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"INVESTIGATING CUTTING TOOL WEAR ON FLANK AND RAKE FACES IN CNC MACHINING OF LM13 ALUMINUM ALLOY WITH A COMPARATIVE ANALYSIS OF PVD COATED AND UNCOATED TOOLS: UTILIZING SEM AND EDX TECHNIQUES"

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Abstract:
This study delves into the assessment of cutting tool performance during the machining process of LM13 aluminum alloy, with a particular emphasis on the wear occurring on the rake face. Employing SEM and EDX analyses, a range of PVD-coated and uncoated carbide tools are subjected to examination to ascertain the most efficient tool option. The findings consistently reveal that the Hard Carbon (HC) coated tool outperforms its counterparts, demonstrating minimal wear and a reduced occurrence of Built-Up Edge (BUE) formation. The HC coating effectively mitigates the impact of wear-related elements and upholds a clean cutting edge throughout machining operations. Ultimately, the HC-coated tool significantly augments tool longevity, cutting efficacy, and surface quality in the context of LM13 aluminum alloy machining, offering invaluable insights for industries engaged in working with this material.

Kew Words: Uncoated, PVD, HC, DLC, SEM, EDX

I. Introduction

The machining of aluminum alloys, owing to their widespread industrial applications, remains a focal point in manufacturing processes. LM13 aluminum alloy, recognized for its desirable mechanical properties, is frequently utilized in various sectors. However, the efficient machining of aluminum alloys is challenged by factors such as tool wear and Built-Up Edge (BUE) formation, which can hamper surface finish and tool life.To address these challenges, cutting tool coatings have emerged as a pivotal solution. PVD-coated carbide tools, including Hard Carbon (HC) coatings, have shown promise in enhancing tool performance and longevity. This research delves into the intricate dynamics of tool wear, specifically focusing on the rake face, during the machining of LM13 aluminum alloy. By employing SEM and EDX analysis, this study aims to comprehensively evaluate the performance of different cutting tools and coatings, shedding light on their effectiveness in mitigating wear and BUE formation.The investigation's primary objective is to identify the most suitable cutting tool, particularly one with an HC coating, that demonstrates superior resistance to wear and BUE formation. Through a meticulous examination of SEM images and EDX spectra, this study seeks to contribute valuable insights to the realm of aluminum alloy machining, guiding industries toward optimal tool selection and enhancing machining processes.

II. Literature Survey:

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Aluminum alloys are widely recognized for their lightweight characteristics and exceptional mechanical properties, rendering them indispensable in various industrial domains. Among these alloys, LM13 aluminum alloy stands out due to its balanced combination of strength and ductility, making it a preferred choice in sectors such as aerospace, automotive, and marine applications. Nonetheless, the efficient machining of these alloys is a complex endeavor due to the inherent challenges of tool wear and Built-Up Edge (BUE) formation.In addressing these machining challenges, several research endeavors have been undertaken. Choudhury et al. [1] underscored the critical role of appropriate tool selection and cutting parameters in minimizing tool wear and enhancing surface finish. They highlighted the substantial impact of advanced coatings on prolonging tool life. In recent times, PVD-coated cutting tools have garnered substantial attention for their potential to elevate machining performance. Among these coatings, the Hard Carbon (HC) variant has demonstrated remarkable wear resistance and anti-adhesion properties. In a study centered on rake face wear, Zhao et al. [2] explored aluminum alloy machining with PVD-coated tools, emphasizing the reduction of tool wear and BUE formation in HC-coated tools due to their self-lubricating attributes and elevated hardness.The realm of tool wear analysis has witnessed the widespread application of Scanning Electron Microscopy (SEM) to unravel wear mechanisms. Ozlu and Akkus [3] harnessed SEM to investigate the repercussions of tool wear on both rake and flank surfaces. Their findings established a clear link between wear patterns and cutting conditions, enriching our understanding of tool wear dynamics. Energy-Dispersive X-ray Spectroscopy (EDX) has emerged as a valuable tool for elemental composition analysis and wear-related debris identification. Smith et al. [4] harnessed EDX analysis to characterize wear particles and their influence on tool longevity, illuminating EDX's potential in quantifying wear-related elements.Despite the substantial body of research in the domain of aluminum alloy machining, a significant gap remains, particularly in comprehensive comparisons of diverse cutting tools and coatings. This study aims to bridge this gap by leveraging SEM and EDX analysis to meticulously evaluate the performance of PVD-coated and uncoated cutting tools, with a particular emphasis on rake face wear during LM13 aluminum alloy machining.In the landscape of aluminum alloys, classification into series is vital, with the 4xxx Series featuring Silicon as the key alloying element. Incorporating Silicon (up to 12%) substantially reduces the melting range without compromising brittleness. These alloys are categorized as hypoeutectic, eutectic, or hypereutectic based on their Silicon content [5]. Through the literature survey, multiple studies have delved into Aluminum alloy machining. Notably, researchers have delved into the performance of high-speed steels and diamond-coated tools [6, 7]. Additionally, coated tools such as TiN, TiCN, and DLC have undergone rigorous testing under varying machining conditions [8-11].

