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Characteristics of cutting forces and chip formation in machining of titanium alloys

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ABSTRACT

Chip formation during dry turning of Ti6Al4V alloy has been examined in association with dynamic cutting force measurements under different cutting speeds, feed rates and depths of cut. Both continuous and segmented chip formation processes were observed in one cut under conditions of low cutting speed and large feed rate. The slipping angle in the segmented chip was 55°, which was higher than that in the continuous chip (38°). A cyclic force was produced during the formation of segmented chips and the force frequency was the same as the chip segmentation frequency. The peak of the cyclic force when producing segmented chips was 1.18 times that producing the continuous chip.

The undeformed surface length in the segmented chip was found to increase linearly with the feed rate but was independent of cutting speed and depth of cut. The cyclic force frequency increased linearly with cutting speed and decreased inversely with feed rate. The cutting force increased with the feed rate and depth of cut at constant cutting speed due to the large volume of material being removed. The increase in cutting force with increasing cutting speed from 10 to 16 and 57 to 75 m/min was attributed to the strain rate hardening at low and high strain rates, respectively. The decrease in cutting force with increasing cutting speed outside these speed ranges was due to the thermal softening of the material. The amplitude variation of the high-frequency cyclic force associated with the segmented chip formation increased with increasing depth of cut and feed rate, and decreased with increasing cutting speed from 57 m/min except at the cutting speeds where harmonic vibration of the machine occurs.

1. Introduction

Titanium alloys have seen increasing demand in the aerospace industry in recent years due to their superior properties, such as excellent strength-to-weight ratio, strong corrosion resistance and ability to retain high strength at high temperature [1,2]. This demand has resulted in the requirement to increase machining speed and consequently the material removal rate.

However, titanium and its alloys are classified as hard-to-machine materials because of their low thermal conductivity, high chemical reactivity and low modulus of elasticity. These unique characteristics result in high cutting temperature, short tool life and high level of tool vibration [2–4]. Therefore, machining of titanium alloys is a high-cost process because it is time consuming and consumables intensive. This is driving increased research efforts to understand the cutting process and the mechanisms of chip formation.

When machining titanium alloys, a segmented chip is normally produced. Segmented chip formation is believed to be due to either the growth of cracks from the outer surface of the chip [5,6] or adiabatic shear band formation which is caused by the localized shear deformation resulting from the predominance of thermal softening over strain hardening [7,8]. The onset of shear localization is determined by the cutting speed, which is very low for conventional machining of titanium alloys [9]. Shear localization results in a cyclic variation of forces (both cutting and thrust) with a significant magnitude variation. The consequent vibration or chatter in the metal cutting process [9] limits the material removal rate and plays an important role in tool wear.

Chip formation and its morphology are important features of metal machining and yield important information on the cutting process itself. In titanium alloy machining, segmented chip formation involves localized shearing which is associated with the generation of cyclic forces and acoustic emission. The frequency of the cyclic strain, load sensor and acoustic emission signals is found to correspond to the frequency of chip segmentation [5,10,11].

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It has been reported that grains within the shear bands have undergone heavy deformation and high-temperature excursions, resulting in phase transformation of the alpha phase from the hexagonal close packed alpha structure to the body centred cubic beta phase [12,13]. In contrast, Velásquez et al. [14] report that no such phase transformation occurs inside the shear bands.

It is therefore clear that there is significant disagreement and controversy surrounding not only the chip formation mechanisms during high-speed machining of titanium alloys but also the metallurgical aspects of the segmented chip. Also, very few published articles explore the variation of the dynamic cutting forces during cutting, which is important for a detailed understanding of the chip formation and tool wear mechanism [3]. The present study aims to increase the understanding of the chip formation mechanism and its relationship to the dynamic change of cutting force in terms of the variation in both frequency and amplitude during the machining of titanium alloys.

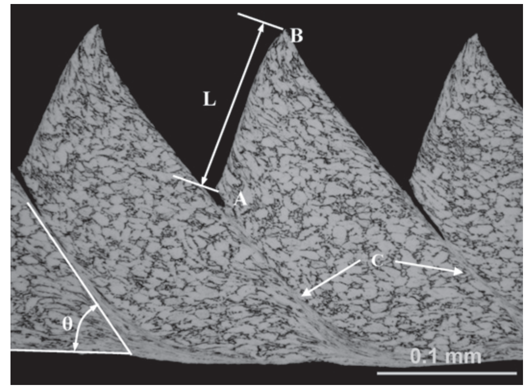

Fig. 2. Cross-section of a typical segmented chip in machining of Ti6Al4V alloy.

2. Materials and experimental procedures

The workpiece used in this study was a Ti6Al4V bar with a diameter of 60 mm. The chemical composition of the workpiece is presented in Table 1. Its microstructure comprises primary alpha plus beta phases as shown in Fig. 1. The grain size of the alpha phase is in the range of $7\pm3\,\mu$m and the average grain size of the beta phase is about 1.06 μm. The hardness varies between 351 ± 30 HV. As the workpiece has undergone a heavy cold deformation, some banded structures with elongated grains still remain after heat treatment.

