Analysis of Surface Roughness, Micro hardness Transition and Specific Energy use Relationship during the outside Turning of Grade 5 Titanium Alloy, Ti6Al4V, using Carbide Tipped Tools on a CNC Lathe

[1]Nicholas Tayisepi*, [2]Emmanuel Ndala, [2]Portia Mupfumira, [2]Garikayi V Nyakujara, [2]Oscar Gwatidzo and [2]Miccurrie D Hudube

[1]Department of Industrial and Manufacturing Engineering, Faculty of Engineering, National University of Science and Technology (NUST), Bulawayo, ZIMBABWE
[2]Department of Industrial and Manufacturing Engineering, Faculty of Engineering, Harare Institute of Technology (HIT), Harare, ZIMBABWE

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Abstract — Modern global manufacturers, especially those of highly specialised application materials such titanium alloy, Ti6Al4V, desire to achieve higher productivity using the most inexpensive, energy efficient and quality machining manufacturing processes in order to remain competitive in the market. The ability of manufacturers to maintain consistent machining standards of quality products derive significantly from the quality of materials and manufacturing knowledge base available to guide the manufacturing planning process. Some quality characteristics of Ti6Al4V machining, such as surface integrity and energy efficient cutting are difficult to ensure that they are achieved during machining due to the widely established difficulties of the cutting of the material. This experimental study focused on the surface integrity – surface roughness, microstructural distortions and micro hardness – and energy efficiency analysis during the mechanical machining of grade 5 titanium alloy. Various measuring tools and devices were applied in generating the analysis characterization of the machining response parameters outlined. Machining process analysis results showed that as the cutting parameters are varied, during the turning of Ti6Al4V, there is significant physical transformation which affect the component surface integrity as well as the energy use efficiency of the process.

Key words — Energy efficiency, Machining, micro hardness, Surface integrity, Ti6Al4V.

I. INTRODUCTION

Manufacturers of titanium alloy components, in the different application sectors, desire that the machined component materials exhibit good mechanical properties, high machinability, and superior surface integrity. Titanium alloys are broadly used in diverse industries such as the biomedical, aerospace, automotive, petrochemical and marine, due to their high strength, excellent toughness, good corrosion resistance, great thermal resistance, and lightweight and good biocompatibility properties. However, the low heat conductivity of titanium alloys, and other attributes such as low elastic modulus and high chemical reactivity at elevated temperatures, makes the machinability of titanium alloys difficult compared to steel alloys, particularly sustenance of the surface integrity of the machining engineered component. Most of the titanium structural components, particularly those used in the aerospace industry, are finish machined (Ozel & Ulutan, 2012). Thus, it is necessary to satisfy the surface integrity requirements of the job when machining the components. Surface integrity refer to the sum total of all the rudiments that pronounce all the conditions subsisting on or at the surface and sub-surface of a machined component work piece, (Choudhury & EI-Baradie, 1997). The surface integrity challenges generated by metal removal operations include the nature of surface topography, topology, residual stresses, surface cracking, surface micro hardness, surface roughness and metallurgy alterations on the component surface. The surface integrity component of surface topography defines the roughness, 'lay' or texture or smoothness of this outermost stratum of the work piece, representing the interfacing film of the component with the environment; whilst the surface metallurgy explain the character of the altered sub-surface layers just below the surface, with respect to the main matrix material as a base. Metallurgical alterations assessment focuses on the effect of the manufacturing processes on the embedded properties of the work piece material, (Sharma & Agarwal, 2017). Thus, surface integrity defines beyond the topological or geometric attributes of surfaces and their inherent chemical and physical properties. Mechanical and metallurgical characteristics and properties are as well encompassed in the same. To the extent that machining engineered titanium alloy component properties such as the service life, fatigue strength, corrosion resistance and tribological performance are influenced by surface integrity, it highlights the essential nature of its consideration in manufacturing operations. Therefore, it is of paramount importance to evaluate the finish machinability of grade 5 titanium alloy, Ti6Al4V with intent to analysing and characterising the surface integrity trends of the material as machined with positive rake angle carbide tipped tools on a CNC lathe machine. This experimental study presents the analysis of the surface integrity machinability factors – surface roughness, microstructure alteration and micro hardness transition; as well as specific energy consumption of the cutting process during flood cooled turning of Ti-6Al-4V titanium alloy using carbide tipped tool inserts, under the influence of varied cutting parameters – cutting speed, feed rate and constant depth of cut of 0.5 mm.

