Comprehensive study of chip morphology in turning of Ti-6Al-4V

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Abstract

In machining of Ti-6Al-4V alloy, the formation of saw tooth chips takes place at relatively low cutting speeds in comparison to other materials such as hardened steels. Study of chip morphology is important to understand the cutting force variation, surface integrity and chip breakability of the alloy. In this work, an attempt has been made to study the effect of cutting speed, feed rate and depth of cut on saw tooth geometry in terms of peak height, valley height, tooth height, segmentation degree, tooth pitch, localized shear angle, bulge angle and chip segmentation frequency, to get better insight about the machinability characteristics of Ti-6Al-4V alloy.

Keywords: Chip morphology; Ti-6Al-4V alloy; turning.

1. Introduction

Ti-6Al-4V is the most widely used alloy of titanium due to its high strength to weight ratio, excellent corrosion resistance, and ability to maintain its strength even at elevated temperature. In Ti-6Al-4V alloy, segmented chips are formed at low cutting speeds comparative to other materials in which chip segmentation takes place at relatively high cutting speeds (Calamaz et al. 2008). Segmented chip is a general term used for wavy chip as well as saw tooth chip (pointed tooth). As suggested by Vyas and Shaw (1999), pointed tooth segmented chip will be called as saw tooth chip in this work to differentiate it from wavy chip. The mechanism of saw tooth chip formation was described by two different theories: adiabatic shear theory and cyclic crack theory. Komanduri and Turkovich (1981) described the mechanism of chip formation in machining of titanium alloy by adiabatic shear. They described chip formation as a two-stage process. In the first stage, plastic instability and strain localization occurs in a narrow band in primary shear zone leading to catastrophic shear failure along the shear surface. In the next stage, gradual build up of the segment with negligible deformation takes place ahead of the advancing tool resulting in serrated chips (Komanduri and Turkovich 1981, Komanduri 1982). Formulation of serrated chip at low cutting speeds in titanium alloy is due to thermo-mechanical instability of the material, which results in intense plastic deformation in a narrow band between segments and relatively negligible deformation in the chip segments (Komanduri and Hou 2002). Nakayama (1974) suggested that the saw tooth formation was due to cyclic cracking instead of adiabatic shear and gross cracks and micro cracks are involved in formation of saw tooth chip. The shear crack initiates at the free surface and extends along the shear plane towards the tool tip. A recent study conducted by Wan et al. (2012) suggests that adiabatic shear sensitivity of workpiece material is a key factor in catastrophic failure during formation of saw tooth chip. If the material is very sensitive to localized shear deformation then the saw tooth formation is due to thermoplastic instability whereas if the material is insensitive to localized shear deformation and susceptible to crack initiation then the cyclic crack initiation and propagation leads to saw tooth chip formation. If the adiabatic shear sensitivity lies between the above two then the saw tooth formation is due to interaction of thermoplastic instability and cyclic crack initiation and propagation.

