An experimental study of flank wear in the end milling of AISI 316 stainless steel with coated carbide inserts

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Abstract. Stainless steel 316 is a difficult-to-machine iron-based alloys that contain minimum of about 12% of chromium commonly used in marine and aerospace industry. This paper presents an experimental study of the tool wear propagation variations in the end milling of stainless steel 316 with coated carbide inserts. The milling tests were conducted at three different cutting speeds while feed rate and depth of cut were at (0.02, 0.06 and 01) mm/rev and (1, 2 and 3) mm, respectively. The cutting tool used was TiAlN-PVD-multi-layered coated carbides. The effects of cutting speed, cutting tool coating top layer and workpiece material were investigated on the tool life. The results showed that cutting speed significantly affected the machined flank wears values. With increasing cutting speed, the flank wear values decreased. The experimental results showed that significant flank wear was the major and predominant failure mode affecting the tool life.

1. Introduction

According to Baddo [1], the annual consumption of stainless steels has gone up to 5% for two decades. However, recent report by EN [1, 2], showed that stainless steel production has increase globally by 8.3% in 2015 [2]. It was estimated that in 2006, a total of about 4 million tons of stainless steels were used for construction purposes globally [1, 3]. This account for about 14% of total quantity used. AISI 316 Stainless steel have become ever more main-stream materials with growing applications in the industrial, marine, chemical processing and construction industries. Generally, Stainless steels are known to be a difficult to machine materials due to their high propensity to their toughness, work harden and moderately low thermal conductivity ability[3, 4]. Flank wear, a well-known and the most predominant types of tool wear can be seen as the rubbing of the wear land against the machined surface causes damage to the surface, flank wear occurs on the relief face which results in the formation of the wear land [5-9]. It can also be a volumetric loss at the top of the tool tip edge that are mainly caused by abrasion, it manifests at a very low operating speed [10].

According to Ciftci [11], the Surface of coated carbide cutting tools should must be able to develop resistance to abrasive wear, hardness and chemically passive to avoid the tool and the work material from interacting chemically with each other during machining. For these objectives to be achieved, in about 1970, coated carbide tools were technologically advanced and developed. This progress was a substantial development in cutting tool technology [12]. Ciftci [11] further explained that, coated carbides are essentially a cemented carbide insert coated with one or more thin layers of wear-resistant material, such as titanium carbide (TiC), titanium nitride (TiN), (TiAlN) used in this research study and/or aluminum oxide (Al₂O₃).

Further studies carried out by [13-15] revealed that that thin and hard coatings can reduce tool wear and improve tool life and productivity. This discovery has led to a situation whereby most of the carbide
tools used in metal cutting industry are currently multilayered coated. According to Ciftci [11] and [16] conclusions, Higher surface roughness values at lower cutting speeds were ascribed to the high BUE formation tendency. Chipping of the cutting edges, which can seldom be validated by SEM inspections, was also discovered to be accountable for the high surface roughness values [17].

2. Methodology and Machine set up
The experimental setup was conducted on a Deckel Maho DMU 40 mono Block CNC machine of 12,000 rpm maximum spindle speed where milling experiments were conducted with soluble castor oil as coolant. The machine parameters used can be found in Table 1. The flank wear rate on the inserts was observed using an equipped image analyzer called ZEISS stereo Microscope version 20 which provides observations with a magnification as high as 150X. It possesses three focal lenses with motorized zoom expansion and resolution adjustment. The panel combines buttons, joystick and touch screen in a compact design, allowing intelligent control of all microscope functions with real time display of main microscope parameters.

| Machine parameters | Low | medium | high |
|--------------------|-----|--------|------|
| Feed rate (mm/rev) | 58  | 243    | 520  |
| Cutting speed (rpm) | 2900 | 4050   | 5200 |
| Depth of Cut (mm)  | 1   | 2      | 3    |
| Coolant type       |     | Castor oil |  |

2.1 Workpiece
The workpiece that was used in this experiment is AISI 316 stainless steel. This type of stainless steel belongs to the family of austenitic stainless steel 300-series which are generally difficult to machine. It is an austenitic chromium nickel stainless steel containing molybdenum Table 2 and Figure 1(a) and (b). The steel contains high percentage of Nickel than 304 stainless steel. The resultant composition of this material in Table 2 and Figures 1(a) and (b) give these steels much improved corrosion resistance in many aggressive environments. The molybdenum addition ensures more resistance to pitting and cavies’ corrosion in chloride containing media, sea water and chemical environments such as sulfuric acid compounds, phosphoric and acetic acids. 316 stainless steel with the properties in Table 2 offers good strength and creep resistance and possess excellent mechanical and corrosion-resistant properties at sub-zero temperatures. When machining 316 stainless steel, unlike other austenitic steels, it alloys group machines with a rough and stringy swarf., rigidly supported tools with as heavy a cut as possible is used to prevent glazing.

| General Chemical properties of 316 Stainless steel (%) | C        | Mn      | P     | S      | Si      | Cr  | Ni  | N  | Mo  |
|------------------------------------------------------|---------|---------|-------|--------|--------|-----|-----|----|-----|
|                                                      | 0.08max | 2max    | 0.045max | 0.03max | 0.75max | 16-18 | 10-14 | 0.1max | 2-3 |

2.2 Cutting tool
The cutting tests were conducted using a 16-mm diameter Indexable end-mill with two cutting edges. Figure 2 shows a sample picture of the tool from Kennametal. KC725M Grade Inserts utilized are composed of carbide grade with a TiAIN coating. A high-performance TiAlN-PVD-coated carbide grade for milling steel, stainless steel and ductile cast iron. The good thermal shock resistance of the
substrate makes this grade ideal for both wet and dry machining. KC725M is primarily for use in general and heavy machining.

