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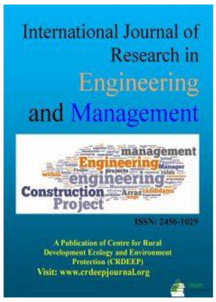

<u>**Full Length Research Paper**</u>

Characterisation of Energy Efficiency Affecting Machining Response Parameters with Cutting Conditions during the Turning Operations of Ti-Alloy Ti6Al4V

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ABSTRACT

Optimising energy usage is an important factor for cost control as well for economic, social and environmental sustainability of manufacturing processes. Energy use reduction, of machining processes, is a key demand facing machining production enterprises. Energy efficiency reveals an extensive field of research and has become increasingly significant in fulfilling multiple requirements in ecological, economic and legislative activities. Energy consumption in cutting processes is still not well understood. In high speed cutting (HSC) factors such as chip formation play an important role towards understanding energy management. In this study the effect of chip formation on energy efficiency was experimentally investigated. Machining parameters were varied in order to understand their impact on energy efficiency during the machining process. Process level deformation of the material was analysed for chip formation - aspects such as chip shear angle, segmentation frequency, chip ratio and chip thickness with regards to how they affect energy use during turning of Ti6Al4V. The research aimed to tackle the challenges of energy optimization during machining and to get an insight about the energy efficient machining of titanium alloys. Turning experiments were conducted with coated carbide tools. Results showed that chip segmentation is consistent with energy consumption minimization. Also the cutting parameters, f_n and v_c significantly affect response parameters such as chip morphology and simultaneously have an impact on energy use efficiency. Further, results showed that chip formation parameters such as chip ratio, segmentation shear angle and the chip speeds in the deformation zone, are significantly affected by the cutting parameters setting whilst specific cutting energy decreases with increasing cutting parameters. Overall it can be concluded that it is feasible to monitor the energy consumption of the machining process by observing the chip system once a determinate optimum point had been established. Recommendation for further work is indicated.

Introduction and background

Environmentalists lobbying, legislation enforcement by national governments and economic pressure require that manufacturing enterprises, particularly machinists of titanium alloys components, reduce energy consumption and greenhouse gases (carbon) emissions from their manufacturing activities (Guo, et al., 2012). The machine tool is a main energy consuming device in the manufacturing enterprise. As such its energy use modelling and energy efficiency evaluation form the basis of energy saving in manufacturing as strides are made towards sustainability of the machining process. Ti6Al4V (Grade 5 titanium alloy also commonly known as Ti-alloys) is the most popular titanium alloy in mainstream use today. It is widely used in the aerospace, automotive and biomedical industries because of its high specific strength, high strength-to-weight ratio, high temperature strength and toughness and exceptionally superb corrosion resistance. Notwithstanding the attractive advantages outlined, the machinability of titanium alloys is difficult due to their low thermal conductivity and diffusivity, low elasticity modulus, high hardness at elevated temperature, and high chemical reactivity at elevated temperatures over 500°C (Veiga, et al., 2013; Baker, et al., 2002; Bagley & Mass, 1960). The combination of low thermal conductivity and a very thin chip results in very high cutting temperature concentrated in a small area on the tool-chip interface.

When machining titanium alloys at increased productivity rates characterised by high material removal rates tool life decreases rapidly due to thermal softening effects (Oosthuizen, et al., 2013). As such, machining is one of the main cost-determining factors of the machining produced titanium alloy components (Baker,, et al., 2003). Also the machining of titanium alloy is resources and energy intensive (Sun , et al., July 14-16, 2010).

Machining operations uses a tool to remove material from the surface of a workpiece whilst forming the desired contour profile of the item through a chip formation process. Ti-alloys exhibit serrated and cyclical chip formation regimes resulting in detrimental force fluctuation and tool vibrations which causes chatter marks on the jobs (Bagley & Mass, 1960). Chip formation and its morphology are important features of metal machining as they yield important information on the cutting process itself. The titanium alloys segmented chips form where the deformation of the chip is inhomogeneous with regions of strong and weak deformation alternating, leading to a serrated back side of the chip (Oosthuizen, et al., 2010). Chip segmentation occurs during the machining of titanium alloys when the rate of decrease in strength resulting from a local increase in temperature equals or exceeds the rate of increase in strength due to strain hardening in the primary shear zone. Due to the low thermal conductivity of titanium, the shear energy on the shear plane increases the temperature, thus softening the material and this leads to more strain in the same shear plane (Shaw & Vyas, 1998 ; Bejjani , et al., 2011). Daymi et al (2009) argued that chip segmentation by shear localisation is a desirable phenomenon during the machining of hard-to-machine materials due to the fact that it reduces the level of cutting forces through improved chip evacuation process. According to Cook (1953), increasing the cutting speed results in increased temperature in the primary deformation zone and when the temperature softening effect in the primary deformation zone is stronger than the strain hardening effect, the chip becomes serrated. Hou & Komanduri (1995) established a critical cutting speed of 9 m/min being the maximum beyond which any machining of Ti6Al4V alloy tend to produce segmented chips as a result of the setting in, into the machining process, of thermoplastic instability. Chip segmentation affects the machining process through generating irregular cutting forces, temperature fluctuations and workpiece surface quality unevenness (Calamaz, et al., 2008). The cyclic segmentation in chip formation results in a large variation of forces acting on the tool tip, which in turn increases the possibility of chatter and tool chipping (Komanduri , 1982). This situation is aggravated by the fact that titanium alloys have a low modulus of elasticity which can cause chatter, deflection and rubbing action. Facts deduced from research findings by Calamaz et al (2008) denote that chip segmentation during orthogonal machining produce cyclic deflection of the tool with a frequency close to that of chip segmentation. These scenarios exert varied levels of demand on the energy required to drive the cutting process. The dominant theories about segmented chip formation are, firstly, the thermoplastic instability theory (Shaw, et al., 1954; Komanduri & Turkovich , 1981) which suggests that the chip morphology is due to the occurrence of plastic deformation instability during the cutting process resulting from the coupling between the thermal softening and work hardening in the primary shear zone. Baker et al (Baker, et al., 2002) asserted that the critical strain value is around 0.25 below which strain hardening occurs and above which Ti–6Al–4V alloy exhibits strain softening. The second theory relate to what is known as the initiation and propagation of cracks, inside the primary shear zone of the workpiece material. This theory as advanced by Vyas & Shaw (2004) in concurrence with Hua & Shivpuri, (2004) argued that the titanium alloy chip segmentation is due to the cyclic process of crack initiation followed by propagation, inside the primary shear zone. Adiabatic shear bands are argued as commonly the precursors to the fracture (Bai & Dodd , 1992). The interaction between the cutting tool and work piece at different cutting conditions also affects chip formation, surface quality of the work piece and tool wear. Optimisation of energy consumption need to be implemented while taking into consideration the machining job parameters of the operation such as chip formation, surface finish and cutting forces obtained from the machining conditions. All these factors have a bearing on the final product quality of the machined component.

