DIN

DEPARTMENT OF INDUSTRIAL ENGINEERING

PhD Course in Mechanics and Advanced Engineering Sciences (DIMSAI)

YEARLY PHD STUDENT REPORT - AY *2016/2017*

Curriculum number *X*
Cycle *XXX*

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Supervisor: *Alessandro Fortunato*

Thermal modeling in Dry Grinding using Single-Grain Grinding FE model Based on CT-Scan Grain Geometry: Theoretical and Experimental Investigations

ALMA MATER STUDIORUM ~ UNIVERSITÀ DI BOLOGNA
IL PRESENTE MATERIALE È RISERVATO AL PERSONALE DELL'UNIVERSITÀ DI BOLOGNA E NON PUÒ ESSERE UTILIZZATO AI TERMINI DI LEGGE DA ALTRE PERSONE O PER FINI NON ISTITUZIONALI

Presentation Outline

- Motivations;
- Theoretical background;
- Thermal defect on gears;
- Modeling and experimental approach;
- CT grain geometry acquisition;
- Single grain grinding FE model;
- Experimental set-up;
- Grain wear study;
- Gear grinding thermal model;
- Conclusions;
- Acknowledgments.

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Motivations

Reduce energy consumption and environmental pollution

Eliminate use of **lubricants** in manufacturing chain

Generating gear grinding: remaining WET process for automotive transmissions production

New machine new **dry grinding** process

Optimize process parameters: high productivity no thermal damages

Predict grinding **temperature** vs process parameters

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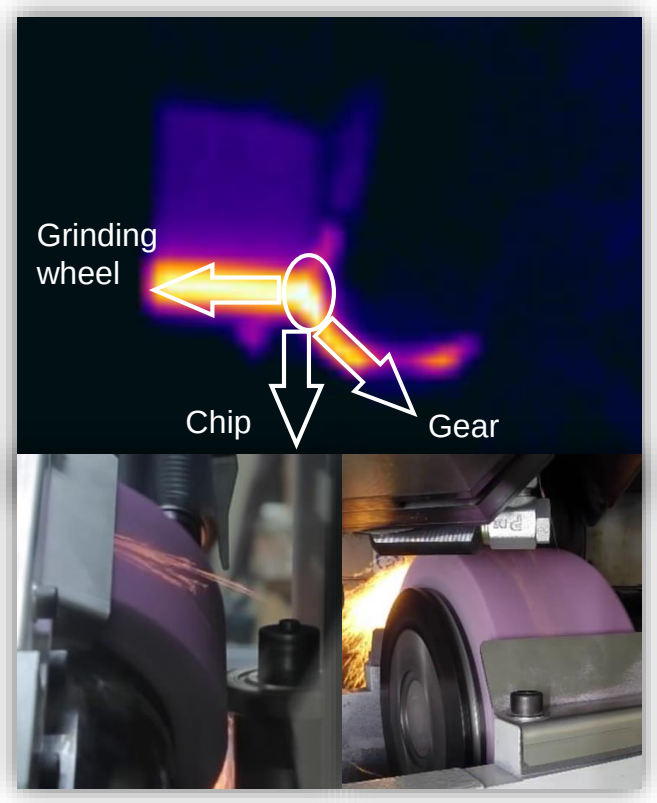
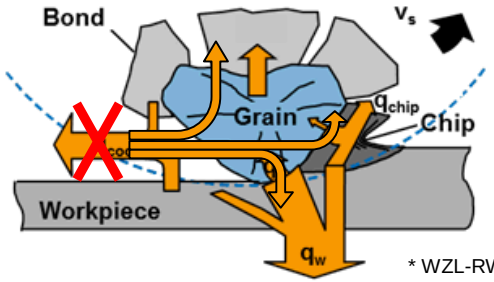
Theoretical background

Heat partition in dry generating gear grinding



Heat partition at grain-material interface



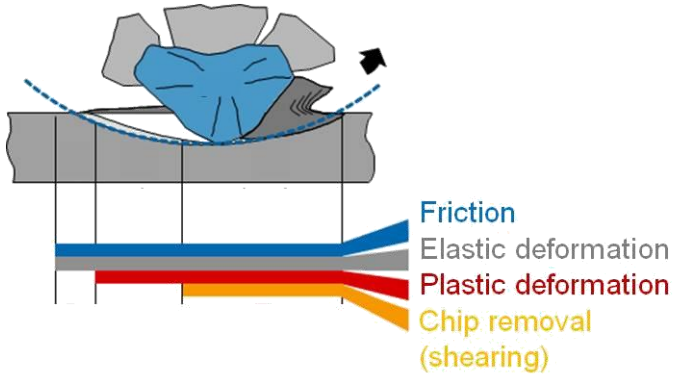
Legend:
v_s = circumferential grinding wheel speed
q_{cool} = heat flux to the coolant
q_g = heat flux to the grinding wheel
q_{chip} = heat flux to the chip
q_w = heat flux to the workpiece

* WZL-RWTH Aachen

Temperature resulting from cutting

$$F_C = A_C \cdot \tau(t; \gamma; \dot{\gamma}; T)$$

F_C = cutting force
A_c = cutting area
τ = dynamic shear stress
t = time
γ = shear strain
$\dot{\gamma}$ = shear strain rate
T = temperature



