TOWARDS ENERGY MANAGEMENT DURING THE MACHINING OF TITANIUM ALLOYS

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ABSTRACT

The manufacturing industry needs to address challenges as regards to the machining process in the multifaceted context of sustainability. The current cost of energy and the reduction in material reserves highlights the need for machining systems to be more energy-efficient. This paper aims to provide a systematic overview of advanced approaches to manage energy and resource efficiency in cutting operations. The research experimentation focuses on the machining of a selected titanium alloy, Ti6Al4V, using carbide cutting tools. Tool wear, chip formation, cutting force and energy use were measured and analysed for selected cutting parameters. The experimental results illustrate the importance of selecting optimum cutting parameters and machining strategy. The results further help to define the boundary conditions for the various input parameters. Future research is also discussed.

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1 INTRODUCTION

Energy efficiency of production systems, especially machining operations, is becoming increasingly relevant and is a key focus of all developing nations [1]. The growing demand, and continued rise in the value of energy, serve to emphasise the importance of enhancing the energy and material-related efficiency of all manufacturing processes. Efficient energy management therefore forms an integral part towards sustainable production systems [2]. Optimising machining processes will also significantly help to address the sustainable manufacturing requirements set by various governing bodies. Efficient energy management also helps to cut the operational costs of manufactured products and to reduce the ecological impact [3].

Titanium alloys are subdivided into *a*-alloys, *β*-alloys and *a*/β-alloys. These alloys form part of the light metals group, due their low density of ρ = ±4.5g/cm³. These alloys also display elevated high temperature strength and can therefore be used at temperatures [4] up to approximately 600˚C. This temperature is much higher than the 350˚C considered as the operating temperature [5] of a typical application such as compressor blades for example. Titanium alloys are used in the aerospace and biomedical industries, due to this exceptional strength-to-weight ratio and superior corrosion resistance [6]. In general titanium alloys are also characterised by a low thermal conductivity of λ = ±7W/m.K, combined with a high melting point (1650˚C). These properties lead to high cutting temperatures [5] at the tool's cutting edge during machining. Ti6Al4V (Grade 5) is the most specified high strength titanium alloy currently used and was therefore selected for use during the current experimental work [8]. According to the material certificate the specific alloy used has an ultimate tensile strength of 969 MPa, a fracture toughness of 100 kJ/m^2 [7] and yield strength of 847 MPa.

Many of the same superior properties that enhance titanium's appeal for most applications also contribute to its being a challenging material to machine. The material's machining difficulties can be divided into thermal and mechanical tool demands. Chemical or more accurately 'tribo-chemical' wear may be considered a thermally activated process, whereby the Ti-alloys and tool material react in such a manner as to remove material from the tool on an atomic scale [9]. In High Speed Machining (HSM) the cutting tool mostly fails catastrophically, due to chipping preceded by extensive crater wear. In High Performance Machining (HPM) the cutting tool typically fractures, when the mechanical load exceeds the physical properties of the tool material. The mechanical demands include the chip load and the influence of different types of vibration.

The recommended cutting speeds (v_c) for titanium alloys are typically 30m/min and up with high-speed steel (HSS) tools and over 60m/min with carbide tools. These low cutting speeds may lead to reduced productivity [10]. This is aggravated by the fact that Titanium alloys have a melting point of 1650 ˚C/1930 K which concentrates high cutting temperatures [11]; at the tool - work piece interface. Furthermore, Ti-alloys have high temperature chemical reactivity with most known cutting tool materials such that at temperatures in excess of 500^{o}C it displays sufficient chemical stability to exhibit low wear rates, low thermal conductivity (K_{Ti} = 7.3 W/mK versus K_{Steel} = 50.7 W/mK) and low modulus of elasticity [8].

Figure 1 illustrates the various levels available for energy management in manufacturing systems. It also shows the input and output between levels and focuses on the energy transformation at process level. Electrical energy is supplied to the CNC lathe and converted in kinetic energy that is used to cut the material at different cutting speeds and feeds and; move the conveyer at a constant speed. At the same time energy is used to supply lubrication at the cutting interface to transport the heat from the cutting tool and to reduce friction.

During the cutting operation at process level the kinetic energy is transformed into various energy outputs. Cutting is a process of high 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, surface quality of the work piece and tool wear.