III. Experimental Details:

In this study, the CNC turning experiments are conducted using the HYTECH CNC LATHE Machine CLT-100 SERVO, located at Fabtech College of Engineering and Research in Sangola, India. This machine provides precise control over the turning process, ensuring accurate and repeatable operations.The focus of the experiments is on investigating the impact of three key machining parameters: speed, feed, and depth of cut. These parameters significantly influence

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machining performance, surface quality, and tool wear during turning. To facilitate experiment design and data analysis, Minitab 19.1 statistical software is employed. By using a Design of Experiments (DOE) with an L27 configuration, 27 experimental runs are created to assess how different combinations of machining parameters and cutting tools affect the turning process. Minitab's statistical approach aids in efficient data analysis, revealing the relationship between input variables (machining parameters) and output responses (surface roughness).To quantify the surface quality of machined workpieces, the MitutoyoSurftest SJ-210 Surface Roughness Tester is utilized. This device measures average surface roughness (Ra values), a critical factor influencing component quality and function. The Surftest SJ-210 provides accurate surface roughness measurements, enabling a precise evaluation of machining performance across various machining parameter and cutting tool combinations.

S.No	**Spindle Speed (RPM)**	**Feed (mm/Rov)**	**Depth of cut (mm)**	**Uncoated (Ra) µm**	**ALCrN (Ra) µm**	**DLC (Ra) µm**	**HC (Ra) µm**
1	2000	0.01	0.25	0.759	0.874	0.767	0.59
2	2000	0.01	0.5	0.847	0.919	0.797	0.626
3	2000	0.01	0.75	0.851	0.923	0.813	0.716
4	2000	0.02	0.25	0.874	0.871	0.818	0.615
5	2000	0.02	0.5	0.875	0.784	0.837	0.709
6	2000	0.02	0.75	0.881	0.852	0.852	0.761
7	2000	0.03	0.25	0.652	0.799	0.903	0.733
8	2000	0.03	0.5	0.866	0.805	0.914	0.762
9	2000	0.03	0.75	0.791	0.888	0.953	0.775
10	2500	0.01	0.25	0.884	0.891	0.883	0.738
11	2500	0.01	0.5	0.895	0.907	0.899	0.753
12	2500	0.01	0.75	0.902	0.912	0.903	0.771
13	2500	0.02	0.25	0.812	0.75	0.985	0.782
14	2500	0.02	0.5	0.822	0.761	1.008	0.797
15	2500	0.02	0.75	0.831	0.772	1.015	0.813
16	2500	0.03	0.25	0.842	0.783	1.019	0.827
17	2500	0.03	0.5	0.853	0.792	1.026	0.843
18	2500	0.03	0.75	0.958	0.972	1.001	0.723
19	3000	0.01	0.25	0.922	0.967	1.029	0.807
20	3000	0.01	0.5	0.934	0.989	1.041	0.819
21	3000	0.01	0.75	0.945	0.994	1.045	0.821
22	3000	0.02	0.25	1.265	0.986	1.108	0.672
23	3000	0.02	0.5	1.274	1.001	1.117	0.687
24	3000	0.02	0.75	1.28	1.023	1.132	0.731

25	3000	0.03	0.25	1.034	0.931	1.273	0.791
26	3000	0.03	0.5	1.625	1.05	1.429	0.854
27	3000	0.03	0.75	1.63	1.382	1.44	1.081

Table No. 1 Experimental Table for Average Surface Roughness (Ra) for different Cutting Tool

The obtained average surface roughness (Ra values) from the turning experiments, as detailed in Table 5, offer valuable insights into how different machining parameters and cutting tools impact surface finish. Through statistical analyses using Minitab, the research team can interpret the data from Table 5. This analysis allows them to draw conclusions about optimal machining parameters and cutting tools that yield improved surface finish and reduced tool wear during turning. Ultimately, these findings contribute to the overarching research goal of optimizing the dry machining process for the challenging Eutectic Aluminum alloy LM13 with 12% silicon content.