Surface roughness is explained as the third up to sixth order deviation of the machined surface from the nominal profile form. The order of surface deviations is explained and specified in the international standards, (Dangar, & Mukherjee, 2014). According to these standards definition, first and second order definitions refer to surface form deviation – circularity, cylindricity, flatness and waviness which are mainly attributed to the machine tool errors, workpiece deformation, vibration, workpiece material inhormogenities, erroneous set-ups and clamping, (Vanrusselt , et al., 2022). Intermittent grooves, dilapidations and cracks, which are associated with the shape and cutting edges condition, process kinematics and chip formation process, refer to what constitute third and fourth order surface deviations. Surface deviations relating to the workpiece material structure and connected to the physical- chemical mechanisms which act on the grain and lattice scale (slip, oxidation, diffusion, residual stress, inter alia) refer to the fifth and sixth order deviations, (Subhajit , et al., 2014). The machined component surface topology or the outermost layers of the machined surfaces display a great lot of both micro-geometrical and macro geometrical deviations from the ideal geometrical surface. In practice, different surface deviations orders are overlaid and generate typical surface roughness contour outlines as shown in Figure 1. Surface roughness is a vital parameter which indicate the machined component product visual suitability for purpose, (Suleiman & Bashir, 2010). It plays a significant role in many applications such as aesthetic requirements, quality assessment standard pass grade for parts subject to fatigue loads in application, precision fits, and fastener holes. Surface roughness inflicts one of the greatest significant restraints for the selection of cutting parameters and machine tools in development of a process. The surface quality of finish turned components is affected by varying degrees of a number of factors such as machine tool and work piece setup, feed rate, inherent characteristics of the work material, work hardness, cutting speed, cutting tool edge condition, depth of cut, cutting edge angles, tool nose radius and tool stability of chatter, and use of cutting fluids. Flood cooling and constant depth of cut were implemented in this experimental study whilst the cutting speed and feed rate were varied to different respective levels.

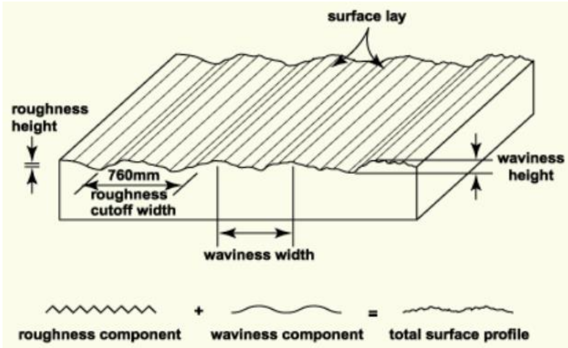


Figure 1. Surface roughness (Sharma & Agarwal, 2017)

Furthermore, surface roughness is an important quality feature which influences the mechanical performance of machined components as well as production costs, (Kalantari, et al., 2020). Surface integrity features – roughness and micro hardness – play an extensive role in determining how the machined object will interface with the environment in which it function. The concept of surface integrity achievement, of machining manufactured components had been investigated by many researchers, for reasons such as understanding the design of efficient machine tool based manufacturing operations. Typically, for example, Hamdi et. Al (2010), examined the influence of feed rate, cutting speed, depth and work piece hardness of cut on surface roughness and cutting force in the hard turning of AISI H11 steel with cubic boron nitride (CBN) 7020. Haresh & Sanket (2014), experimentally studied power consumption and surface roughness effects and characteristics generated during turning operation of EN-31 alloy steel with coated tungsten carbide tool, TiN+Al2O3+TiCN, under different cutting parameters - spindle speed, depth of cut and feed rate. Esmaeil et al (2009) investigated the hard machining of AISI D3, effect of four cutting parameters using response surface methodology and central composite experimental design, in attempting to optimise surface finish and cutting force, and realized increase in these performance parameters under the operation of the established optimum cutting parameters, (Esmaeil , et al., 2009) . Kalantari, et al, (2020) research findings established that the performance and product life of complex machined parts, utilized in the leading industries, depends on the surface integrity aspects such as microhardness, surface roughness, Ra and grain size. Box Behnken experimental design methodology was utilized by Suleiman and Bashir (2010) to study surface roughness using multiple linear regression analysis. They hierarchically ordered the influence of feed rate, cutting speed and spindle speed influence on the surface roughness, (Suleiman & Bashir, 2010). The machinability of Ti6Al4V alloy, for good surface quality and energy use efficiency, is a vital aspect which requires further extensive understanding by the machining industry. This study analyses the surface integrity components – surface roughness, microstructure alterations and micro hardness -, to establish the accentuation trends of cutting parameters on the machined component. The study outcome is anticipated to provide vital insights for parameter selection to get improved results on surface roughness, microhardness and specific energy use during the machining of Ti6Al4V alloy.

II. MATERIALS AND METHODS

The full factorial design of experiments plan was utilised for planning the 18 machining experiments of Ti-alloy as resultant from the input variable parameters combination generated from Table 1. The experiments were conducted on a Siemens controller run Efamatic Computer Numerically Controlled (CNC) lathe machine with a maximum spindle speed of 4500 RPM, shown in the experimental setup in Figure 2.

TABLE I: CODING LEVELS OF THE INPUT (INDEPENDENT) VARIABLE TEST PARAMETERS

Cutting parameter	Notation	Units	Symbol	Coding of Factor Levels					
				1	2	3	4	5	6
Cutting speed	v_c	m/min	X_1	50	70	100	150	200	250
Feed rate	f_n	mm/rev	X_2	0.1	0.2	0.3			
Depth	*DoC*	mm	X_3	0.5	0.5	0.5	0.5	0.5	0.5

Depth of cut, constant

The experimental process involved the outside turning of Ti6Al4V which was supplied in cylindrical billet form of diameter 75.4 mm. The specimens machining linear length used was 180 mm per single machining run. A cleaning cut of 0.5 mm depth was removed from the surface of each specimen, using a tool tip not involved in the experimental process, in order to avoid possibility of vibrations induced by specimen non concentricity during the experiment machining runs.

