Investigation on Cutting Feasibility on Ni-CBN on HSS Substrates for Aerospace Material

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Abstract. The study involves coating the high-speed steel (HSS) tool with cubic Boron via electroless nickel co-deposition. The surface coating of Ni-CBN was deposited via electroless nickel where the process of involved chemical reactions as the ceramic CBN powders was embedded within the layer. By introducing the electroless nickel process, the coating cost and procedure could be simplified. The electroless deposition has been extensively practised in industry, and the most prevalent coating offers excellent corrosion, wear and abrasion resistance, ductility, lubricity, electrical properties, and hardness. Thus, the introduction of the new electroless nickel (Ni-CBN) tools can be a contribution to the industry. This paper discussed on comparing the performance of Nickel-cubic boron nitride (Ni-CBN) HSS tool substrates and with uncoated HSS tool for its surface tolerance in milling of Aluminium Alloy 7075. The process variables selected during experimentation based on Taguchi L9 are cutting speed, feed rate, and depth of cut with three different levels for each parameter. Result shows, the lowest flank wear for coated measured is 51.34 μm while the highest is 380.26 μm. The highest surface roughness for uncoated is 1.154 μm and lowest 0.42μm. Meanwhile, for coated substrates, the highest Ra is 0.787μm and lowest 0.251μm. At the end of the analysis, the Ni-CBN HSS cutting tools are generally able to slightly reduce the tool wear with the longest tool lifetime 195 minutes compared uncoated 143 minutes. Therefore, it is concluded that the Ni-CBN HSS tool end mill are generally able to reduce the tool wear.

1. Introduction

Nowadays, the productions of coating technology are demanding because of the need for higher productivity rates for industry consumption. Many researchers are developing new technology based on new materials, tools materials, and the evolution method of coatings characterization to maintain the industrial and scientific interest in this field. It shows the growing market of cutting tools has been developed [1]. The application of coated tools has become more critical in the machining process and mostly been made by thermal spraying processes such as Physical Vapor Deposition (PVD) and Chemical Vapor Deposition (CVD). The significant problems of these processes are that they are costly due to high temperature and complex procedures. By introducing the electroless nickel process, the coating cost and method could be simplified [2].

The electroless deposition has been extensively practised in industry, and the most prevalent coating offers excellent corrosion, wear and abrasion resistance, ductility, lubricity, electrical properties, and hardness [3]. Thus, the introduction of the new electroless nickel (Ni-CBN) tools can be used as an alternative and be a contribution to the industry.
Cubic boron nitride (CBN) has already established itself in many areas of machining. CBN being the second hardest material known to man, after diamond, is produced artificially [4]. The CBN tools have excellent mechanical and thermal properties, such as strength at high temperature, abrasion resistance and hardness second only to that diamond. Multilayer CBN coatings represent a new deposition method that can improve adhesion on metal substrates. This multilayer CBN structure showed outstanding adhesion in atmospheric conditions, even with high residual stress. Compared to monolayer CBN coatings, the multilayer CBN films had lower elastic moduli, and their critical loads were twice as high [5]. Many kinds of research had been shown on CBN tools performance in the past few years [6, 7]. The application of CBN as cutting material is a promising approach and could have a significant impact on productivity. Sharad N. Yevad [8] has proven that a composite CBN-TiN coating can be applied to a machine tool. The composite shows excellent CBN-to-TiN and composite coating-to-carbide substrate adhesion. This statement can be supported by [9], which stated that the characterization results show a relatively uniform coating with continuous CBN particle dispersion in an adherent TiN matrix on complex geometry cutting inserts.

In [10] concluded the HSS cutting tool was successfully coated with Ni/YSZ composite via electroless nickel co-deposition process. The average thickness of the coating is 59 μm with a uniform and smooth surface where TiN coated shows the most consistent performance in surface roughness results. In another experiment, it proved that the machining surface roughness is affected by cutting speed in milling Al/SiC metal matrix composites. The best surface roughness is obtained with increasing cutting speed from 300 mm/min to 450 mm/min. The surface roughness of the work materials obtained is gradually decreased from 1.3 μm to 0.6 μm [11].

Milling is the most used machining process for metal cutting purpose. The milling process usually involves a few different operations, but it depends on the shape of the final product and the state of the raw piece. Milling is required for giving a precise finish and adding a few features like slots or threaded holes. The cutting tool quality can determine the performance of the cutting process. Uhlmann [4] state that the machining of high-performance workpiece materials requires significantly harder cutting materials. In hard machining, the first tool wear occurs due to high process forces and temperatures. There are many cutting tools available in the industry, and it can be generally divided into coated and uncoated. The coated cutting tools are usually performed better than the uncoated ones. Standard commercialized coated cutting tool are AlN, TiN, TiAlN and other [10]. Therefore, in this study, a new approach of Ni-CBN is investigated as this ceramic-metal surface coating is very well known for its high thermal, wear and corrosion resistance. It is also known as an alternative material for the cutting tool coating. Besides, the layer will be processed via electroless nickel co-deposition, which is simple, without consuming electrical power and less costly compared to conventional thermal spraying processes [12].

