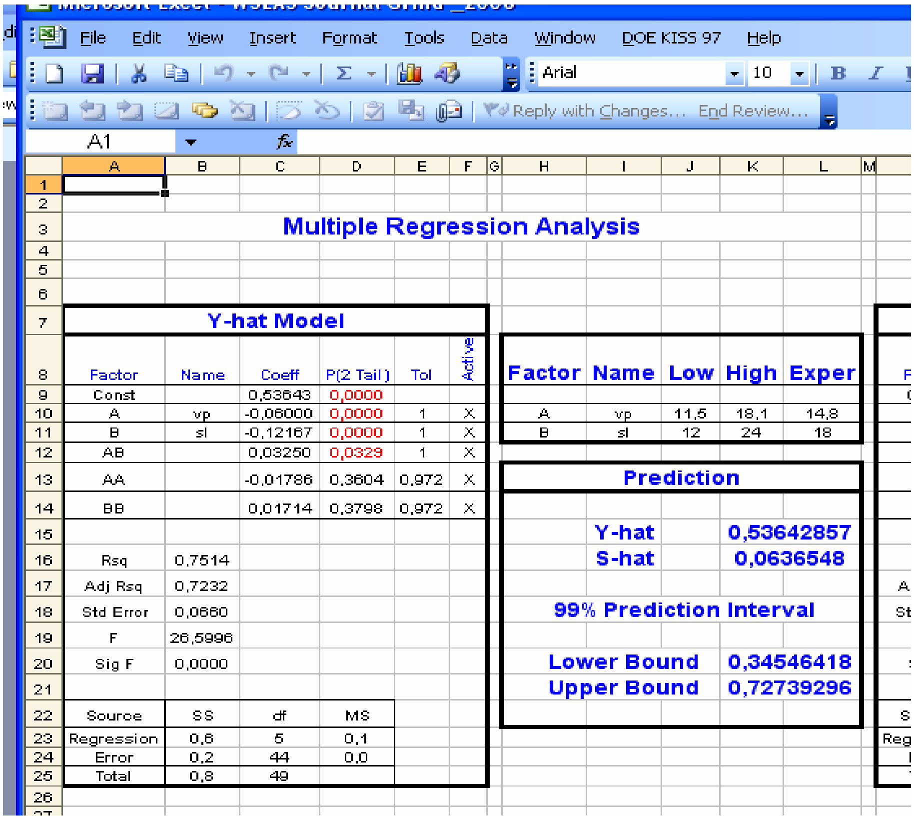
1. A factor is considered to have significant influence on the output as long as the P (2 Tail) value is less. or equal, to 0,05.
2. The second order factors of the input variables, v_p^2 and s_l^2, do not have significant influence on R_a parameter.
3. Based on the above, the relationships (7) and (8) turn into:

$$R_a = 1.624 - 0.049v_p - 0.045s_l + 0.002v_ps_l \text{ [µm]} \quad (10)$$

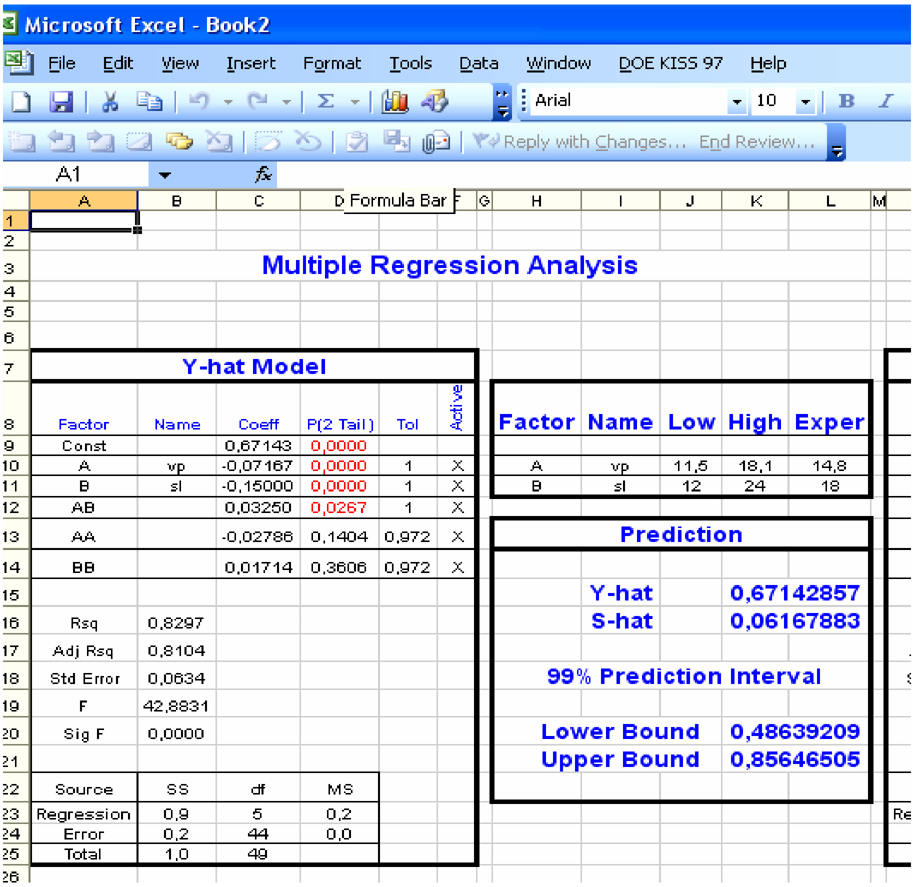
and, respectively,

$$R_a = 1.77 - 0.043v_p - 0.044s_l + 0.001v_ps_l \text{ [µm]} \quad (11)$$

Using DOE KISS, it can be plotted the Pareto Chart of coefficients, that points the influence of input variables, on the output variable is.



40C130 sprayed material



MET 4 sprayed material

Fig. 8 DOE KISS -regression analysis results

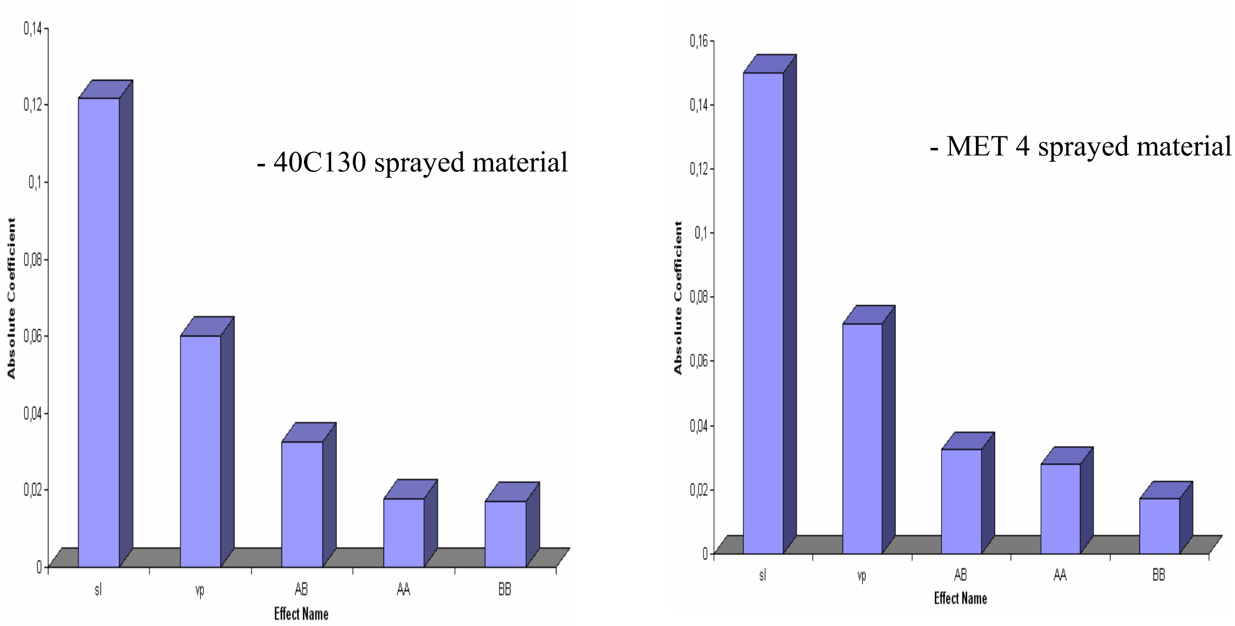
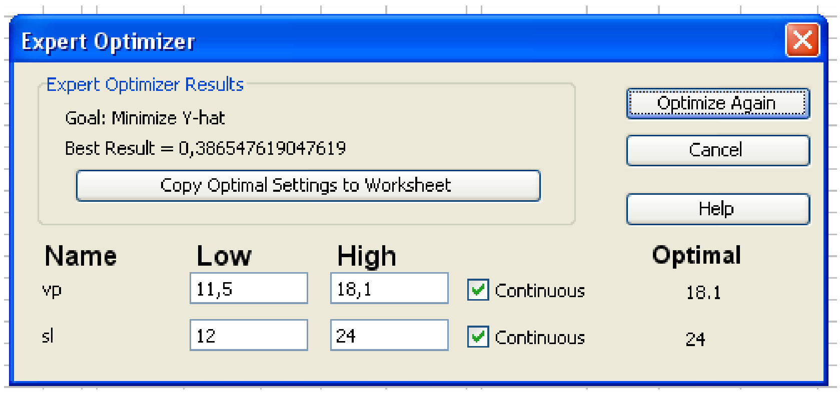


