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EXPERIMENTAL RESEARCH ON THE MACHINING OF 2099 AL-LI ALLOY FOR AIRCRAFT APPLICATIONS USING UNCOATED AND DLC-COATED MILLING TOOLS

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Abstract: *The aerospace industry continuously seeks lightweight materials with high strength-to-weight ratios, and the 2099 Al-Li alloy has emerged as a promising candidate due to its superior mechanical properties and corrosion resistance. However, machining this advanced material presents significant challenges related to tool wear and surface quality. This study investigates the milling performance of 2099 Al-Li alloy using both uncoated and diamond-like carbon coated tools. Experimental trials were conducted under varying cutting parameters to analyze tool wear, surface roughness and tool-life. The results indicate that DLC-coated tools enhance machining performance by reducing tool wear and improving surface finish compared to uncoated tools. These findings provide valuable insights for optimizing the milling process of Al-Li alloys in aerospace applications.*

Key words: *alloy, coating, diamond, machining, milling tools, tool-life.*

1. INTRODUCTION

The 2099 Al-Li alloy is highly significant in aerospace applications due to its low density, high strength, excellent fatigue resistance, and superior corrosion resistance compared to conventional aluminum alloys. The addition of lithium reduces the alloy's weight while enhancing its stiffness, making it ideal for aircraft and spacecraft structures where weight savings are critical. The 2099-T83 alloy is used in the structure of Airbus A380 and A350 aircraft as crossbeams, stiffeners, seat and false rails or other parts of the floor structure.

In aerospace applications, Al–Li alloys, particularly the 2099 alloy, provide significant technological advantages due to the favorable combination of reduced weight and enhanced mechanical properties. The addition of lithium, the lightest metallic element, leads to a reduction in alloy density of approximately 3% for each percent of lithium added, resulting in substantial weight savings in aerospace structures and improved overall fuel efficiency. This reduction in weight does not compromise mechanical performance; on the contrary, Al–Li 2099 exhibits high specific strength and stiffness, making it especially suitable for critical structural applications such as aircraft fuselages, wings, and spacecraft components. These properties enable the design of lighter structures capable of withstanding high mechanical loads under demanding operating conditions.

Another important advantage of this alloy is its superior fatigue behavior and enhanced damage tolerance, which are essential for extending the service life of aerospace components subjected to cyclic loading. Additionally, Al–Li alloys demonstrate improved corrosion resistance compared to conventional aluminum alloys, particularly with respect to stress-corrosion cracking, contributing to increased reliability and reduced maintenance requirements. Improved thermal stability is a further key benefit of the 2099 Al–Li alloy, as it maintains its mechanical properties over a wide range of temperatures. This characteristic makes it suitable for both commercial and military aerospace applications, where components are often exposed to significant thermal variations. Overall, these

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advantages support the growing adoption of Al–Li alloys in modern aerospace engineering.

Al–Li alloys, particularly alloy 2099, are widely used in a range of aerospace applications due to their low density, high specific mechanical properties, and excellent durability. In aircraft manufacturing, these alloys are commonly employed for fuselage panels and bulkheads, where weight reduction combined with high structural integrity is essential for improving fuel efficiency and payload capacity. They are also used in wing components, where high stiffness and fatigue resistance are critical for withstanding aerodynamic loads and repeated flight cycles. In the space sector, Al–Li alloys are applied in spacecraft structural components, benefiting from their high strength-to-weight ratio and good thermal stability under extreme operating conditions. They are especially suitable for launching cryogenic fuel tanks, as they maintain mechanical performance at very low temperatures while offering improved resistance to crack initiation and propagation. Additionally, these alloys are used in helicopter components, where reduced mass, enhanced fatigue life, and corrosion resistance contribute to improved performance, reliability, and service life [1], [2].

The objectives of this research are to ensure a high quality of the machined parts by achieving low surface roughness, to obtain high durability of the cutting inserts during the machining process, and to evaluate and compare the behavior of uncoated and DLC-coated inserts under specific operating conditions.

2. DESIGN OF THE EXPERIMENT

According to Montgomery [3], the Design of Experiments (**DOE**) represents a structured methodological approach for planning, conducting, and analyzing experiments, with the aim of obtaining the maximum amount of relevant information using a minimum number of experimental trials. In the fields of mechanical and aerospace engineering, this methodology is widely applied for process optimization, material behavior evaluation, and performance assessment of mechanical components.

