Cutting Energy and Wear in Bandsawing Operation When Cutting Ti-6Al-4V Alloy

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ABSTRACT

Titanium and its alloys have found wide application in the aerospace, automotive and biomedical industries owing to their good strength to weight ratio and excellent corrosion resistance. However, these alloys have poor machinability, which is attributed to their high strength and low thermal conductivity leading to high cutting temperatures. This paper reports on the experimental data associated with the forces, and specific cutting energy with the wear of tungsten carbide tipped (TCT) bandsaw blades while machining titanium alloy Ti-6Al-4V.

1. INTRODUCTION

Bandsawing is a widely used metal cutting operation in a variety of industries, cutting-of to size raw material for secondary processes. This cutting-off process can offer an advantage of high automation possibilities, low kef loss, straightness of cut, good surface finish and a long tool life [1]. Bandsawing is now a well understood process, due to the scientific work carried out by several researchers [2-5], which was stimulated by demands for higher efficiency, better accuracy and improved surface quality.

The characteristic feature of the material removal in bandsawing operation is the function of the cutting edge with limited sharpness (5 μm to 15 μm) with the layer of material being removed also being very small (5 μm to 50 μm). The cutting action in bandsawing operation is intermittent, with several cutting edges in contact with the workpiece material. This is one of the major differences between the sawing operation and the other single-point cutting operation, e.g. turning, where only one sharp edge is in contact with the workpiece material. Moreover, the chip needs to be accommodated in the gullet and ejected at the end of the cut [6].

Titanium and its alloys are used extensively in aerospace owing to their excellent combination of high specific strength (strength-to-weight ratio), which is maintained at elevated temperature, their fracture resistant characteristics, and their exceptional resistance to corrosion. They are also being used increasingly (or being considered for use) in other industrial and commercial applications, such as petroleum refining, chemical processing, surgical implantation, pollution control, nuclear waste storage, food processing, and marine applications [7]. They have become established engineering materials available in a range of alloys and in all the wrought forms, such as billet, bar, plate, sheet, strip, hollows, extrusions and wire. The machinability of titanium and its alloys is generally considered to be poor owing to several inherent properties of the materials. Titanium is chemically reactive and, therefore, has a tendency to weld to the cutting tool during machining, thus leading to chipping and premature tool failure. Its low thermal conductivity increases the temperature at the tool/workpiece interface, which affects the tool life adversely. Additionally, its high strength maintained at elevated temperature and its low modulus of elasticity further impairs its machinability.

Traditionally, high speed steels (HSS) and cemented carbides have been employed to cut/machine titanium alloys. The main disadvantage of high speed steel cutting tools is that it undergoes severe plastic deformation when cutting at elevated temperatures above 600 ºC. Tungsten carbide cutting tools have proven their superiority in

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almost all the machining process and interrupted cutting (end milling, tapping and broaching) of these difficult to cut alloys. Technical feasibility of further improvement of cutting properties and life of tool materials by design of new compositions has been essentially exhausted [8]. That is why a great deal of attention has been directed towards improvement of life and wear resistance of the metal cutting tools by producing hard surface coatings.

One of the challenges in design of cemented tungsten carbide tools is the optimization of toughness with straight tungsten carbide alloys with the superior crater resistance of alloyed carbides containing high levels of titanium carbide. This has led to the development of coated carbide tools, which amounts for the major portion of all commercial metal cutting inserts sold worldwide.

Different kinds of coatings, physical vapour deposition (PVD) or chemical vapour deposition (CVD), and different coating materials (e.g. TiC, TiN, TiCN, Al_2O_3) have led to their application in specialized areas [9]. Both are used to deposit single and multilayer coatings. In PVD coatings, the deposition temperature is below 600 °C and therefore does not adversely affect the bulk mechanical properties. The use of CVD techniques where the temperatures are in the range of 850-1000 °C means that the substrate material will have to be re-treated to restore the bulk mechanical properties [10]. Moreover, with PVD coatings, the sharpness of the cutting edge is greater, making cutting forces smaller and hence lengthening tool life.

Previous work [6] was related to the bandsawing of steels, using bi-metal bandsaws. This paper reports the initial work of the present research, which is focused on use of un-coated and coated tungsten carbide bandsaws for machining titanium alloy Ti-6Al-4V.

