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EFFECTS OF COBALT CONTENT ON MACHINING FORCES, SURFACE FINISH AND TOOL WEAR IN TUNGSTEN CARBIDE TURNING INSERTS WHILE DRY TURNING

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ABSTRACT

Four grades of tungsten carbide turning inserts were tested for wear, forces and surface finish during non-lubricated finishing passes. The grades were 10, 4, 3 and 2% cobalt by mass. Tests indicated that brittle fracture was an issue with the harder grades (4, 3, and 2%), resulting in accelerated tool wear. This is likely avoidable by using proper edge preparation. Main cutting forces did not vary significantly with cobalt content, while tangential forces did show a decrease at the softest carbide grade (10% Co). Surface finish was related inversely with cobalt content. 10% Co produced the best surface on average, while 2% Co produced the worst.

INTRODUCTION

In many modern machining applications, cutting fluid is being removed from the process in order to simplify the waste stream and reduce human exposer to harmful chemicals. However, due to seizure events, built-up-edge (BUE) and accelerated tool wear, good surface finish is often not achievable without a cutting lubricant. This study aims to determine if the cobalt content of a tungsten carbide tool effects important machining parameters such as forces, tool wear and surface finish all without a cutting fluid.

NOMENCLATURE

Rq Roughness- RMS Surface Roughness (µm)
Fc- Main Cutting Force (N)
Ft- Tangential Force (N)
µ- Coefficient of Friction
f- Crossfeed (µm/revolution)
ERA- Effective Rake Angle

LITERATURE REVIEW AND HYPOTHESIS

Considering conventional cemented carbide tools, significant improvement in the properties is achieved in tools with finer grain size as described by Fabijanić et al [1]. Another criterion that plays a pivotal role in the performance of cemented carbides is the percentage of the cobalt binder in the tool. The cobalt content might have implications on tool wear, surface roughness of the machined part and the cutting forces.

The results obtained by Chandrashekar et al. [4] indicate that increasing cobalt content will reduce the hardness, increase the toughness and increase tool wear. This is because the cobalt is softer and more ductile than the tungsten carbide [5,6]. Cobalt is preferred to be FCC-structured since it has higher ductility and therefore higher fracture toughness than HCP-structured cobalt [5].

The machined surface roughness depends on the geometry of the cutting tool and the edge preparation technique. Cutting tools used for hard cutting are typically prepared with chamfered and/or honed edges, which provide a stronger edge that is less prone to premature fracture. Additionally, surface roughness also depends on the tool wear.

Cutting performance such as surface integrity, tool wear, tool fracture, and cutting temperature correlate strongly with cutting forces [6]. Cutting force is important in machining to provide a distinctive trademark of the underlying mechanics. It predominantly determines the energy consumed and machining power requirements of the process. Kamely et al. [7] have concluded that the same tool geometry with different thermal properties can yield cutting forces with a noticeable difference. For example the case of CBN-L tools with only TiAlN coatings and CBN-L tools with a coating of TiAlN/Al2O3/TiCN [7].

From these past observations, it is predicted that higher cobalt content will result in increased wear rates, and resulting higher forces and worse surface finish during dry finish turning.

EXPERIMENTAL PROCEDURE

Each turning insert was used to turn a face on a 4” disc of 1045-alloy steel. The feed was set to 40 µm/rev, depth of cut was set to 100 µm, while speed varied from 300 sfpm at the outer diameter of 4” down to 50 sfpm at the inner diameter of 0.5”. The tools used in this study had their cutting edges ground to a sharp corner, with a 0° rake angle. The geometric machined surface (ideal) for a generic set of feeds and speeds is shown below in Figure 1.