![Typical microstructure of 316 SS](image1)
![The dimension of the work piece used (200 x 55 x 25) mm.](image2)

**Figure 1**: (a) Typical microstructure of 316 SS (b) The dimension of the work piece used (200 x 55 x 25) mm.

![Indexable tool inserts and tool holder from Kennametal](image3)

Li=12.06, S=3.7, W=6.74, Bs=1.3, Re=1.19, hm=0.082

**Figure 2**: Indexable tool inserts and tool holder from Kennametal

3. Analysis and Discussion

3.1 Effects of cutting Speed on Tool life

The combination of cutting speeds at constant feeds has a tremendous significant importance on the value of tool life. In the cutting tests carried out on AISI 316 stainless steel, an increase in cutting speed at a constant feed produced a visible reduction in tool life. Looking closely at Figures 3 (a) (b) and (c), an increase in cutting speed validates the reduction in tool life. It is also noticeable that even at constant feed rate of various cutting speed, a reduction in tool life is also experienced. In Figure 3(a), at high speeds of 310mm/min and feeds of 0.06 mm/rev, almost no effect was observed on the tool for the first 10 mins of tool life. Consequently, the same trend was observed in Figures (b) and (c). However, at low feed of 0.02mm/rev (Figure 3(b)), the tool life almost double at high speed of 97mm/min when compare to Figure 3(c) at feed rate of 0.06 mm/rev and speed about 310mm/min. this could due to chip load at this feed rate. To conclude on the effect of cutting speed on tool life, one can say highspeed end milling of AISI 316 should be carried out at low values of feed such as 0.02mm/rev.
3.2 Modes of wear during machining AISI 316 stainless steel

Built-up edge, crater wear and Notch wear are the types of flank wears that are noticeable on the tool cutting edge at the location corresponding to the original surface of the machined part see Figures 4(a), 4(b) and Figures 5(a), 5(b). Flank wear is a groove development that occurs concurrently on the face and flank of the tool at the depth of cut. This may be because of Machining parts with severe (hard or oxidized) surfaces. It occurs because the original work surface is harder and more abrasive than the internal material due to work hardening from previous machining. Flank wear was noticeable as a mode of failure observed during the cutting experiments.
Figure 4: (a) Flank Wears at cutting speed $V = 205\text{m/min}$ (b) Flank wear at cutting speed $V = 261\text{m/min}$

Figure 5: (a) Flank Wear at cutting speed $V = 146\text{m/min}$ (b) Flank Wear at cutting speed $V = 205\text{m/min}$

This mode was clearly noticeable at conditions of the two highest cutting speeds (205 and 261) m/min and low feeds (0.02 mm/rev) used in this study (see Figures 4(a), 4(b) and Figures 5 (a), 5(b)). This failure is however due to the work hardening effect produced in the workpiece surface after being machined at low feeds. On the tool face, crater wear appears as a shallow trough in localized areas (Figure 5a). This patterns indicate that the tool material is diffusing into the chip. It causes very high temperatures on the tool face especially when carrying out test without coolant. Crater wear will keep rising until it reaches the cutting edge leading to chipping or fracture. Another common flank wear that was noticeable was BUE which is caused by low surface feet per minute or poor shearing action of the workpiece material (Figures 5(a) and (b)). The work piece material is stick to the face of the tool due
to sometimes an attraction of the work material to the insert or its coating which eventually results into chipping of the tool cutting edges.

4. Conclusion
The conclusions drawn from this study on end-milling of AISI 316 stainless steel using a newly developed multilayered coated carbide tool is that an increase in cutting speed resulted in a dramatic reduction in tool life. The tool lives of the highest three cutting speeds used in this study (146, 205 and 261 m/min) were not too far from one another while the tool life at Spindle speed = 2900rpm (cutting speed = 146m/min) was almost doubled and the most predominant mode of tool failure was flank wear. It was also discovered that Built Up Edge happened at high values of cutting speeds (205 and 261 m/min) and feeds, which come to an agreement with the findings by Abou el Hossein et [17] and Sun et [16]. Crater wear was noticeable because of material being diffused into the chip at a very high temperature when machining at a low cutting speed of 146m/min. This type of wear (crater) could be worse if coolant is not applied. A low feed of 0.02m/rev will be ideal to maximize the tool life when machining AISI 316 Stainless steel.

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