RESIDUAL STRESS DISTRIBUTION AND DISTORTION
PRODUCED BY MACHINING OF
HIGH STRENGTH THERMAL RESISTANT ALLOYS

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ABSTRACT

The residual stress and distortion produced by milling and grinding of 4340 steel, D6ac steel, maraging steel, Inconel 718, Ti-6Al-4V, and pressed and sintered tungsten are presented. In addition, the residual stress distribution produced by electrical discharge machining (EDM), electrochemical machining (ECM), electropolishing (ELP), and peening are shown for Inconel 718.

Surface grinding tends to produce a resultant tensile stress within the surface layer. The magnitude and depth of the residual stress distribution is determined by grinding wheel grade, wheel speed, depth per pass, grinding fluid, and the sharpness of the grinding wheel. By judicious selection of grinding parameters, it is also possible to produce residual compressive stress in grinding.

In milling, the predominant residual stress tends to be compressive. The sharpness of the cutter appears to be the most important factor in determining the magnitude and depth of the residual stress in milling and other chip removal operations. EDM resulted in residual tensile stress, while ECM and ELP produced essentially zero stress in the workpiece. Shot peening introduced a compressive residual stress pattern regardless of the previous residual stressed condition of the machined surface.

The distortion in the workpiece resulting from all the machining operations was found to be proportional to the integrated residual stress distribution in the surface layer.
Residual stress and associated distortion produced by various machining operations and materials are presented as follows:

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<th>Operation</th>
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<td>Surf. Grind</td>
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<td>3</td>
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<td>Face Mill</td>
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<td>Inconel 718, Aged, 41 Rc</td>
<td>Surf. Grind</td>
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<td>Inconel 718, Aged, 41 Rc</td>
<td>Surf. Grind</td>
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<td>19</td>
<td>Inconel 718, Aged, 41 Rc</td>
<td>Surf. Grind</td>
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<td>20</td>
<td>Ti-6-4, Aged, 370 BHN</td>
<td>Face Mill</td>
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<td>Face Mill</td>
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<td>Ti-6-4, Aged, 370 BHN</td>
<td>Surf. Grind</td>
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<td>Ti-6-4, Aged, 370 BHN</td>
<td>Surf. Grind</td>
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<td>AISI 4340, Q&amp;T, 50 Rc</td>
<td>Grind, ELP, Peen</td>
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<td>25</td>
<td>Inconel 718, Aged, 44 Rc</td>
<td>Surf. Grind</td>
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<td>Inconel 718, Aged, 44 Rc</td>
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<td>28</td>
<td>Inconel 718, Aged, 44 Rc</td>
<td>ELP, Peen</td>
</tr>
</tbody>
</table>
Change in Deflection versus Wheel Speed
for Surface Grinding D6AC Steel Quenched and Tempered to 56 Rq

Effect of Wheel Grade
- Cross Feed: .050 inches/pass
- Down Feed: .002 inches/pass
- Table Speed: 40 feet/minute
- Depth of Cut: .010"n
- Specimen Size: .070 x 3/4 x 4-1/4"
- Grinding Fluid: Soluble Oil (1:20)

Residual Stress in Ground Surface
D6AC Steel Quenched and Tempered to 56 Rq

Effect of Wheel Grade
- Wheel Speed: 6000 feet/minute
- Down Feed: .002 inches/pass
- Cross Feed: .050 inches/pass
- Table Speed: 40 feet/minute
- Depth of Grind: .010"
- Grinding Fluid: Soluble Oil (1:20)
- Specimen Size: .060 x 3/4 x 4-1/4"

FIGURE 3

FIGURE 4
Residual Stress in Ground Surface
D6AC Steel Quenched and Tempered to 36 Rc

Wheel: See below
Wheel Speed: See below
Down Feed: See below
Cross Feed: .050 inches/pass
Table Speed: 40 feet/minute
Depth of Grind: .010"
Grinding Fluid: Soluble Oil (1:20)
Specimen Size: .060 x 3/4 x 4-1/4"

