Experimental research methodology for testing DLC-coated milling tools used in machining parts in the aeronautical industry

Nicolae Ioan Pasca [1], Mihai Banica[2], Marius Cosma[3], Nicolae Ungureanu[4], Vasile Nasui[5]*

Abstract: *This paper presents the experimental research methodology used to test milling tools coated with amorphous diamond-like layers (DLC – Diamond-Like Carbon), in order to evaluate their performance in machining processes. The study aims to determine the influence of DLC coating on wear behavior, machining efficiency and surface quality obtained, compared to milling tools. The proposed methodology includes the selection and characterization of milling tools, the definition of machining parameters, the establishment of test conditions and the measurement of output parameters such as surface roughness, durability and tool wear evolution. The experimental results are statistically analyzed to highlight the technological and economic advantages of using DLC coatings in the machining of aluminum alloys. The study contributes to the optimization of milling processes and the extension of tool life.*

Keywords: coating, diamond, experiment, research, tool

1. INTRODUCTION

This paper presents the research methodology of the experiment carried out in the Machining department of Universal Alloy Corporation Europe, testing uncoated and DLC diamond-coated cutting inserts using several different cutting parameters in order to obtain the durability of the cutting inserts. The main objective of this paper is to show the steps of experimental research.

Experimental research plays an essential role in scientific and technological progress, providing a quantitative approach to the investigation of phenomena and processes. The study of any phenomenon involves the use of laws, concepts and parameters related to substance, energy and information [1].

2. STUDY OF SPECIALTY LITERATURE

Rigorous experimental research involves several essential steps, which contribute to the validity and reproducibility of the results obtained:

Hypothesis formulation: a clear, testable hypothesis is formulated, which expresses a prediction regarding the relationship between the variables studied;

- Experiment planning:
  - experimental design: choosing the appropriate type of design;
  - participant selection: defining the target population and establishing the sampling method.
- Experiment execution:
  - manipulation of the independent variable: implementing the experimental treatment or intervention;
  - control of confounder variables: identifying and eliminating external influences that may affect the results;
- Data collection: using appropriate tools and techniques for the precise measurement of dependent variables.
- Data analysis:
  - descriptive statistics: synthesizing the data obtained (e.g. means, standard deviations);
  - inferential statistics: testing hypotheses using appropriate methods (e.g. t-test, ANOVA, linear regression);
- Interpretation of results: the results are analyzed in the context of the formulated hypothesis and the specialized literature, highlighting the theoretical and practical implications;
- Reporting of results: the communication of the conclusions is done in a clear, complete and transparent way, so that the study can be reproduced and validated by other researchers. [2].

Modeling is a fundamental tool in experimental research, providing a theoretical framework necessary for understanding, testing and optimizing complex systems. The main contributions of modeling are:

- Hypothesis formulation and experimental design: mathematical models support the identification of relationships between variables, allowing the formulation of coherent hypotheses and the efficient design of experiments [3];
- Interpretation of experimental data: by correlating the results with theoretical models, it is facilitated the understanding of the observed phenomena and the extraction of knowledge from the experimental data [4];
- Optimization of experimental processes: predictive models contribute to the identification of optimal process parameters, reducing errors and increasing the efficiency of experiments [5];
- Validation and generalization of results: comparing experimental results with model predictions allows their validation and the extension of conclusions to other conditions or scales [6];
- Prediction of system behavior: models offer the possibility to explore the behavior of systems in unexperimental scenarios, without additional laboratory costs [7];
- Identification and control of variability: statistical models help to detect sources of variability and

improve the reproducibility of results [8];
- Reduction of research costs and time: model-based simulations allow to reduce the number of experiments required, saving time, materials and financial resources [9].

