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RESEARCH

Influence of Coating Chemical Composition and Thickness Layer on the Wear Behavior of Cutting Tools a Business Analytics Approach

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ABSTRACT

The present work analyzed the effect of coating chemical composition and thickness layer over the wear behavior of cutting tools intended for the manufacture of steel molds for injection of various materials. A business analytics approach using design of experiments was implemented to optimize wear measurements taking into account the coating variables as well as the manufacturing cost involved. Confirmatory tests carried out on real manufacturing conditions showed a wear reduction of up to 5.7 times while achieving a minimum cost of coating.

1. INTRODUCTION

In the metal-mechanic tooling industry, the efforts to optimize tooling efficiency are defined by the triad: a) minimum manufacturing costs, b) longer useful life related to minimizing wear, and c) lower energy consumption related to coefficient of friction (COF) [1]. In machining processes, the costs associated with tooling are greater than 35 % of the total production costs and this is where most of the studies found in the literature are aimed [1]. In this regard, efforts have been made for more than five decades targeting the application of tool coatings [2,3] to reduce COF and tool wear, thereby increasing their useful life [4-6]. These technologies have evolved in such a way that the application of layers of a few microns has shown a significant influence on the tribological properties mentioned previously, along with a positive economic impact. More recently the use of multilayers has opened a wide range of possibilities for improvement with the use of materials such as: aluminum, titanium and chromium [7-9].

On the other hand, an accelerated way to save resources for the research and development of new combinations of coatings is the use of specialized tribometers performing tests under standardized conditions such as ASTM G77-98 [10]. It is important to try to simulate the parameters of the real process in the tribometers such as the spatial configuration (contact type), contact pressures, speed, type of lubrication and the materials to be used. Controlling these variables and bringing them as close as possible to the real process ensures a pilot phase with a high probability of success. Furthermore, this reduces testing time with a certainty of success above 95 % [11].

The contribution of this work is related to the analysis of new combinations of coating layers (see table 1) materials such as nitrides of Ti, Al, and Cr and thicknesses of layers (ranging from 3 to 5 μm) to increase the useful life (wear reduction) of the cutting tools used in the machining process of steel molds taking into consideration the layer cost.

2. EXPERIMENTAL METHODS AND MATERIALS

2.1 Experimental Methods

Figure 1 presents the methodology used in this work, showing the chronological steps followed from the selection of the materials through the statistical analysis taking into account the pilot test and the business optimization at the manufacturing floor.

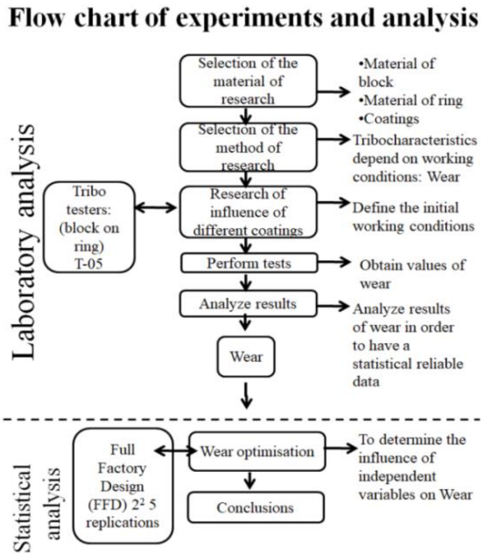

Fig. 1. Research Methodology.

The column on the left represents the tools used, the central column the chronological steps and the column on the right the outputs of each step.

2.2 Materials

The most commonly used materials for the manufacture of coatings are nitrides of Al, Ti and Cr [7,8], thus new combinations of material percentages and layer thicknesses were proposed (85/15) according to maximum and minimum processing capacity of the coating chamber. Four types of coatings were used, all of them with multilayers of varying thicknesses according Table 1 using a Physical Vapor Deposition (PVD) technology chamber. Coatings were performed by Oerlikon Balzers.