Wheel: 32A46K8YBE
Wheel Speed: 6000 feet/minute
Down Feed: Low Stress

Wheel: 32A46H8YBE
Wheel Speed: 2000 feet/minute
Down Feed: .002 inches/pass

FIGURE 9
Change in Deflection versus Tool Wearland
for Face Milling D16C Steel Quenched and Tempered to 66 R<y
Effect of Tool Wearland and Depth of Cut

Cutter: 4" Dia. Single Tooth Face Mill with
C-2 (883) Carbide
AR: 0° TR: 10°
RR: -15° Incl: -10°
CA: 45° Clearance: 10°
ECEA: 5°
Cutting Speed: 97 feet/minute
Feed: .006 inches/tooth
Depth of Cut: See below
Cutting Fluid: Dry

FIGURE 6

Residual Stress in Milled Surface
D16C Steel Quenched and Tempered to 66 R<y
Effect of Tool Wearland

Tool: 4" Dia. Single Tooth Face Mill
With C-2 (883) Carbide
AR: 0° TR: 10°
RR: -15° Incl: -10°
CA: 45° ECEA: 5°
Peripheral Clearance: 10°
Cutting Speed: 97 feet/minute
Feed per Tooth: .006"
Depth of Cut: .016"
Width of Cut: 3/16"
Cutting Fluid: Dry
Specimen Size: 1/4 x 3/16 x 6.1/4"

FIGURE 7
Change in Deflection versus Wheel Speed
for Surface Grinding Pressed and Sintered Tungsten
95% Density, 3.4 R.

Effect of Wheel Speed

Wheel Grade: 32A465VB0
Wheel Speed: See below
Down Feed: .001 in./pass
Table Speed: 40 feet/minute
Grinding Fluid: See below

Distortion - change in deflection in 3.5" gage length

2000  3000  4000
Wheel Speed - feet/minute

Soluble Oil (1:20)
KNO₂ (1:20)

FIGURE 8
Distortion Resulting From Surface Grinding
Inconel 718, Solution Treated and Aged, 4140
Effect of Wheel Grade and Wheel Speed

- Gross Feed: .050 inches/pass
- Down Feed: .001 inches/pass
- Table Speed: 40 feet/minute
- Depth of Grind: .010" 
- Specimen Size: .060 x 3/4 x 4-1/4" 
- Grinding Fluid: Highly Sulphurized Oil

Distortion - change in deflection at 3.5" gage length

Wheel Speed - feet/minute

FIGURE 17
Residual Stress After Surface Grinding
Inconel 718, Solution Treated and Aged, 41 Rz

Effect of Wheel Speed
Aluminum Oxide Wheel

- Wheel Grade: 32A46J8VBE
- Cross Feed: .050 inches/pass
- Table Speed: 40 feet/minute
- Depth of Grind: .010"
- Down Feed: .001 inches/pass
- Grinding Fluid: Highly Sulphurized Oil
- Specimen Size: .060 x 3/4 x 4-1/4"

Residual Stress After Surface Grinding
Inconel 718, Solution Treated and Aged, 41 Rz

Effect of Wheel Hardness
Aluminum Oxide Wheel

- Wheel Speed: 6000 feet/minute
- Cross Feed: .050 inches/pass
- Table Speed: 60 feet/minute
- Depth of Grind: .010"
- Down Feed: .001 inches/pass
- Grinding Fluid: Highly Sulphurized Oil
- Specimen Size: .060 x 3/4 x 4-1/4"

FIGURE 18

FIGURE 19
DISTORTION RESULTING FROM SURFACE GRINDING
TITANIUM ALLOY 6A1-4V, AGED, 370 BHN
EFFECT OF WHEEL GRADE AND WHEEL SPEED

CROSS FEED: .050 INCHES/PASS
TABLE SPEED: 40 FEET/MINUTE
DEPTH OF GRIND: .010"
DOWN FEED: .002 INCHES/PASS
GRINDING FLUID: KNO₂ (1:20)
SPECIMEN SIZE: .060 x 3/4 x 4-1/4"