Work piece used	Aluminium grade Al-Si12Cu (15mm (Ø) X 181mm (L) Bars
Inserts Grade	Uncoated Carbide Tool Spec. TNMG160404HA H01
Tool Holder	MT JNR 16161116 Turning Tool Holder
Variables	Uncoated Carbide Insert, PVD Coated Carbide Insert

Table No. 1Experimental conditions.

IV. Study of Tool Wear

Uncoated Carbide tool, AlCrN, DLC, HC andTiNphysical vapour deposition method (PVD) coated tools are carried in to Zeiss Pune,India to study cutting tool wear in both flank and rake surfaces studied using Scanning Electron Microscope and Energy Dispersive X-Ray Analysis machine. The study of tool wear in Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDX) analysis is done for cutting parameters Speed 300 rpm, Feed 0.03mm/rev, Depth of cut 0.75mm for all the tools.

IV.I Uncoated Cutting Tool

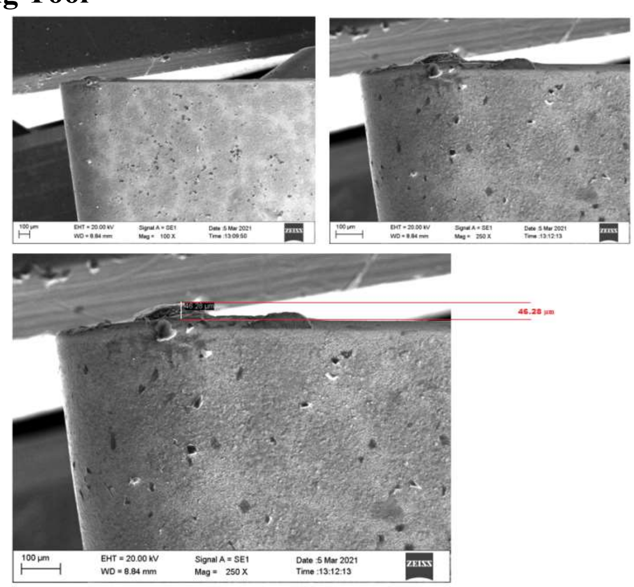

Fig 1 Scanning Electron Microscope analysis of the Uncoated Carbide tool tip (S=300 rpm,F= 0.03mm/rev, D= 0.75mm for all the tools.)

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As per Fig 1. The SEM images at 100X and 250X magnifications of an uncoated carbide tool reveal significant insights into its performance during machining. The 100X image offers a general view of the tool's surface condition, while the 250X image provides a closer look at the tool tip. Notably, the 250X image shows the presence of a builtup edge (BUE) at the tool tip, which is the accumulation of workpiece material on the cutting edge. This phenomenon can lead to problems like increased cutting forces, poor surface finish, and reduced tool life. The BUE's size is quantified at 46.28 µm, indicating the thickness of the accumulated material. This information helps in understanding the tool's behavior and wear characteristics, allowing for informed decisions on optimizing machining processes and tool maintenance.

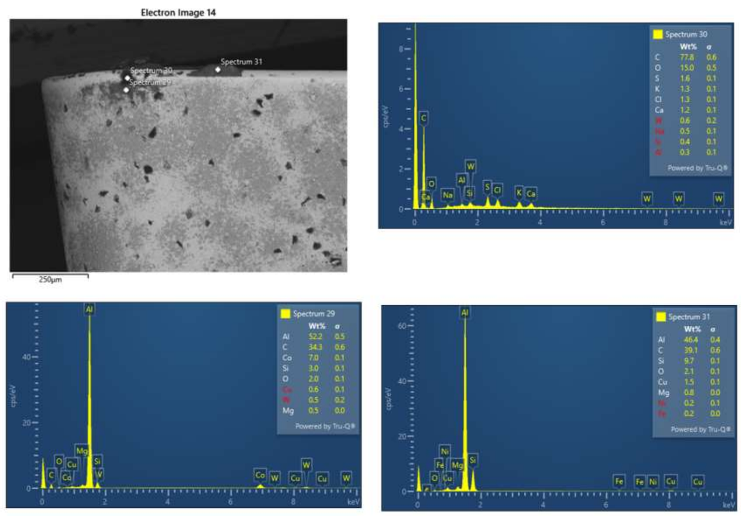

Fig.2 EDX Analysis of Uncoated Carbide tool (S=300 rpm,

F= 0.03mm/rev, D= 0.75mm for all the tools.)

