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Technical Paper

High performance computing simulations to identify process parameter designs for profitable titanium machining

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ABSTRACT

The objective of this paper was to conduct a study of the multi-level multi-variable design space in titanium machining through high performance computing (HPC) simulations that was otherwise too vast to be explored by physical experiments alone. For tool wear-based performance metrics, this resulted in a validated set of machining parameters for achieving profitable material removal rates (MRR) (optimized cost of processing and tooling) across multiple operational configurations, alloys, tool geometries, and process conditions. The approach was to include all machining-related variables and their distributions available within the software as inputs to finite-element models (FEM) of the machining process. The time intensiveness of conducting such large numbers of lengthy simulations was handled by wrapping Third Wave Systems AdvantEdge FEM machining simulation software with Dassault Systemes iSight to automate the building of experimental designs and their parallel execution on a HPC cluster. Results were analyzed using SimaFore software to identify key characteristics through bivariate analyses. A subset of simulations was validated through physical experiments, and these were in turn used to augment physically untested regions in the design space. Based on this, an MRR-based cost model for orthogonal turning was derived to drive optimal machining setups. This study showed the feasibility of integrating and automating a HPC loop involving the generation of suitable design of experiments (DOE), creating simulation jobs, deploying/executing it on a HPC cluster, and scripting outputs in a useful format. Besides highlighting the challenges in reading/transferring data across different software and in handling/compiling large amounts of data, this study also shed light on the need for benchmarking processor–operating system–software combinations for computational efficiency.

1. Introduction

1.1. Motivations and challenges

The overarching focus of this paper was to integrate software in a partially-automated loop to efficiently conduct a large number of simulations/analyses over a HPC cluster, in order to understand how to cost-effectively realize the most profitable MRR when machining titanium alloys. The motivations for this work were twofold. First was the need to map and understand the productivities involved when machining titanium alloys under various process conditions, from a profitability standpoint. The associated challenges involve the prohibitive nature of conducting a large number of physical experiments to explore the multi-level multi-variable design space due to the cost involved, and time/effort/resources needed. When considering the simulation route to explore this design space, a major hurdle encountered was the time intensiveness of conducting even a single machining FEA simulation on a high-end workstation (a typical job takes several hours to complete); this renders design space exploration via simulations using a high-end (stand-alone) workstation impractical from a time/effort standpoint. This leads us to the second motivation for this work, which is to leverage a HPC cluster to be

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able to explore and map the vast design space in order to identify profitable process parameter combinations for titanium alloy machining. Though the time intensiveness of running a large number of FEA simulations could potentially be mitigated via a HPC cluster, the major associated challenges involve being able to handle the large amount of input parameter data, the efforts involved in setting up these simulation jobs ready for submission to the cluster, and analyzing an even larger output dataset so that useful conclusions could be drawn in a timely manner. In order to address the challenges, a consolidated approach to setup, conduct and analyze a large number of machining FEA simulations was carried out in partnership with three commercial software; the major steps involved partially-automating the loop of creating DOE, deploying it into the FEA software to generate simulation jobs, running these on a cluster, and analyzing results.

1.2. Background and literature review

1.2.1. Titanium alloys – machining considerations/needs

The highly desirable material property combinations of titanium alloys such as its high strength-to-weight ratio and excellent corrosion resistance make it an attractive material alternative for many engineering applications. However, high raw-material and processing costs are major barriers to its widespread adoption. Efforts are underway for the development of cheaper grades to reduce raw-material costs and thus increase its use in certain commercial markets (*e.g.*, automotive) [1–8]. When considering the processing of titanium alloys, the machinability is generally poor, thus increasing processing cost via either extended cycle time (labor cost) or increased tool wear (tooling cost). This results in titanium alloys being classified as 'difficult-to-machine' materials, though it use in the commercial automotive industry could lead to significant savings in energy/life-cycle costs [9–11], except for low-volume batches [12–16]. The poor machinability of titanium alloys (especially the workhorse alloy, Ti–6Al–4V) is due to its unique combination of low thermal conductivity and elastic modulus along with high chemical reactivity and high temperature strength. As a result, even ultra-hard tool materials such Polycrystalline Diamond (PCD) and Cubic Boron Nitride (CBN) wear away often in an unpredictable manner; thus, from a net-cost standpoint, some of the most economical cutters still are 'throwaway' straight carbide inserts [17–19]. Though guidelines exist for machining titanium alloys [20–23], operating within the recommended range of process parameters still result in frequent and catastrophic wear. Thus, there is a critical need to explore the vast parameter design space when machining titanium alloys with carbide/other tools.