2. Cutting Test Programme

Full product testing is expensive and time-consuming. In the current research work, the performance of the un-coated and coated bandsaw teeth was evaluated using a "single tooth time compression technique" previously developed by Sarwar [11].

2.1. Carbide Teeth Details

All the teeth were examined for any defects, and geometrical features were measured using optical microscope. The details for the uncoated and coated teeth are presented in Table 1.

Table 1: Measured and tabulated properties of the un-coated tooth and TiN coated tooth

	Uncoated tooth	**Coated tooth**
Avg. tooth tip thickness	1.599 mm	1.590mm
Rake angle	9.8 ° (avg)	9.9 ° (avg)
Clearance angle	32.1 ° (avg)	32.2 ° (avg)
Tooth damage	None	None
Appearance		Golden yellow
Cutting edge radius	7 µm (avg)	7 µm (avg)
Microstructure of edge	Tungsten carbide, cobalt binder	Tungsten carbide, cobalt binder
Microstructure of backing material	Tempered martensite	Tempered martensite

2.2. Surface Treatment of the Teeth

A batch of teeth was coated specifically for these tests. They were titanium-nitride coated by Oerlikon Balzers, using the PVD arc evaporation technique, giving the coating a thickness of approximately 5 microns. The chemical composition of the coated teeth is shown in Table 2.

Table 2: Chemical composition of Balzers TiN coated TCT (Tungsten Carbide Tipped) tooth, measured using the EDX. Average of 3 TiN coated teeth

Element	**Titanium**	**Nitrogen**
Avg. Wt. %	82.34	17.66

2.3. Workpiece Material Composition and Hardness

Workpiece material (Ti-6Al-4V) chemical composition and mechanical properties are shown in Table 3 and Table 4 respectively.

Table 3: Chemical composition of Ti-6Al-4V. Measured using the EDX system attached to scanning electron microscope

Element	N	C	Fe	O	Al	V	Ti
Avg. wt%	0.05	0.10	0.30	0.20	60	4.0	Bal.

Table 4: Tensile and mechanical properties of uni-directionally rolled Ti-6Al-4V sheet [12]

	Tensile strength (MPa)	Yield strength/ (MPa)	% elongation	Tensile modulus (GPa)	Hardness Rockwell HRc
Longitudinal	945	870	7	100	32.2
Transverse	1105	1061	7.5	130	33

2.4. Cutting Conditions

Two different feed rates were chosen for the cutting tests, using both the un-coated and coated teeth. These cutting conditions are shown in Table 5.

Table 5: Machining parameters for the cutting tests

	Cutting speed (m/min)	Feed (µm)	Avg. width of cut (mm)
Set A	50	30	1.402
Set B	50	50	1.402

3. Results and Discussions

3.1. SEM Analysis of the New and Un-used teeth

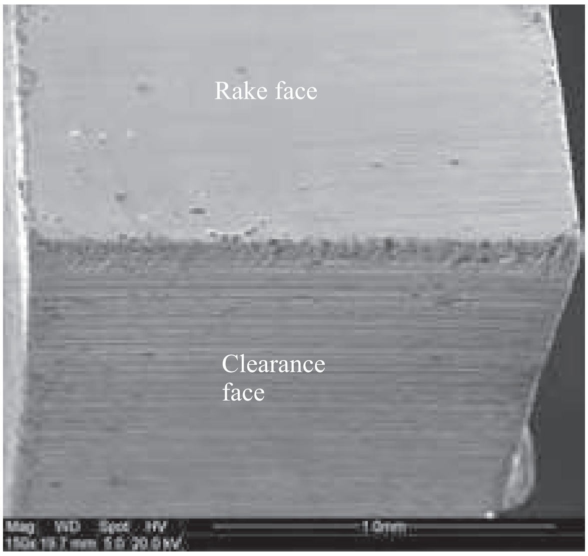
In order to observe the cutting edges of the worn teeth, all the 4 teeth were observed under scanning electron microscope before any tests were carried out. All these are shown in Figure 1.

The edge is smooth and appears to be free of any defects on both the rake and clearance faces. The coating is continuous and smooth on both the faces.