Turning was conducted on a 3.5 hp Hafco Metal Master lathe (Model AL540) by dry machining with a CNMX1204A2-SMH13A-type tool supplied by Sandvik. The rake angle was +15°, angle of inclination was -6° and the entry angle was 45°.

A 3-component force sensor (PCB Model 260A01) with an upper frequency limit of 90 kHz was placed under the tool holder to record the dynamic changes in the cutting forces. Thus, the forces recorded were the forces placed on the tool holder at that position, not the actual forces placed on the tool. However, these forces can be used as indicators of the forces on the tool because a linear relationship should exist between the forces on the tool and forces on the tool holder at the testing point for a given tool geometry. The forces recorded were the feed force (F_X), thrust force (F_Y) and cutting force (F_Z), respectively. Data logging software Scoup® was utilised with a sampling rate of 50 kHz to collect the force signals. The limit of effective frequency recorded was one third of the sampling rate, i.e., 16 kHz. Noise with magnitude of 5 mV (corresponding to forces of 2, 2 and 10 N in the *X*, *Y* and *Z* directions, respectively) was detected with this system.

Chips obtained after machining were mounted with epoxy so that they stood on their edge in order to make the cross-section after polishing straight across its length. The polished chips and as-received workpiece material were etched with Kroll's reagent to reveal their microstructures.

The cross-section of a typical segmented chip obtained is shown in Fig. 2, including the geometrical features that have been measured. Line A–B is the cross-section of the original undeformed surface and its length is characterised by *L*. For each cutting condition, typically 50 measurements were performed to determine an average value for *L*. The slipping angle (θ) is defined as the angle between the shear band and the tangent of the machined surface at the end of the shear band.

It should be noted that severe plastic deformation only occurred in a very narrow region, which is defined as the shear band [7,9,14,15] and marked by *C* in Fig. 2. The formation of a shear band is caused by shear localization and is not influenced by the banded structures observed in the microstructure in Fig. 1. The equally spaced shear bands are one of the characteristics of the segmented chip.

Table 1
Chemical composition of workpiece alloy (mass percentage).

C	Al	O	Fe	V	H	N	Ti	Y
0.010	5.86	0.120	0.200	4.02	0.0023	0.007	Bal.	<0.0050

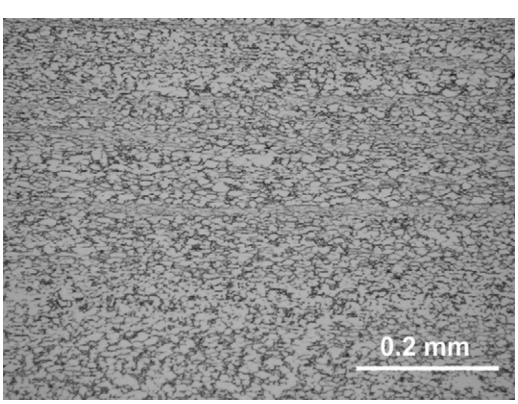

Fig. 1. Microstructure of workpiece material.

3. Results and discussion

3.1. Influence of feed rate

It was found that severe tool vibration occurred with feeds less than 0.122 mm and cutting speeds larger than 60 m/min at any depth of cut. A series of cuts at a cutting speed of 75 m/min and depth of cut (DoC) of 1.50 mm were selected to show the effect of this vibration on the cutting forces. The results are shown in Fig. 3. Cutting forces generally increased with feed, however, a drop in cutting forces was observed in the feed range 0.122–0.149 mm. This is because the tool vibration at lower feeds (below 0.149 mm) caused larger cutting forces (Fig. 3b). This drop in force is more significant in the feed direction (28%) compared with the other two directions (~6%).

Because of the tool vibration at low feeds, the average chip thickness made at a feed of 0.122 mm is 0.13 mm, which is larger than that (0.10 mm) made at a feed of 0.149 mm. Therefore, the

