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Machinability of Ti6Al4V as influenced by cutting velocity, tool feed and cutting depth

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Abstract

Due to its application versatility, machining of Ti6Al4V alloy has been considered an important topic in the field of industrial manufacturing. To avoid machining-induced detrimental effects on the environment, dry machining of this difficult-to-machine alloy is a trending subject of matter. Therefore, the present study intends to explore different machinability indices such as tangential cutting force components, temperature evolved at tool-tip and wear of uncoated carbide inserts under the variations of machining parameters. A detailed study on tool wear modes and micro-morphology characteristics of evolved chips are also carried out for the present experimental analysis.

Keywords: Ti6Al4V; dry machining; tool wear

1. Research Background

Titanium and its alloys contribute substantially to aerospace industry because of their low density properties, good resistance to fracture and corrosion, and high specific strength [1]. The aerospace industry prefers Ti6Al4V alloy, a form of α+β titanium alloy, because of its high strength/weight ratio and ability to sustain that strength even at higher temperature values. Besides the above-mentioned advantages, Ti6Al4V alloy is also classified as 'difficult-to-machine' material because of its higher chemical reactivity for different grades of cutting tools and poor material properties (like elastic modulus and thermal conductivity). To avoid operational health hazards, to reduce environmental pollutions associated with machining, and to cut the extra added costs (of coolant purchase, storage and its disposal) in machining, dry machining is adopted by many researchers in recent days [2-4]. Although the tool wear is obvious during dry machining, an uncoated tungsten carbide (WC-Co) is still a preferred tool as it exhibits good thermal conductivity, shock resistance, high toughness, hardness receptivity, and economical.

Ibrahim et al. [5] reported adhesion as the dominating wear mechanism of uncoated WC-Co tool during dry turning of Ti6Al4V alloy under varied machining parameters (cutting speed, feed, and depth-of-cut); besides which abrasion and tool chipping, were also observed. The increment of cutting force was studied by Sun et al. [6] as influenced by varying tool feed rate, depth of cut and machining speed, during dry machining of Ti6Al4V alloy by a coated carbide insert. For dry turning of Ti6Al4V alloy under varied cutting speed and tool feed conditions, Li et al. [7] used a coated carbide insert to examine the variations in cutting forces and chip macro-morphology. Spiral chips with increased radius were noticed at increased cutting speed and feed respectively. Sun et al. [8] concluded that flank wear of an uncoated WC-Co tool is a dominating mode of tool failure for dry turning of Ti6Al4V and width of the same was found to be increased with cutting speed.

Fan et al. [9] studied different wear behaviors (such as adhesion, diffusion, and peeling-off of the adhered layer) with increased cutting speed during dry turning of Ti6Al4V alloy using an uncoated WC-Co tool. For dry turning of

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Ti6Al4V alloy with higher machining speeds, Sun et al. [10] reported failure of uncoated carbide tool due to progression of tool flank wear. The variations of chips' micro-morphological features were also analyzed with regard to cutting sped variation. Hernández et al. [2] and Hernández et al. [11] reported rise in cutting force magnitudes and wear of tool faces (both flank and rake) of the coated WC-Co insert for variations in tool feed and cutting speed while dry turning of Ti6Al4V alloy. Also, the effect of varying cutting speed and feed on various chip micro-morphological features including pitch, chip thickness, and shear angle was reported. Kumar and Senthil [3] used WC-Co inserts (both untreated and cryogenic treated) to perform dry turning of Ti6Al4V alloy and observed proportionate increment of cutting force and surface roughness values for variations in different machining parameters. Liang et al. [12] examined different tool failure modes of an uncoated WC-Co tool by carrying out turning of Ti6Al4V alloy in dry conditions using an uncoated WC-Co tool, by varying cutting speed. The dissolution-diffusion and chemical wear were observed to be the dominant wear mechanism for the WC-Co tool at higher speeds. For high-speed dry machining of Ti6Al4V alloy, Swain et al. [13] reported adhesion and chemically influenced oxidation wear as the dominating wear mechanism of a WC-Co tool (uncoated). Also, the tool feed, cutting speed and cutting depth positively contributed to increment of tool flank wear.

Though removing material from this difficult to machine alloy is not a new area of interest, finding out the most suitable machining method which also protects the environment from machining induced hazards is still a challenging task. The main focus of this work is to study the effect of varying machining parameters (feed; and depth-of-cut) on machinability indices like tangential cutting force, tool-tip temperature, and tool wear during dry machining of Ti-6Al-4V alloy with the conventionally used uncoated WC-Co cutting tool. The study also speaks about the micro-morphological parameters of the evolved chips.