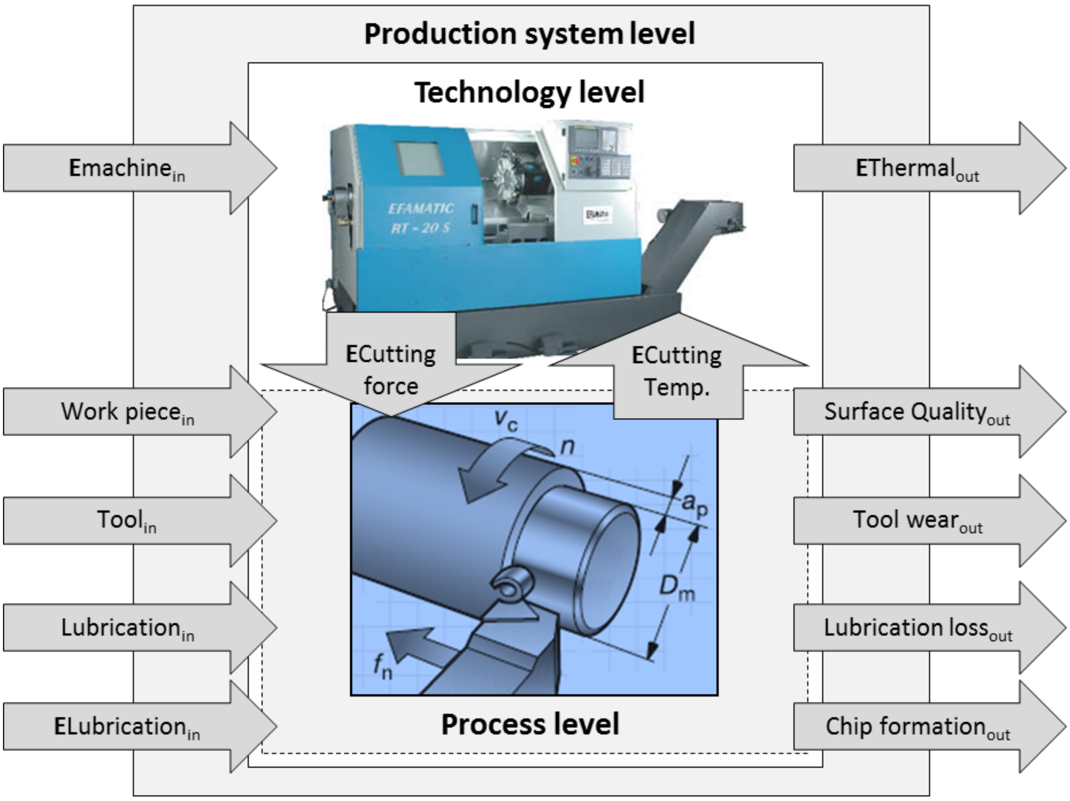

Figure 1: The input and expected output at different levels of a machining operation that effects energy management [2]

The main objective of this research is therefore to investigate this interaction and transformation to eventually be able to optimise the machining process with regards to energy efficiency for machining in general but more specifically for the machining of titanium alloys.

2 CURRENT UNDERSTANDING OF MACHINING TITANIUM ALLOYS

Machining is an important manufacturing process and is mostly involved where high precision components are required [12, 13]. Machining is one of the main cost drivers of manufactured products, especially when hard-to-machine materials (e.g. Ti-alloys) are formed. The cost of titanium alloy components is increased further because of the common practice in the aviation industry of overall material removal rates in excess of 90%. Tribo-chemical and impact related wear mechanisms are important aspects that tool materials need to deal with. Titanium's chemical reactivity becomes problematic at temperatures above 500˚C. Apart from diffusion wear, it has a strong affinity to adhere (weld) to the tool cutting surface. Once a built up edge develops, tool failure follows rapidly [14]. Tool failure can be initiated by one or a combination of several types of wear, which in an advanced stage usually leads to failure [15]. Further challenges may arise when other important production factors, as displayed in Figure 2, are taken into account. Productivity will always be a compromise between tool life and the material removal rate (MRR) and the manufacturers need to utilize HSM and HPM effectively and efficiently.

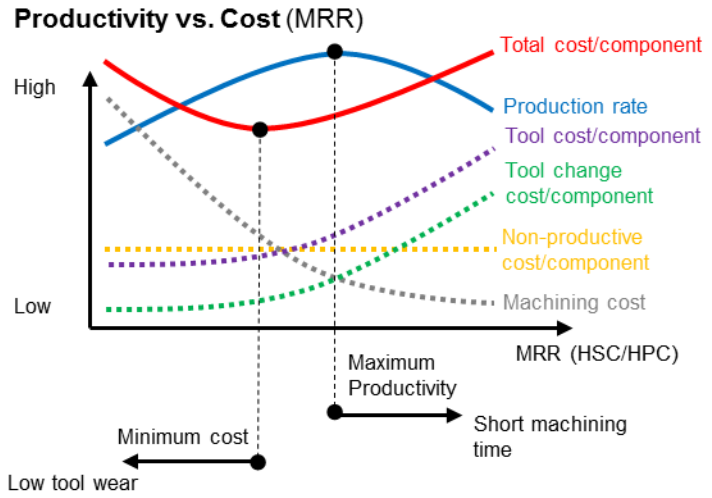

Figure 2: The trade-off between tool life and material removal rate to increase productivity

Figure 3 illustrates the effect of varying cutting speed (thermal load) on various productivity parameters with the eventual goal of optimizing energy use [16]. One of the important objectives is to increase the v_c as high as possible without adversely affecting the surface integrity of the Ti-component. Surface integrity (quality) refers to the outermost surface layers of a machined component. It consists of topography effects such as surface roughness (R_a), changes in the metallurgy (phase transformations and inclusions) and the introduction of other surface layers such as oxides and contaminants. Mechanical effects such as voids and cracks and deformation layers that induce mechanical property changes (typically hardness) also play a role. Since Ti-alloys are used in the aerospace industry the characteristics of the machined surface have to conform to aerospace regulations [17]. If the work piece is exposed to oxygen and nitrogen at high temperature (high v_c), these elements will diffuse into the base material and make the components brittle.

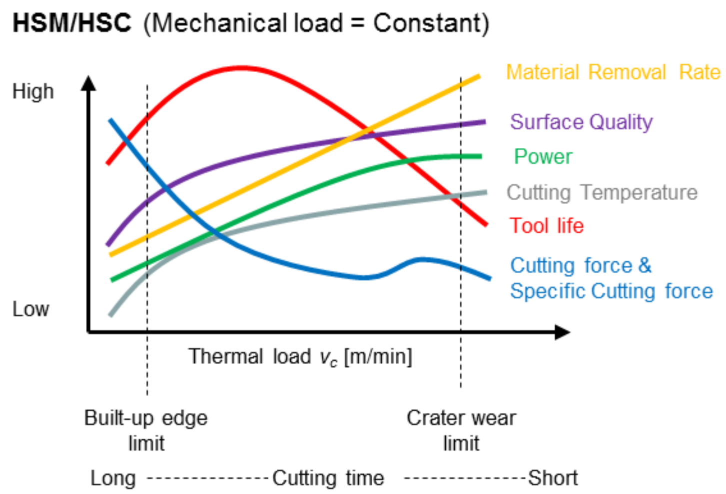

Figure 3: The effect of thermal load (cutting speed) on various productivity parameters (Adapted from [16])

The cutting tool will fail catastrophically when the cutting speed (v_c) is too low due to chatter and/or the effect of increased cutting force due to diminished thermal softening; or when v_c is too high due to chipping preceded by extensive crater wear. Figure 4 illustrates the effect of a varying chip load (mechanical load) on various productivity parameters [16]. Cutting forces are mainly determined by the maximum un-deformed chip load, the cutting speed (v_c) and the average flank wear (V_B). Still, little consideration is given with regards to an energy perspective.

