Emerging Trends in Grinding of Materials

K. Philip Varghese, Ph.D.

Group Leader, Advanced Application Engineering
Agenda

• Introduction (Company and Presenter)
• Emerging Materials: What and Why?
• Grinding Processes to be covered
  • Surface grinding (γ-TiAl)
  • Creep-feed grinding (γ-TiAl, IN718)
  • Large Diameter Disk Slotting (IN718)
  • Face grinding (IN718)
  • Belt polishing (IN718)
  • Gear grinding from solid (8620, 4140)
• Abrasives technology to be covered (Bonded, Super Abrasives, and Coated products)
• Summary
• Questions/Discussions
Agenda

• Introduction *(Company and Presenter)*
Introduction - Saint-Gobain Abrasives

A portfolio of products that offer powerful, precise and user friendly abrasive solutions for every market and for every step of the abrasive process...

- Bonded abrasives
- Coated abrasives
- Thin wheels
- Superabrasives
- Construction Products

...Enabling our customers to shape and surface-finish all types of materials even in the most complex and challenging applications, from DIY home improvement to highly technical precision engineering.
Introduction - Saint-Gobain Abrasives

1. Northboro R&D Center
   - Polymer composites
   - Ceramic materials
   - Abrasives
   - Habitat

2. Saint-Gobain Recherche
   - Glass
   - Surfaces
   - Construction materials
   - Habitat

3. Chantereine R&D Center
   - Automotive glass
   - Building glass
   - Thin films
   - Acoustics and optics

4. Centre de recherches et d'études européen (CREE)
   - High temperature
   - Mineral material processing
   - Powder processing
   - Functional ceramics

5. Herzogenrath R&D Center
   - Flat Glass
   - Thin films
   - Complex glazing products

6. Saint-Gobain Research India
   - Abrasives and plastics
   - Building and automotive glass
   - Habitat solutions for hot-humid climates

7. Saint-Gobain Research Shanghai
   - Polymer materials
   - Abrasives
   - Powder processing
   - Optics and inspection

**About 300** patents filed by the Sector each year

**About 2/3** of the Group's R&D spending

2,100 researchers work for the Sector, with 2/3 in multi-business centers
Introduction - SGA Grinding Technology Centers (GTC)

Four Locations:

- Higgins Grinding Technology Center (HGTC) Northborough / Massachusetts/USA
- European Grinding Technology Center (EGTC) Norderstedt / Germany
- Saint Gobain Research India (SGRI) Chennai / India
- China Grinding Technology Center (CGTC) Shanghai / China
Introduction - Higgins Grinding Technology Center (HGTC)

Mission:

- To the advancement of grinding technology and abrasive products.
- To the development of grinding systems with maximum value to our customers.
Introduction – Speaker (Dr. K. Philip Varghese)

Education
2000  B.E. in Production Engineering
2003  M.S. in Mechanical Engineering
2008  Ph.D. in Mechanical Engineering

CR Foundation
2008 – 2011: Chief Scientific Officer

Saint-Gobain Abrasives/Norton
2011 – Current: Group Leader, Advanced Application Engineering
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• Introduction *(Company and Presenter)*
• Emerging Materials: *What and Why?*
Grinding Titanium Aluminides (γ-TiAl)

- **Low density**, titanium aluminides based on Ti₃Al and TiAl for applications in
  - advanced aerospace engine components (latter stages of the compressor or turbine sections), airframe components
  - automotive valves and turbochargers.
- The γ-TiAl phase apparently remains ordered upto its melting point of approximately 1450 °C (2640 °F).
- γ-TiAl can be **processed by conventional methods**, including casting, ingot metallurgy, and powder metallurgy.
- General Electric certified and implemented TiAl in the new GEnx-1B engine for the Boeing 787 Dreamliner that entered service in 2011.