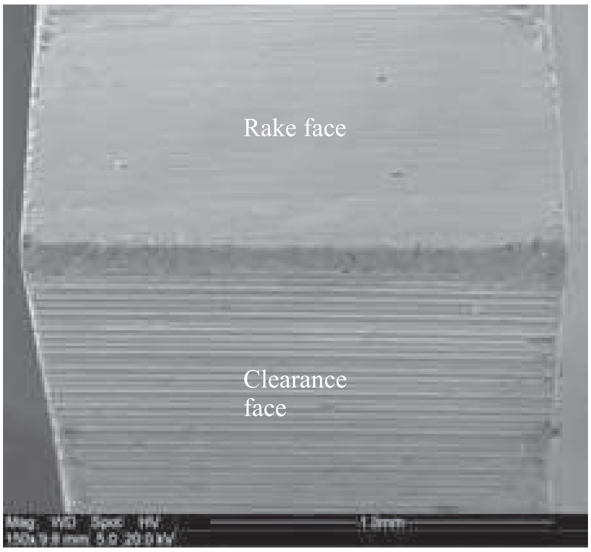
3.2. SEM Analysis of the Teeth after 800 Cuts

The un-coated and coated teeth after performing 800 cuts were observed under the electron microscope in order to observe the wear and the degradation that took place. The images are shown in Figure 2.

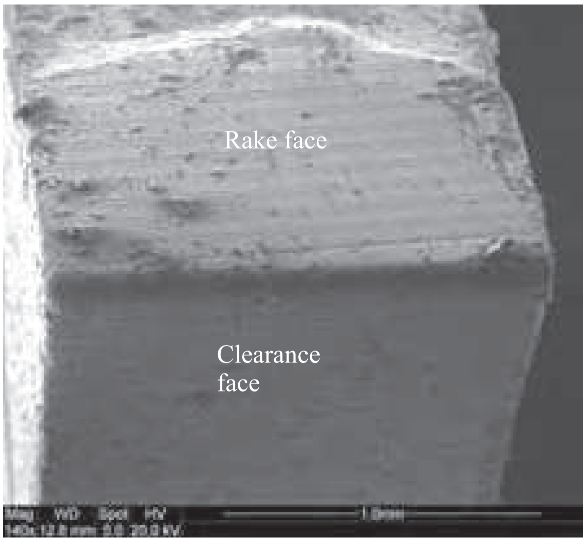
The images show that the cutting edges are intact for both the un-coated and coated teeth, although they seem to be wearing out at one of the corners. This effect is more pronounced in the un-coated teeth compared to the coated teeth.



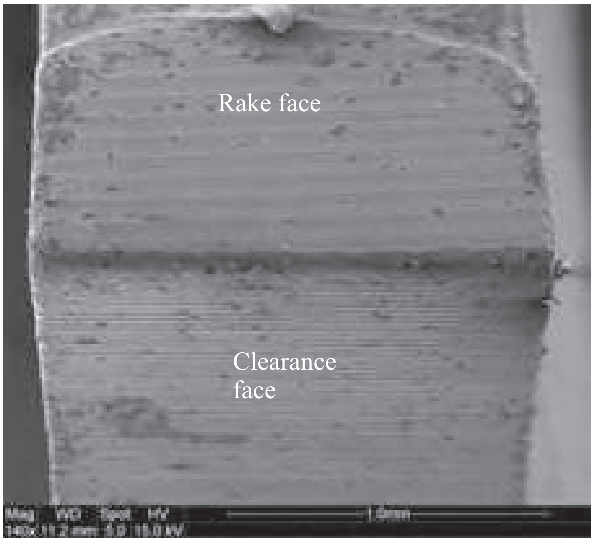
Uncoated Sample A; Depth of cut 30 µm; Un-used



Uncoated Sample B; Depth of cut 50 µm; Un-used



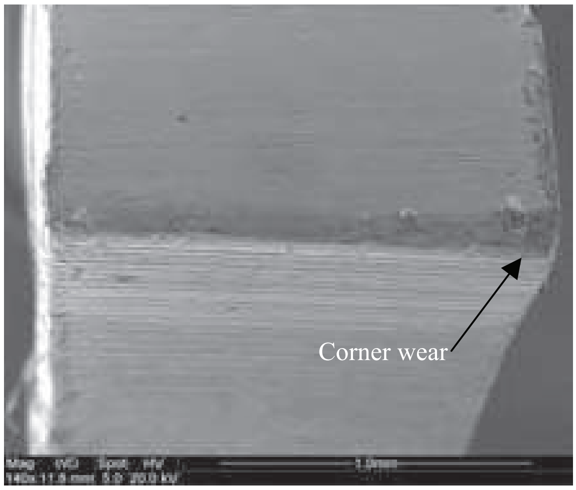
TiN coated Sample A; Depth of cut 30 µm; Un-used



