High Performance Grinding (HPG) of Nickel-based Superalloys

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(with help from Dave Graham, John Hagan)
Saint-Gobain Abrasives
Speaker Bio

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
AGENDA

• Introduction
• Trends and application of nickel and nickel-based superalloys
• Ni-based superalloys introduction
  • Main elements & properties
  • Evolution & processing
• Machining challenges of nickel-based superalloys
• What is High Performance Grinding?
• Creep-feed grinding test of nickel-based superalloys
• The impact of coolant – oil vs. water soluble
• Why use engineered abrasives for Ni-based superalloys?
• Grinding of Ni-based Superalloys – 2018 & Beyond
• Summary
SAINT-GOBAIN ABRASIVES

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

- Bonded abrasives
- Coated abrasives
- Thin wheels
- Superabrasives
- Construction blades & machines
- Accessories & systems

Shaping and surface-finishing solutions for all types of materials even in the most complex and challenging applications, from highly technical precision engineering to DIY home improvement.
Global Grinding Technology Centers

Mission:
• Advance Abrasives Technology
• Provide solutions to customers
- Oil and Gas Extraction
- Refining and Petrochemical Processing
- Power Generation
- Aerospace
- Chemical Processing and Other Process Industries such as Nuclear, Motorsport
# Nickel-based Superalloys: Main Elements and Properties

## Element Wt% Table

<table>
<thead>
<tr>
<th>Element</th>
<th>Wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni</td>
<td>37-79.5</td>
</tr>
<tr>
<td>Ti</td>
<td>0-5</td>
</tr>
<tr>
<td>Al</td>
<td>0-6</td>
</tr>
<tr>
<td>Mo</td>
<td>0-28</td>
</tr>
<tr>
<td>Co</td>
<td>0-20</td>
</tr>
<tr>
<td>Cr</td>
<td>5-22</td>
</tr>
<tr>
<td>Nb</td>
<td>0-5.1</td>
</tr>
<tr>
<td>W</td>
<td>0-15</td>
</tr>
<tr>
<td>C</td>
<td>&lt;0.3</td>
</tr>
</tbody>
</table>

## Alloy Properties Table

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Melting temperature (°C)</th>
<th>Precipitation temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alloy X</td>
<td>1260</td>
<td>760</td>
</tr>
<tr>
<td>Alloy 718</td>
<td>1260</td>
<td>845</td>
</tr>
<tr>
<td>Waspaloy</td>
<td>1230</td>
<td>980</td>
</tr>
<tr>
<td>Alloy 901</td>
<td>1200</td>
<td>980</td>
</tr>
<tr>
<td>Alloy X-750</td>
<td>1290</td>
<td>955</td>
</tr>
<tr>
<td>M-252</td>
<td>1200</td>
<td>1010</td>
</tr>
<tr>
<td>Alloy R-235</td>
<td>1260</td>
<td>1040</td>
</tr>
<tr>
<td>René 41</td>
<td>1230</td>
<td>1065</td>
</tr>
<tr>
<td>U500</td>
<td>1230</td>
<td>1095</td>
</tr>
<tr>
<td>U700</td>
<td>1230</td>
<td>1120</td>
</tr>
<tr>
<td>Astroloy</td>
<td>1230</td>
<td>1120</td>
</tr>
</tbody>
</table>

## Tensile Strength and Properties

<table>
<thead>
<tr>
<th>Alloy</th>
<th>UTS (MPa) at 21 °C, 540 °C, 760 °C</th>
<th>Y.S. (MPa) at 21 °C, 540 °C, 760 °C</th>
<th>Tensile elongation (%) at 21 °C, 540 °C, 760 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni based</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Astroloy</td>
<td>1415, 1240, 1160</td>
<td>1050, 965, 910</td>
<td>16, 16, 21</td>
</tr>
<tr>
<td>Inconel 587©</td>
<td>1187, 1035, 830</td>
<td>705, 620, 605</td>
<td>28, 22, 20</td>
</tr>
<tr>
<td>Inconel 600</td>
<td>660, 560, 260</td>
<td>285, 220, 180</td>
<td>45, 41, 70</td>
</tr>
<tr>
<td>Inconel 718</td>
<td>1435, 1275, 950</td>
<td>1185, 1065, 740</td>
<td>21, 18, 25</td>
</tr>
<tr>
<td>Nimonic 75</td>
<td>745, 675, 310</td>
<td>285, 200, 160</td>
<td>40, 40, 67</td>
</tr>
<tr>
<td>Nimonic942©</td>
<td>1405, 1300, 900</td>
<td>1060, 970, 860</td>
<td>37, 26, 42</td>
</tr>
<tr>
<td>René 95</td>
<td>1620, 1550, 1170</td>
<td>1310, 1255, 1100</td>
<td>15, 12, 15</td>
</tr>
<tr>
<td>Udiment 720</td>
<td>1570, ...</td>
<td>1195, ...</td>
<td>13, ... 9</td>
</tr>
</tbody>
</table>