The following steps were performed in order to deposit the coatings. First the surfaces were cleaned using an alkaline liquid bath, then the samples were loaded on the coating chamber. Finally two coating layers were applied, first the layers with Al and Ti targets were set on the coating chamber with preset proportions, vacuum is applied and a controlled Nitrogen atmosphere is deployed. Then, the second layer was applied now with an Al and Cr targets.

Table 1. Layer thickness and chemical composition.

Coating ID	Materials % Coating on Layer 1	Materials % Coating on Layer 2	Total thickness of coating layer (μm)
R1	TiAlN (50/50)	AlCrN (70/30)	3
R2	TiAlN (50/50)	AlCrN (70/30)	4
R3	TiAlN (85/15)	AlCrN (70/30)	3
R8	TiAlN (85/15)	AlCrN (70/30)	4

Cermet cutting tools used during this study were made of a 10 % Cobalt (Co) and 90 % Tungsten carbide (WC). This material shows a 92 HRA Hardness with a minimum transverse rupture strength (TRS) of 500,000 psi; mechanical properties of the material were certified by tungsten carbide supplier according to ANSI C-2/10 classification.

3. WEAR TESTING

3.1 Laboratory tests

Wear testing was carried out on T-05 tribotester with block-on-ring in non-conformal spatial configuration according to Fig. 2. T-05 tribotester meets test standards: ASTM D 2881, ASTM D 3704, ASTM D 2714, and ASTM G77 [10].

The wear tests consisted on a stationary block (made of inconel 718 and coated) mounted on a ring (D2 steel as shown on Fig. 2) that rotates while subjected to a constant load of 300 N. The speed of the ring was kept constant at 270 rpm for the duration of the test (3,000 seconds). The wear delta is measured for each test, which is the vertical linear decrease of both the block and ring materials (Fig. 3). The resolution of the wear measurement is up to 0.1 µm.

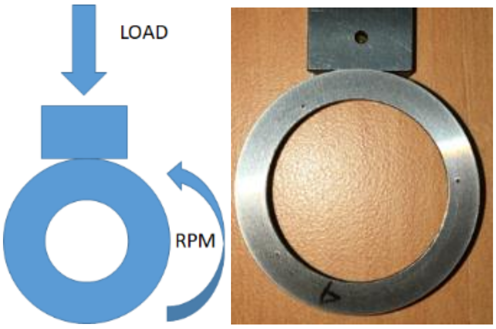

Fig. 2. Block (coated) on ring tribotester and type of contact.

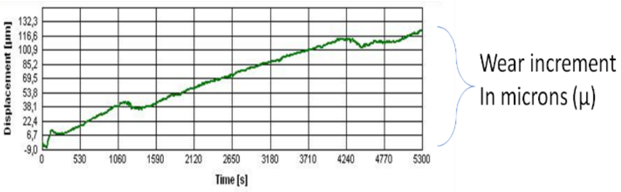

Fig. 3. Wear measurement on tribotester.

For each combination, between 3 and 5 tests were done in order to have reliability in the data according to the DIXON statistical test [11].

3.2 Experimentation on real manufacturing conditions

For the field test, conventional cutting tools were used with the coatings combinations as shown in Table 1. To measure the tooling wear a 3D surface analyzer Alicona Edge Master was used. The analyzed wear area is 2x2 mm and the resolution of the wear measurement could be up to nm. The increase in the radius (µm) of the cutting edge of the tool was taken as the wear measurement according to Fig. 4. Five replicates per combination were set in order to achieve significant degrees of freedom for the statistical tools used.

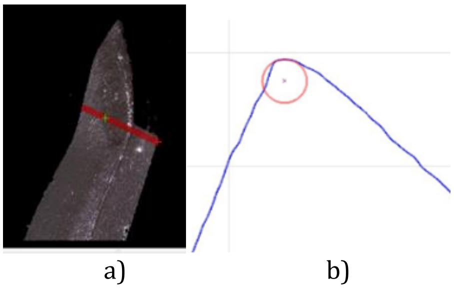
a) b)

Fig. 4. Measurement of tool wear in: a) 3D, and b) 2D.