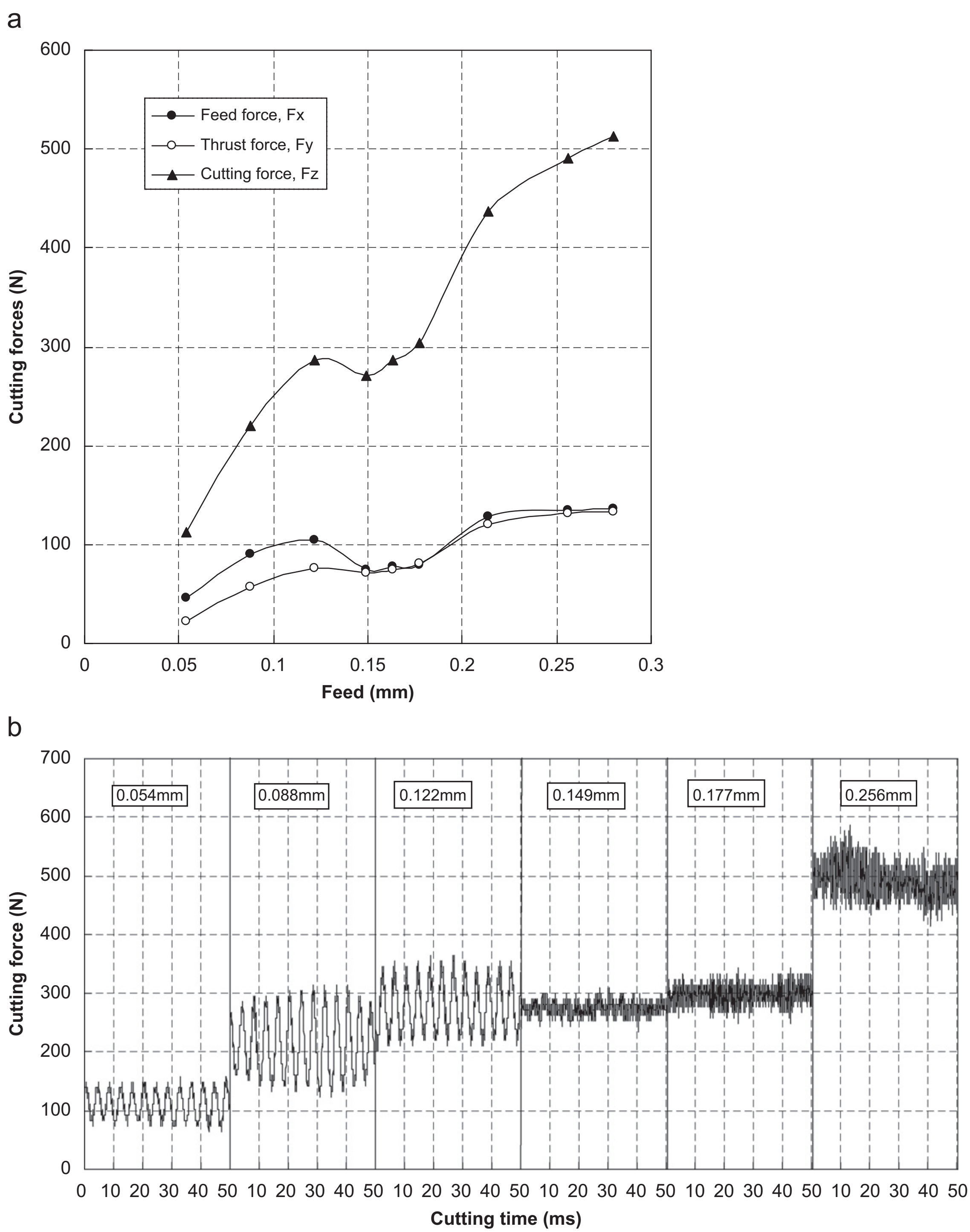

Fig. 3. Effect of feed on the (a) cutting forces and (b) amplitude variation of cutting force at a cutting speed of 75 m/min.

cutting forces, especially feed force, are larger at a feed of 0.122 mm than those at a feed of 0.149 mm.

It should be noted that the cutting force (F_Z) is the dominant force component, being about 4 times that of the feed force (F_X) and thrust force (F_Y), respectively; therefore, the discussion of cutting forces is focused on the cutting force (F_Z) since the variation of F_X and F_Y follows the same trend as F_Z.

It was also found that the frequency of tool vibration was constant at 260 Hz and independent of feed between 0.054 and 0.122 mm. The amplitude variation of the low-frequency vibration increased with feed from 0.054 mm and reached a maximum at a feed of 0.122 mm, reducing to zero at a feed of 0.149 mm. However, the amplitude variation of the cutting force kept increasing with increasing feed rate, and the frequency also increased with increasing feed rate. The smallest vibration occurred at a feed of 0.149 mm.

This force oscillation, which occurred when cutting at low feed rates and high cutting speed, is attributed to the low modulus of elasticity of titanium and high cutting temperature. The combination of low modulus of elasticity and small cross-sectional area of removed materials (product of feed and depth of cut) makes the chip stiffness very low at high cutting temperatures. This vibration produced chips with varying thickness and width (as shown in Fig. 4a) and led to a rough machined surface.

This vibration can be eliminated by changing the tool entry angle or increasing feed rate. The effect of cutting speed, depth of cut, feed rate and tool geometry on this vibration will be investigated in depth in a follow-up publication.

The maximum feed at which low-frequency vibration occurred was a function of cutting speed. The higher the cutting speed, the larger was the maximum feed rate. The chip made with a feed of 0.280 mm shows uniform segmentation as shown in Fig. 4b. Therefore, a larger feed rate is required for higher cutting speeds in order to eliminate the low-frequency vibration.

Similarly with the variation of chip segment spacing with undeformed chip thickness [8], the length L was found to increase linearly with the feed (shown in Fig. 5), which resulted in the cyclic force frequency being inversely proportional to the feed.