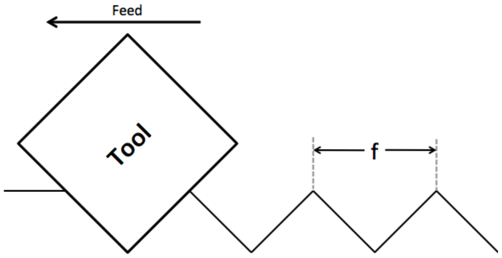

Figure 1. Theoretical Machined Surface Geometry

Tool wear will be measured as a function of cutting time. Each facing operation will last about 1.75 minutes. Each cutting tool will be optically inspected for rake wear volume after 7 and 14 minutes of cutting. A total of 14 minutes (8 facing operations) of cutting time will be performed on each tool. Wear land volume will be measured on the rake face of each tool via a laser confocal microscope. A diagram depicting common flank and rake wear patterns are shown in Figure 2. The volume of crater wear will be measured in this study.

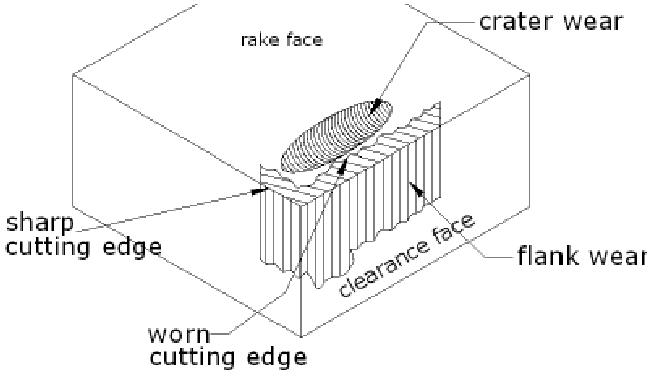

Figure 2. Diagram of Flank and Rake Wear for a Square Nosed Tool

Forces will be recorded via a piezoelectric load cell mounted between the tool and the tool post. Main cutting and tangential forces will be recorded throughout several of the facing operations.

CHARACTERISATION OF CUTTING TOOLS

Before any cutting experiments were conducted, cobalt content, grain size, and hardness of each tool was tabulated. Table 1 displays this data for the four tools tested.

Table 1. Material Properties of Cutting Tools

Cobalt Content (%)	WC Grain Size (μm)	Hardness (Hv)
2	<1	2570
3	<1	2280
4	≈1	2100
10	>1	1800

As seen in Table 1, hardness increases inversely with cobalt content. Grain size decreases as cobalt content decreases. Cobalt content and grain size data were provided by the tool manufacturer. Hardness values were measured using a Vickers micro-indenter.

TOOL WEAR AND BUILT UP EDGE

Before each cutting was used, after 7 minutes and after 14 minutes of cutting, each tool was measured for wear and BUE in a Keyence VKX-1100 laser confocal microscope. Figure 3 shows an example of a wear measurement on the microscope. The purple area represents wear land, which is defined as area more than 1 μm below the reference plane. The reference plane is defined at an unused area of the tool.

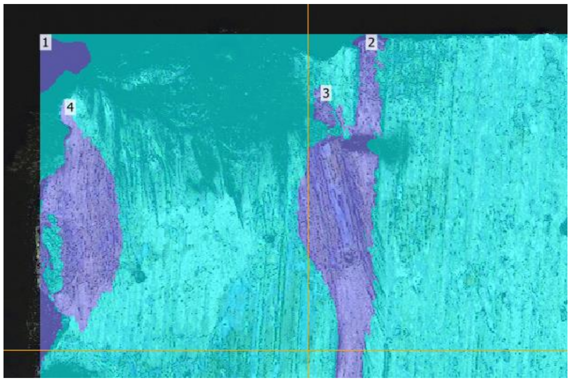

Figure 3. Wear Land as Measured by the VKX Microscope, 200x Magnification, 10% Cobalt, 14 Minutes of Cutting

The top of the blue area in Figure 3 represents the cutting edge of the square nosed tool. The purple channel on the right represents where the front of the chip wears the rake face of the tool. Figure 4 shows the same micrograph as Figure 3, except now, BUE is being measured instead of wear volume. The red area shows built up area. This is defined as any land more than 1 μm taller than the reference plane as defined above.