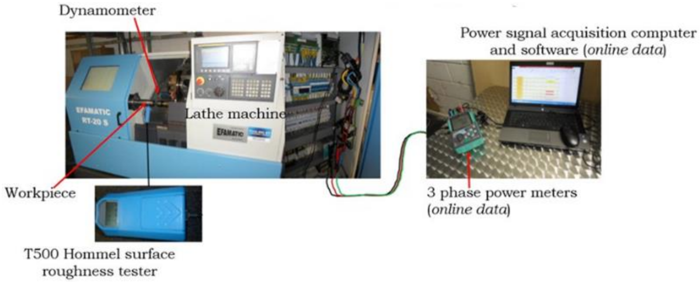


Figure 2. Experimental machinery and equipment set-up

2.1 Surface Roughness Measurements

The main surface roughness evaluation parameter utilized is the arithmetical mean roughness value (R_a), was assessed, in accordance with the ISO 4287-1997/Amd 1: 2009 standard (ISO, 2009). The hand held Hommel surface tester T500, shown in Figure 3, was the device used to measure, R_a, the surface quality standard for acceptance or rejection of the machined component.

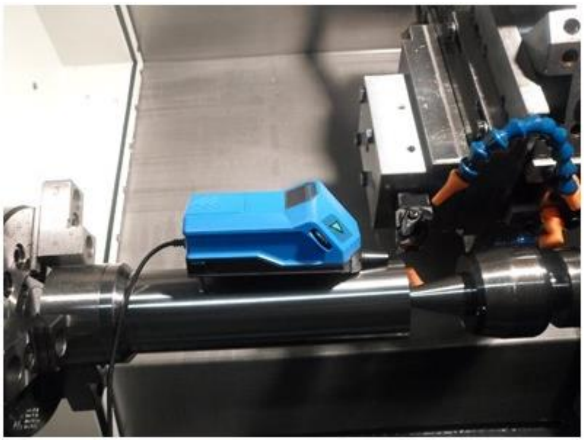


Figure 3. Surface measurement

The tester probe maximum traverse distance is 6 mm having a sampling length of 4.8 mm with measurement range of 0.05 – 10.0 µm (R_a) and testing accuracy of ± 0.15 µm.

The surface roughness measurements were taken at four (4) different points along the circumference of the specimen workpiece after every machining pass, 180 mm linear length, after drying the workpiece. The average of the four measurement readings would be recorded.

2.2 Energy Power Measurements

The Kyoritsu Electrical three Phase Digital Power Meter, Model 6301, (Figure 4) was utilised in Power measurements recording. The power measuring device has an indicated meter frequency accuracy of ±3dgt.

KEW POWER PLUS 2 software power signal recordings were captured and read off an Acer Aspire 5551 Laptop running on Windows 10. The energy measurements were conducted in conformance with the ISO standard ISO/DIS 14955-2 (ISO, 2015) which prescribe the methods for measuring energy supplied to machine tools and machine tool components.

2.3 Micro-hardness Measurements

In order to qualitatively evaluate the surface topography changes, (Griffith, 2001), on the machined surface, small sections - equivalent of 15 x 15 x 10 mm^3 volume blocks - were sawed off the machined specimens. The machined specimen were cut into smaller segments in order to expose the required sub-surfaces for micro hardness and metallurgical changes examination and measurement. In order to conduct the micro hardness and micro-structure changes assessment, the sawn samples were hot mounted in Leco PR-25 Hot mounting machine, hand held during mechanical grinding and polishing on a Struers Labo Pol-25 Grinding and Polishing. machine. The polished sample specimens were then etched in Kroll reagent solution which comprised 94% water, 4% nitric acid (HNO_3) and 2% hydrofluoric acid (HF). The samples

Figure 4. Three phase Kyoritsu power meter

2.3 Micro-hardness Measurements

were dipped in the chemical etchant for a period of 15 – 20 seconds and cleaned in running water before being dried and placed under the optical microscope lens for observation. Grain size and distortions were observed in the sub-surface zone of the mounted specimens.

The micrograph images, of the parent material, presented in Figure 5, denote no visible distortions in the material. The grains were fairly distributed across the section. Figure 6 shows the digital micro hardness testing machine.

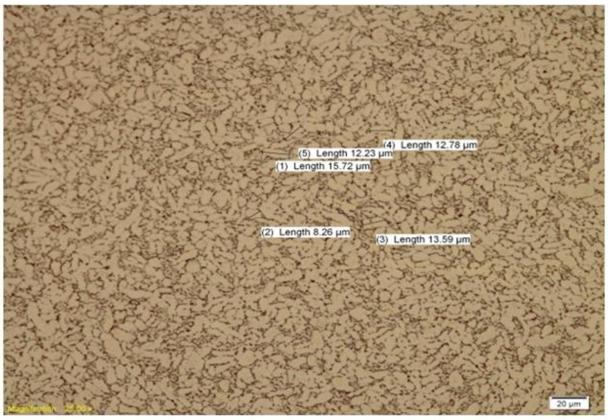


Figure 5. Micrograph of Ti6Al4V alloy parent material grain structure showing average grain sizes

Figure 5 TIME HM-6 digital Micro-hardness testing machine

II RESULTS

A. Cutting parameters, Surface Roughness and energy interactions

The results of the surface integrity characteristic – surface roughness - of the machined specimens are presented under this section. Surface roughness is important in controlling the quality and purposeful performance of machined components (Bonneya, et al., 2007). The interaction and influence of the machining parameters on the surface roughness, especially, was analysed in this study and the main outcomes established are presented in the ensuing. The interaction relationship of the surface roughness, under the effect of the variable cutting parameters influence, and the energy use and efficiency of the machining process is also presented.