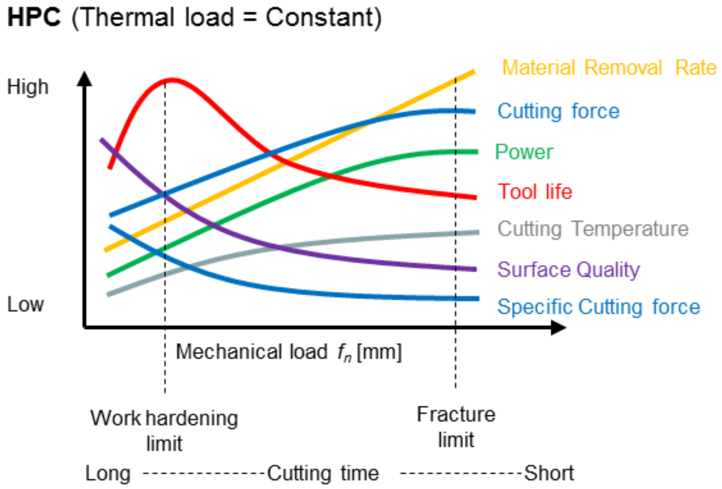

Figure 4: The effect of mechanical load on various productivity parameters (Adapted from [16])

The specific energy as related to cutting may be determined by a number of approaches as summarised in Figure 5. Specific energy is used as the fundamental indicator of energy efficiency in machining [18]. The most effective indicator of green machining lies in the consideration of the total energy used by the machine tool and necessary auxiliary equipment in relation to the volume of total material removed (in effect is specific energy).

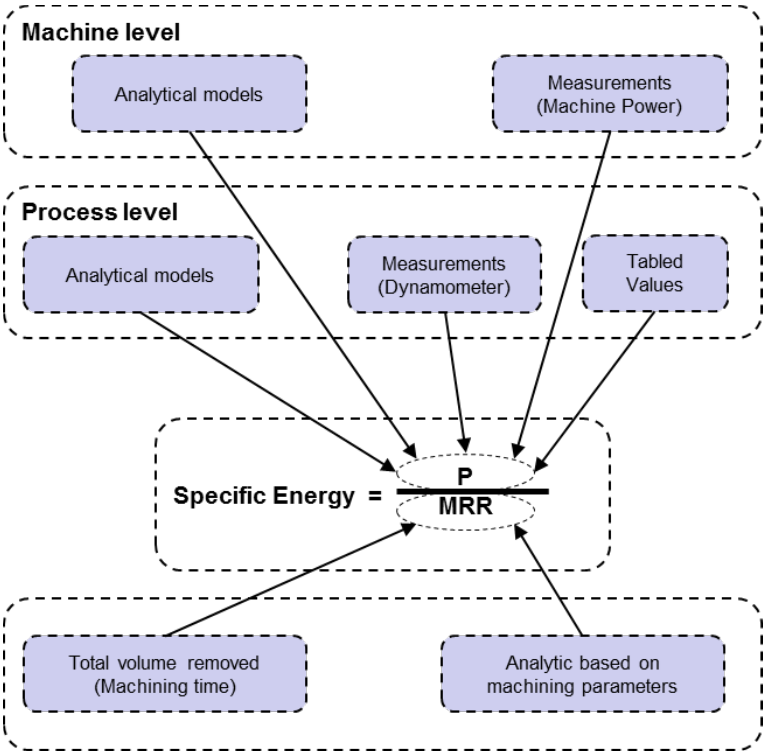

Figure 5: Various approaches for defining Specific Energy [18]

A process level specific energy definition necessitates an efficiency (ή) factor for the machine tool that needs to be taken into account. The specific energy may therefore be defined relative to cutting force (F_c), power (P) and total energy (E) [18]:

$$U_1 = \frac{F_c}{b * t} \quad (1)$$

$$U_2 = \frac{P}{MRR} \quad (2)$$

$$U_3 = \frac{E}{V} \quad (3)$$

Where U_i is the specific energy, F_c the cutting force, b is width of cut, t is feed rate, P is power and MRR is Material Removal Rate. The total energy definition (eqn. 3) tends to be the most comprehensive as it encompasses the total energy (E) and relates it further to the total volume (V) of material removed. Segmented chips are semi-continuous and saw-toothed in appearance. It is usually closely associated with difficult-to-machine metals such as titanium alloys or machining at high cutting speeds [24]. Segmented chip formation is believed to be due to adiabatic shear band formation which is caused by the localized shear deformation resulting from the predominance of thermal softening over strain hardening [19]. Strain softening has been introduced in a flow stress model in order to explain the segmented chip formation [21]. Serrated (segmented, inhomogeneous) chips have zones of high and low strain and occur in metals with low thermal conductivity and strength that decreases sharply with temperature [22]. The heat generated and dissipated in segmented chip formation is illustrated in Figure 6. Periodic crack initiation at the free surface of the work material ahead of the tool and the subsequent propagation pathway toward the tool tip may also have a role to play in the formation of segmented chips [20].