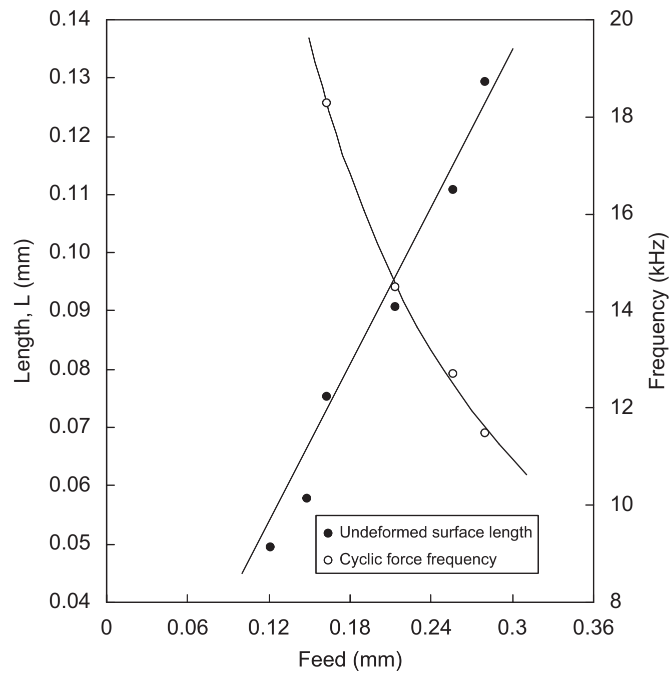

Fig. 5. Effect of feed on the chip morphology and cyclic force frequency at a cutting speed of 75 m/min.

3.2. Effect of cutting speed

Since machine-dependent vibration occurred at a low feed rate, discussion in this study is concentrated on the effects associated with large feed rates. The dynamic cutting forces and chip formation at small feed rates will be discussed in a follow-up publication.

The effect of cutting speed on the cutting force is shown in Fig. 6. A cyclic force was produced starting at a cutting speed of 16 m/min. The cyclic force frequency increased linearly with cutting speed up to 113 m/min, at which the frequency reached the upper limit of the data logging system.

The amplitude variation of the cyclic force generally decreased with cutting speed except at cutting speeds of 20, 37.5, 75, 132 and 264 m/min where the cyclic force frequencies were close to multiples of 260 Hz, the intrinsic harmonic frequency of the cutting. The dependence of reduction of amplitude variation of cyclic force on the cutting speed is stronger when the cutting speed is higher than 75 m/min because of the significant increase

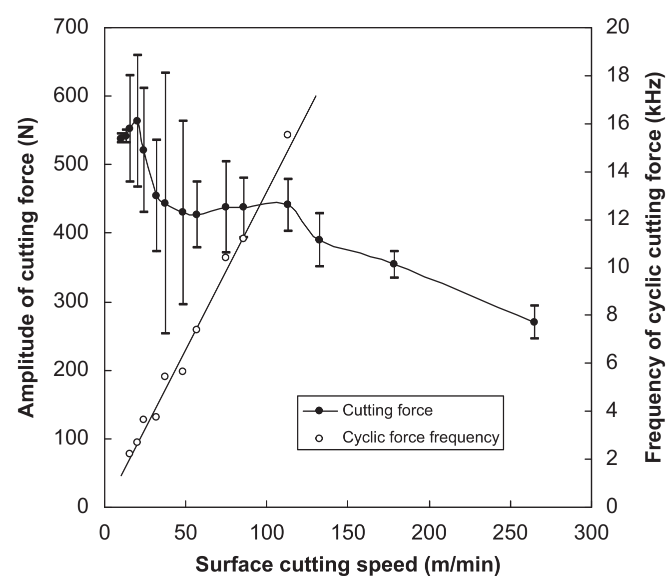

Fig. 6. Effect of cutting speed on the amplitude of force and force variation and variation of frequency at a feed of 0.280 mm and depth of cut of 1.50 mm.

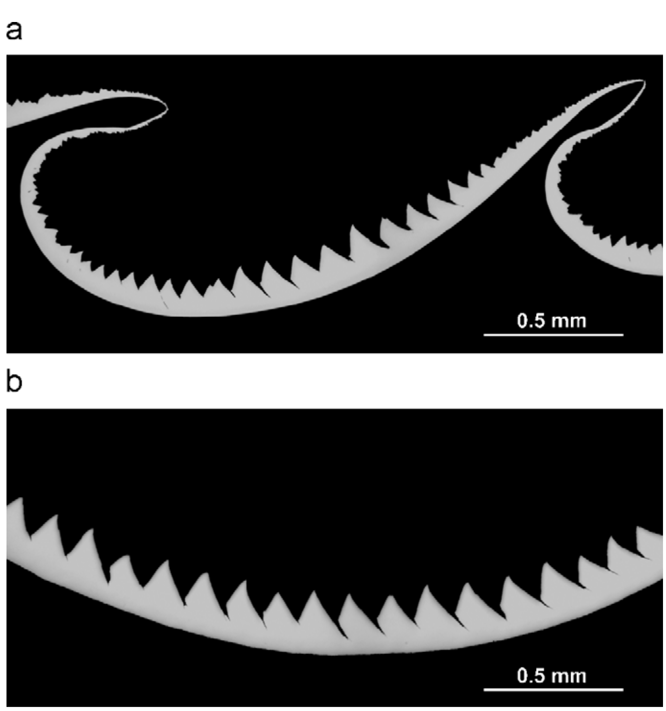

Fig. 4. Chips made at a feed rate of (a) 0.054 mm and (b) 0.280 mm and a cutting speed of 75 m/min.

in cutting temperature. The thermal softening reduces not only the strength of the workpiece but also its modulus. The former is related to a reduction of cutting force and the latter affects the variation in cutting force amplitude.

