Advances in Grinding Tools and Abrasives

by

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Outline

1. **Motivation and Scope**
2. **Basic Grinding Tool Technology**
3. **Engineered and Hybrid Grinding Tools**
4. **Smart Grinding Tools**
5. **Outlook for sustainability and future research**
6. **Conclusion**

Motivation

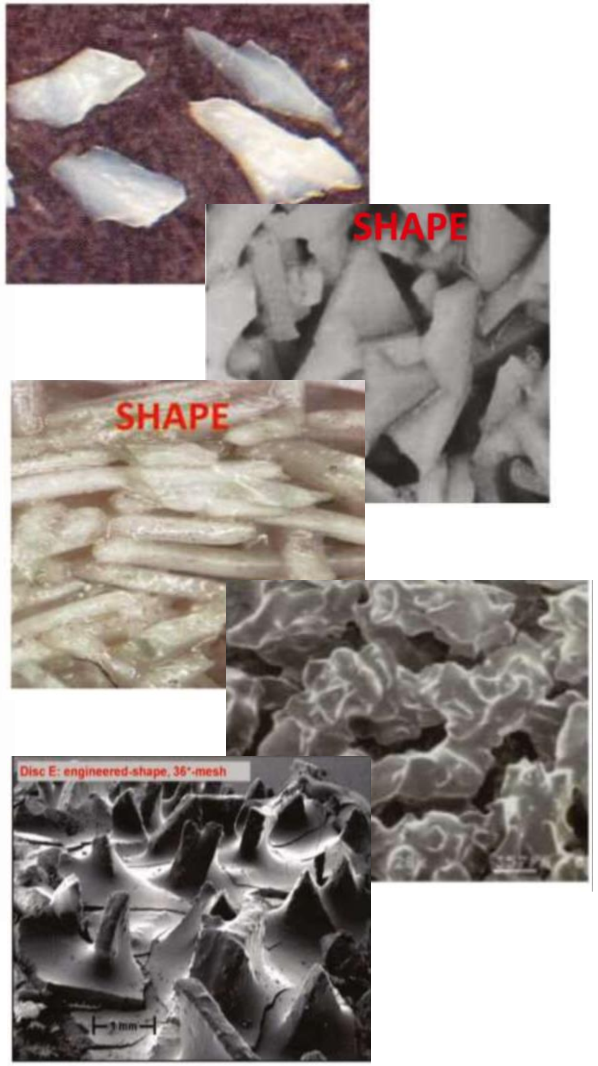
First, some thoughts on the automation of grinding operations…

Medieval Tapestry of Blade Finishing (circa 13th century)

Optical Glass Grinding Machine (circa 15th century)

Motivation

From automation to diversity!

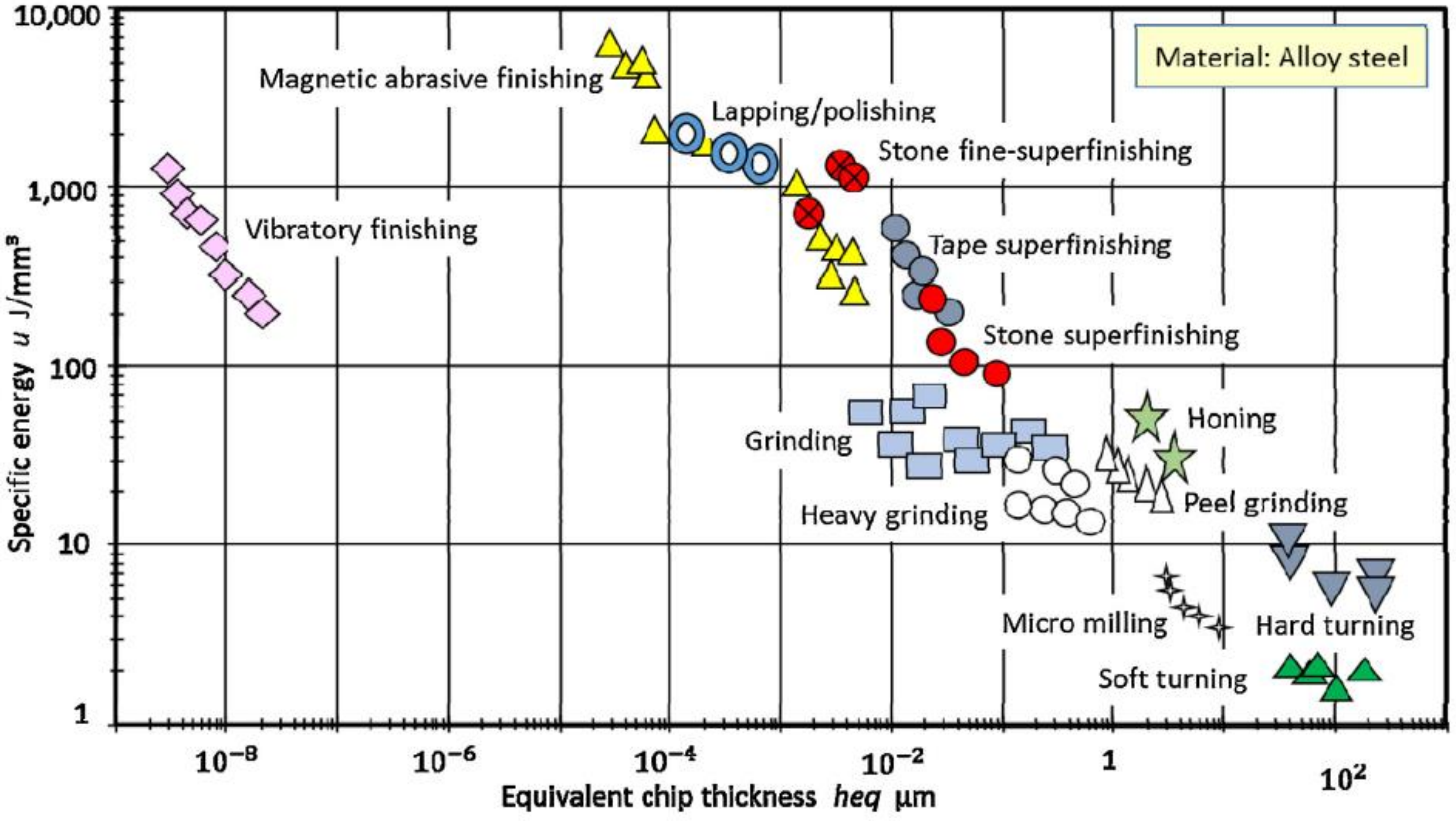


Motivation

Market volume based on sales reports from: Robert Bosch GMBH, Henkel (Germany), 3M Company (US), Saint-Gobain S.A. (France), Fujimi Incorporated, Asahi Diamond Industrial (Japan), Tyrolit Group (Austria), Deerfos (Korea), Sak Industries, and Carborundum Universal Ltd (India). (source: Markets and Markets)