Efficiency expresses the relationship between the amounts of resources deployed for a task as compared to the output achieved from the activity (ISO 9000:200, 2000). Energy efficiency explains the efforts being made on the application of a production resource such as a machine tool with the intention of minimising energy use. The various levels available for energy management in manufacturing systems are illustrated on Figure 1 which shows the input and output between the levels. It also focuses on the energy transformation at process level. During machining, electrical energy is supplied to the CNC lathe and converted to kinetic energy that is used to cut the material at different cutting speeds and feeds. At the same time, energy is used to supply lubrication at the cutting interface to transport the heat from the cutting zone and to reduce friction. During the cutting operation at process level the kinetic energy is transformed into various energy outputs. Cutting is a process involving highly localised stresses and extensive plastic deformation and shearing, in which the high compressive and frictional contact stresses on the cutting tool result in the various cutting forces. The specific energy required to produce the chip is a function of the mechanical energy to produce shear in the work piece and the frictional energies consumed by the chip tool interaction on rake and flank faces of the tool. During this transformation a significant fraction of the energy in the form of heat is transferred to the chip and tool from the shear-plane and tool-chip interface respectively. This interaction between the cutting tool and work piece at different cutting conditions also affects chip formation, cutting force, surface quality of the work piece, tool wear, material removal rate and energy use.

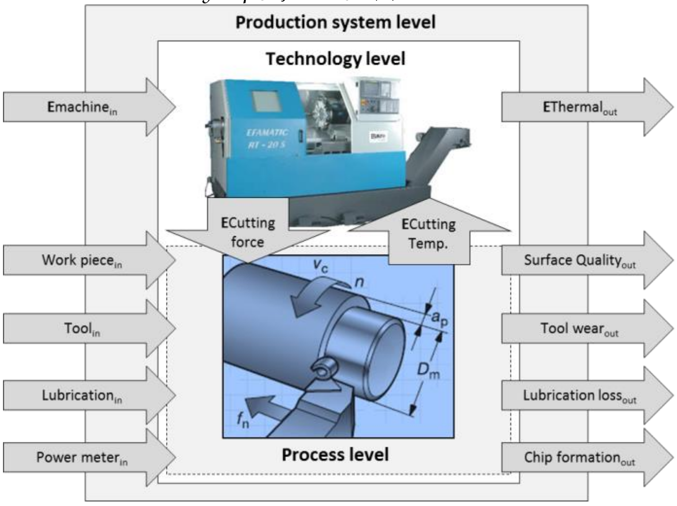


Fig 1: The input and expected output at different levels of a machining operation that affects energy management (Oosthuizen, et al., 2013; Tayisepi , et al., 2016)

Material behavior of titanium alloy and chip morphology parameters

At room temperature, titanium (an allotropic element) has hexagonal close packed (hcp) crystalline structure known as (alpha) α-Ti but forms a body centred cubic (bcc) crystalline structure around 900 °C known as (Beta) β-Ti. Typically, 6% of Aluminium and 4% vanadium are used as phase stabilisers to obtain an α+β alloy phase (Nemat-Nasser & Isaacs, 1997). During the mechanical machining of titanium alloys, it has been found that due to plastic instability and adiabatic shearing chip serration occurs. Workpiece materials often undergoes secondary shearing after the primary shearing zone and a saw-tooth shape chip segment forms (Sima & Ozel, 2010). The underlying cause of chip serration is often associated with adiabatic shear formation (Komanduri & Hou, 2002).

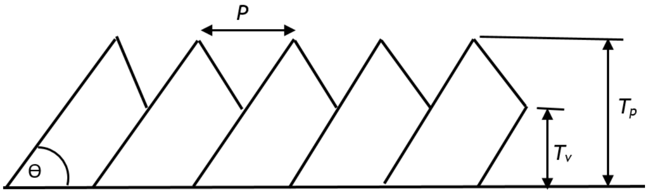


Fig 2: Segmented chip morphology parameters

The plastic deformation intensity in the cutting zone can be expressed in terms of the parameters (Miroslav , et al., 2013). Metallographic chip samples were collected with the intention to characterise the cutting zone significant deformation process parameters on the chip and analyse how these impact on the energy use efficiency of the turning process of Ti6Al4V. Some of the chip parameters were measured whilst some were derived from calculations using geometrical relationships of the cutting condition parameters and the measured chip parameters. The chip deformation features: chip ratio, chip shear speed, chip speed, deformation angle and segmentation frequency were calculated. Segmentation teeth pitch (p) on Figure 2, maximum chip thickness (peak height – T_p), minimum thickness (valley height – T_v) and the segmentation shear angle (Θ) were measured using a stereo microscope. Segmentation or cracking (cycle) frequency (SF) is calculated from knowing the chip speed or shear plane speed, teeth pitch (p) and the cutting speed (Miroslav , et al., 2013; Vyas & Shaw, 1999).

