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Development and Analysis of Tool Wear and Energy Consumption Maps for Turning of Titanium Alloy (Ti6Al4V)

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Highlights

- Tool wear and specific energy consumption in turning Ti-6Al-4V alloys are considered under varying cutting conditions
- Wear rate and specific cutting energy maps are developed against feed rate and cutting speed grid for selection of suitable cutting parameters
- Low, moderate and high wear and energy regions are identified on these maps that help in the selection of appropriate cutting conditions
- The analysis of tool-workpiece interaction shows that tool wear and energy consumption is strongly influenced by the chip compression ratio, shear angle and the tool-chip contact length

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Development and Analysis of Tool Wear and Energy Consumption Maps for Turning of Titanium Alloy (Ti6Al4V)

Abstract

Machine tools are the main source of electric power consumption in industrial operations. Thus, in manufacturing, energy-efficient and cleaner production methods are preferred to mitigate production costs. Titanium alloys are known for their poor machinability and are generally characterized by low tool life, high energy consumption and poor surface quality due to its unique physical and mechanical properties. This research aims to evaluate the tool wear rate (*R*) and the specific cutting energy (SCE) at varying cutting conditions by developing tool wear and energy maps using unified cutting tests. Uncoated H13A tools were used during single-point turning of Ti-6Al-4V alloy by employing Full Factorial Design of Experiments. Based on experimental data, comprehensive process maps were developed for monitoring wear and energy data. These maps showed regions of (low moderate and high) wear and specific energy consumption. It was observed that while machining Ti-6Al-4V alloy the recommended cutting condition (V= 100 m/min and f = 0.16 mm/rev) enhances the tool life and reduces energy consumption together with high material removal rate. It was also deduced that instead of low speed, using a higher speed of 125 m/min will increase MRR by 127 % and SCE by 16 %, which is more feasible in a production environment. From tool-chip contact length and chip morphology analysis, a strong correlation indicated the reason behind the occurrence of various zones on the maps. It has been found that high wear and energy zone occurred due to the larger contact length and higher chip compression ratio when machining at high speed. The developed maps can be used to help the manufacturers achieve the economic and energy-efficient goal of machining.

Keywords: Ti6Al4V alloy, Wear map, Energy map, Contact length, Energy consumption

List of Abbreviations and symbols

P_{act}	Actual cut power
P_{air}	Air cut power
r	Chip compression ratio
h_2	Chip thickness after the cut
CNC	Computer Numerical Control
V	Cutting speed
d	Depth of cut
EDX	Energy Dispersive X-Ray
f	feed rate
VB	Flank wear
MRR	Material removal rate
NC	Numerical Control
rpm	Revolutions per minute
SEM	Scanning electron microscopy
SCE	Specific cutting energy
h_1	undeformed chip thickness
R	Wear rate Parameter

1. Introduction

Machining accounts for over 15 % by value of all manufactured products in industry [1]. The key challenges during the machining practices include the minimization of energy, tool cost, and part quality standards [2]. The tool wear and the energy utilized in removing a specific volume of material is a key way to know the machinability characteristics and the resourceful optimization of the cutting process [3, 4]. It is also estimated that about 60 % of the energy used in the industry accounts for manufacturing [5]. The study of the tool wear and Specific Cutting Energy (SCE) during machining processes therefore carries great interest in manufacturing industries. Previous research on the turning of Al6061 showed that SCE is independent of the type of machine tool and thus SCE consumption in machining relies on machining conditions, tool material and the machining strategy [6, 7].

Ti-6Al-4V is an alpha-beta alloy with high strength to weight ratio and remarkable corrosion resistance properties at a higher temperature that makes it a material of preference in applications including marine, aerospace, biomedical and automotive industries [8]. Despite superior mechanical properties, these alloys compared to other materials exhibit poor machinability. Their low elasticity modulus, low thermal conductivity, and high chemical reactivity are the main reasons for relative low machinability [9]. A comparison of properties of Ti6Al4V with other commonly used aerospace alloys is presented in Table 1. As a result, cutting tools are exposed to high cutting temperature and mechanical loads that result in high tool wear and chatter of the machine tool, machining these alloys is costly when compared to other materials [10]. One of the highly used alloys of titanium is Ti6Al4V as it makes about 50 % of the total production of titanium alloys [11]. Therefore, Ti6Al4V has been the focus of several researches with foremost emphasis on machinability assessment, experimental and numerical analysis as well as modeling and optimization studies [12-14]. Furthermore, the development of suitable coating for titanium-based alloys is also a popular research area [15].

Table 1. Mechanical properties comparison of Ti6Al4V with other alloys [12, 16]

Property	Material					
	Titanium	Ti-6Al-4V	Ti-6Al-6V-2Sn	Ti-10V-2Fe-3Al	Inconel 718	Al 7075-T6 Alloy
Density (g/cm^3)	4.5	4.43	4.54	4.65	8.22	2.81
Hardness (HRc)	10–12	30–36	38	32	38–44	~7 (equivalent)
Ultimate tensile strength (MPa)	220	950	1050	970	1350	572
Yield strength (MPa)	140	880	980	900	1170	503
Modulus of elasticity (GPa)	116	113.8	110	110	200	71.7
Ductility (%)	54	14	14	9	16	11
Fracture toughness (MPa m$^{1/2}$)	70	75	60	-	96.4	20–29
Thermal conductivity (W/mK)	17	6.7	6.6	7.8	11.4	130
Max. operating temperature (°C)	~150	315	315	315	650	-

Tool wear is an important gauge that determines the machinability of material in a cutting process. It has an impact on the surface quality of the parts machined [17, 18]. Significant work on the tool wear study for Ti-6Al-4V in turning and milling has been presented in the past [12, 13, 16], where the flank wear rate was plotted on a feed-cutting speed plot, and regions of low, moderate and high tool wear were identified. Study of the different regions showed that the interaction of tool and material is more chemical in nature compared to ferrous alloys where the interaction is mostly mechanical in nature. Recently, researchers have also focused studies on machinability that include the study of the wear mechanisms [19], the performance of coated tool material during machining [20] , the tribological features of different tools [21] and the analysis of process parameters in micromachining [15, 22]. Nevertheless, the effective machining of titanium alloys still requires special attention for optimizing the tool life and energy consumption [23].

A significant aspect of machining is the sustainability of the process. This challenge can be addressed by focusing on one of the three prime pillars of sustainability i.e. economy, environment and social issues [24]. Consequently, minimizing the energy utilization of the machines during the material removal processes is one of the ways to achieve environmental sustainability in manufacturing as higher energy consumption results increase in co_2 emissions and manufacturing cost during machining [25]. There has been an abundant amount of work related to the wear studies but energy studies during machining have been given less attention except a few researchers [26-29]. Recently, numerous models were suggested to study the cutting energy consumed in machining several materials. Kara & Li [28] proposed a unit process energy model for turning and milling that provides a consistent prediction of energy consumption at a specified material removal rate. The fundamental modeling approach assessed the energy state of the machine. The two states of the machine tool include the basic energy state and the tip energy state. The first state makes the machine ready to cut whereas in the second state the energy is utilized in material removal. He et al. [30] also proposed an applied method for NC machines in investigating the energy consumed by the components of the machine by taking into account the NC codes parameters and the machine power characteristics. These numerical models can be used for other machine tools and processes keeping in mind the complexity of the system but the type of material, the nature of the process and the machine tool capacity leads to ambiguity in creating such generic models.