The variation of average cutting force with the cutting speed is more complicated. It increased initially with cutting speed up to 21 m/min due to strain hardening and then decreased dramatically with cutting speed from 21 to 57 m/min, which is attributed to thermal softening due to the increased cutting temperature. Therefore, the temperature sensitivity of the workpiece predominates over the strain rate sensitivity within the cutting speed range. A small increase in the cutting force (10 N) was observed from 57 to 75 m/min followed by a constant cutting force within the cutting speed range 75–113 m/min and a gradual decrease beyond 113 m/min.

The second increase and the constant cutting force at intermediate cutting speeds shown in Fig. 6 is believed to be due to the unique strain rate hardening characteristics of titanium alloys. It is generally accepted that the deformation of metals is governed by the Johnson–Cook law. The flow strength is a function of strain (ε), strain rate ($\dot{\varepsilon}$) and temperature (T) as follows [16]:

$$\sigma = (\sigma_0 + B\varepsilon^n)\left(1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)(1 - T^{*m}) \tag{1}$$

Since the cutting process is a metal deformation process, the cutting force reflects the strength of the workpiece material. The strain rate hardening factor $(1 + C\ln(\dot{\varepsilon}/\dot{\varepsilon}_0))$ is believed to dominate the flow stress at low cutting speed up to 21 m/min, since the temperature is unlikely to be high. The thermal softening factor, $1 - T^{*m}$, dominates the flow stress and causes the decrease in the cutting force in the cutting speed range of 21–57 m/min.

However, a dramatic increase in the strength of titanium alloys with strain rate occurs at strain rates greater than $10^3\,s^{-1}$ and that cannot be described by the logarithmic relationship [17,18]. This dramatic increase in strength with strain rate is believed to contribute to the second increase and the constant cutting force in the cutting speed range of 57–113 m/min. The rapid increase in strength, in turn, increases the cutting temperature and causes the subsequent gradual decrease in the cutting force with cutting speed due to the intensive heating that occurs during dry machining.

The chip length dramatically changes at a cutting speed of 57 m/min. Short chips are produced at a cutting speed of 57 m/min and below, but the chips made at a cutting speed of 75 m/min or above are much longer.

An increase in the cutting force with increasing cutting speed and a minimum cutting force have been observed in the machining of steel [15,19], but the cutting speed at which the cutting force starts to increase with increasing cutting speed is much higher when machining steel than that when machining titanium alloys. This makes it difficult to increase the cutting speed when machining titanium alloys.

The cutting force and chip formation process when machining at a feed of 0.280 mm and a cutting speed of 16 m/min for depths of cut ranging from 0.50 to 2.00 mm have also been evaluated. The dynamic change in the cutting forces with cutting time at a depth of cut of 1.50 mm is shown in Fig. 7.

It was observed in Fig. 7 that periods of large force fluctuations (dynamic force) occurred randomly during machining and were superimposed on the static force. These force fluctuations are more significant in the Y and Z directions than in the X direction. For a 1.50 mm depth of cut, the average static cutting force (F_Z) was about 536 N with less than 5% (level of noise) fluctuation. This is the result of the continuous chip formation as shown in Fig. 9.

The average dynamic cutting force in the Z direction was 555 N with $\pm$77 N fluctuation, slightly higher than the average static force (536 N), while the peak dynamic cutting force was 632 N, much higher than the average static cutting force.

Analysis of the force data revealed that the frequency of the cyclic force fluctuations was about 2228 Hz, regardless of the depth of cut. The results of this analysis are plotted in Fig. 8. It can be seen that all the forces increased linearly with the depth of cut because a large volume of material was removed at a larger depth of cut. In addition, the amplitude of force fluctuation increased linearly with increasing depth of cut. It should be noted that the ratio of the peak cyclic force to the average static force is constant, 1.18, regardless of the depth of cut.