Source: Advanced Materials, VSB Technical Univ. of Ostrava
Nickel-based Superalloys: Evolution and Processing

Relative life-time

Creep strength
Thermal fatigue resistance
Corrosion resistance

Polycrystalline
Polycrystalline directionally solidified
Single crystal

Source: Advanced Materials, VSB Technical Univ. of Ostrava

Source: The Superalloys, Roger C. Reed

Temperature for 1000-hour creep life at 137 MPa, °C

Wrought
Conventionally cast
Directionally solidified
Single crystal

(a)
(b)
(c)
Machining Challenges of Nickel-based Superalloys

Common Methods
- Turning
- Milling
- Grinding
- Broaching
- Other non-conventional methods

Common Problems
- Strength retention at high temperatures
- High dynamic shear strength
- Hard carbides causing abrasiveness
- Work hardening
- Poor thermal diffusivity
- Chip management issues

Source: Superalloys, A technical guide, M. Donachie
Machining Challenges of Nickel-based Superalloys

Common Tool Life Issues
• Excessive flank wear
• Excessive crater wear
• Cutting edge loss due to fracture, plastic flow etc.
• High cutting temperatures 1400 - 1850 °F (760 - 1010 °C)

<table>
<thead>
<tr>
<th></th>
<th>Increasing Machinability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AF2–1DA</td>
</tr>
<tr>
<td>2</td>
<td>Rene´ 95</td>
</tr>
<tr>
<td>3</td>
<td>U-500</td>
</tr>
<tr>
<td>4</td>
<td>Rene´41</td>
</tr>
<tr>
<td>5</td>
<td>INCO 718</td>
</tr>
<tr>
<td>6</td>
<td>Waspaloy</td>
</tr>
<tr>
<td>7</td>
<td>Incoloy 901</td>
</tr>
</tbody>
</table>

Source: Journal of Matl. Engg & Performance, Veldhius et. al., 2010
White Layer Formation
The white layer is a very thin outer layer of material that is harder than the underlying material (high friction energy and heat generated due to tool wear or high cutting speeds or high feedrates)
- Can be 2 – 4 µm thick under finish machining conditions

Mechanisms
- phase transformation due to rapid heating and cooling
- grain refinement due to severe plastic deformation
- reactions of the surface with environment.

Increasing cutting speeds on ME16 alloy

Source: Journal of Matl. Engg & Performance, Veldhius et. al., 2010

Machining Challenges of Nickel-based Superalloys

- Presence of white layer can result in reduction of fatigue life (6 - 8 times)
- As the white layer increases in thickness, the fatigue life decreases.
- Surface residual stresses and near-surface residual stress profiles are significant factors for fatigue life.
- The depth of maximum compressive residual stress in subsurface is not critical.
- Ground white layer can be different from a turned white layer in microstructure, composition and properties.

Machining Challenges of Nickel-based Superalloys

Fatigue test samples (WEDM, broached, ground) Fatigue bending test

Source: Reference: D. Willing, CIRP, 2014 on IN718

Source: Machining Science & Tech., V.G. Navas, 2008 on AISI O1
What is High Performance Grinding (HPG)?

What is HPG?
• Mentioned in general terms by J. Kopac, 2006.
• Reintroduced by Klocke, Sebastian and Barth in 2016 as a type of Grinding.

Characteristics
• Raising Productivity
  • By increasing MRR
  • By increasing flexibility
• Achieving similar or excellent surface quality
• Feasibility of machining novel or difficult to machine materials
Creep-feed Grinding Test of Ni-based Superalloys

**Machine Tool**
40 HP Spindle, 4 + 1 Axis

**Coolant**
Straight Oil, 52 gpm flow rate, pressure 200 psi with scrubber nozzles 800psi

**Wheels Tested (16”)**
TG280G20 – Vitrium Bond TG2 wheel
TG280H20 – Vitrium Bond TG2 wheel

**Material**
IN-718, Waspalloy

**Conditions**
Vs - 8,500 sfpm
Depth of cut - 0.100”, Total 0.7”, increasing feed rates

**Dressing**
Traverse dressing with BPR rolls, speed ratio - 0.85, overlap ratio - 2
Creep-feed Grinding Test of Ni-based Superalloys