More recently researchers have employed the use of maps for a comprehensive study of the wear [12, 16] and energy consumption [3, 31] for various materials. The use of such maps remains useful in foreseeing the outcome of input machining parameters on the response parameter and thus provides a comprehensive understanding of the machining process under consideration. On the other hand, numerical studies were reported for the analysis of cutting forces, energy consumption and energy efficiency in machining Aluminum [32], Steel [33] and Titanium alloys [34]. The numerical models in these studies were based on Johnson-Cook constitutive plastic model where the cutting parameters and machining conditions have been shown to affect the forces and energy requirement during the process. The current research also emphasizes the study of wear and energy consumption of Ti-6Al-4V alloys for various parameter settings (speed and feed) by developing the wear and energy maps. Due to the higher energy consumption, shorter tool life and its wide applicability in several industries the machining analysis for these alloys need to be carefully thought-out. As the tool wear and the energy (SCE) utilized in removing the unit volume of material are associated with the product quality and the energy cost of machining, consequently, a suitable selection of the cutting condition will outcome in minimum cutting energies and ensure longer tool life. Developing wear and energy maps for Ti-6Al-4V can be very helpful on the shop floor, in selecting the cutting conditions that will help machinists produce products of better quality by reducing energy cost and enhancing tool life. From recent work on Ti6Al4V alloy [4, 35-37], it was confirmed that there is a strong influence of tool's flank wear on SCE particularly in the high wear zone.

The use of nanofluids (NFs) has been reported to offer many advantages while machining hard to cut alloys owing to its high thermal conductivity and good heat dissipation properties compared to the base fluids [38]. Studies related to the MQL-nanofluids have shown better results for energy consumption, tool wear and roughness [39]. This approach utilizes less quantity of the oil together with improved heat transfer properties and is considered a sustainable way to use cutting fluids and lubricants [40]. Thus, various models were developed in the past to assess the suitability for reducing the power and energy requirement using hybrid lubrication methods [41, 42].

The cutting tool manufacturer also advises the machinists about the recommended cutting conditions keeping in mind the tool life but its impact regarding energy consumption is rarely understood. Which in the long run may lead to non-profitable practices in an industrial setup especially for titanium alloys. The assessment of energy consumption under varying cutting conditions is a way for developing an SCE map for turning of Ti6Al4V alloy. In addition to the tool wear map, this research work has developed a comprehensive energy map that plots the SCE against the wide range of cutting speeds and feed rates, to date no such map has been presented for machining Ti6Al4V alloy. Therefore, this study has analyzed the wear and SCE consumption during turning Ti6Al4V alloy, using the wear and energy maps approach.

2. Experimental details

Turning experiments were carried out on a Ti6Al4V workpiece. A CNC Turning machine (YIDA Manufacturing Co. ML-300) was utilized in this work which had a spindle power of 18 KW and a maximum speed of 3500 rpm. Detailed specifications of the machine are provided in Table 2 below.

Table 2. Specifications of the machine tool used in the experimentation

Sr. #	**Machine**	ML 300 CNC Turning Machine
1	**Manufacturer**	YIDA Precision Machining Company, Taiwan
2	**Control**	Fanuc
3	**Spindle Power**	18 kW
4	**Total Power**	26 kW
5	**Max. Chuck Diameter**	300 mm
6	**Stroke**	700 mm

The experimental setup for turning of the alloy material is shown in Fig. 1. The same stock of material was used for all cutting tests to achieve unified results. The mechanical and physical properties, as well as the composition of the alloy, are given in Table 1 and Table 3. Cutting experiments were performed with dry conditions in the interest of cleaner manufacturing using H13A grade uncoated inserts. The inserts used were having 0° rake angle, 7° clearance angle and no chip breaker. The conditions in this study were selected based on the earlier reported works as well as the tool manufacturer recommendation for cutting Ti-6Al-4V alloy. The experimental runs using Full Factorial Design of Experiments are presented in Table 4. The importance of cutting speed and feed rate on controlling machining responses like tool wear, energy consumption, surface roughness, and material removal rate has been widely mentioned previously [43-45]. But cutting speed has been identified as a significant factor for the increase in the tool wear followed by the feed rate [43, 46]. The insignificance of the depth of cut on tool life has also been reported by many scholars [47, 48]. Thus, a constant value of depth of cut (1 mm) was used in the experimental analysis to simplify the case for the development of maps.

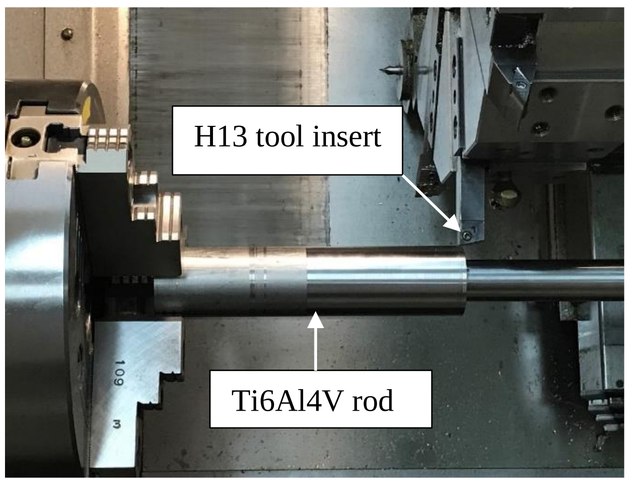

Fig. 1 Turning set-up used for machining

Table 3. Chemical composition of Ti-6Al-4V (weight %)

Ti	V	Al	Fe	Cu	Cr
89.44	4.2	5.7	0.15	0.003	0.0023

Table 4. Full Factorial Experimental design used for turning

Parameter	**Range**
Cutting speed, *V* (m/min)	50, 75,100,125,150
Feed, *f* (mm/rev)	0.12, 0.16, 0.2, 0.24
Depth of cut, *d* (mm)	1

2.1 Tool wear measurement

The wear rate parameter *R* is estimated using Eq (1). where the logarithmic values of the fraction of *VB* (flank wear) to l_s (Spiral cutting length) are taken into consideration.

$$R = log\ [VB/l_s] = log\ [VB/1000tV_c] \qquad (1)$$

The cutting time for which the tool is actively engaged with the workpiece is given by Eq (2)

$$t = \pi Dl/1000fVc \qquad (2)$$

For the tool's flank wear measurement, the ISO single point testing standard (ISO 3685) has been followed; which is the maximum flank wear $VB_{\max}$ = 0.6 mm as well as the average flank wear *VB* = 0.3 mm for the useful life of the tool [49]. The cutting speed for the experiments varied between 50 m/min to 200 m/min over the feed rate in the range 0.12 - 0.24 mm/rev, while maintaining a constant depth of cut of 1 mm. After each cutting pass made, the cutting inserts were inspected with an optical microscope for estimating the wear according to ISO Specification.