Source: F.C. Campbell, Lightweight Materials – Understanding the Basics
Grinding Titanium Aluminides (*γ*-TiAl)

Traditional Grinding Solution

- Using Vitrified SiC wheels
  - High purity, very brittle, green silicon carbide abrasives, held using a dedicated vitrified bond
  - Lesser loading/capping than Alox wheels
  - High firability of SiC helps to lower threshold power/forces, allows cooler cutting (limit heat damage risk)

Challenges

- Loading of grinding wheels
- Parts susceptible to burn
- Parts susceptible to cracking
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Surface Grinding $\gamma$-TiAl with SiC wheels

**Wheel List**
- SiC - E24
- SiC - G12
- SiC - G24
- SiC - I8
- SiC - I10
- SiC - L8

- Wheel travels left to right (climb/downcut)
- Grinds performed in sets of 3, part inspected between sets

2” grind length
## Test Conditions & Measurements

<table>
<thead>
<tr>
<th>Machine</th>
<th>Elb Brilliant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode: Slot Grinding</td>
<td></td>
</tr>
<tr>
<td>Coolant: WS</td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>48-2-2 γ TiAl</td>
</tr>
<tr>
<td>Operational Parameters</td>
<td>DOC: 0.006, .012, 0.018 in</td>
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<tr>
<td>Table Speed: 50 to 200 ipm</td>
<td></td>
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<tr>
<td>Vs: 30 m/s</td>
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<td>Grind Length: 2 in</td>
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<tr>
<td># passes per slot: up to 18</td>
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<tr>
<td>Outputs/Measurement</td>
<td>Power, forces</td>
</tr>
<tr>
<td>Corner radius (graphite coupons)</td>
<td></td>
</tr>
<tr>
<td>Surface roughness (Ra, Rz, Wt)</td>
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<tr>
<td>Dressing Conditions</td>
<td>BPR Diamond Roll</td>
</tr>
<tr>
<td>Dress Comp: 10 uin/rev</td>
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<tr>
<td>Plunge Rate: 0.0005&quot; DOC for 20 passes</td>
<td></td>
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<tr>
<td>Speed Ratio: +0.8</td>
<td></td>
</tr>
</tbody>
</table>

### Workpiece schematic

![Workpiece schematic diagram]

\[
h_c = \left(\frac{V_w}{V_z}\right)\left(\frac{DOC}{D_z}\right)^{\frac{1}{2}} \frac{1}{kC}\right)^{\frac{1}{2}}
\]

BECAUSE RIGHT CHOICES MATTER™
Results: Power, Force vs. Time Behavior

- Power & forces climb rapidly after dressing as function of pass #
- Wheel faces & bulk porosity observed to be free of significant loading
- Metal adhesion / capping observed on grain tips
Results: Effect of operational parameters on damage

- At constant $MRR'$, material damage is avoided at low DOC, high table speeds.

**Material Damage Comparison**

$Q' = 0.60 \text{ in}^3/\text{min-in}$

Note: No damage observed but test stopped after 0.108 in$^3$ of material removal.

<table>
<thead>
<tr>
<th>Table Speed [in/min]</th>
<th>DOC [in]</th>
<th>Material removed before observed damage [in$^3$]</th>
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<tr>
<td>600</td>
<td>0.001</td>
<td>0.12</td>
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<tr>
<td>100</td>
<td>0.006</td>
<td>0.10</td>
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<tr>
<td>50</td>
<td>0.012</td>
<td>0.08</td>
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<tr>
<td>8</td>
<td>0.075</td>
<td>0.06</td>
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</table>

Immediate damage observed.
Surface Grinding γ-TiAl with Superabrasives

Superabrasive Wheel List

- EP 60/80# Diamond
- EP 100/120# Diamond
- EP 60/80# cBN
- EP 100/120# cBN

- Wheel travels left to right (climb/downcut)
- Grinds performed in sets of 1, part inspected after each grind

2” grind length
cBN grains resulted in increasing power (and force) as a function of grind #, whereas diamond was observed to be more stable over time.

Same trend was observed at two grits sizes (60/80 & 100/120)
Results: Power, Force vs. Time Behavior

- Diamond wheels displayed lower power & specific energy compared to cBN wheels at both grit sizes (60/80 & 100/120)

- Very low threshold power observed (grit/work interaction is dominant)
  - Effect of grit size on power/threshold power also observed
Rapid power increase as a f(pass #) for cBN and L-grade SiC wheels

G-grade SiC wheels resulted in high wheel wear, but no material damage was observed

EP Diamond wheel removed significantly more material compared to the SiC and cBN wheels

Low power increase observed in diamond wheel as a f(pass) relative to SiC and cBN wheels
Surface grinding $\gamma$-TiAl with New Paradigm wheel