FE Model to calculate forces ⇨ Temperature

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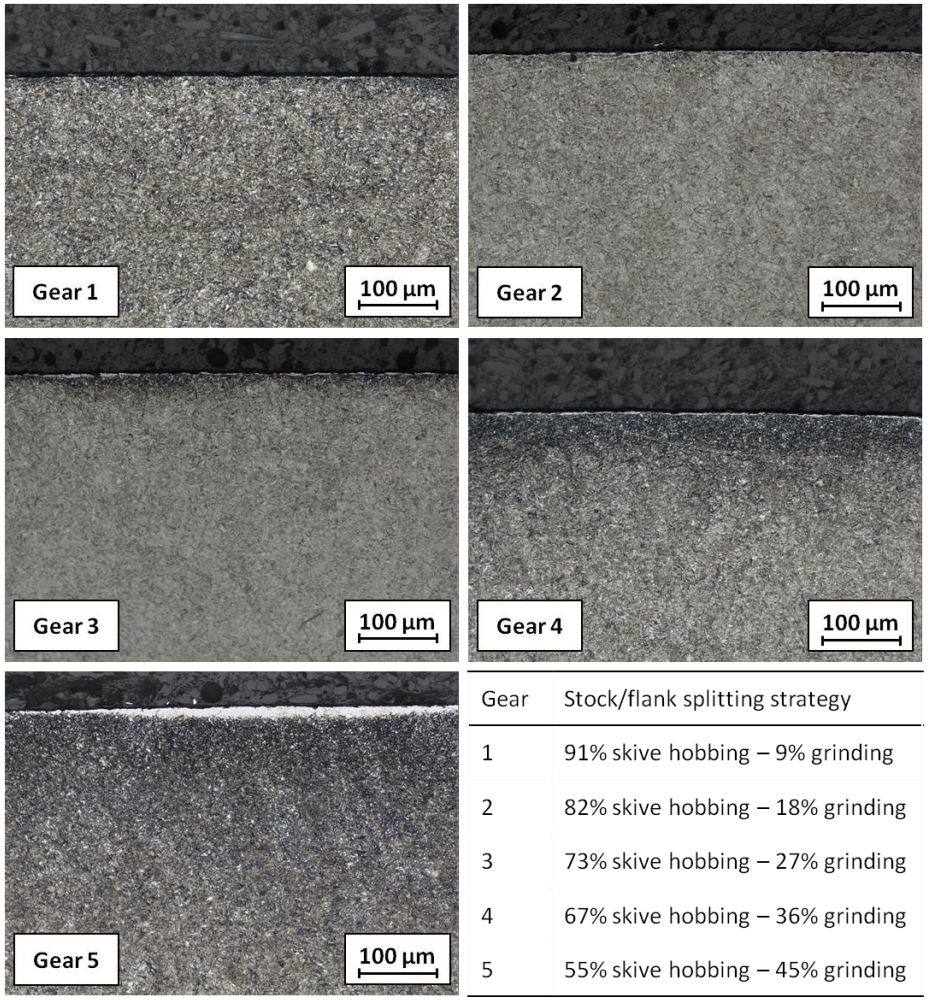
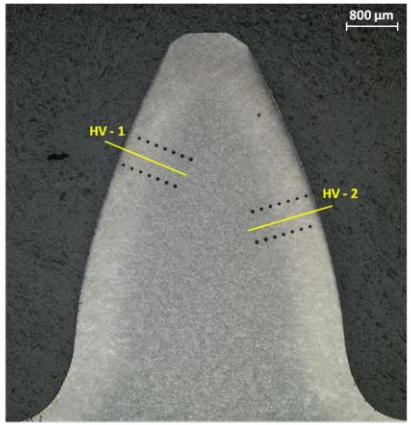
Thermal defect on gears

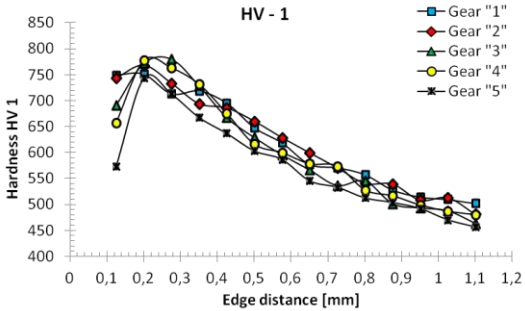
Case study of high performance automotive gear
Skive hobbed and ground dry with SAMP SG-160

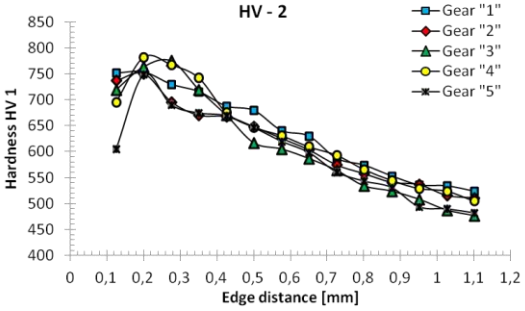
Microstructural changes – grinding burns



Gear	Stock/flank splitting strategy
1	91% skive hobbing – 9% grinding
2	82% skive hobbing – 18% grinding
3	73% skive hobbing – 27% grinding
4	67% skive hobbing – 36% grinding
5	55% skive hobbing – 45% grinding







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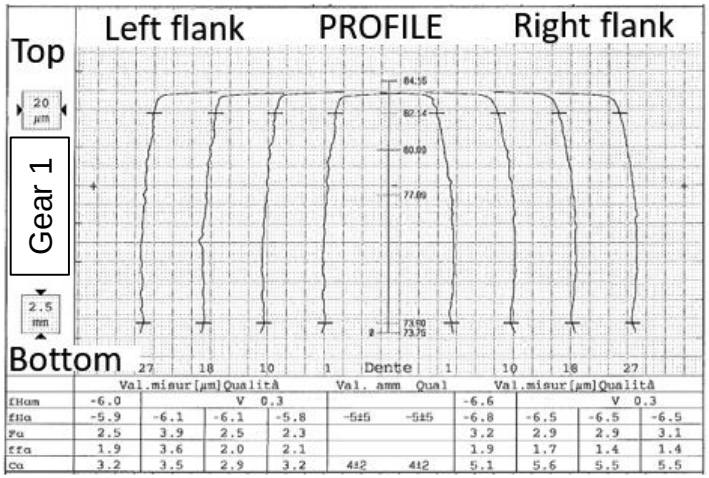
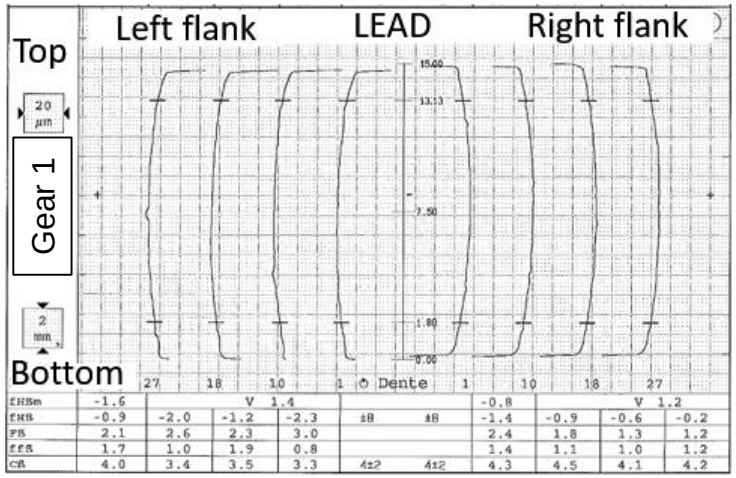
Thermal defect on gears

Thermal deformation – over cutting

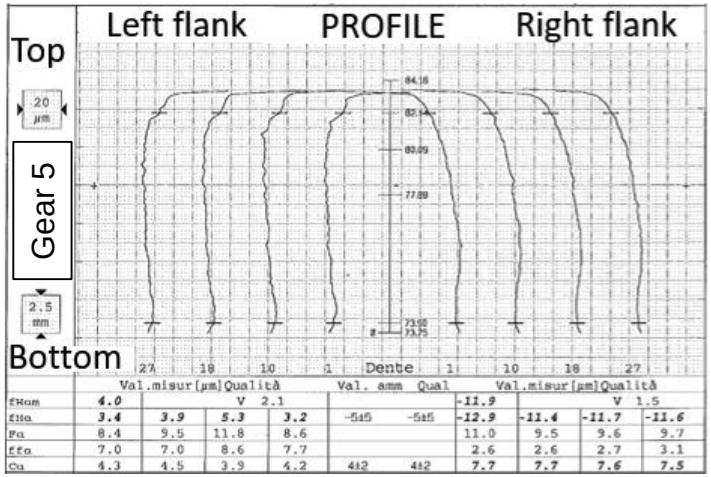
Case study of high performance automotive gear
Skive hobbed and ground dry with SAMP SG-160



