ME – PhD Thesis Defense

In situ analysis of large strain deformation in tool-workpiece contacts

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ABSTRACT

Large strain plastic deformation is central to manufacturing operations like metal cutting, rolling, and extrusion. Standard approaches for describing and understanding this deformation, such as analytical methods, numerical simulations, and post-mortem experimental studies, often fail to capture critical spatiotemporal details. This failure can be attributed to simplifying assumptions, the need for complex constitutive material models, and difficulty in relating spatial deformation to globally measured quantities (example forces). Imaging-based *in situ* analysis techniques, like Digital Image Correlation (DIC), have gained popularity in recent years due to advantages such as material and process independence and the ability to evaluate unsteady and inhomogeneous deformations. This technique involves analyzing an image sequence of the deformation process to obtain full field kinematic quantities such as displacements and strains, an understanding of which can provide critical information about the process performance. However, the occurrence of frictional interfaces, potential plastic flow instabilities, and unconstrained free surfaces make DIC analysis of manufacturing processes extremely challenging.

Among these challenges, the formation of a dead material zone near the tool tip is particularly significant. This stationary undeformed region impacts material flow, chip formation, and the quality of the finished surface. Despite its importance, the unsteady and inhomogeneous deformation near the dead zone remains poorly understood, primarily due to the lack of direct observation methods capable of resolving the spatial and temporal details of its evolution. Addressing this gap is essential for improving manufacturing processes and optimizing their outcomes.

In this work, we develop a framework for analyzing the time-dependent, inhomogeneous deformation of a prototypical manufacturing process---rigid tool deforming a metallic workpiece. The primary objective is to relate the deformation fields to the final surface and subsurface properties, with a particular focus on phenomena occurring near the tool tip, such as the evolution of dead material zones, and this is realized in three stages.

In the first part, we develop a 3-axis CNC-based experimental test bed and a random grid based DIC method, termed Ensemble Averaged Digital Image Correlation (EADIC). Unlike conventional DIC methods, EADIC is capable of measuring strains close to interfaces and evolving free surfaces while simultaneously ensuring subset compatibility using ensemble averaging. The result is accurate strain estimation very close to critical interfaces such as tool-workpiece contact and residual deformed surface. EADIC was also benchmarked against algebraically generated deformations and DIC standards, as well as compared with free and commercial DIC software.

We use this framework in the second part to study the classical unsteady deformation in orthogonal cutting. In the process, we uncover the nature of the underlying deformation mechanics that have hitherto remained largely speculative. Our results strongly suggest that traditional assumptions like the existence of a single shear plane/zone are inaccurate; the deformation is highly inhomogeneous and often temporally unsteady. By quantifying this inhomogeneity, a hypothesis for unsteady deformation near the tool tip is proposed, involving material 'pinning' near the tool tip, internal shear, and formation of a stationary undeformed zone- termed as a dead material zone. We illustrate the necessity of pinning events for the formation of dead material zone and subsequent time evolution. Furthermore, this mechanism appears to be operative in multiple microscopically unrelated materials (for example, Al and Ti alloys). The effects of various process parameters, such as tool geometry and depth of cut, are also studied, along with characteristic synchronized force signatures. The results are summarized in the form of a non-dimensionalized process map.

In the final part of this work, the implications of the spatiotemporal deformation in the vicinity of the tool tip for the finished surface are quantified. The effect of novel process changes, such as laser surface treatment and additive manufacturing, is studied. Our investigation quantifies the importance of spatio-temporal deformation and suggests alternative routes for improving process performance and final surface quality.

ABOUT THE SPEAKER

Deepika Gupta is a PhD candidate in Mechanical Engineering at the Indian Institute of Science (IISc), Bangalore, working with Dr. Koushik Viswanathan at the Laboratory for Advanced Manufacturing & Finishing Processes (LAMFiP). Her research focuses on the mechanics of manufacturing processes, image processing, and fracture mechanics. Her work has been recognized with the Best Doctoral Symposium Award at the ASME Manufacturing Science and Engineering Conference in 2022.