The average Surface roughness, R_a, measurements were recorded after every machining pass in accordance with the procedure of surface roughness testing outlined above. No special preparation of the sample was required for the hand held machine surface roughness measurement process. The specimens were only dried of the coolant after each machining pass in readiness to taking the surface roughness measurement.

The results presented Figure 6 show the variation of surface roughness with rising cutting speed. It is evident, from the graph that, as cutting speed rises the surface roughness decreases. The plot presented surface roughness R_a, R_{max} and R_z result plots which all tended to reduce with increasing cutting speed. The results corroborate with the findings by Mawanga (Mawanga, 2012) who studied the surface integrity of high speed machining of grade 4 titanium alloy.

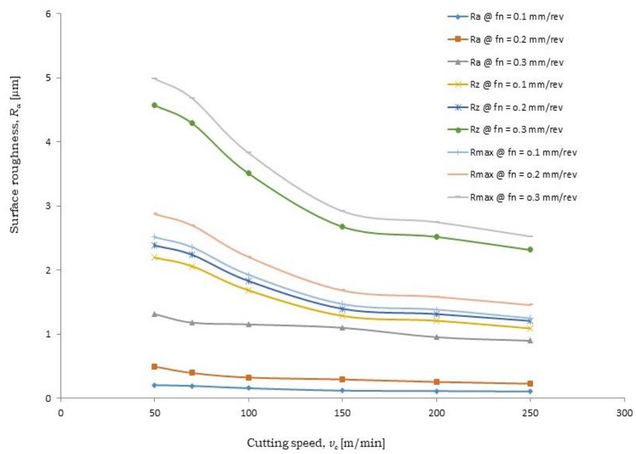


Figure 6. Surface roughness – R_a, R_z, R_{max} as a function of cutting speed (microns)

The results plot of the variation of surface roughness, R_a, with cutting speed at the three feed rates are presented in Figure 7, wherein it is clear that higher cutting speeds produce finer surface finish in all the 3 feed rates. Thus. The signature surface profile, R_a, however seem to show coarsening of the specimen surface texture, with increasing feed rate, much as it also decreased with cutting speed increase.

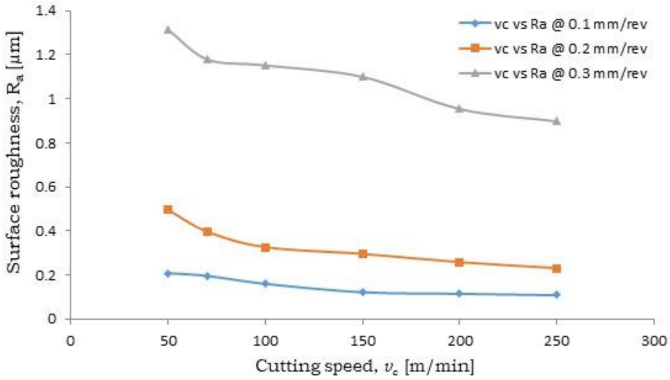


Figure 7. Surface roughness, R_a vs cutting speed at changing feed rates

The effect of the variable cutting parameters, on the surface roughness, can be shown in interrelatedness to the energy use efficiency of the machining process. Results shown in Figure 8, exhibit the interaction of work piece surface roughness and specific cutting energy, respectively, as function of the feed rate. The plotted results show that increasing the feed rate resulted in rougher work piece surfaces, but, simultaneously, the specific cutting energy will be reducing. Whilst, the variation of total machining energy, ETME, actual cutting energy, EACU and specific cutting energy, SE respectively, in interaction with the surface roughness, R_a are presented in Figure 9. ETME, refer to the gross amount of energy required to run the machine cutting process as well as the auxiliary functions, whilst EACU refer to the exact energy amount

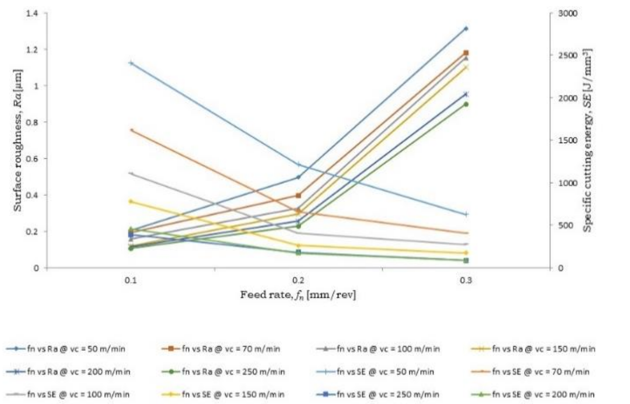


Figure 8 Surface roughness (R_a) and specific cutting energy (SE) vs feed rate (f_n)

required to execute the actual material separation process by the machining or cutting process excluding the machine none cutting functions, and SE explains the amount of energy required to separate a unit volume of material removed by the cutting process from the specimen workpiece. The energy plot profile curvature, in Figure 9, suggest the existence of an optimum operating point in order to realise the intended surface roughness at an energy optimum operating parameters combination.