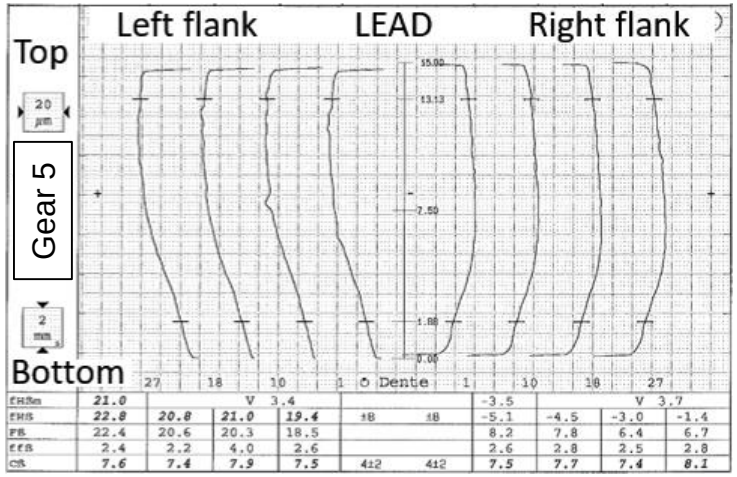
	Val.misur[µm]	Qualità			Val. amm	Qual	Val.misur[µm]	Qualità		
fHam	-6.0		V 0.3				-6.6		V 0.3	
fHa	-5.9	-6.1	-6.1	-5.8	-5±5	-5±5	-6.8	-6.5	-6.5	-6.5
Pa	2.5	3.9	2.5	2.3			3.2	2.9	2.9	3.1
ffa	1.9	3.6	2.0	2.1			1.9	1.7	1.4	1.4
Ca	3.2	3.5	2.9	3.2	4±2	4±2	5.1	5.6	5.5	5.5



fHBm	-1.6		V 1.4				-0.8		V 1.2	
fHB	-0.9	-2.0	-1.2	-2.3	±8	±8	-1.4	-0.9	-0.6	-0.2
PB	2.1	2.6	2.3	3.0			2.4	1.8	1.3	1.2
ffB	1.7	1.0	1.9	0.8			1.4	1.1	1.0	1.2
CB	4.0	3.4	3.5	3.3	4±2	4±2	4.3	4.5	4.1	4.2



	Val.misur[µm]	Qualità			Val. amm	Qual	Val.misur[µm]	Qualità		
fHam	4.0		V 2.1				-11.9		V 1.5	
fHa	3.4	3.9	5.3	3.2	-5±5	-5±5	-12.9	-11.4	-11.7	-11.6
Pa	8.4	9.5	11.8	8.6			11.0	9.5	9.6	9.7
ffa	7.0	7.0	8.6	7.7			2.6	2.6	2.7	3.1
Ca	4.3	4.5	3.9	4.2	4±2	4±2	7.7	7.7	7.6	7.5



fHBm	21.0		V 3.4				-3.5		V 3.7	
fHB	22.8	20.8	21.0	19.4	±8	±8	-5.1	-4.5	-3.0	-1.4
PB	22.4	20.6	20.3	18.5			8.2	7.8	6.4	6.7
ffB	2.4	2.2	4.0	2.6			2.6	2.8	2.5	2.8
CB	7.6	7.4	7.9	7.5	4±2	4±2	7.5	7.7	7.4	8.1

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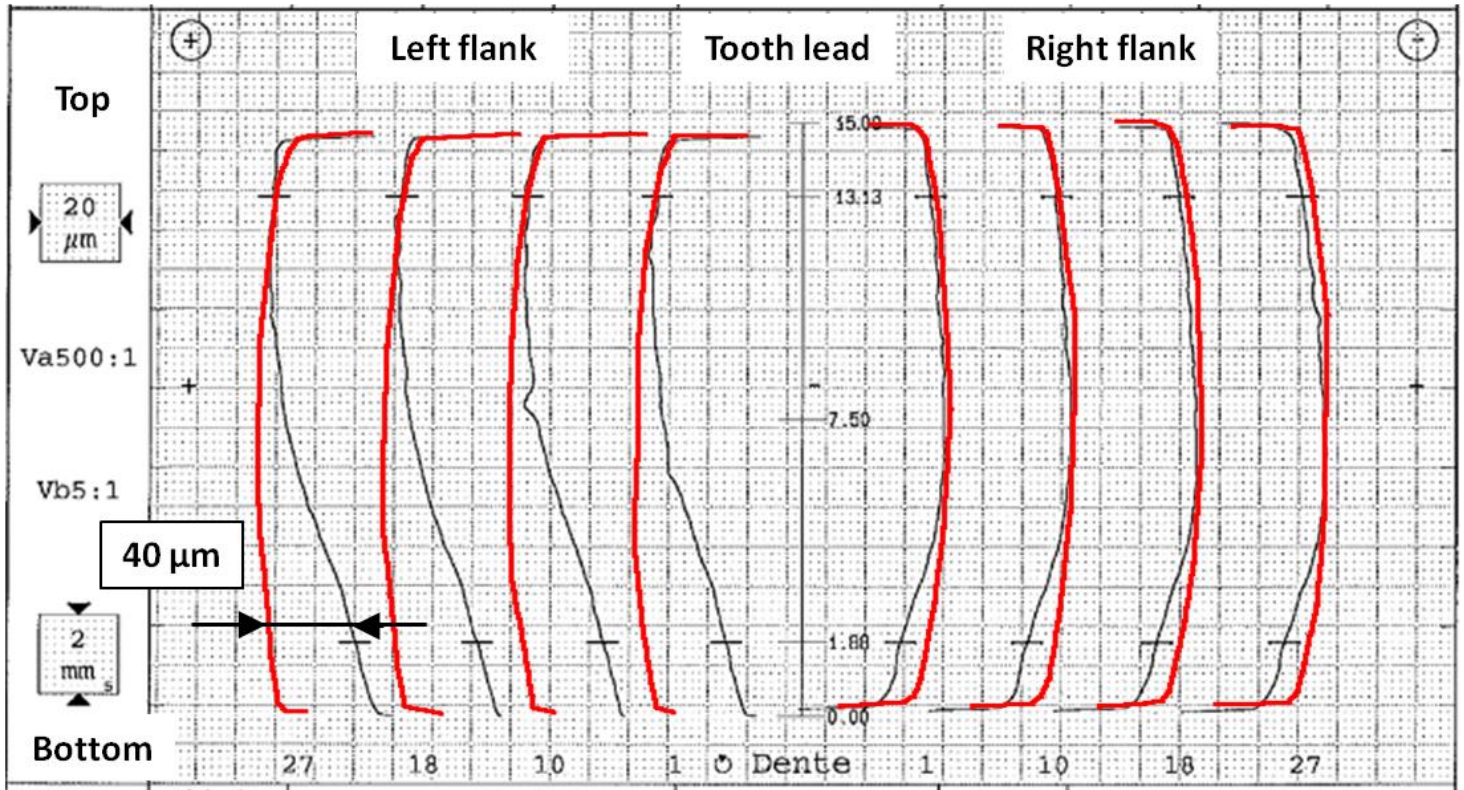