Advantages of Norton Paradigm

- Easy to Profile
  - Can be profiled on the machine using Diamond rolls in both traverse and plunge dress modes:
- Up to 42% of natural porosity achievable creating a topography that lends itself to “free” cutting states.
- 100% Metal bond best suited for “pulling” heat from Heat sensitive materials

![Image of Diamond grains]
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  • Creep-feed grinding *(γ-TiAl, IN718)*
Creepfeed Grinding $\gamma$-TiAl with SiC wheels

- Wheel travels left to right (climb/downcut)
- Grinds performed in sets of 1, part inspected after each grind

<table>
<thead>
<tr>
<th>Creepfeed Wheels</th>
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<tr>
<td>SiC – G24</td>
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<tr>
<td>SiC – E24</td>
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</table>

5” grind length
## Test Parameters & Measurements

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<tr>
<td>Mode:</td>
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<td>Coolant:</td>
<td>WS</td>
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<td><strong>Material</strong></td>
<td>48-2-2 γ TiAl</td>
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<td><strong>Operational Parameters</strong></td>
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<td>Vs:</td>
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<td>Grind Length:</td>
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<td># passes per slot:</td>
<td>up to 2</td>
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<td><strong>Outputs/Measurement</strong></td>
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<td>Power, forces:</td>
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<td>Corner radius (graphite coupons):</td>
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<td>Surface roughness (Ra, Rz, Wt):</td>
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<td><strong>Dressing Conditions</strong></td>
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<tr>
<td>Speed Ratio:</td>
<td>+0.8</td>
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</table>

[Workpiece schematic]

[Wheel (Top View)]

[Top View]

[Sectioned View]
Results: NCD Creepfeed Testing

No wheel breakdown or part damage was observed in two passes at lower MRR’s:

- Wheel breakdown observed during second pass at 0.9 in³ / min.in
- Correlated with mild burn in the parts
Results: NCD Creepfeed Testing

- G-grade wheel showed improved corner holding and higher G-ratio relative to E-grade wheel at same MRR'.
  - Dressing implications for damage vs form.
Creepfeed grinding $\gamma$-TiAl with New SiC wheel

- No clear advantage or disadvantage in power compared to standard wheels
- New SiC wheels had lower power & threshold power
- New SiC wheels were able to reach higher MRR'
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  • Large Diameter Disk Slotting *(IN718)*
Large Diameter Disk Slotting

Step 1.
Slotting

Step 2.
Rough Profiling

Step 3.
Finish Profiling

Wheels

Quills

Ground Component
Creep Feed Slotting (IN-718)

- **Wheels Tested**
  - TG280-F20 VTX2
  - 5NQX46-H16 VTX2

- \( V_s = 8,500 \) sfpm

- **Material**
  - IN-718
  - Two 1” thick plates stacked

- **Depth of cut**
  - 0.100 DOC

- **Coolant**
  - Oil
  - 200 psi
  - Scrubber nozzles 1,000psi
  - Bottom extinguishing nozzle 7 gpm
Product Technology & Terminology

**TGII Extruded Grain**
- Shape Long Thin Grain 8:1 Aspect ratio
  - Very low Loose Pack Density
  - High Force Necessary to Initiate Cutting
- Good Hardness and wear resistance
- Micro Fractures to Keep Grain Sharp

**NQ Grain**
- Shape Sharp Edges aspect ratio ~ 1:1
  - Average Loose Pack Density
  - Low Force Necessary to Initiate Cutting
- Good Hardness and wear resistance
- Micro Fractures to Keep Grain Sharp

Source: US Army Handbook
Product Technology & Terminology

- Low Loose Pack Density with Agglomerated Fused Secondary Grain – Vortex 2
- High Adhesive Strength – Vitrium
- Low Bond % Volume – Vitrium
Creep Feed Slotting (IN-718)

- **Removal Rates**
  - TG280-F20 VTX2
    - 2.0 – 18.0 in³/min/in
  - 5NQX46-H16 VTX2
    - 1.0 – 7.0 in³/min/in

- Slot Depth 0.5”

- 4 Slots per Condition to get wheel wear

- 4 Slots per Dress
Creep Feed Slotting (IN-718)

