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Letters

A novel approach for in-situ characterization and probabilistic prediction of cutting tool fatigue in machining of Ti-6Al-4V

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A B S T R A C T

The wear behavior of cutting tools is highly complex due to combined thermal, mechanical, and chemical loads. As a result, most current tool-wear prediction methodologies are either empirical or highly over-simplified analytical or numerical models of stable abrasive and diffusive wear mechanisms. To predict the complex physics of catastrophic tool edge chipping, which in practice bounds feasible process parameters, this manuscript presents a novel approach for in-situ characterization of tool edge fatigue loads and probabilistic prediction of the likelihood of time to fracture. The results of the analysis suggest encouraging possibilities for more physics-informed and data-driven process design.

1. Introduction

The tribological conditions at the tool/chip interface, and the resulting loads imposed on the cutting tool, are inherently difficult to measure due to the small length scales, high velocities, and large gradients in stress and temperature within the micron-scale interfacial regions near the tool edge [1]. Due to these gradients, single-point measurements taken with miniaturized thermocouples, pyrometers, strain gauges, or other sensors are insufficient to properly characterize how loads are imposed and evolve within the cutting tool during machining and progressive wear. Therefore, innovative characterization techniques of thermal and mechanical loads are necessary for obtaining fundamental insights into the unique loads applied to cutting tools during the machining process.

An early approach for full-field study of stress in cutting tools leveraged the phenomenon of photoelasticity [2]. In-situ studies with photoelastic tools were performed to capture the stress field imposed on the tool in cutting of lead and the significant effect of rake angles on these interfacial stresses [3,4]. Practically, photoelastic cutting tools, typically made of birefringent glasses or epoxy resins, limit cutting to soft materials at low speeds and feed rates to avoid rapid tool-wear.

Split tools allow for machining of harder metals than photoelastic tools. For example, the technique was used to show interfacial stresses in machining of aluminum alloys [5]. Moreover, studies of machining nickel–chromium steel with carbide have also been performed [6]. Split tool experiments are limited as the design is bounded by the stiffness and rigidity of the two tool halves and preventing chips from entering the airgap [6].

Typical abrasive and thermal/chemical wear modeling is based on average or peak forces, but fatigue failure is often observed when serrated or segmented chip formation, chatter, or interrupted cuts, as in milling, result in cyclically variable forces [7–9]. Brittle fracture is common in cemented carbide materials [10] as well as ceramic tool materials and coatings [11]. Carbide tools, known for their high strength, are often used when cutting hard to machine aerospace alloys like Inconel 718 and Ti-6Al-4V [12]. However, the low thermal conductivity of these alloys lead to adiabatic shear banding and the creation of serrated chips [13,14]. Predictive tool wear studies have been created for flank wear [15] but studies on cracking and fatigue of tools have mainly been centered around thermal cracking [16]. Wear due to friction and fatigue in carbide tools has been studied to develop predictive models for rake face crater wear [17].

The present study utilizes Digital Image Correlation (DIC) to enable the first reported measurements of nanometer-scale displacements in high elastic modulus carbide cutting tools subject to cyclical loads of cutting titanium alloy Ti-6Al-4V. DIC has been widely used to study displacements, strain, and strain rate in workpiece material, with most work focused on the primary shear zone [18–20] and some with the workpiece's sub-surface [21,22]. Based on this powerful in-situ experimental technique, a novel approach

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for physics-informed and data-driven prediction of cutting tool fatigue failure is subsequently presented, leveraging finite element stress analysis and Monte-Carlo probabilistic techniques to predict the likelihood of time to failure as a function of process parameters.

2. Material and methods

Orthogonal cutting experiments were performed on a custom-built in-situ characterization setup with high-speed microscopy and time-correlated force analysis capabilities, seen in Fig. 1**a** [21]. A Photron SA-Z camera equipped with a Mitutoyo video microscope was used to capture high-speed micrographs for digital image correlation (DIC) analysis (Fig. 1d), as well as to study tool/chip contact lengths (L) and chip formation cycles, as illustrated in Fig. 1b-c. Cutting forces were captured with a custom KISTLER 3-component load cell fixture with a high natural frequency (≈20 kHz), necessary to measure the dynamic forces of serrated chip formation.