fHßm	21.0		V 3.4				-3.5		V 3.7	
fHß	22.8	20.8	21.0	19.4	±8	±8	-5.1	-4.5	-3.0	-1.4
Fß	22.4	20.6	20.3	18.5			8.2	7.8	6.4	6.7
ffß	2.4	2.2	4.0	2.6			2.6	2.8	2.5	2.8
Cß	7.6	7.4	7.9	7.5	4±2	4±2	7.5	7.7	7.4	8.1

Gear 1 — Gear 5

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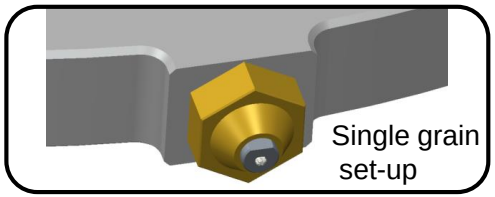
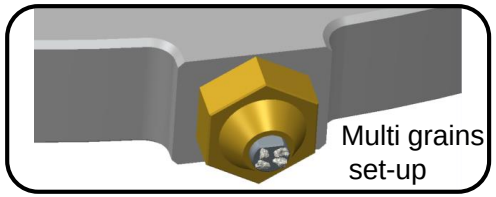
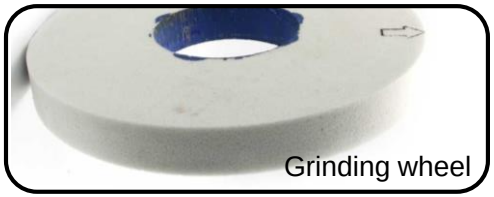
Modeling and experimental approach

Model the interaction between grain and material to:

- Predict stress and strain state at the material-grain interface;
- Calculate cutting forces developed by a single abrasive grain;
- Obtain peak temperature and temperature distribution;
- Use the single-grain results in a multi-grain model “to understand how multiple grains act during cutting”.







Single grain model challenges

- Undefined grain geometry
- Uncertain cutting area
- Unknown grain wear

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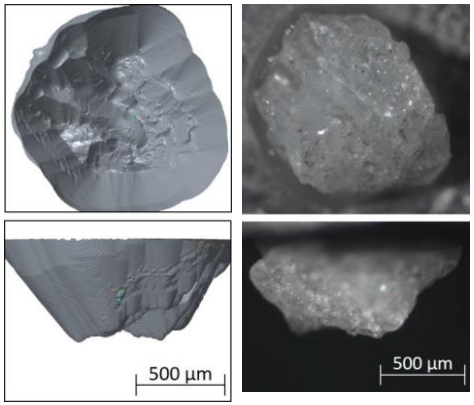
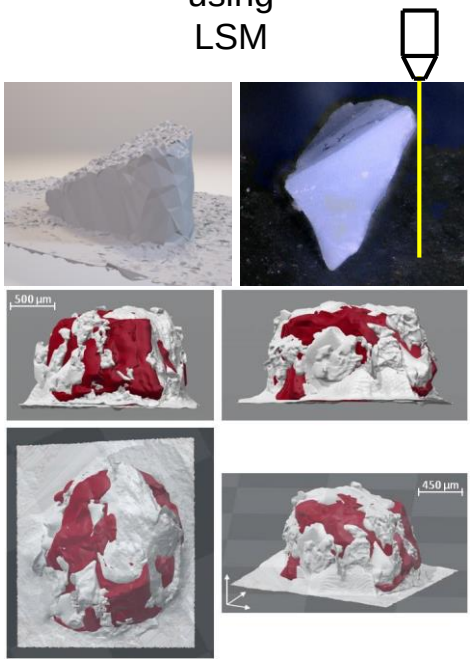
Grain geometry acquisition methods

Grain geometry acquired using Contact Stylus

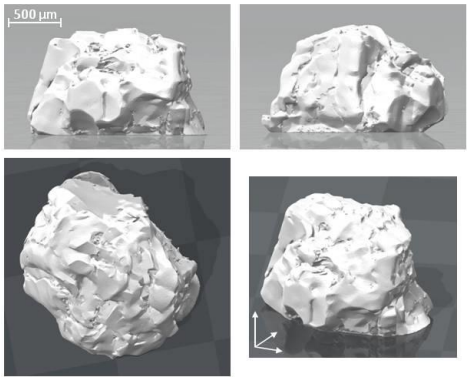


Stylous: tip angle 90°
tip radious 2 µm
filtering the real grain geometry

Grain geometry acquired using LSM



Grain geometry acquired using CT



Only limitation:
machine resolution

* Guerrini G., Bruzzone A. A. G., Crenna F. Single grain grinding: an experimental and FEM assessment
10th CIRP conference on Intelligent Computation in Manufacturing Engineering – CIRP ICME'16

* *Guerrini G. et al. Abrasive grains micro geometry: a comparison between two acquisition methods
11th CIRP conference on Intelligent Computation in Manufacturing Engineering – CIRP ICME'17