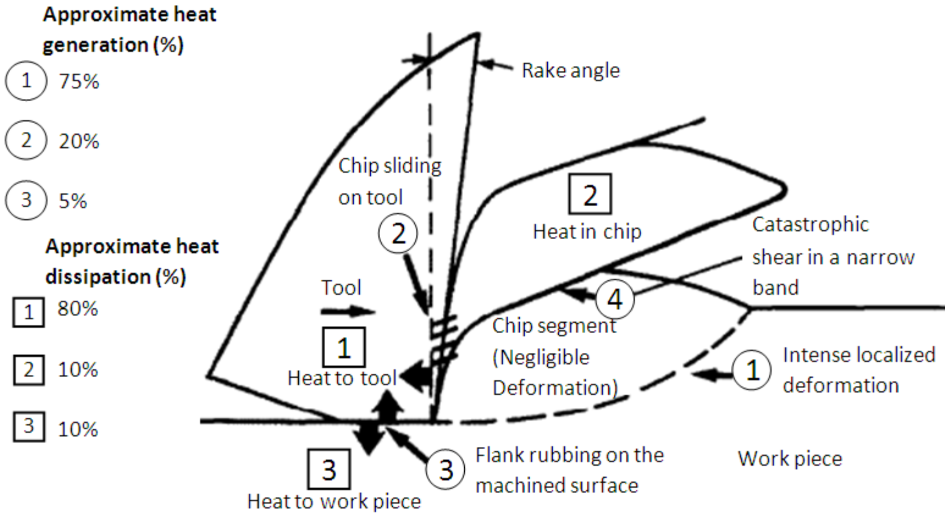

Figure 6: Segmented chip formation: Heat generated and dissipated in segmented chip formation (Adapted from [23])

Segmented chips may also be formed when hard brittle materials are machined at high speeds and feeds [20].

3 EXPERIMENTAL SETUP AND DESIGN

Turning experiments were performed on an Efamatic CNC lathe (model: RT-20 S, Max. spindle speed 6000 RPM). A Kistler, Model 9625B, 3-axis dynamometer along with Type 9441 B Charge Amplifiers and a National Instruments multi-channel data acquisition system were used (see Figure 9). This dynamometer was used to measure the three components of the cutting force: F_x - radial force, F_y - tangential and main cutting force and F_z - axial feed force. Labview Signal Express data acquisition system was used to the output the data to a windows based personal computer via USB.

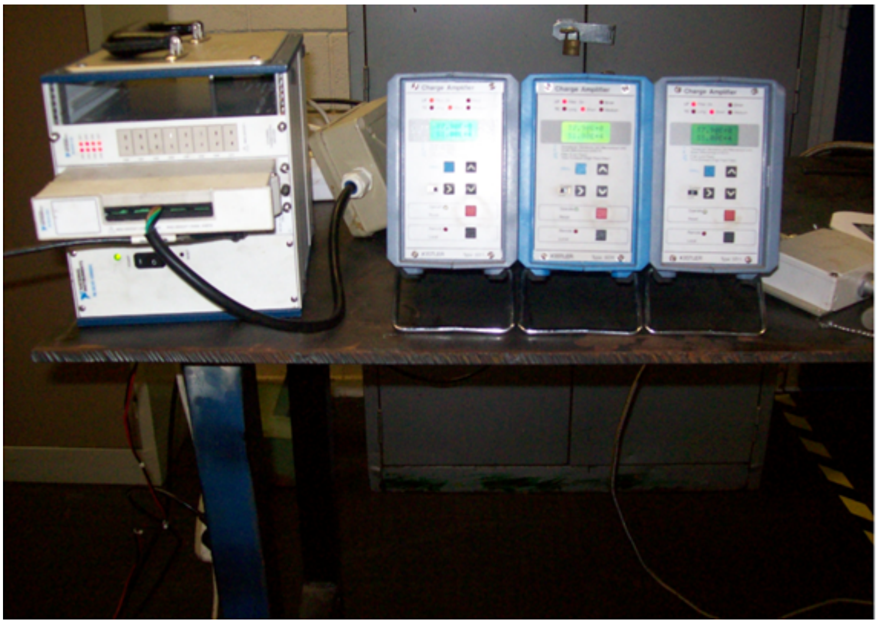

Figure 7: Dynamometer data acquisition

A solid carbide tool (CNXMX 12 04 A2-SM with coating) in a Sandvik tool holder (DCLNL 2525 M12) was used for turning Ti6Al4V with conventional flood cooling. Ti6Al4V (Grade 5) titanium alloy was supplied in annealed condition at 36 HRC as a solid round bar (Ø=75.4 mm x 180 mm long). The work piece chemical composition and mechanical strength characteristics (as per materials certificate) are presented in Tables 1 and 2 respectively.

Table 1: ***Chemical Composition of the Titanium Alloy Material used***

Element	Al	V	C	Fe	N	O	H	Others	Ti
% Content	6.0	4.1	0.02	0.14	0.01	0.16	0.001	0.5	89.069

Table 2: ***Mechanical Properties***

Mechanical Characteristic	Treatment Condition	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)	Reduction of Area (%)
State/Value	Annealed	969	847	13	28

The cutting conditions were varied during the experimental process with cutting speed, v_c= 150- 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 3685-1977 (E) for single point turning tools a wear criterion of V_B=300 µm [25] was used for all the machining experiments.

Tool wear was observed and measured using a Mitutoyo Optical tool makers microscope model 176-801D. Power measurements were taken using a KYORITSU ELECTRICAL 3 PHASE DIGITAL POWER METER MODEL 6300 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 8.

Figure 8: Experimental set-up

4 EXPERIMENTAL RESULTS AND DISCUSSION

Optical measurements of the tool wear and chip formation were taken at different cutting speed and feed rate conditions. Cutting forces were also monitored during cutting operations. The effect of cutting speed and feed rate on tool wear is graphically illustrated in Figure 9. The dominant wear mechanism was flank wear, followed by crater wear. As the cutting speed increased the crater increased on the rake surface of the tool. An increase in mechanical load (f_n) caused an increase in fracture mechanisms.