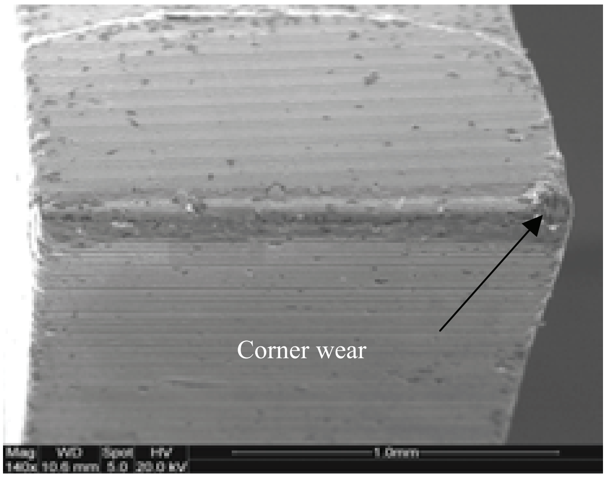
TiN coated Sample B; Depth of cut 50 µm; Un-used

Figure 1: SEM images of the un-used un-coated and coated teeth, showing the morphology of the unused surface

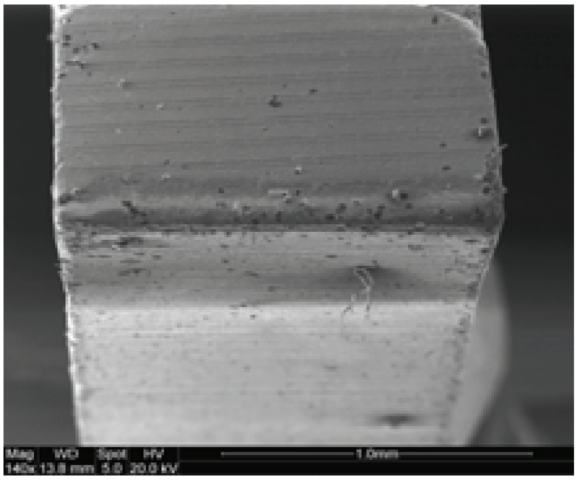
Uncoated Sample A; Depth of cut 30 µm; 800 cuts.



Uncoated Sample B; Depth of cut 50 µm; 800 cuts.



TiN coated Sample A; Depth of cut 30 µm; 800 cuts.

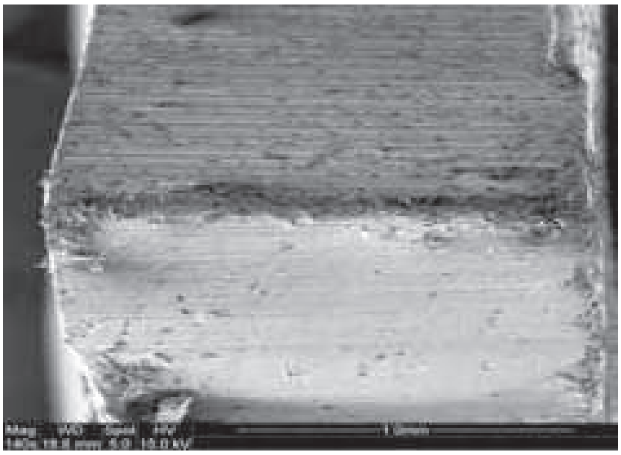


TiN coated Sample B; Depth of cut 50 µm; 800 cuts.

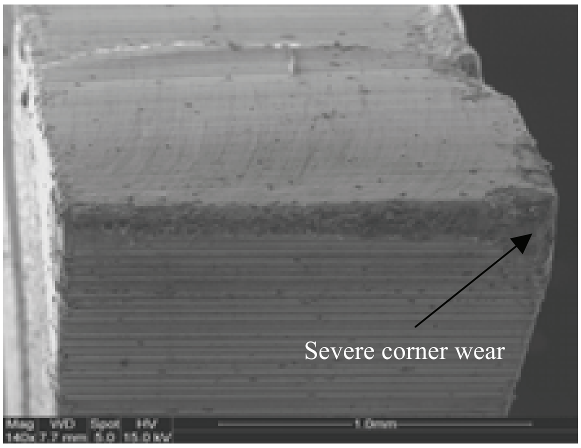
Figure 2: SEM images of the un-coated and coated teeth after 800 cuts, showing the morphology of the cutting edges and the faces