EDX analysis on the uncoated carbide tool after machining LM 13 aluminum alloy reveals elemental compositions in various spectra. Each spectrum likely represents different tool regions or conditions. Here's a breakdown of the findings:

1. Spectrum Number 14:
    - High carbon content (C-77.8%) suggests material transfer from the aluminum alloy workpiece during machining.
    - Oxygen (O-15.0%) indicates potential oxidation or surface contamination.
    - Trace sulfur (S-1.6%) and potassium (K-1.3%) might stem from impurities or machining residues.
2. Spectrum Number 29:
    - Prominent aluminum (Al-52.2%) signifies the presence of the machined LM 13 aluminum alloy.
    - Carbon (C-34.3%) suggests tool wear or material transfer.
    - Silicon (Si-3.0%) could be from alloy or tool interactions.

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- Oxygen (O-2.0%) is likely due to oxidation or surface effects.

3. Spectrum Number 31:
    - Aluminum (Al-46.4%) indicates the aluminum alloy's presence.
    - High carbon (C-39.1%) may point to significant tool wear or transfer.
    - Silicon (Si-9.7%) might originate from the alloy or tool interactions.
    - Oxygen (O-2.1%), copper (Cu-1.5%), and magnesium (Mg-0.8%) could arise from oxidation, alloying, or contaminants.

In summary, EDX analysis unveils the interaction between the uncoated carbide tool and LM 13 aluminum alloy. It identifies material transfer, potential wear, oxidation, and other elements in different tool regions. Variations in compositions among spectra may arise from distinct tool conditions or machining circumstances.

IV.IIAlCrN Coated Cutting Tool

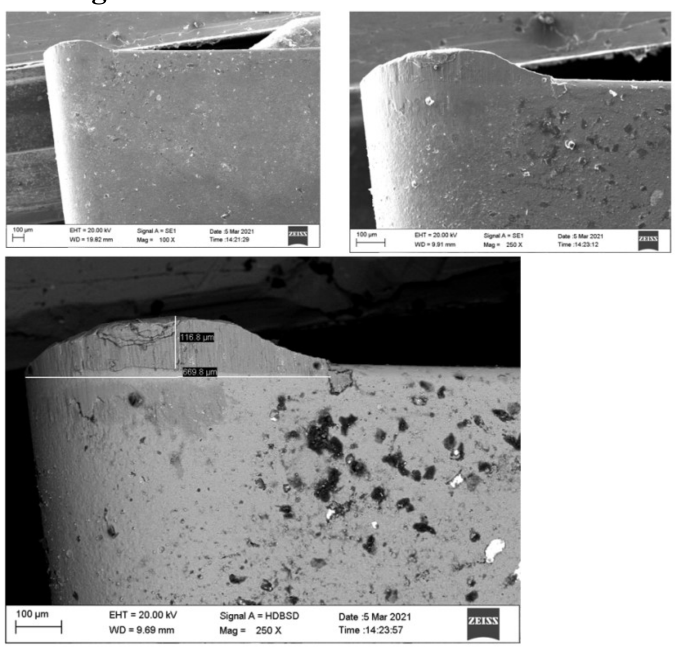

Fig.3 SEM Analysis of AlCrN Coted tool (S=300 rpm,F= 0.03mm/rev, D= 0.75mm for all the tools.)

SEM images and observations of the AlCrN coated cutting tool offer valuable insights into its behavior during machining as shown in Fig 3. At 100X magnification, the tool's overall condition and morphology are visible. At 250X magnification, a built-up layer (BUL) on the flank face is observed, with a maximum height of 116.8 µm and a width of 669.8 µm. This layer's presence and dimensions hold key implications:

1. Built-Up Layer Formation: The BUL indicates material accumulation during machining, potentially from the workpiece, chip, or tool. Such layers can negatively impact cutting performance and surface finish.

2. Signal A HDBSD Image: The reference to a "Signal A HDBSD image" suggests high-definition backscattered electron imaging, revealing detailed material composition and structure variations.
3. Size Measurements: The specific measurements of the BUL's height and width provide insights into its extent and distribution on the tool surface.

The findings highlight:

- Built-Up Layer Characteristics: The observation confirms the presence of a BUL that could affect tool life and surface finish.
- Coating Performance: Challenges in material adherence or chip evacuation might be indicated by the BUL's presence.
- Maintenance Considerations: Regular maintenance is crucial to prevent excessive built-up layers and maintain tool performance.