Based on the research conducted by Kerlinger and Lee [4], the main steps required for the design of the experiment were established as follows:

1. Definition of the objective, consisting of the comparison of the performance of uncoated cutting inserts and DLC-coated cutting inserts in the milling process of aluminum–lithium alloys.
2. Identification of the experimental variables, as follows:
   - independent variables:
     - feed per tooth: f_z = 0.167, 0.2 and 0.226 [mm/tooth]
     - type of cutting inserts: uncoated and DLC coated
   - dependent variables:
     - tool-life of the cutting inserts [min]
     - surface roughness of machined surfaces, R_a [µm]
     - spindle load of the CNC machine [%].
   - control variables:
     - CNC machine: Bavius PBZ HD600
     - cutting fluid: TRIM MicroSol 590XT
3. Establishment of the experimental design, which involved:
   - definition of the experimental groups:
     - uncoated cutting insert group
     - DLC-coated cutting insert group
   - application of randomization to reduce the influence of systematic errors and to eliminate anomalous results
4. Data collection: carried out using standardized Microsoft Excel forms for each set of cutting inserts involved.
5. Analysis of the obtained data: by importing and processing the data in the Microsoft Excel environment for process modeling purposes.
6. Interpretation of the results: to highlight the influence of the analyzed factors on the milling process performance.

3. THE NECESSARY EQUIPMENTS FOR THE TESTS

The experiment was conducted in serial production conditions using the **Bavius PBZ HD 600** CNC machine such as the one presented in Figure 1. This type of CNC can machine profiles and plates up to 6000 mm long, 800 mm wide and 575 mm high. The maximum speed of the spindle is 30000 revolution per minute, and the maximum power is 80 kW/h [5].

Fig. 1. CNC machine Bavius PBZ HD 600

For each machining operation, dedicated fixtures were designed and manufactured. As shown in Figures 2 and 3, these fixtures include custom-shaped locating channels matching the negative geometry of the raw material, ensuring accurate positioning, repeatability, and improved process stability.

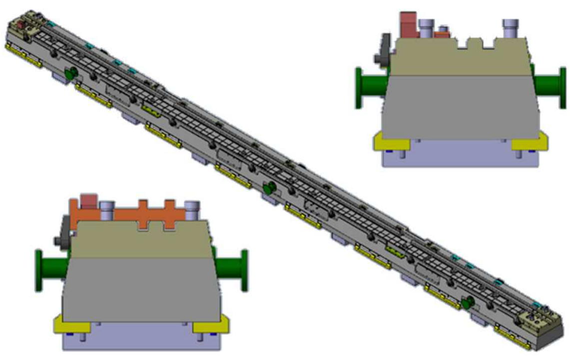

Fig. 2. First Machining Operation clamping device

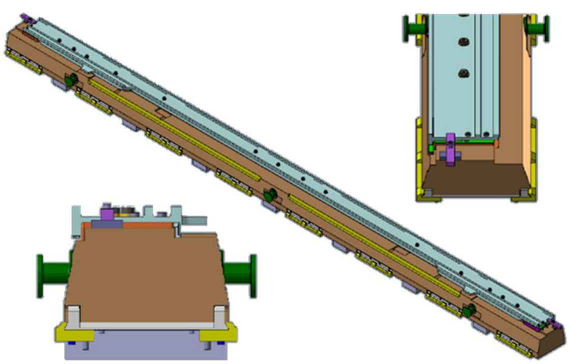

Fig. 3. Second Machining Operation clamping device

The milling tools used for D32R4 tool are:

- milling body MAPAL **ICM901-032-086-A063-Z3R-XD15**
- cutting inserts:
  - uncoated inserts: MAPAL **XDHT1504 40R-U10-HU612**
  - DLC coated inserts: MAPAL **XDHT1504 40R-U11-V0105-P**
- assembly screws MAPAL **M4x7.8-TX15-IP, Torx-Screw**

This type of milling tool can machine up to 18 liters per minute in materials such as aluminum. Due to fine balancing system, the tool can have micron precision at spindle speeds up to 35000 rpm. The tool has internal cooling channels to ensure heat dissipation and chip removal. The milling inserts can be uncoated and diamond coated, depending on the application [6].