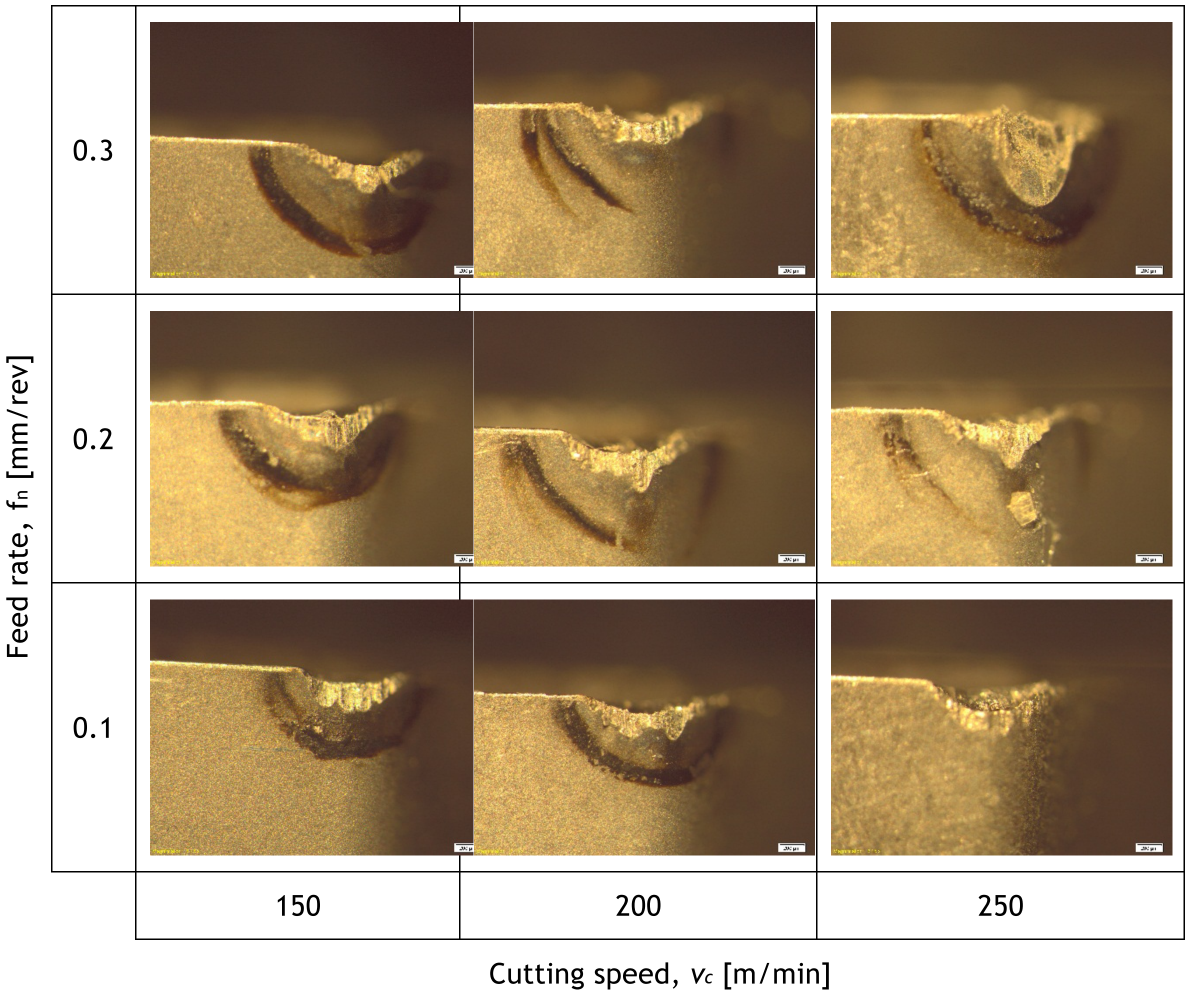

Figure 9: The effect of cutting speed and feed rate on tool wear

The total power consumption of the lathe as a function of cutting speed for the different feed rates is presented in Figure 9. This data was obtained during the first pass (l_m=170mm) and therefore assumes minimal tool wear. As expected the data clearly shows that an increase in cutting speed and feed rate leads to increased power consumption. Increasing the cutting speed and/or feed rate implies an increased material removal rate that will translate to an increased power requirement. These relationships are not linear. An increase in cutting speed from 100 m/min to 250 m/min implies an increase of 67% in material removal rate. The power consumption only increases on average for the three feed rates by 24%. The same is true for an increase in feed rate from 0.1 mm/rev to 0.3 mm/rev which imply a 200% increase in material removal rate but this only translates to an average increase in power of 27%. This clearly indicates the importance and effect that the ancillary support systems associated with the turning process on a typical CNC lathe has. These include the coolant system, overall mechanical losses (bearing friction etc.), electronic control, hydraulic drive system and the compressed air system. The energy usage associated with these is significant and remain largely constant during the machining operation.