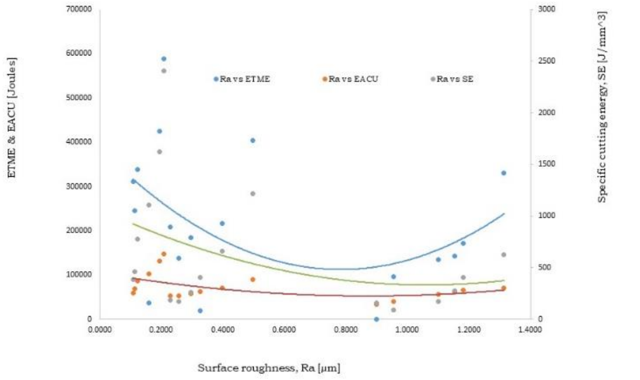


Figure 9 Total machining energy (ETME), actual cutting energy (EACU) and specific cutting energy (SE) vs surface roughness, Ra

The variation of specific cutting energy as a function of changing surface roughness is presented in Figure 10, wherein the mathematical relationship between surface roughness and the specific cutting energy is given by equation displayed on the plot.

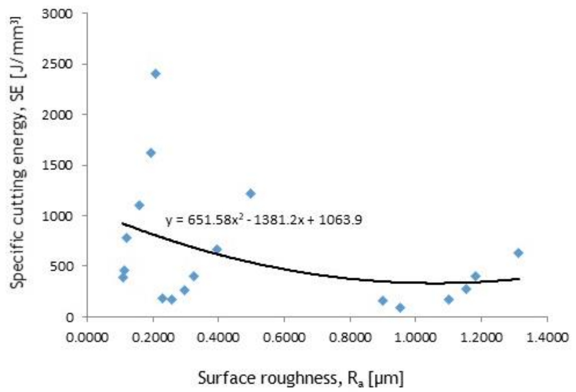


Figure 10. Specific cutting energy as a function of R_a

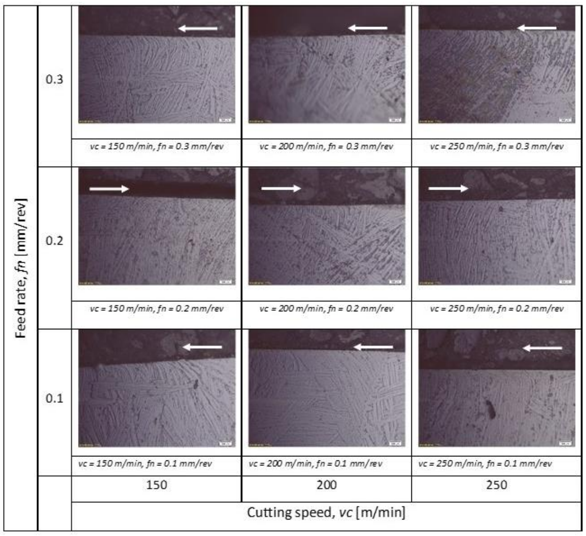
B. Microstructure analysis results

Material processed by mechanical machining experience surface and sub-surface microstructural changes deriving from the thermo-mechanical nature effects of machining. Such microstructural changes signpost an inclination towards important mechanical properties modification of the machined component (Che-Haron & Jawaid , 2005). The structural alterations, which the material experience at micro level, include inter alia, grain size changes and distortions due to exposure to the shearing mechanical forces and heat concentration generated at the cutting zone, during the machining process.

As regards the micro-structure analysis and micro-hardness measurement, in this study, samples preparation was carried out as explained above. The aim of microstructural analysis was to evaluate the influence of the machining process on the surface and subsurface microstructure, of the Ti6Al4V workpieces, as well the energy use interactions. The grain size, orientation with respect to the machining direction and grain microstructural distortions were the investigated parameters. These aspects of the machining process include grain morphology, grain orientation and dislocation, material phase transformation and dynamic recrystallization.

The results presented, in Tables 2 and 3, display the microstructure microscopic view of the machined surface resulting from new and worn tool tip, generated during the turning of Ti6Al4V at the high cutting speed ranges (v_c = 150 – 250 m/min and f_n = 0.1 - 0.3 mm/rev). The direction of progression of the cutting action is indicated by the white arrows. The microstructure microscopic views showed a machining affected film/zone, of the specimens, of 5 – 10 μm depth at the surface. The layer had grains which showed a pattern of having been affected by refinement, deformation and re-orientation aligned with the main cutting direction of traverse (application) of the cutting tool on the machined job.