- **5NQX**
  - $V_w = 70$ ipm
  - $Q' = 7$ in³/min/in

- **TG280**
  - $V_w = 180$ ipm
  - $Q' = 18$ in³/min/in

More Recent test in Waspaloy with TG2 wheel at 7 in³/min/in yielded a G-Ratio of ~ 19
Creep Feed Slotting (IN-718)

- Comparison with Slotting using ½” carbide end mills at recommended feeds and speeds
- Grinding with 5NQX46 and TG280 wheel

<table>
<thead>
<tr>
<th>Tool</th>
<th>DOC</th>
<th>Dia</th>
<th>SFPM</th>
<th>rpm</th>
<th>IPT</th>
<th>Teeth</th>
<th>ipm</th>
<th>in³/min</th>
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<td>0.5</td>
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<td>4.6</td>
<td>1.15</td>
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<td>1238</td>
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<td>6.1</td>
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<table>
<thead>
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<th>width</th>
<th>ipm</th>
<th>in³/min</th>
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<td>0.5</td>
<td>70</td>
<td>3.50</td>
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<tr>
<td>TG280</td>
<td>0.1</td>
<td>0.5</td>
<td>180</td>
<td>9.00</td>
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</table>

Milling — Carbide Endmill

Grinding
Agenda

• Introduction *(Company and Presenter)*
• Emerging Materials: *What and Why?*
Grinding PM Ni Based Superalloys (Rene 95, Astroloy, IN-100, N-18 etc.)

• **Application HPT/LPT disks**
  - 200-300°C range in the bore and up to 650°C in the rim
  - Rotational speed > 10,000 rpm (Mech. Stress > 1000 MPa in the bore for take-off)
  - Oxidizing/corrosive environment.

• **PM Alloys vs. Cast Alloys**
  - Grain size is smaller (< 7 microns)
  - Contains higher alloy content
  - Uniform structure, homogeneous distribution of phases
  - Low thermal conductivity
  - Work hardening is severe
  - Adhesion to tool surface

• **Advanced PM Ni-Based Super Alloys**
  - New engine development programmes pushing the use of newer advanced PM Ni based alloys
  - Drivers:
    • capability of significant grain size evolutions
    • metallurgical stability for long term exposures up to 750°C
    • higher creep and fatigue resistance
    • and a density lower than 8.35 g/cm³.
  - Machining solutions becoming closer to being impractical
    • Up-to 30% reductions in cutting speeds from 3rd generation (40 m/min – 28 m/min)
    • Low productivity not being able to meet existing and future demands
Grinding PM Ni Based Superalloys (Rene 95, Astroloy, IN-100, N-18 etc.)

Productivity issues while machining new PM Ni Base Superalloys

- Reduction in cutting conditions
- Surface Condition effect on Fatigue Strength – White layer

Turning ME16, 30 m/min, 0.1225 mm/rev, 0.125 mm (source: Veldhuis et. al., 2009)

White Layer @ 30 m/min: 2-4 microns
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  • Face grinding (IN718)
Large-diameter Disk Grinding (IN718)

- **Machine: Campbell 930**
  - 3 linear axes and two rotary axes
  - B axis Positioning only
  - spindle mounted on the B-axis
  - 40 Hp Spindle

- **Material: IN 718**
  - ~ 15” Diameter
  - ~ 0.3” stock removal
Large-diameter Disk Grinding (IN718)

Side 1 — First Plunge outside 35° Surface, Second Plunge Inside 35° Surface

Wheel = TGX
- $Q' = 3.97 \text{ in}^3/\text{min/in}$
- Oil Coolant
- Specific Energy = 4.8 Hp/in$^3$/min
Large-diameter Disk Grinding (IN718)

Inside, Outside 35° & Bottom Surfaces Roughed

Inside, Outside 35° & Bottom Surfaces Finished

Ra = 33.5 µin
Rz = 253 µin
Large-diameter Disk Grinding (IN718)

Wheel = TGX
- \( Q' = 3.97 \text{ in}^3/\text{min/in} \)
- Oil Coolant
- Specific Energy = 4.8 Hp/in\(^3\)/min
Large-diameter Disk Grinding (IN718)

Outside & 45° Surfaces Roughed

Outside & 45° Surfaces Finished

Ra = 39.5 µin
Rz = 236 µin
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  • Face grinding *(IN718)*
  • Belt polishing *(IN718)*
Robotic Abrasive Applications

Abrasive media:

- **Coated abrasives**, such as belts, discs, flap wheels, and specialty shapes
- **Nonwoven abrasives**, such as wheels, belts and discs
- **Abrasive brushes**, such as radial wheels and cup wheels

Source: R. McNamee, The Fabricator, 2014
Robotic Abrasive Applications

Essentials for Robotic deburring/polishing

• Controlled pattern of the engineered structure allows for a consistent cut rate as well as surface finish.