2. Experimental Details

Ti6Al4V alloy of initial diameter 50 mm is chosen as work material. The elemental composition of the alloy is shown in Table 1 [1]. A set of dry turning experimental trials were performed on a high-speed precision lathe machine (NH26, HMT, Bangalore, India) under various machining parameters (*(v = 71, 92, 119 m/min, f = 0.1 & 0.16 mm/rev, doc = 0.35mm)*; and (*v = 72, 93, 121 m/min, doc = 0.25 & 0.35 mm; f = 0.1mm/rev)*). Uncoated tungsten carbide (WC-Co) inserts (with ISO designation: SNMA 120408 with 0.8 mm nose radius) are used for the present machining trials. PSBNK2020K12 is used as a tool holder. Tool inserts are placed over the tool holder for obtaining desired tool geometry: -6° inclination angle, -6° rake angle, 75° approach angle. A new cutting edge of the tool insert is used in every trial (with each trial for 30 seconds) for maintaining the same initial cutting conditions.

Table 1. Elemental composition of Ti6Al4V alloy.

Element	Ti	Al	V	Sn	Fe	Si	Mo
Weight [%]	89.7	6.31	3.28	0.43	0.24	0.04	0.01

Cutting forces (only tangential component) and tool-tip temperatures evolved during machining, are measured using a force-torque dynamometer (Kistler 9272, Kistler Instruments AG, Switzerland) and a non-contact type digital mode infrared thermometer (AR882, Solarman Engineering Project Pvt. Ltd., India) respectively.

Primary inspection is done using Optical Microscope (GMBH 37081, Carl Zeiss, Oberkochen, Germany) to understand tool flank wear and chip micro-morphology. The captured micrographs are then utilized to calculate tool flank wear width and chip micro-morphological features with the help of ImageJ software. Scanning Electron Microscope (SEM) (JSM 6480LV, JEOL, TOKYO, JAPAN) is used for secondary inspection to understand the main failure modes of cutting insert. Detailed elemental composition is obtained through Energy Dispersive X-ray Spectroscopy (EDS) analysis.

3. Results and Discussion

Fig. 1 (a) and (b) respectively display the effect of tool feed rate on the tangential component of cutting force and temperature generated at tool-tip during the machining trials. Fig. 1(a) shows that increasing the tool feed increases cutting forces in tangential direction, which could be due to the increased strain hardening effect of work material and extensive tool wear [11]. On the other hand, a decrease in temperature values at the tool-tip (of carbide inserts) with an increment of tool feed rate (at each cutting speed) is observed in Fig. 1(b), as a major amount of cutting heat is believed to be carried out by the evolving chips. During dry turning of OHNS, fall in tool-tip temperature with tool feed rate was however reported by Chikalthankar et al. [14].