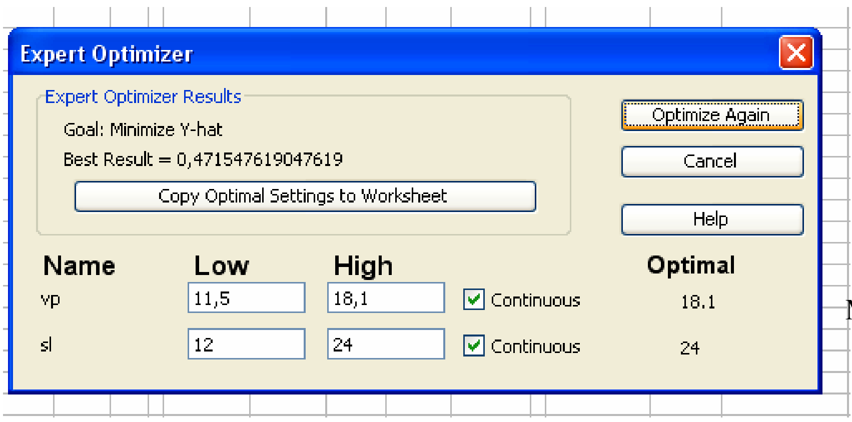
Fig. 9 Pareto chart of coefficients

It considers, both, each independent variable and their reciprocal interactions for their influences on the dependent variable – see Figure 9.

This software, DOE KISS, also provides an Expert Optimizer – see Figure 10, that sets the input values as to minimize exit value