Thus, SF = v_{ch}/p . (1)

Where v_{ch} is the chip velocity and p is the teeth pitch or segment length.

During the machining of Ti6Al4V the teeth peak height represents the maximum thickness portions of the chip teeth segments and the valley heights indicate the thickness of the continuous portions of the chip. The tooth height (T_h) indicates the portion between the peak (T_p) and valley (T_v) and this is the thickness of the separated portion of the chip. T_h is thus computed as the difference between T_p and T_v. Hence;

$$T_h = T_p - T_v \tag{2}$$

The degree of segmentation (G) expresses the ratio of the tooth height to the peak height. It is calculated from (Upadhyay , et al., 2014): $G = {(T_p - T_v)}/{T_p} = {T_h}/{T_p}$ (3)

The other parameters which are calculated include the following (Miroslav , et al., 2013; Upadhyay , et al., 2014):

The cutting ratio, R is computed from:

$$R = T_p/T_v = v_{ch}/v \tag{4}$$

Where v_{ch} is the chip velocity (speed) and v is the cutting speed.

The deformation angle, Θ is determined from:

$$\theta = {\cos\gamma_n}/{R - \sin\gamma_n} \tag{5}$$

Where γ_n is the tool rake angle in degrees.

The chip speed, v_{ch} can be derived from cutting speed thus:

$$v_{ch} = v_c \sin\theta/(\cos\theta - \gamma_n) \tag{6}$$

Shear speed, v_{sh} can also be calculated from

$$v_{sh} = v_c \frac{\cos\gamma_n}{(\cos\theta_1 - \gamma_n)} \quad (7)$$

In similar way chip deformation can be expressed as:

$$\gamma_{sh} = \frac{\cos\gamma_n}{\cos(\theta_1 - \gamma_n).\sin\theta_1} \quad (8)$$

Where γ_{sh} is the shear angle in degrees

Aim, significance and objectives of the study

Thus, subsisting from the foregoing, from an economic perspectives improved energy efficiency of the machining process of Ti-alloy components is urgently required. Chip formation and energy use efficiency were, experimentally, considered in this study. The study aimed to enhance fundamental understanding of the energy use trends during the Ti6Al4V cutting process by monitoring the chip formation regime. The energy consumption trends, during the machining of the material, can be obtained by investigating the interaction of the chip morphology features with energy use intensity as the cutting parameters are varied. The overall intention and significance of the research is to find ways of improving energy use efficiency during the machining production of Ti-alloys by focusing on chip formation and energy efficiency as observation points of the cutting process.

Literature perusal (Neugebauer, et al., 2011) shows that previous studies have been done to understand energy efficiency of cutting processes and chip formation mechanisms during the machining of titanium alloys (Sun , et al., July 14-16, 2010; Sutter & Molinari, 2005). However none incorporate the dynamics of chip formation impact on the energy efficiency of the machining process. Few studied (Ezugwu & Wang, 1997) the energy consumption of the machining process due to the interaction of the input parameters. The present study is, furthermore, aimed at enhancing the understanding of the chip formation mechanism and its relationship to the energy efficiency of the machining process, particularly the influence of the variation of the cutting parameters combination on the interaction of chip formation with energy efficiency during machining Ti6Al4V on a typical machining centre. The chip morphology parameters focused on in this study were chip shear segmentation angle, cutting ratio, segmentation pitch, teeth height, chip thickness, degree of segmentation, chip velocity, shear velocity and segmentation frequency among others. The intension was to establish the relationship between chip morphology characterised by geometrical measurements empirically obtained as well as the measured energy use rate as the cutting parameters were varied. Particularly the research should determine the relationship trends between the chip morphology features and the specific cutting energy and the total machining energy use as the cutting parameters combinations vary and increase in magnitude. The ultimate intention is to identify the chip formation trends which minimises energy use. The research question therefore would answer on how could chip morphological features be interpreted to reflect the behaviour the energy use trends during the machine process of Ti6Al4V and how can the machining outcomes, such as chips produced during machining, be utilised to read into the energy efficiency level of the current job cutting process as well as in predicting the energy consumption behaviour of the future Ti-alloy cutting job assuming that it is processed the same range of cutting parameters as used in this experimental study.

The practical steps embarked on in order to address the set out goals of the study included conducting empirical experimental studies of outside turning of grade 5 titanium alloy, carrying out diverse analyses of the adduced data using Minitab 20 statistical package and several precision measurement tools and instrumentry such as stereo microscope in taking various measurements of the chip profile. The input parameters were extensively characterised with fundamentally chip morphology and energy use response parameters as a basis to deduce conclusions regarding the interaction of energy consumption, as the cutting parameters were varied, as intepreted through the observation window of chip formation.

Experimental set-up and design

Machining experiments were conducted on the lathe machine in order to establish the parameters combination which will allow energy use optimisation. The influence of chip formation on energy consumption of the machining process was analysed. Turning experiments were performed on an Efamatic CNC lathe (model: RT-20 S, Maximum spindle speed 6000 RPM).

A solid cemented carbide tipped tool (ISO code designated CNMX 12 04 A2-SM H13A with coating) in a Sandvik tool holder (DCLNL 2525 M12) was used for turning Ti6Al4V with conventional flood cooling. This tool with chip breaking technology is recommended for cutting Ti-alloy by some researchers (Sandvik Coromant, 2010) and is generally used in the industry (Oosthuizen, et al., 2010). Further particulars of the tool are: positive rake angle 15^o, -6^o inclination angle and 45^o entry angle.

The experimental material Ti6Al4V (Grade 5) titanium alloy was supplied in annealed condition at 36 HRC as a solid round bar (Ø=75.4 mm x 250 mm long). The experimental parameters used and specimen mechanical strength characteristics (as per materials certificate) are presented in Tables 1 (a and b respectively).