4. LABORATORY RESULTS

The average wear results of the laboratory tests are shown in Fig. 5. The total amount of wear includes the contribution of both elements (block and ring) as a tribosystem. In this figure an important influence of the coating is suggested since the difference between (R1, R2, R3 and R4 was dramatically reduced in comparison with the sample without coating), but it is not clear (since we are only taking into account averages over controlled laboratory conditions) to determine the influence of the four coating combinations over the wear behavior.

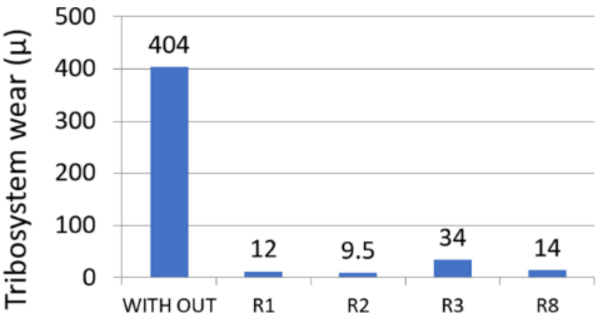

Fig. 5. Wear measurement on tribotester for researched coatings combinations.

5. FULL SCALE MANUFACTURING EXPERIMENTAL DESIGN

All statistical methodologies described in this section can be referred to [12-15]. In addition, all statistical analysis will be carried out at α = 0.05 significance level.

Following the results from the laboratory, in this section it will be analyzed the statistical influence between the output variable tool wear (w), measured in µm over the radius of the cutting edge (as seen on Fig. 4), and the two independent variables: coating thickness (ct) measured in μm, and material composition (mc). Table 2 shows the control variable codification and levels to be explored. This coding is useful to obtain the orthogonal experimentation matrix in order to obtain unbiased parameters.

Table 2. Independent variable coding.

Coating thickness	**ct**
-1	4
+1	3
Material composition	**mc**
-1	TiAl (50 %/50 %)
1	TiAl (85 %/15 %)

Five replicates were selected to obtain enough degrees of freedom in the 2^2 Full Factorial Design (FFD) proposed in Table 3. The order of the experiments was assigned at random as it can be seen in the second column of the table in order to promote response independence as required in [12-15].

Table 3. 2^2 Full Factorial Design and experimentation order.

Experiment number	Order of experiments	mc	ct
1	5	1	1
2	3	1	1
3	15	1	1
4	6	1	1
5	9	1	1
6	10	1	-1
7	1	1	-1
8	5	1	-1
9	14	1	-1
10	4	1	-1
11	3	-1	1
12	11	-1	1
13	1	-1	1
14	5	-1	1
15	10	-1	1
16	8	-1	-1
17	11	-1	-1
18	12	-1	-1
19	16	-1	-1
20	7	-1	-1

Twenty cutting tools were coated according to Table 3. Each tool was used to machine D2 steel on a CNC machine center with operation conditions of: 2000 RPM of spindle, 3.81 cm/ min of speed rate and 0.06 mm of depth; on a steel plate of 90 by 60 cm. Wear measurement was taken as the edge radius of the cutting tool as shown on Fig. 4 using a surface analyzer Alicona EdgeMaster.

6. FULL SCALE STATISTICAL OPTIMIZATION

6.1 The influence of thickness and material composition coating on wear

The purpose of this section is to explore the influence of the two control variables: coating thickness and material composition, in order to find out the combination that produces minimum wear. Design of experiments tools are used as described in [12-15].

Table 4 shows the twenty wear measurements (as explained in 3.2) according to the experimental matrix using the coding from Table 2.