Fig. 4. Milling tool NeoMill-Alu-QBig D32R4 [6]

The equipment needed for measuring and dynamic balancing is **Haimer Tool Dynamic 2009** which is presented in figure 5. The machine is necessary because the radial runout should be closer to 0 gmm.

Fig. 5. Haimer Tool Dynamic 2009 [7]

To measure acoustic emissions, the **Steinberg SBS-SM-135C** [8] device was used, which has a measurement range from 35 to 135 dB with an accuracy of ± 1.4 dB. The sound meter is presented in the left part of figure 6 and in the right part of figure 6 is presented the

Hofmann MI-2100 [9] which measures the vibration of the spindle.

Fig. 6. Steinberg SBS-SM-135C and Hofmann MI-2100

4. THE MATERIAL USED – 2099 T83

The raw material used for the machining experiment are extruded profiles with lengths between 5000 and 6000 mm long, depending on the position of the part in aircraft`s structure. The shape and some of the dimensions are presented in figure 7.

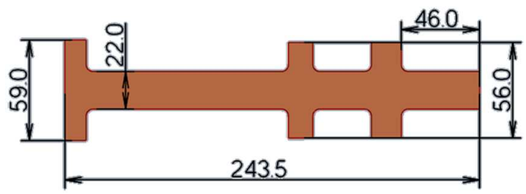

Fig. 7. The section of the raw material

Aluminum-lithium alloy 2099 is a third-generation alloy developed for aerospace and space applications due to its low density, high strength, superior rigidity, and good corrosion resistance. It is primarily used for structural components such as fuselages, wings, and cryogenic tanks, providing a lighter alternative to traditional aluminum alloys [10].

Table 1 presents the chemical composition ranges of the 2099 Al-Li alloy, highlighting the main alloying elements and the allowable impurities. The relatively high levels of copper and lithium indicate their key role in enhancing mechanical strength and reducing density, which are essential for aerospace applications. Elements such as zinc, magnesium, and manganese contribute to precipitation strengthening and microstructural stability, while zirconium is associated with grain refinement. The very low allowable levels of iron, silicon, and beryllium reflect strict control of impurities to maintain optimal mechanical properties and machinability [11].

Table 1

Chemical composition of 2099 alloy [11]

	Cu	Li	Zn	Mg	Mn	Zr	Ti	Fe	Si	Be
Min	2.4 %	1.6 %	0.4 %	0.1 %	0.1 %	0.05 %	-	-	-	-
Max	3.0 %	2.0 %	1.0 %	0.5 %	0.5 %	0.12 %	0.1 %	0.07 %	0.05 %	0.0001 %

5. PHYSICAL EXPERIMENT AND THE INTERPRETATION OF THE DATA

The experiment was taken out under conditions of serial production of the parts, respecting the internal procedures regarding the machining of batches of parts.

Notations used for the experiment:

- S – spindle speed [rpm]
- v_f – feed speed [mm/min]
- f_z – feed per tooth [mm/tooth]
- 241-360 – numbering of used insert sets
- UC – the uncoated inserts
- DLC – the Diamond-Like Carbon coated inserts
- F1/F2 – the corners of the milling insert
- T_{min} – the minimum tool-life obtained
- T_{med} – the average tool-life obtained
- T_{max} – the maximum tool-life obtained

The experiment begins with the assembly of the cutting inserts onto the milling cutter body, using the designated assembly screws. The newly formed tool assembly is subsequently measured and dynamically balanced to ensure proper rotational stability during operation. Following measurement and balancing, the cutting tool is mounted in the spindle of the machining center. The clamping device is then installed and accurately aligned on the machine tool vise. Subsequently, the workpiece is positioned and aligned within the fixture to guarantee repeatability and machining accuracy.

The machining process is initiated under the predefined cutting conditions. When wear is observed on the first cutting edge of the inserts, this condition is considered to indicate that the maximum tool-life has been reached, and the inserts are rotated to enable machining using the second cutting edge. The edgers or corners of the insert are presented in figure 8 with orange and green colors.

Fig. 8. Cutting insert

The corresponding tool-life durations are recorded in dedicated data collection forms. Finally, the experimental data are imported into specialized software applications for further processing and analysis. The experimental procedure begins with the machining of the workpieces in Operation_1, which represents the initial stage of the manufacturing process. Experimental results for the 12 tests performed are presented in figures 9-20.

