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Full Length Article

Dimensional inequalities in chip segments of titanium alloys

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ABSTRACT

A change in segment shape and geometry provides vital information about the strain in the chip segments, plastic deformation and correspondingly a pattern of energy consumption during a machining. These machinability parameters are related with segment dimensions using dimensional inequalities. Dimensional inequalities capture geometrical features of chip segments such as segment width, length of free chip surface, length of uncut segment, shear angle, included angle and their correlation with each other. To validate these inequalities, chip freezing experiments and numerical simulations were performed by changing the initial temperature of work piece from room, to LN_2 pre-cooled, to elevated temperature of 260 °C. Measurements of chip segment dimensions both, experimentally and numerically validate the proposed inequalities.

1. Introduction

Segment shape and geometry provide vital information about the strain in the chip segments, formation and correspondingly a pattern of energy consumption during machining process Brown and Komanduri [2] observed that chip segmentation is found to occur due to negative stress-strain characteristics of material at a large strain, formation of void around second phase particles and its propagation into micro -crack in the primary shear zone. In titanium alloys, researchers attributed the formation of segmented chips due to thermal softening in a small shear zone that leads to the formation of shear bands [22]. Heat conduction and inertia effects were considered to predict the formation of shear band phenomenon [1]. Also, it was observed that transformation of chip from a continuous to a serrated one is characterized by a dimensionless number which represents a competition among parameters such as effect of inertia, strain hardening [20], elastic unloading and viscous loading [21].

Various studies have been undertaken to model such a heterogeneous deformation of material using parameters like segment shape [11–13], segment shear strain [17], segment width [14], segmentation frequency, segment ratios [6] and included angle [16]. Joshi et al. [11] observed that segment shape changes with the change in the initial temperature of the work piece. It changes from a semi-circular at LN2 cooled temperature to a trapezoidal one at room temperature, and to a shape of an irregular rectangular at 260 °C. Joshi et al. [11] correlated segment shape to a deformation during machining. Sutter and List [16] found that the segments become triangular in shape due to cracks propagating over the entire chip thickness at a very high cutting speed of 4800 m/min.

Chip segment ratio which represents a ratio of difference between maximum and minimum chip thickness to a maximum chip thickness was used to model chip morphology [4,6]. A Higher segment ratio indicates a fracture as a predominant mechanism of segment formation and a higher plastic deformation during machining [10,13].

Olson et al. [9] studied variation in the segment width with the processing conditions. Segment width was observed to increase linearly with the feed rate. Also, at a cutting speeds smaller than 720 m/min, segment width varies in a direct proportion to cutting velocity ($V^{3/4}$) [8]. The segment angle is another parameter studied by the researchers. It is the shear angle deformed as the material passes through the shear zone and measured on the formed segment. The segment angle was observed to decrease from 60° to 45° with an increase in the cutting speed from 20 to 4800 m/s. Also, during machining of titanium alloys, for a material of higher strength, a lower segment angle was observed [13].

Chip segment frequency is yet another parameter used by researchers to model the chip morphology. Segmentation frequency was correlated to the fluctuations in the cutting forces during machining [16]. Also, chip segmentation frequency matched well with the frequency of variation in the cutting forces during machining operation [15]. Chip segmentation frequency was observed to increase with an increase in the cutting speed and feed rate [22].

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Table 1
Experimental specifications.

S.N.	Parameters	Specification
1.	Machine	CNC lathe
2.	Tools/Tool holder	Carbide tools of grade KC5010 and geometry TNGP 3305, Tool holder PTGNR1616
3.	Environments	LN2 precooled, room, 260 °C
4.	Cutting speed (m/min)	23.4 to 146.2 at room temperature and 23.4 to 91.8 at LN2 precooling and at elevated temperature
5.	Feed rate (mm/rev)	0.11, 0.22, 0.33

Shear strain in a segmented chip was predicted as a sum of strain within the segment called as a homogeneous shear strain and that inside the shear bands called as a catastrophic shear strain [17]. Metallographic observations from the segmented chips were used to evaluate the strain in shear band and segments [19].

The above research shows that segment dimensions has a relation with machinability of material in terms of cutting forces, their fluctuations and plastic deformation. The existing studies on chip segmentation in machining are primarily limited to identifying the effect of processing parameters on segment dimensions [18,5]. However, little work was done to capture geometrical features of chip segments and their correlations with the uncut segment which is a part of work piece. Therefore, this paper tries to relate the dimensions of segment with respect to each other and with respect to the dimensions of uncut segment, both experimentally and using numerical simulations. These dimensional parameters of chip segments are used to access the efficiency and effectiveness of machining process.