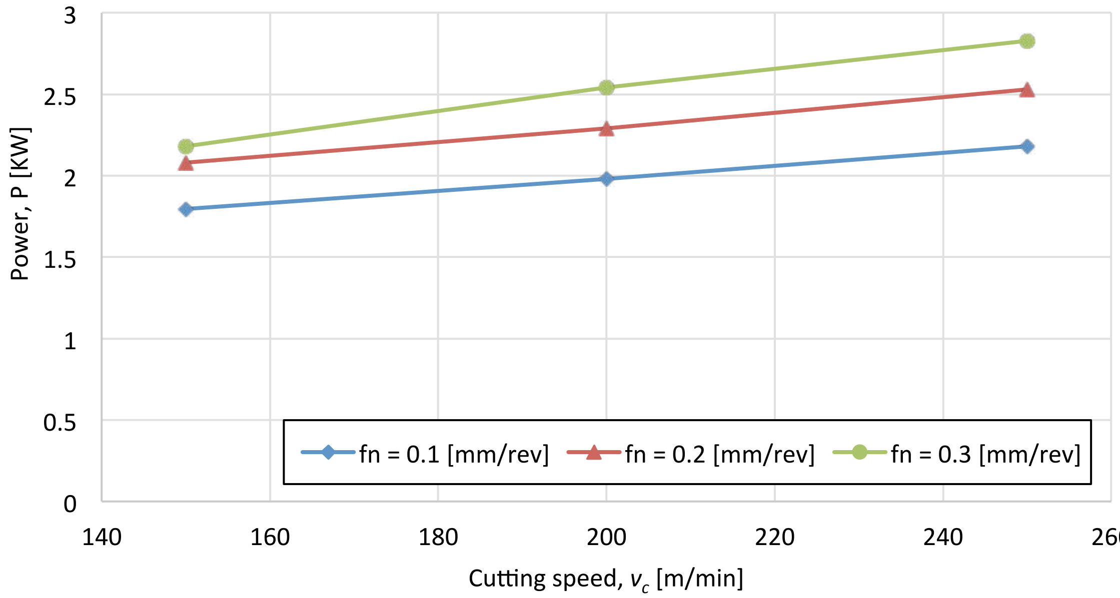

Figure 10: The effect of cutting speed for various feed rates on the measured power

The total energy consumed to cut one pass (length of cut, l_m=170mm) as a function of cutting speed and feed is displayed in Figure 11. The data clearly shows that energy use decreases dramatically as a function of increased feed rate and cutting speed. In all cases the same amount of material was removed albeit with dramatically different energy consumptions. When cutting at the highest cutting speed (250 mm/min) with the largest feed rate (0.3 mm/rev) and comparing to the lowest cutting speed (150 m/min) and lowest feed rate (0.1 mm/rev) there is a dramatic 5.6 × difference in energy consumption.

This equates largely to the machining time. It is clearly beneficial to operate the machine on an as needed basis only and for the shortest possible time. This once again points towards the energy consumption of the ancillary systems of the machine tool and the mechanical losses during operation. The data points towards possibly large energy savings related to high speed machining on typical CNC machine tools.

This is further emphasised in Figure 12 where energy is depicted as a function of material removal rate. It clearly shows that the energy usage is strongly influenced by material removal rate. High material removal rates are generally commensurate with high performance and high speed machining and may have significant benefits as far as total energy use during machining.

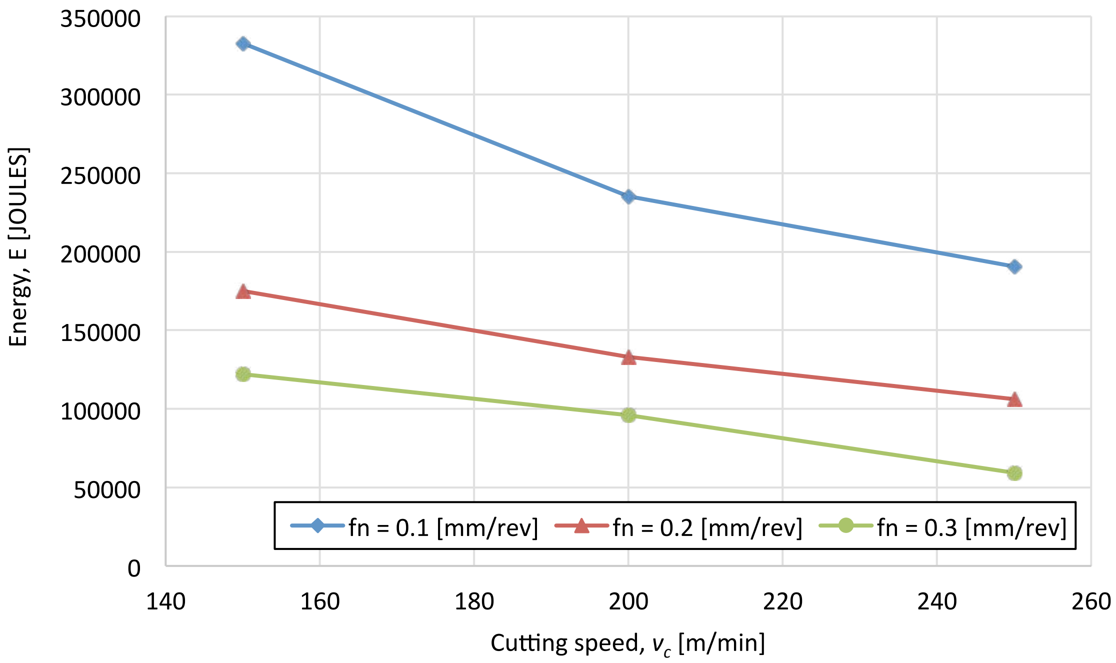

Figure 11: Total machine energy use as a function of cutting speed and feed rate to conduct one full pass (l_m =170 mm)