TG/TGII Grain

- A shaped grain made by replacing post-sinter crushing with a pre-sinter extrusion process.
- The resulting needle shaped grains, designated TG and TG2, have extreme aspect ratios.
- High toughness, have a very low packing density.
- Wheels made with this grain have a very high level of permeability/porosity and excellent coolant carrying capacity.
- In terms of chip modeling, the high aspect ratio presents a shape factor comparable to a much larger blocky grain, which in turn creates a much larger chip and lower specific cutting energy.
Creep-feed Grinding Test of Ni-based Superalloys

Vitrium 3 bond technology

- Low volume, high strength bond
- Less bond interactions at the grinding zone
- Better form/profile holding
Creep-feed Grinding Test of Ni-based Superalloys

High Porosity

- Supply of coolant in the grinding zone
- Facilitate removal of chips and residue
- Thinner bond bridges reduce bond interaction with the workpiece resulting in low thermal degradation

Grain + Bond + Porosity = Product tailor-made for grinding Ni-based Superalloys

Random orientation during mixing process leading to open porosity and high permeability.
Creep-feed Grinding Test of Ni-based Superalloys – Specific Energy

### Specific Power

- **TG280-H20VTX2 (718)**
  - \( y = 0.0102x + 1.0357 \)
  - \( R^2 = 0.9939 \)
- **TG280-H20VTX2 (Waspalloy)**
  - \( y = 0.0091x + 1.1546 \)
  - \( R^2 = 0.9983 \)
- **TG280-G20VTX2 (718)**
  - \( y = 0.0088x + 1.1079 \)
  - \( R^2 = 0.9967 \)
- **TG280-G20VTX2 (Waspalloy)**
  - \( y = 0.0083x + 1.1353 \)
  - \( R^2 = 0.9933 \)

### Specific Grinding Energy

- **TG280-H20VTX2 (718)**
  - \( y = 196.05x^{0.481} \)
  - \( R^2 = 0.9997 \)
- **TG280-H20VTX2 (Waspalloy)**
  - \( y = 152.74x^{0.42} \)
  - \( R^2 = 0.9942 \)
- **TG280-G20VTX2 (718)**
  - \( y = 172.39x^{0.481} \)
  - \( R^2 = 0.996 \)
- **TG280-G20VTX2 (Waspalloy)**
  - \( y = 195.33x^{0.519} \)
  - \( R^2 = 0.9984 \)
Creep-feed Grinding Test of Ni-based Superalloys – G-ratio & Surface Finish

G-ratio

Surface Finish

Surface Finish

G-ratio

Surface Finish

Surface Finish

IN718 (TG - H Grade)
IN718 (TG - G Grade)
Waspalloy (TG - H Grade)
Waspalloy (TG - G Grade)

TG280-H20VTX2 (718)
TG280-H20VTX2 (Waspalloy)
TG280-G20VTX2 (718)
TG280-G20VTX2 (Waspalloy)
## Creep-feed Grinding Test of Ni-based Superalloys - Metallurgy

<table>
<thead>
<tr>
<th>Sample</th>
<th>( Q' ) (mm³/sec/mm)</th>
<th>Maximum Depth of Longitudinal Surface Distortion (µm)</th>
<th>Maximum Depth of Transverse Surface Distortion (µm)</th>
<th>Maximum Depth of Longitudinal Strain Lines (µm)</th>
<th>Maximum Depth of Transverse Strain Lines (µm)</th>
<th>Longitudinal Imperfections (µm)</th>
<th>Transverse Imperfections (µm)</th>
<th>White Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>IN718 - 3</td>
<td>193.5</td>
<td>15.2</td>
<td>5.1</td>
<td>30.5</td>
<td>15.2</td>
<td>Tearing 10.2</td>
<td>Tearing 5.1</td>
<td>none</td>
</tr>
<tr>
<td>IN718 - 6</td>
<td>193.5</td>
<td>10.2</td>
<td>10.2</td>
<td>25.4</td>
<td>45.7</td>
<td>Tearing 10.2</td>
<td>Tearing 7.6</td>
<td>none</td>
</tr>
<tr>
<td>Waspaloy - 4</td>
<td>161.3</td>
<td>5.1</td>
<td>5.1</td>
<td>15.2</td>
<td>20.3</td>
<td>none</td>
<td>none</td>
<td>Tearing 15.2</td>
</tr>
<tr>
<td>Waspaloy - 5</td>
<td>161.3</td>
<td>10.2</td>
<td>5.1</td>
<td>15.2</td>
<td>25.4</td>
<td>none</td>
<td>Gouge 15.2</td>
<td>none</td>
</tr>
</tbody>
</table>
Creep-feed Grinding Test of Ni-based Superalloys – Coolant Impact