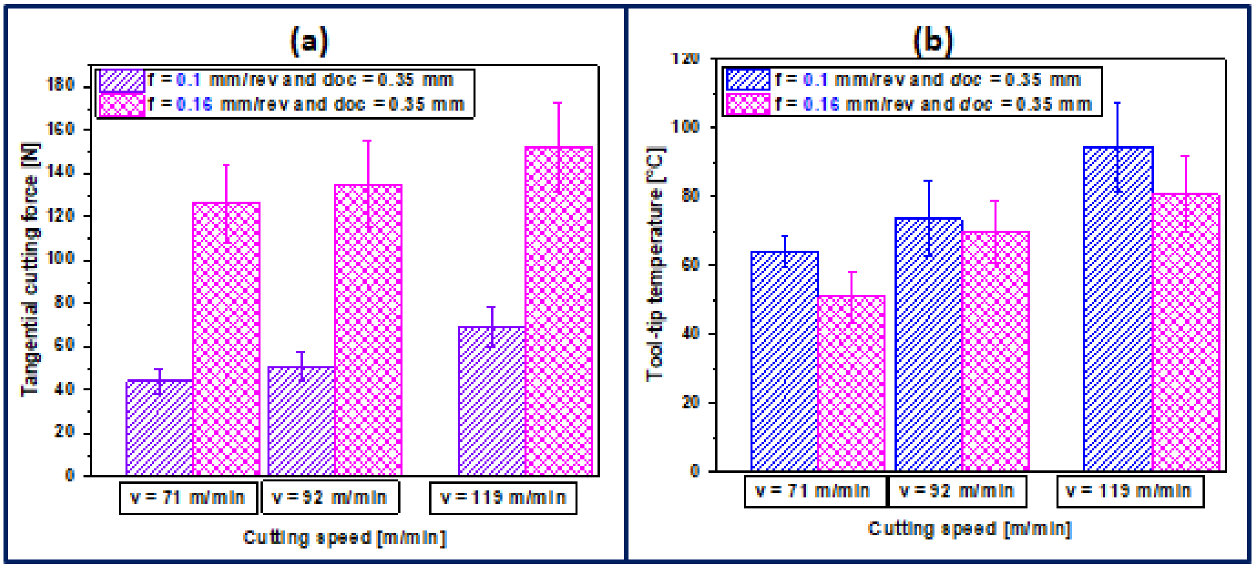


Fig. 1: Effect of feed variation on: (a) tangential cutting force and (b) tool-tip temperature.

The influence of depth-of-cut on tangential cutting force and tool-tip temperature is shown in Fig. 2 (a) & (b) respectively. An increase in cutting force is observed with an increase in cutting depth (at each cutting speed). This is because the tool edge comes in contact with a higher amount of work material that originates a high temperature in the machining zone and a severe plastic deformation in the tool. Strain-hardened work material requires high cutting forces to undergo the required plastic deformation needed to form a chip [6]. Also, an increase in tool-tip temperature is observed as cutting depth increases (as in Fig. 2 (b)), due to the combined effect of poor thermal characteristics of work material, and severe plastic deformation which obstructs the flow of heat from the machining zone. As cutting depth increases, more amount of work material to be machined comes in contact with the tool resulting in increased friction. Since the machining is performed in dry conditions, the friction at the work-tool junctions also contributes to machining zone temperatures [3].

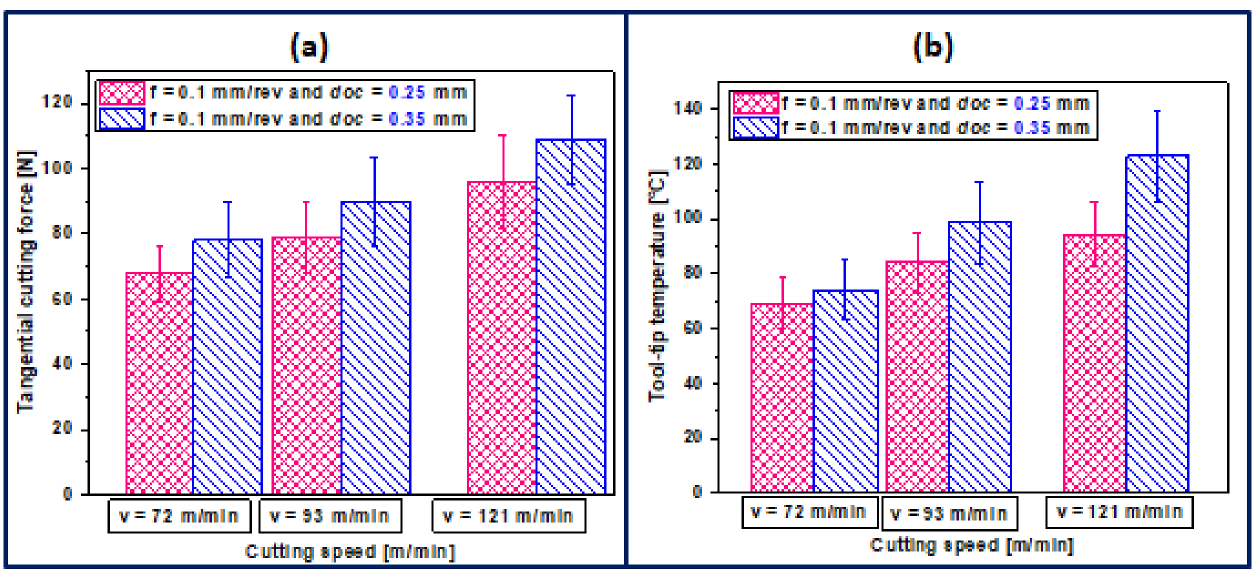


Fig. 2. Effect of depth of cut variation on: (a) tangential cutting force and (b) tool-tip temperature.