An annealed sample of Ti-6Al-4V was metallographically polished and etched with Kroll's reagent to reveal the microstructure for enhanced contrast. At larger uncut chip thickness values (150> h > 25 μm), high-speed micrographs were taken with a Mitutoyo M Plan 20x objective at 45,000 fps, resulting 1 μm/pixel resolution. For finishing cuts (h < 20 μm), a 50X objective with 400 nm/pixel resolution and frame rate of 180,000 fps were employed. For this initial study, cutting speed remained constant at 60 m/min. DIC displacement fields were determined using the open source MATLAB program NCORR.

As illustrated in Fig. 1e, captured cutting forces, chip contact length, and depth of cut were used as inputs for simple static elastoplastic finite element analysis in Autodesk Nastran software to determine a stress intensity factor relating the measured average contact pressure ($P_{apparent}$). The results of this high-speed (~10 s computational time) analysis revealed an peak equivalent Von Mises stress (σ_{max}) within the tool of approximately 1.34. This results is specific to the selected tool geometry (5° rake and 7° flank angles, 5 μm cutting edge radius, K68 tungsten carbide material properties). A sharp tool is used to replicate typical tool edge radii used in finish machining and milling (~5 to 10 μm), based on the relatively small feed rates used during the experiments.

3. Results and discussion

To display the proposed approach above, eleven cuts with true (in-situ measured) uncut chip thickness values ranging from 150 to 6 μm were performed. Analysis of forces, contact lengths, and DIC displacement fields showed significant differences between 'roughing' cuts on the order of 100 μm and 'finishing' cuts below approximately 20 μm uncut chip thickness. At higher values of h, the intensity of tool loads during a given chip formation cycle first increase as material is strain-hardened and plastically deformed in front of the tool and then suddenly decrease as the intense heat in the primary deformation zone leads to adiabatic shear banding and slip of a newly formed serration, as illustrated in Fig. 2.

As the tool progresses through the work material the chip formation cycle repeats itself with significant variability in time and magnitude, resulting in specific upper and lower bounds for the fatigue load. Completion of a chip formation cycle for h = 100 μm and v_c = 60 m/min occurs approximately every 80 μs. This frequency, as well as its stochastic variability, are significantly affected by process parameters and tool geometry. In general, a tool will be subject to millions of chip serration events per minute, so even relatively short cuts yield statistically valid data sets for an in-depth analysis of serration frequency at each condition.

Analysis of a 22-μm uncut chip thickness cut, shown in Fig. 3, shows that the loads within the cutting tool decrease both in magnitude and range as seen in the less intensely red tool tip, while the frequency of oscillation is increased. When comparing Figs. 2 and 3, it should be noted that the former was obtained with a 20x

