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STATISTIC MODELS OF CUTTING TOOL DURABILITY FUNCTION IN TURNING 40C130 THERMAL SPRAY COATINGS

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Straturile obţinute prin pulverizare termică sunt utilizate pe scară largă în industrie, datorită caracteristicilor deosebite pe care le au. Generarea acestora se realizează printr-un proces de pulverizare termică care, de cele mai multe ori, este urmat de prelucrarea prin aşchiere a structurii metalice multistrat astfel obţinute. Unul dintre cele mai utilizte procedee de prelucrare îl reprezintă strunjirea, astfel încât este util să se cunoască influenţa parametrilor de prelucrare asupra durabilităţii sculei aşchietoare.

Lucrarea prezintă etapele şi rezultatele cercetărilor realizate în scopul determinării unor modele statistice pentru funcţia durabilitate sculă aşchietoare – la strunjirea metalului pulverizat termic 40C130 .

Thermal spray coatings are widely used in industry because of their various and good characteristics. In order to generate them, there has to be a metallizing process that, usually, is followed by machining of the multilayer metallic structure thus obtained. One of the commonly used machinig procedure is represented by turning so, the influence of machining parameters on cutting tool's durability is worth to be known.

This paper presents the stages and results of researches carried out in order to determine statistic models for durability function – in turning sprayed 40C130 .

Key words: thermal spray, coatings, durability, experiments, regression function

1. Introduction

Metallizing process consists of [1] spraying molten metal onto a surface, to form a coating. The material, being pure or alloyed metal, is melted in a flame and atomized, by a blast of compressed air, into fine spray; this spray builds up onto a previously prepared surface to form a solid metal coating.

So, in order to obtain thermal spray layers, there have to be an energy source for heating powder or wire form material to a molten or near-molten state and a gas to propel the material toward the target substrate (of the workpiece) – see figure 1.

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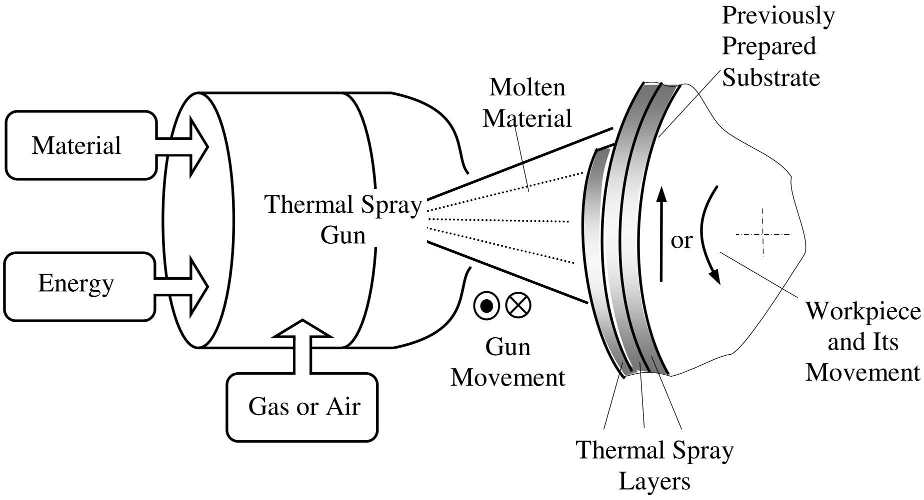


Fig. 1. Scheme of the Thermal Spray Process

The thermal sprayed material is a new metallurgical material with physical properties different than the original metal, and its structure is a multilayer one, with lenticular or lamellar grains.

The kinetic energy of material's molten particles is, usually, generated by air and so, the metallizing process occurs in normal atmospheric conditions, where chemical interactions appear. There are oxides and, less, carbides inclusions outlining the grain of particle boundaries and, that is why, the thermal spray coatings are very hard.