Fig. 3 shows optical micrographs exhibiting the effect of feed on the flank wear of uncoated carbide inserts. The measured values of flank wear width with increased cutting feed are plotted in Fig. 4, which states an increase in width of flank wear increased tool feed (at each cutting speed). As feed increases, the longitudinal movement of the cutting tool advances per revolution of the work material. Therefore, an increased amount of work surface (hardened material) rubs over the flank face of the cutting tool and erodes the material over the flank face which increases flank wear width. A similar increasing trend of flank wear width with increased feed was reported by da silva et al. [15]. The worn out flank widths describe higher values with increased depth of cut, which are plotted in Fig. 5 and can be attributed to the amount of machined surface rubs over tool flank surface causing extensive tool abrasion and thereby resulting in a progressive flank width which supports the reporting by Swain et al. (2021).

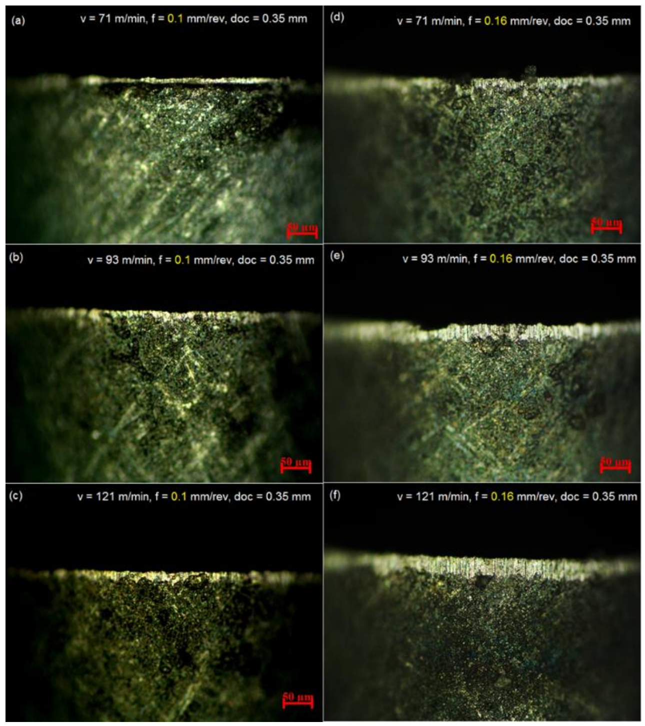


Fig. 3. Optical micrographs exhibiting influence of tool feed on tool flank wear.

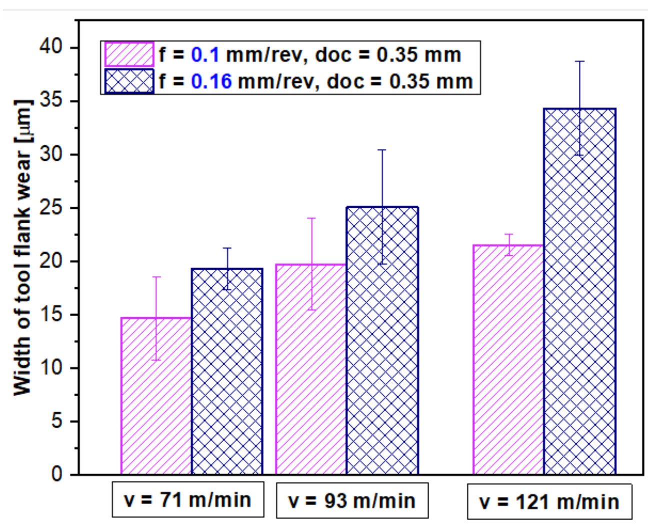


Fig. 4. Influence of feed variation on tool flank wear.

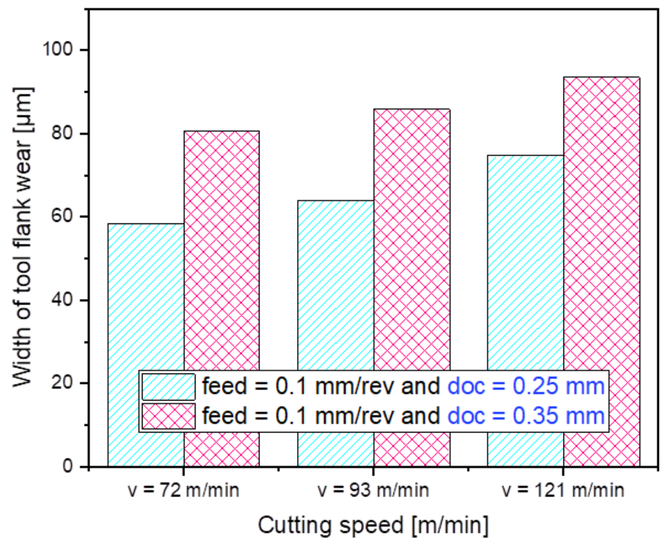


Fig. 5. Influence of depth of cut variation on tool flank wear.