3.3. SEM Analysis of the Teeth After 1500 Cuts

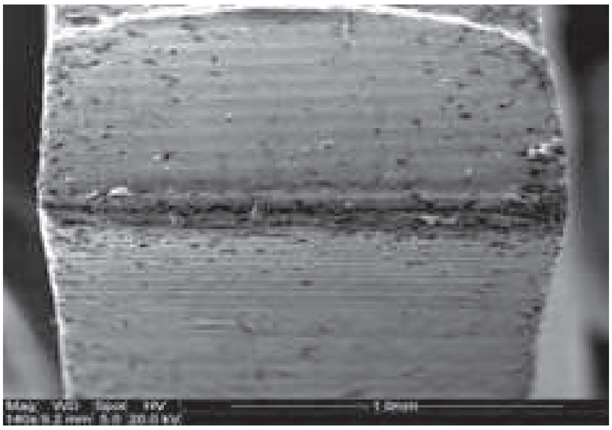
All the teeth (un-coated and coated) after performing 1500 cuts were observed under the electron microscope in order to observe the wear and the degradation that took place. The images are shown in Figure 3. It is evident from the images that the un-coated teeth have experienced a greater degree of wear as compared to the coated teeth. This degradation can be clearly observed in the images shown in Figure 4. The corners of the un-coated teeth have experienced a great degree of wear and degradation, and small particles of the workpiece material seem to adhere to the surface of the un-coated teeth, suggesting that the mechanism of wear is adhesive wear. Although, workpiece particles are also present on the surfaces of the coated teeth, but they are less in number as compared to the particles adhering to the un-coated teeth.



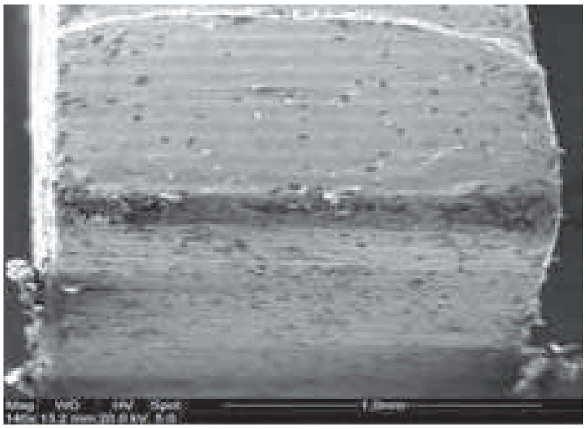
Un-coated Sample A; Depth of cut 30 μm; 1500 cuts



Un-coated Sample B; Depth of cut 50 μm; 1500 cuts

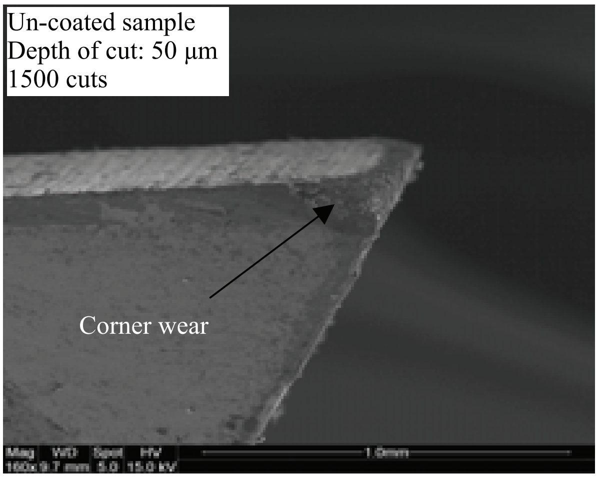


TiN coated Sample A; Depth of cut 30 μm; 1500 cuts



TiN coated Sample B; Depth of cut 50 μm; 1500 cuts

Figure 3: SEM images of the un-coated and coated teeth after 1500 cuts, showing the morphology of the cutting edges and the faces