2. Methodology
The methodology is divided into three parts: Electroless Coating, Machining and Cutting Feasibility.

2.1 Electroless Coating
The high-speed steel (HSS) cutting tool with standard dimension Ø6 mm was used as a substrate of CBN. The end mill requires sensitising to activate the HSS cutting tool surface by the four pre-treatment processes consecutively. Characters of the substrate sample were treated by chemical etching and mechanical blasting. Reinforcement ceramic particles of Cubic Boron Nitride (CBN) powder will use. CBN powders have exceptional thermal conductivity and provide improved surface integrity in the grinding of hardened alloy steels, tool steels, nickel, and cobalt-based superalloys. Figure 1 below shows End Mill Cutting Tool.
A CBN powder of 50g/l was added to the electroless nickel solution along with the cutting tool. The coating processes were taken in a beaker. The coating time was kept constant at 60 minutes. The bath temperature was kept constant at 89 ± 20°C. The powder is held in suspension in the nickel solution by either mechanical stirring or air bubbling agitation methods. Mechanical stirring was done by Jenway hotplate with a magnetic stirrer, and air bubbling was performed at 1.2W air pressure. The whole coating process sequence is simplified in Figure 2.

2.2 Cutting Feasibility

The software MINITAB 14 was used for analyze the influence and also the efficiency range of parameters on the magnitude of surface roughness for Aluminium Alloy 7075. The process variables selected during experimentation based on Taguchi L9 are cutting speed, feed rate, and depth of cut with three different levels for each parameter. The details of the machining cutting parameters are provided in Table 1.

| Machining Parameters | Units     | Values     |
|----------------------|-----------|------------|
|                      |           | Low | Medium | High  |
| Spindle Speed        | (RPM)     | 1860| 2650   | 3450  |
| Feed Rate            | (min/mm)  | 180 | 257    | 334   |
| Depth of Cut         | (mm)      | 1   | 2      | 3     |
The Orthogonal Array of experiment involved three nickel Co-Deposition process parameters shows in Table 2 below. A Taguchi Method of DOE approach with three parameters at three levels gave L9 for each substrate. This experiment uses cutting tool HSS Ni-CBN coated and HSS uncoated which contributed to 18 experiments. The depth of cut and feed rate were designated based on preferences specified by the end mill producers. The selected values of spindle speeds referred to the suggested change of speed to move the experiment into the “high cutting speed” type [13, 14].

Table 2. The Orthogonal Array of Machining Process Parameter and Level for Coated and Uncoated HSS Cutting Tool.

|   | C1: Cutting Speed, v (rpm) | C2: Feed Rate, F (mm/min) | C3: Depth of Cut (mm) |
|---|---------------------------|---------------------------|-----------------------|
| 1 | 1800                      | 180                       | 1                     |
| 2 | 1800                      | 257                       | 2                     |
| 3 | 1800                      | 334                       | 3                     |
| 4 | 2650                      | 180                       | 1                     |
| 5 | 2650                      | 257                       | 2                     |
| 6 | 2650                      | 334                       | 3                     |
| 7 | 3450                      | 180                       | 1                     |
| 8 | 3450                      | 257                       | 2                     |
| 9 | 3450                      | 334                       | 3                     |

The cutting feasibility will be tested on aerospace material Aluminium Alloy 7075. The milling pocket dimension for machining is 40 mm x 35 mm. This test method describes a laboratory procedure for determining the flank wear, and surface roughness for nanocoated and uncoated tools using Zeiss Stemi 20000-C Microscope Profile Optical Video Measuring System for tool wear and Surface Tester SJ-210 for surface roughness.

2.3 Machining
After the coating was done for HSS end mills, the diameter of CBN composite coated cutting tool was measured for the thickness using digital micrometer. The machine that used for machining is Deckel Maho DMU 50 CNC Machine. The characteristic of uniform thickness of electroless coating enabled the measurement. The results are obtained by taking three readings for each tool bit to get average thickness. Then, the samples of the HSS substrates are taken for analysis to view the presence of the coating elements and also to observe the coating surface under JSM-7800F Field Emission Scanning Electron Microscope (FESEM).

Later, the cutting tools were tested for its machining performances. The machining profile was done using 18 pockets which using two cutting tools. Nine pockets will be run using cutting tool with coated HSS end mill, and nine pockets will be runs for uncoated HSS end mill. The size of each pocket is 40 mm x 35 mm on material Aluminium Alloy 7075, shown in Figure 3. The interval for each cut is 0.2 mm, while the reading of surface roughness is taken every 0.2 mm.
The feed rate, spindle speed and depth of cut was kept constant throughout the end milling process. The machined profile was used as the basis of the surface roughness measurement. The machined surface will be tested using Surftest SJ-210-Series 178-Portable Surface Roughness Tester for surface roughness shown in Figure 4. At the same time, tool wear will be tested using a Zeiss Stemi 20000-C Microscope Profile Optical Video Measuring System pictured in Figure 5.
3. Results and Discussion
The result will discuss on the surface roughness analysis, tool wear analysis and characterisation for Ni-CBN coated cutting tool.