Fig. 6 shows a detailed tool wear mechanism when the tool was operated at v = 92 m/min, f = 0.1 mm/rev and doc = 0.35 mm. A thin layer of work material is observed to have adhered upon tools' rake face causing adhesion wear which is mostly influenced by: (1) continuous contact between chip and tool, (2) higher affinity of the work elements to chemically react with the tool. The EDS results shown in Fig. 7 exhibit the presence of Ti (72.71 %), W (17.17 %), V (4.66 %), Al (4.16 %), and Fe (1.29 %), which confirm material adhesion from work-alloy on the rake face of carbide insert. Besides adhesion, abrasion and chip-sticking is also noticed on the rake surface of the uncoated insert. Because turning is performed in dry conditions, a lot of heat is produced at the chip-tool interface due to friction. Thereby, the hot chips rolling over the rake face stick to the cutting insert which got softened due to high temperatures. As stated by Ibrahim et al. [5], the rolling chips that pass over the tool face remove softer tool material and thus leave grooves on the tool face (abrasion wear phenomenon). Scratches upon the tool rake face confirm that the tool had also suffered due to abrasion wear.

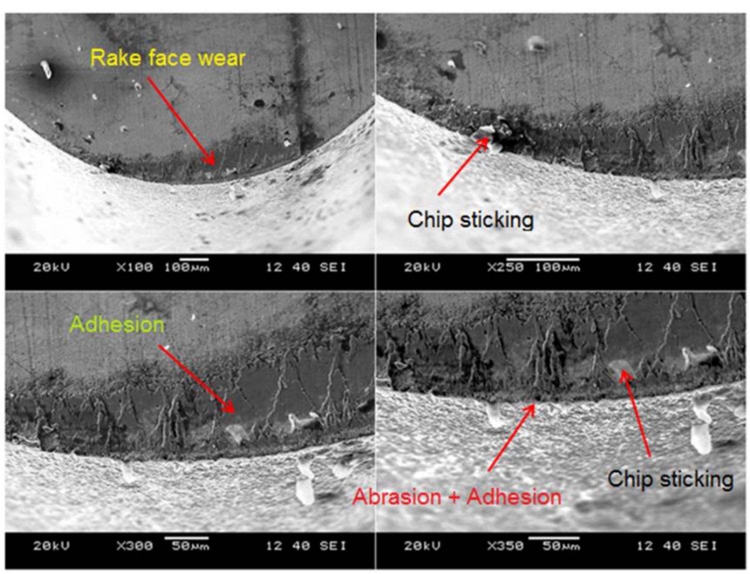
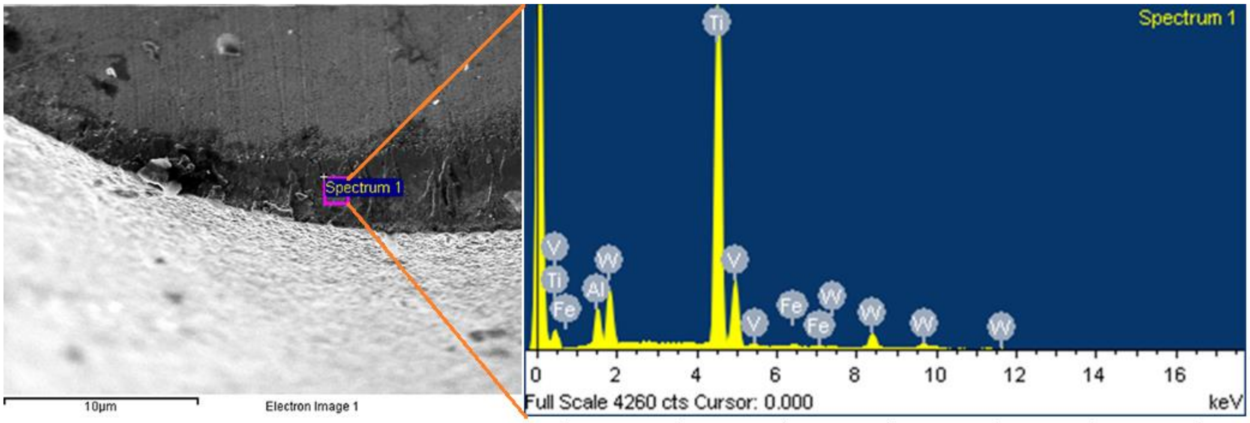


Fig. 6. Detailed tool wear mechanisms: Tool operated at v = 92 m/min, f = 0.1 mm/rev and doc = 0.35 mm.