If metallizing is used for building up worn parts, usually, after spraying, the coatings need to be machined – by turning or/and grinding. It is very important [1] the particles to be cleanly sheared, without plucking them out of the coating and without drawing them in such a way as to produce "feathers".

There are very poor data regarding machinability of thermal spray coatings, presented by references. Most of them are *qualitative*, referring to values range of machining parameters (speed surface, feed, depth) and cutting tools' type and characteristics. Interdependence relations of coating characteristics on machining parameters are seldom presented. Also, one can notice that there are very few studies on Romanian thermal spray materials [4], most of them referring to materials produced (and machined) by famous UK producers – such as METCO.

Based on the above mentioned aspects, it has been considered necessary to determine some dependence relations concerning characteristics of machined thermal spray coatings, obtained from Romanian materials, and parameters of machining technological system involved.

This paper presents the way there were determined two dependence statistical models of cutting tool's durability on turning parameters (cutting speed, cutting feed, cutting depth).

2.Design of Experiments

Optimum characteristics in machining thermal spray coatings can be obtained if there are *quantitative data*, which should be expressed [2] as multivariable function.

Thus, a process occurring into a certain technological system, is defined by variables connected through relation as:

$$Y = \Gamma\left(x_1, x_2, \ldots, x_j, \ldots, x_n\right) \tag{1}$$

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.

The purpose is to determine optimum Γ so, there must be established the values and variation field of each input, as well as the experiments' structure that fits best.

Thus, there were studied *controllable inputs*, x_i, such as: *machining time* (T [min]) and *cutting parameters* - *speed* (v [m/min]), *feed* (s [mm/rev]), *depth* (t [mm])

Constant inputs were considered to be *environment characteristics* (temperature, humidity) and *cutting tool* (CT – metallic carbides Romanian tools, conventionally called K30) *characteristics* - *nose radius*, r [mm];

Uncontrollable (noise) inputs were *Vickers micro-toughness* ($HV_{0,05}$) of the electric arc thermal sprayed 40C130 and *vibrations of the technological system* - at constant speed exterior cylindrical rough turning, on SN 500×1500 lathe.

The measured values of the *output*, Y, were *cutting tool's wear* – VB parameter [mm] and, consequently, *cutting tool's durability* - T [min]

In order to determine Γ type of dependence there were considered, the real and coded values of controllable inputs. These are presented in table 1.

There have been studied two types of experiment designs – a fractional factorial three level design (with 6 runs) [2], [3] and a full factorial two level design (with 8 runs) [5] – see table 2.

Table 1

Coded and real values of the controllable inputs, x_j

v [m/min]			s [mm/rev]			t [mm]		
(-1)	(0)	(1)	(-1)	(0)	(1)	(-1)	(0)	(1)
10	17.3	30	0.10	0.14	0.20	0.30	0.42	0.60

Table 2

Experiment Designs

Fractional Factorial Design (P1.2)	Run	x_1	x_2	x_3	Full Factorial Design	Run	x_1	x_2	x_3
	1.	+1	-1	-1		1.	-1	-1	-1
	2.	-1	+1	-1		2.	-1	-1	+1
	3.	-1	-1	+1		3.	-1	+1	-1
	4.	+1	+1	+1		4.	-1	+1	+1
	5.	0	0	0		5.	+1	-1	-1
	6.	0	0	0		6.	+1	-1	+1
						7.	+1	+1	-1
						8.	+1	+1	+1

3. Statistic Models

In order to determine durability function, first, there had to be determined cutting tool *wear function*, that represents the dependence of cutting tool's wear on machining time:

$$VB = a + b \cdot T + c \cdot T^2 + d \cdot T^3 \tag{2}$$

where: VB is the cutting tool wear parameter, [mm];
T – machining time, [min].

So, for each experience of the program, the samples were continuously machined. At convenient time intervals, $[0, T_1]$, $(T_1, T_2]$, ..., $(T_{f-1}, T_f]$, the VB parameter was measured - T_f value represents the machining time close to the moment when catastrophic wear occurs.