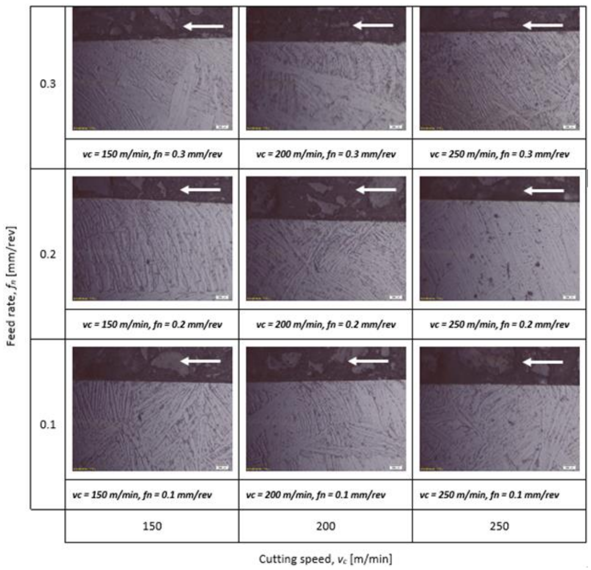
Table 2. The effects of cutting speed and feed rate on the work piece sub-surface with a new cutting tool edge



The sub-surface deformation process is prompted by the existence of severe shear stresses produced during high speed machining. The microstructure results in Table 2 specimens seem to display more deformation effect from application of a new tool as compared to Table 3 specimens results, from a worn tool. Adducing from these results, it can be established that worn tools do not have much effect on the machined work piece sub-surface layer as much as new tools which tended to produce rougher surfaces than worn tools. These result findings, of microstructure distortions, tend to complement the types of defect findings which were reported by Che-Haron & Jawaid, (2005).

Furthermore, there was also no other clear pattern of evidence of sub-surface defects - such as cracks, laps and visible tears (Jawahir, et al., 2011) consistent with the adjusted cutting conditions - after turning Ti6Al4V alloy under the flood cooling conditions. The nature of the microstructural changes witnessed, on the assessed specimens, give testimony to the thermo-mechanical loading chronicle of the machining process on the specimens material.

Table 3. The Effect of Cutting Speed and Feed Rate on the Work piece Surface Integrity with a Worn Cutting Tool Edge



C. Micro-hardness analysis results

A material hardness concerns its resistance to scratching or indentation by other hard bodies. Mechanical machining induces micro hardness alteration on the material's mechanical hardness property at the surface and sub-surface layers levels due to the stress cycles these material layers gets exposed to during the process of being machined. An investigation of the micro hardness of the machined Ti6Al4V was carried out in this study in order to obtain a better understanding of this characteristic behaviour of the material as it relates to the variation of the cutting parameters. The Knoop hardness (H_K) testing technique was the method used to analyse micro hardness in this research, with the intention to relate the effect of cutting parameters with the resultant surface and sub-surface layer mechanical properties, of the machined component. The hardness of a materials, typically lies between 3 times, respectively, of the yield strength and the ultimate tensile strength (UTS) (Zhang , et al., 2011).

The specimen preparation for the micro hardness measurements and the equipment used for testing were explained above. The bulk material was measured nearby the centre of the diameter 75.4 mm workpiece and was established to be 367 H_K. That was the average hardness utilised as the bulk material reference hardness in this research. Results shown in graphs cluster plots in Tables 4 to Table 10 graphically present the micro-hardness results. The legend label average hardness (Ave Hardness) in the 7 graphs relate to the bulk material hardness.

According to the Tables of graphed results, a comparison of the mechanical properties – micro hardness – of the bulk material and the machined specimens surface and sub-surface, it is evident that there is significant increase in the hardness in the machined components surface and sub-surface layers. Evident also is the fluctuation of the micro hardness state of the machined surfaces between micro hardness increase and decrease, due to thermal softening as shown by the undulations in the curve plots of the graphs. This study established, through the 7 graphs cluster ensuing(Figure 11 to Figure 17), that on average the micro hardness of the machined surface and sub-surface layers increased by an average of 513.73 H_K compared to the bulk material micro hardness of 367 H_K, which indicates an average micro hardness percentage increase of 40%.

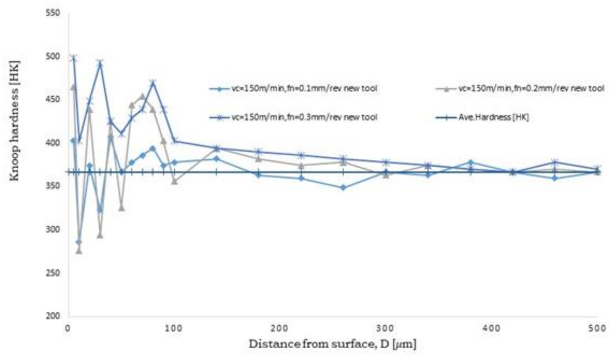


Figure 11. *Micro-hardness versus distance from the surface at v_c = 150 m/min with new tool (Average hardness is 367 $\pm$ 10 HK)*

Maximum micro hardness value of 498.4 H_K (35.8% hardness increase above the bulk material hardness of 367 H_K) occurs at the depth of 5 μm at the cutting speed of 150 m/min and a feed rate of 0.3 mm/rev.