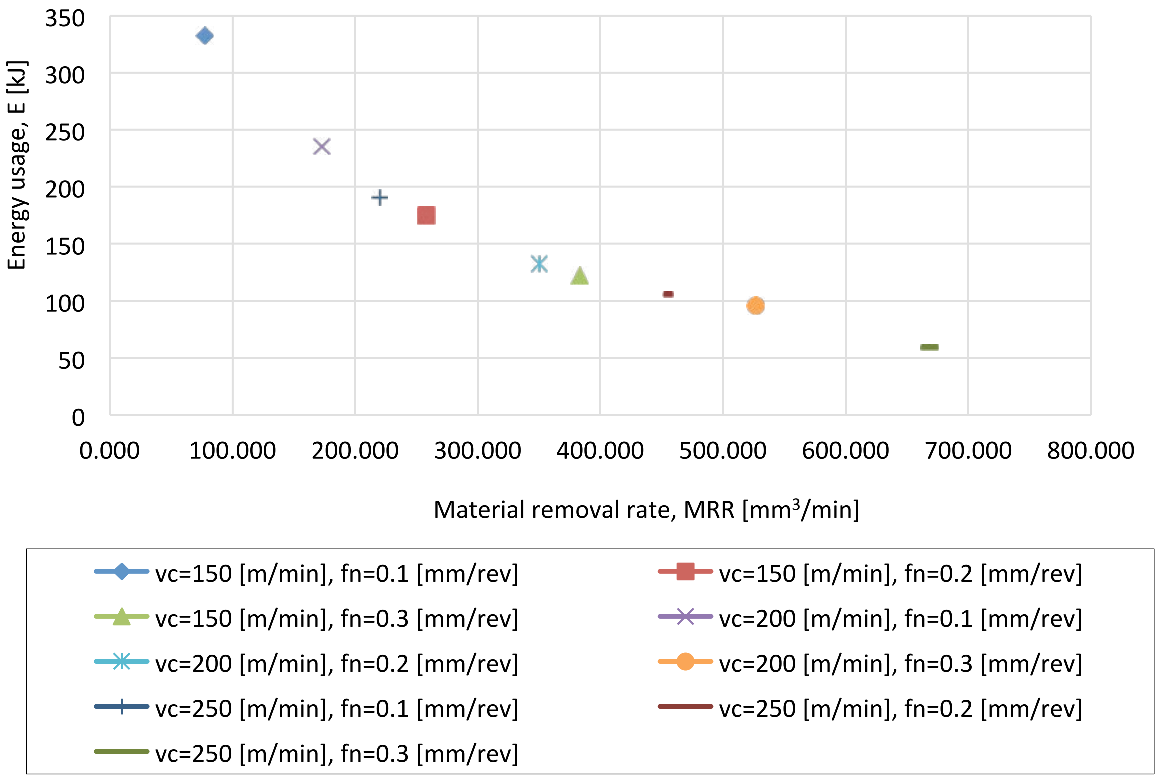

Figure 12: The effect of material removal rate on energy usage for different cutting conditions

The progression of flank tool wear as a function of cut length for the various cutting parameter sets investigated is presented in Figure 13. The data clearly show that tool wear is strongly influenced by the cutting speed and feed rate. An increase in either cutting speed or feed rate increases the tool wear rate. An increase in cutting speed increases the thermal loading by essentially increasing the rate of heat generation and therefore leads to higher tool-work piece interface temperatures that increase the tool wear rate.

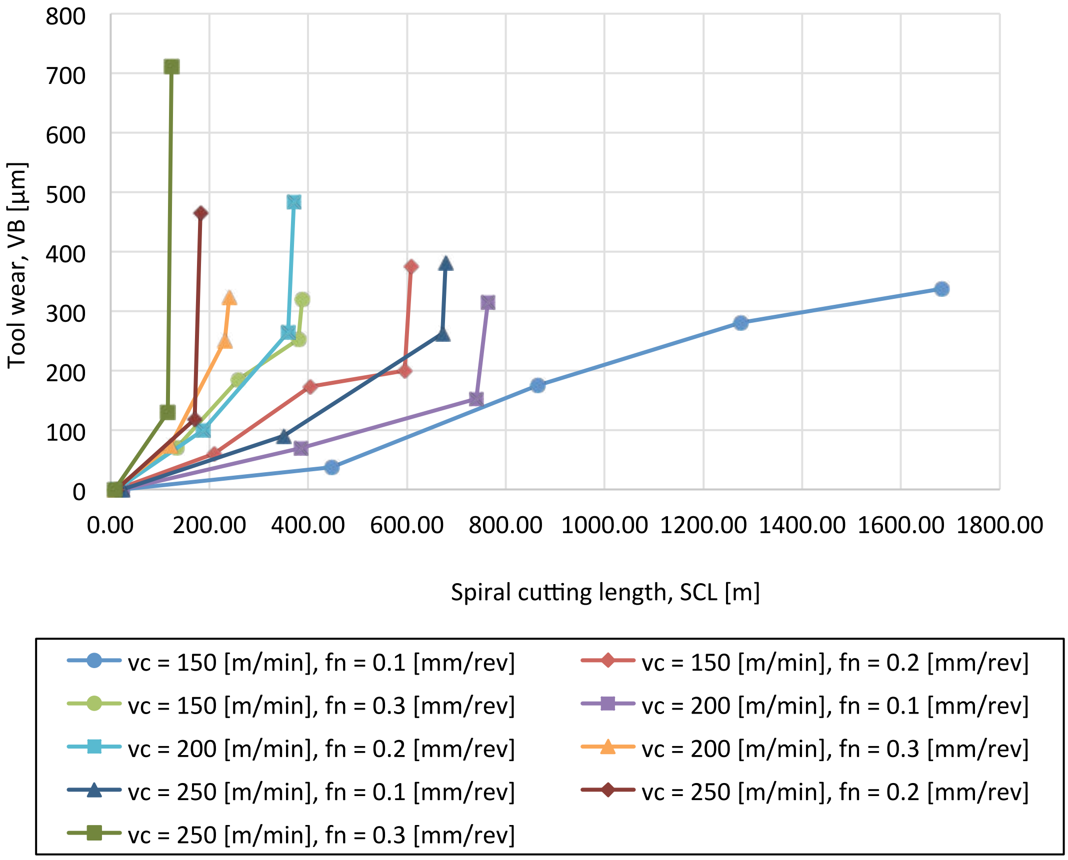

Figure 13: The spiral cutting length until a tool wear of V_B=300µm is reached for different cutting speeds and feed rates

These higher temperatures along with titanium's low thermal conductivity and high chemical affinity leads to increased localized welding and chip adhesion that increases the tool wear rates on the flank and rake faces. The same is essentially true for an increase in feed rate except that the higher thermal loading is now a function of the higher cutting forces induced by the higher feed rates. In both cases an increased thermal loading is induced that cannot be effectively controlled by the cooling technique (flood cooling) employed.