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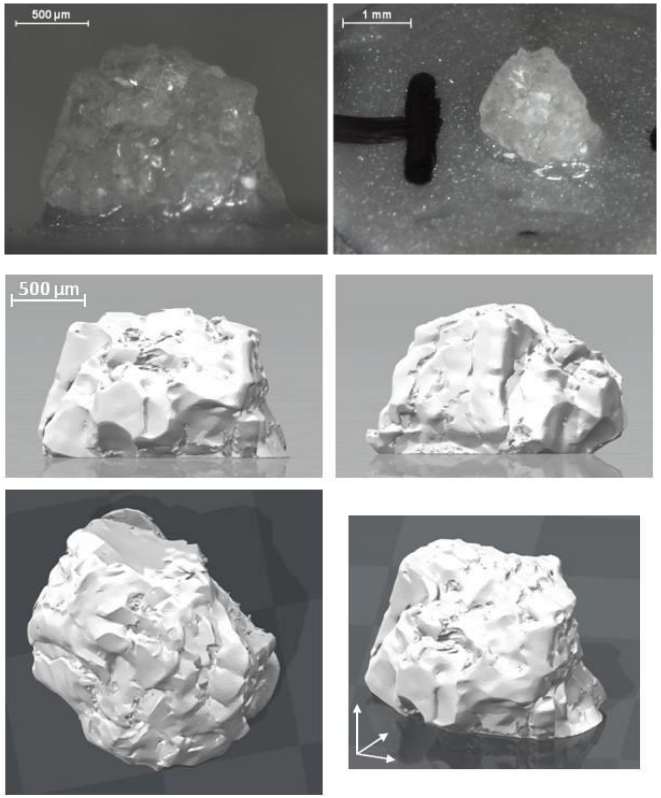
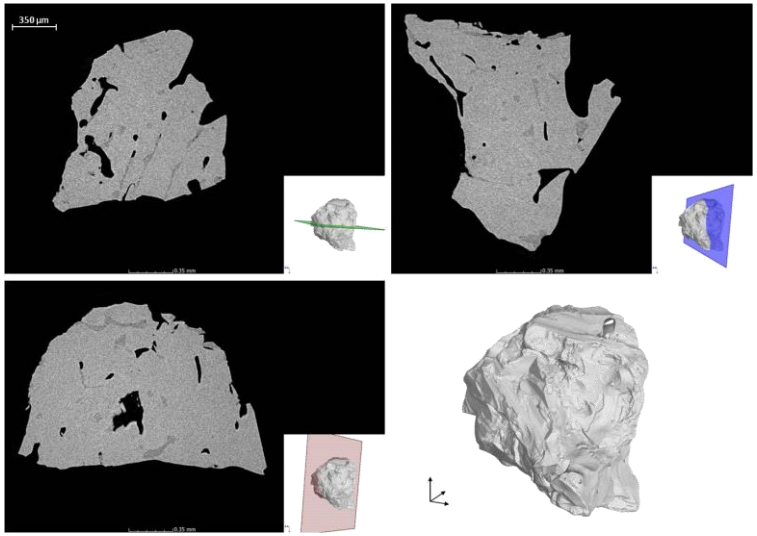
CT grain geometry acquisition

Single grain:



CT-Zeiss
Metrotom 800
PMRC
Georgia Tech, Atlanta



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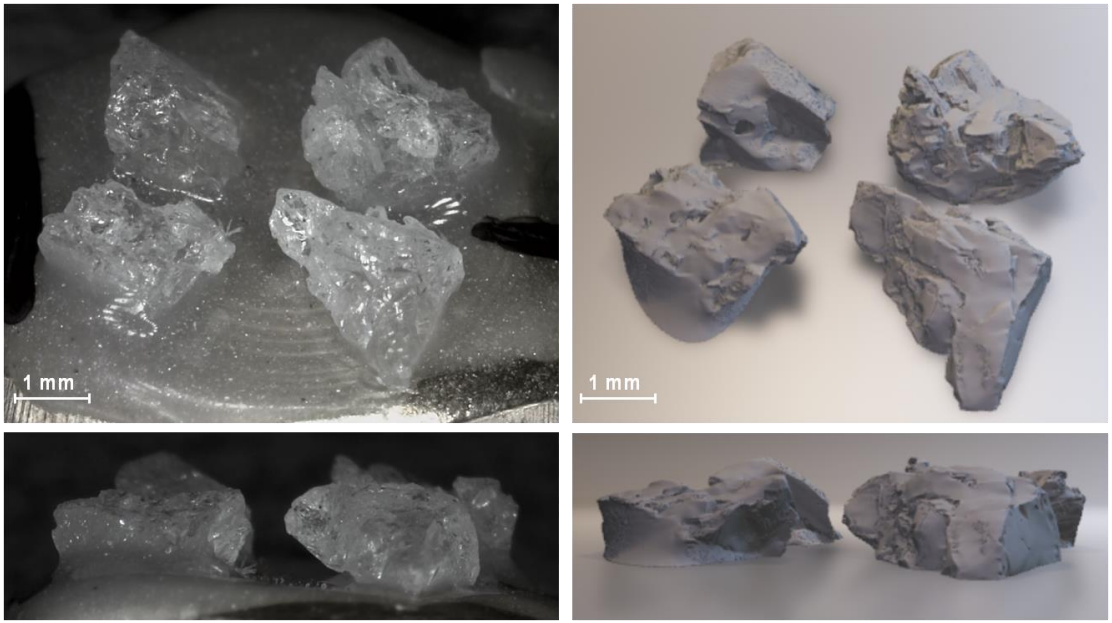
CT grain geometry acquisition

CT-Zeiss
Metrotom 800
PMRC
Georgia Tech, Atlanta

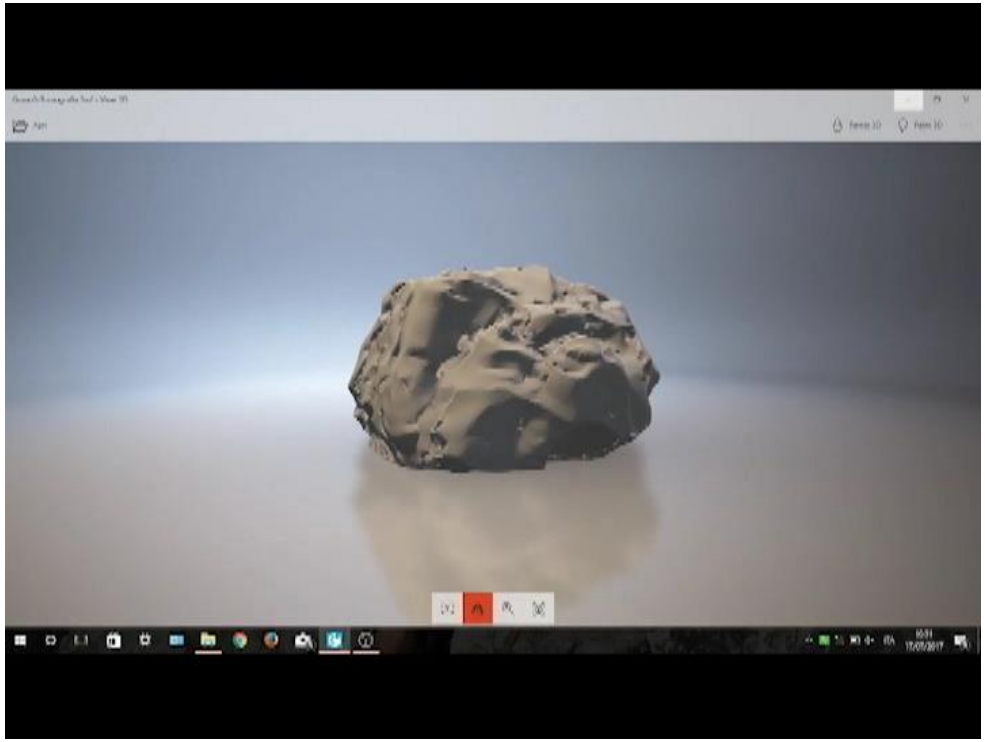
Multi grains:



CT grain geometry acquisition

Advantages:

- Entire geometry measured with one acquisition
- Detection of different materials
  e.g. bonding, holder etc…
- Complete 3D geometry available for modelling
- Positive rake angles detection
- Internal structure



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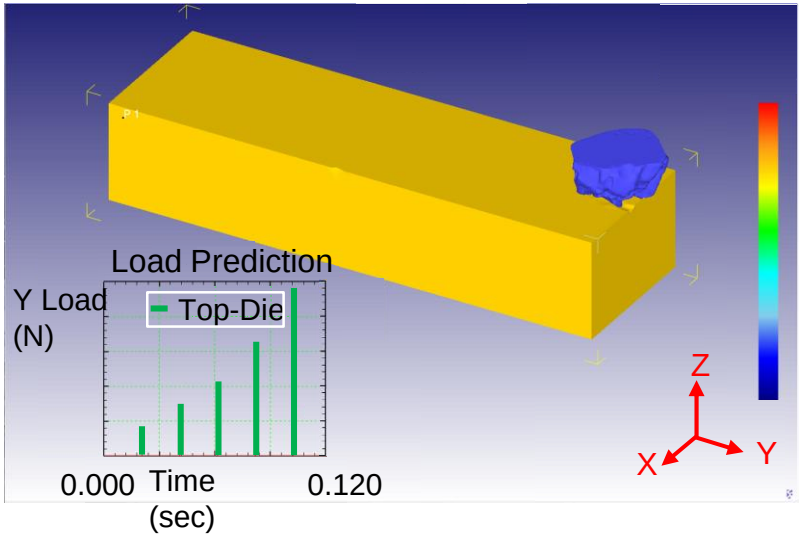
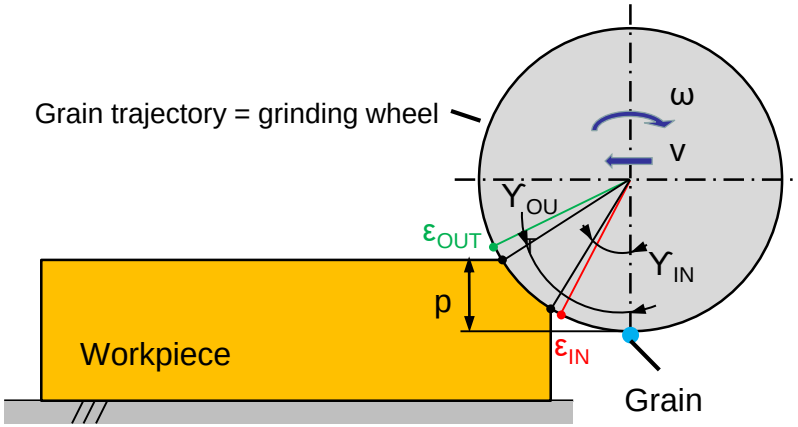
Single grain grinding FEM model

- Software:
  DEFORM 3D
- Constitutive material model:
  modified Johnson-Cook
- Friction model:
  constant coefficient
- Fracture model:
  Cockcroft & Latham
- Mesh optimization:
  Mesh windows
- Local remesh criteria:
  Abs. interference depth
- Time step optimization:
  Function of time





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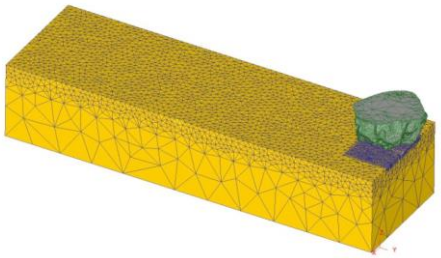
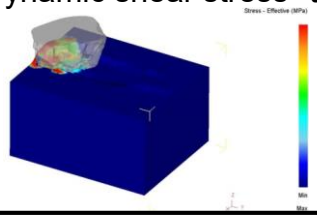
Model outputs

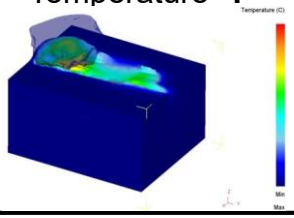


Cutting Area “**A**”

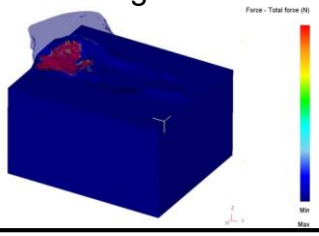
Dynamic shear stress “**τ**”



Temperature “**T**”



Grinding force “**F**”



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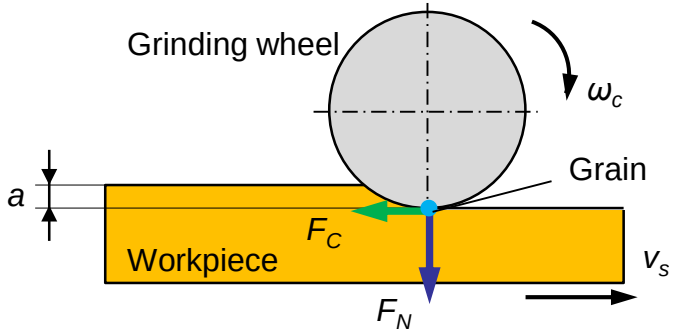
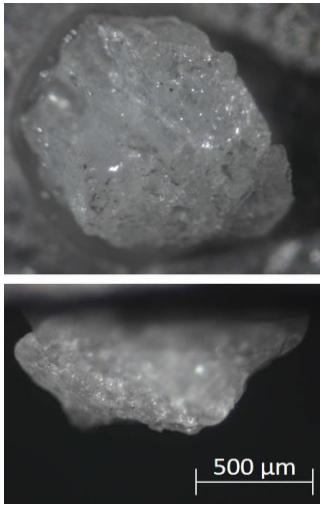
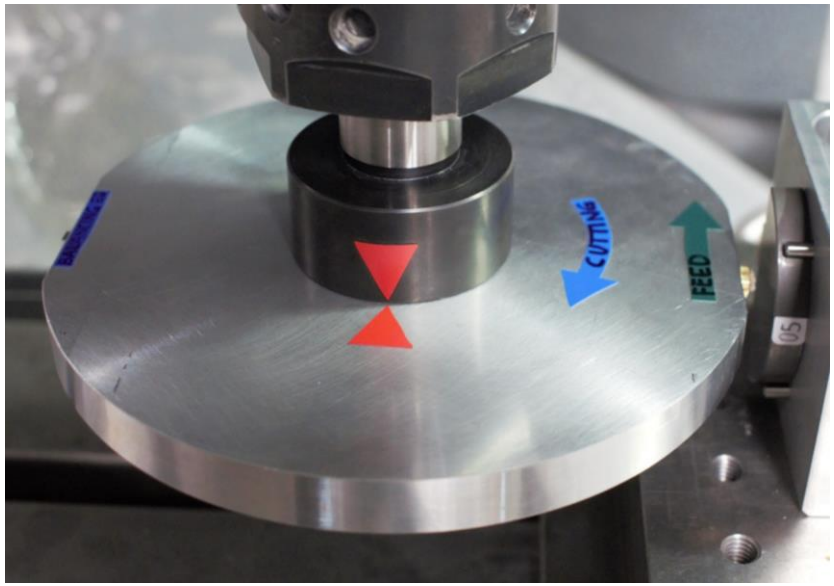
Experimental set up (PMRC-Georgia Tech, Atlanta)