40C130 sprayed material



MET 4 sprayed material

Fig. 10 Expert optimizer

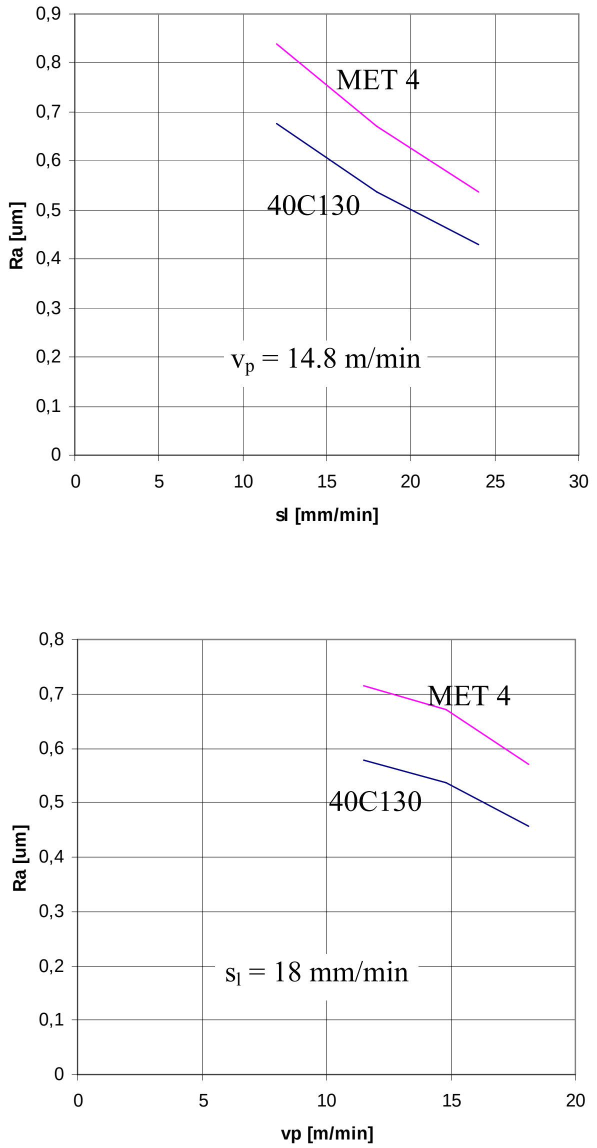


Fig. 12 Graphs of surface roughness, R_a ,variation on grinding machining parameters

Some graphs, corresponding to models determined by relations (10) and (11) are presented in Figure 11.

Studying the real situations, as well as the experimentally obtained results, it has been considered of interest to statistically determine, *if*, the sprayed material characteristics, do influence surface roughness. Because one important sprayed coating characteristics is represented by their hardness, this one was considered as another independent variable, in statistical determining the mathematical model of R_a surface roughness parameter.

Table 7

REGS – regression analysis results

40C130 and MET 4				
Regression Coefficients				
a_0	a_1	a_2	a_3	a_4
5.150	-0.459	-0.680	0.104	-0.349
Significance Quantifiers				
R_0	R_1	R_2	R_3	R_4
244.620	4.920	25.230	0.860	7.180
Adequacy Quantifier , R^*				
0.955				
q_j Quantifier				
$q_{v_p}=\left(\frac{v_{p\max}}{v_{p\min}}\right)^{a_1}$	$q_{s_l}=\left(\frac{s_{l\max}}{s_{l\min}}\right)^{a_2}$	$q_{s_t}=\left(\frac{s_{t\max}}{s_{t\min}}\right)^{a_3}$	$q_{HV}=\left(\frac{HV_{\max}}{HV_{\min}}\right)^{a_4}$	
0.812	0.624	1.091	0.771	

So, experiments were carried out, using the P2.1 Full Factorial Design (see Table 2), the results obtained (see Table 5) and statistically analyzed – with REGS program. – see Table 7.

The statistical model determined is:

$$R_a = 172.431 \cdot v_p^{-0.459} \cdot s_l^{-0.680} \cdot s_t^{0.104} \cdot HV^{-0.349} \quad [\mu m] \quad (12)$$

and, knowing that an image is much more suggestive than 1,000 words, there are presented some graphs of R_a parameter variation – see Figure 13 and Figure 14.