Element(s)	Ti	W	V	Al	Fe
Wt. [%]	72.71	17.17	4.66	4.16	1.29

Fig. 7. EDS results confirming work material adhesion: Tool operated at v = 92 m/min, f = 0.1 mm/rev and doc = 0.35 mm.

Fig. 8 indicates a detailed tool wear mechanism when the tool was operated at higher cutting speed (about 121 m/min), keeping tool feed and cutting depth respectively at 0.1 mm/rev and 0.35 mm. Severe adhesion, chip-sticking, pressure-welded chips are observed on the tools' rake face during machining. As higher cutting speeds and larger depth-of cut allow a large volume of deformed work-material to slide on the rake surface, it results in severe adhesion which is confirmed by the abundant traces of Ti (95.3 %), Al (2.5 %), and V (2.2 %) as shown in Fig. 9. Chips are forcibly welded to the tools' rake face due to the increased amount of cutting loads. Also, oxidized chips are observed on the tool face as a result of the high chemical reactivity (associated with high cutting temperatures) of the work material with the tool. Since machining is done in an open and dry environment, atmospheric oxygen tends to react with hot work-tool material which results in oxidation of stuck chips. This is confirmed by the traces of Ti (67.72 %), W (15.73 %), O (9.71 %), V (4.19 %), Al (1.97 %), and Co (0.69 %) as shown in Fig. 9. The discussed wear modes at higher cutting speeds were previously conferred by authors [12-13].