• Compliant fixturing or tooling refers to the ability to control the amount of force between the workpiece and the tool.

• Conformability refers to the ability of the abrasive to match, or reach, the various contours and intricacies of the workpiece.
Target Application

Polishing the airfoil surfaces of turbine engine blades or blisks

- The blades and the rotor are machined/ground from solid piece of Ni-based superalloy or titanium
- Various stages have different sized blades with some less than 1"
- Finish requirement = 5-10 µ-in
- Challenges
  - Tooling geometric constraints
  - Life of tooling due to size restrictions
  - Tight tolerances
  - Long process time

Fixed Abrasive Polishing

• Twin Challenges
  – part geometry and precise robotic programming to ensure maneuverability and access to all areas of interest on the part becomes critical
  – to avoid over-cutting or excess stock removal than what is desired to achieve the finish and cosmetic specifications on a component
Test Methodology

Machine: Dynabrade Benchtop Sander

Work Material: IN 718 (20 µ-in Ra)

Concave Surface Polishing

Convex Surface Polishing
Product Technology: Norax Engineered Abrasives

Features

• Multi-layer of erodeable structured abrasive grain

• As the belt wears, dull abrasive particles are lifted out of the belt and a new layer of sharp abrasive is exposed to the work surface

• The continuous replacement of dulled abrasive particles can result in longer belt life, higher cut rates, and a more consistent surface finish.

• A surface powder grinding aid is incorporated into this line of belts to increase initial belt aggressiveness and decrease grinding temperature.
Product Technology: Norax Engineered Abrasives

- Patterns and performance differences

Characteristics:

- QUAD:
  - For high pressure applications
  - Good wear resistance
  - Uniform cut rate

- TRI-HELICAL:
  - For medium pressure applications
  - Multi-purpose
  - Very consistent cut rate

- FINE TRI-HELICAL:
  - All purpose
  - Very flexible
  - Consistent cut rate

- PYRAMID:
  - For low pressure applications
  - Fast cut rate
  - Good self-sharpening properties
Test Details

• The work pieces were weighed before and after each grind.
• The contact time recorded, allowed for the stock removal rates to be calculated.
• Knowing the amount of material removed allowed for an approximate depth of cut calculation, using the contact area and the material density.
• The surface finishes were recorded before and after polishing using a profilometer and a profile scan.

Grinding Sequence for 10 piece run:
• X22 U264
• X16 U264
• X5 U254
Estimated Stock Removal (depth)

Calculated Stock Removal (depth) vs. Belt Specification

<table>
<thead>
<tr>
<th>Belt</th>
<th>Concave Side</th>
<th>Convex Side</th>
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</thead>
<tbody>
<tr>
<td>X22-U264</td>
<td>0.0004</td>
<td>0.0004</td>
</tr>
<tr>
<td>X16-U264</td>
<td>0.0002</td>
<td>0.0001</td>
</tr>
<tr>
<td>X5-U254</td>
<td>0.0004</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

10 piece Grinding Test Data
Surface Finish Ra

Average Surface Finish for Each Condition
Ra μin - Convex Surface

Pre-grind Surface: 18
X22/X16 U264: 7
X30/X22/X16 U264: 6
X22/X16 U264/X5 U254: 4

Legend:
- Convex - Perpendicular to grind
- Convex - Parallel to grind
Surface Finish Rz

Average Surface Finish for Each Condition
Rz \( \mu \text{m} \) - Convex Surface

<table>
<thead>
<tr>
<th>Condition</th>
<th>Convex - Perpendicular to grind</th>
<th>Convex - Parallel to grind</th>
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<tbody>
<tr>
<td>Pre-grind Surface</td>
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<td>112.6</td>
</tr>
<tr>
<td>X22/X16 U264</td>
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<tr>
<td>X22/X16 U264 /X5 U254</td>
<td>28</td>
<td>20.4</td>
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</table>
Surface Finish Ra