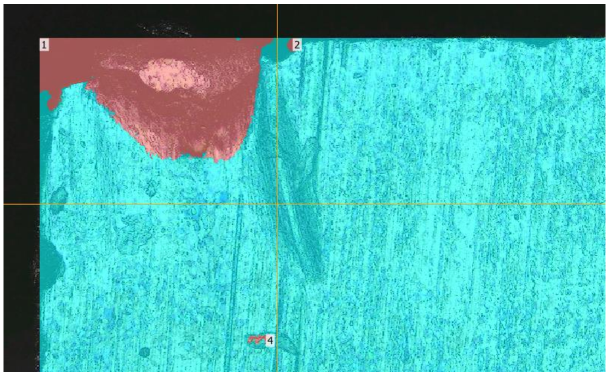

Figure 4. Built Up Edge as Measured by the VKX Microscope, 200x Magnification, 10% Cobalt, 14 Minutes of Cutting

10% Cobalt

Figure 3 and Figure 4 show the wear and BUE profiles of the 10% cobalt tool after cutting for 14 minutes. Figure 5 plots the wear and BUE volume as a function of cutting time. It can be seen that BUE was a much more pronounced phenomenon on the rake face of the tool than wear. Wear increase linearly, largely along the front and trailing edges of the chip, this can be seen in Figure 3 as the two vertical purple streaks. A large BUE was detected on the tool at 7 and 14 minutes of cutting time. This resulted in an effective rake angle (ERA) of about +26° as measured on the VKX.

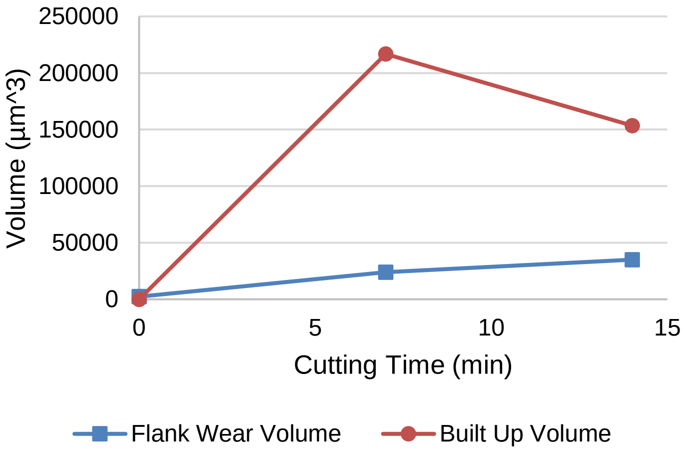

Figure 5. Flank Wear and Built Up Volume as a Function of Cutting Time, 10% Cobalt

4% Cobalt

The purple area in Figure 6 shows the wear land as measured by the VKX on the 4% cobalt tool after 14 minutes of cutting. A large crater exists behind the cutting edge of the tool. This is the result of brittle fracture when the tool made contact with the workpiece. This likely could have been avoided with proper edge preparation. ERA was measured at about +17°.

