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Machining Process Measurements: A Titanium Machining Example*

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ABSTRACT

The cutting of metals with a sharp tool—machining—has been a field of experimental and analytical study for over a century. Research continues to improve the understanding and effectiveness of the machining of special materials like aircraft titanium alloys. Recent advances in high-speed microvideography are being applied to the study of machining in experiments at NIST. A high-speed camera provides data for analysis of the segmented chip formation that occurs when cutting Ti-6Al-4V alloy. Because machining is a very high rate process, with strain rates in the range of 10^3 to 10^6 per second, obtaining appropriate material properties for modeling is a challenge. Therefore, the titanium machining research effort is coupled with the NIST Pulse-Heated Kolsky Bar project for obtaining high-rate material properties. This paper presents current research aimed at comparing machining process measurements with modeling predictions based on Kolsky bar material property tests.

Introduction

The machining of titanium alloys is difficult as compared to steel because titanium has a low thermal conductivity, a low modulus of elasticity, work hardens, and is chemically reactive. The low thermal conductivity causes increased tool temperatures compared to those encountered when cutting traditional steel alloys. The low modulus of elasticity, which is approximately half that of steel, can allow increased part deflection during machining. High depths of cut are often used to get beneath the layer hardened by a previous cut, which in turn causes increased temperatures and cutting forces. The chemical reactivity of titanium presents a challenge. "When machining titanium, complete seizure occurs between the tool and the chip due to a chemical reaction and the formation of a stable, titanium carbide bonding interlayer." [1] This bonding of the work piece material to the tool, and then a periodic shear-band formation and separation, leads to a highly segmented chip formation process. The application of high-speed microvideography allows us to examine the segmented chip forming process at industrially-relevant cutting speeds.

The high strength-to-weight ratio of titanium makes it an extremely attractive material for many modern aircraft and other commercial applications. Therefore, increasing the overall efficiency of the titanium alloy machining processes, despite the many challenges, is an increasingly important research area. Our current research project involves studying the chip formation process and measuring associated forces when machining titanium alloy Ti-6Al-4V. The long range goal of our project is to extend physics-based titanium-machining models to the reliable prediction of process phenomena such as chip morphology, cutting forces, and tool wear. This will enable optimization of process parameters, which will improve the efficiency of titanium machining.

Experimental Configuration

Traditionally, machining has been experimentally studied by using an orthogonal cutting geometry. In our experimental arrangement we are achieving this orthogonal cutting geometry by machining the edge of a thin disk. The cutting edge of a tool is fed into the rotating disk in a direction perpendicular to the spindle axis. The chip removed from the edge of the disk has a thickness controlled by the feed rate of the tool into the disk. The machine tool used for this series of experiments is a modified computer-controlled grinding machine that allows the rotating disk to be lowered onto the stationary cutting tool at a precisely controlled rate. The high-speed camera is mounted on an external stand and remains fixed with respect to the tool. The tool is mounted on a three-axis tool force measuring transducer. The disk diameter is approximately 120 mm and its thickness is 3.30 mm. For the test reported here the feed rate was 0.3 mm/rev, thereby producing a chip 3.30 mm wide and approximately 0.3 mm thick, or a width-to-thickness of approximately 11. With this width-to-thickness ratio, a plane-strain deformation assumption can be used in analyzing the process.

The chip formation process is observed with a high speed camera which records at 180 000 frames per second. Each frame contains an area covered by 128 pixels square. A microscope objective is used for the camera lens producing a field of view of approximately 0.7 mm square. The actual magnification is determined by photographing a calibrated target using the same camera settings and focus. The titanium disk was prepared with a random grinding pattern to aid in the observation of the chip formation process. With our set-up, a scratch spacing of less than 10 μm can be distinguished.

Experimental Results

The high-speed camera captures how the individual chip segments are formed in the machining process. A short series of frames is shown in Figure 1, illustrating one chip segment being formed. The edge of the tool is visible on the right side of the frame. The sequence is for frame numbers 225 to 255, showing every other frame, for a total time of approximately 172 μs. This sequence is typical of the process and it equates to a segment formation frequency of about 6 kHz. The cutting speed used in this test was 1.25 m/s, making a material displacement of about 13.9 μm between the displayed images. Frame 225 shows the tip of the tool just starting to compress the titanium to form a segment. By Frame 245 the segment has continued to deform and in Frame 247 the shear band is beginning to form. By Frame 255 the segment is clearly separated and it has started to move down the tool rake face. Future work will involve analyzing the strain produced during the segment formation using displacements observed between successive images. Knowing the strain as a function of time and using appropriate material flow stress values (obtained for samples of the same material by using our Kolsky bar), we will be able to begin estimating forces required for the deformation process.

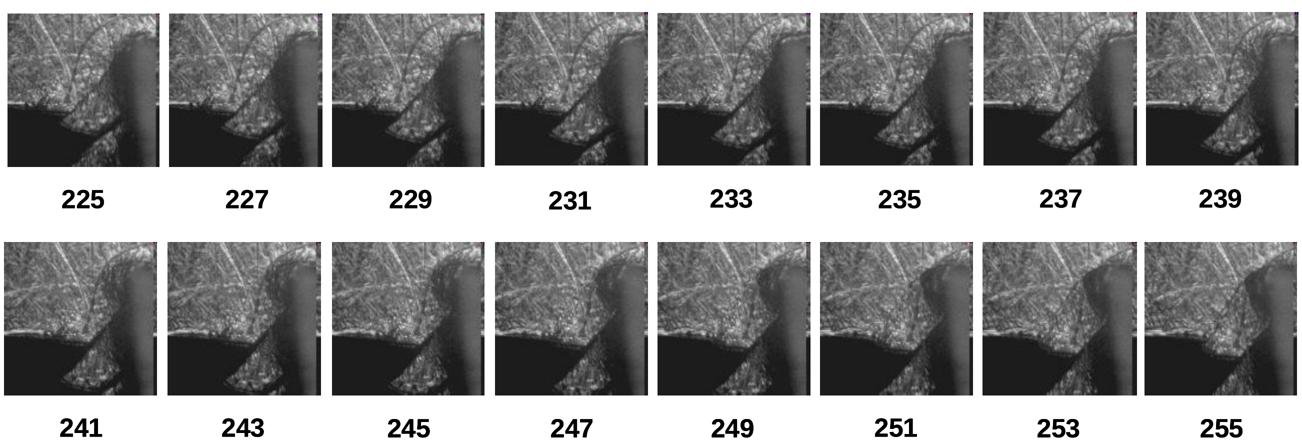

Figure 1. Forming of one segment in a Ti-6Al-4V machining experiment. A series of single frames from the high speed video recording, with individual frame numbers, are shown. The time between displayed images is 11.1 μs for a total of 167 μs in this sequence. The field of view is approximately 0.7 mm square and the tool (6º rake angle) is shown on right side of each image.

References

[1] Kramer, B.M., D. Viens, S. Chin, “Theoretical Consideration of Rare Earth Metal Compounds as Tool Materials for Titanium Machining”, Annals of the CIRP 42/1 (1993), pp.111-114.