With CurveExpert 1.3 program and the experimental data obtained [3], there have been plotted the *cutting tool wear curve* and determined the *regression polynomial third order function*.

An image of the cutting tool's wear is presented in figure 2, while an example of the regression function curve, as well its statistic model are presented in figure 3 – for run 1, fractional factorial design.

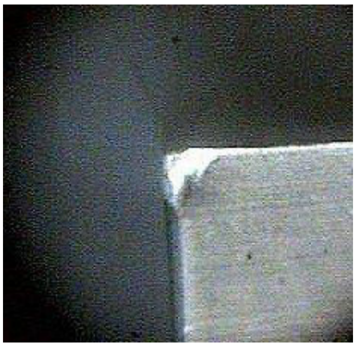
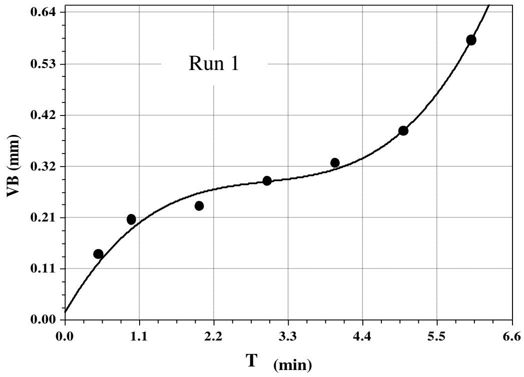


Fig. 2. Wear of cutting tool – in rough turning of 40C130



$$VB = 0.0153 + 0.2428 \cdot T - 0.0768 \cdot T^2 + 0.0087 \cdot T^3$$

Standard error, $\sigma = 0.02097$
Correlation coefficient, $R = 0.99578$

Fig. 3. Cutting tool wear – regression function

Cutting tool *durability (life time) function* represents the dependence relation of cutting tool's durability on the influencing factors (v, s, t, etc.).

Based on the cutting tool wear regression functions, for each experience of the experimental program there were determined the values of T - representing the time while the durability criterion is reached (VB = 0,4 mm – in rough turning).

These, T, values, are considered to be the Y (output) for each of the regression programs used.

The software for regression analysis are REGS [3] – for fractional factorial design, and DOE KISS [5] – for full factorial design and the number of replicates is 3, for both of them.

The medium values (y-hat) of cutting tool durability, T [min], obtained in each designed experiment type run are presented in table 3.

Table 3

Experimental data – cutting tool durability, T [min]
medium values [y-hat]

Designed experiment	Run							
Fractional Factorial Design P(1.2)	1	2	3	4	5	6		
	5.050	7.480	6.120	3.080	4.920	5.180		
Full Factorial Design	1	2	3	4	5	6	7	8
	7.640	6.470	7.500	4.430	5.200	4.970	4.980	3.430

The regression function determined with DOE KISS is polynomial type:

$$Y = a_0 + \sum_{i=1}^{k} a_i z_i + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} a_{ij} z_i z_j + \sum_{i=1}^{k} a_{ii} z_i^2 \tag{3}$$

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

$$Y = A_0 x_1^{A_1} x_2^{A_2} x_3^{A_3} \tag{4}$$

which, by logarithm, are similar to (3) but, that there are, only, first order polynomial factors, with no interactions or second order ones included.