Table 1: Experimental parameters and specimen mechanical properties

(a) Experimental Parameters

Parameter	Condition
Cutting speed, [v_c], m/min	50, 70, 150, 200, 250
Feed rate, [f_n], mm/rev	0.1, 0.2, 0.3
Depth of Cut, [*DoC*], mm	0.5 constant

(b) Material properties for Ti6Al4V (Grade 5)

Ti6Al4V mechanical properties	
Ultimate Tensile Strength [MPa]	969
0.2% Yield Strength [MPa]	847
Young's Modulus [GPa]	115
Elongation [%]	13
Hardness [HRC]	36

Coolant	Flood	Heat Treatment Condition	Annealed

The cutting conditions were varied during the experimental process with cutting speed, v_c = 50 - 250 m/min and f_n = 0.1 - 0.3 mm/rev. The depth of cut was kept constant at 0.5 mm. To conform with the ISO Standard 3685-1993 (E) for single point turning tools a wear criterion of flank wear, V_B = 300 µm (Katuku, et al., 2009) was used for all the machining experiments.

Online power measurements were taken using a KYORITSU ELECTRICAL 3 PHASE DIGITAL POWER METER MODEL 6305 with the KEW POWER PLUS2 power signal recordings captured and read off an Acer Aspire 5551 Laptop running on Windows 7. The experimental set-up is shown in Figure 3.

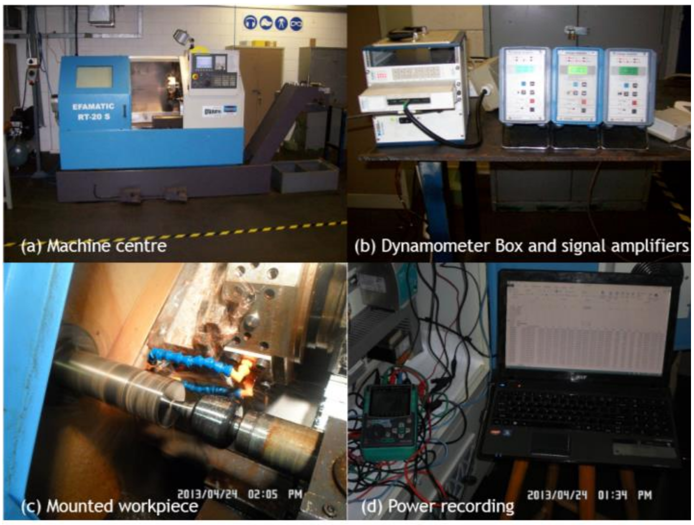


Fig 3: Experimental set-up

Chips were collected at determinate intervals (at the start - new tool and at the end – worn tool – of an experiment) during the machining experiments. Chips were then mounted, ground, polished and etched for morphology photographing, parameter measurements and analysis. The influence of feed rate and cutting speed on chip formation is investigated through a metallographic analysis. Chip formation aspects related to the deformation process, such as chip ratio, chip segmentation, shear angle, segmentation pitch and segmented teeth height were characterised for the varying cutting parameters. Some of the chip morphology aspects were computed from the chip parameter measurements data collected during the experimental study. The characterised chip morphology aspects are analysed relatively with specific cutting energy. Chips from different cutting speeds and feed rates were analysed.

Results and discussion

The purpose of the experimental study was to establish, if any, correlation can be deduced between chip morphology geometrical characteristics with energy use reduction of the machining process. These observations and measurements were done and taken for the different cutting condition parameter combinations used. Qualitative and quantitative (whereby different physical parameters of the chips and energy used were measured) results of the analysis are presented on the outline ensuing.

Chip Formation interaction with cutting parameters and machining energy

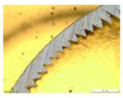
Chips were collected and initially observed macroscopically. It was observed that the chip formation system was segmented for all the cutting parameter combinations used on the study. Chips were measured and analysed with the aid of an optical microscope for several parameters. Table 2(a) and (b), respectively show the chip morphology at respectively varying cutting speeds at 0.3 mm/rev feed rate and at varying feed rates at a cutting speed of 150 m/min. It is apparent from the images that chip overall thickness tended to increase with the increase of feed rate, whereas it remains almost constant with the increase in cutting speed. The uncut chip thickness (h_u), however, decreased with increasing cutting speed. Thus the saw teeth tend to get more pronounced with increased feed rate. The undeformed surface width in the segmented chip tended to increase linearly with the feed rate increase but was seemingly less affected by the cutting speed.

Chip segmentation frequency was one of the important parameters considered because it explains the segmentation process that arises resultant from the plastic instability, vibrations and thermo-mechanical separation of the material due to the various cutting process aspects playing out in the cutting zone (Sullivan , et al., 1978). This is the frequency with which the shearing planes are formed during the cutting process. Chip segmentation frequency is indirectly related with the feedrate (Figure 4a). Segmentation frequency (representing the influence of cutting conditions on the appearance frequency of the shear bands) decreases with increasing feed rate for all the cutting speeds considered (50 m/min to 250 m/min). This result is consistent with the finding by Belhadi et al (2010) on the machining of hardened steel 35NCD16 of 52 HRC with a CBN tool. When feed rate gets larger it entails that the chip segments get to be fewer per given length of machining run (180 mm length of machined specimen in this study).

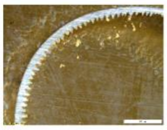
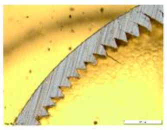
Figure 4b, shows the interaction of cutting speed, the specific cutting energy and chip segmentation frequency. The results show that segmentation frequency increases with increasing cutting speed for all the three feed rates considered (0.1 to 0.3 mm/rev). As segmentation frequency increases specific cutting energy decreases. Energy use reduction derives from the reduced cutting forces as the cutting zone temperature, which promotes thermal softening of the separating zone at the chip-tool-workpiece material interface, increases due to the increased chip load in a poor heat conducting material that grade 5 titanium alloy is.