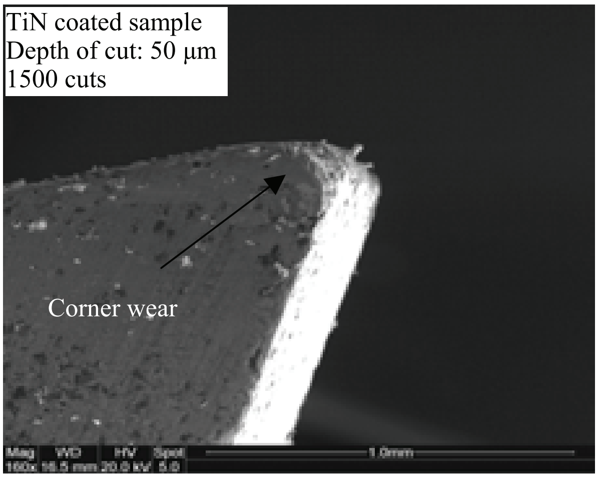


Figure 4: SEM images of the un-coated and TiN-coated teeth, after 1500 cuts, showing the wear at the corners of the edges

3.4. Specific Cutting Energy Determination

The specific cutting energy has been calculated using the following equation:

$$E_{sp} = F_v/A_{chip} \quad (1)$$

Where, E_{sp} = specific cutting energy (J/m^3), F_v = cutting force (N) and A_{chip} = cross-sectional area of un-deformed chip (m^2).

The Esp-value is a measure of the energy required to remove a unit volume of workpiece and will reflect the efficiency of the cutting process.

The specific cutting energy for all the cutting tests were measured and are plotted against the total length of workpiece material machined. The results for the un-coated and coated teeth at 30 µm and 50 µm depth of cut are presented in Figure 5 and Figure 6 respectively.

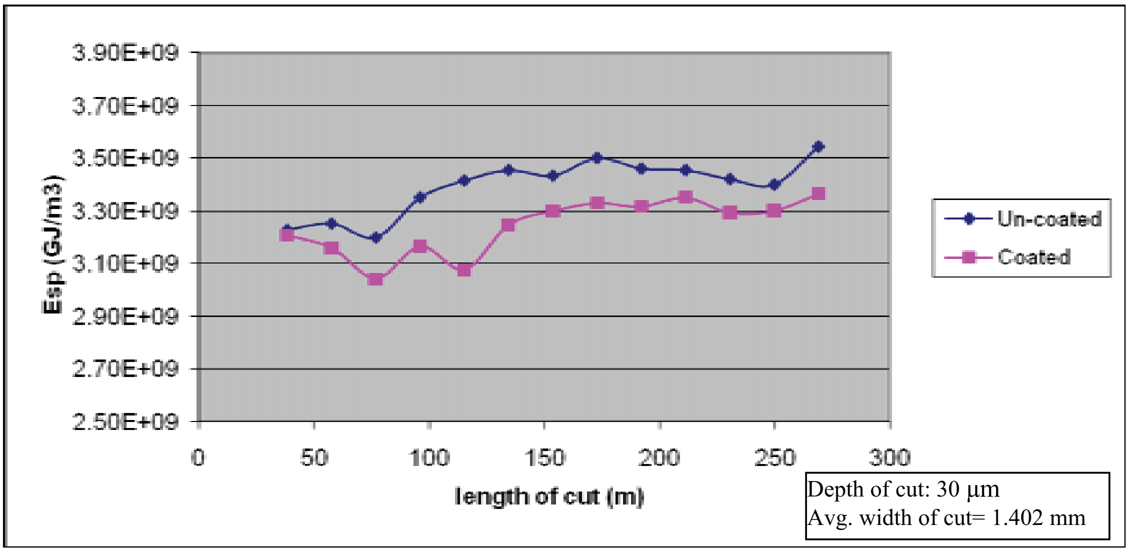


Figure 5: Variation in Esp with the length of cut for the un-coated and coated teeth. Depth of cut: 30 µm, avgerage width of cut: 1.402 mm