5.1 Machining 1st operation

The experimental procedure begins with the evaluation of the first machining operation. Figure 9 illustrates the diagram of the obtained values when testing the uncoated cutting inserts with f_z of 0.167 [mm/tooth]. This is followed by Figure 10, which presents the results corresponding to f_z = 0.226 [mm/tooth], and Figure 11, where the data associated with a f_z = 0.2 [mm/tooth] are shown.

Subsequently, the experiment continues with the testing of DLC-coated inserts, following the same machining approach and sequence of cutting parameters. The tests are carried out at feed per tooth values of 0.167, 0.226, and 0.2 [mm/tooth], ensuring a consistent basis for comparison between uncoated and coated tools under identical working conditions.

Figures 9–14 present the diagrams of the obtained values for Tests 1–6.

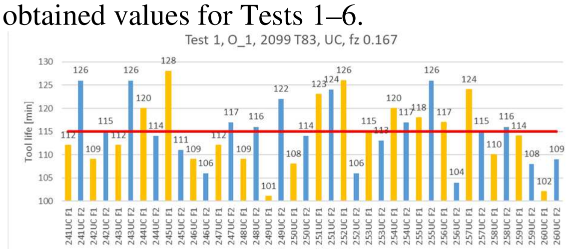

Fig. 9. Test 1, O_1, 2099, UC, f_z 0.167

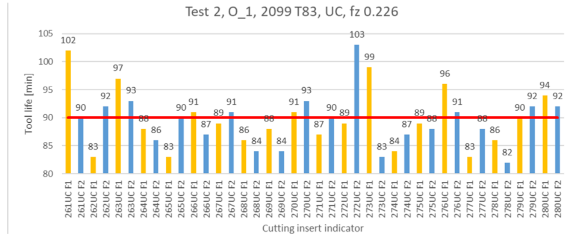

Fig. 10. Test 2, O_1, 2099, UC, f_z 0.226

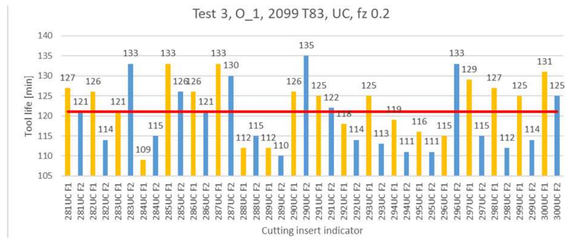

Fig. 11. Test 3, O_1, 2099, UC, f_z 0.2

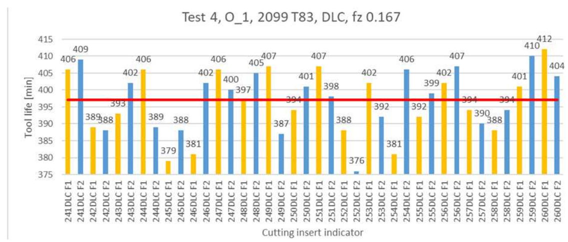

Fig. 12. Test 4, O_1, 2099, DLC, f_z 0.167

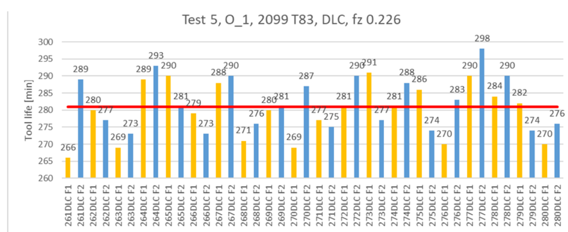

Fig. 13. Test 5, O_1, 2099, DLC, f_z 0.226

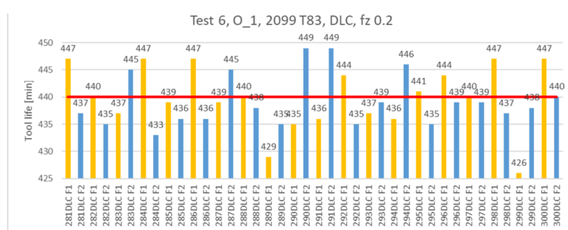

Fig. 14. Test 6, O_1, 2099, DLC, f_z 0.2

The experimental results obtained after Machining Operation_1 of Alloy 2099 highlight the significant influence of tool coating and cutting parameters on tool-life, surface roughness, spindle load, and acoustic emission. The experimental results are presented in the Table 2.