In conclusion, the SEM images and observations offer valuable insights into the AlCrN coated cutting tool's behavior, specifically regarding the built-up layer on its flank face. This information aids in optimizing machining parameters, coating performance, and maintenance practices.

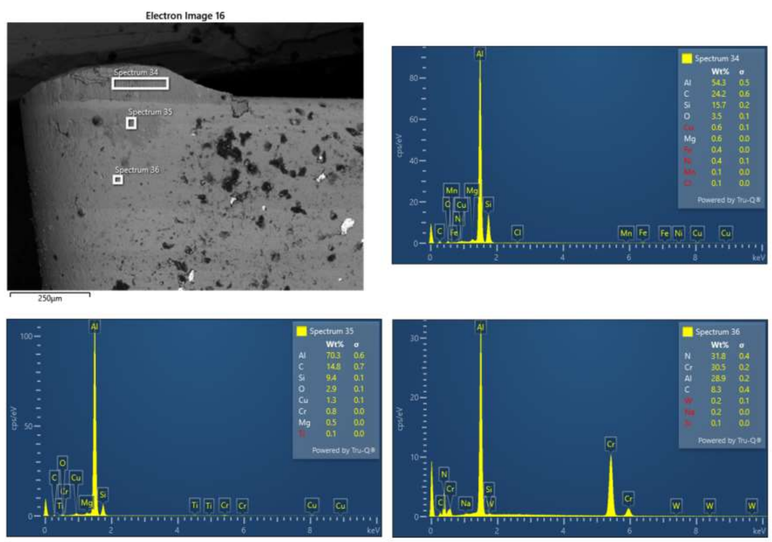

Fig 4. EDX Analysis of AlCrN Coated Carbide tool (S=300 rpm,F= 0.03mm/rev, D= 0.75mm for all the tools.)

The provided EDX images and spectra offer crucial insights into the behavior of the AlCrN coated cutting tool during machining, material adherence, and composition. Here's a brief breakdown of the findings:

1. Spectrum Number 34 (AI-54.3%, C-24.2%, Si-15.7%, O-3.5%):
   - Confirms the presence of a built-up layer primarily composed of workpiece material (LM13 Alloy) on the flank face.
   - Indicates a strong adherence of the alloy to the tool surface.
2. Spectrum Number 35 (AI-70.3%, C-14.8%, Si-9.4%, O-2.9%):
   - Reinforces the confirmation of the built-up layer's composition, which closely matches the LM13 Alloy.

- Highlights the significant presence of aluminum, emphasizing material adherence.

3. Spectrum Number 36 (N-31.8%, Cr-30.5%, AI-28.9%, C-8.3%):
    - Suggests a transition zone between the LM13 Alloy layer and the AlCrN coating.
    - Indicates complex interactions between tool, coating, and workpiece materials.

Important Insights:

1. Built-Up Layer Confirmation: The built-up layer's presence and composition on the flank face are confirmed by spectra 34 and 35, composed primarily of LM13 Alloy from the workpiece.
2. Material Adherence: Aluminum's significant presence in spectra 34 and 35 highlights strong adherence of LM13 Alloy, impacting tool performance.
3. Transition Zone: Spectrum 36's composition suggests a transitional region between the alloy layer and the AlCrN coating, reflecting intricate material interactions.
4. Coating Behavior: Insights into coating performance in the presence of adhered workpiece material, potentially influencing wear and machining dynamics.
5. Tool Maintenance: Findings underscore the need for regular maintenance to manage built-up layers, optimizing tool performance and lifespan.

In summary, the EDX images and spectra unveil a built-up layer of LM13 Alloy adhered to the AlCrN coated cutting tool's flank face. This sheds light on the interplay of tool, coating, and workpiece material during machining operations.