Table 2. Chip Morphology pictorial images

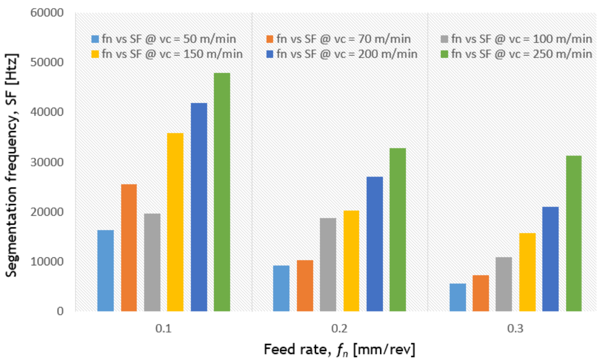
(a) Chip morphology results – changing cutting speed at constant feed rate

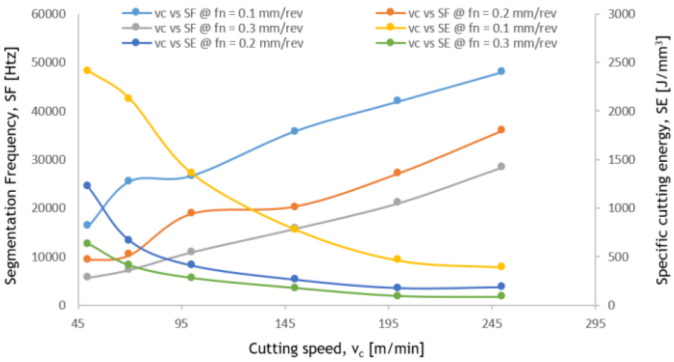
	50 m/min	70 m/min	100 m/min	150 m/min	200 m/min	250 m/min
0.3 mm / rev						
	EACU = 70484 J Enery η = 22.21%	EACU = 65550 J Enery η = 24.12%	EACU = 60618 J Enery η = 35.66%	EACU = 56808 J Enery η = 43.42%	EACU = 40117 J Enery η = 42.13%	EACU = 33730 J Enery η = 46.71%

(b) Chip morphology results – changing feed rate at constant cutting speed

	0.1 mm/rev	0.2 mm/rev	0.3 mm/rev
150 m/min			
	EACU = 86699 J Enery η = 26.54%	EACU = 57970 J Enery η = 34.28%	EACU = 56808 J Enery η = 43.42%

According to earlier research findings (Oosthuizen, et al., 2013), increasing feed rate and cutting speed generally lead to higher material removal rates by the process of high performance cutting and high speed machining respectively. Fig 4 (a) and (b), respectively, show the microstructure geometrical chip feature results plot of specific cutting energy and chip shear angle as functions of feed rate; and specific cutting energy and chip shear angle as functions of cutting speed. The chip shear angle is a morphological feature of significant influence on the chip thickness, cutting forces and the extent to which temperature rise of the cutting zone can be minimised (Dolinsek, et al., 2004). This has an impact on the energy demand of the cutting process, due to the force required to cause shearing of the chips within the adiabatic shear bands. The chip reduction coefficient increases with decrease in the shear segmentation angle. This causes the chip thickness to increase as the shear angle decreases, due to the subsequent low chip sliding velocity on the tool crater surface. According to the results, shown in Fig 4(a), the chip shear angle tended to decrease with increasing feed rate for all the cutting speed conditions considered (50 m/min to 250 m/min).





(a) (b)

Fig 4: (a) Feed rate vs segmentation frequency (b) Cutting speed vs Segmentation frequency vs

Shown in Fig 4(b) plot, are the results presenting specific cutting energy and chip shear angle as function of cutting speed. It is apparent that as cutting speed increases both specific cutting energy and chip shear angle decrease. The energy use tends to decrease, due to reduction in the cutting forces as the material resistance to separation decreases. Reduction of the shear angle entail that the shearing surface area increases and, in turn, the cutting force and power required to separate the material increases and the heat increases, in the cutting zone, as the feed rate increases. However, the energy use decreases (as shown by the reduction in the specific energy consumption in the plot of Table 3(b)), due to reduction of the cutting/processing time when the material removal rate, inadvertently, increases. Deriving from the variation of both shear segmentation angle and specific cutting energy as a function of the cutting parameters. It is apparent that specific cutting energy decreases as the shear angle decreases. This occurs, also, as the cutting parameters and invariantly, the material removal rate (MRR) increases (Oosthuizen et al 2013). Higher cutting speed and feed rate are associated with increasing material removal rate. Integrated consideration of the MRR against cutting parameters curve as well as the chip shear angle against cutting parameters curve, it seem to suggest that lower shear angles are energetically favourable during the cutting process. Lower shear angles occur at increased operating conditions, hence, are associated with higher productivity. Thus, lower γ_{sh} favours higher MRR and low specific energy use. The results presented in Fig 5(a) and (b) show that increasing cutting parameters (feed rate and cutting speed respectively) is associated with general decreasing of segmentation shear angle.

(a) Specific cutting energy and chip shear angle as functions of feed rate	(b) Variation of chip segmentation angle, San, and specific cutting energy, SE, as function of cutting speed, v_c