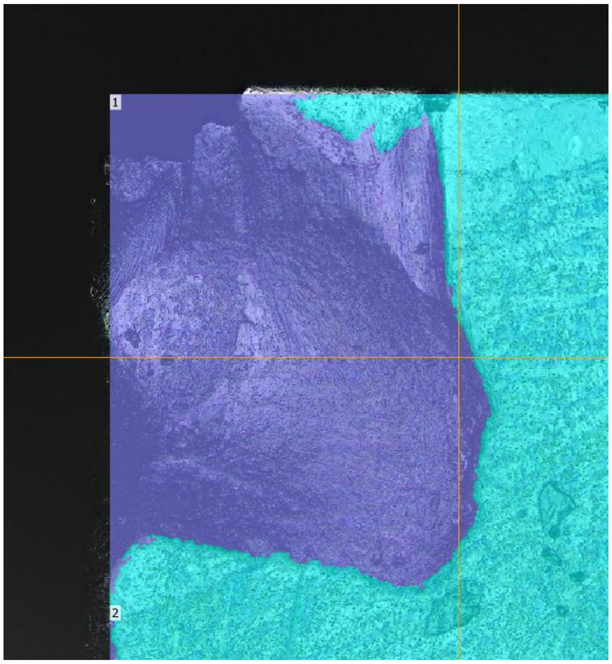

Figure 6. Wear Land as Measured by the VKX Microscope, 200x Magnification, 4% Cobalt

Figure 7 plots the wear and BUE volume as a function of cutting time. BUE was not a significant presence on the tool at any point. This likely indicates that the brittle fracture occurred early on, leaving little flat area for the BUE to adhere. Wear volume was about 30 times the magnitude of the wear measured on the 10% tool. This is due to the brittle fracture.

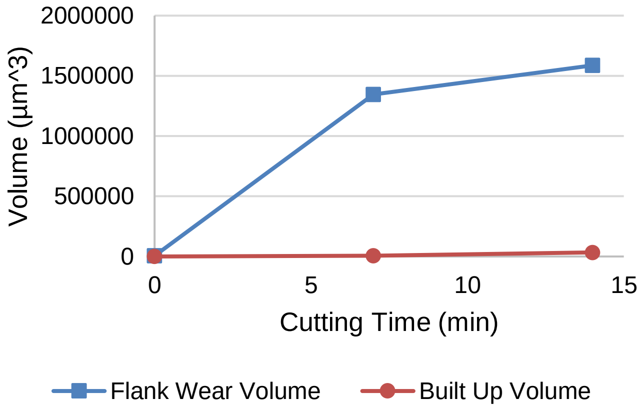

Figure 7. Flank Wear and Built Up Volume as a Function of Cutting Time, 4% Cobalt

3% Cobalt

The purple area in Figure 8 shows the wear land as measured by the VKX on the 4% cobalt tool after 14 minutes of cutting. Most wear measured on the tool exists in the large gouge in the center of the micrograph. This is where the thickest part of the chip slides during cutting.

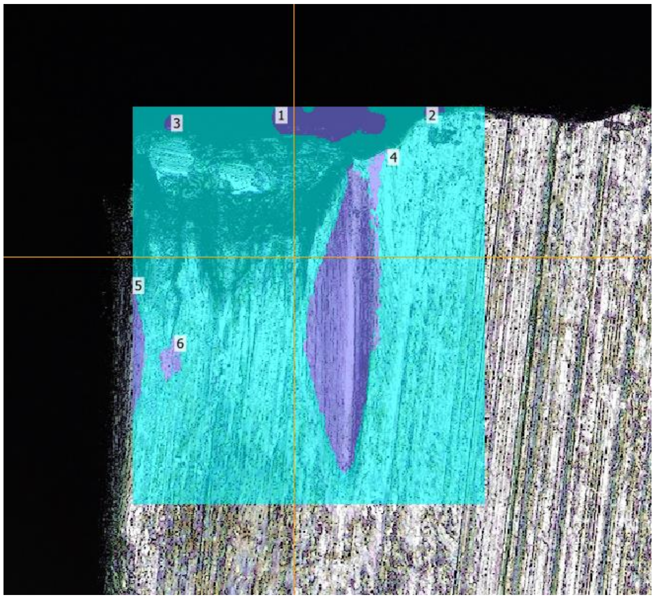

Figure 8. Wear Land as Measured by the VKX Microscope, 200x Magnification, 3% Cobalt

Figure 9 shows a large BUE present (the red area) on the cutting edge of the tool. It is much larger than the wear volume observed on the tool. This BUE resulted in an ERA of about +25°.