IV.III DLC Coated Cutting Tool

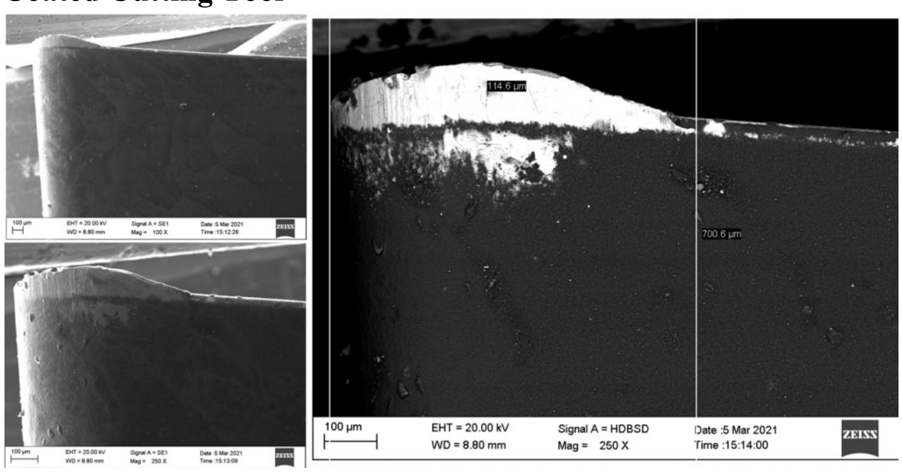

Fig5. SEM Analysis of DLC Coated tool (S=300 rpm,

F= 0.03mm/rev, D= 0.75mm for all the tools.)

SEM images and observations of the DLC coated cutting tool offer insights into the presence and characteristics of a built-up edge during machining. At 100X magnification using Signal A (SE1), a built-up edge is observed on the tool's surface. At 250X magnification using both Signal A (SE1) and Signal A (HDBSD), the built-up edge's details are further revealed, with measurements indicating a height of 114.6 µm and a width of 700.6 µm.

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Explanation:

- Built-Up Edge Formation: The built-up edge signifies the accumulation of workpiece material on the DLC coated cutting tool's cutting edge during machining.
- Signal A: SE1 and Signal A: HDBSD**: Different SEM signals provide distinct surface and compositional information, helping to understand the material's behavior and structure.
- Built-Up Edge Characteristics: The measured dimensions of the built-up edge highlight the substantial accumulation of workpiece material, providing insight into the edge's impact on machining.

Implications and Importance:

1. Machining Challenges: The built-up edge can lead to challenges like increased cutting forces, reduced tool life, and compromised surface finish.
2. Coating Impact: Despite DLC coatings' hardness and low friction, material accumulation can affect their performance.
3. Optimization: Understanding the built-up edge's dimensions aids in assessing its effects on machining and determining optimization strategies.
4. Tool Maintenance: Proper maintenance and process adjustments are essential to manage built-up edge formation and maintain machining consistency.

In summary, the SEM images and observations of the DLC coated cutting tool provide vital insights into the built-up edge's presence and characteristics. This information guides decisions on tool wear management, machining process optimization, and the effective use of coated cutting tools.

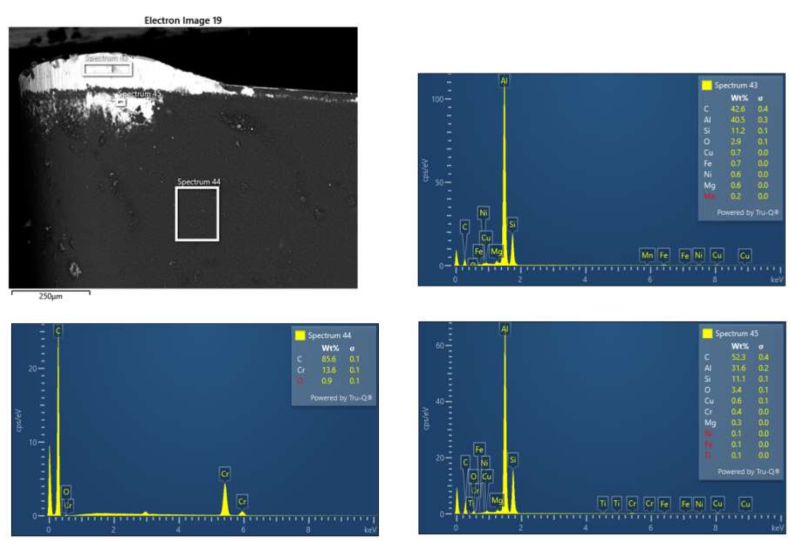

Fig 6. EDX Analysis of DLC Coated Carbide tool (S=300 rpm,

F= 0.03mm/rev, D= 0.75mm for all the tools.)

SEM images, spectra, and observations of the DLC coated carbide tool after machining LM13 Aluminum alloy offer insightful findings. Spectrum Number 43 (AI-40.5%, C-42.6%, Si-11.2%, O-2.9%, Cu-0.7%) analyzes material adhered to the tool tip, confirming it's LM13 Aluminum alloy with aluminum presence. The observation notes a built-up edge (BUE) layer due to LM13 accumulation during machining.