Grinding Sequence:
- X22 U264
- X16 U264
- X5  U254

- Each red dot is a Ra measurement taken from the workpieces ground in the 10 piece run
- 3 measurements taken for each piece in the perpendicular direction
- 1 measurement taken from each piece in the parallel direction
#35 Convex Polished

**Area Parameters**

- $S_a$: 0.29 µm
- $S_q$: 0.37 µm
- $S_z$: 2.52 µm
- $S_p$: 1.36 µm
- $S_v$: 1.19 µm
- $S_t$: 2.55 µm

**Extracted 2D Profile Parameters**

### Amplitude parameters - Roughness profile

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Std dev</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_p$</td>
<td>0.40</td>
<td>0.05</td>
<td>0.29</td>
<td>0.55</td>
</tr>
<tr>
<td>$R_v$</td>
<td>0.37</td>
<td>0.05</td>
<td>0.28</td>
<td>0.49</td>
</tr>
<tr>
<td>$R_z$</td>
<td>0.77</td>
<td>0.08</td>
<td>0.60</td>
<td>1.01</td>
</tr>
<tr>
<td>$R_a$</td>
<td>0.13</td>
<td>0.02</td>
<td>0.10</td>
<td>0.18</td>
</tr>
<tr>
<td>$R_q$</td>
<td>0.17</td>
<td>0.02</td>
<td>0.13</td>
<td>0.22</td>
</tr>
</tbody>
</table>

### Amplitude parameters - Waviness profile

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Std dev</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_p$</td>
<td>0.49</td>
<td>0.15</td>
<td>0.20</td>
<td>0.97</td>
</tr>
<tr>
<td>$W_v$</td>
<td>0.45</td>
<td>0.12</td>
<td>0.19</td>
<td>0.76</td>
</tr>
<tr>
<td>$W_z$</td>
<td>0.93</td>
<td>0.23</td>
<td>0.39</td>
<td>1.49</td>
</tr>
<tr>
<td>$W_a$</td>
<td>0.19</td>
<td>0.06</td>
<td>0.08</td>
<td>0.34</td>
</tr>
<tr>
<td>$W_q$</td>
<td>0.23</td>
<td>0.06</td>
<td>0.10</td>
<td>0.38</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Part #</th>
<th>Measured Surface</th>
<th>$R_a$ (uin) high</th>
<th>$R_a$ (uin) low</th>
<th>$R_a$ (uin) mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>Convex polished</td>
<td>7.1</td>
<td>3.9</td>
<td>5.1</td>
</tr>
</tbody>
</table>

**Representative 2D Profile**
Part Before and After Grind

Rough Finish

X5 U254 (Part #41)
Lay Direction On Ground Parts

• In loose abrasive applications, such as chemical vibratory polishing or extrude hone, the surface finish is typically the same irrespective of the measuring direction.

• When utilizing the coarser belts the grind-lines were evident and the surface measurements in the perpendicular direction were indeed greater than measured in the parallel direction.

• The grind-lines were greatly reduced when following a sequential process with a series of belts.

• Parallel and perpendicular surface finish measures were the same showing a non-directional lay on Inconel 718 material, very similar to a loose abrasive process.
X5 U254 Belt After Grinds

Convex Grind

Concave Grind

10 piece Grind
Convex X5 U254 (Concave was very similar)

Used on Concave Side

Unused

10 piece Grind
Workpiece Surface Temperature after Grind

**CONCAVE SIDE**

![Graph showing part surface temperature for the concave side.]

**CONVEX SIDE**

![Graph showing part surface temperature for the convex side.]

- X22 - U264
- X16 - U264
- X5 - U254
## Estimated Cycletimes

### INPUTS

<table>
<thead>
<tr>
<th></th>
<th>Blade Design 1</th>
<th>Blade Design 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Blades</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td>Blade depth (a)</td>
<td>1.2</td>
<td>2.2</td>
</tr>
<tr>
<td>Blade Width (b)</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Concave side Number of passes across blade</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Convex side Number of passes across blade</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Concave side Number of steps to blade depth</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Convex side Number of steps to blade depth</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Estimated None contact time per blade (seconds)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Belt Change Time (seconds)</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Number of belts: X30/X22/X16/X5</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