For the case of Ti6Al4V alloys, it has been found that the tool wear pattern usually outcomes a linear trend for the wear progression as shown in Fig. 2. Therefore, the wear rate in such cases does not matter (whether it's calculated at the wear criterion or prior to that) as long as the useful tool life limit is not surpassed. For this reason, the linear length of the cut was kept 100 mm for all the cutting tests to rationalize the length of cut of such an expensive material.

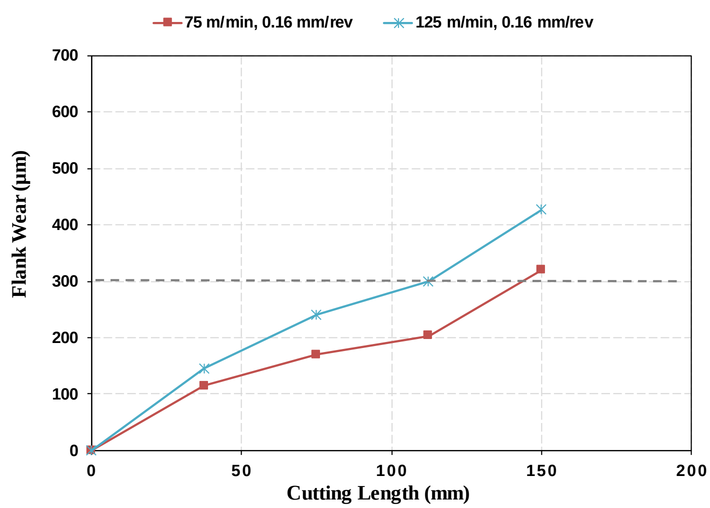

Fig. 2 Trends of wear progression of carbide tool in turning Ti6Al4V alloy

Fig. 3 shows the typical micrograph of a used insert highlighting the flank wear land. The values measured from the micrographs of all the inserts, VB_{max} values, were used in estimating the wear parameter *R*.

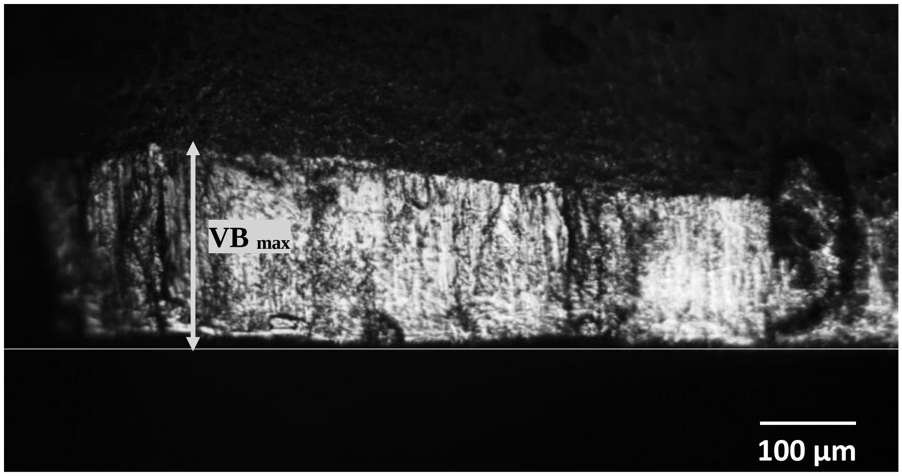

Fig. 3 Optical image showing tool wear land for the measurement of tool flank wear at 20X magnification.

2.2 Measurement of Specific cutting energy (SCE)

To record the power data at the main supply of the machine, a power analyzer (CW 240F) made by Yokogawa Electric was used. The power analyzer was connected to the main control of the CNC machine where probes for voltage and current were used to measure the electrical energy drawn by the machine tool. The experimental procedure for energy meter attachment along with the setup is shown in Fig. 4. The two-cycle approach as employed by Kara and Li [28] was used for the estimation of SCE. The first cycle measured the power data where the machine tool was not engaged in cutting the work material but all the components were electrically energized, known as air cut power (P_{air}) and the second cycle where the material removed by work-tool engagement named as actual power (P_{actual}). This cycle was repeated for each experimental run and thus it recorded and measured average P_{air} and P_{actual} for every cut (Fig. 5). The difference between the two powers resulted in the average energy consumed as given by Eq (3).

$$P_{cut} = P_{actual} - P_{air} \tag{3}$$

To obtain the Specific Cutting Energy (SCE) and the Specific Total Energy (STE), the representative power has been normalized over the material removal rate (MRR) as given by Eq (4) and Eq (5), respectively.

$$SCE = P_{cut} / MRR \tag{4}$$

$$STE = P_{actual} / MRR \tag{5}$$

And MRR can be estimated using Eq (6)

$$MRR = V x f x d \tag{6}$$

Specific Cutting Energy is most commonly represented in J/mm^3. Fig. 5 explains the difference in the power values for the measurement of SCE.