- Machine:
  Okuma MILLAC 44V - CNC mill
- Dynamometer:
  Kistler 3 axial Type 9257B
- Workpiece:
  20MnCr5, Case hardened
- Abrasive grains:
  Fused pure Al_2O_3, FEPA 16; 24; 36
- Process parameters:
  Cutting speed v_c: 30; 40 m/s
  Depth of cut a: 100;150 µm
  Feed rate v_s: 500; 1000 mm/min







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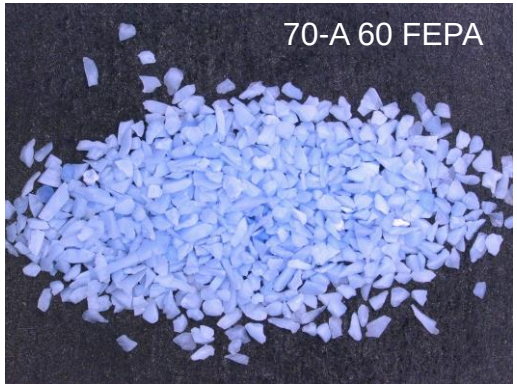
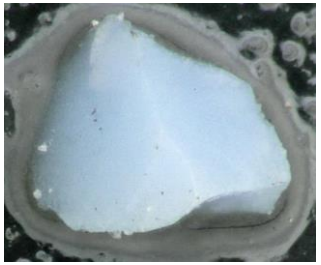
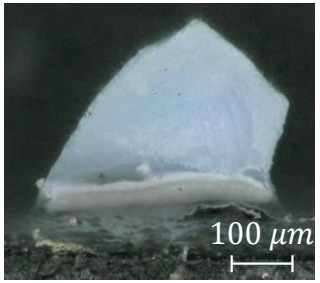
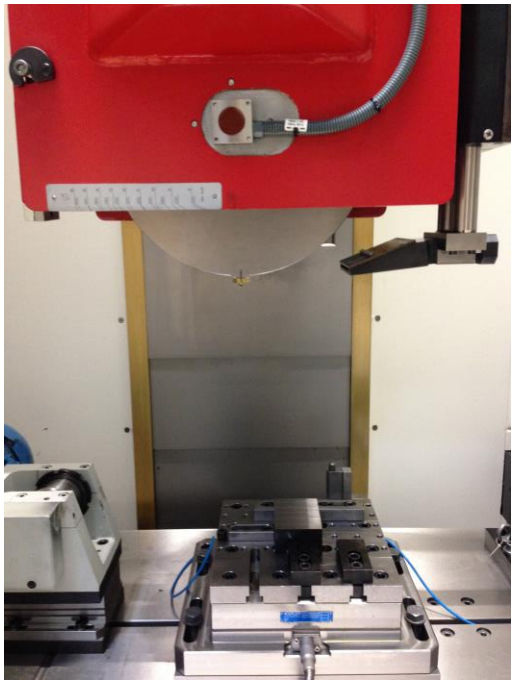
Experimental set up (WZL-RWTHAachen, Aachen)

- Machine:
  Blohm PROFIMAT 608 MT - CNC
- Dynamometer:
  Kistler 3 axial Type SN
- Workpiece:
  20MnCr5, Case hardened
- Abrasive grains:
  Pure fused white Corundum “EKW”,
  Blue sapphire Corundum “70-A”
  FEPA 60 and 80
- Process parameters:
  Cutting speed v_c: 35; 45; 63 m/s
  Depth of cut a: 5; 10; 15 µm
  Feed rate v_s: 1000; 1500; 3000 mm/min









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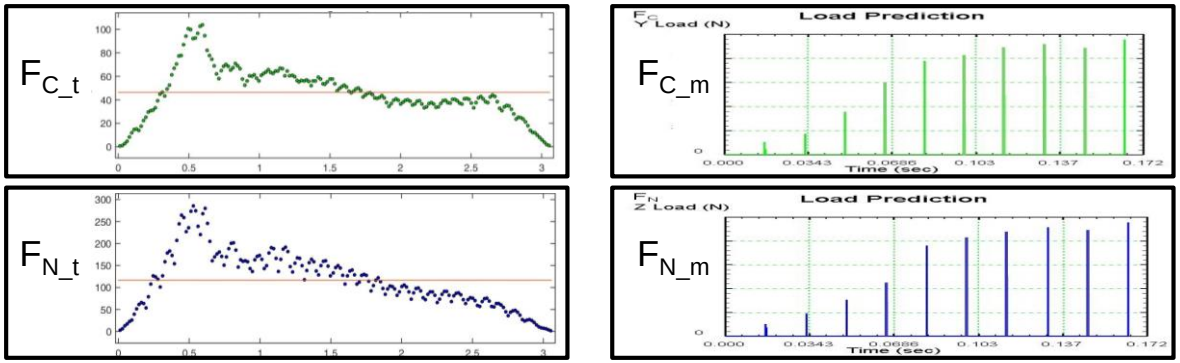
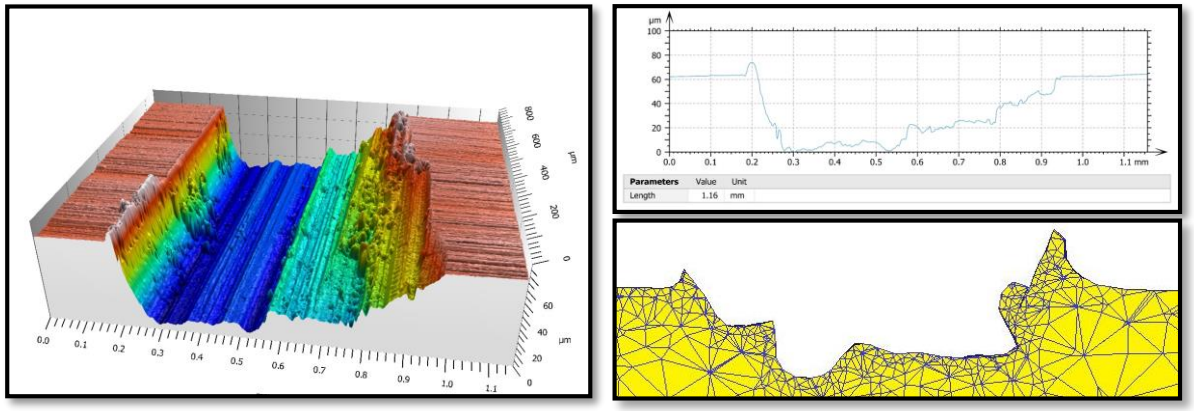
Model validation procedure