The results obtained by regression analysis, with *REGS program*, are presented in table 4, where:

$$\begin{gathered} a_0 = \ln A_0, \quad a_i = A_i \ (i = 1,2,3) \\ x_1 = v, \quad x_2 = s, \quad x_3 = t \quad \text{and} \quad Y = T \end{gathered} \tag{5}$$

Table 4

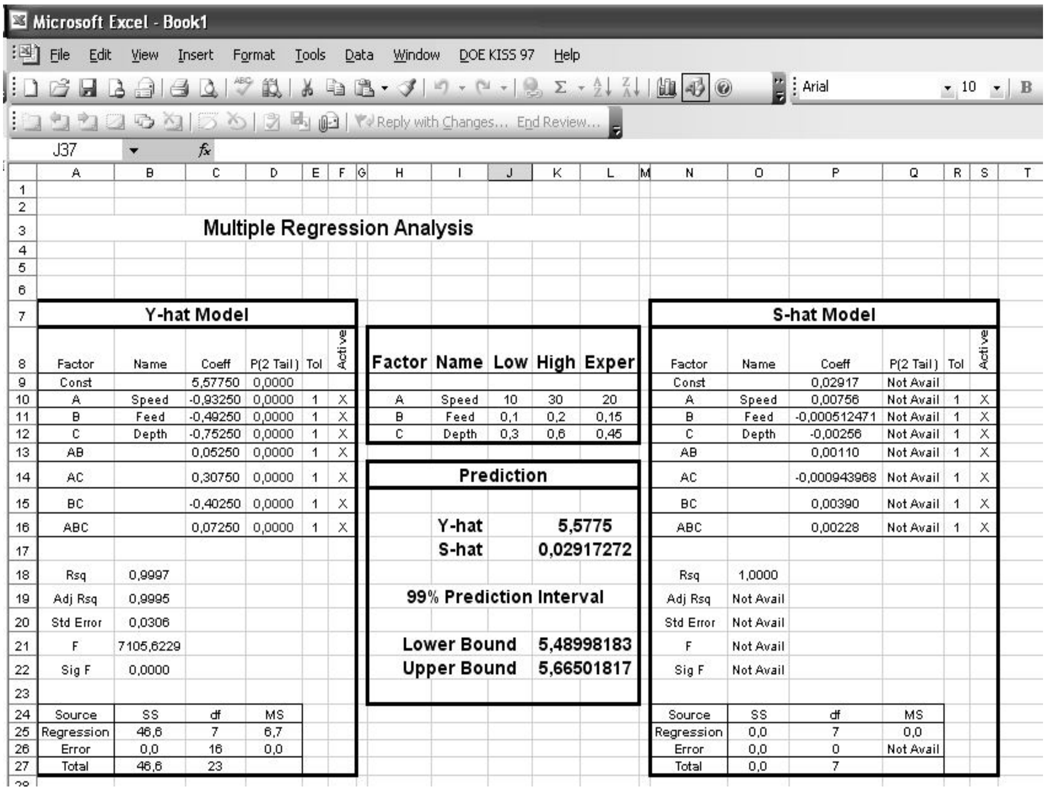
REGS – regression analysis

Regression Coefficients			
a_0	a_1	a_2	a_3
2,191	-0.491	-0.212	-0.501
Significance Quantifiers			
R_0	R_1	R_2	R_3
853.260	15.510	1.150	6.430
Adequacy Quantifier , R^*			
0.003			

Thus, statistical model for cutting tool durability is:

$$T = e^{A_0} v^{A_1} s^{A_2} t^{A_3} = 8.944 \cdot v^{-0.491} \cdot s^{-0.212} \cdot t^{-0.501} \tag{6}$$

The analysis' results for full factorial design, using *DOE KISS software*, are presented in fig. 4.