2. Experimental specifications

A Ti6Al4V pipe of 1 mm thickness was used to perform orthogonal turning experiments using quick-stop device. The schematic of the device and working principles have been explained elsewhere [11–13]. This device stops the cutting action instantaneously, leaving a partially deformed chip segment attached on the work, called as a chip root. Orthogonal turning experiments were performed under the three machining environments by changing the initial temperature of work piece from room to LN2 precooling to elevated temperature of 260 °C. A detailed experimental procedure for precooling work piece using LN2 and preheating work piece using oxy-acetylene flame has been explained elsewhere [11–13]. Specifications of tool, tool holder, and processing parameters used for the experimentation are given in Table 1. SEM observations of chips and chip roots were carried out on FEI model, QUANTA 200, ESEM with a magnification ranging from 50X to 200X. Segment dimensions were measured using image J software and each dimension is an average of six to seven readings. Measurements were taken on SEM images of chips obtained with the same scanning angle and at high magnification to enhance the accuracy of measurements.

3. Dimensional inequalities in segmented chips

An image of a typical segmented chip observed under scanning electron microscopy (SEM), formed during machining of titanium alloys is shown in Fig. 1a. Uncut segment (*ABCD*) before undergoing through shear zone and the segment formed (A'B'C'D') after passing through the shear zone is shown in Fig. 1a. It is observed that a part of work material transforms to form a segment by moving through the shear zone. If material was deformed only under the action of shear stress, the formed segment would have been of a trapezoidal shape. However, the formed segment shape differs from the trapezoidal one as shown in Fig. 1a, due to various dimensional changes that occur in the uncut segments while it is being transformed through shear zone. Shear angle ($\varnothing$) changes to segment included angle (θ). Uncut segment length (l) changes to length of free surface of segment (l_f). Thickness of uncut chip (t) changes to a segment width (w), see Fig. 1a.

The variations in the dimension of uncut and formed segment were correlated using the mathematical model called dimensional

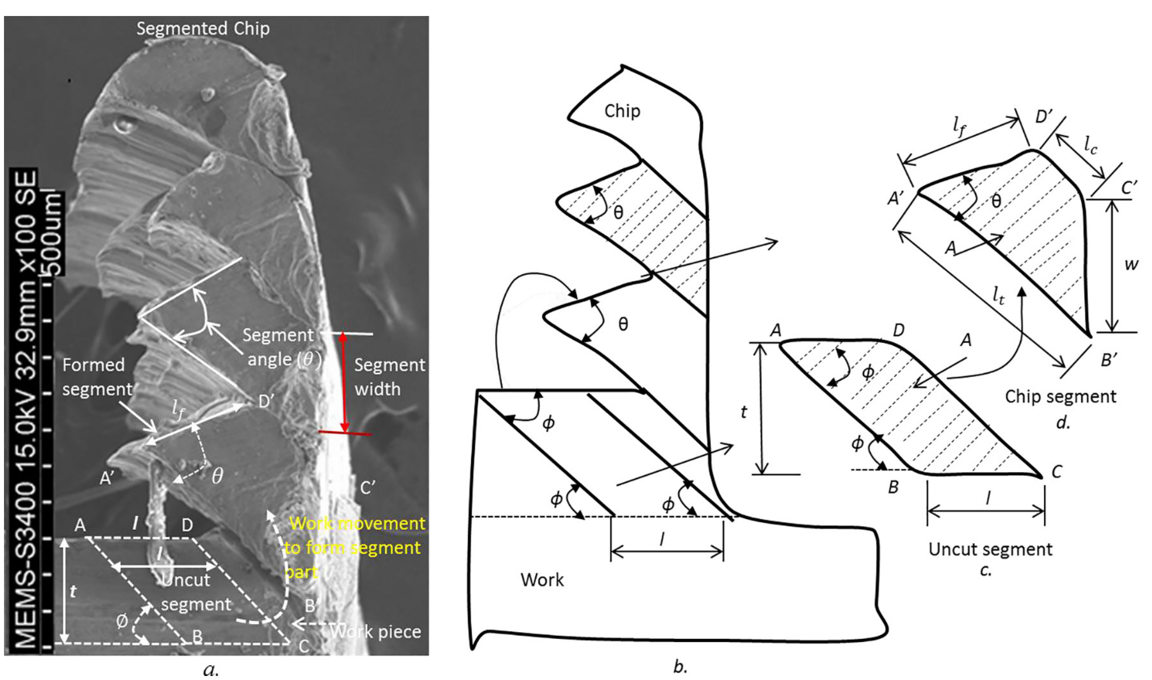

Fig. 1. *A*–*d* Details of segmented chips *a*. SEM images of chip root formed during machining of titanium alloy *b*. Schematic of chip root and various dimensions of *c*. uncut and *d*. formed segment.

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