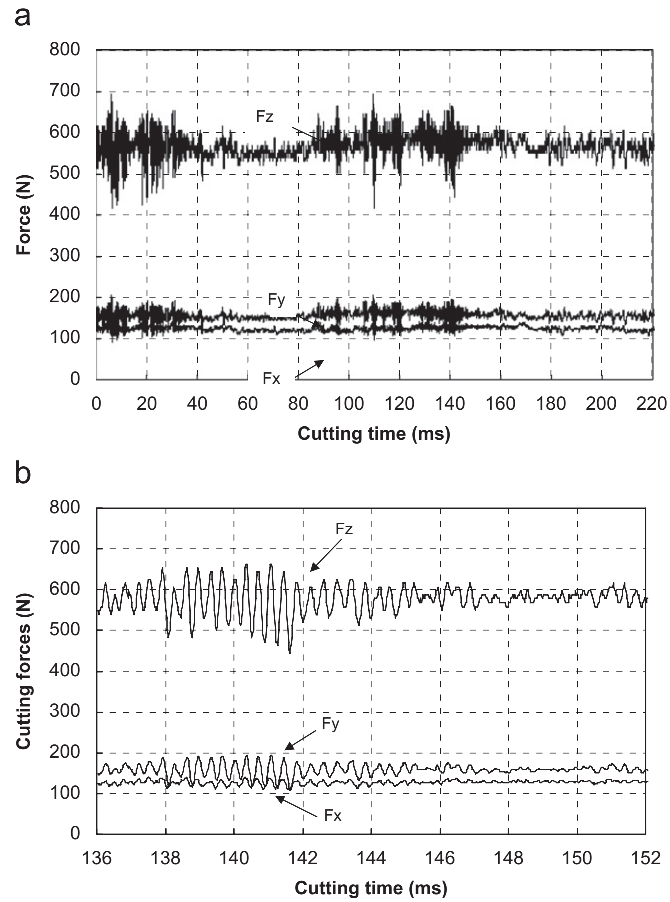

Fig. 7. (a) Variation in cutting forces with time at cutting speed of 16 m/min, depth of cut of 1.50 mm and feed of 0.280 mm, (b) is extracted from (a) to show more details.

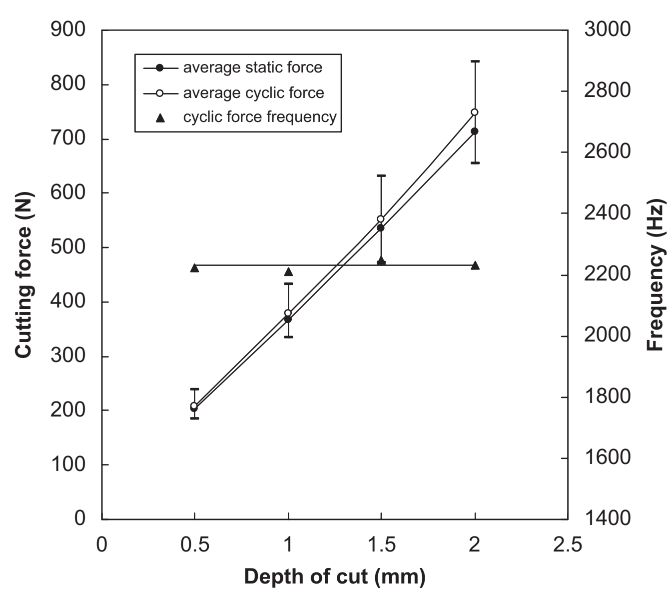

Fig. 8. Variation of static and dynamic cutting force and cyclic force frequency with depth of cut at a cutting speed of 16 m/min and feed of 0.280 mm.

The mixture of features associated with both dynamic and static cutting forces in a single cut reflects a mixture of segmented and continuous chip formation, which has not been reported previously. This can be clearly seen in the cross-section of a chip in

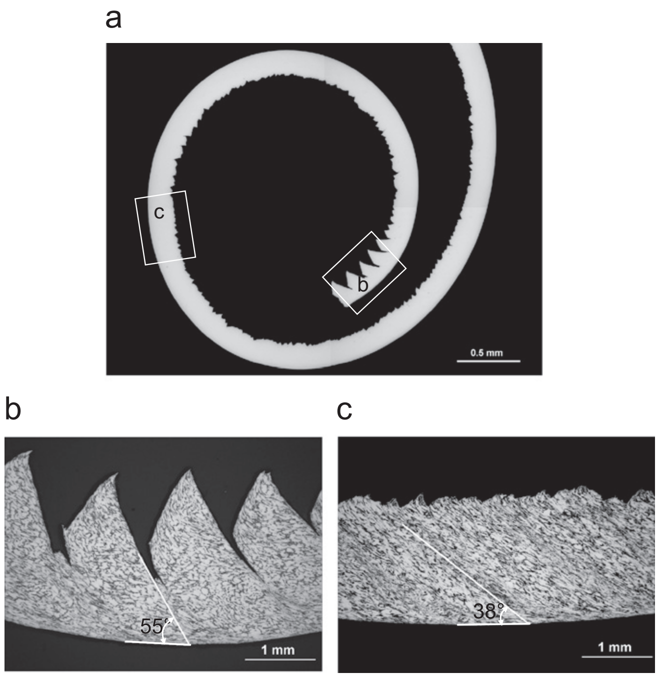

Fig. 9. Cross-sections of chip with mixed segmented and continuous chips at a cutting speed of 16 m/min, depth of cut of 1.50 mm and feed of 0.280 mm.

Fig. 9. The cutting parameters were feed of 0.280 mm, cutting speed of 16 m/min and depth of cut of 1.50 mm.

Few, sharp, periodic and aperiodic "saw-teeth" were found in the continuous chip in Fig. 9a. In the periodic segmented chip region, the segmentation frequency (f_c) can be calculated by the ratio of cutting speed (V) to the length of undeformed surface (L) [11], i.e.,

$$f_c = \frac{V}{L} \quad (2)$$

At the cutting speed of 16 m/min ($V = 266.67$ mm/s), the measured length of the undeformed surface is $L = 0.116$ mm, and the calculated segmentation frequency is $f_c = 2299$ Hz. This agrees very well with the cyclic force frequency, $f_f = 2228$ Hz, indicating that the cyclic force fluctuation is caused by the segmented chip formation process. This agrees with the previously established link between the segmentation frequency and cyclic force frequency obtained by the methods of variation of strain and load and acoustic emission [5,10,11].