Shaw et al. (1991) studied the effect of cutting speed and feed rate on tooth pitch, specific cutting energy and cutting ratio for Ti-6Al-4V alloy. They found tooth pitch independent of cutting speed but observed almost linear increase with increase in feed rate. Specific cutting energy was found to decrease with increase in cutting speed and feed rate however decrease in case of feed rate was exponential. Cutting ratio was reported as independent of cutting speed whereas it increased with increase in feed rate (Shaw 2005). Hua and Shivpuri (2004) developed a FEM model based on crack initiation for prediction of chip morphology and segmentation in orthogonal machining of Ti-6Al-4V alloy. Based on a simulation study they concluded that with increase in cutting speed, crack propagation shifts
from tool tip to the free surface of the deformed chip in shear zone, converting the chip from discontinuous to a serrated one. Gente et al. (2001) studied chip formation in Ti-6Al-4V alloy in the cutting speed range of 300 m/min to 6000 m/min. They used a quick stop method that was able to provide rapid deceleration from 2500 m/min in a very short distance. When cutting speed and chip thickness was increased beyond 2000 m/min and 50 µm respectively, partially separated segments were observed. In addition, the shear strain was found almost independent of cutting conditions. Cotterell and Byrne (2008) used high speed imaging system to study the chip formation process and determined the segment shear angle and bulge angle in the cutting speed range of 4 to 140 m/s. With increase in cutting speed, the segment shear angle increased and approached a value close to $40^\circ$ whereas the bulge angle tended to decrease and approached a constant value of $27^\circ$. Shear strain of chip and shear strain within the segment decreased with increase in cutting speed and became almost constant at high values of cutting speed. The chip segmentation frequency was found to increase linearly with cutting speed and decrease with feed rate. Sun et al. (2009) observed that the force frequency of cyclic force produced during the formation of segmented chips was same as the chip segmentation frequency. Bayoumi and Xie (1995) investigated the metallurgical aspects of shear localized chip formation in Ti-6Al-4V alloy. Study of the effect of cutting conditions on shear band formation and shear banding frequency was also carried out. Molinari et al. (2002) studied adiabatic shear banding by measuring shear band width and separation distance between bands. The shear bandwidth was found to vary as inverse of cutting velocity ($V^{-1}$) whereas separation distance varied as $V^{-3/4}$ for cutting velocity greater than 12 m/s. Sun and Guo (2008) characterized the morphology of top surface, free surface, back surface and cross section surface of chips obtained in end milling. Wan et al. (2012) studied the variation of segment spacing, adiabatic shear band width and degree of segmentation with cutting speed, feed rate and rake angle. They reported an increase in the value of the above mentioned parameters with increase in cutting speed and feed rate, and decrease in rake angle.

Chip morphology is important for studying the machinability of titanium alloys and gaining better understanding of the fundamental phenomena governing machinability, such as mechanics of machining process, thermal aspects associated with the cutting process, vibrations etc. Sun and Guo (2008) provided 3D morphology of chip but study of some more parameters is still required for complete characterization. Other studies reported in published literature are with limited number of chip morphology parameters which stands in the way of a comprehensive understanding of chip morphology. Thus, there is a need to conduct a comprehensive study of chip morphology and the manner in which it is affected by the cutting parameters. Therefore, an attempt has been made to experimentally study the effect of cutting parameters on chip morphology in terms of peak height, valley height, tooth height, segmentation degree, tooth pitch, shear angle, bulge angle and chip segmentation frequency in turning of Ti-6Al-4V alloy.

2. Experimental details
A rigid, high power precision lathe (model: NH22; make: HMT, India) equipped with specially designed experimental set-up and data acquisition system was used for the experimental work. PCBNR 2525 M12 (Mitsubishi Material Co.) tool holder was used to hold the CNMG120408 tool bit of uncoated cemented carbide (ISO S-grade). The tool geometry is as follows: back rake angle = $-6^\circ$, side rake angle = $-6^\circ$, principal cutting edge angle= $75^\circ$, end cutting edge angle = $5^\circ$, nose radius = $0.8$ mm.

Experiments were conducted according to the Box Behnken Design (BBD) of Response Surface Methodology. The experimental design involves variation of three factors (cutting speed, feed rate, and depth of cut) at three levels as mentioned in Table 1. This requires 15 experimental runs including three replications of the centre point. The range and levels were selected on the basis of literature review, tool manufacturer recommendations and machining constraints. Table 2 shows the parametric combinations for the experiments and the corresponding response parameters.