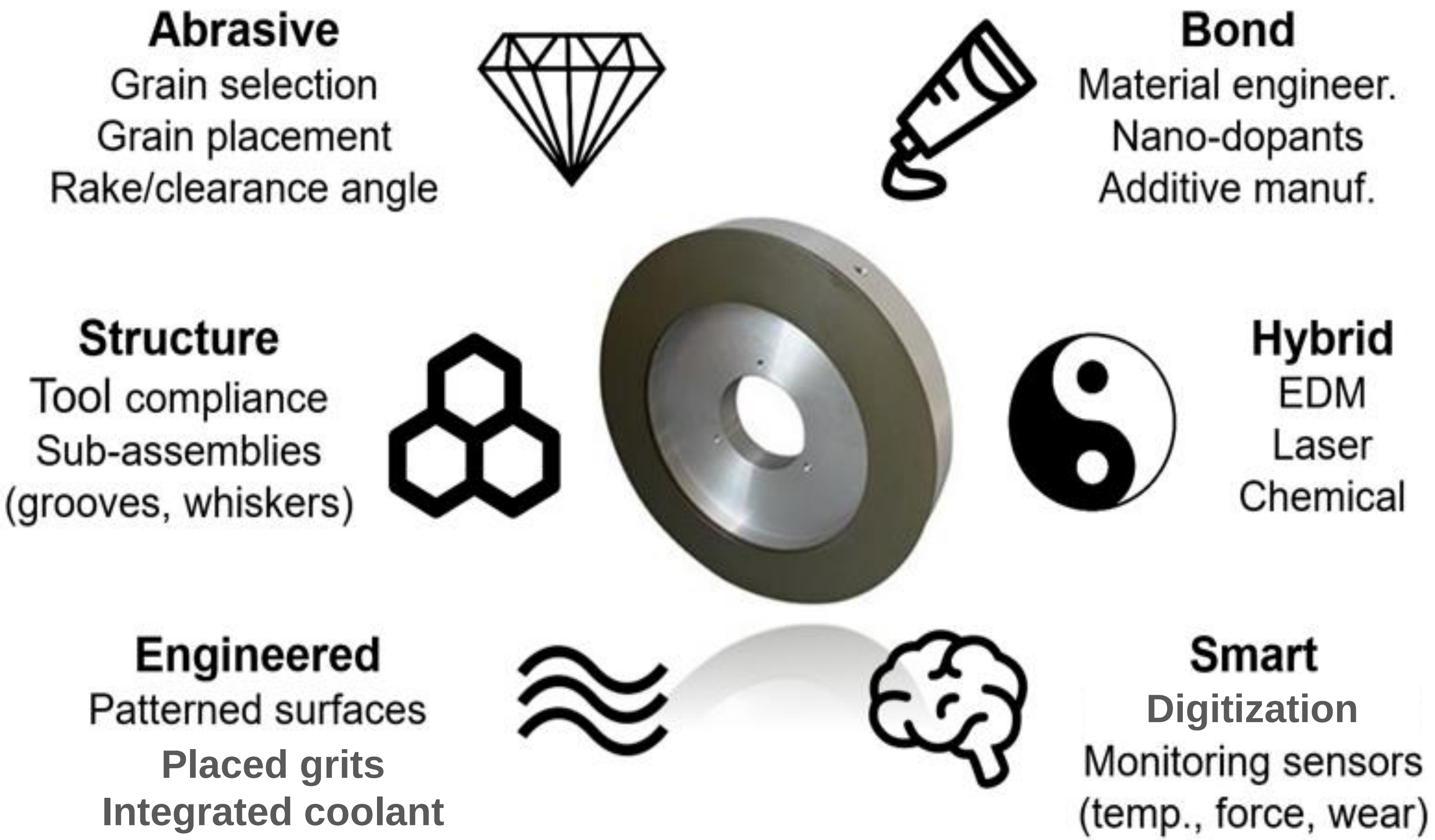
Motivation

About the energy intensiveness of grinding and finishing processes…

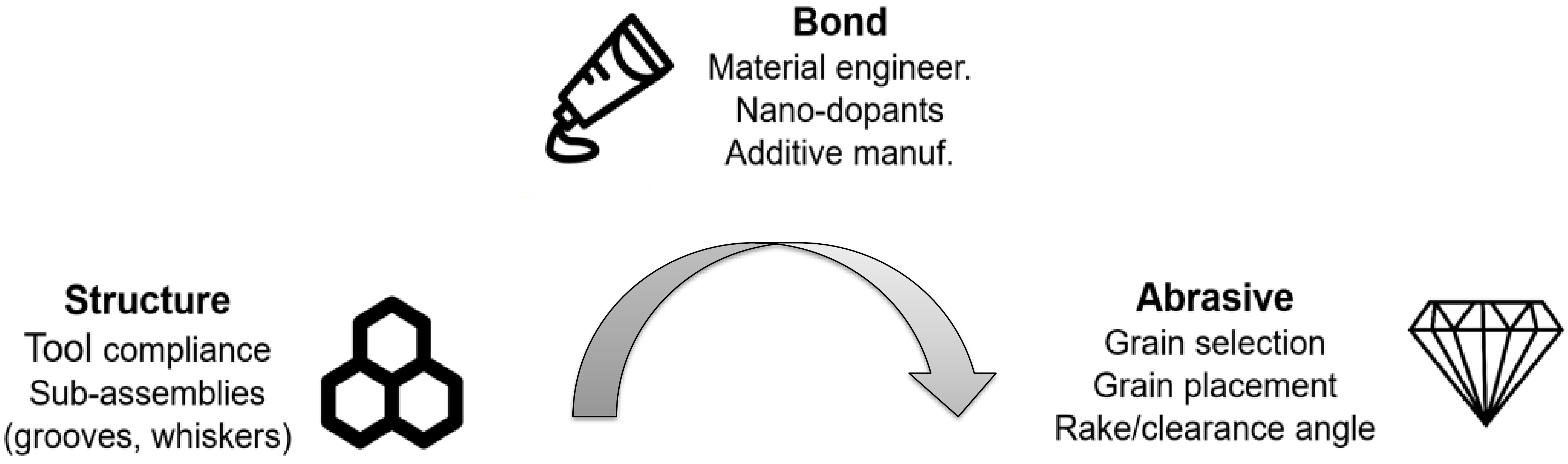


Source: Hashimoto et al., Abrasive fine finishing, CIRP Annals, 2016

Scope of Keynote Paper



Basic Grinding Tool Technology

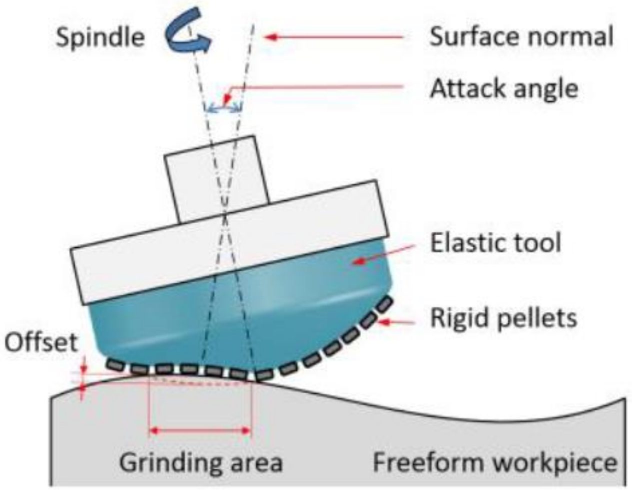


- Adoption of superabrasives in the latter part of the 20th century led to a number of issues when used in combination with stiff grinding tools and equipment (e.g. regenerative chatter).
- To mitigate these issues a number of **fully or partially elastic grinding tools**, as well as **partially compliant bond materials**, have been proposed.

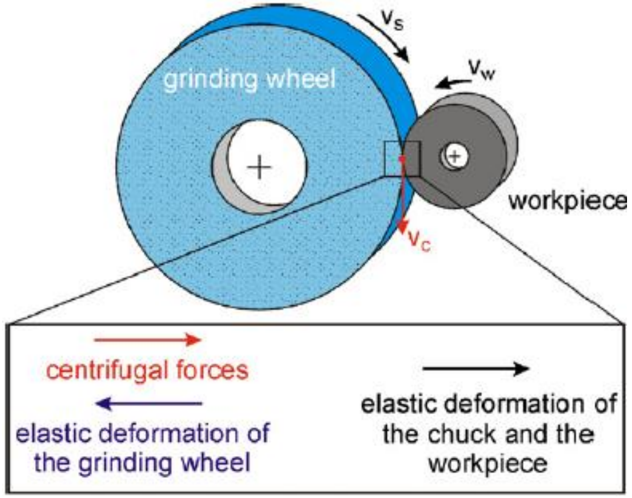
Compliance

--- → +++

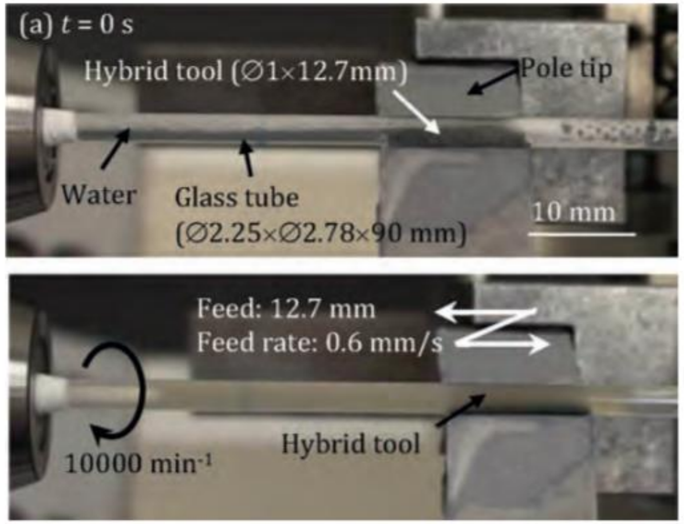
Conventional



Shape Adaptive Grinding (2014)



Elastic Wheels (2009)

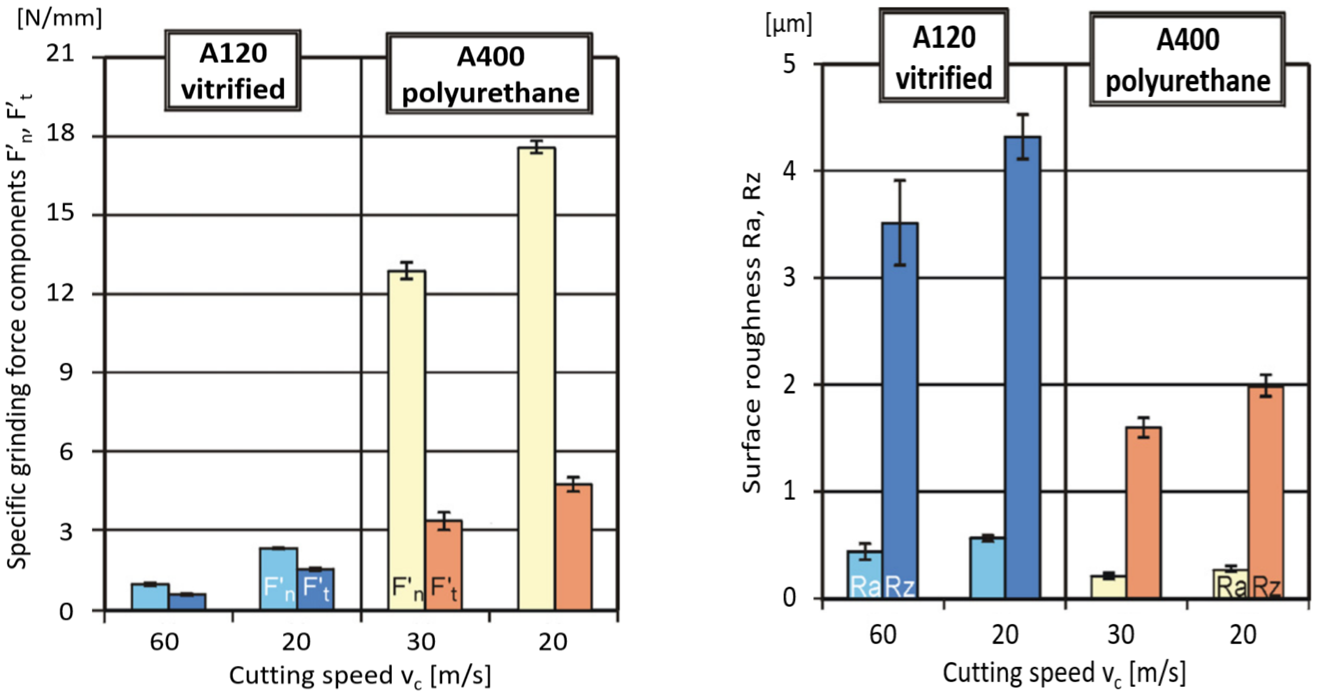


Dissolvable bond (2015)

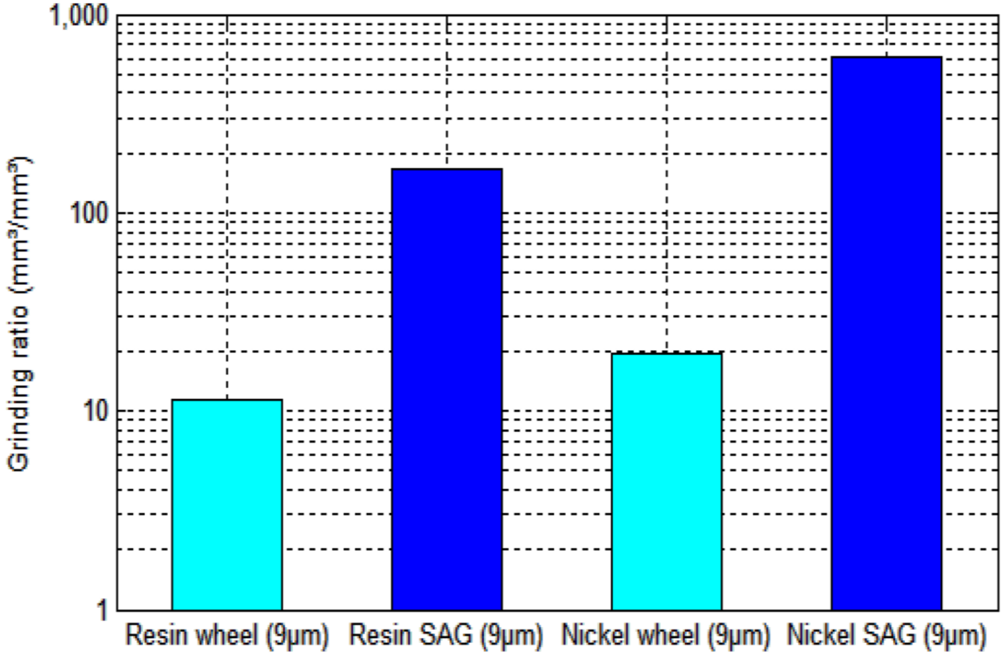
Basic Grinding Tool Technology: Tool Structure

Compliant grinding tools offer some attractive advantages:

- Higher specific grinding force under similar operating conditions.
- Improved surface roughness of the finished parts.
- Improved grinding ratio and lifetime of the grinding product.
- Less resource/energy intensive binder material (leading to improved sustainability).



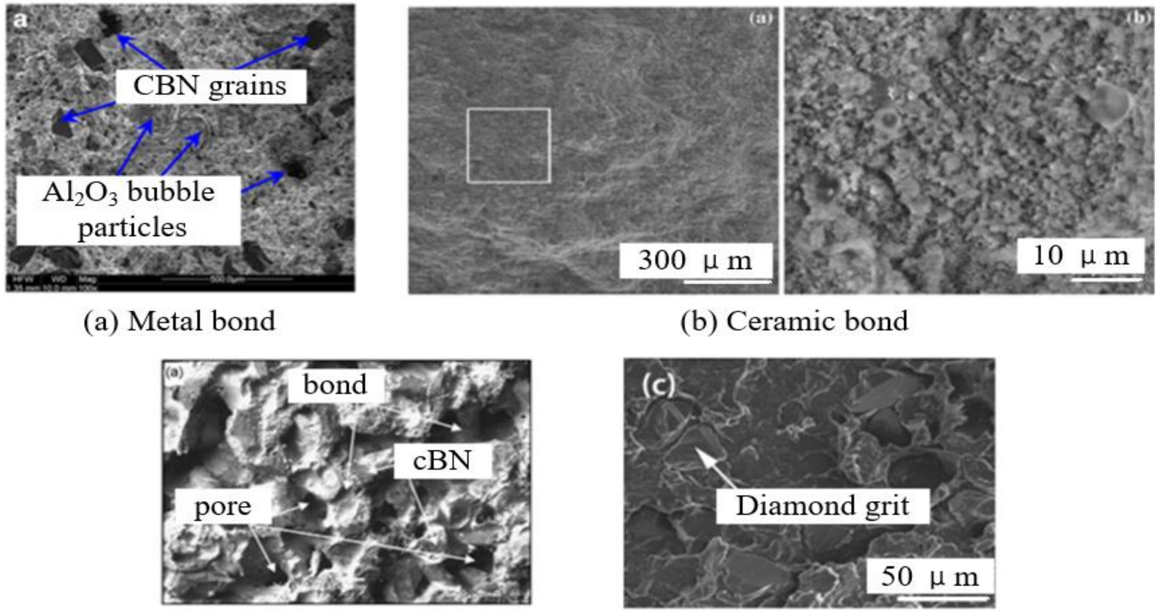
Performance of vitrified bond vs. elastic polyurethane wheel (2009)