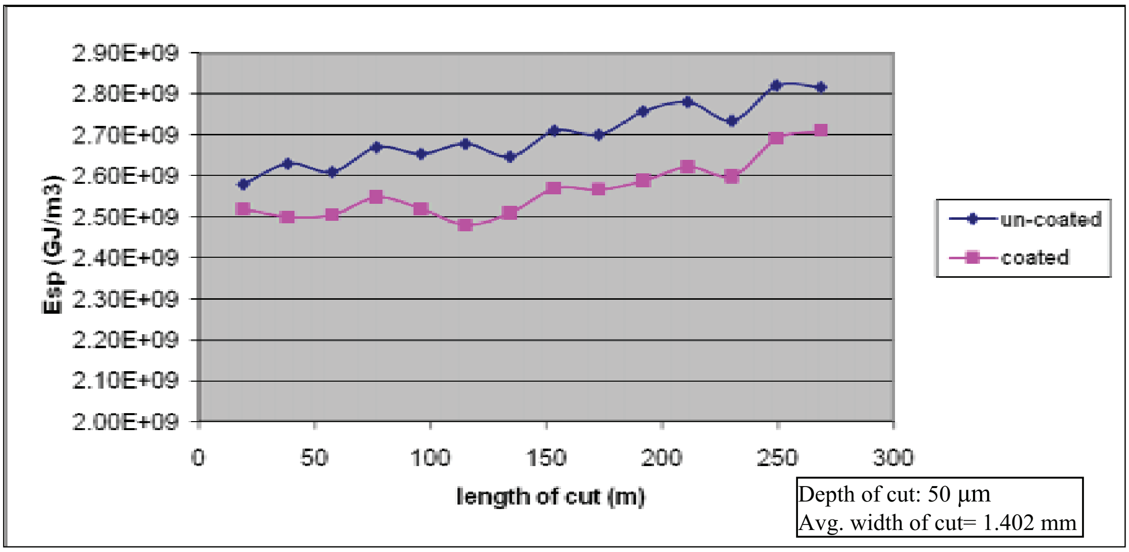


Figure 6: Variation in Esp with the length of cut for the un-coated and coated teeth. Depth of cut: 50 µm, avgerage width of cut: 1.402 mm

The above results show that TiN-coated bandsaw teeth to perform more efficiently based on the specific cutting energy values. The lower specific cutting energy is due to the combination of the following:

- Immediate formation of smooth and continuous chip as soon as the cutting edge comes into contact with the workpiece material.
- The flow of the chip along the rake face without any hindrance, which is due to the improved friction conditions created at the tool/ workpiece interface because of the TiN coating.

The reduction in the Esp clearly indicates the improvement in cutting conditions and the cutting efficiency when cutting with TiN-coated teeth. It is also evident from the energy values as well as from the SEM images that there was less adhesion of the workpiece material on the tool, because of the TiN coatings.

4. Conclusions

- The PVD TiN coatings can be applied to the segments of the bandsaw blades, used for machining titanium alloys.
- Simulation cutting tests have proved that TiN coatings improve cutting performance and life, as demonstrated by the improvement in specific cutting energies.

References

[1] *J.V. Owen; "Bandsaws join the mainstream", Manufacturing Engineering, 1997.*

[2] *M. Sarwar; "Performance characteristics of Titanium-Nitride coated bandsaws", IITT-International, 1986.*

[3] *P.M. Archer, S.R. Bradbury and M. Sarwar; "Evaluation of performance and wear characteristics of bandsaw blades", 5th National Conference of production Research, Huddersfield Polytechnic, 1989.*

[4] *M. Sarwar and P. J. Thompson, "Cutting Actions of blunt tools", International MTDR Conference, Manchester, 1981.*

[5] *M. M. Ahmad, B. Hogan and E. Goode, "Effect of Machining parameters and workpiece shape on bandsawing process", International Journal of Machine Tools and Manufacture, Vol.29, No.2, pp 173-183, 1989.*

[6] *M. Sarwar, M. Persson and H. Hellbergh; "Wear and failure modes in bandsawing operation when cutting ball bearing steels", Wear, Vol.259, No.7-12, pp.1144-1150, 2005.*

[7] *E.M. Trent and P.K. Wright, "Metal Cutting", Butterworth-Hinemann, Boston, 2000.*

[8] *L.A. Dobrzanski, "Structure and properties of high speed steels with wear resistant cases or coatings", Journal of Materials Processing Technology, Vol.109, No.1-2, pp.44-51, 2001.*

[9] *J. Kopac, "Influence of cutting material and coating on tool quality and tool life", Journal of Materials Processing Technology, Vol.78, No.1-3, pp.95-103, 1998.*

[10] *C. Subramanian and K.N. Strafford, "Review of multi-component and multilayer coatings for tribological applications", Wear, Vol.165, No.1, pp.85-95, 1993.*

[11] *M. Sarwar, Confidential Report, Northumbria University, UK.*

[12] *ASM Handbook Volume 2: Properties and Selection: Nonferrous Alloys and Special-Purpose Materials, 10th Edition, 1994.*