<table>
<thead>
<tr>
<th>Table 1. Levels of independent variables for turning</th>
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<td>Variable</td>
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<td>Cutting Speed ($V$)</td>
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<td>Feed rate ($f$)</td>
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<td>Depth of cut ($d$)</td>
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A water miscible, vegetable oil based cutting fluid (Vasco 1000, Blaser Swisslube) was mixed in 5% concentration with water and all the experiments were carried out under flood cooling environment. Chips obtained during the experiments were dried and collected for further examination. As tubular/helical chips are formed during machining they are clamped in lab made aluminum clamps to keep them straight. These chips are then mounted in epoxy and polished to reveal cross-sectional area of chip. Scanning electron microscopy of chips was performed with field emission scanning electron microscope (FE-SEM) (FEI-Quanta 200®) to obtain the images of tooth section perpendicular to the width of chip. FE-SEM was
operated in secondary electron image (SEI) mode for image acquisition. An accelerating voltage of 20 kV and an image size of 1024*884 pixels was used for getting quality images of chip section. The obtained images were then analyzed with the help of ImageJ 1.37v software to determine different parameters of chip morphology.

Table 2. Parametric combinations for the experiments and corresponding response parameters

<table>
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<tr>
<th>Cutting parameter</th>
<th>Chip morphology parameters</th>
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3. Chip morphology parameters

Typical tooth section of a chip is shown in Fig. 1, which confirms the obtained chip to be saw tooth. A typical chip segment can be divided into two parts: separated portion and continuous portion. Separated portion has undeformed surface on one side and part of catastrophically shear failed surface separated from the following segment on the other side. Continuous portion of the chip has intense shear band on both sides whereas the bottom of the continuous portion is the intensely sheared surface, which was in contact with the tool.

The thickness of the chips obtained in machining of Ti-6Al-4V alloy is not constant and varies from maximum to minimum, creating an alternate peak and valley structure. Peak height ($t_p$), valley height ($t_v$), tooth pitch ($p_C$), localized shear angle ($\phi_{seg}$) and bulge angle ($\rho_{seg}$) were measured directly from the images of saw tooth section obtained by scanning electron microscope whereas geometrical relations were used to determine the remaining parameters. The peak height indicates the total thickness of chip (continuous and separated portion) whereas the valley height represents the thickness of continuous portion of chip. The chip portion between peak and valley region, herein after called as tooth height ($t_T$) represents the thickness of separated portion of the chip and is computed by the relation

$$t_T = t_p - t_v$$

Segmentation degree ($G_s$) is the ratio of tooth height to peak height and is calculated by the relation

$$G_s = \frac{(t_p-t_v)}{t_p}$$

Chip segmentation frequency or cracking frequency ($f_{CS}$) is given by (Vyas and Shaw 1999)

$$f_{CS} = \frac{V_c}{p_C}$$

where $V_c$ is chip speed.

As cutting ratio $r = \frac{p_C}{p} = \frac{V_c}{V}$, the above equation can be rewritten as

$$f_{CS} = \frac{V}{p}$$

where $p$ (work pitch) = $t_T*sec\phi_{seg}$

3. Results and Discussions

Experimentally obtained values of peak height ($t_p$), valley height ($t_v$), tooth pitch ($p_C$), localized shear angle ($\phi_{seg}$) and bulge angle ($\rho_{seg}$) for various experimental runs are shown in Table 2. Using the experimental data, model development and analysis of experimental results were carried out with the help of Design-Expert 7.0.0 software. Subsequent analysis is based on the values obtained from these models.

The variation of peak height, valley height and tooth height with cutting speed, feed rate and depth of cut are shown in Fig. 2. It is evident from the figure that feed rate has the most significant effect on $t_p$, $t_v$ and $t_T$ and accounts for 94%, 78% and 98% of total variability. All these response parameters have shown a continuous increase in feed rate. Not much variation in the value of $t_p$, $t_v$ and $t_T$ was observed with increase in cutting speed and depth of cut. However, for 95% confidence interval cutting speed has shown a significant effect on $t_p$ and $t_v$ accounting for 3% and 14% of total variability whereas its effect on $t_T$ was found insignificant. The effect of depth of cut on $t_p$, $t_v$ and $t_T$ was found insignificant.

Increase in cutting speed leads to high heat generation in the cutting zone resulting in reduced peak height and increased shear instability. This increased shear instability results in a reduction in valley height and increase in tooth height thus increasing the chip segmentation. The variation of tooth height with

Fig. 1 Tooth-section of chip
increase in cutting speed is almost constant and statistical analysis suggests it to be insignificant. However, as peak height is also decreasing with cutting speed, instead of considering it as a standalone parameter it should be studied as change in tooth height per unit peak height called as segmentation degree.