It was also found that the chip was thicker in the continuous part of the chip (0.193 mm) compared with the thickness in the segmented part (0.184 mm), which suggests that larger slipping between segments occurs.

Examining this chip under higher magnification reveals a difference in deformation during the segmented and continuous chip formation (Fig. 9b and c). Continuous and uniform shearing with smaller slipping angle (38°) was found during the continuous chip period. In the sharp "saw-tooth" period, a narrow shear band with heavier deformation and larger slipping angle (55°) was observed. Shearing with both smaller and larger slipping angles was also found in regions in which the aperiodic saw-tooth chips were formed.

Due to the inhomogeneous structure of the workpiece material, some areas would exhibit good plastic deformability at low cutting speed, resulting in continuous chip formation (Fig. 9c) and static cutting forces. Some areas however with poor plastic deformability will not be able to deform at this cutting speed, therefore, resulting in segmented chip and dynamic cutting forces (Fig. 9b). The critical cutting speed for the onset of segmented chip depends on the microstructure, but the shear band of the segmented chip is independent of microstructure.

With increasing cutting speed, the plastic deformability became poorer; the static force duration gradually reduced and eventually disappeared at a cutting speed of 75 m/min. The cyclic force duration became more dominant as a result of the increased proportion of the segmented chip with the cutting speed from 16 m/min and reaching 100% segmentation at the cutting speed of 75 m/min. In agreement with previous findings [15,20], the undeformed surface length of the segmented chip was found to be independent of the cutting speed as shown in Fig. 10, suggesting that the segmentation frequency is directly proportional to the cutting speed according to Eq. (2) [11]. This explains the linear increase of the cyclic force frequency with cutting speed as shown in Fig. 6.

The coexistence of continuous and segmented chips in one cut is difficult to explain using the existing chip formation models [5,12]. The adiabatic shear model based on the thermoplastic shear instability states that shear localization occurs when the effect of thermal softening predominates over the effect of strain hardening [9]. This cannot explain the mixture of segmented chip and continuous chip present in one cut because the strain hardening and thermal softening should be constant across the length of cut in one cut after the thermal equilibrium has been established. Therefore, a new physical model considering the relationship between dislocation velocity and strain rate is required to explain the formation of the segmented chip.

3.3. Characteristics of the cyclic force

The relationship between the segmentation frequency calculated by Eq. (2) and the measured cyclic force frequency is shown in Fig. 11. Very good correlation once again indicates that the cyclic force is the result of chip segmentation.

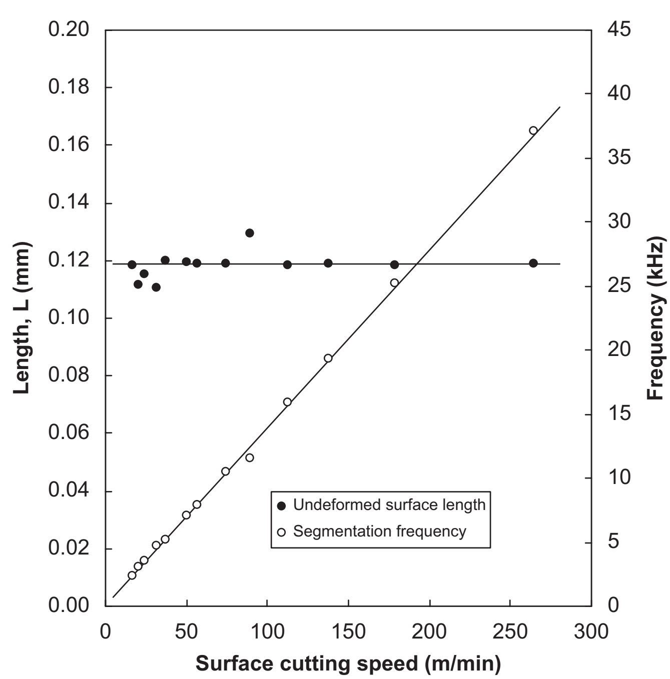

Fig. 10. Effect of cutting speed on undeformed surface length and segmentation frequency.