The HSS end mill cutting tool was successfully coated with CBN composite via electroless coating. The images of HSS cutting tool coated and uncoated were shown in Figure 6 below.

![Uncoated HSS Tool](image1) ![Coated HSS Tool](image2)

**Figure 6.** Cutting Tool Image (a) Uncoated HSS Tool (b) Coated HSS Tool

3.1 Surface Roughness Analysis
The cutting tool quality is the main factor to contribute for better surface roughness analysis. The result Ra of machined Aluminium Alloy 7075 for coated and uncoated cutting tool were recorded and compared in Table 3.

| No of Test | Cutting Speed,V (RPM) | Feed Rate, F (mm/min) | Depth of Cut (mm) | Surface Roughness, Ra |
|------------|-----------------------|-----------------------|-------------------|-----------------------|
|            |                       |                       |                   | Coated (µm) | Uncoated (µm) |
| 1          | 1860                  | 180                   | 1                 | 0.576       | 0.695         |
| 2          | 1860                  | 257                   | 2                 | 0.787       | 1.154         |
| 3          | 1860                  | 334                   | 3                 | 0.890       | 1.220         |
| 4          | 2560                  | 180                   | 2                 | 0.481       | 0.534         |
| 5          | 2560                  | 257                   | 3                 | 0.301       | 0.586         |
| 6          | 2560                  | 334                   | 1                 | 0.412       | 0.619         |
| 7          | 3450                  | 180                   | 3                 | 0.296       | 0.485         |
| 8          | 3450                  | 257                   | 1                 | 0.251       | 0.421         |
| 9          | 3450                  | 334                   | 2                 | 0.527       | 0.729         |

Table 3 shows the combination high cutting speed and medium feed rate at Test no. 8 for coated tools where it produce good surface finish Ra 0.251µm. Meanwhile, the combination low cutting speed and high feed rate at Test no 3 for uncoated will resulted bad surface finish with high surface roughness Ra 1.22 µm. It shows that the interaction between high-value feed rate and high-value spindle produce good surface finish [15, 16]. Mohammed [17] also states that the interaction between the cutting speed and feed rate are significantly affecting the surface roughness.

3.2 Tool Wear Analysis
By using Zeiss Stemi 20000-C Microscope Profile Optical, Video Measuring System Tool wear will examine every 0.2 mm of machining. According to ISO 8688-21:1989, as stated previously, it is noted that the lowest tool wear is the best and most durable for end mill cutting tool. Figure 7 shows the tool wear on the cutting tool before and after the machining process.
The flank wear trend in Figure 8 shows that the substrates performed better for coated end mill based on cutting time. Test no 3 and 5 produce longest tool life with 195 minute. Figure 9 shows the flank wear trend for uncoated end mill based on cutting time. The substrates performed scattered than coated end mill. Test no 3 produce longest tool life with 143 minute for uncoated tools.

The highest combination of parameters and time will produce high cutting time. It will cause the occurrence of tool wear. The interaction between the cutting speed and feed rate is significantly affected tool wear [15, 18, 19].
3.3 Characterisation

The samples of the HSS substrates are taken for analysis to view the presence of the coating elements and also to observe the coating surface under JSM-7800F Field Emission Scanning Electron Microscope (FESEM). Figure 10 obtained by morphological image mapping, the scanning image is then processed and matches with the elements. The bubbles in the chart represent the elements present on the surface area, while Table 4 shows the composition of elements.

![Figure 10. EDX Spectrum Chart with Elements Composition](image)

| Element | Weight % |
|---------|----------|
| B       | 20.69    |
| C       | 16.71    |
| N       | 9.16     |
| O       | 15.01    |
| P       | 4.20     |
| Ni      | 34.22    |
| Total   | 100.00   |

In this analysis, the goal is to prove that the element of the Ni-CBN is present. As observed in Table 4 and Figures 10, the elements are indeed present, so the electroless coating is fundamentally considered as a success. The finding from this FESEM results is the elements deposition that is present on the surface of the sample, the type of elements are also validated via the EDX spectrum mapping that produces the elements chart and their composition.

4. Conclusion

The electroless Ni-CBN coating has been successfully performed on HSS end mills with a diameter of 6 mm. As a result, the average thickness of the coating HSS cutting tool is 15 μm. Two types of cutting tools were selected and compared which are HSS uncoated and HSS coated. Two types of cutting tools were selected and compared, which are HSS uncoated and HSS coated. The performance of these two types shows the lowest flank wear for coated measured is 51.34 μm, while the highest is 380.26 μm. The highest surface roughness for uncoated is 1.154 μm and lowest 0.42μm. Meanwhile, for coated substrates, the highest Ra is 0.787μm and lowest 0.251μm. At the end of the analysis, the Ni-CBN HSS cutting tools are generally able to slightly reduce the tool wear with the longest tool
lifetime 195 minutes compared uncoated 143 minutes. Therefore, it is concluded that the Ni-CBN HSS tool end mill are generally able to reduce the tool wear.

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