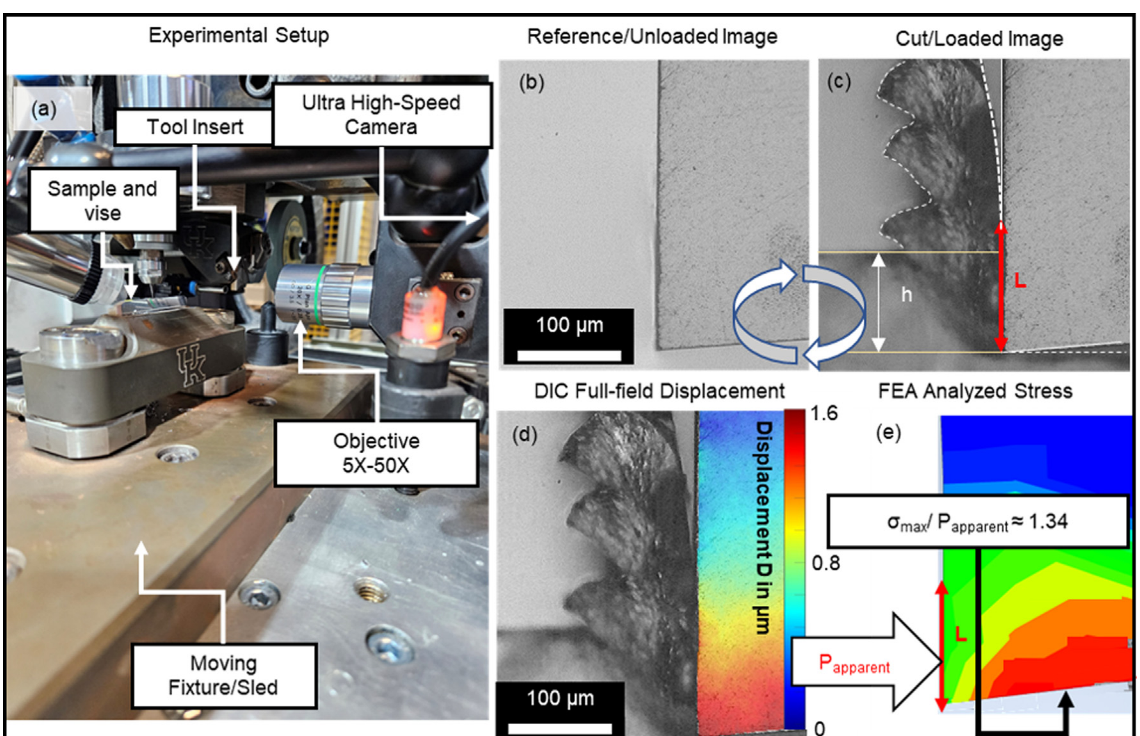

Fig. 1. Overview of experimental setup (a) and inverse methodology for tool stress analysis (b-e).

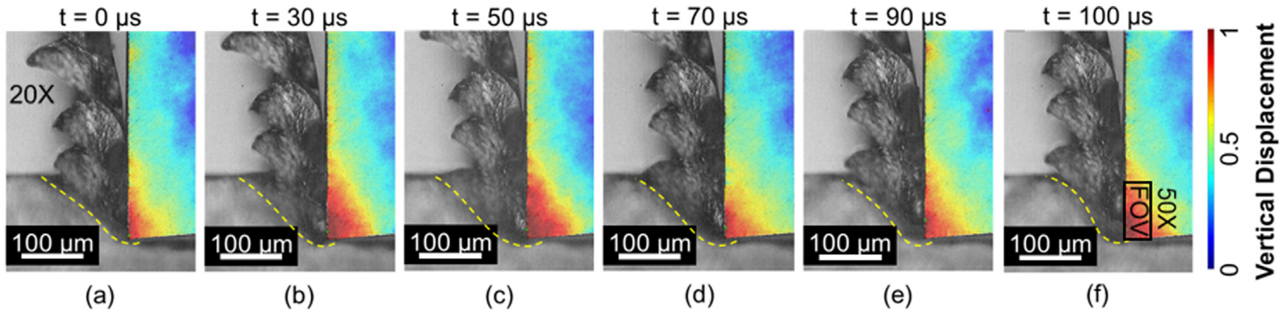

Fig. 2. Large dynamic variation of vertical displacements at h = 100 µm, v_c = 60 m/min.

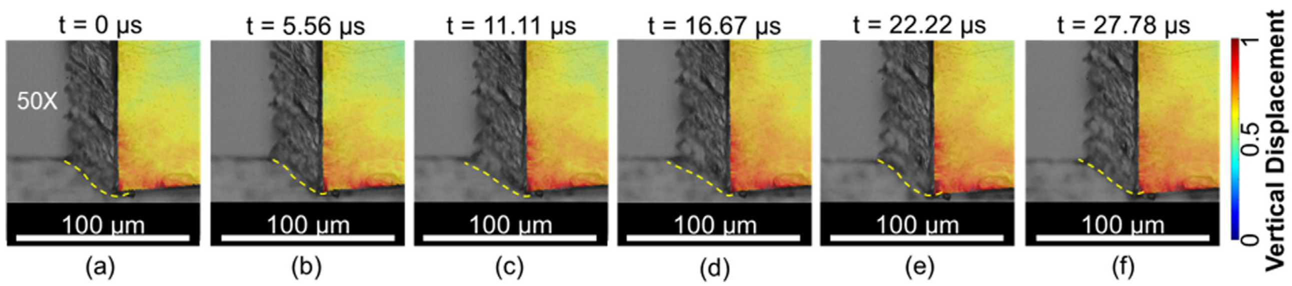

Fig. 3. Small dynamic variation of vertical displacements at h = 22 µm, v_c = 60 m/min.

objective and the latter a 50x objective, yet both feature the same relative displacement scale. The frequency of chip formation in Fig. 3 is approximately 30 µs, almost three times higher than the rate at h = 100 µm. Qualitatively, the severity of chip serrations in Fig. 3 can be seen to be much less than Fig. 2. Therefore, it is hypothesized that careful analysis of chip serration mechanics and associated load profiles allows for probabilistic determination of physical limits of the resulting fatigue loads.