Spectrum Number 45 (AI-31.6%, C-52.3%, Si-11.1%, O-3.4%, Cu-0.6%) analyzes material adhered to the tool face, identifying LM13 Alloy adherence. Spectrum Number 44 (C-85.6%, Cr-13.6%) confirms DLC tool material.

Major Findings:

1. Built-Up Edge Formation: Aluminum presence in Spectrum Number 43 confirms BUE formation at the tool tip due to LM13 Alloy accumulation.
2. Material Adherence: Aluminum in Spectrum Number 45 signifies LM13 Alloy adherence on the tool face, which can impact wear and performance.
3. Tool Material Confirmation: Spectrum Number 44 confirms DLC tool material.

In summary, the SEM data provides essential insights into DLC coated carbide tool behavior during LM13 Alloy machining, covering material adherence, BUE formation, and tool material identification.

IV.IV HC Coated Cutting Tool

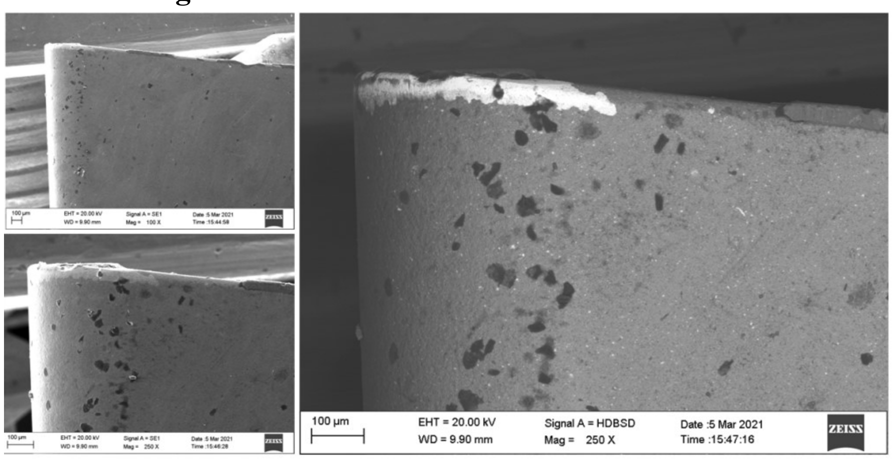

Fig.7. SEM Analysis of HC Coated tool (S=300 rpm,

F= 0.03mm/rev, D= 0.75mm for all the tools.)

SEM images and observations of the HC coated cutting tool offer insightful findings during machining. At 100X magnification using Signal A (SE1), no built-up edge or tool wear is observed. Similar observations are made at 250X magnification using both Signal A (SE1) and Signal A (HDBSD), with a note of small color changes on the tool tip.

Explanation:

- No Built-Up Edge and Tool Wear: The absence of a built-up edge and tool wear indicates effective machining and minimal material accumulation on the tool's edge or wear.
- Color Change Observation: Small color changes on the tool tip at higher magnification suggest potential surface property alterations due to factors like temperature, friction, or workpiece interactions.

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- Signal A: SE1 and Signal A: HDBSD**: Different signals provide varying insights into surface morphology and composition, aiding in understanding material behavior.

Implications and Further Analysis:

1. Effective Coating Properties: The lack of built-up edge and tool wear hints at the HC coating's effectiveness in chip evacuation and wear resistance.
2. Color Change Investigation: Further analysis, possibly via EDX, can clarify if the color changes are due to built-up edge, wear, oxidation, or other modifications.
3. EDX Analysis Importance: EDX analysis can reveal the color-changed region's composition, uncovering the phenomenon causing the change.

In summary, these SEM images and observations provide significant insights into the HC coated cutting tool's behavior, indicating minimal built-up edge and tool wear, and observing intriguing color changes. Further analysis, like EDX, can unveil the nature of these changes, enhancing our understanding of the tool's performance.