Multiple Regression Analysis

Y-hat Model

Factor	Name	Coeff	P(2 Tail)	Tol	Active
Const		5,57750	0,0000		
A	Speed	-0,93250	0,0000	1	X
B	Feed	-0,49250	0,0000	1	X
C	Depth	-0,75250	0,0000	1	X
AB		0,05250	0,0000	1	X
AC		0,30750	0,0000	1	X
BC		-0,40250	0,0000	1	X
ABC		0,07250	0,0000	1	X

Rsq	0,9997
Adj Rsq	0,9995
Std Error	0,0306
F	7105,6229
Sig F	0,0000

Source	SS	df	MS
Regression	46,6	7	6,7
Error	0,0	16	0,0
Total	46,6	23	

Factor	Name	Low	High	Exper
A	Speed	10	30	20
B	Feed	0,1	0,2	0,15
C	Depth	0,3	0,6	0,45

Prediction

Y-hat	5,5775
S-hat	0,02917272

99% Prediction Interval

Lower Bound	5,48998183
Upper Bound	5,66501817

S-hat Model

Factor	Name	Coeff	P(2 Tail)	Tol	Active
Const		0,02917	Not Avail		
A	Speed	0,00756	Not Avail	1	X
B	Feed	-0,000512471	Not Avail	1	X
C	Depth	-0,00256	Not Avail	1	X
AB		0,00110	Not Avail	1	X
AC		-0,000943968	Not Avail	1	X
BC		0,00390	Not Avail	1	X
ABC		0,00228	Not Avail	1	X

Rsq	1,0000
Adj Rsq	Not Avail
Std Error	Not Avail
F	Not Avail
Sig F	Not Avail

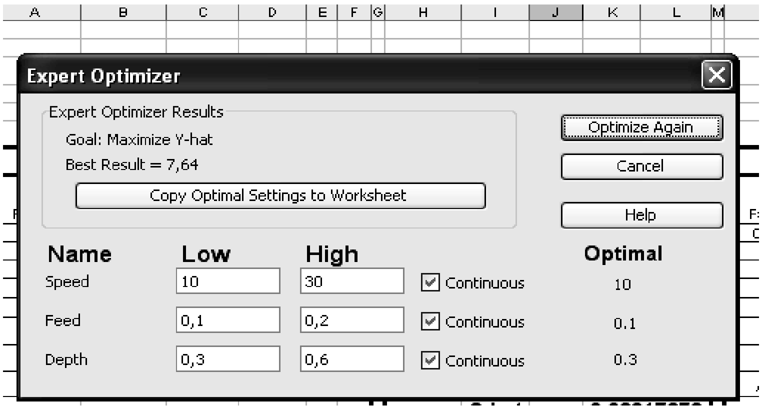
Source	SS	df	MS
Regression	0,0	7	0,0
Error	0,0	0	Not Avail
Total	0,0	7	

Fig. 4. Regression analysis results – performed with DOE KISS software

Thus, statistical model for cutting tool durability is:

$$\begin{aligned} T &= 5.5775 - 0.9325 \cdot v - 0.4925 \cdot s - 0.7525 \cdot t + 0.0525 \cdot vs + \\ &\quad + 0.3075 \cdot vt - 0.4025 \cdot st + 0.0725 \cdot vst \end{aligned} \tag{7}$$

DOE KISS, also provides an Expert Optimizer which sets the input values (for two factors with greatest influence), as to maximize T values. The results are shown in figure 5.



Expert Optimizer Results

Goal: Maximize Y-hat

Best Result = 7,64

Name	Low	High		Optimal
Speed	10	30	☑ Continuous	10
Feed	0,1	0,2	☑ Continuous	0.1
Depth	0,3	0,6	☑ Continuous	0.3

Fig. 5. DOE KISS software – optimized values of inputs, so as to maximize the output

4. Conclusion

The statistic models determined for cutting tool durability function are adequate. For both, fractional factorial design and full factorial design, all controllable inputs considered – cutting speed (v), feed (s) and depth (t) have significant influence on output – durability (T) ; the decreasing order of influence being v, t, s.

The full factorial design, whose regression analysis was performed by DOE KISS software, points out the effect of interactions – meaning second and third order factors.

The obtained models can be used to determine optimum values for machining parameters so as to obtain the maximum durability of the cutting tool. There, also, can be determined the expression of optimum cutting speed- v_{T_o} [m/min], by extracting the v variable from the mathematic relationship.

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