Grinding ratio of conventional wheels vs. SAG (2015)

Basic Grinding Tool Technology: Binder Material

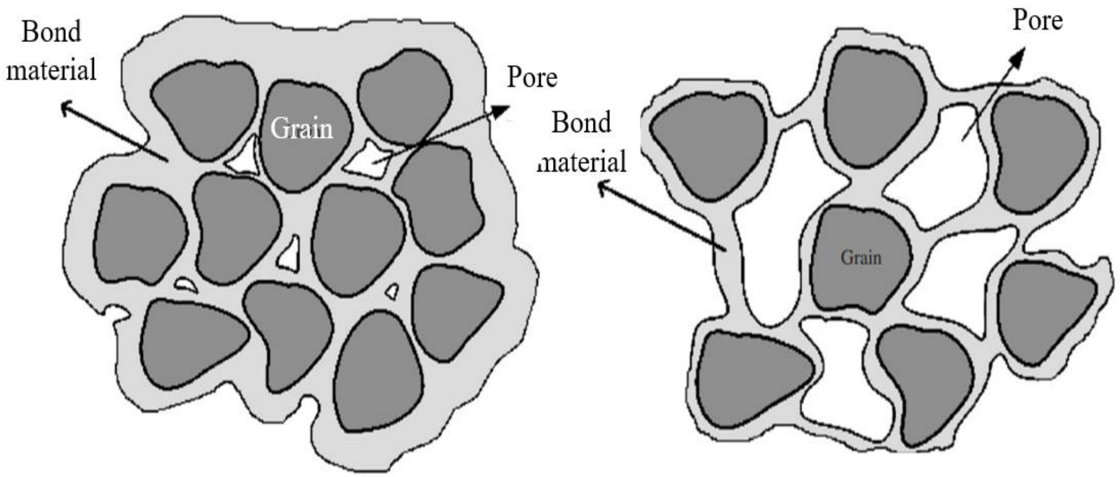
- In recent literature, diverse types of conventional binder materials have seen continued development, including metal, electro-plated, ceramic, glass-ceramic, resin, etc.
- By using **different proportions of the ingredient materials**, the structure of wheel bonds can take different appearances, including high density, low porosity or bridge-bonding.
  - ↳ Example: Alumina bubble particles can be employed as pore-forming agents inside Cu-SnTi alloy bond to fabricate porous metal-bonded CBN composite blocks and grinding wheels.



(a) Metal bond (b) Ceramic bond

(c) Glass-ceramic bond (d) Resin bond

SEM images of various binder materials (2013, 2009, 2019)

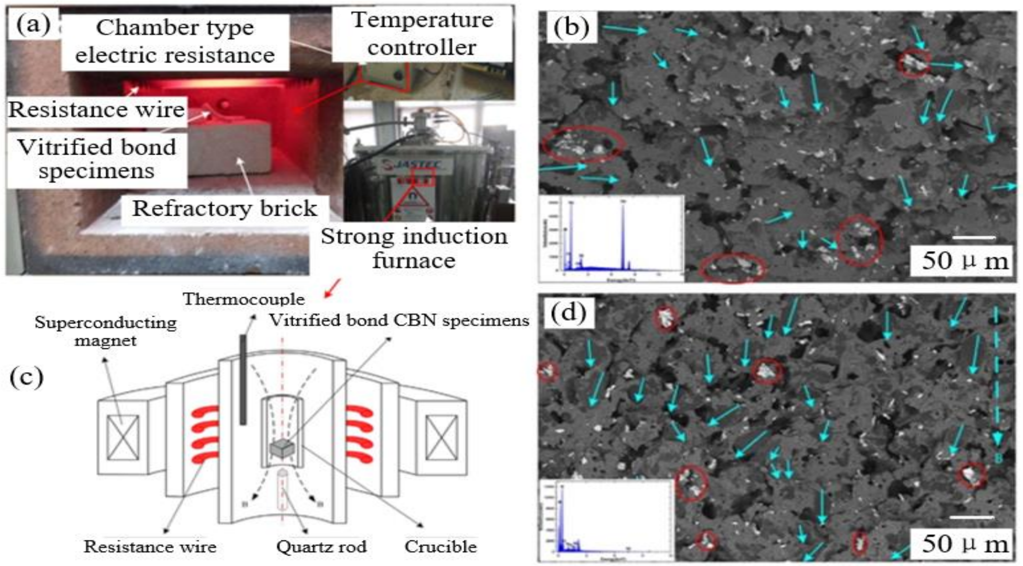


Schematics of closed and open “bridge-type” bonds (2007)

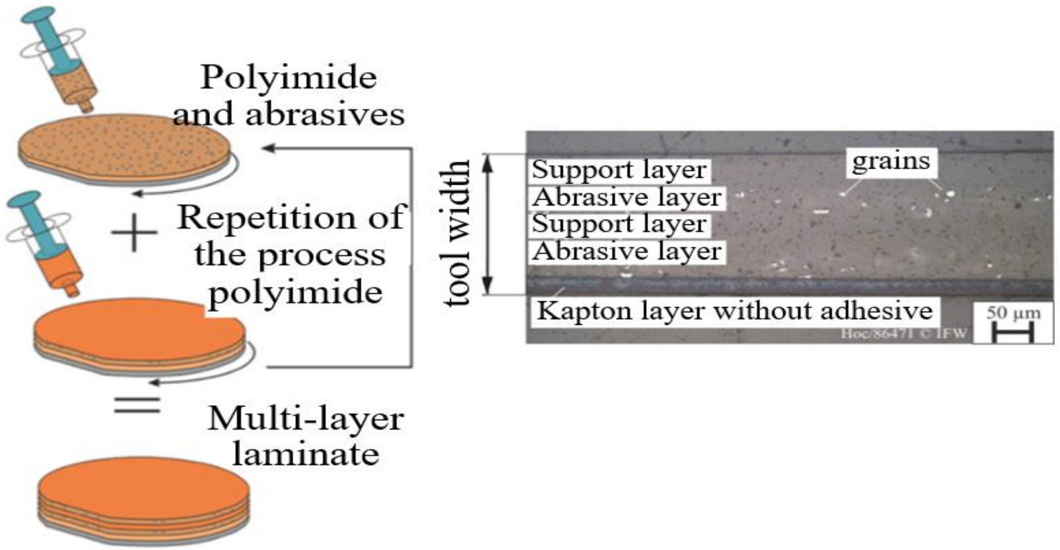
Basic Grinding Tool Technology: Binder Material

Interesting new approaches have been proposed to control binder at the nanoscale:

- **Chemical vapour-deposited diamond fibres** used to grind soda glass: the grinding mechanism involves the formation by ductile flow of glass ribbons adjacent to the grinding grooves (similar to single point turning).
- **A strong magnetic field can be introduced** in the preparation of ceramic bonded CBN grinding tools: the magnetic field facilitates Ni migration and aggregation in the vitrified bond, rotates abrasives, and forms new substances that increase the stability of vitrified bond CBN composites.
- **Bond material can also be multi-layered**: The first layer type contains abrasives and the second is a support layer without abrasives. These layers are piled alternately and act like a monolithic tool in the grinding process.



Magnetic field assisted sintering (2018)

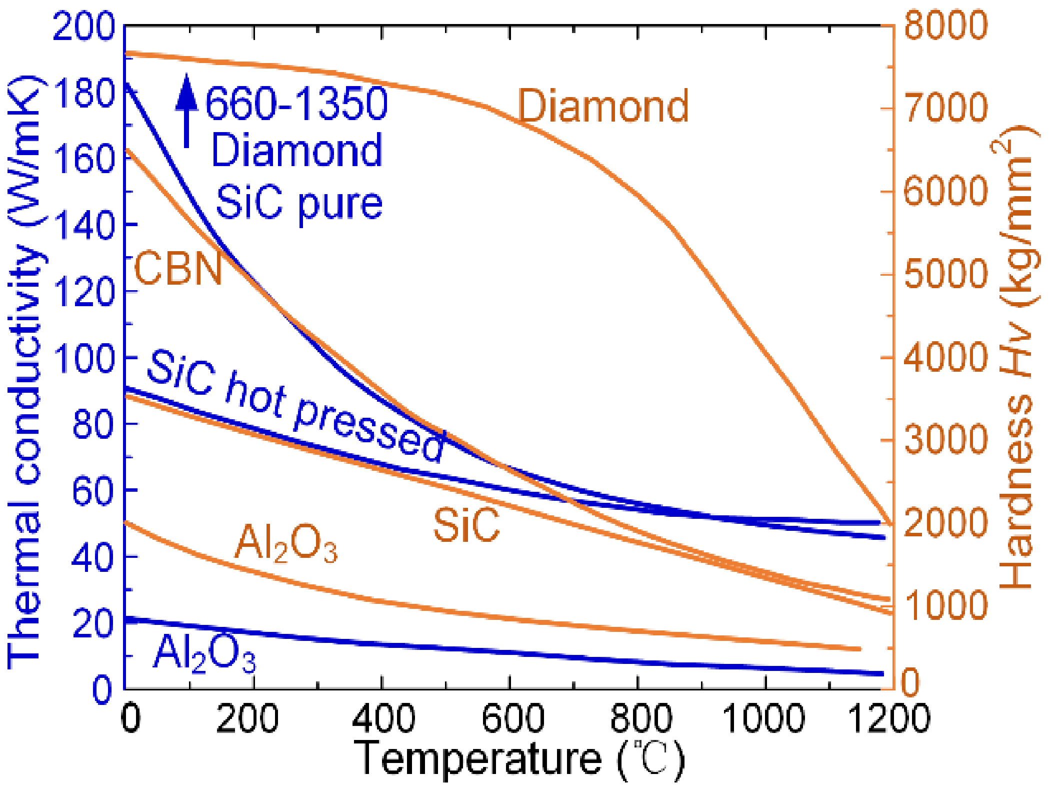


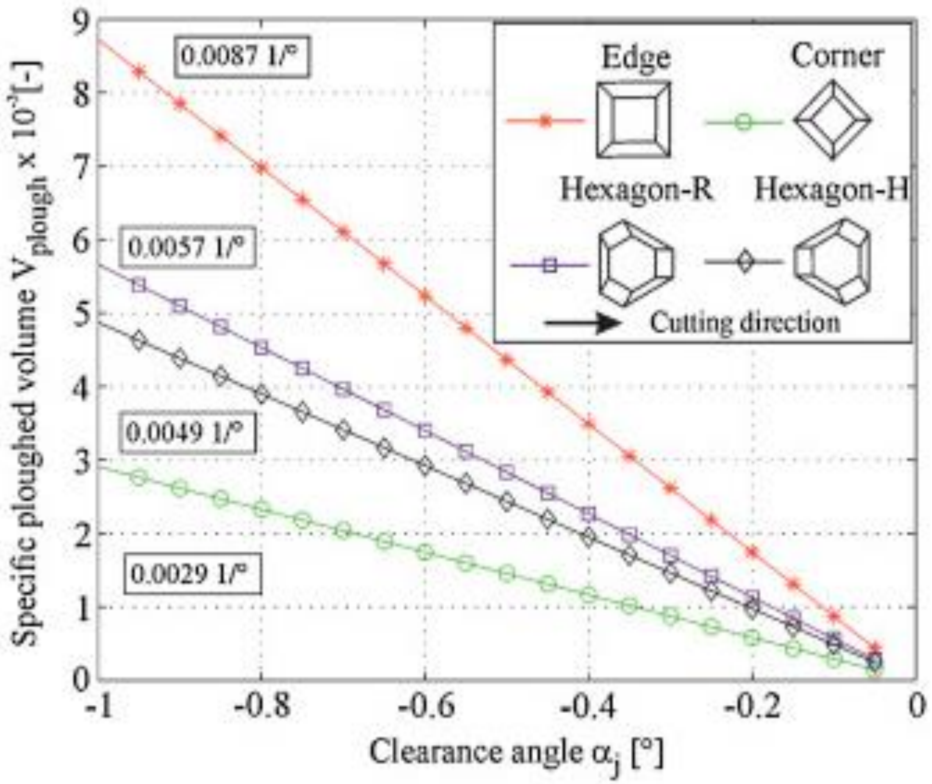
Process of multi-layer bond and sample cross-section (2018)

Basic Grinding Tool Technology: Abrasives Technology

The most basic aspects of abrasive behavior can be summarized as follows:

- Mechanical, thermal and chemical properties influence the selection for particular grinding operations. Thermal conductivity is a particularly crucial factor in high-performance applications.
- Geometrical properties also play a role, as small negative clearance angle causes specific cutting force increases due to material ploughing.