The coating of cutting tools plays an essential role in increasing their performance, durability and reliability during machining processes. The main advantages offered by coatings are:
- Increased resistance to wear and abrasion, which extends the life of the tools and reduces the frequency of their replacement, an essential aspect in demanding machining conditions;
- Reduction of friction, which contributes to the reduction of cutting forces and the temperature generated in the contact area, thus improving dimensional accuracy and surface quality;
- Prevention of material accumulation on the cutting edge, through anti-adherence properties, which ensures efficient chip flow and prevents tool blocking;
- Protection against corrosion and oxidation, especially in chemically aggressive environments or in the case of machining non-ferrous metals;
- Improving the quality of machined parts, by obtaining smoother and more uniform surfaces, reducing the need for additional finishing operations [10].

The application of DLC (Diamond-Like Carbon) coating requires rigorous preparation of the cutting tool surface to ensure optimal adhesion and long-lasting performance of the deposited layer. The main stages are:
- Mechanical cleaning – consists of removing residues and oxide from the surface, by methods such as brushing, grinding or sandblasting with abrasive particles;
- Degreasing – elimination of traces of oils, greases or other organic impurities, by washing with solvents or specific degreasing solutions;
- Pickling and activation – depending on the type of material, the surface can be chemically pickled and heat treated to improve the adhesion of the DLC layer;
- Substrate preparation – may include texturing or superficial etching, in order to create microscopic anchors that facilitate the durable fixation of the deposited layer;
- Quality control – visual and technical inspection of the surface is carried out before coating is applied, to eliminate any defects that may affect the final quality of the layer.

Strict adherence to these steps is essential to obtain a high-quality DLC coating, with optimal wear resistance, adhesion and protection properties during processing [11].

3. EXPERIMENT DESCRIPTION

The experiment scheme is shown in Figure 1. The first column shows the required human resources. The center column shows the required machines and the last column shows the required activities. Because the experiment is carried out in a production facility, we had access to all the necessary resources, dedicated people to operate each necessary machine.

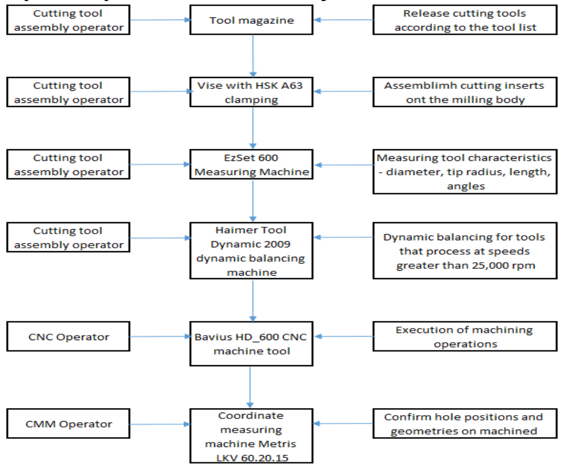

Fig. 1 Experiment scheme

The experiment begins by mounting the cutting inserts on the cutter body, after which the cutter is placed in the machine tool spindle. The durability is counted by the machine tool software and appears on the control panel under the cutting tool details. The durability is counted only while the program is working with feedrate. The cutting inserts are visually monitored after each part is machined.

The machine tool post-processor allows checking the cutting tool in the magazine while another tool is in the spindle. After it is found during the visual check that the inserts are worn, the durability obtained is noted on the form related to the insert set and the inserts are rotated to machine with the second corner. After they are worn on both sides, the inserts are taken to measure the wear and defects that have occurred. The loads on the spindle and the acoustic emissions obtained will be recorded in the form accompanying the cutting inserts. The roughness R_a will be measured in 4 critical areas and the values will be recorded in an Excel file. The 4 areas are shown in Figure 2.

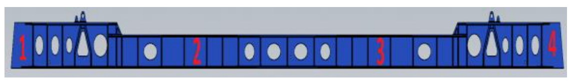

Fig. 2 Critical areas for roughness measurement

Given that the experiment is carried out under serial processing conditions, dimensional verification of the parts is required, which is carried out according to the dimensions given for measurement in the measurement sheet.