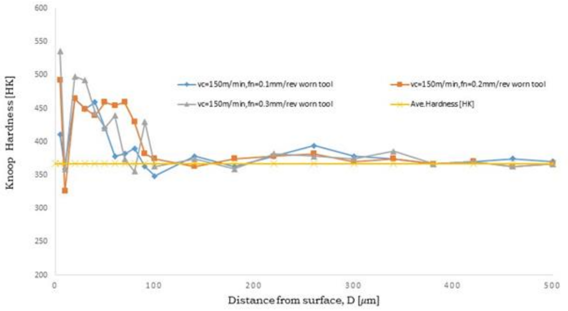


Figure 12. Micro-Hardness versus Distance from the Surface at v_c = 150 m/min with Worn Tool (Ave. hardness is 367±10H_K)

Highest micro hardness of 535 H_K (45.8% increase from bulk material value) is experienced at 5 μm below the surface at the cutting speed of 150 m/min and feed rate of 0.3 mm/rev.

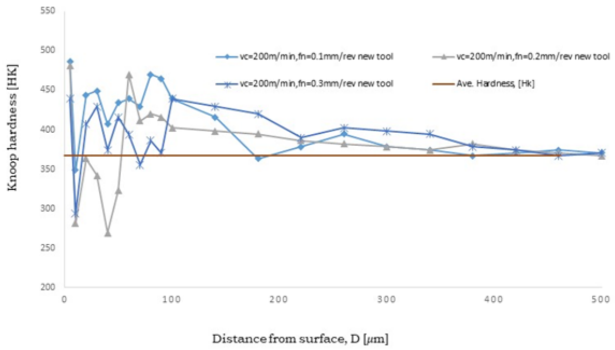


Figure 13. Micro-hardness versus Distance from the Surface at v_c = 200 m/min with New Tool (Ave. hardness is 367±10H_K)

Peak micro hardness values of 480.97 H_K, (an increase of 31.1%), occurred at the feed rate of 0.2 mm/rev respectively at a depth of 5 μm

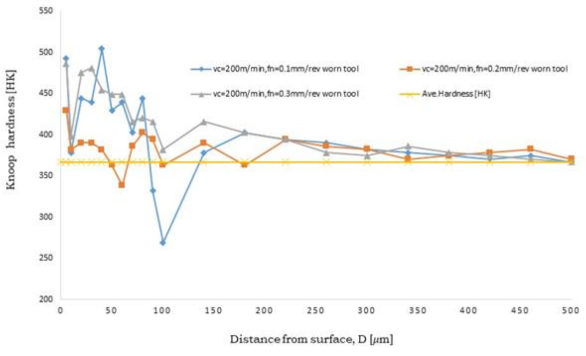


Figure 14. Micro-hardness versus Distance from the Surface at v_c = 200 m/min with Worn Tool (Ave. hardness is 367±10HK)

The micro hardness peaks to 486.6 H_K (an increase of 32.6%) at the feed rate of 0.3 mm/rev on the 200 m/min cutting speed at the depth of 5 μm. Thermal softening occurs about 100 μm depth from the surface when cutting at 200 m/min and feed rate of 0.1 mm/rev for a worn tool.

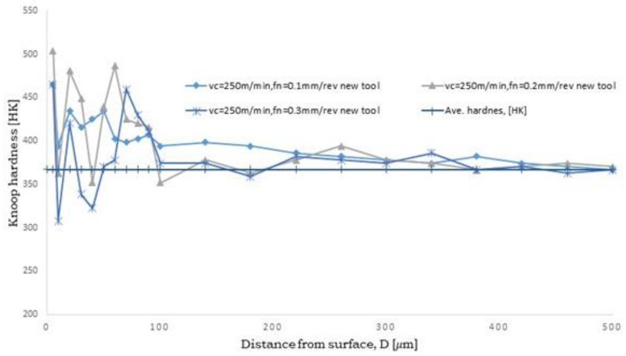


Figure 15. Micro-hardness versus Distance from the Surface at v_c = 250 m/min with New Tool (Ave. hardness is 367±10H_K)

Highest micro hardness measured was 504.15 H_K. This represents an increase of 37.4% from the bulk material hardness value of 367 H_K and it occurred at a feed rate 0.2 mm/rev at a depth of 5 μm from the surface.

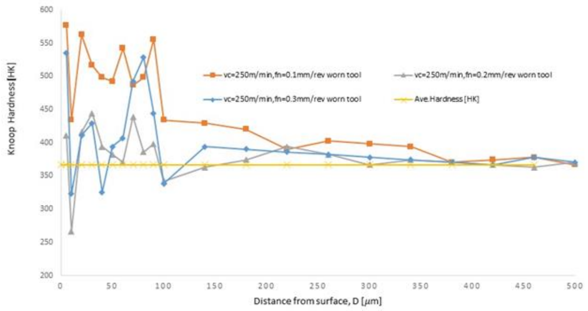


Figure 5.106 Micro-hardness versus Distance from the Surface at v_c = 250 m/min with Worn Tool (Ave. hardness is 367±10HK)

Figure 16. Micro-hardness versus Distance from the Surface at v_c = 250 m/min with Worn Tool (Ave. hardness is 367±10HK)

Highest micro hardness recorded was 577.26H_K (a 57.3% increase on the bulk hardness of material, 367 H_K) obtained when machining at cutting speed of 250m/min and feed rate of 0.1mm at a depth of 5 μm. micro hardness reduction of 12.1% (322.65 H_K) at 0.3 mm/rev feed rate within the depth interval of 30 – 50 μm.