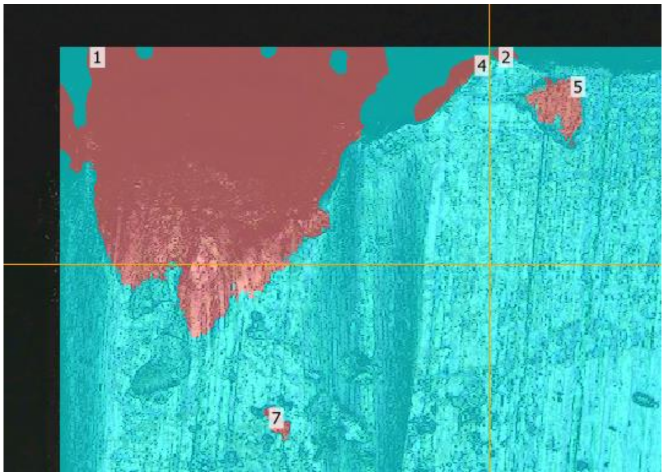

Figure 9. Built Up Edge as Measured by the VKX Microscope, 200x Magnification, 3% Cobalt

Figure 10 show the wear and BUE volumes for the 3% cobalt tool. Wear volume progressed linearly, but is small in comparison to built up volume. Wear volume and BUE volume were on the same order as the 10% tool.

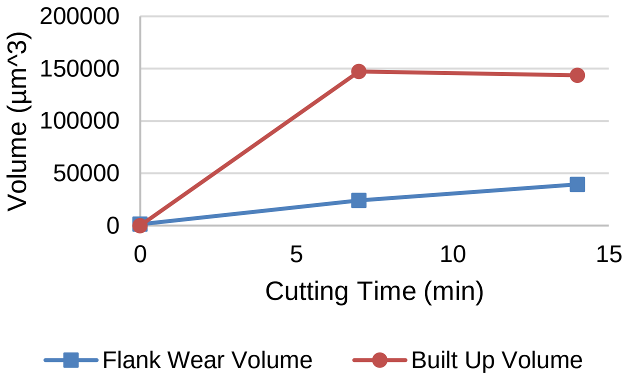

Figure 10. Flank Wear and Built Up Volume as a Function of Cutting Time, 3% Cobalt

2% Cobalt

The purple area in Figure 11displays a similar trend that was seen on the 4% carbide tool; a large brittle fracture that affects the geometry of the cutting edge. Unlike the 4% tool, this fracture resulted in an ERA of -35°.

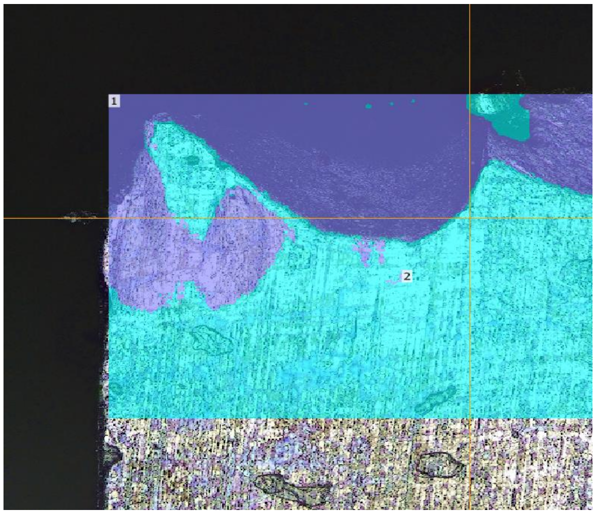

Figure 11. Wear Land as Measured by the VKX Microscope, 200x Magnification, 2% Cobalt, 14 Minutes of Cutting

Figure 12 plots the wear and BUE volume as a function of cutting time. BUE was not a significant presence on the tool at any point. This likely indicates that the brittle fracture occurred early on, leaving little flat area for the BUE to adhere. Wear volume was about 15 times the magnitude of the wear measured on the 10% tool. This is due to the brittle fracture.