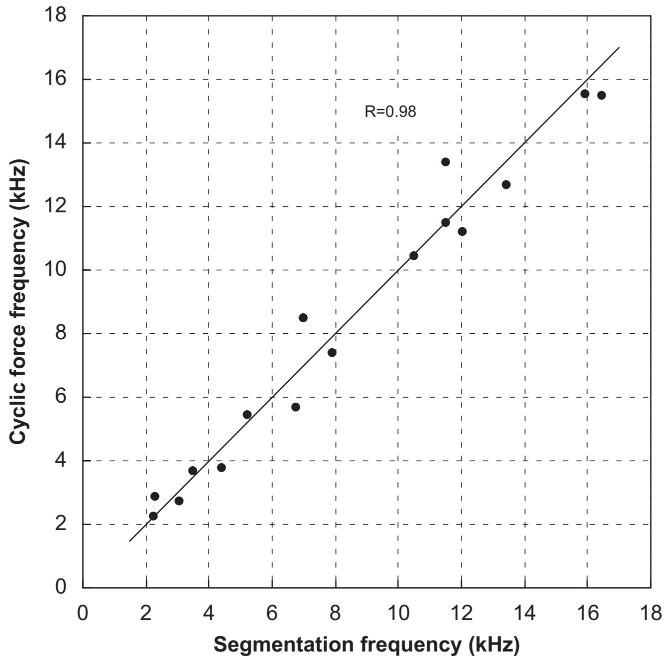

Fig. 11. Correlation between the cyclic force frequency and chip segmentation frequency for different cutting speeds and feed rates.

Therefore, the cyclic force frequency (f_f) can be written as

$$f_f = f_c = k\frac{V}{f} \tag{3}$$

where k is a constant. It is clear that the cyclic frequency is directly proportional to the cutting speed and indirectly proportional to the feed rate.

As discussed in the last two sections, the amplitude variation of cyclic force ($\Delta F = F_{\max}–F_{\min}$) is determined as a function of feed, depth of cut and cutting speed. It was found that ΔF increases linearly with the depth of cut and is inversely proportional to cutting speed. Empirically, a linear relationship is found between ΔF and $(\mathrm{DoC} \times f2)/V$ as shown in Fig. 12 for cutting speeds higher than 75 m/min.

The linear relationship in Fig. 12 can be expressed as

$$\Delta F = K\frac{\mathrm{DoC} \times f^2}{V} \tag{4}$$

where K is a constant related to the workpiece material. It should be pointed out that the relationship given in Eq. (3) does not apply for (i) cutting speeds lower than 57 m/min where a mixture of continuous and segmented chip formation processes is present and (ii) cutting speeds at which the machine harmonic frequency amplifies the amplitude variation of the cutting force. Eq. (4) overestimates the former case and underestimates the latter.

From this relationship, we can draw a conclusion that an appropriate depth of cut, feed rate and cutting speed should be set to eliminate the low-frequency vibration and reduce the variation in the amplitude of the cyclic force associated with chip segmentation.

4. Conclusions

Both the segmented chip, associated with a cyclic cutting force and the continuous chip, associated with a static force have been found in one cut at low cutting speed and large feed rate when turning Ti6Al4V alloy. The maximum cyclic cutting force present

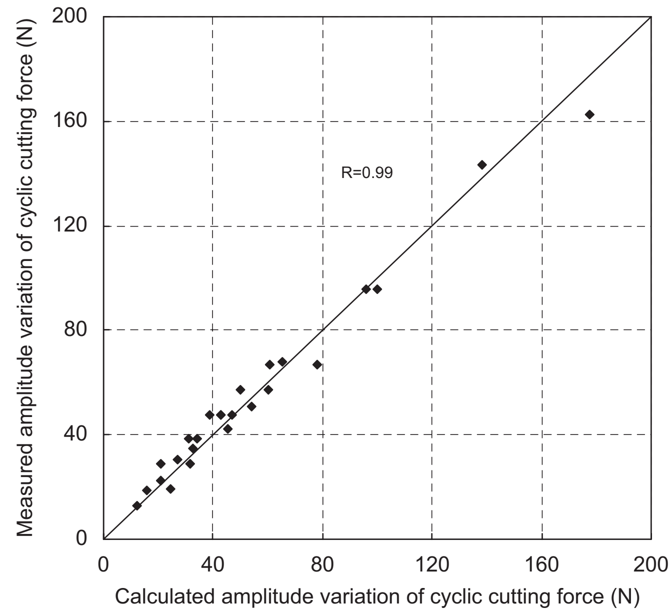

Fig. 12. Correlation between the measured and calculated variation in amplitude of cyclic force due to chip segmentation.

during the segmented chip formation is 1.18 times the average static cutting force present during continuous chip formation regardless of the depth of cut. The slip angle in the segmented chips is larger than that in continuous chips. The proportion of segmented chips in a single chip increases with cutting speed and reaches 100% at the cutting speed of 75 m/min.

The high frequency of the cyclic force is caused by the segmented chip formation process, and the length of the undeformed surface in the segmented chip is independent of the cutting speed and the depth of cut, but increases with feed rate. This results in the frequency of the cyclic force being directly proportional to the cutting speed and inversely proportional to the feed rate. The variation in the amplitude of the high-frequency cyclic force associated with segmented chip formation increases with increasing depth of cut and feed rate, and decreases with increasing speed from 57 m/min except at cutting speeds at which the cyclic force frequency matches the machine harmonic frequency.

Generally, the cutting force decreases with cutting speed due to thermal softening, however, the observed increase in cutting force with cutting speed from 10 to 21 and 57 to 75 m/min has been attributed to two phases of strain rate hardening.

Based on this work, it is suggested that a new physical model needs to be developed in order to explain the formation of segmented chips when machining titanium alloys.

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