4. EXPERIMENT FORMULATION

The plan for the experiment presented in this paper is as follows:

4.1 Operational definitions

Durability: is the period of time between two consecutive resharpenings. It is denoted by „T" and

measured in minutes. [12]
DLC coating: is a thin layer of amorphous carbon deposited on the active surface of a tool used in machining, which partially mimics the properties of diamond [13].
Roughness: the irregularities that form the microgeometry of the machined surfaces.
Cutting tool wear: is the progressive process of deterioration of the cutting edge and the contact surfaces of the tool, caused by mechanical, thermal and chemical interaction with the machined material during the cutting process [14].

4.2 Input data

To carry out the experiment, the known data are:
- Material: profiles obtained by extrusion. Aluminum alloys: 2196 T8511, 2099 T83 and 2043 T83;
- Cutting tool: the cutter body (tool holder) has HSK 63-A clamping. On it, 3 cutting inserts XDHT150440R-U11-HP665-P are assembled using M4x7.8-TX15-IP fixing screws as shown in Figure 3;

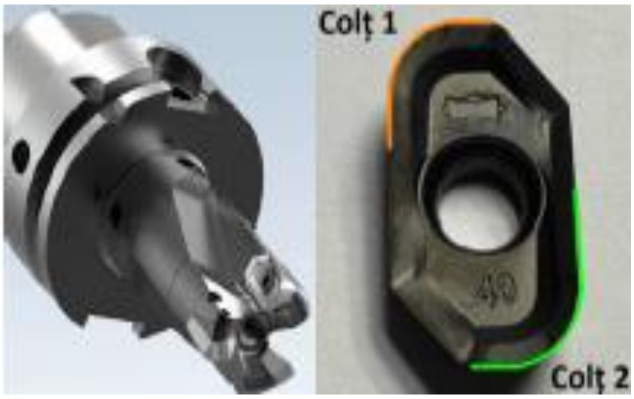

Fig. 3 Tool-holder assembly [15]

- Parameters used: 3 different parameters will be used to investigate tool durability using several variables:
  - S=28000 [rot/min], V_f=14000 [mm/min], f_z=0.167 [mm/rot];
  - S=28000 [rot/min], V_f=19000 [mm/min], f_z=0.226 [mm/rot];
  - S=27000 [rot/min], V_f=16200 [mm/min], f_z=0.2 [mm/rot], where:

  S – spindle speed;
  V_f – feed rate;
  f_z – feed per tooth.
- Type of cutting inserts: uncoated inserts and DLC coated inserts.

4.3 Simplifying assumptions

- The durability of DLC coated inserts is higher than that of uncoated inserts.
- Using the parameter f_z=0.226 mm/rot will imply higher spindle loads and, implicitly, higher insert wear.

4.4 Data collection form

The form contains data about:
- Insert set number;
- Milling cutter equip date;
- Durability obtained for each insert set;
- Observation column to note visible defects or other issues that could influence durability.

4.5 Location, date and time of the experiment

As presented in the previous chapters, the experiment takes place in the Machining Department of a company where parts for the aeronautical industry are machined. The experiment began in January 2022 and the last data collected was in December 2024 as over 720 sets of cutting inserts were tested.

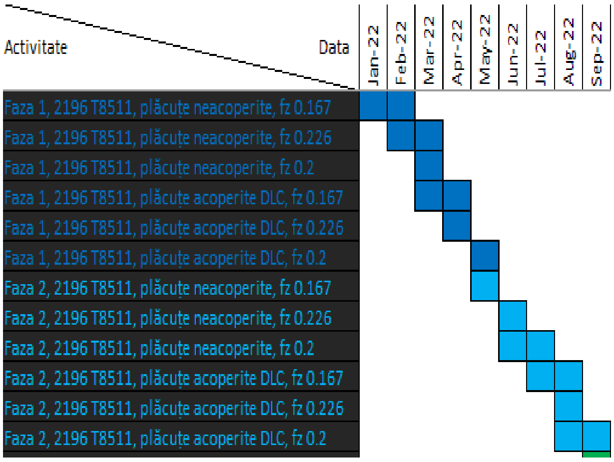

Fig. 4 Screenshot from Gantt chart

To have visibility of all activities, a Gantt chart was created. On the left side of Figure 4, the activities are presented and on the right side, the dates for completing the activities are presented.