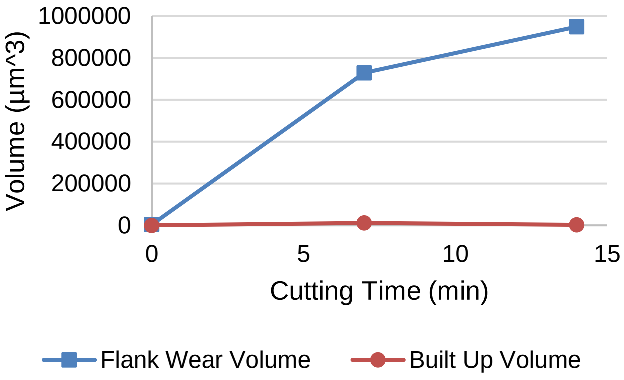

Figure 12. Flank Wear and Built Up Volume as a Function of Cutting Time, 2% Cobalt

Figure 13 displays all four wear curves as a function of cutting time. The 10% curve is hidden behind the 3% curve, these tools didn't suffer a catastrophic brittle fracture during cutting. The 2% and 4% tools showed a much larger wear area than the others due to these fracture events.

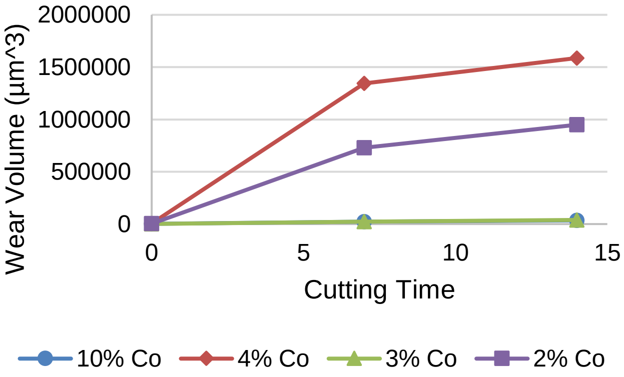

Figure 13. Wear Curves for all Four Grades Tested as a Function of Cutting Time

FORCES AND FINISH

During the first cut, after 7 minutes, and after 14 minutes of cutting, main cutting and tangential forces were recorded via a piezoelectric load cell. Figure 14 and Figure 15 show how these forces changed with elapsed time for each grade of carbide.

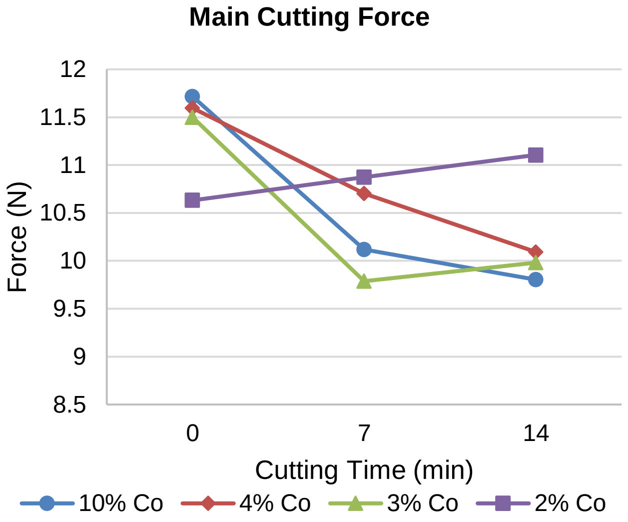

Figure 14. Main Cutting Force as a Function of Elapsed Cutting Time for all Four Grades of Tool

As seen in Figure 14, main cutting force decreased for all grades except for the 2% grade. This is the hardest of the four tools. This decrease in forces could be considered a "break in" behavior. Increases in the forces experienced by the 2% grade are a result of the large negative effective rake angle caused by the brittle fracture event [8]. The average magnitudes of the forces for each grade are not significantly different across the elapsed time period.