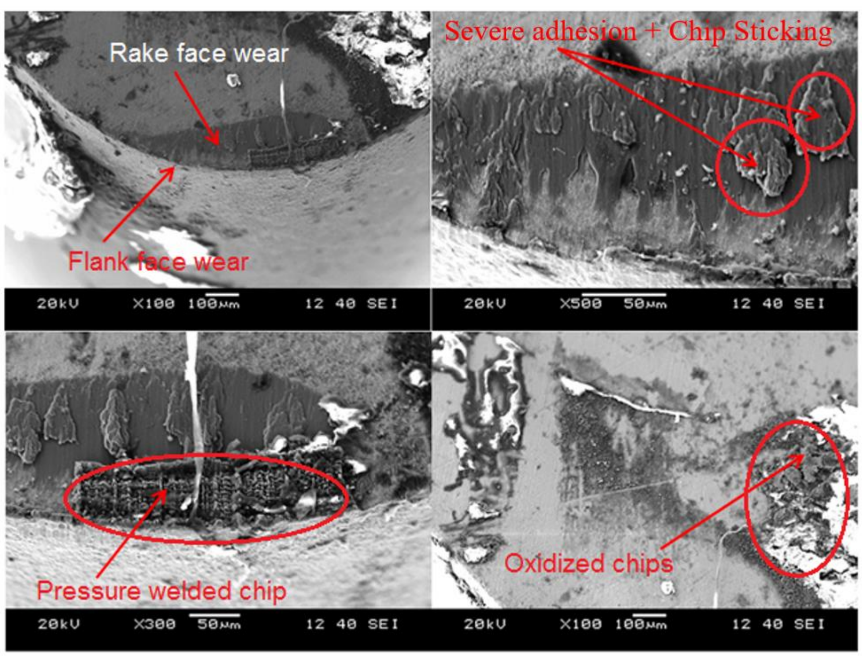
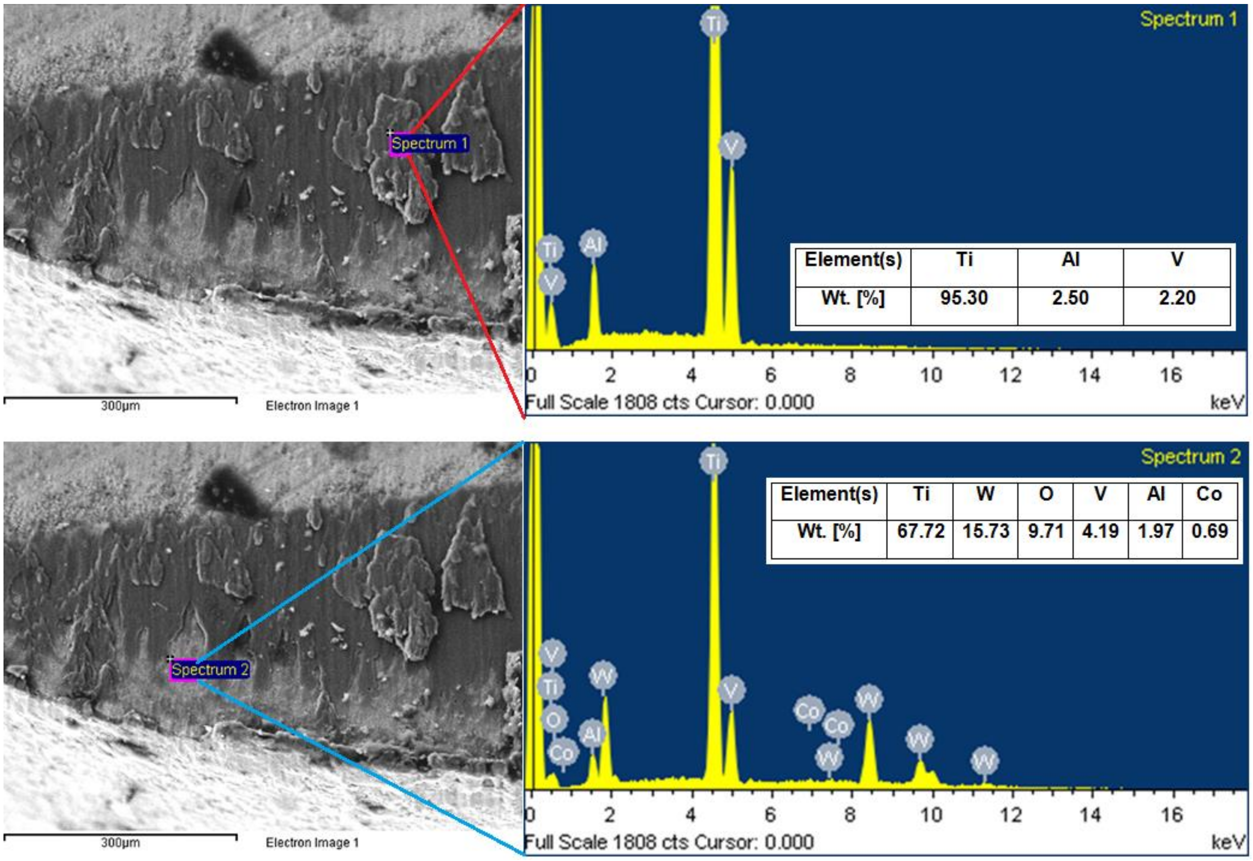


Fig. 8. Detailed tool wear mechanisms: Tool operated at v = 121 m/min, f = 0.1 mm/rev and doc = 0.35 mm.



Element(s)	Ti	Al	V
Wt. [%]	95.30	2.50	2.20

Element(s)	Ti	W	O	V	Al	Co
Wt. [%]	67.72	15.73	9.71	4.19	1.97	0.69

Fig. 9. EDS results confirming work material adhesion at localized areas of tool rake face: Tool operated at v = 121 m/min, f = 0.1 mm/rev and doc = 0.35 mm.

As noticeable changes were not observed in the chips' colour and structure, present study is further extended to study chips' micro-morphological features including pitch of chip segments *(P)*, equivalent chip thickness *(t)*, chip segmentation frequency (f_s), and shear angle (θ). Serrated chips obtained by varying machining parameters ((v = 92 m/min, f = 0.1 & 0.16 mm/rev, doc = 0.35mm); and (v = 92 m/min, doc = 0.25 & 0.35 mm; f = 0.1mm/rev)) exhibiting various chip micro-morphological features as influenced by varying feed and depth-of-cut are shown in Fig. 10 (a) & (b) respectively.