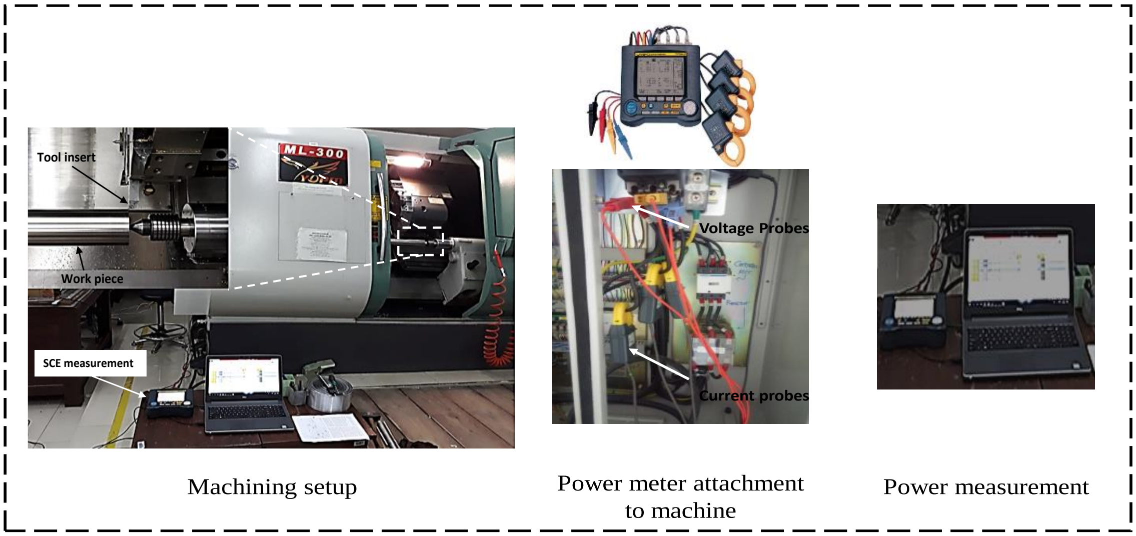

Fig. 4 Experimental setups for measurement of cutting power

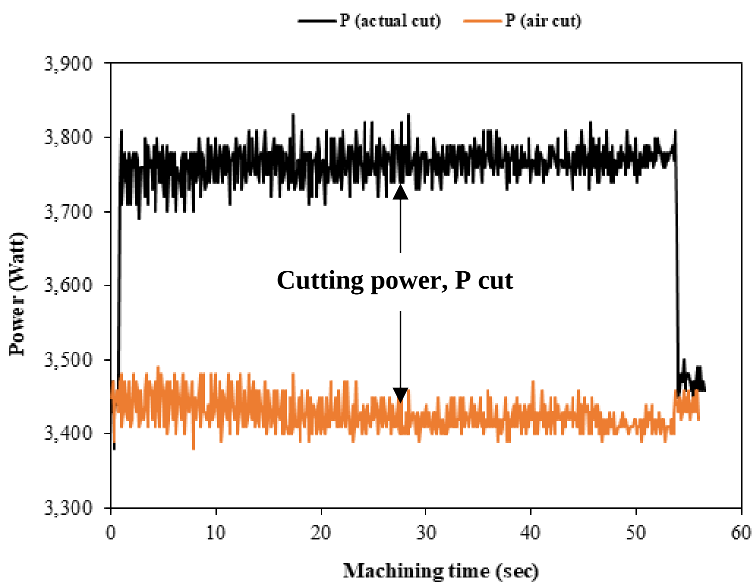

Fig. 5 The energy consumption of the actual cut, and air cut values recorded: V = 100 m/min and f = 0.16 mm/rev.

2.3 Measurement of tool-chip contact length (l_c)

The superficial marks left on the tool surface after the cutting process performed is generally revealed by the optical and scanning electron microscopy (SEM) of the tool inserts. The contact length (l_c) of the worn inserts was measured from the contact marks using an optical microscope (MT-8530) manufactured by Meiji as shown in Fig. 6

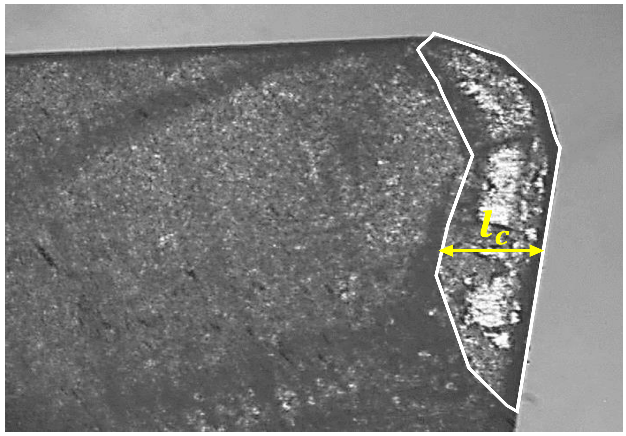

Fig. 6 Measurement of the tool chip contact length

3. Results

3.1 Development of wear map

The flank wear rate (*R*) for all the cutting conditions (Table 3) were calculated using Eq. (1) and the flank wear (*VB*) values measured from the microscopic images of the inserts. Wear map in Fig. 7 shows the values of parameter *R* plotted on the feed-speed grid taking the x-axis for the cutting speed and the y-axis used for the feed rate. This map developed can be classified into different regions characterized by low, moderate and high wear zones. Furthermore, a region of high tool wear is clearly evident in the midst of low and moderate regions as shown in Fig. 7. Additional tests were carried out in the vicinity of these zones to confirm the occurrence of various regimes for data repeatability. The outcomes of the additional test also resulted in the values of *R* that fall in the high wear zone with a minor deviation in the values thus confirming the presence of the high wear zone amid the moderate and low tool wear zone. This region lies in the limits of speed ranging (55 – 70) m/min and feed rate of (0.16 - 0.2) mm/rev. Cutting tests were repeated wherever deemed necessary for data repeatability.

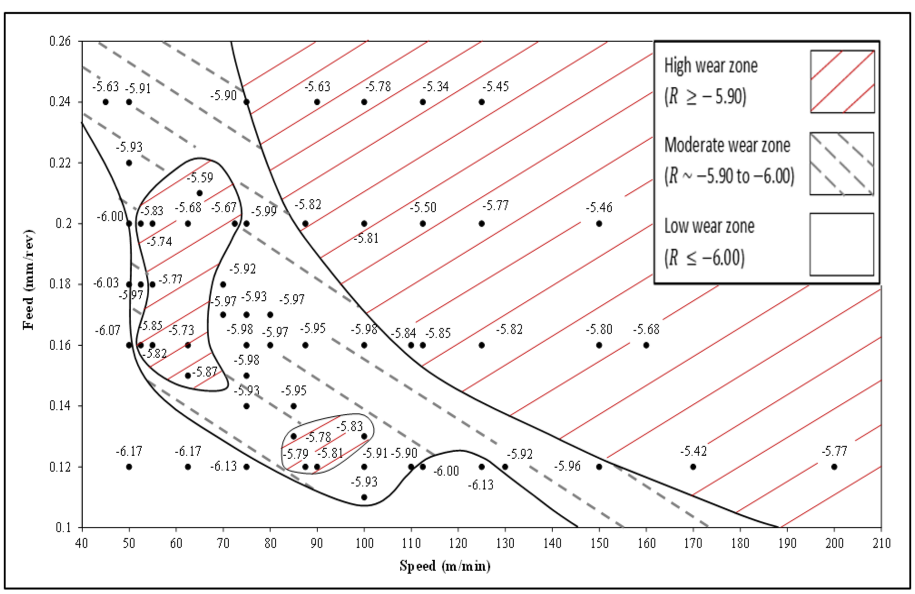

Fig. 7 Map showing wear rate for turning Ti6Al4V

3.2 Development of Specific Cutting Energy (SCE) map

The SCE data obtained from the experimentation was used for the development of the energy map where SCE was plotted on a feed – speed plan as shown in Fig. 8. Analogous to the wear map, the energy map also showed the presence of different energy zones. The regions were based on the extent of the values of SCE obtained during this research. These regions are highlighted as low (value up to 0.99), moderate (1.10 to 1.15) and high (above 1.10) SCE values. A similar approach was also used by researchers for developing the energy map during machining aluminum (Al 6061-T6) alloys [3, 31, 50, 51].