### OUTPUTS

<table>
<thead>
<tr>
<th></th>
<th>Blade Design 1</th>
<th>Blade Design 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concave Time per pass (seconds)</td>
<td>0.55</td>
<td>0.55</td>
</tr>
<tr>
<td>Convex Time per pass (seconds)</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Concave Side Total time per blade (seconds)</td>
<td>2.2</td>
<td>8.8</td>
</tr>
<tr>
<td>Convex Side Total time per blade (seconds)</td>
<td>3.2</td>
<td>12.8</td>
</tr>
<tr>
<td>TOTAL TIME PER BLADE (seconds)</td>
<td>17.1</td>
<td>33.3</td>
</tr>
<tr>
<td>TOTAL TIME PER BLISK PER BELT GRIT SIZE (minutes)</td>
<td>10.2</td>
<td>20.0</td>
</tr>
<tr>
<td>TOTAL TIME PER BLISK (minutes)</td>
<td>41</td>
<td>80</td>
</tr>
</tbody>
</table>

### Estimated Stock Removal

<table>
<thead>
<tr>
<th></th>
<th>X30 - U264</th>
<th>X22 - U264</th>
<th>X16 - U264</th>
<th>X5 - U254</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated</td>
<td>0.001 in</td>
<td>0.0004 in</td>
<td>0.00012 in</td>
<td>0.00004 in</td>
</tr>
<tr>
<td>Stock Removal</td>
<td>X30 - U264</td>
<td>X22 - U264</td>
<td>X16 - U264</td>
<td>X5 - U254</td>
</tr>
<tr>
<td></td>
<td>0.001 in</td>
<td>0.0004 in</td>
<td>0.00012 in</td>
<td>0.00004 in</td>
</tr>
</tbody>
</table>
Agenda

• Introduction (Company and Presenter)
• Emerging Materials: What and Why?
• Grinding Processes to be covered
  • Surface grinding (γ-TiAl)
  • Creep-feed grinding (γ-TiAl, IN718)
  • Large Diameter Disk Slotting (IN718)
  • Face grinding (IN718)
  • Belt polishing (IN718)
  • Gear grinding from solid (8620, 4140)
Grinding Gears from Solid

• **Why?**
  – Quick response to Customer needs
  – Elimination of tooling lead time
  – Reduced tooling cost
  – Reduced tooling inventory
  – Competitive cycle time
  – Capital Equipment Cost Avoidance

• **Who?**
  – Job Shops
  – Producers of Large Gears
  – Maintenance and Repair Facilities
  – Gear Box Rebuilders
  – Producers of Specialty Gears

• **When?**
  – Short Lead Time
  – Special Form
  – Small to Medium Lot Size

![Graph showing cost per part vs. batch size](image)
Grinding Gears from Solid

Test Material: 8620
- Prior to Heat Treatment
  - 3 Diametral Pitch
    - Form Depth 0.750"
  - Involute Approximation
  - Thickness 3"
    - Two 1.5” parts Stacked

Test Process
- Creep Feed Form Grind
  - Up and Down Grind
- Non Continuous Dress
- Castrol Variocut B27 (straight oil)
- Coolant Velocity Matches Wheel Velocity
- High Pressure Cleaning Nozzles
- Coolant Flow Guide

Key Technology Drivers
Grinding Gears from Solid

• **Machine Tool**
  – 40 HP Spindle
  – 4 + 1 Axis
  – 45 gpm Coolant
  – Straight Oil

• **Abrasive Technology**
  – TGII Vitrium Bond Wheel
  – 5NQ Agglomerated Vitrium Bond Wheel
Grinding Gears from Solid

Productivity @ 7.0 Q’
- Time per Gap ~ 52 Seconds
- Grind Time ~ 30 minutes
- ~ 35 Minutes @ 6.0 Q’ (15 & 17.5 Min per 1.5” thick Gear)

Wheel Life
- 575 Gears per Wheel — TG2 @ Q’ = 6.0
- 445 Gears per Wheel — NQ @ Q’ = 6.0
- 394 Gears per Wheel — TG2 @ Q’ = 7.0

Specific Power

G-Ratio

Gear
12” OD
34 teeth
0.75” Whole depth
1.5” Thick

Specific Removal Rate (in³/min/ln)

BECAUSE RIGHT CHOICES MATTER™
Grinding Gears from Solid

Specific Grinding Energy

- Specific Grinding energy is an indication of the efficiency of a removal process.