Based on the basic FEM analysis described previously, the peak stress for each cutting condition was determined and plotted against the number of load cycles per minute in Fig. 4**a**. Moreover, a regression fit of published fatigue strength data for a fine-grained tungsten carbide material similar to Kennametal K68 grade was plotted to indicate the relative magnitude of process-induced loads against the strength of the tool material [23]. Notably, both the cutting tool material and the process-specific fatigue loads exhibit substantial standard deviations. The horizontal error bars indicate three standard deviations of the number chip formation cycles, while the vertical error bars indicate the upper and lower limits of the peak stress based on three standard deviations for the combined experimentally-determined variability of the peak force and contact length, respectively.

To predict the likelihood of failure from the information shown in Fig. 4a, Monte Carlo simulations were performed for 10,000

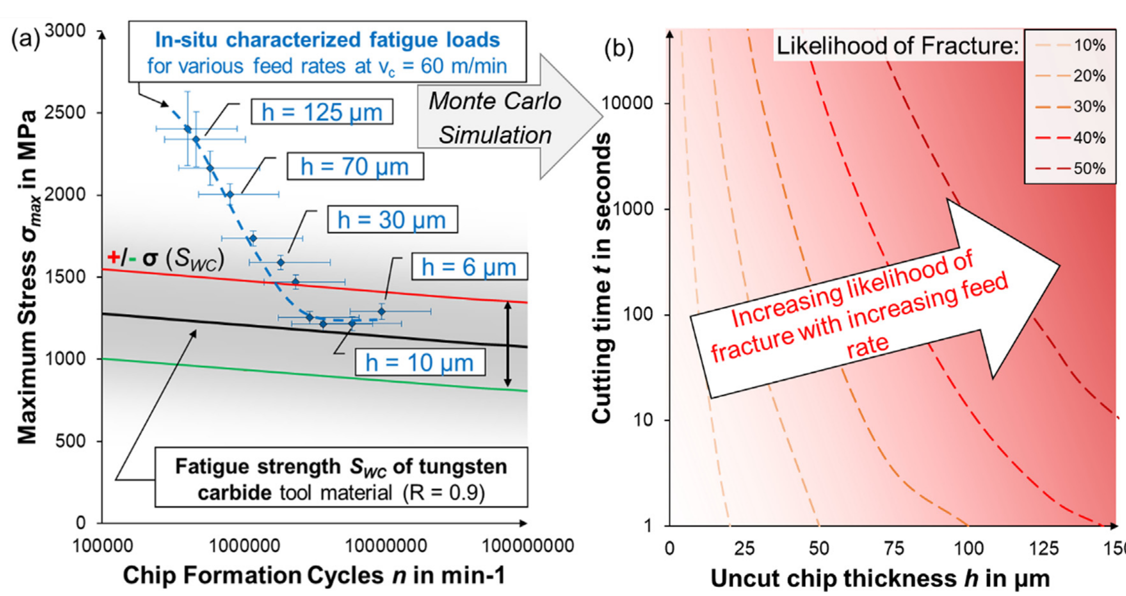

Fig. 4. Comparison of in-situ characterized fatigue loads and tool fatigue strength (a) and Monte-Carlo simulation results for likelihood of fracture as function of cutting time and uncut chip thickness (b).

instances at each of the uncut chip thickness values, using the mean maximum stress to calculate the percentiles of cycles-to-failure distribution. The results of this analysis, shown in Fig. 4b, indicate that for uncut chip thicknesses of less than approximately 25 μm it is unlikely ($P_{failure}$ < 20 %) to fail through brittle tool edge fracture within the first 10,000 s (167 min) of machining. For cuts larger than 100 μm, a 50 % chance of fracture within the first 1000 s was calculated. This is significant, as the abrasion and diffusion-wear limited tool-life at greater uncut chip thickness values in cutting of Ti-6Al-4V at 60 m/min is likewise on the order of 10–50 min. Therefore, similar analysis for diffusion and abrasive wear mechanisms could allow for multi-physics tool-wear prediction.

4. Conclusions

This paper shows preliminary findings for a new tool stress analysis technique based upon optical and numerical methods. This technique is envisaged as an alternative to expensive and time-consuming machinability trials and computationally expensive chip formation analysis with FEA software. Future work will leverage the experimental technique described in this paper to determine the variable state of pressure and friction at the tool chip boundary to construct physics-informed and data-driven models of friction in metal cutting to support the design of more effective cutting tool materials and geometries. Moreover, when coupled with other multi-physics models of the thermo-mechanical loads of cutting, as well as in-process tool condition monitoring (e.g., via cutting forces, acoustic emissions, or with optical techniques), the present approach could provide a pathway for more robust probabilistic prediction of different tool-wear regimes, allowing for more nuanced process parameter optimization and formulation of Digital Process Twins.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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