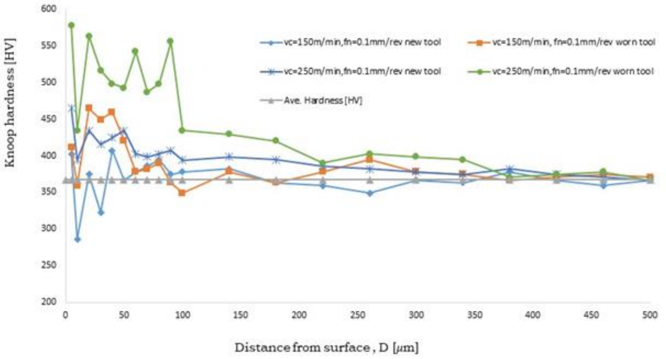


Figure 17. *Micro-hardness versus Distance from the Surface at v_c = 150 m/min and 250 m/min at feed rate f_n = 0.1 mm/rev with new and worn tool respectively (Ave. hardness is 367 ± 10HK)*

The results show general dominance of micro hardening from 5 – 100 μm distance below the surface at cutting speeds 150 m/min and 250 m/min and both tool conditions, except the softening experienced between 5 – 40 μm below the surface when machining at 150 m/min at feed rate of 0.1 mm/rev with a new tool.

The micro hardness results presented above attest the underlying consequence that the machining process have on the surface and subsurface micro hardness performance of the machined component. Generally, there was an increase in the micro hardness detected for all the cutting parameter combinations between the depths of 5 μm and 200 μm. Micro hardness change had been detected along the radial direction of all the machined specimens (Figures 11 – 17). The micro hardness gradient was typified by work hardening deriving from the machining process. The work piece surface and sub-surface micro hardness gradient tended to decrease from the machined surface to the bulk material hardness in the depth range of 5 μm to 500 μm. Generally, the micro-hardness effect inclined to decreasing towards the bulk material hardness below the surface in all the cases.

The increase, in workpiece surface and sub-surface, micro hardness emanates from the effect of imbalance in the heat generated between tool/workpiece interface and that absorbed by the workpiece surface and subsurface. Thus, causing the material to locally melt and intermittently cooling, during the shearing that occur during the material separation process under cutting. The decrease in micro hardness (apparent in all the graph plots – Table 4 to Table 10) is attributable to the heat prompted thermal softening, of the material rather, which occurs in the cutting zone due to the shearing process which happen during the cutting. The fact that Ti6Al4V is not a good conductor of heat, entails that the heat generated - at the cutting zone - remains concentrated in the cutting zone, (Mawanga, 2012). That prompts soaking and softening, of the workpiece material and the cutting tool, around the cutting zone just underneath the surface.

IV CONCLUSION

The experimental study sought to carry out an analysis of surface roughness, micro hardness transition and specific energy use relationship during the outside turning of Grade 5 Titanium Alloy, Ti6Al4V, using carbide tipped tools on a CNC Lathe. The aim was to establish clear understanding on the transformation processes which take place on these machining response parameters as the variable input parameters are changed during the machining process of Ti6Al4V alloy. This knowledge base is vital in enhancing clarity of the cutting process condition transition state to the titanium machining industry. Machining experiments were conducted on the CNC lathe machine, online measurements were recorded, offline measurements were taken and some samples were collected for further analyses using the various equipment and devices as explained. After evaluation and analysis of the results, the following conclusions were reached:

Component surface roughness decreases as the cutting speed increases, however this condition is also associated with rapid tool wear when machining Ti6Al4V due to its poor thermal conductivity. Higher feed rates are also associated with surface roughness coarsening as well as component surface microstructural distortion. Specific energy of the machining process decreased as the cutting speed and feed rate were increased suggesting energy efficient machining improvement as the cutting conditions were increased to a higher range implying higher material removal process.

Mechanical machining processed material undergo surface and sub-surface microstructural changes due to the effects of thermo-mechanical nature of machining. Such microstructural alterations suggest an inclination towards significant mechanical properties alteration of the machined component (Che-Haron & Jawaid , 2005; Nouari & Makich , 2014). In the Ti6Al4V alloy samples analysed in this research, there was evidence of plastic deformation of the machined surface of the top layer with a film layer of 5 – 10 μm where the grains showed a pattern of grain refinement and reorientation towards the direction of traverse (application) of the cutting tool on the machined job.

In all instances of the cutting conditions arrangement, work hardening of the deformed top layer - beneath the machined surface up to a depth of 500 μm - higher granular distortion and micro hardness, than the bulk material hardness, was determined to exist. On the other hand, annealing of the material - caused by thermal softening due to the heat generated from the tool/work interaction at the friction prone cutting zone - caused the subsurface layers to soften below the average hardness of the bulk material of the workpiece also at different depth intervals. Worn tools tended to affect the machined surfaces differently and gave higher surface distortion and micro hardness than new tools.

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