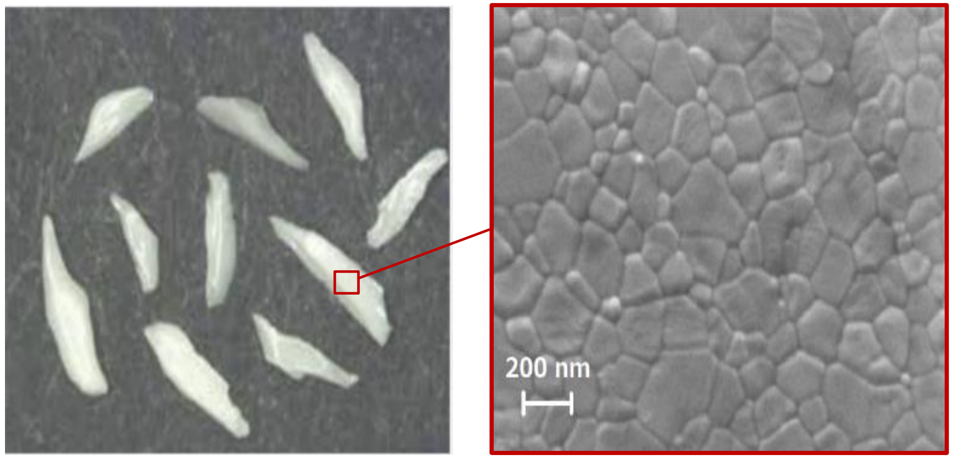


Basic Grinding Tool Technology: Abrasives Technology

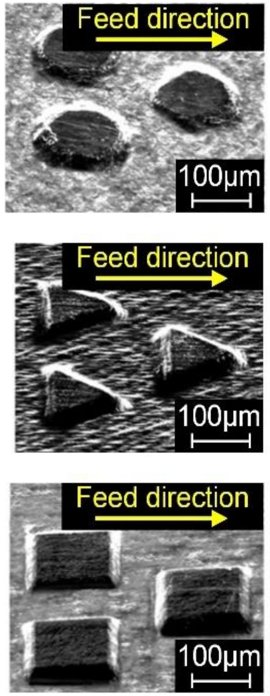
Recent advances in abrasive selection and shaping:

- A combination of sol-gel and explosive fragmentation process can produce **abrasive grains composed of uniformly distributed sub-micron crystals**, designed to fracture conchoically under stress.
  - ↳ Wear and friction coefficient are substantially reduced, so energy consumption can be greatly reduced.

- **Abrasives of controlled shape** and crystallographic orientation can be created by pulsed laser ablation on thick CVD diamond film.
  - ↳ Circular grits yield the highest cutting forces.



Micro structured abrasives (2019)



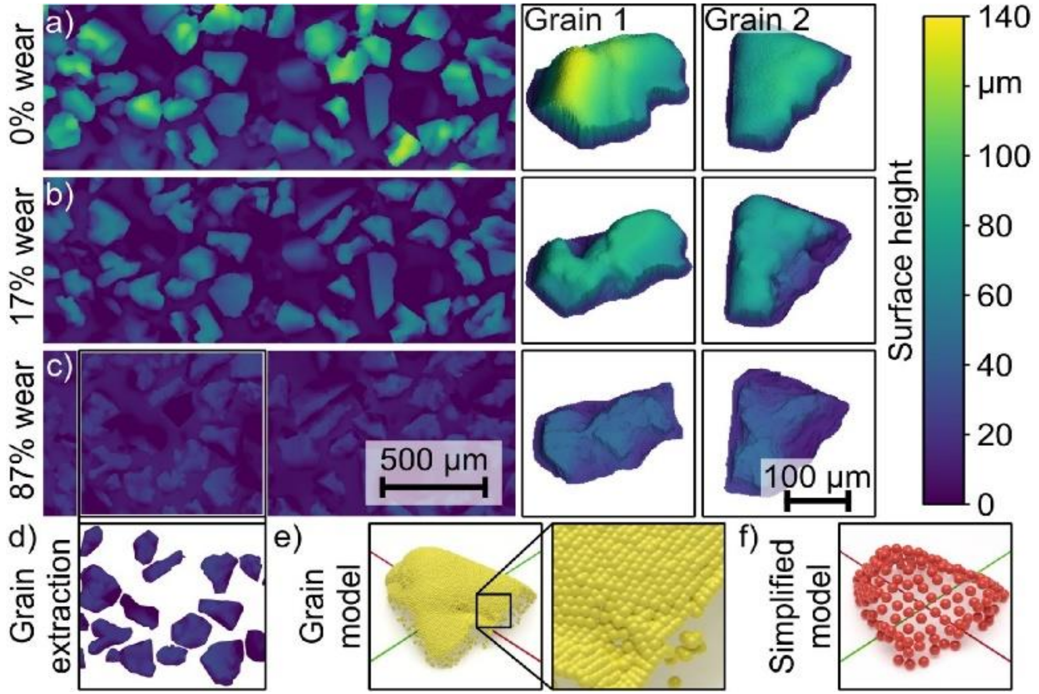
	Ductile (Cu)	Brittle homogen. (Al2O3)	Brittle heterogen. (SiC/SiC)
Circular	Benchmark	Benchmark	Benchmark
Triangle	31%	66%	45%
Square	50%	44%	42%

Force reduction as function of grit shape (2009)

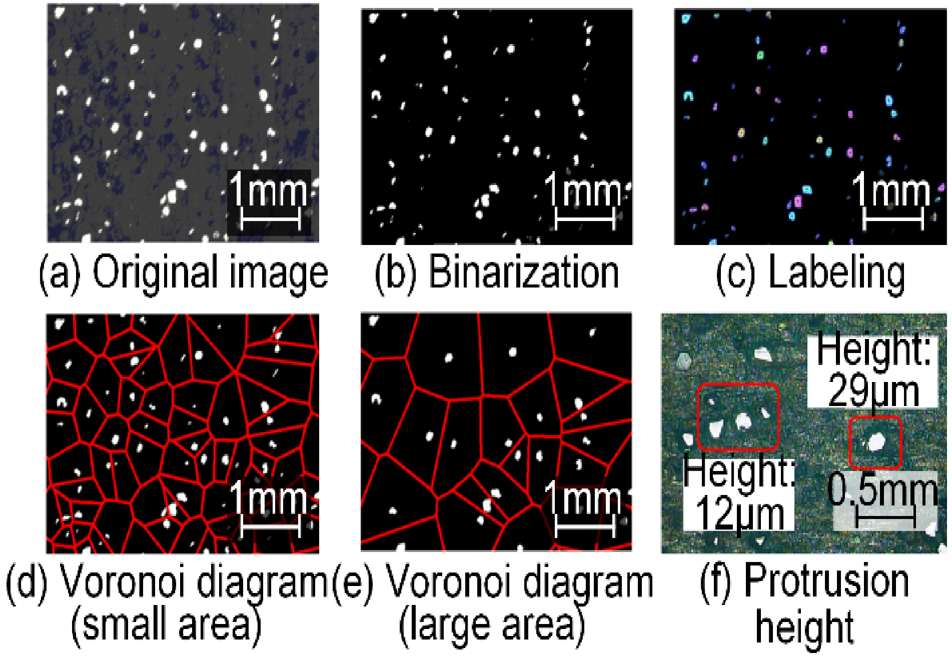
Basic Grinding Tool Technology: Abrasives Technology

Recent advances in characterization of abrasives condition on grinding wheels:

- Description of arbitrarily shaped grains based on point clouds can represent the grinding wheel wear evolution process (a database can be built by measuring the grain shape under different wear degrees).
- Using a line scan camera and Voronoi diagram, the random distribution of abrasive grains can be described. This allows extraction of cutting edge information, including centre of wear area and wear flat of the grains.



Point cloud representation of grinding wheel wear (2018)



Wheel surface topography analysis using line scan camera (2016)

Engineered and Hybrid Grinding Tools

Engineered
Patterned surfaces
Placed grits
Integrated coolant

Hybrid
EDM
Laser
Chemical

Engineered Grinding Tools: Integrated Coolant

- Grinding wheels with internal metal-working fluid supply aim to improve fluid supply for high contact lengths.
- The wheel is provided with channels that begin at centre and discharge the fluid at the bond circumference.
- However, the **high efforts required to manufacture such concepts** often do not pay off in terms of process improvement… so they hardly find their way into industrial applications.

Parts and assembly of grinding wheel with internal coolant supply channels optimized for hydrodynamic properties (2011)

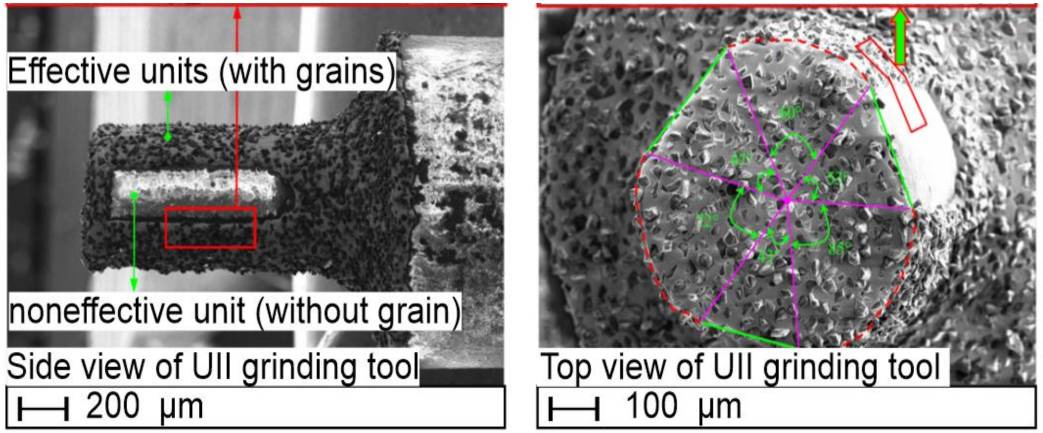
Engineered Grinding Tools: Wheel Patterning/Shaping

The 1st approach to wheel patterning/shaping is bond alteration:

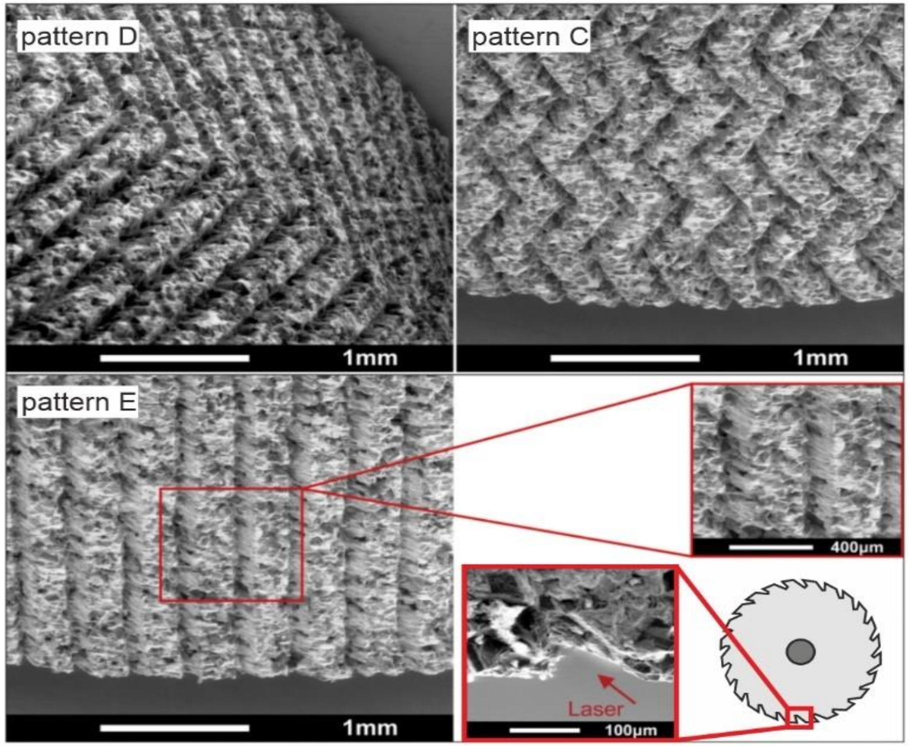
- Circular saws, abrasive blasting or special dressing methods can be employed to produce various patterns on the grinding wheel surface (especially precise machining can be achieved by laser ablation).
- Some **advantages** of patterned wheels**:**

  Higher heat transfer, lower forces/alteration of surface layer.
- Some **disadvantages:**

  More vibration, higher workpiece roughness, higher tool wear.