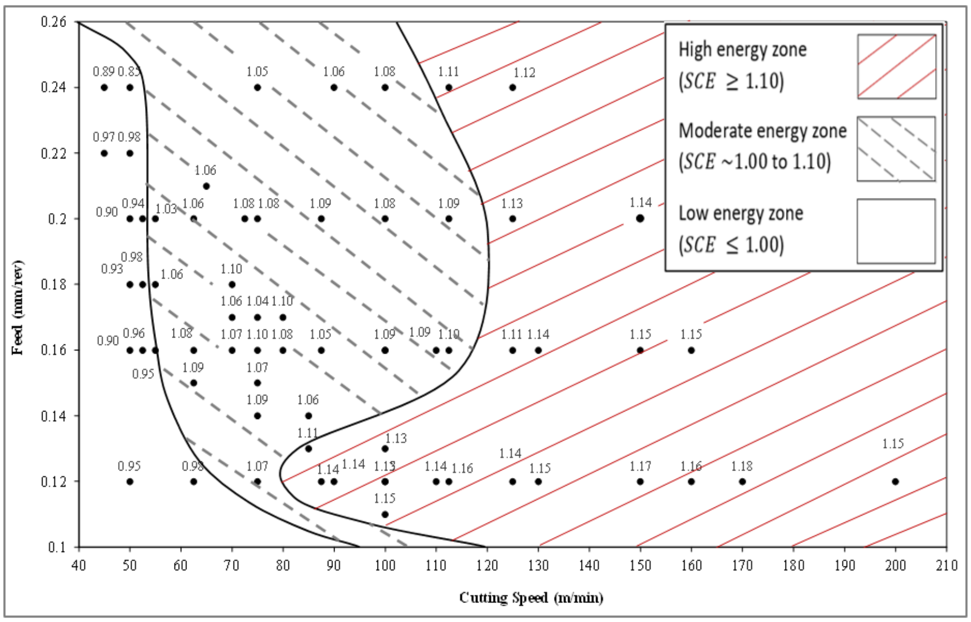

Fig. 8 Map presenting SCE for turning Ti6Al4V

3.3 Selection of suitable cutting conditions

In the shop floor environment, the machine operators select cutting parameters combination that provides the best results in the roughing as well as finishing operations. Three major factors for consideration are the tool life, MRR and surface quality. The aim is to achieve highest MRR while maintaining best surface quality at the minimum cost of the tool (i.e. tool consumption). The fixed cost of machine tools is high; however, owing to the longer useful life of the machine tool, its share in product cost is almost negligible. However, if appropriate machining conditions are not considered, the running cost will increase which in the case of titanium machining is the tool cost. In that perspective, the important aspect is to select suitable machining conditions for better tool life. These cutting conditions from tool suppliers also fall in the avoidance zone, which is characterized by a very high tool wear rate on the wear map. Thus, the operators might be using the cutting combination that may fall in the avoidance zone as a result not achieving better tool life. It is thus recommended that the proposed maps may be used along with the cutting tool manufacturers' recommendations.

It can also be observed from the wear map that a recommended cutting speed of 55 m/min falls in the avoidance zone, which suffer the same tool wear as compared to a cutting speed of 125 m/min (high wear region) for a constant f = 0.16 mm/rev. Therefore, instead of a low cutting speed, using a speed of 125mm/min will increase MRR by 127 % and SCE by 16 %, which is more feasible. Apart from that, a major effect is observed in the Specific Total Energy (STE) which is known to decrease with high cutting speeds as shown in Fig. 9.

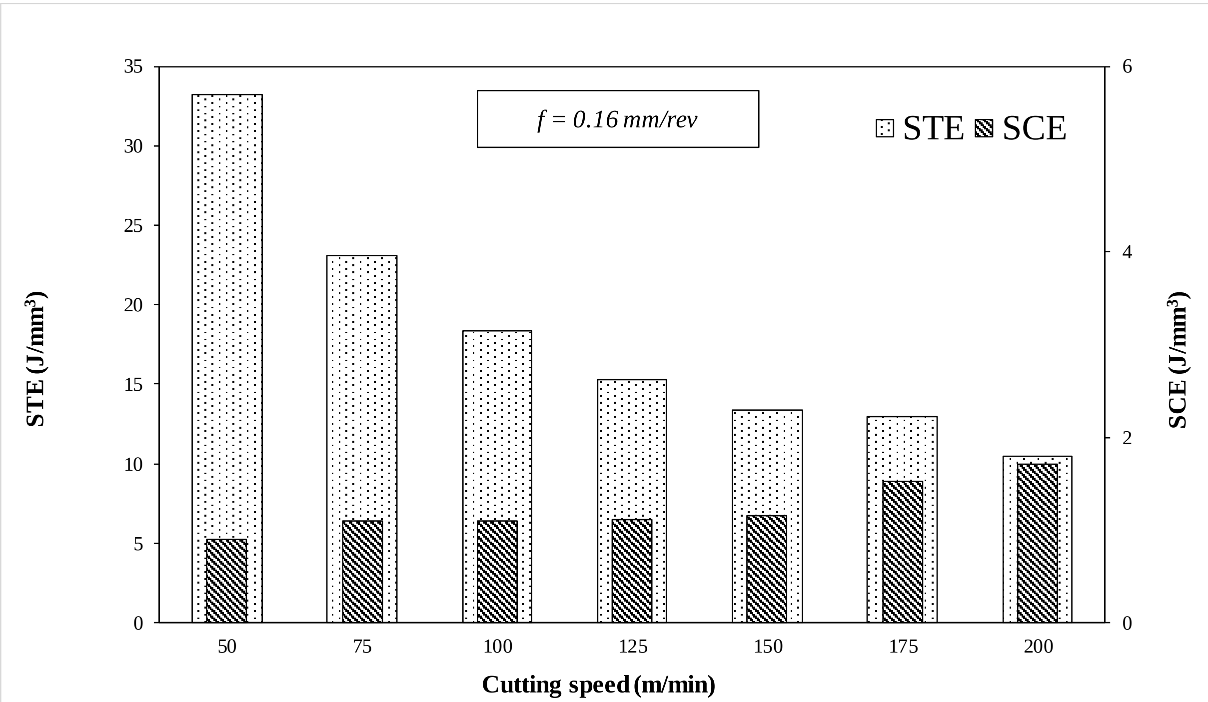

Fig. 9 Trends of Specific Total Energy consumption for machining Ti6Al4V alloy

Therefore, using a higher cutting speed (125mm/min) will result in the same tool life but relatively higher MRR and lower energy consumption. In the light of the above discussion, the recommended cutting condition (V= 100 m/min and f = 0.16 mm/rev) for turning Ti6Al4V alloy identified in this research work. This proposed cutting condition was selected considering the energy consumption and tool life together with high MRR. Thus, the advantage of the high material rate and improved tool life could be possibly achieved by candid selection of cutting conditions from the wear and energy maps.

4. Discussion and analysis

The various region on both wear and energy maps occurred because of the varying tool-workpiece interaction at different cutting combinations. Therefore, the microscopic analyses of the inserts and chips were carried out to explain the occurrence of various regimes on the developed maps.