Table 2

Experimental results for Machining Operation_1 of the 2099 Aluminum Alloy

1st Op.	UC, f_z 0.167	UC, f_z 0.226	UC, f_z 0.2	DLC, f_z 0.167	DLC, f_z 0.226	DLC, f_z 0.2
T_{min} [min]	101	82	109	376	266	426
T_{max} [min]	128	103	135	412	298	449
T_{med} [min]	115	90	121	397	281	440
R_a min÷max [μm]	0.579÷0.940	0.874÷1.670	0.687÷0.916	0.448÷0.863	0.748÷1.514	0.618÷1.214
Max Spd. load [%]	20	76	37	45	82	56
Max noise level [dB]	99	121	115	96	128	116

Tool-life: a clear improvement in tool-life is observed when using DLC-coated inserts compared to uncoated inserts, irrespective of the cutting regime. For uncoated tools, the average tool-life varies between 90 and 121 minutes, with minimum values as low as 82 minutes under higher feed conditions. In contrast, DLC-coated inserts exhibit substantially higher tool-life, with average values ranging from 281 to 440 minutes, and maximum values reaching up to 449 minutes. This represents an increase in tool-life of approximately 3 to 4 times, which can be attributed to the reduced friction coefficient and improved wear resistance provided by the DLC coating.

Surface Roughness: values indicate a generally improved surface quality when using DLC-coated inserts. For uncoated tools, roughness ranges from 0.579 to 1.67 μm, with the highest roughness values recorded at increased feed rates. DLC-coated inserts produce lower and more stable roughness values, ranging from 0.448 to 1.514 μm. The reduction in roughness can be associated with more stable cutting conditions, reduced built-up edge formation, and lower tool wear progression.

Spindle Load: the maximum spindle load shows considerable variation depending on both cutting parameters and tool type. Uncoated inserts exhibit spindle load peaks up to 76%, indicating higher cutting resistance and less stable machining conditions. In comparison, DLC-coated tools generally operate at lower or more controlled spindle loads (between 45% and 82%), despite the higher tool tool-life. This suggests a more efficient load distribution and improved tribological behavior at the tool–workpiece interface.

Noise Level: the maximum noise level follows a similar trend to spindle load. Uncoated inserts generate noise levels up to 128 dB, while DLC-coated tools generally exhibit lower or comparable noise levels, with minimum values down to 96 dB. Reduced noise emission is typically associated with improved cutting stability and reduced vibration, further confirming the beneficial effect of the DLC coating.

5.2 Machining 2nd operation

The same procedure is applied for the second machining operation. Figures 15–20 present the diagrams of the obtained results for Tests 7–12.