Shear localization is easier to break and relatively ideal to dispose for automated machining. Wan et al. (2012) observed that hardness of shear-localized portion is higher than that of the remaining segment. Hence, the shear-localized chip is easier to break.

The variation of segmentation degree with cutting parameters is shown in Fig. 3. It is evident that the segmentation degree increases almost linearly with cutting speed. Effect of feed rate on segmentation degree is comparatively less as it remains almost constant with increase of feed rate from 0.16 to 0.20 mm/rev and then increases sharply with further increase in feed rate. Depth of cut does not cause any significant change in segmentation degree. Segmented chips are desirable in titanium alloy machining as they ensure good chip breakability. Bayoumi and Xie (1995) stated that a segmented chip which contains some evidence for shear localization is easier to break and relatively ideal to dispose for automated machining. Wan et al. (2012) observed that hardness of shear-localized portion is higher than that of the remaining segment. Hence, the shear-localized chip is easier to break.

Effect of change in input cutting conditions on $\theta_{seg}$ and $\rho_{seg}$ is shown in Fig. 4. $\theta_{seg}$ increased continuously with increase in cutting speed and feed rate, but decreased slightly with increase in depth of cut. Cutting speed and feed rate account for 38% and 12% of total variability in $\theta_{seg}$. When the $\rho_{seg}$ data was subjected to ANOVA analysis, no input parameter was found to have a significant effect and as a result the mean value model was found most appropriate. $\rho_{seg}$ was found scattered around a mean value of 23.67$^0$ with a standard deviation of 2.25$^0$. The angles $\theta_{seg}$ and $\rho_{seg}$ are generally used for computing shear strain and shear strain rate within the chip segment of shear localized chip and thus help in assessment of chip deformation. The summation of $\theta_{seg}$ and $\rho_{seg}$ represents the tooth included angle and it was always found greater than 45$^0$ for all the experimental sets. Observations of Cotterell and Byrne
(2008) also indicate that tooth included angle was greater than 45° in machining of Ti-6Al-4V alloy.

Saw tooth formation causes a cyclic variation of cutting force during machining. Sun et al. (2009) observed that the frequency of the cyclic force was similar to chip segmentation frequency. So, the segmentation frequency is an important parameter as it also indicates the cyclic force frequency. Variation of segmentation frequency is shown in Fig. 7 wherefrom it is evident that cutting speed and feed rate have a significant but opposite effect on segmentation frequency i.e. it increases with increase in cutting speed and decreases with increase in feed rate. Cotterell and Byrne (2008) also observed a similar variation of chip segmentation frequency with cutting speed and feed rate. Percentage contribution of cutting speed is highest accounting for 75% of the total variability, whereas that of feed rate was 24%. Chip segmentation frequency remained almost constant with increase in depth of cut.

Fig. 5. Variation of \( \phi_{seg} \) and \( \rho_{seg} \) with (a) cutting speed, (b) feed rate and (c) depth of cut

Fig. 6. Variation of tooth pitch with (a) cutting speed, (b) feed rate and (c) depth of cut
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Fig. 7. Variation of segmentation frequency with (a) cutting speed, (b) feed rate and (c) depth of cut

4. Conclusions
Following specific conclusions were drawn:
1. Feed rate is the most dominating parameter affecting the peak, valley and tooth height. However, segmentation degree is most affected by cutting speed.
2. \( \theta_{seg} \) increases with increase in cutting speed and feed but decreases slightly with increase in depth of cut. No specific trend was observed for \( \rho_{seg} \).
3. Feed rate has the maximum effect on tooth pitch. The tooth pitch increases with increase in feed rate.
4. Chip segmentation frequency was affected the most by cutting velocity and then by feed rate. The frequency increases linearly with increase in cutting velocity and decreases with increase in feed rate.

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References