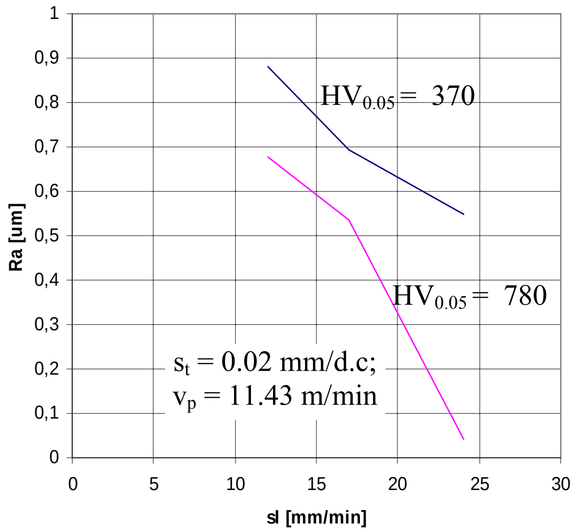


Fig. 13 Graphs of surface roughness, R_a ,variation on grinding machining parameters, HV hardness considered

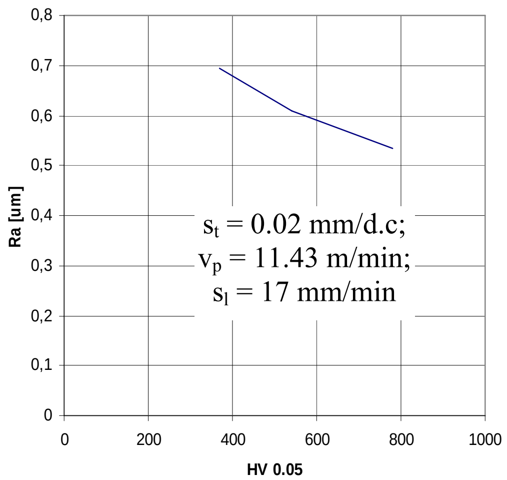


Fig. 14 Graphs of surface roughness variation on sprayed coating's HV $_{0.05}$ hardness

4 Conclusion

Thermal spraying process, the properties of the metallized coatings, their machining process and the quality of the final structure, thus obtained, are submitted to a continuous scientific and technological research.

One important machining procedure, usually used in order to obtain part's specified geometrical precision characteristics, is grinding. In order to study the quality of these multilayer structures, referring to surface roughness after grinding, there have been determined multivariable regression [1] functions. They were obtained by using special theoretical and experimental research programs. The variation range and values of independent variables [3] considered were precisely established.

Regression analysis, performed with REGS program, pointed out that all statistical models were adequate and, the strongest influence on surface roughness was that of longitudinal speed feed, s_l. The variable that did not significantly influence the R_a parameter was the transversal speed, s_t

Regression analysis, performed with DOE KISS software, considered only the two most important variable that influence R_a parameter, as it resulted from REGS regression analysis. This DOE KISS software showed the adequacy of statistical obtained models and the influence on surface roughness of the studied variables, as well as one of their interactions. For, both, materials studied, the statistic models were similar, meaning there were the same factors that did, significantly, influence grinded surface roughness values.

As anticipated, from experience, the greatest influence was that of *longitudinal feed speed,* s_l. When studying the micro-hardness metallized layer characteristic, it proved out (from regression analysis) that it is a variable with high influence on R_a parameter values, the second, as importance.

One major *deficiency* of the determined regression functions is their limited application only to the studied metallized coating, 40C130 / MET 4 and grinding wheel couple. Also, the adequacy of regression models results is "guaranteed", for the values of independent variables within the considered variation ranges but, it also, can be used for values "not so far" do the limits considered

Maybe, the most important application of the determined statistic models is ***their future application to an automated active control system***.

It means that, once settled the input variables values, the grinded coating surface roughness is permanently measured and, if, its values are not the expected one, by a feed-back loop, there should be a command to the grinding machine systems. As result, either the longitudinal feed speed, s_l , or part rotational speed, v_p, would be adjusted so that, the optimum R_a parameter values, of the grinded coatings could be obtained.

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