Non-cylindrical tool for interrupted micro-grinding (2019)

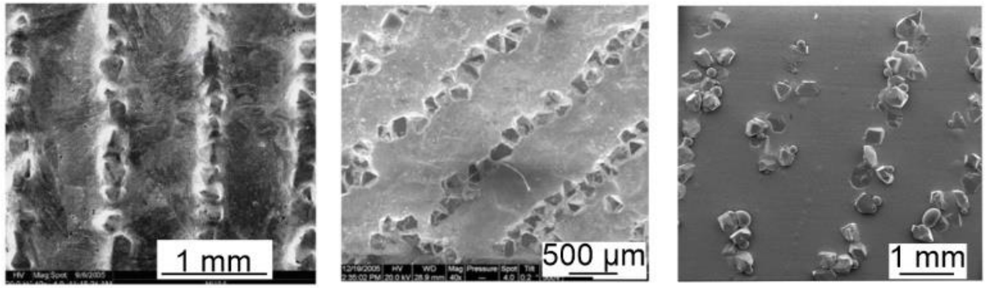


Examples of grinding wheels structured by laser (2014)

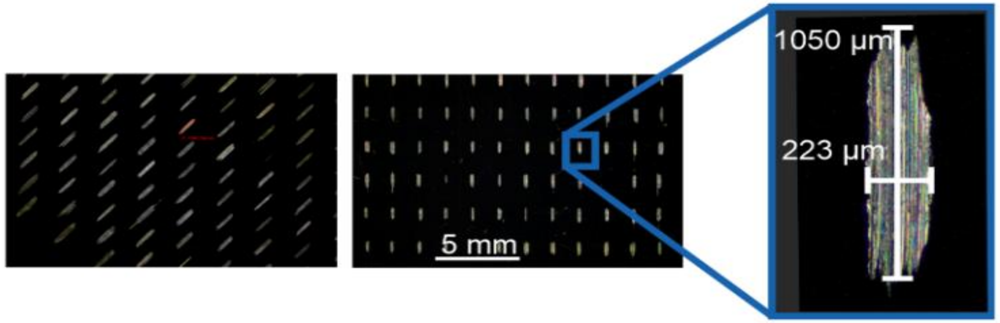
Engineered Grinding Tools: Wheel Patterning

The 2nd approach to wheel patterning is grit placement:

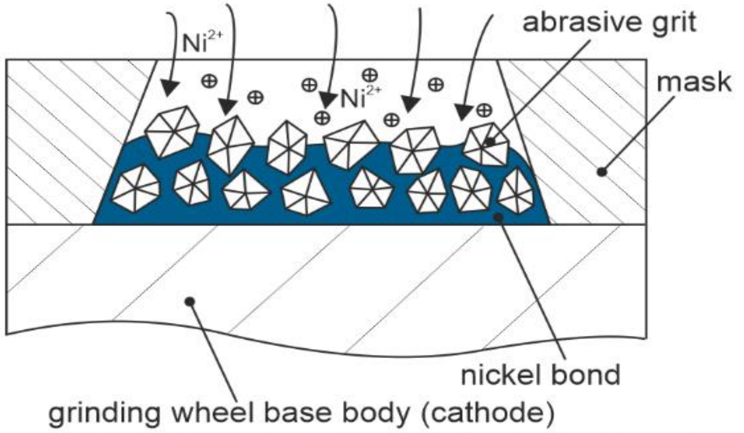
- Honeycomb patterns can be achieved by using **masks when electroplating grinding wheels**. The masks prevent grits from adhering to occluded area in the plating process.
- Automated devices can also **glue dots on the basic body** of grinding wheels. Grits are then spread on the basic body and adhere to the spots resulting in grit patterns matching the glue pattern.

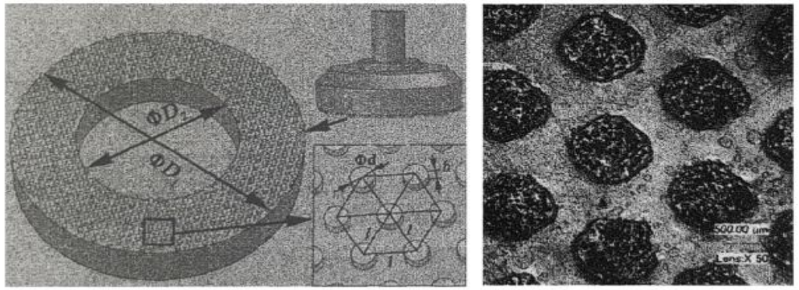


Grinding wheels with grits arranged in grit lines (2009, 2010, 2008)



Microstructures ground with defined grit pattern (2017)



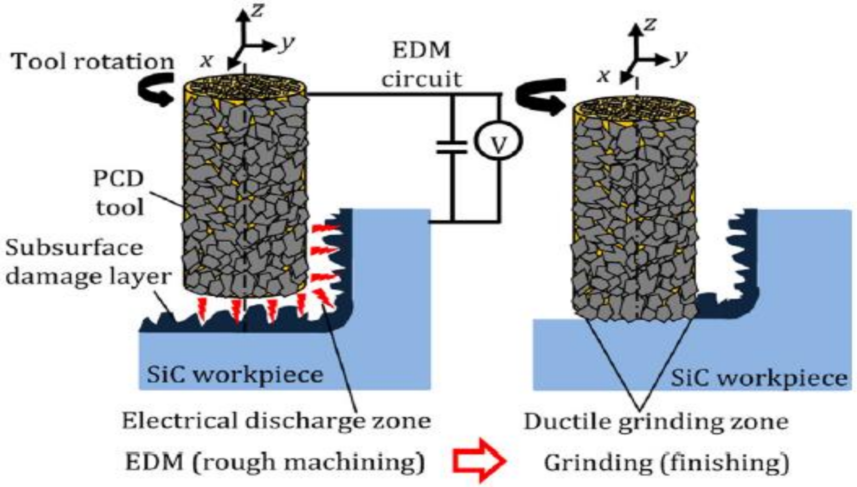


Principle of honey-comb layering technique (2010)

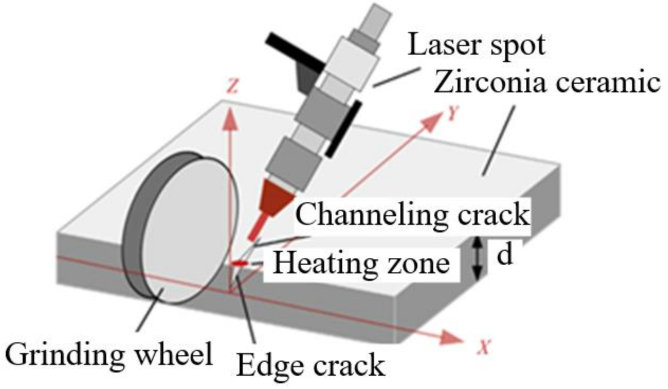
Hybrid Grinding Processes

- **Chemo-mechanical** tools are produced by mixing various abrasives (SiO_2, Fe_2O_3, MgO, TiO_2…) into the binder material (e.g. polyurethane), as they react differently with the workpiece substrate to promote material removal and prevent pad clogging.
- Although **electro-mechanical** machining has been well established for several decades, new applications keep appearing. Example: micro-machining of single crystal SiC (by decomposition into Si and C).
- T**hermo-mechanical** processes commonly use laser irradiation to improve grinding performance. Decreased grinding force comes from reduced scratch hardness of ceramics after laser irradiation. Laser irradiation can also induce lateral cracks which prevent further crack propagating into the base.

Chemo-mechanical wheel (2006)



Electro-mechanical process (2015)



Thermo-mechanical process (2020)

Smart Grinding Tools

Smart

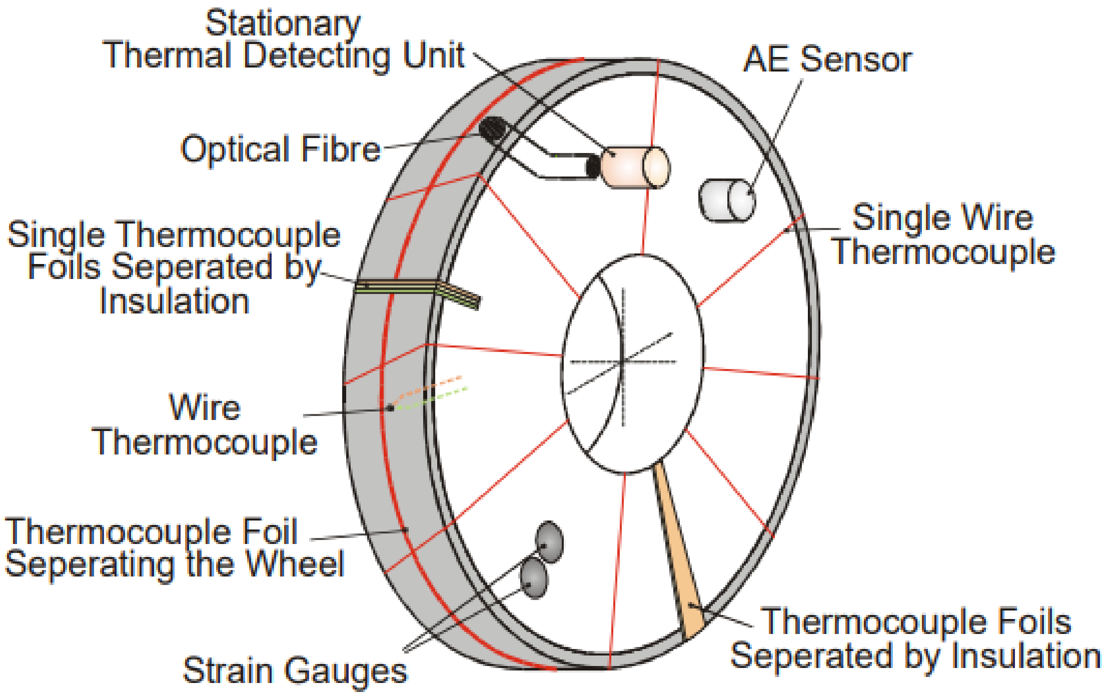
Digitization

Monitoring sensors
(temp., force, wear)