Table 4. Experimental design and response measures.

mc	ct	w (μm)
1	1	37.50
1	1	62.25
1	1	66.25
1	1	313.25
1	1	64.85
1	-1	86.00
1	-1	83.75
1	-1	82.88
1	-1	97.75
1	-1	95.89
-1	1	104.68
-1	1	126.57
-1	1	90.63
-1	1	74.00
-1	1	98.32
-1	-1	80.37
-1	-1	65.50
-1	-1	61.88
-1	-1	93.88
-1	-1	88,82

Table 5. 2^2 FFD initial ANOVA table.

Source of variation	df	Adjusted SC	Adjusted SM	p-value
mc	1	558.8	558.78	0.693
ct	1	2,031.8	2,031.83	0.454
mc x ct	1	1.7	1.75	0.982
Error	16	55,269.0	3,454.31	
Total	23	57,861.3		

Table 5 shows the Analysis of Variance for the 2^2 full factorial design (FFD), notice that the degrees of freedom (df) for the error is above 15 (16 in the table) as suggested by [12,13].

As one can observe from Table 5 mc and the interaction (mc x ct) are not significant. According to [12,13], at most one control variable can be removed at a time (Pooling) from the ANOVA table. So the first candidate to be eliminated is the interaction mc x ct (highest p-value).

Table 6 shows the ANOVA table for the experiment after removing the interaction.

Table 6. 2^2 FFD ANOVA table resulting after pooling out the interaction.

Source of variation	df	Adjusted SC	Adjusted SM	p-value
mc	1	558.8	558.78	0.684
ct	1	2,031.8	2031.83	0.440
Error	17	55,270.7	3251.22	
Total	19	57,861.3		

From Table 6 one can observed that mc is not significant, therefore mc must be pooled out from the analysis.

Table 7 shows the final ANOVA table for the analysis.

Table 7. 2^2 FFD Final ANOVA table.

Source of variation	df	Adjusted SC	Adjusted SM	p-value
ct	1	2,032	2,032	0.429
Error	18	55,830	3,102	
Total	19	57,861		

Table 7 confirms that none of the control variables (coating thickness and material composition) are significant (at the levels tested).

Hence, the four combinations tested have non-significant difference on wear. Thus, the least costly combination is the one to be chosen for production: material at a coating thickness of 3 μm (+1 experimentation level) with a material composition 50 % - 50 % of TiAl (-1 experimentation level).

6.2 The influence of the coating on wear

In this section it will be tested if the coating has a significant effect on wear. Twenty new experimental units with no coating were tested (same criterions than in section 6.1) and compared against the 20 data points in Table 4. Descriptive statistics are shown on Table 8.

Table 8. Test on the influence of the coating over wear.

	Sample size	Average (μm)	Sample std. dev. (μm)
With coating (wc)	20	93.8	55.2
Without coating (nc)	20	535	291
Average wc-nc		-441.3	

Now the differences in wear mean is going to be analyzed by the following hypothesis test (using the data in Table 8):

$$Ho: \mu_{wc} - \mu_{nc} = 0$$

$$Ha: \mu_{wc} - \mu_{nc} \neq 0$$

Using [12] a very low p value was obtained with 20 degrees of freedom, thus one cannot reject that the influence of the layer is significant (Ha) and has an estimate value of a reduction of 441.3 μm on wear. At a five percent significant one can compute the confidence interval of the difference on wear at (-579.5; -303.1).

7. CONCLUSIONS AND FURTHER RESEARCH

As a final conclusion of the experimentation carried out in this work, coating has a significant effect on wear, an average reduction of 441.3 μm versus the no coating version. Four combinations of coating were tested, the statistical analysis lead to the conclusion that the four of them were non significantly different on the wear response. Thus, for production purposes to minimize manufacturing cost one must process the material at a coating thickness of 3 μm (+1 experimentation level) with a material composition 50 % - 50 % of TiAl (-1 experimentation level) since this combination is the least costly.

Hence, the business analytics solution presented does not only minimizes wear but also promotes business competitiveness by achieving minimum variable manufacturing cost.

Further research pends ahead by exploring more materials and coating thicknesses. More manufacturing applications could also be studied beyond wear as COF and temperature.

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