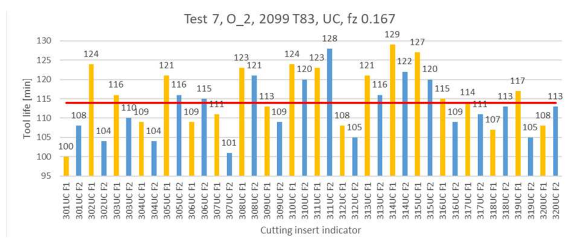

Fig. 15. Test 7, O_2, 2099, UC, f_z 0.167

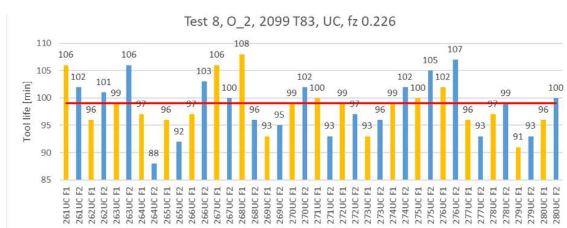

Fig. 16. Test 8, O_2, 2099, UC, f_z 0.226

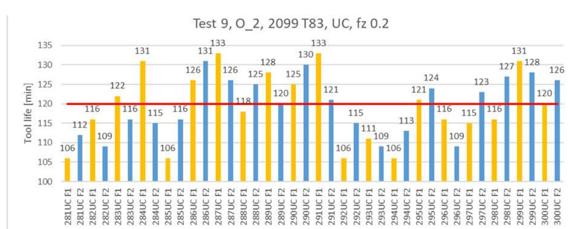

Fig. 17. Test 9, O_2, 2099, UC, f_z 0.2

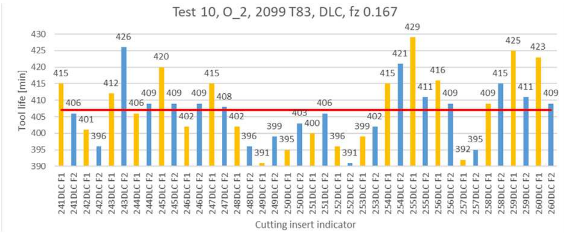

Fig. 18. Test 10, O_2, 2099, DLC, f_z 0.167

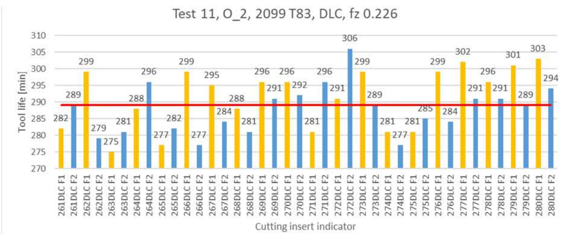

Fig. 19. Test 11, O_2, 2099, DLC, f_z 0.226

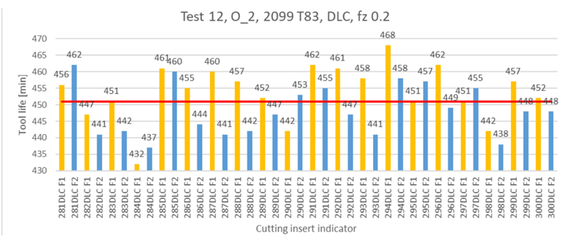

Fig. 20. Test 12, O_2, 2099, DLC, f_z 0.2

After completing all experimental tests, the data obtained were systematically collected, organized, and analyzed to ensure a clear interpretation of the results and their relevance to the machining process.

The experimental results obtained after Machining Operation_2 of Alloy 2099 highlight the significant influence of tool coating and cutting parameters on tool-life, surface roughness, spindle load, and acoustic emission. The experimental results are presented in Table 3.

Tool-life: for Machining Operation_2, uncoated inserts exhibit average tool-life values ranging between 99 and 120 minutes, with minimum values as low as 88, indicating accelerated wear under higher feed conditions. In contrast, DLC-coated inserts show a substantial improvement in tool-life, with average tool-life values between 290 and 451 minutes, and maximum values reaching 468 minutes. Compared to uncoated tools, the use of DLC-coated inserts leads to an increase of tool-life of approximately 3.5 to 4 times, demonstrating the effectiveness of the coating in reducing wear mechanisms during this machining operation.

Table 3

Experimental results for Machining Operation_2 of the 2099 Aluminum Alloy

2nd Op.	UC, f_z 0.167	UC, f_z 0.226	UC, f_z 0.2	DLC, f_z 0.167	DLC, f_z 0.226	DLC, f_z 0.2
T_{min} [min]	100	88	106	391	275	432
T_{max} [min]	129	108	133	429	306	468
T_{med} [min]	114	99	120	407	290	451
R_a min÷ max [µm]	0.626÷1.037	0.911÷1.742	0.597 ÷1.124	0.561÷0.908	0.866÷1.851	0.774÷1.425
Max Spd. load [%]	21	78	38	41	81	66
Max noise level [dB]	92	117	106	96	127	111

Surface Roughness: the measurements indicate a similar trend to that observed in Operation_1. For uncoated inserts, roughness values range from 0.597 to 1.742 µm, with higher values recorded at increased feed rates. DLC-coated inserts produce more consistent and generally lower roughness values, ranging from 0.561 to 1.851 µm. Although isolated higher roughness values appear at elevated feed rates, the overall surface quality achieved with DLC-coated tools remains more stable due to reduced tool wear and improved cutting-edge integrity.

Spindle Load: the maximum spindle load values reflect the mechanical stability of the machining process. Uncoated inserts show spindle load peaks up to 78%, indicating increased cutting resistance and potential instability. DLC-coated inserts operate under more controlled spindle load conditions, with values between 41% and 81%, despite the higher tool-life. This behavior suggests improved tribological conditions at the tool–workpiece interface, resulting in more efficient material removal.