4.1 Tool – chip contact length

The wear on the flank side of the tool also relates to the contact length resulted from the tool-chip interaction [52]. Contact length is generally the length for which the chip and the tool remain in contact during the cutting action. It is reported that larger contact lengths result in the higher temperature of the tool during the turning process thereby affecting important aspects of machining including the tool wear phenomena, dynamic forces, cutting power and the chip morphology [53]. Tool material and geometry, workpiece material, machining condition, and the cutting environment are the key factors responsible for affecting the contact length during the machining process [52, 54]. Fig. 10 shows the variation in the contact length with an increase in feed and cutting speed in turning Ti-6Al-4V, with *R* values plotted against each condition. The contact length for the worn inserts was measured from the contact marks using an optical microscope.

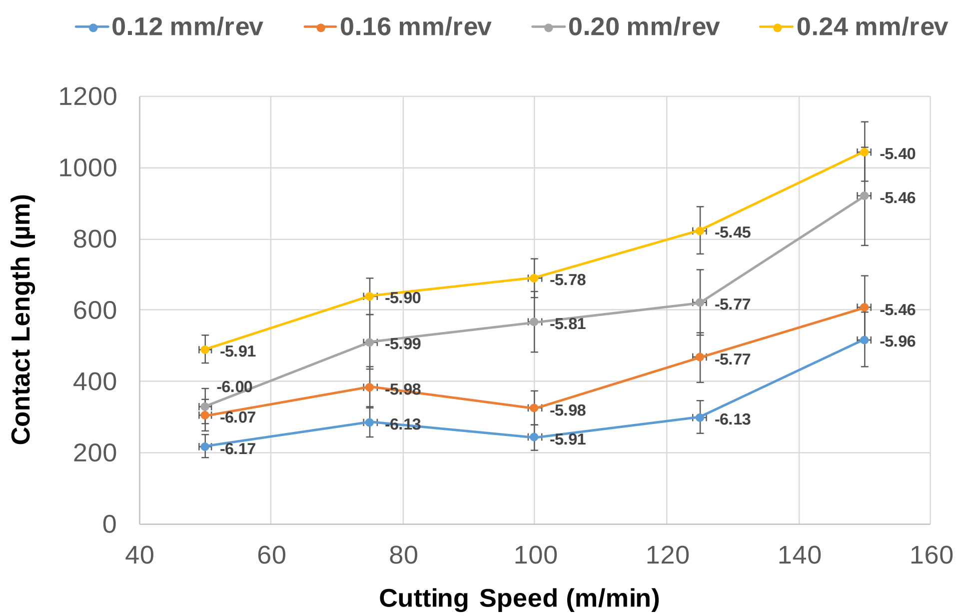

Fig. 10 Influence of the cutting conditions on the contact length

The maps presented highlights that the SCE and wear rate increase with an increase in the cutting speed during the turning process. This increase in SCE and *R* is attributed to the growth in contact length at a higher speed. A similar trend of *R* with cutting speed and feed rate was also reported during turning Ti6Al4V [16], thus strengthening the reported results. From the energy map approach, the contact length is of great importance. The growth of the contact length with increasing cutting speed is mainly responsible for the increasing trend of SCE on the energy map. The temperature at the interface of the tool-chip upsurges at higher cutting speeds that disturb the heat transfer at the interface thereby affecting the tool life and producing unwanted frictional forces. Earlier research [53, 55] has also reported a similar trend of the contact length during machining Ti-6Al-4V and EN19 steel. The specific energy requirement for removing a certain amount of material at high cutting speed is linked to this increase in the contact length because at a higher speed some of the energy is wasted in the form of heat dissipation and overcoming unwanted friction, as the tool reaches a high temperature.

4.2 Chip morphology analysis

SEM and optical images of the chip were analyzed to find the chip compression ratio. Fig. 11 shows the SEM micrograph of the chip where chip thickness after the cut is shown by h_2 and shear plane angle by φ. The uncut chip thickness value in the case of single point turning equals the feed rate. These values were used in Eq (6) to find the compression ratio [56].

$$Compression\ ratio, r = \frac{h_2}{h_1} \qquad (6)$$

Chip compression is related to the chip deformation during the machining process. Therefore, this ratio can be used to estimate the efficiency of chip formation, shear angle, forces and energy consumed during a cutting process [57]. Usually, a larger value of r corresponds to a smaller value of shear plane angle that leads to higher strain and energy consumed during the process. The chip obtained from machining Ti6Al4V alloy is discontinuous and in segments, therefore the continuous chip model cannot represent the true chip formation process [58]. Using continuous chip model leads the resultant shear angle greater than 45° which is not practically possible according to Merchant theory [59]. Therefore, Komanduri et al. [58, 60, 61] stressed the importance of developing suitable parameters for characterizing the chip formation in case of titanium alloys machining. Thus, experimental methodology reported in the literature [62] for measuring the chip compression ratio of titanium machining with h_2 (chip thickness) has been adopted in the current research.

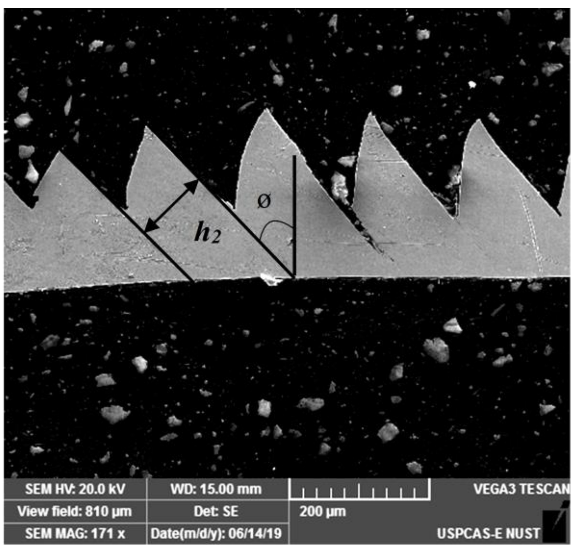

Fig. 11 Micrograph showing the chip segment of Ti6Al4V

The chip compression ratio is shown in Fig. 12 with the SCE values plotted against the respective cutting condition. The graph shows that the chip compression ratio is higher when cutting speed is high whereas it is lower at a higher feed rate. This trend was also reported in earlier researches [63]. The higher value of the chip compression ratio indicates high strain in the chips which in turn implies a large amount of energy and cutting forces [64]. Thus, the high energy zone on the energy map is due to the higher values of *r* obtained at high cutting speed. Conversely, the *r* value decreases as the cutting feed increased. Therefore, low SCE values were achieved on the energy map as the feed rate increased during the cutting experiments. This is due to the shift in the cutting mechanism from rubbing and ploughing to shearing as the cutting feed increased. It is also worth mentioning that the SCE measured during the current research represents the energy consumed at the interface; shearing the material, overcoming the friction, the formation of new surfaces and the momentum changes. Whereas the trends of the chip compression ratio can be related to the portion of the energy utilized in shearing the material only. Thus, SCE maps provide a comprehensive approach to the total energy consumed at the cutting interface per unit material removed.