**WSO Test**
- Machine: Magerle
- Material – IN718
- Wheel Speed: 8,500 sfpm
- 2.5mm DOC & 1,270 mm/min
- \( Z' = 53.8 \text{ mm}^3/\text{sec/mm} \)

**Oil Test**
- Machine: Campbell
- Material – IN718
- Wheel Speed: 8,500 sfpm
- 2.5mm DOC & 4,572 mm/min
- \( Z' = 193.5 \text{ mm}^3/\text{sec/mm} \)
Creep-feed Grinding Test of Ni-based Superalloys – Coolant Impact

**Specific Power**

- MRR' (mm³/sec/mm)
- Specific Power (W/mm)
- TG280 - Oil
- TG280 WSO

**Specific Energy**

- MRR' (mm³/sec/mm)
- Specific Energy (J/mm³)
- TG280 - Oil
- TG280 WSO

**G-ratio**

- MRR' (mm³/sec/mm)
- Effective G-Ratio
- TG280 — Oil
- TG280 — WSO
Why use Engineered Abrasives for Ni-based Superalloys?

**Work material**
Inconel 718 HT
2” wide x ½” deep profile
Grinding form from Solid

**Grinding Wheels Evaluated:**
- 38A60-E24VS3P
- 3NQX60-E24VTX2
- TG2120-E24VTX2
Wheel Size Ø20” x 3”
Dressed in profile using Norton Diamond Roll
Why use Engineered Abrasives for Ni-based Superalloys?

**Dressing**
- Reverse plated diamond (30/40)
- Speed Ratio - 0.9
- Dress Rate - 40 ipr
- Total wheel dress amount (.001” to .003”)

**Coolant**
- Type – Water Soluble Oil
- Master Chemical Trim E812 VHP 10% mix
- Flowrate - 52 gpm
- Wheel Speed – 4,500 fpm

38A60-E24V53P – Q’ = 1.2 in³/min/in
3NQX60-E24VTX2 – Q’ = 1.2 in³/min/in
TG2120-E24VTX2 – Q’ = 1.2 in³/min/in
Why use Engineered Abrasives for Ni-based Superalloys?

- **Peak Power during Grind**
  - 38A60-E24V53P: 57 hp
  - 3NQX60-E24VTX2: 45 hp
  - TG2120-E24VTX2: 44 hp

- **Surface Finish Ra (µin)**
  - 38A60-E24V53P: 20 µin
  - 3NQX60-E24VTX2: 25 µin
  - TG2120-E24VTX2: 32 µin

- **G-Ratio Based on Dress Amount**
  - 38A60-E24V53P: 0.77
  - 3NQX60-E24VTX2: 1.20
  - TG2120-E24VTX2: 2.80
Why use Engineered Abrasives for Ni-based Superalloys?

**Dressing**
- Reverse plated diamond (30/40)
- Speed Ratio - 0.9
- Dress Rate - 40 ipr
- Total wheel dress amount (.001” to .003”)

**Coolant**
- Type – Water Soluble Oil
- Master Chemical Trim E812 VHP 10% mix
- Flowrate - 52 gpm
- Wheel Speed – 4,500 fpm

38A60-E24VS3P – $Q' = 0.8$ in³/min/in
3NQX60-E24VTX2 – $Q' = 1.2$ in³/min/in
TG2120-E24VTX2 – $Q' = 3$ in³/min/in
Why use Engineered Abrasives for Ni-based Superalloys?
Product Improvements
• Grinding with lower threshold forces/power – sharp edges at lower loads
• Grinding with lower SGE – cooler cutting
• Higher product life – higher % product utilization

Deliverables
• Retain finish – Workpiece quality
• Higher productivity – Higher removal rates at the same power
• Lower dress frequency – lower wear on the dresser
• Lower abrasive cost/part – cost savings to customers
Grinding - **Key Advantages**

- Higher MRR - **Productivity**
- Better Surface finish (Ra, Rz), lower chipping, cracking - **Quality**
- Absent or minimal white layer - **Quality**
- Surface compressive residual stresses - **Integrity**
- Minimal impact on wheel/belt life with newer generation of work materials - **Versatility**
- Many product choices - **Diversity**