Noise Level: the maximum noise level recorded during Machining Operation_2 follows trends consistent with tool condition and spindle load. Uncoated inserts generate noise levels up to 117 dB, whereas DLC-coated inserts exhibit comparable or slightly reduced noise levels, with minimum values of 96 dB. Lower acoustic emission is typically associated with smoother cutting action and reduced vibration, confirming improved process stability when using coated tools.

A comparison between Machining Operations 1 and 2 shows similar overall trends. In both operations, DLC-coated inserts significantly outperform uncoated inserts, providing a tool-life increase of approximately three to four times and more stable surface roughness.

Machining Operation_2 exhibits slightly higher tool-life and comparable roughness values, indicating a more stable wear progression. Spindle load and noise level trends remain consistent across both operations, confirming that the influence of tool coating is dominant over operation-related variations.

6. WEAR OF CUTTING TOOLS

Figures 21 and 22 present the uncoated cutting inserts after machining, with the wear zones clearly identified and measured. The observed wear is predominantly located along the cutting edge and flank surface, indicating a combination of flank wear and edge degradation.

Figure 21 highlights flank wear progression, with measured values ranging from about 0.08 mm up to 0.30 mm. This indicates a gradual increase in wear along the contact area between the tool and the machined surface.

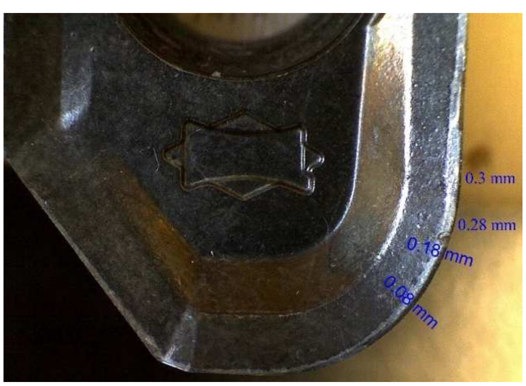

Fig. 21. Wear of uncoated inserts, frontal view

Figure 22 shows the wear values measured along the cutting edge that vary between approximately 0.11 mm and 0.32 mm, suggesting non-uniform wear distribution. The maximum wear is concentrated near the active cutting zone, which is directly involved in material removal, while lower values are observed towards less engaged regions of the insert.

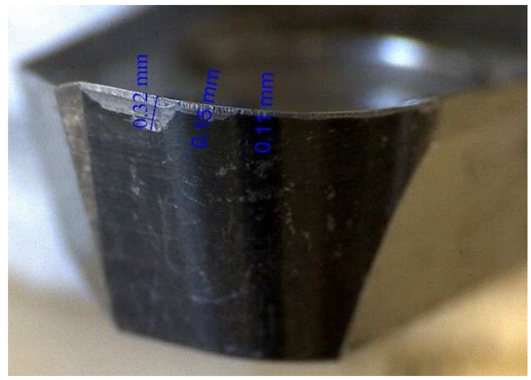

Fig. 22. Wear of uncoated inserts, isometric view

Overall, the wear patterns suggest that the uncoated inserts are significantly affected by mechanical and thermal loads during machining, leading to progressive edge deterioration. The variation in wear values also reflects the influence of cutting conditions and local contact stresses along the tool edge.

Figures 23 and 24 show the DLC-coated cutting inserts after machining, with the wear zones identified and measured. Compared to uncoated tools, the wear distribution appears more localized but includes more pronounced damage in specific regions.

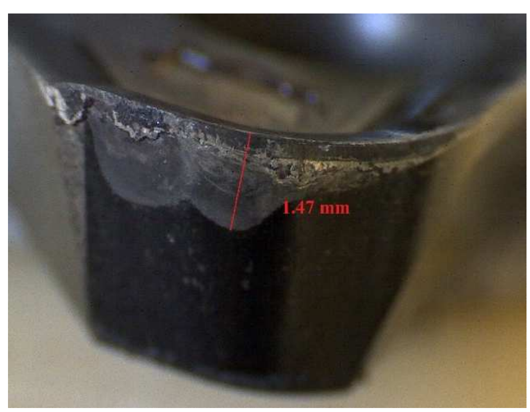

Fig. 23. Wear of DLC inserts, frontal view

Figure 23 shows a significant wear zone observed along the cutting edge, with a maximum measured value of approximately 1.47 mm. This indicates the occurrence of localized edge degradation, most likely associated with adhesion and subsequent material pull-out or micro-chipping during cutting.