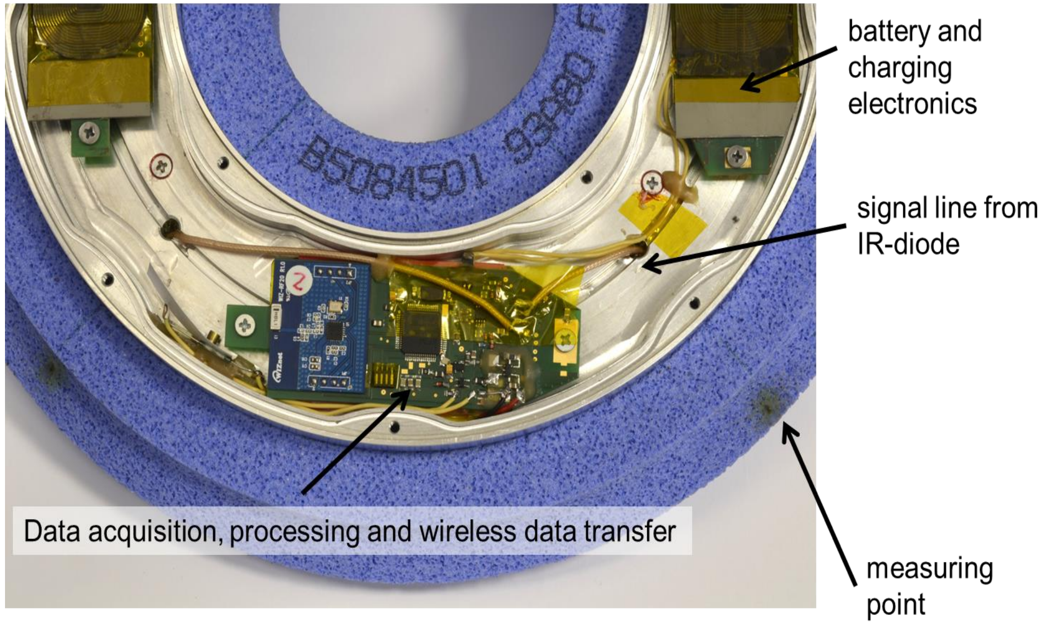
Smart Grinding Tools: Sensors and Telemetry

- The term “smart” is connected with attributes like: adaptive processes, self-learning machines, intelligent use of networks, the cross-link of things (IoT), etc.
- Advanced microcontrollers enable complete integration of the data acquisition and processing within the grinding wheel. Measuring sample rates up to 5 MHz have been demonstrated.

  ↳ The use of smart grinding tools can contribute to improving sustainability and saving resources!



Possible measuring techniques within grinding wheels (2000)



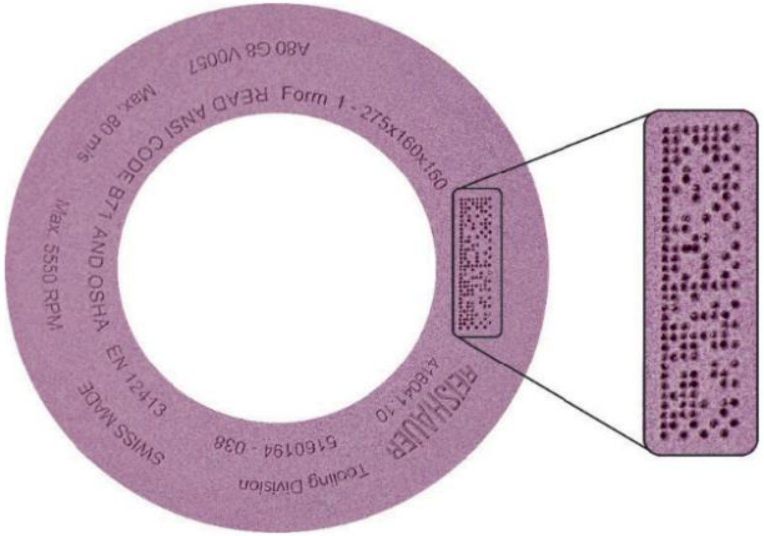
Integration of electronics for telemetry (2017)

Smart Grinding Tools: Digitization

Also options for exchanging data such as specifications or dimensions:

- **QR codes and RFID-Chips** can be adopted.
  - ↳ RFID-Chips have advantage that the information can be overwritten again and again!
- The use of tools with QR-Codes and RFID-Chips can result in significant advantages for the user in terms of process automation, tool management and work safety.
  - ↳ Example: Collisions due to incorrect geometry data or exceeding recommended speeds can be avoided.

Possible measuring techniques within grinding wheels (2000)



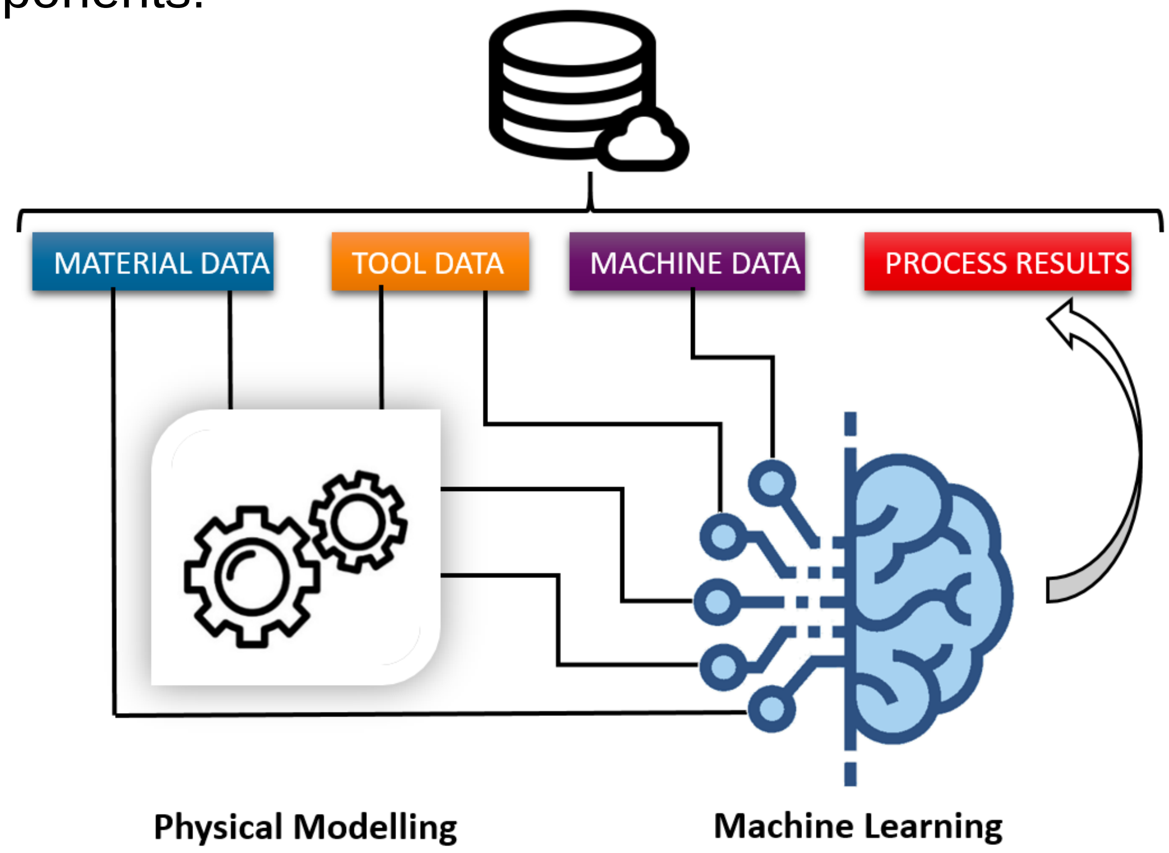
Integration of electronics for telemetry (2017)

Smart Grinding Tools: Machine Learning

"Smart grinding" also includes predicting and optimizing the outcome of machining trials.

Our approach at Kyoto University relies on 3 components:

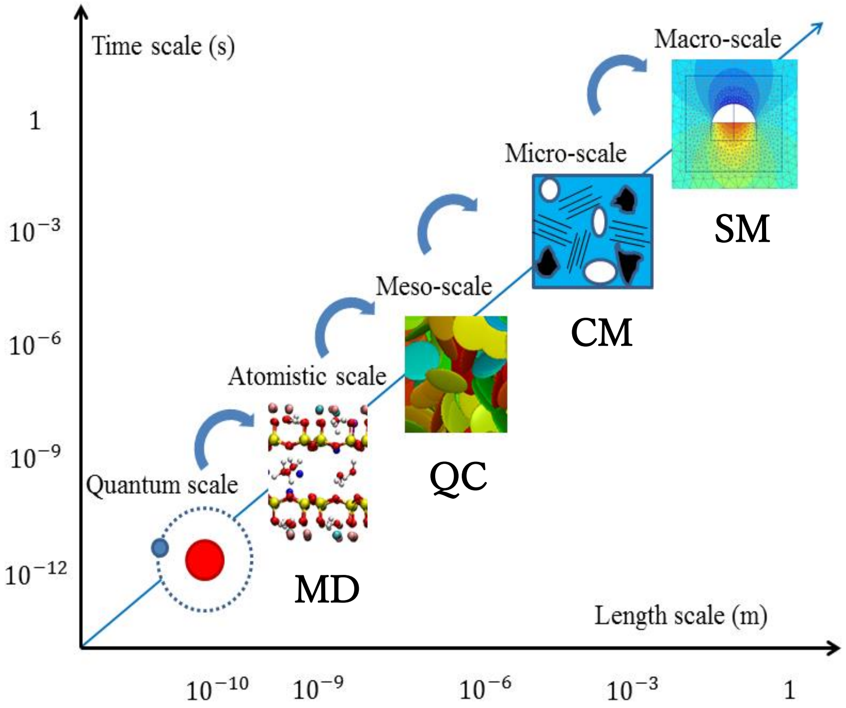
- Simplified physical modelling models that capture important phenomenon (brittle/ductile transition, size effect...)
- Organization and mining of historical process databases
- Couple the physical model and data with machine learning algorithms, for prediction of process results

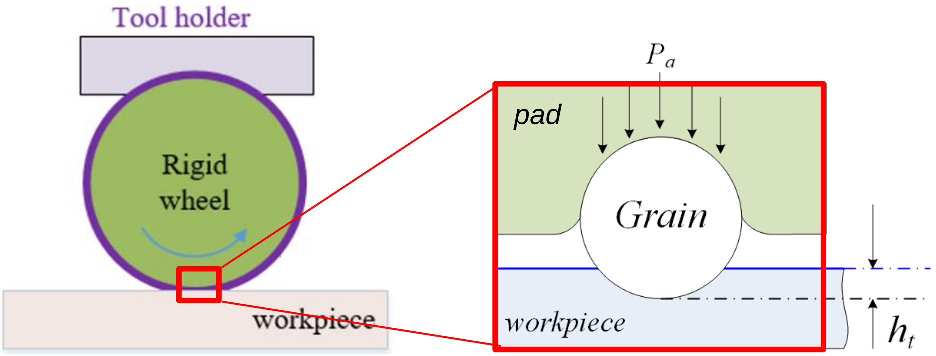


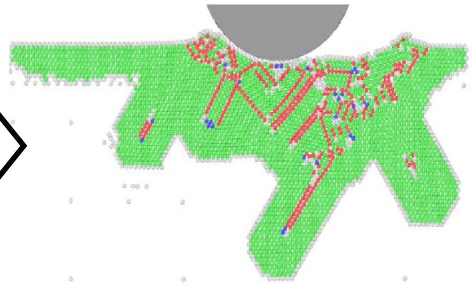
Smart Grinding Tools: Machine Learning

Extensive use of <u>multi-scale modelling</u> of machining processes, including:

- Molecular Dynamics (**MD**) for atomic level material response
- Quasi-Continuum (**QC**) for abrasive/workpiece interactions
- Continuum-Mechanics (**CM**) for tool/abrasive interactions
- Structural-Mechanics (**SM**) for tool/workpiece interactions