The pitch of chip segments in a saw-toothed chip profile is defined as the longitudinal distance measured on any two successive points (peak/valley) on a serrated chip profile, and it is highly influenced by machining parameters, tool wear, and chips' deformation rate. In agreement with Das et al. [4], the pitch is found to be increasing with cutting feed and cutting depth respectively. The number of chip segments formed per unit time is known as chip segmentation frequency, which inversely varies with the pitch of chip segments and it is measured by using the formula (in Equation (1)) reported by Upadhyay et al. [16]. Therefore, chip segmentation frequency is observed to follow a decreasing trend with the increase in cutting feed and cutting depth.

$$f_s = \frac{v}{p} \tag{1}$$

P = pitch (µm)
f_s = chip segmentation frequency (kHz)
v = cutting speed (m/min)

From Fig. 10, the thickness of the collected chips is observed to be increasing with cutting feed and cutting depth respectively. It is measured by using Equation (2). As the cutting feed/depth increases, the amount of work material coming in contact with the tool also increases. As stated earlier, hot chips flowing on the rake face tend to get pressure welded and carry away some tool material, thereby increasing shear plane area which in turn results in increased chip thickness. Vilches et al. [17] also stated a similar outcome during dry turning aluminum alloys by varying cutting feed.

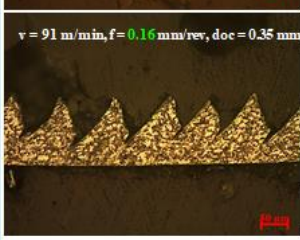
$$t = h_v + \frac{h_p - h_v}{2} \tag{2}$$

t = equivalent chip thickness (µm)
h_p = height of the peak (µm)
h_v = height of the valley (µm)

The shear angle is the angle between the cutting velocity vector and the shear plane. It is highly influenced by the increased chip thickness due to the higher plane of shear. The more is the chip thickness lesser the shear angle. As mentioned earlier that the chip thickness is observed to be increased with cutting feed and cutting depth. Therefore, the shear angle is observed to be decreasing with increased cutting depth. On contrary, an increase in shear angle is observed with increased feed which might be due to less plane of shear deformation. By varying tool feed and cutting depth, Upadhyay et al. (2014) were however found a similar result for the obtained chip samples.

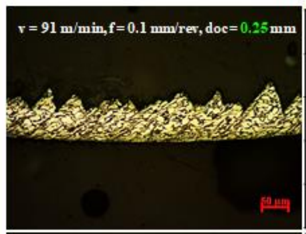
(a)

Parameters	Mean value	St. Dev.
P [µm]	42.5	2.293
t [µm]	71.24	5.739
f_z [kHz]	2.73	0.149
θ [°]	40.76	2.066

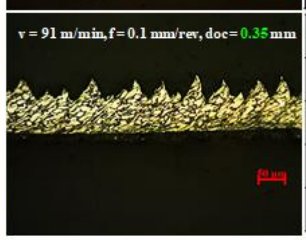


Parameters	Mean value	St. Dev.
P [µm]	92.85	10.782
t [µm]	88.12	0.407
f_z [kHz]	1.436	0.185
θ [°]	45.07	2.527

(b)



Parameters	Mean value	St. Dev.
P [µm]	35.79	11.246
t [µm]	59.68	10.135
f_z [kHz]	3.44	0.955
θ [°]	42.57	1.657



Parameters	Mean value	St. Dev.
P [µm]	54.02	6.641
t [µm]	72.94	4.167
f_z [kHz]	1.737	0.231
θ [°]	37.61	1.143

Fig. 10. Chip micro-morphological parameters as influenced by: (a) feed variation and (b) depth of cut variation.

4. Conclusions

Through the present experimental analysis performed on Ti6Al4V alloy under varying machining parameters following conclusions are to be noted.

- An increase in feed rate from 0.1 to 0.16 mm/rev resulted in a 117.14% increment in cutting force by reducing the tool-tip temperature for about 16.32% at the cutting speed of 119 m/min.
- At 121 m/min and 0.1 mm/rev, increasing cutting depth from 0.25 mm to 0.35 mm caused increment in both cutting force and tool-tip temperature by 12.24% and 35.41% respectively.
- Though increase in both cutting depth and tool feed rate causes an increase in width of flank wear, varying depth of cut contributes more to flank wear as compared to the feed variation. Obvious wear modes like adhesion, abrasion, chip sticking and oxidized chips are revealed on the edges of cutting tools.
- A brief comparative assessment for chip micro-morphological parameters is also carried out to highlight the behavior of produced chips with variations in machining parameters.

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