This calls for the simulation/mapping of the titanium machining process across the design space via HPC clusters. Sweeping the vast multi-variable multi-level design space through simulation will augment the knowledge that can be practically obtained by physical experiments. A better understanding of the dominant variables that affect tool life in titanium machining will be obtained via simulation results that span multiple configurations, alloys, tool geometries, and cutting conditions. Such validated (simulation-supported, with high degree of confidence) parameter designs will help drive process planning. Integrating data analytics software onto a machine tool controller will allow for visualization of the (evolving) variable sensitivities, and could provide close to real time control and optimization of the cutting process with the aid of feedback from force/temperature sensors.

1.2.2. Applicability of high performance computing to machining

High performance computing (HPC) in its simplest form refers to a cluster of processors working in parallel to provide significant computing power; its performance is dictated by the computing capacity of individual processors, their number, usage strategy, etc., as well as by the communication efficiency and data management between processors [24]. The computing resources could be in the form of dedicated clusters of processors, across a grid or a cloud [25]. When considering HPC applicability to machining, its much sought-after implementation-level of being able to analyze large volumes of in-process (sensed) data for close to real time control/optimization is still in its infancy. Currently, HPC use is limited to pre/post-event simulation/analyses of machining processes. Most commonly, these are either (FEA) simulations of the machining process or sensitivity analyses of sensed machining process output datasets. The performance of HPC clusters (in dedicated/grid/cloud configurations) for handling data-heavy FEA [26–32] jobs spanning a number of application areas, including machining specific FEA [33] has been detailed by numerous investigators. Additionally, it should be noted that although there have been numerous efforts in model-based or data-driven (*e.g.*, Bayesian) estimations of machining output parameters (such as force components or rudimentary measures of tool wear), there has not been a software-integration effort involving a HPC cluster for machining tool wear estimation so far.

1.3. Research gaps and future needs

Altogether, this scenario points to a number of research questions and gaps, especially in light of the recent advances made in big-data, automation, and cloud/mobile computing capabilities. First, given the current levels of computing powers readily accessible, there is a critical need to elucidate the fundamental behaviors within physical processes (such as machining), and to explore the process across its extended design spaces; in other words, there is the need (and capability) to now map and understand all possible aspects of a process, which was previously constrained by data volumes and/or computing resource needs. Next is the realization that the raw computing/processing power needed is just one of the components within a process flow loop, and that the capability to read/transfer and handle large volumes data is critical at every step. Question that arise include concerns on compatibility issues between software, data readability/transferability within the process flow loop, usability of the conclusions drawn, etc. This paper address these basic questions, and strives to conduct a software integration involving a HPC cluster.

2. Methodology

This project had two concurrent purposes. First, the integration and partial-automation of generating a suitable design of experiments (DOE), creating a large number of corresponding FEM simulation jobs, and deploying it onto the HPC server was successfully accomplished, in addition to scripting the large volume of simulation results to be output in a format readable by the data analytics software. And second, a detailed scrutiny of the multi-level multi-variable design space in machining titanium alloys from a profitability standpoint was enabled through (validated) simulations, which was otherwise not feasible to be explores via cutting experiments alone. The major steps involved are outlined below:

1. *Machining simulation design*: The first step was to formulate the experimental design of simulation runs, conduct trial runs for initial physical experiment validations, and to select the final subset of input and output variables relevant for analyses. For this, an initial assessment of comparative tool performance for a number of tool substrates was conducted. Then, a master list of all available input parameters in the Third Wave Systems AdvantEdge FEM simulator was compiled. Then, a subset of 12 variables and their respective ranges were selected. Similarly, a