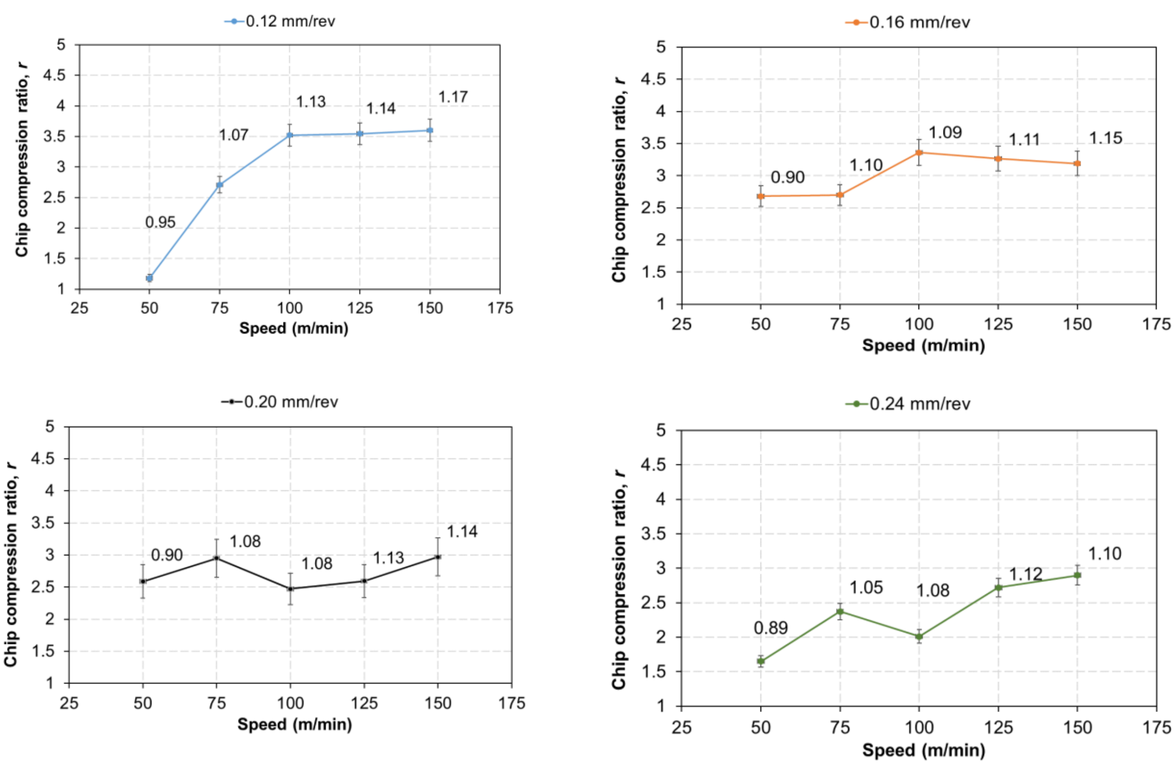

Fig. 12 Chip compression ratio during turning Ti6Al4V at the various cutting combination

The chip images in Fig. 13 represent five cutting speeds and a contact feed rate. With the change in the cutting state from low-speed condition to high-speed condition, the degree of segmentation increases that further complicates the cutting mechanics. Chip segments are more regular at high cutting speed (Fig 13 c-e) revealing adiabatic shear bands with higher serration characteristics. When chip segmentation occurs, the cutting process becomes unstable as a result of adiabatic shearing bands which significantly fluctuates the cutting forces and energy.

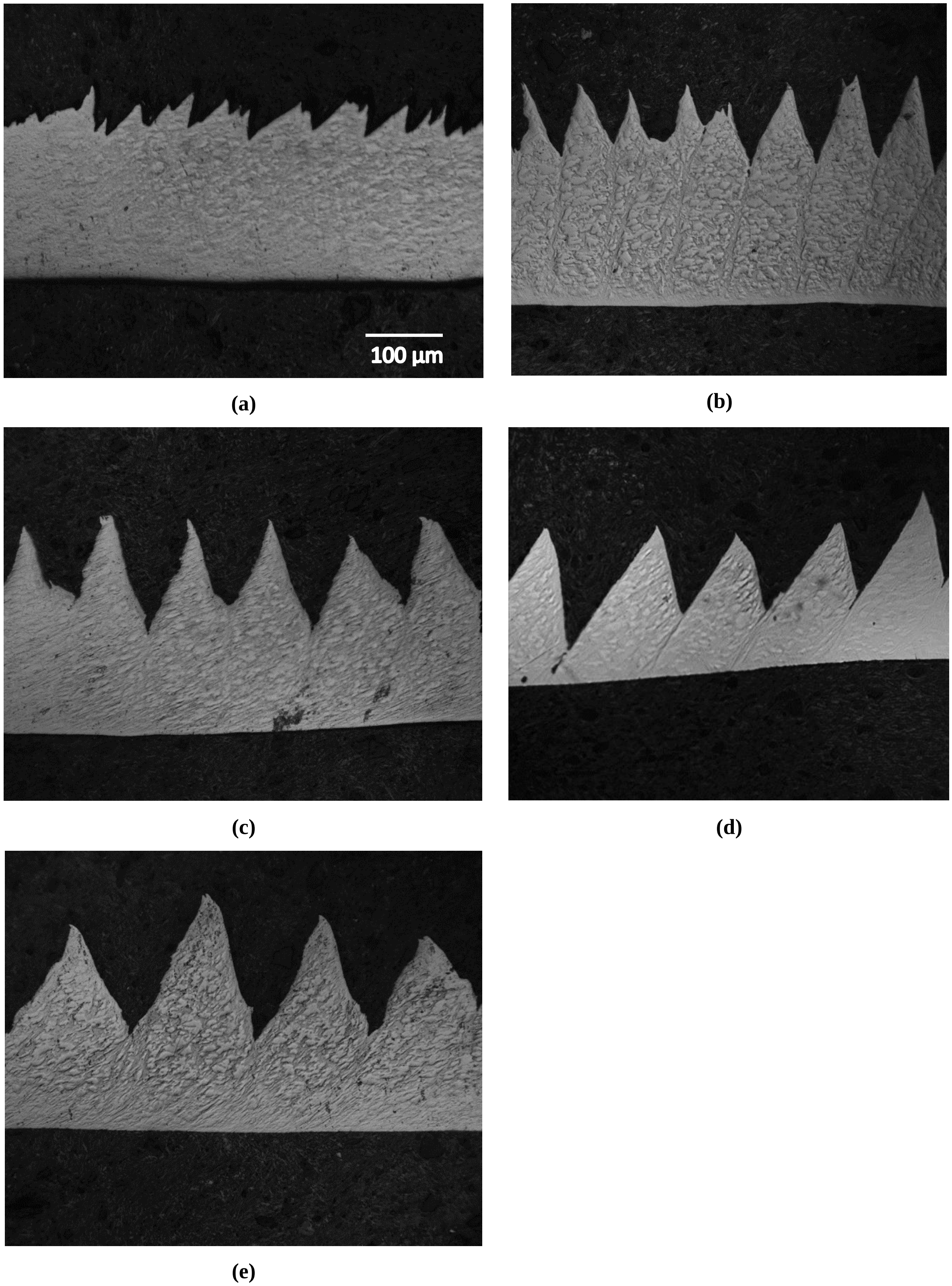

Fig. 13 Microscopic images of chip at feed 0.16 and cutting speed (a) 50 m/min, (b) 75 m/min, (c) 100 m/min, (d) 125 m/min and (e) 150 m/min (Magnification 20 X)