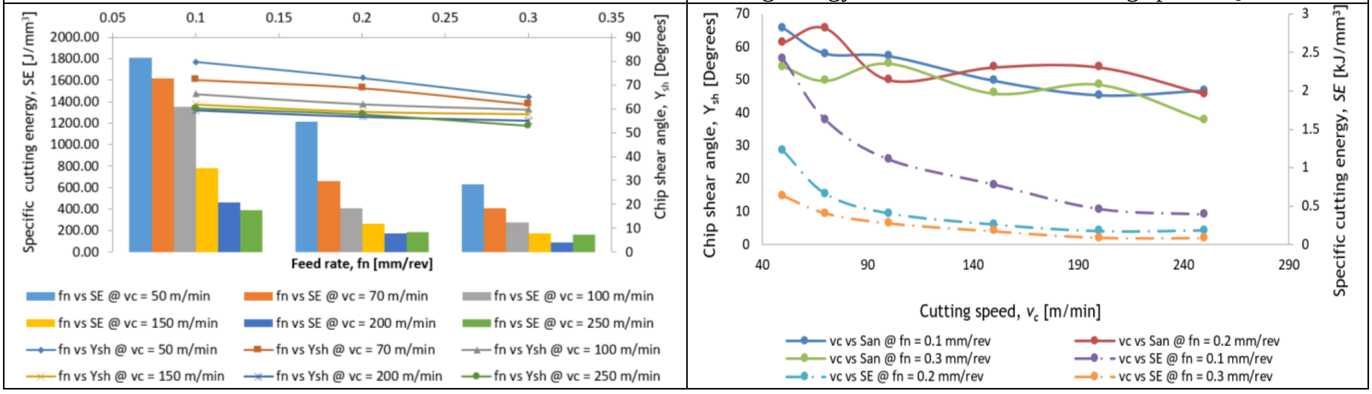


Fig 5. Variation of chip shear angle with feed rate and cutting speed

The degree of segmentation results are presented in Fig 6. (a) and (b) respectively. The graph results presented in Table 4(a) and (b), respectively, tends to suggest the fact that there is positive correlation between the degree of segmentation and an increase in the cutting parameters (f_n and v_c). Energy use reduction occurs, during the machining process, as the cutting speed increases (Table 4(b) graph). It, thus, can be inferred from the results shown in the graph in Table 4(a) that an increase in the degree of segmentation is correlated with a decrease in the plastic deformation energy. This can be taken as strong evidence that chip degree of segmentation is, indeed, energetically favourable (Miroslav , et al., 2013) as it reduces the mean plastic deformation energy within the chip. The more segmented the chip is the less energy usage is needed to form it.

(a) Variation of chip degree of segmentation, G, as function feed rate, f_n	(b) Variation of chip degree of segmentation - G, Specific cutting energy - SE as function cutting speed, v_c

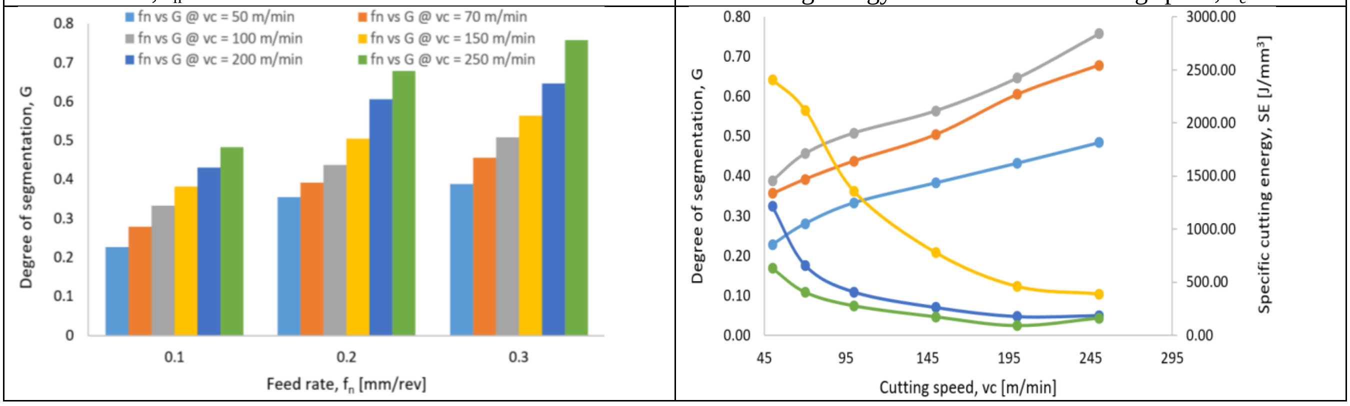


Fig 6. Degree of segmentation versus cutting parameters as well as specific cutting energy

As observable and as detailed in ensuing sections the chip segmentation formation will be transiting also as the cutting conditions are adjusted. As the cutting speed or feed rate increases, the temperature of the cutting process increases. This renders the resistance to plastic deformation of the material to decrease. The metal starts deforming plastically when the applied stress, reaches the level of flow stress as it is mostly influenced by temperature, strain, strain rate and material properties. The results presented show that increasing cutting parameters (cutting speed and feed rate respectively) is associated with general decreasing of chip segmentation shear angle and specific cutting energy. This tends to suggest the fact that there is positive correlation between the degree of segmentation and the energy use reduction during the machining process. It, thus, can be inferred that a decrease in the degree of segmentation is correlated with an increase in the equivalent plastic deformation energy. This can be taken as strong evidence that chip segmentation is indeed energetically favourable (Miroslav , et al., 2013) as it reduces the mean plastic deformation energy within the chip. The more segmented the chip is the less energy usage is needed to form it. The average flow stress in a shear band along the length of the new shear decrease with increasing v_c. Thus it is feasible to monitor the energy consumption of the machining process indirectly by observing the chip system once a determinate optimum point had been established.

It is observable, in the graphical plot of Figure 7 that chip thickness (T_p) tends to initially decrease and then increase with increasing cutting speed. It is apparent that, at the lowest cutting speed, the chip thickness is low whilst it consumes more energy. As cutting speed increases, chip thickness becomes bigger in size and specific cutting energy usage decreases. When chip segmentation is energetically favourable (Belhadi, et al., 2010), it would be expected that the mean specific cutting force becomes smaller as the cutting speed increases, and the degree of segmentation becomes larger. The reason for the change in the slope of the chip thickness profile may be attributed to the changes in the material parameters, microstructurally, due to exposure to the high thermal environment in the cutting zone. The thermo-chemical activities around the cutting zone changes the flow stress behaviour and, thus, changes the work necessary to achieve a certain amount of plastic deformation.