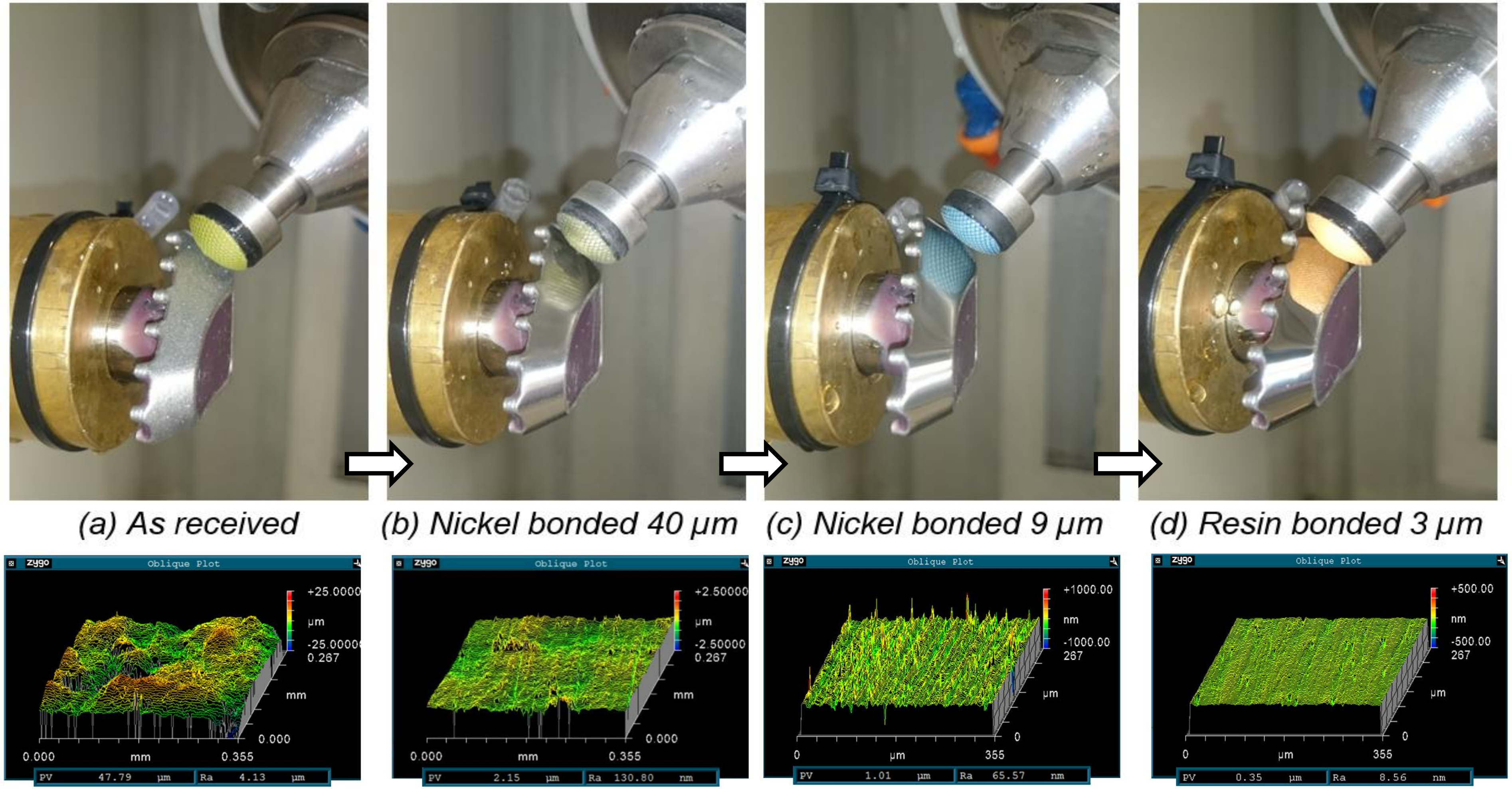




QC simulation of polishing on Nickel

Smart Grinding Tools: Machine Learning

The tool type selected for this research is our own “Shape Adaptive Grinding” process.



Roughness: **Ra 4130 nm** **Ra 130 nm** **Ra 65 nm** **Ra 8 nm**

Finishing of titanium alloy (Ti4Al6V) component produced by Selective Laser Sintering.

Smart Grinding Tools: Machine Learning

We recently organized "Human vs. Machine" parameter selection trials.

- Objective: achieve best possible productivity: $min(\frac{\partial Ra}{\partial t})$
- Human operators: myself and 2 technicians.

	Operator #1	Operator #2	Operator #3
Years of experience	15 years	6 years	2 years

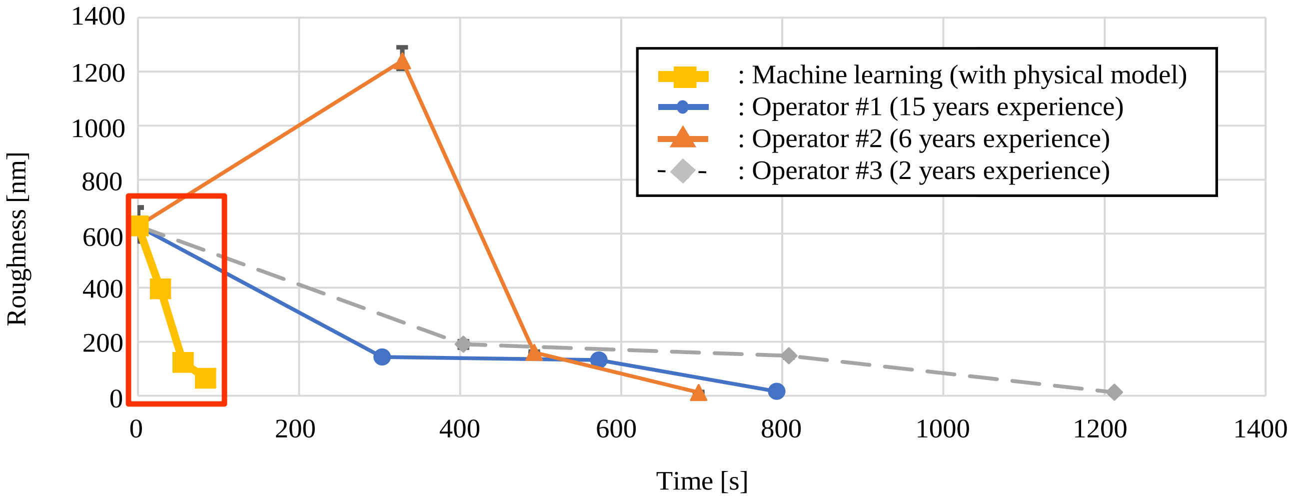
- Parameter selection: tool (7 types) and path parameters (9 entries).

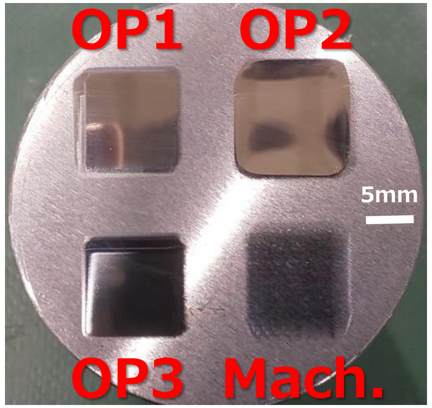
	Tool radius [mm]	Binder Material	Abrasives [µm]
a)	10	Resin	3
b)	10	Nickel	9
c)	10	Nickel	40
d)	10	Nickel	80
e)	5	Nickel	9
f)	5	Resin	9
g)	5	Resin	40

Path Parameters
Tool radius[mm]
Pellet material
Abrasive size[µm]
Tool offset[mm]
Attack angle[deg]
Spindle speed[rpm]
Surface feed[mm/min]
Track spacing[mm]
Number of passes

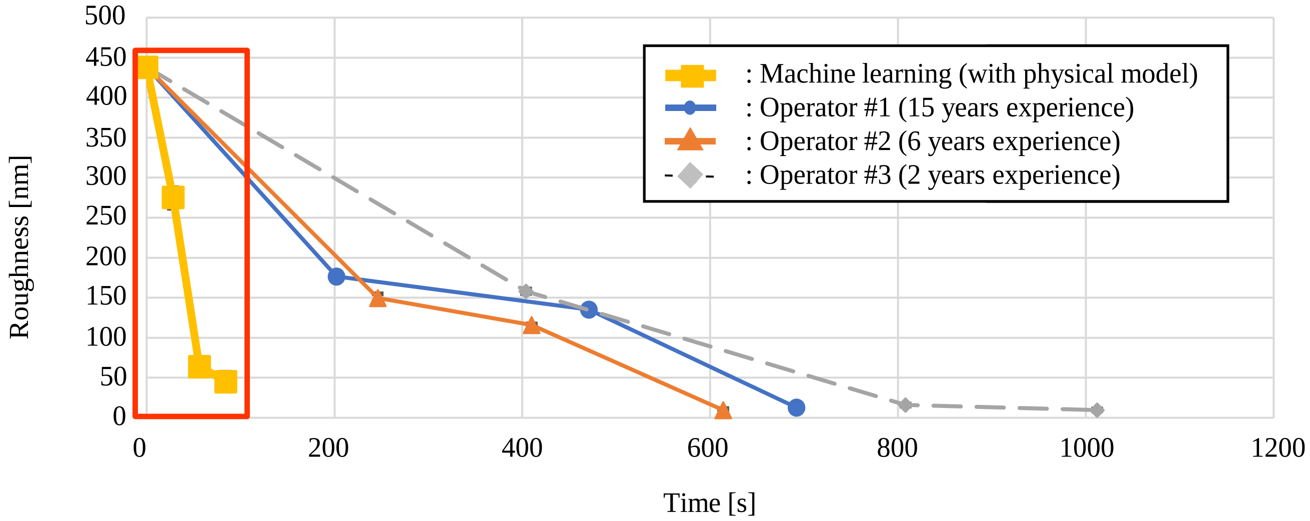
Smart Grinding Tools: Machine Learning

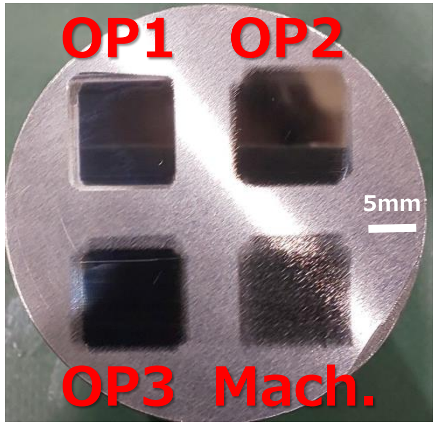
Though final roughness is not quite as good, the machine learning algorithm consistently “out-smarts” experienced machine operators in terms of productivity (including myself!)