Radial & Tangential force

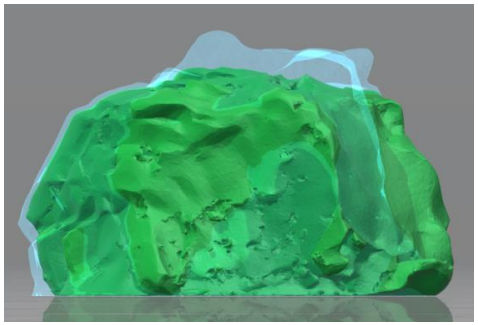


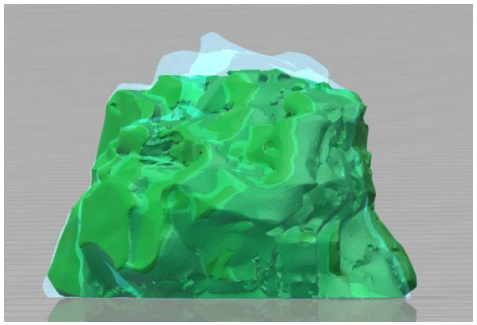
Cutting area & scratch cross-section



Grain wear study

Grain:
CT acquisition





Volume before grinding: 1.55 mm^3

Volume after grinding: 1.35 mm^3

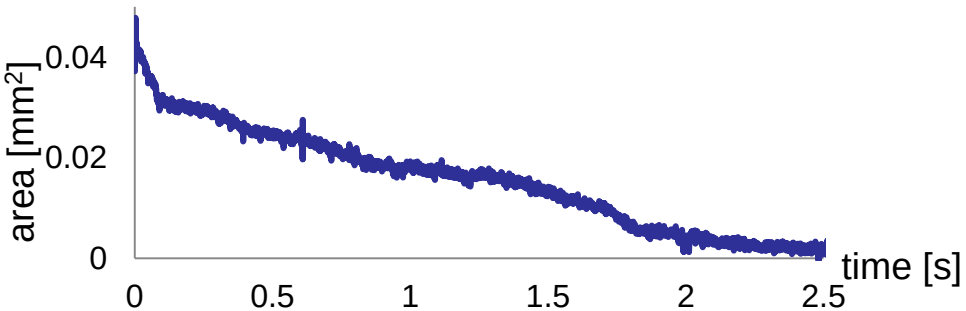
Grain volume loss: volume: 0,20 mm^3

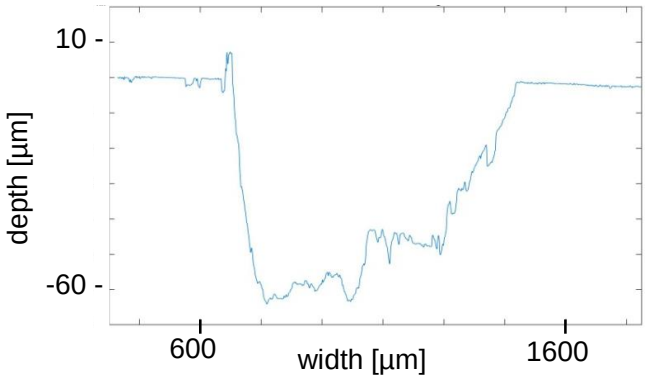
Total grinding passes: 178

Total ground length: 21,8 mm

Material removed 0,34 mm^3

Scratch:
LSM acquisition





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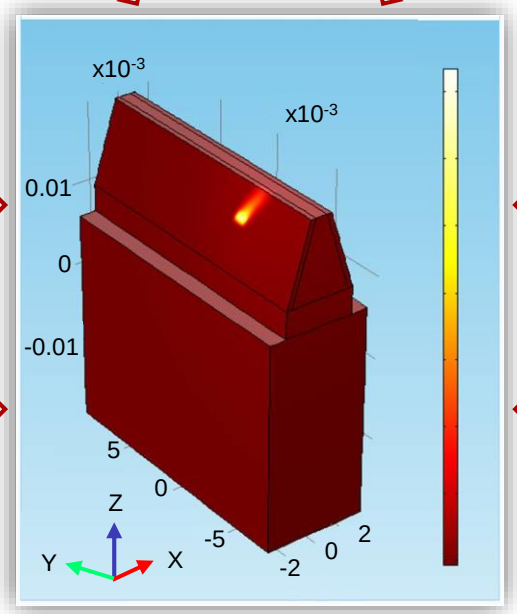
Gear grinding thermal model

Gear data: geometry and material

Grinding wheel data: grits density etc…

Grinding area dimensions and shape

Temperature peaks from FEM model



Real process kinematic

Machine power consumption

Gear temperature: tooth surface and bulk material

Grinding burn threshold temperature

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Conclusions

Grain geometry acquisition:

- Computed Tomography to obtain real grain geometry without artifacts;
- Internal structure of the grain is given from CT acquisition;
- The 3D model of the grain is reconstructed from CT measurements.

Single grain grinding model :

- Real grain geometry is used as single-grain grinding tool with no approximations;
- The cutting model has been validated through tests with force measurements;
- The model can be used to calculate grinding forces and predict the temperature at the grain-material interface

Grain wear study:

- The volume reduction of the grain can be calculated from CT acquisitions before and after grinding;
- The variation of the grain geometry due to wear is reflected on the variation of the scratch cross section;
- These information can be use to define the best grain for a particular application.

Gear grinding thermal model:

- The model predicts when and where a thermal defect occurs;
- The model has been validated with test conducted in production environment;
- The model can be used to optimize the grinding parameters avoiding grinding burns.

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Thank you

Thermal modeling in Dry Grinding using Single-Grain Grinding FE model
Based on CT-Scan Grain Geometry:
Theoretical and Experimental Investigations

Candidate: *Giacomo Guerrini*
Supervisor: *Alessandro Fortunato*

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