- Traditional grinding processes typically have grinding energies 2 to 3 or more times those seen in this process
Rough Grind from Solid & Grind to Finish

Material: 4140 Through hardened to Rc 53-57

Abrasives: 5NQX60-G20VTX2

Wheel Speed: 6,400 sfpm
Depth of Cut per pass: 0.050”
Feed rate: 100 ipm
\[ Q' = 5\text{in}^3/\text{min/in} \]
Power: 20.5 Hp/in
Whole depth: 0.640”
Face Width: 11”
G-ratio: \(~100\) — (less than 0.004” diametric wear/tooth with 14” wheel)
Grind time per Tooth: 115 seconds

Material: 4140 Through hardened to Rc 53-57

Abrasives: 5NQX60-G20VTX2 and TG280-G20-VTX2

Wheel Speed: 6,200 sfpm
Depth of Cut per pass: 0.003” & 0.006”
Feed rate: 300 ipm
\[ Q' = 0.9\text{in}^3/\text{min/in} \text{ & } 1.8\text{in}^3/\text{min/in} \]
Power (Hp/in): <10 @ 0.003 DOC and <17 @ 0.006 DOC
Whole depth: 0.640”
Face Width: 11”
G-ratio:
\[
\begin{align*}
\text{At 0.003” DOC} \\
5NQX: & \quad \sim 1,250 \\
TG2: & \quad >3,000 \\
\text{At 0.006” DOC} \\
5NQX: & \quad \sim 100 \\
TG2: & \quad >3,000
\end{align*}
\]
Grind to Finish Data

**Specific Power**
- After Dress
  - [Graph showing Specific Power vs. Specific Material Removal Rate for TG280 and 5NQX]

- After Grinding
  - [Graph showing Specific Power vs. Specific Material Removal Rate for TG280 and 5NQX]

**Finish (Ra) Vs Material Removed**
- @ Q' = 1.8 in³/min/in
  - [Graph showing Ra (μm) vs. Material Removed (mm²/mm) for TG280 and 5NQX]

**New Grain Coming Soon!!**

**TQ grain**
- Lower Threshold forces than TG2
- Cooler Cutting Action
Grinding Gears from Solid

**Hobbing Parameters**
- Coated HSS 2 start Hob
- Rough Axial advance Per Part Rev: 0.032”
- Number of Rough Passes: 5
- Finish Axial advance Per Part Rev: 0.020”
- Time per Rough Pass: 230 min
- Time for Finish Pass: 323 min
- Total cutting time: 24.5 hours

**Grinding Parameters**
- Wheel — 5NQX Vitrium Bond
- Wheel Speed 6,000 sfpm
- Roughing Passes at 2.5 in³/min/in
- Finish Passes at 1.0 in³/min/in
- Time per Tooth Rough Passes: 1.6 min
- Time per Tooth Finish Passes: 1.1 min
- Total Dress Amount per Gear: 0.58 in
- Total Dress Time per Gear: 175 min
- Total Grind & Dress Time per Gear: 10.9 hours

**Material: 8620**
- Hardness: 28-32 Rc
- Tooth Depth: 0.470”
- Tooth Length: 7”
- Number of Teeth: 175
Grinding Gears from Solid

**Hobbing Parameters**
- Carbide 2 start Hob
- Rough Axial advance Per Part Rev: 0.030
- Number of Rough Passes: 5
- Finish Axial advance Per Part Rev: 0.020
- Time per Rough Pass: 74 min
- Time for Finish Pass: 110min
- Total cutting time: **8.0 hours**

**Grinding Parameters**
- Wheel — TG
- Wheel Speed 6,000 sfpm
- Roughing Passes at 1.1 & 2.2 in³/min/in
- Finish Passes at 0.25 in³/min/in
- Time per Tooth Rough Passes: 1.8 min
- Time per Tooth Finish Passes: 0.3 min
- Total Dress Time per Gear: 41.6 min
- Total Grind & Dress Time per Gear: **4.0 hours**

**Material: 4140**
- Hardness: 28-32 Rc
- Tooth Depth: 0.438"
- Tooth Length: 7.25"
- Number of Teeth: 80
Summary

We are using the best abrasive technology to break traditional barriers (SGE, surface finish) and expand grinding technology and applications!!
THANK YOU!!!