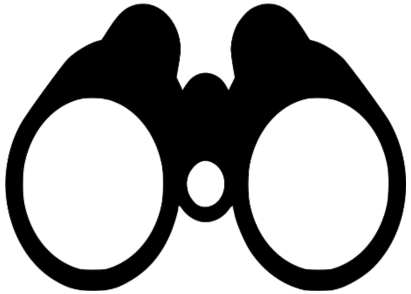
Inconel





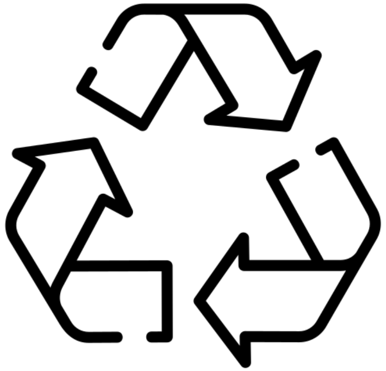
STAVAX

Outlook for the future



Future Applications

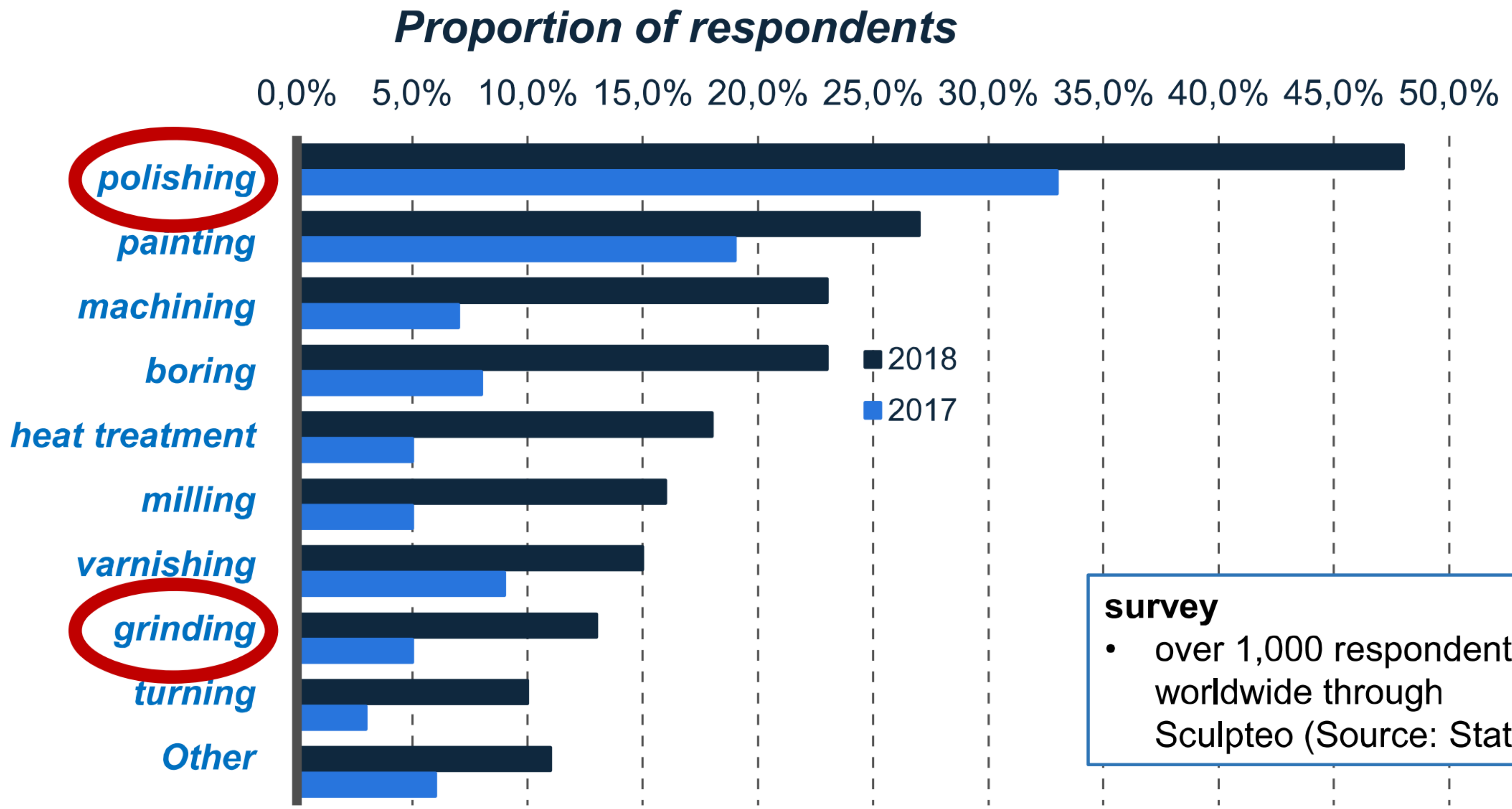
Sustainability



Recycling

Outlook: Prospects for Grinding/Polishing of AM Parts

the most used surface treatments after 3D printing

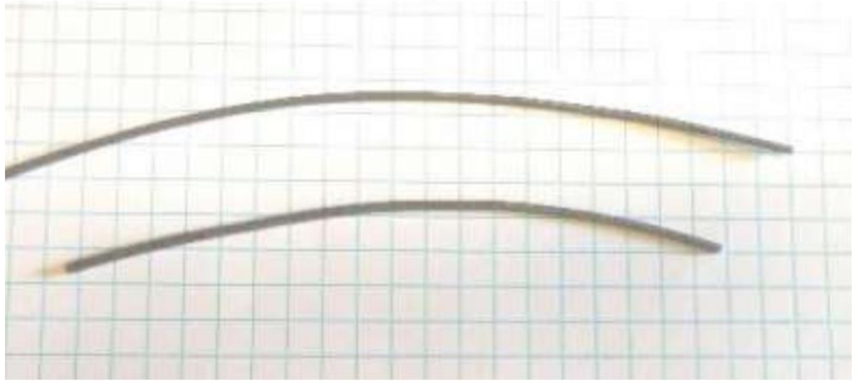


survey
- over 1,000 respondents worldwide through Sculpteo (Source: Statista)

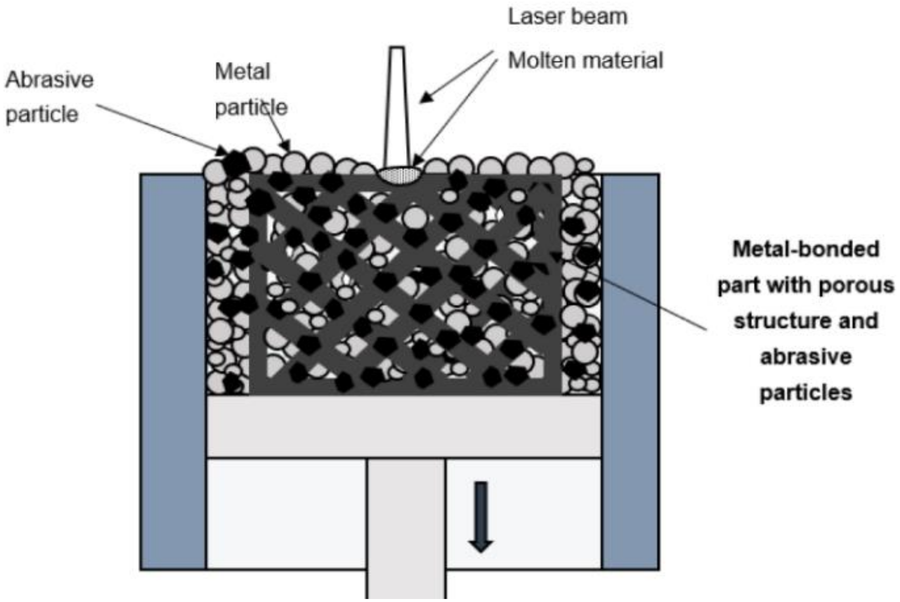
Outlook: Prospects for production of Grinding Tools by AM

Source: 3M

- Emerging industrial technology for 3D printing of vitrified bond wheels.
- Scope for complex internal structures with functional purpose.
- Indication of <u>higher removal rates</u> and <u>lower grinding force</u>



PLA filaments with SiC grits



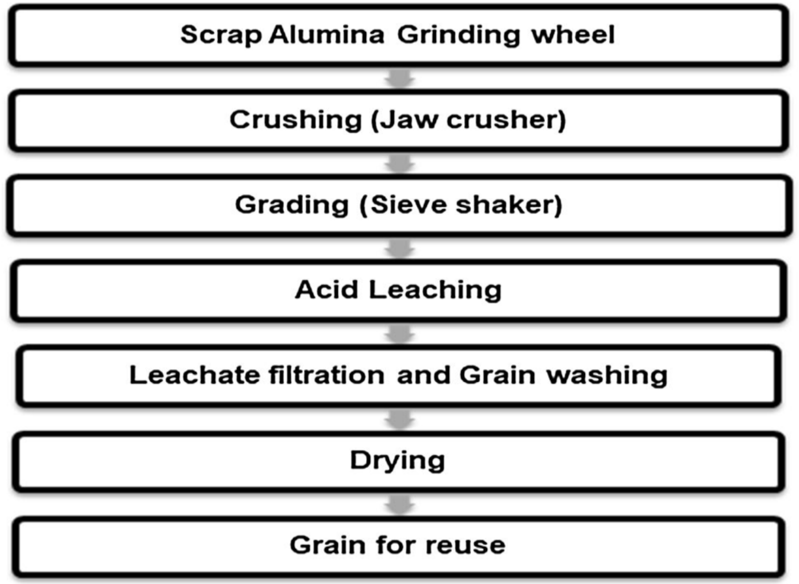
SLM fabrication of grinding wheel with high porosity (2021)

Outlook: Sustainability and Recycling

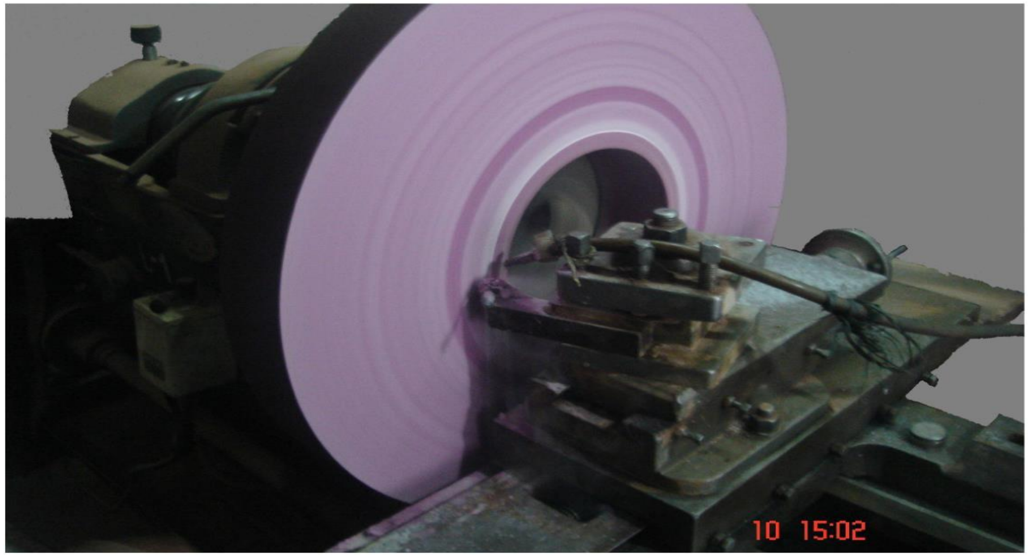
Spent grinding wheels have a high potential for recyclability:

- For conventional grinding wheels (without base body) **one-third of virgin grains** are usually not used and **can be recovered** by special techniques.
- Instead of being single use, **spent wheels can be reformed** for use in other applications.

  ↳ Example: Crankshaft grinding wheels have large diameters of more than 1000 mm. After use, they can be reformed for grinding cam shafts, axle shafts, differential housing… (diameter 600~750 mm)



Procedure to recover grains from spent grinding wheels (2018)



Setup for reforming spent crankshaft grinding wheels (2012)

Conclusions

- **New types of compliant tools** offer numerous advantages in terms of grinding forces, improved roughness, higher form accuracy, as well as increased tool life.
- Recent **advances in hot-pressing technology and pore-forming additives** are allowing controllable porosity of the binder. Binder materials are increasingly capable of shedding grit at a normalized rate thanks to the use of bond bridges that equalize stresses on the abrasives.
- Meanwhile, the use of **nano-dopants and multi-layering** is contributing to higher bending strength and chemical resilience of bonding materials.
- New capabilities in the abrasive sieving process are providing insights into the influence of abrasive shape (e.g. quasi-spherical, elongated, etc.) on the grinding mechanism. This combines with the **increasing availability of engineered abrasives**, with controllable inner micro-structure and carefully crafted shape.
- Various approaches including **laser ablation and abrasive blasting** can now be employed **to produce discontinuous grinding products** with a level of detail now reaching the microscopic scale.
- **Hybrid processes** are available in a wide variety of combinations, including **mechanical, chemical, electrical and thermal**. They can simultaneously improve material removal characteristics and surface integrity.
- A **trade-off** exists **between the extra energy spent producing engineered wheels and abrasives,** and the **energy recovered from superior performance** of both the tool in-process and the end-product.

THANK YOU

FOR LISTENING

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