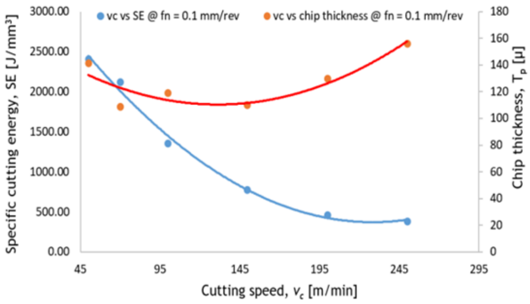


Fig 7: Variation of specific cutting energy & chip thickness as function of cutting speed, v_c

Figure 8, shows the variation of specific cutting energy and chip thickness, as functions of the feed rate. The results show that chip thickness increases with increasing feed rate, whilst, specific cutting energy decreases simultaneously. A change in the feed rate affects the chip thickness and, resultantly, affects the heat dissipation capability of the chips to the machining environment. This also affects the resultant chip morphology. Increasing feed rate is, inadvertently, associated with increased heat generation, in the cutting zone, due to increased chip load. Increased chip thickness is also, correspondingly, associated with increasing tool-chip contact length. This tends to increase the heat conduction surface, such that, the heat carried away, in the chip, increases. In turn, the temperature increase in the cutting zone slows and the adiabatic shearing process occurrence rate tends to reduce. As a result, this causes a reduction in the generating frequency of the segmented chip during machining when feed rate rises. This explains the increased chip segment thickness size as the feed rate is increased. Yet, increased chip segmentation thickness size is associated with corresponding reduction in specific cutting energy use, as shown on Figure 8 .

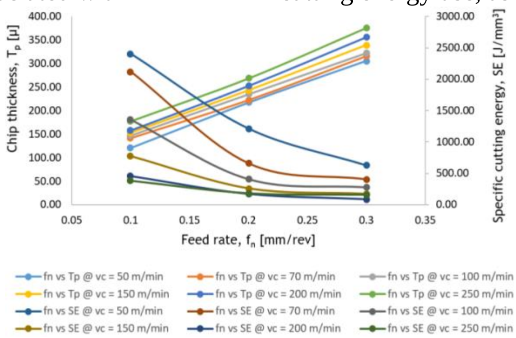


Fig 8. Variation of chip thickness and specific cutting energy as function of feed rate

The results, presented in Figure 9, show the variation of specific cutting energy and chip ratio as functions of varying cutting speed. It is apparent that cutting speed has a significant effect on the chip ratio and has an effect on the chip morphology resultantly. Specific cutting energy decreases with increasing cutting speed, whilst the chip ratio decreases with increasing cutting speed before increasing again as the cutting speed continues to increase. The profile of the chip ratio plot suggest the existence of an optimum chip ratio point during the machining of the Ti6Al4V material. The results of, respectively, specific cutting energy and chip velocity as function of cutting speed and feed rate are shown, in Figure 10(a) and (b). Chip velocity is the speed with which the chip segment slides on the tool rake face (Poulachon & Moisan, 2000). There is need to determine an energy efficient chip removal rate, as the chip velocity is varied. This is due to the fact that, applying too slow a rate implies excessive heat generation, in the cutting zone, and it can be detrimental to tool life due to chip load. On the other hand, too high chip velocity implies excessive heat generated in the cutting zone. This can also be detrimental to tool life and the integrity of the surface of the material being machined. It is apparent, in Figure 10(a), that chip velocity rises as cutting speed increases. Specific cutting energy decreases as cutting speed increases and as the chip velocity rises. Results in Figure 10(b) show that chip velocity decreases as the feed rate increases. The results thus, show that, both cutting speed and feed rate have considerable influence on the chip shear velocity. Chip shear velocity increases with increasing cutting speed, whilst, specific cutting energy decreases

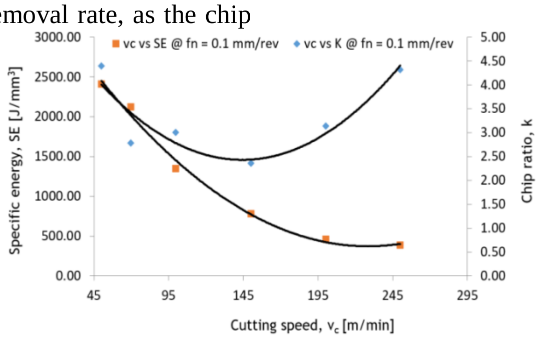
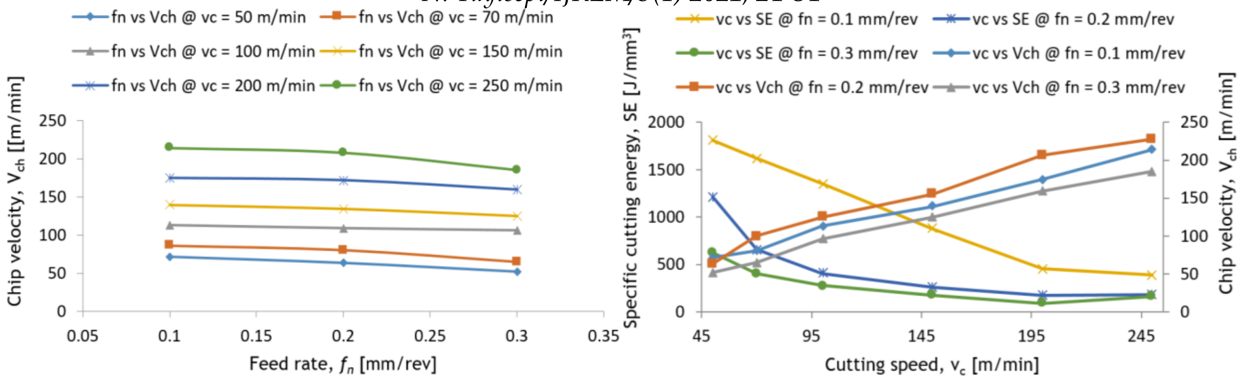