4.6 Needed resources

- Human resources:
  - Tool assembly operator;
  - CNC operator;
  - Coordinate measuring machine operator.
- Material: semi-finished alloys 2196, 2043, 2099
- Equipment:
  - CNC machining center;
  - cutting tool measuring and balancing machines;
  - coordinate measuring machine;
  - microscope;
  - laptop.
- Measuring and control devices:
  - caliper;
  - roughness meter;
  - calibrated pins;
  - thickness gauges.

4.7 Data processing

Once the data is collected, it will be centralized in Excel files. The data will be structured in the form of tables to which filters will be applied to make it easy to understand. Charts will be created from the tables. Minitab software can also be used for better visualization of the charts.

4.8 Eliminating outliners

To detect outliers in experimental data, the IQR (Interquartile Range) method was used, which provides robust detection, independent of the data distribution.

In descriptive statistics, the IQR interval is a measure of statistical dispersion. The IQR is an example of a cut-off estimator, defined as the reduced 25% interval that improves the accuracy of the statistics.

Steps to follow:

- Sort the data in ascending order;
- Calculate:
    - Q_1 = first quartile (25% of the data are lower);
    - Q_3 = first quartile (25% of the data are lower).

- $IQR = Q_3 - Q_1$ (4.1)

- Define the acceptance interval (Ia):

$$Ia = [Q_1 - 1.5 \cdot IQR, Q_1 - 1.5 \cdot IQR] \quad (4.2)$$

- Any value outside this interval is considered an outliner and can be eliminated [16].

4.9 Graphic processing

Graphical processing is essential in the analysis of experimental data. 2D and 3D graphs will be drawn for better visualization of input and output data, for identifying outliers, for analyzing trends or relationships between variables, or for comparing the effects of DLC coating of wafers versus uncoated wafers.

4.10 Conclusionos of the experiment

The results of experimental research conducted to date, following this methodology, contribute to the optimization of milling processes and to the increase of tool life.

The evaluation of the performance of milling tools coated with amorphous diamond (DLC) layers in mechanical machining processes is also considered.

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Authors addresses

[1]*Pasca, Nicolae. Technical University of Cluj Napoca, North University Center of Baia Mare, European University of Technology, European Union 62A V. Babes St., RO-430083, Baia Mare Romania, Tel. 0264-202975. E-mail: nicu.pasca2604@gmail.com*
[2]*Banica, Mihai. Department of Engineering and Technology Management, Faculty of Engineering, Technical University of Cluj Napoca, North University Center of Baia Mare, European University of Technology, European Union 62A V. Babes St., RO-*

430083, Baia Mare Romania, Tel. 0264-202975. E-mail: mihai.banica@imtech.utcluj.ro
[3]*Cosma, Marius. Department of Engineering and Technology Management, Faculty of Engineering, Technical University of Cluj Napoca, North University Center of Baia Mare, European University of Technology, European Union 62A V. Babes St., RO-430083, Baia Mare Romania, Tel. 0264-202975. E-mail: Marius.Cosma@imtech.utcluj.ro*
[4]*Ungureanu, Nicolae. Department of Engineering and Technology Management, Faculty of Engineering, Technical University of Cluj Napoca, North University Center of Baia Mare, European University of Technology, European Union 62A V. Babes St., RO-430083, Baia Mare Romania, Tel. 0264-202975.*
E-mail: Nicolae.Ungureanu@imtech.utcluj.ro
[5]*Nasui, Vasile. Department of Engineering and Technology Management, Faculty of Engineering, Technical University of Cluj Napoca, North University Center of Baia Mare, European University of Technology, European Union 62A V. Babes St., RO-430083, Baia Mare Romania, Tel. 0264-202975. E-mail: Vasile.Nasui@imtech.utcluj.ro*

Contact person
**Pasca, Nicolae. Technical University of Cluj Napoca, North University Center of Baia Mare, European University of Technology, European Union 62A V. Babes St., RO-430083, Baia Mare Romania, Tel. 0264-202975. E-mail: nicu.pasca2604@gmail.com*