The chip compression ratio can also be related to the shear angle during the cutting process. A larger value of the chip compression ratio (*r*) means a lower value of the shear plane angle. In the current research, the shear angle was measured experimentally from the chip samples polished as shown in Figure 11. The influence of cutting speed and feed rate on the shear angle is shown in Fig. 14. A low shear angle means higher cutting forces and energy for a certain machining condition. It can be observed that increase in the cutting speed has decreased the shear angle. The scatter in the shear angle may be attributed to the variation in the tool wear and the adiabatic shearing of the material. Since the cutting conditions correspond to various regions of the wear and SCE maps, therefore variation in the shear plane occurred under all cutting conditions.

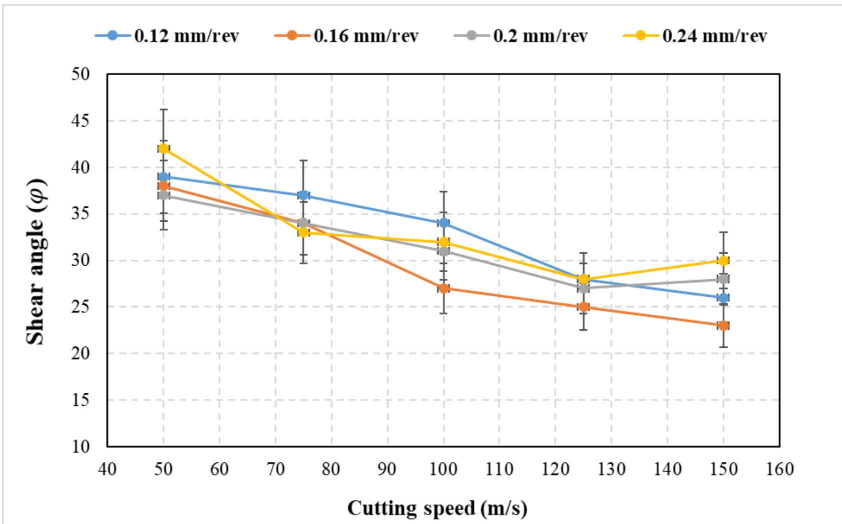

Fig. 14 Experimental shear plane angle *(φ*) obtained at various cutting speeds

4.3 Wear Mechanisms Analysis

Machining of Ti6Al4V material is complex to understand as in most cases multiple wear mechanisms may be present simultaneously that makes evaluation and analysis of tool wear very hard. The major cause of flank and crater tool wear of uncoated tools has been credited to the dissolution-diffusion and chipping [65]. It was reported earlier that during titanium alloys machining, the wear on the tool is also promoted by the chemical instability and adherence of the chip material onto the cutting edge [66]. The used inserts were analyzed under SEM to identify the type of wear mechanism that occurred in the cutting process. The main wear mechanisms observed are detailed in Fig. 15. It was found that the workpiece material has transferred to the tool surface and has caused adhesive wear to the tool surface. Tool chipping was also observed under high cutting speed. Thus adhesion-dissolution and tool chipping coupled with the poor thermal conductivity of the workpiece material is the main reason for high tool wear during machining Ti6Al4V alloys.

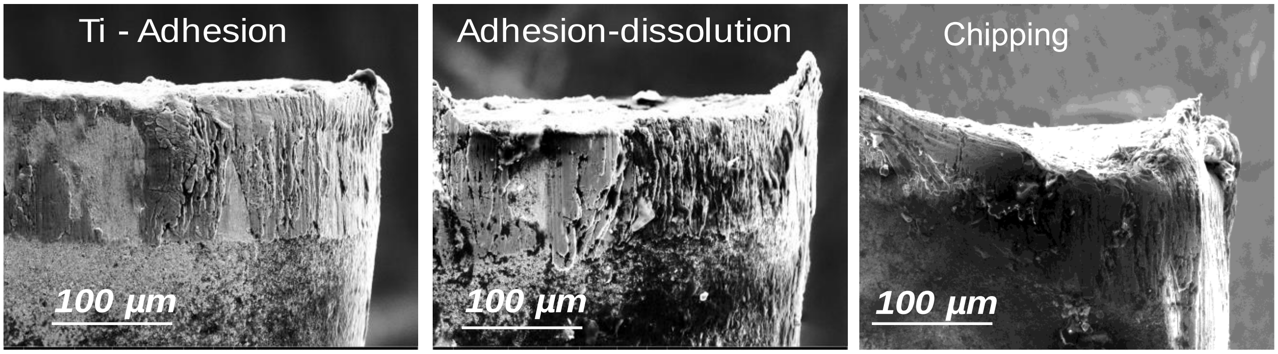

Fig. 15. Tool wear mechanisms in turning Ti-6Al-4V alloy

5 Conclusions

A wear map has been developed and analyzed together with the cutting energy map that can be carefully used for selecting the machining parameter which will minimize the energy costs as well as improve the tool life. Key points from the analysis of the experimental results are summarized as follows.

- The wear rate *R* intensifies when the cutting speed and feed rate is increased. This increase is mainly due to the high contact length at the interface that promotes tool deterioration.
- Tool chip contact length is increased when cutting speed and feed rate both are increased that further promotes wear mechanism along with high localized temperature at the contact point. The increased wear of the tool flank also fluctuates the SCE consumed in turning Ti6Al4V alloy.
- The analysis of the chip compression ratio revealed that it increases at higher cutting speed, thus lowering the shear plane angle and increase in SCE.
- The results suggest that cutting condition i.e. V = 100 m/min and f = 0.16 mm/rev, is recommended for dry turning Ti6Al4V alloy using uncoated tools and the *MRR* can be improved by 127 % using appropriate cutting parameters from the developed maps.
- A region of high tool wear corresponding to the cutting condition range (V = 55 – 70 m/min and f = 0.16 - 0.2 mm/rev) observed on the wear map requiring the tool interface investigation.
- The two maps in combination can be used to achieve sustainable machining goals in a situation where tool life and energy are to be minimized and thus reducing manufacturing cost for automotive and aerospace products made of Ti-6Al-4V.
- Further research will be conducted for the numerical and experimental analysis in the high tool wear and energy zones for a broader understanding of the nature of machinability of such difficult to cut alloys.

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