Tangential forces for each grade are shown in Figure 15. Similarly to main cutting force, tangential force decreased for the three softer (higher cobalt) grades as the tool wore. Likely the same mechanisms as seen in Figure 14 describe this "break-in" behavior. The negative ERA likely describes the increase in tangential force experienced by the 2% grade. The average magnitude of the tangential forces is not significantly different for the three hardest grades (lowest cobalt). However, the soft 10% grade showed a significant decrease in tangential force, reflecting a lower coefficient of friction for this tool. This is likely due to a decrease in seizure events on the rake face of the tool. Decreasing tangential and cutting forces on the three softer grades is likely due to the positive ERAs taken on by the tool [8].

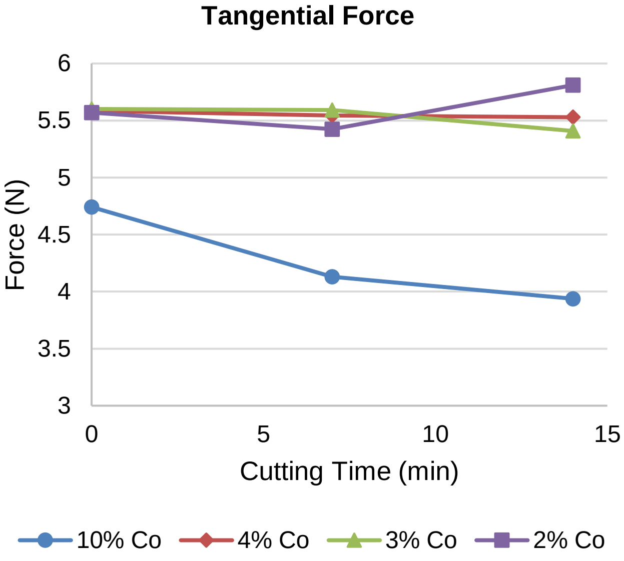

Figure 15. Tangential Force as a Function of Elapsed Cutting Time for all Four Grades of Tool

Figure 16 shows the average values of main cutting and tangential force for each of the grades. As mentioned above, main cutting force did not change as a function of carbide content, while tangential force did, but only for the highest cobalt content grade.

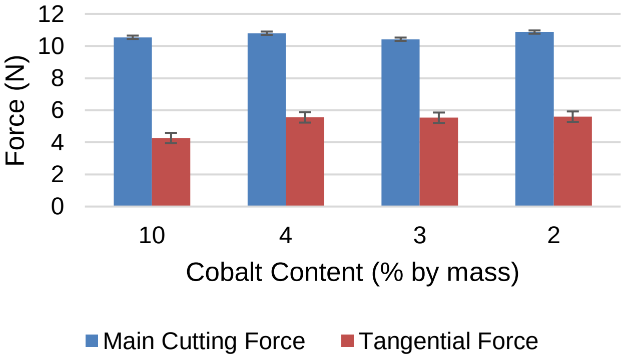

Figure 16. Time Averaged Cutting and Tangential Forces for all Four Grades of Tool

Figure 17 shows the relationship between cobalt content, elapsed cutting time, and Rq (rms) surface roughness of the machined part. The 3 and 4 % cobalt grades displayed little change in surface roughness across the time period. This indicates that a change in effective rake angle is likely the cause for the decrease in forces [8], rather than rounding of the cutting edge profile, which would cause continually degrading roughness. For the soft 10% cobalt tool, the finish improved as the tool wore. This indicates that some tool nose rounding likely occurred in addition to some possible effective rake angle increases. The increased roughness experienced by the hard 2% cobalt tool is likely due to increased plowing as the cutting edge deteriorated after brittle fracture.