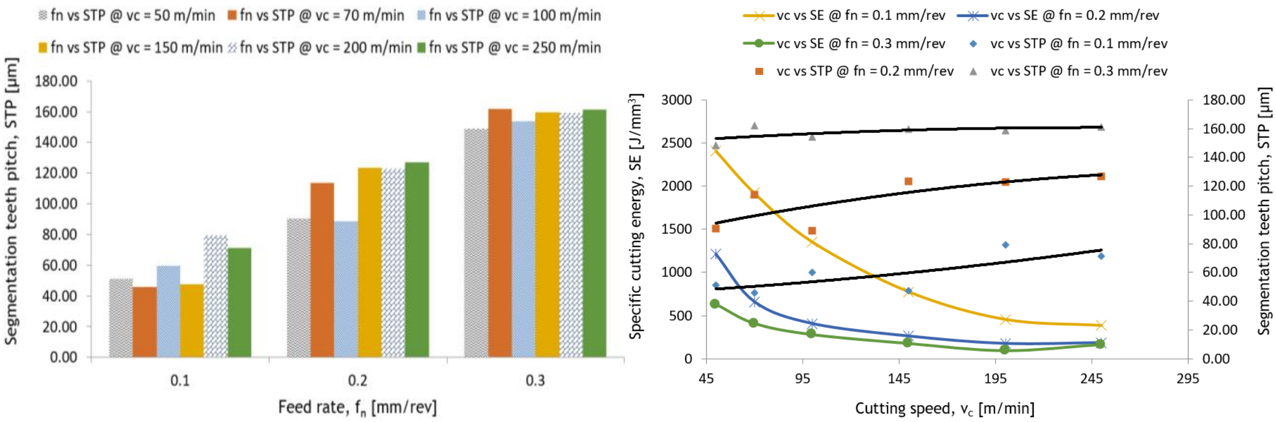
Fig 9. Specific cutting energy and cutting ratio as functions of cutting speed



(a) (b)

Fig 10(a) Cutting speed vs specific cutting energy and chip velocity as well as; (b) Chip velocity as a function of feed rate

The results, presented in Figure 11(a) and (b), respectively, show the variation of specific cutting energy (SE) and segmented teeth pitch (STP) as function of cutting speed (v_c); and the variation of segmentation teeth pitch as a function of feed rate (f_n). It is apparent, from both graphs, that the teeth segmentation pitch increases with both increasing cutting speed and feed rate. However, the influence of feed rate (Figure 11(a)) on the variation of teeth segmentation pitch is more pronounced as compared to the influence of cutting speed (Figure 11(b)). In Figure (11b), it is apparent that, as teeth segmentation pitch, nominally, increases with increasing cutting speed, the specific cutting energy will be decreasing. Results, from the earlier reported work (Oosthuizen et al 2013), , increasing cutting speed and feed rate leads to increased material removal rate and reduced energy use demand. Results from this pperformed experimental results, indicate the variation in the teeth parameters, as the cutting conditions are varied. There seem to be apparent associative relationships, as energy use is apparent and can use can be observably reduced and can, thus be used to monitor the same during machining processes.



(a) (b)

Fig 11(a) Chip segmentation teeth pitch as a function of feed rate; (b) Cutting speed vs specific cutting energy and segmentation teeth pitch

Conclusion

The paper describes results obtained on the basis of an experimental study of the turning of Ti6Al4V and analysing the energy use trends and how it is impacted on by the geometric characteristics of the segmented chip formation. The experimental study results demonstrate significant insight into the process of chip formation morphology characteristics as well as showing how these features relate to energy use during the machining of titanium alloys. The experimental study also permitted the analysis of specific attribute of the deformation process as well as its intensity on energy use. As such the following conclusions were reached:

The experiment results showed that the chip formation, for the range of cutting parameters used, was segmented. This is a result of interrelated mechanisms experienced in the cutting zone during the machining process such as shear localisation, adiabatic shear bands formation, catastrophic shearing, extensive crack initiation and propagation among other processes. These observations seem consistent with the earlier findings (Poulachon & Moisan, 2000; Dolinsek, et al., 2004), that segmented chip morphology results from the effect of interaction of factors forming the cutting conditions. The cutting conditions include aspects such as work material mechanical, thermo-chemical and thermal characteristics; the cutting conditions used; variation in the tool-chip-workpiece material tribological circumstances; variation in the sliding features at the primary shear zone and the dynamic response of the machine tool system to the cutting process behaviour. The research results showed that chip formation parameters such as chip ratio, segmentation shear angle and the chip speeds in the deformation zone, are significantly affected by the cutting parameters setting whilst specific cutting energy decreases with increasing cutting parameters.

Feed rate increase has more significant influence on the chip thickness whilst specific energy decreases on the same. The influence of cutting speed increase is insignificant on the chip thickness whilst however specific cutting energy decreases on the same.

Increasing cutting speed is associated with increased strain rate and rapid temperature rise in the cutting zone. This contributes to the instability phenomena of the thermo-mechanical cutting zone material. This also leads to increased segmentation teeth pitch, decreased segmented teeth height, not so significant increased chip thickness and increased frequency of the chip segments. These chip geometrical attributes increase and decrease whilst specific cutting energy decrease with increasing cutting speed.

Specific cutting energy decreases with increasing degree of segmentation. Cutting speed appeared to have more pronounced influence on the degree of segmentation than feed rate.

There is an optimum cutting speed at which segmentation teeth pitch indicates efficient energy use. Feed rate seem to have a more adverse influence on the segmentation teeth pitch. Also the plot of chip ratio as a function of cutting speed suggests the existence of an optimum and efficient energy use point whilst the cutting speed is varied.

Chip segmentation frequency inversely related with the feed rate increase whilst it increased with increasing cutting speed which appeared to have more significant influence.
Thus overall it can be concluded that it is feasible to monitor the energy consumption of the machining process indirectly by observing the chip system once a determinate optimum point had been established. Further work relates to the determination of optimum machining parameters which correlates with energy efficient machining of titanium alloys, particularly Ti6Al4V, using chip formation as the observed element.

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