Modelling Enhanced Machining Processes

Hadi Moali Project Supervisor: Dr. Quanren Zeng MEng Mechanical Engineering 2024/25

The Challenge

High-performance alloys, such as Ti-6Al-4V and Inconel-718, can be difficult to machine due to:


Poor Surface Finish


Tool Wear

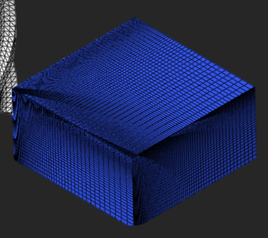

Short Tool Life


Coolant Costs

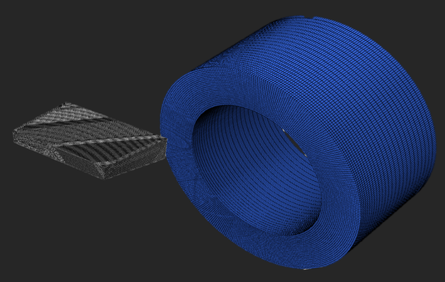
Industrial Applications

Tough alloy production is wide-scale aerospace, medical and automotive industries.

Milling

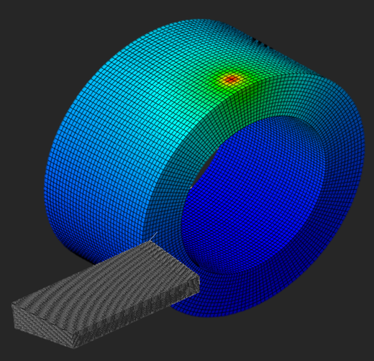


Turning

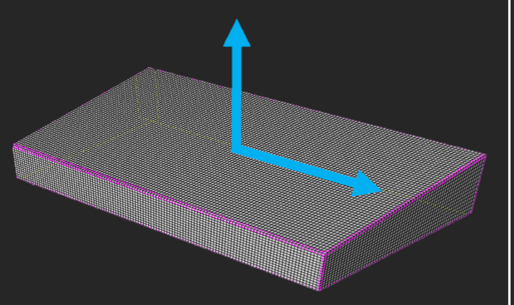


Can be enhanced by…

Thermal Source



Ultrasonic Vibration



$$u(t) = A \cdot \sin(2\pi f t)$$

Objectives

- Develop a **Finite Element Model** of various machining and material conditions
- Implement heat and vibration models representative of industrial configurations
- **Simulate** and analyse important machining behaviours
- **Validate** the enhanced machining models with **experimental procedures**
- **Perform a parametric study** to investigate the **relationship of machining enhancements** for future optimisation

Vibrationally Assisted Machining

Micron-amplitude oscillation at a specified frequency disrupts continuous cutting force degradation

Numerical Modelling

Several analytical and empirically-derived models were used for predictive accuracy and validation:

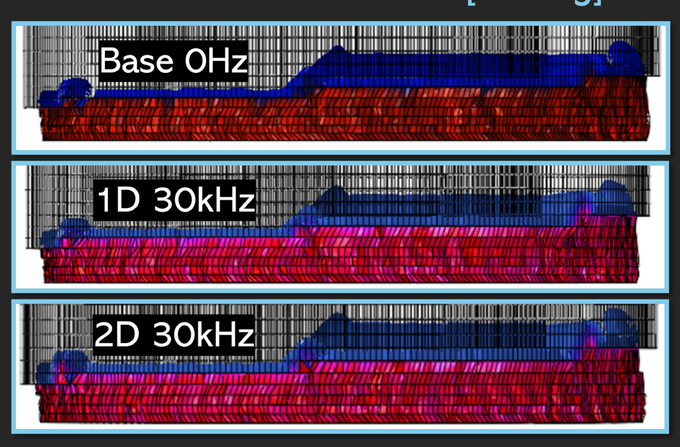
- Johnson-Cook Plasticity and Damage Model for Material Stress Modelling
- Archard's Law for material wear volume
- Taylor's and Usui's Models for tool life with temperature dependency
- Blok's Frictional Heating Model for temperature distribution
- Merchant's Orthogonal Cutting Model for shear and chip morphology behaviour
- Zener-Holloman Parameter for assessing the rate of dynamic recrystallisation during heating

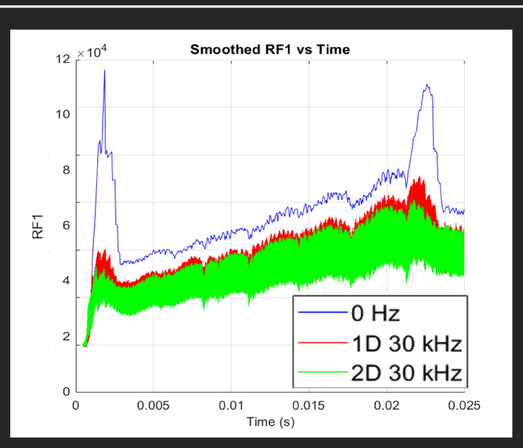
Experimental Validation

Using a DMG-50 Mori 5-Axis CNC Mill:

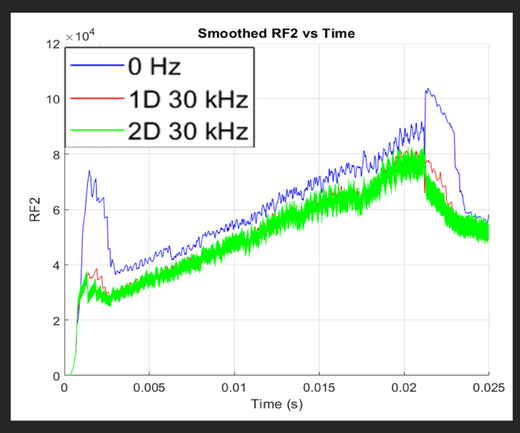
- Side cuts on Al6082-T6 blocks were performed at 0, 15, 20kHz vibration at 15µm amplitude
- Chips collected, and examined along with the sample surface finishes under a microscope
- Cutting force data on tool recorded and compared with simulation data

Simulated Surface Finish [Turning]



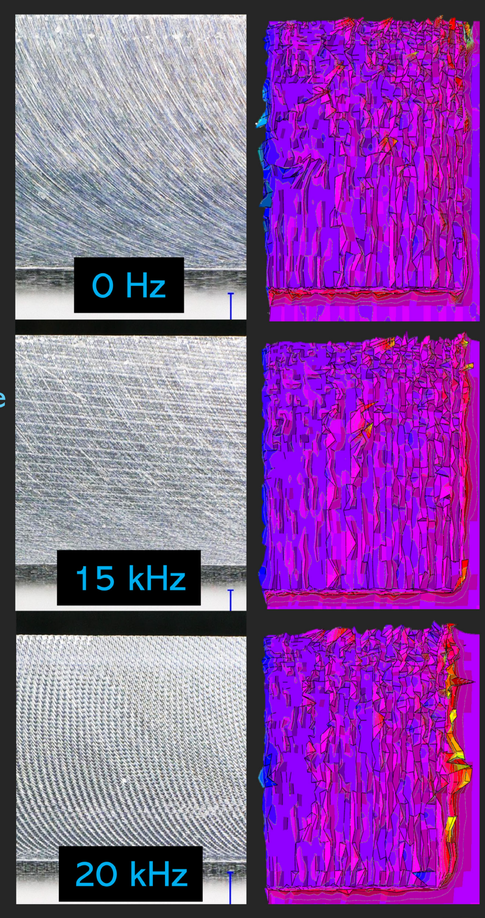


Simulated Force [Depth of Cut] against time



Simulated Force [Feed] against time

Surface Finish Results [Milling]



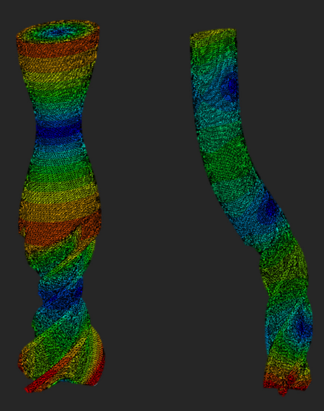
Thermally and Vibrationally Assisted Machining

Thermal Softening: A reduction in strain hardening rate based on an increase in temperature

Modal Analysis

A modal analysis was conducted to quantify the natural frequencies of the system and ensure simulation stability.

This was conducted up to the first 200 matching eigenvalues between 0 Hz and 3MHz (to account for simulation upscaling).


59428 Hz

48269 Hz

Conclusions

- Developed validated FEA models for machining of Ti-6Al-4V and Al6082-T6.
- Vibration-assisted machining reduced cutting forces and improved chip segmentation, confirmed by experiment.
- Modal analysis prevented resonance artifacts, isolating true ultrasonic effects.
- Findings lay groundwork for integrating thermal enhancement in future simulations using Zener–Hollomon and harmonic models.

For the full report, as well as more simulation videos, profiles, and graphs, scan the QR Code for access:

Future Work

- Validate combined laser–ultrasonic machining experimentally on CNC platforms.
- Refine output processing for more accurate temperature–response coupling.
- Explore multi-frequency elliptical vibration strategies.
- Generalize simulation framework for new heat sources and geometries using a universal thermal input parameter.
- Optimize amplitude, feed rate, and frequency for material-specific performance.

Ref: Tool Wear Image: Liu, GJ., Zhou, ZC., Qian, X. et al. Wear Mechanism of Cemented Carbide Tool in High Speed Milling of Stainless Steel. Chin. J. Mech. Eng. 31, 98 (2018). https://doi.org/10.1186/s10033-018-0298-2
Tool Fracture Image: Harvey Performance Company (2024) Tool breakage - in the loupe machinist blog, Harvey Performance Company. Available at: https://www.harveyperformance.com/in-the-loupe/tag/tool-breakage/page/2/
Poor Surface Finish Image: D, S. (2023) Poor surface surface finish milling steel: Model Engineer & Workshop Magazine, Model Engineer Workshop Magazine. Available at: https://www.model-engineer.co.uk/forums/topic/poor-surface-surface-finish-milling-steel/
Boudali, H., 2025. Vibration–Thermal Fusion Background Illustration. Commissioned artwork. Digital illustration. Commissioned by Hadi Moali for academic presentation at University of Bath.
Cutwel Ltd. (n.d.) What is the best coolant to use for your material and application? Available at: https://www.cutwel.co.uk/blog/what-is-the-best-coolant-to-use-for-your-material-and-application.html (Accessed: 18 May 2025).

Department of Mechanical Engineering
UNIVERSITY OF BATH