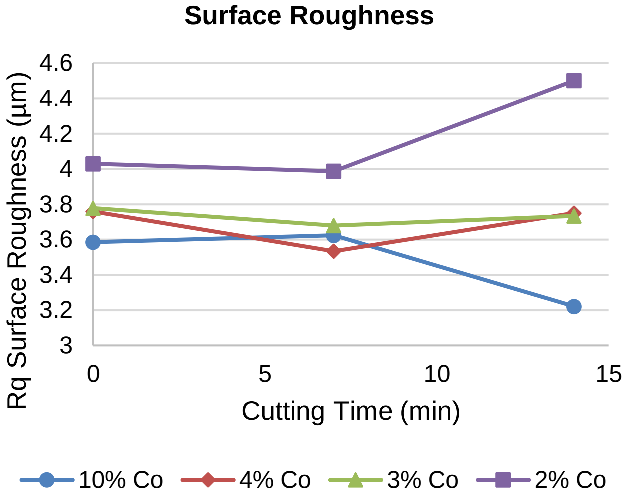

Figure 17. Surface Roughness as a Function of Elapsed Cutting Time for all Four Grades of Tool

Figure 18 displays the relationship between average roughness, average coefficient of friction and cobalt content. Average surface roughness decreased as the cobalt content was increased. Coefficient of friction did not change significantly for the three harder tools. A significant decrease in friction was experienced for the 10% cobalt tool. This is due to decreased events of seizures. This also explains the improved surface roughness produced by the softer tool.

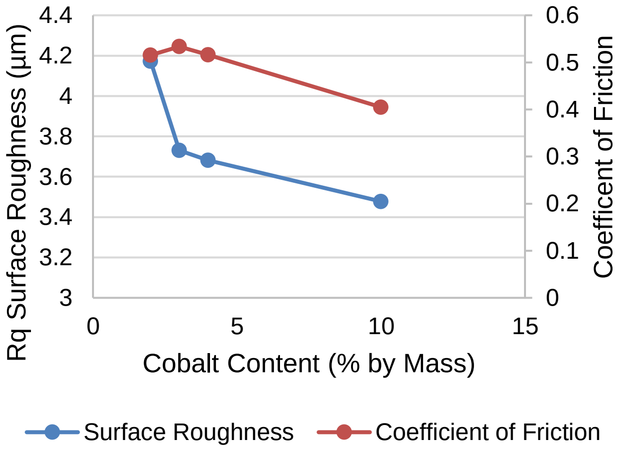

Figure 18. Average Machined Surface Roughness and Coefficient of Friction as a Function of Cobalt Content

CONCLUSIONS

Two of the three harder grades suffered from a brittle fracture event, causing skewed wear volume numbers and altering surface roughness and forces. While decreased fracture toughness is expected with lower cobalt content, these events might have been avoided with proper edge preparation. On the two tools in which brittle fracture did not occur, wear and BUE volume were very similar. Longer cutting time would be required to differentiate wear behavior.

While average cutting force didn't seem to be a function of cobalt content, the change in forces with respect to time did. The three softer grades caused decreasing forces as the tool wore while the hardest grade increased forces. These trends are due to the effective rake angles that the nominally zero rake tools took on due to wear and BUE. Positive ERAs reduced forces, while negative ERAs increase forces. This agrees with literature [8].

Tangential forces were very similar among the three harder grades. However, it significantly decreased on the soft 10% grade. This decrease in friction is likely due to a reduction in seizure events on the rake face of the tool.

Surface roughness was better on three softer grades, likely due to a decrease in seizure events caused by the negative ERA on the hardest grade. 10% cobalt produced the best surface finish on average. From these results, it would be recommended that a higher cobalt content tool should be used for dry finishing passes on mild steel due to its increased fracture toughness and lower coefficient of friction, which resulted in the best average surface roughness.

In order to improve the study in the future: a) cutting time needs to be increased to further exaggerated wear differences between the different grades b) replicates of each experiment need to be conducted and c) proper edge preparation needs to be done.

ACKNOWLEDGMENTS

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