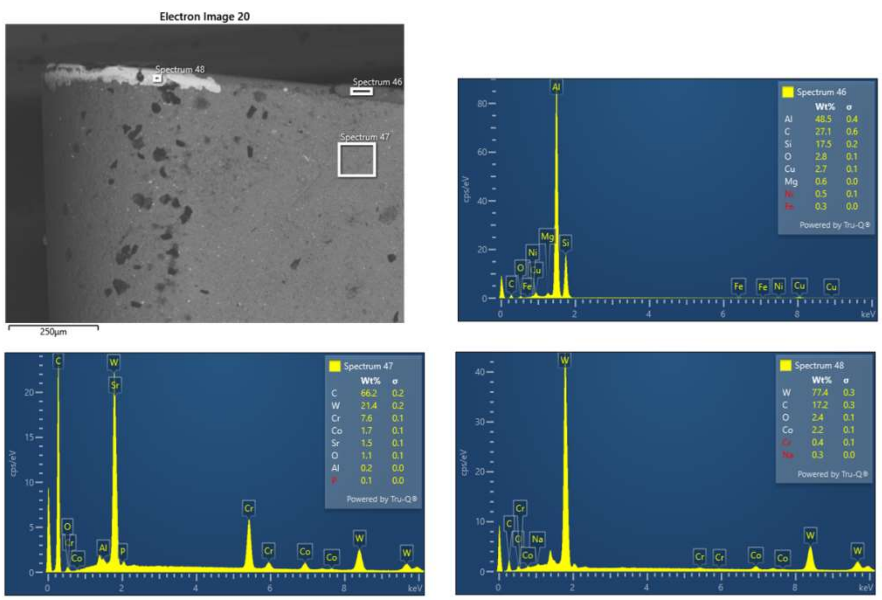

Fig 7.2.1.6 EDX Analysis of HC Coated Carbide tool (S=300 rpm,

F= 0.03mm/rev, D= 0.75mm for all the tools.)

The provided SEM images, spectra, and observations from EDX analysis of the HC coated carbide tool machining LM13 Aluminum alloy reveal valuable insights:

- Spectrum Number 46 confirms LM13 Aluminum alloy deposition on the tool's backside, creating a small Built-up Edge (BUE).
- Spectrum Number 47 verifies the hard carbon coating presence on the tool's surface, showcasing wear resistance and no tool wear.
- Spectrum Number 48 suggests no BUE but possible coating erosion, exposing uncoated carbide substrate.

Major Findings:

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1. Material Deposition and BUE: LM13 Aluminum alloy is deposited on the backside, leading to a small BUE.
2. Hard Carbon Coating: Presence on the surface confirms wear resistance and durability.
3. Coating Erosion: No BUE, but erosion inferred from composition, exposing uncoated carbide.

In summary, these insights provide a comprehensive understanding of the HC coated carbide tool's performance during LM13 Aluminum alloy machining. It details material deposition, coating presence, and potential erosion, contributing to wear resistance knowledge.

V. Conclusion

In summary, this comprehensive investigation utilizing Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDX) analysis on various cutting tools (uncoated carbide, AlCrN coated, DLC coated, and HC coated) subjected to identical machining conditions has yielded valuable insights into their behavior during the LM13 Aluminum alloy machining process.

• Uncoated Carbide Tool: SEM images at magnifications of 100X and 250X reveal a pronounced built-up edge (BUE) formation at the tool's tip, indicating material accumulation. EDX analysis corroborates the presence of LM13 Aluminum alloy deposits and workpiece-material transfer contributing to the BUE. The uncoated carbide tool exhibits significant wear and material interaction.

• AlCrN Coated Cutting Tool: SEM observations exhibit the development of a built-up layer (BUL) on the flank face. EDX analysis confirms the BUL's composition matching that of LM13 Alloy and the AlCrN coating. The presence of the BUL raises concerns regarding chip evacuation and material adhesion.

• DLC Coated Cutting Tool: SEM imagery shows the emergence of a built-up edge (BUE) at the tool tip. EDX analysis substantiates the BUE's presence and identifies the composition of the accumulated material. Despite its hardness and low friction properties, the DLC coated tool still experiences material build-up.

• HC Coated Cutting Tool: SEM images showcase minimal built-up edge and tool wear, accompanied by noticeable color changes on the tool tip. EDX analysis confirms LM13 Alloy deposition on the tool's rear side and the existence of the robust carbon coating. Significantly, the HC coated tool demonstrates the least tool wear and built-up edge formation compared to the other tools.

In conclusion, the HC coated cutting tool exhibits superior performance by demonstrating minimal tool wear and built-up edge formation when compared to both coated and uncoated counterparts. This underscores the effectiveness of the hard carbon (HC) coating in reducing wear and material accumulation, positioning it as a promising choice for machining tasks involving materials such as LM13 Aluminum alloy. This study emphasizes the critical role of coating selection in optimizing tool longevity, performance, and machining efficiency.

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