Micrograph images of the chip formation are presented in Figure 14. It shows mainly segmented chip formation with the chip segmentation frequency tending to increase with a decrease in the feed rate. Considering the images, cutting speed does not have a significant effect on the segmentation. As expected the width of these chips also increases with an increase in feed rate.

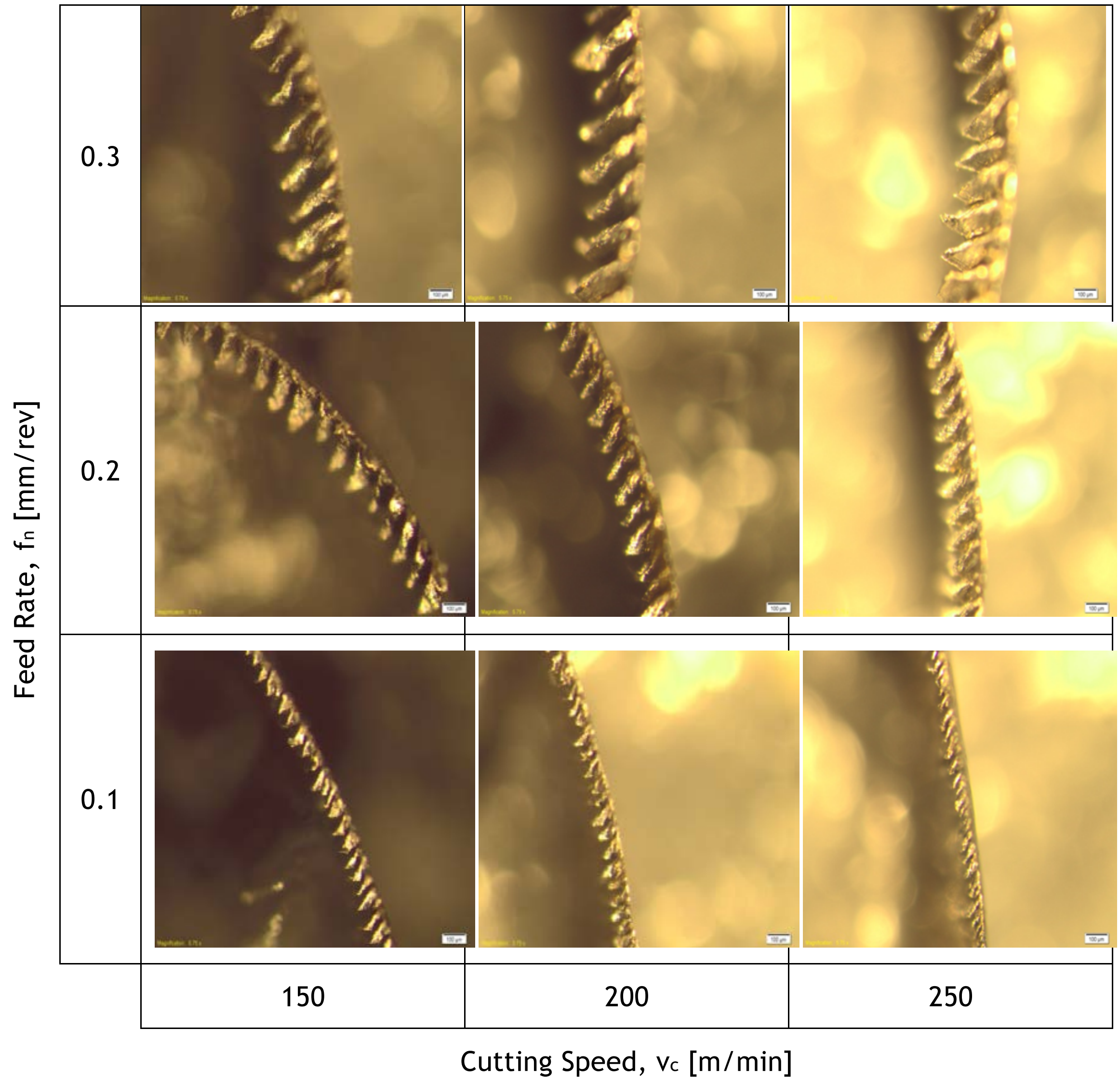

Figure 12: The effect of different cutting conditions on chip formation

Cutting forces were measured in 3 dimensions using the Kistler Dynamometer. Forces were measured normal and horizontal to the work in the depth of cut feed direction axis (F_x), parallel to the work axis (F_z) the cutting feed force and tangential to the work rotating diameter (F_y). Although the results are not published in this paper, the forces tend to increase with an increase in feed rate and display a small decrease with an increase in cutting speed.

5 CONCLUSION

The concept of energy management in machining operations is discussed. The research experiments focused on the machining of titanium alloys using carbide cutting tools. The experimental results illustrate the importance of selecting optimum cutting parameters and machining strategy. As far as overall energy management is concerned the data clearly demonstrated that higher material removal rates are preferred for significantly lower energy consumption. This is largely the effect of reduced machining time at the higher material removal rates with essentially for the same energy usage rate associated with the machine tool ancillary support systems. The higher material removal rates do however lead to increased tool wear. Further analysis of the experimental data and additional work aims to expand on the current investigation with the eventual aim of intelligent management of the machining process as far as energy usage is concerned. The experimental results show that there is significant scope for improved energy management during machining and more specifically during machining of Ti-alloys.

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