Figure 24 highlights wear development on the flank surface, where the measured wear reaches about 0.30–0.32 mm. In addition, an extended affected zone of approximately 1.33 mm is visible, suggesting a combination of flank wear and coating degradation over a larger contact area.

Fig. 24. Wear of DLC inserts, isometric view

Overall, the wear pattern of the DLC-coated inserts suggests that, while the coating contributes to reducing uniform wear, it may also lead to localized damage once the coating begins to degrade. The presence of both moderate flank wear and more severe edge deterioration indicates the combined effect of mechanical stresses and coating failure during machining.

7. CONCLUSION

The following conclusions are based on the results of machining tests with uncoated carbide tools versus DLC-coated carbide tools on Aluminum-lithium alloy 2099:

1. The average tool-life (T_{med}) of DLC-coated inserts is significantly higher than that of uncoated inserts for all analyzed cutting conditions.
2. In the case of DLC-coated inserts, although overall tool-life values are considerably higher, an increase in feed per tooth also results in a decreasing trend in tool-life, albeit less pronounced compared to uncoated inserts.
3. The minimum and maximum tool-life values (T_{min} and T_{max}) recorded for DLC-coated inserts are substantially higher than those obtained for uncoated inserts, confirming the enhanced stability of the milling process when coated tools are employed.
4. Surface roughness analysis indicates that DLC-coated inserts generally produce lower R_a values, particularly at a f_z = 0.167 [mm/tooth], where the most favorable surface quality is achieved.
5. An increase in f_z has a detrimental effect on R_a for both uncoated and DLC-coated inserts, confirming the direct relationship between feed rate and surface quality degradation.
6. The spindle load increases significantly with increasing feed per tooth, reaching maximum values of 76÷82% at f_z = 0.226 [mm/tooth].
7. Under identical cutting conditions, DLC-coated inserts generally generate higher spindle loads than uncoated inserts.
8. The noise level rises with increasing f_z, with the highest values recorded at 0.226 mm/tooth, 117÷128 [dB].
9. For the same machining parameters, the use of DLC-coated inserts tends to result in slightly higher noise levels, which can be correlated with increased cutting forces and energy consumption.
10. From an industrial perspective, the results confirm that DLC-coated inserts are recommended for long-duration machining operations and applications requiring high surface quality, while uncoated inserts can be effectively used under less demanding cutting conditions.
11. The DLC-coated inserts exhibit a more concentrated wear pattern, with localized severe edge damage, indicating that once the coating fails, wear progresses rapidly in confined zones rather than uniformly.
12. Compared to uncoated tools, flank wear remains relatively controlled, suggesting that the DLC coating provides initial

protection by reducing friction and adhesion, thereby slowing down general wear mechanisms.

13. The presence of extended affected areas combined with localized edge degradation indicates a transition from protective coating behavior to substrate exposure, where coating delamination or failure leads to accelerated wear under mechanical and thermal loads.

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Cercetare experimentală privind prelucrarea aliajului 2099 al-li pentru aplicații aeronautice utilizând freze neacoperite și acoperite cu DLC

Rezumat: Industria aerospațială caută în permanență materiale ușoare cu raporturi rezistență-greutate ridicate, iar aliajul 2099 Al-Li a apărut ca un candidat promițător datorită proprietăților sale mecanice superioare și rezistenței la coroziune. Cu toate acestea, prelucrarea acestui material avansat prezintă provocări semnificative legate de uzura sculelor și calitatea suprafeței. Acest studiu investighează performanța de frezare a aliajului 2099 Al-Li utilizând atât scule neacoperite, cât și scule acoperite cu carbon de tip diamant. Au fost efectuate teste experimentale sub diferiți parametri de așchiere pentru a analiza uzura sculelor, rugozitatea suprafeței și durata de exploatare a sculelor. Rezultatele indică faptul că sculele acoperite cu DLC îmbunătățesc performanța de prelucrare prin reducerea uzurii sculelor și îmbunătățirea finisajului suprafeței în comparație cu sculele neacoperite. Aceste descoperiri oferă informații valoroase pentru optimizarea procesului de frezare a aliajelor Al-Li în aplicațiile aerospațiale.

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