DISTORTION - CHANGE IN DEFORMATION IN 1.5" GAGE LENGTH

WHEEL SPEED - FEET/MINUTE

FIGURE 22

RESIDUAL STRESS AFTER SURFACE GRINDING
TITANIUM ALLOY 6A1-4V, AGED, 370 BHN
EFFECT OF WHEEL SPEED

WHEEL GRADE: 39C6018VK
CROSS FEED: .050 INCHES/PASS
TABLE SPEED: 40 FEET/MINUTE
DEPTH OF GRIND: .010"
DOWN FEED: .002 INCHES/PASS
GRINDING FLUID: KNO₂ (1:20)
SPECIMEN SIZE: .060 x 3/4 x 4-1/4"

RESIDUAL STRESS - KS

TENSION

6000 FEET/ MINUTE

4000 FEET/ MINUTE

2000 FEET/ MINUTE

DEPTH BELOW SURFACE - INCHES

FIGURE 23
RESIDUAL SURFACE STRESS IN AISI 4340
(QUENCHED AND TEMPERED, 50 R_c) PRODUCED BY
SURFACE GRINDING

GRINDING CONDITIONS

<table>
<thead>
<tr>
<th></th>
<th>Gentle</th>
<th>Conven.</th>
<th>Abusive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheel</td>
<td>A46HV</td>
<td>A46KV</td>
<td>A46MV</td>
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<tr>
<td>Wheel Speed ft./min.</td>
<td>2000</td>
<td>6000</td>
<td>6000</td>
</tr>
<tr>
<td>Down Feed in./pass</td>
<td>&quot;LS&quot;</td>
<td>.001</td>
<td>.002</td>
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<tr>
<td>Grinding Fluid</td>
<td>Sulf.</td>
<td>Sol. Oil (1:20)</td>
<td>Dry</td>
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<tr>
<td></td>
<td>Oil</td>
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</tbody>
</table>

CONVENTIONAL GRIND (+.0157)

GENTLE GRIND (+.0040)

ELECTROPOLISH (+.0030)

ABUSIVE GRIND (+ SHOT PEEN (-.0352)*

* Numbers in parenthesis indicate specimen distortion in 3-1/2" gage length.

DEPTH BELOW SURFACE - INCHES
### RESIDUAL SURFACE STRESS IN INCONEL 718 (SOLUTION TREATED AND AGED 44 R<sub>c</sub>) PRODUCED BY SURFACE GRINDING

<table>
<thead>
<tr>
<th>Grinding Conditions</th>
<th>Gentle</th>
<th>Conventional</th>
<th>Abusive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grinding Wheel A611W</td>
<td>A61XK</td>
<td>A6MYV</td>
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<tr>
<td>Wheel Speed ft./min.</td>
<td>2000</td>
<td>6000</td>
<td>6000</td>
</tr>
<tr>
<td>Down Feed in./pass</td>
<td>&quot;LS&quot;</td>
<td>.001</td>
<td>.002</td>
</tr>
<tr>
<td>Cross Feed in./pass</td>
<td>.050</td>
<td>.050</td>
<td>.050</td>
</tr>
<tr>
<td>Table Speed ft./min.</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Depth of Grind in.</td>
<td>.010</td>
<td>.010</td>
<td>.010</td>
</tr>
<tr>
<td>Grinding Fluid Sulf. Sol. Oil Dry Oil (1:20)</td>
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<td></td>
</tr>
</tbody>
</table>

#### EDM CONDITIONS

<table>
<thead>
<tr>
<th>Rough EDM</th>
<th>Finish EDM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency, kc</td>
<td>256</td>
</tr>
<tr>
<td>Amperes</td>
<td>2</td>
</tr>
<tr>
<td>Capacitance, µfd</td>
<td>.05</td>
</tr>
<tr>
<td>Voltage</td>
<td>35</td>
</tr>
</tbody>
</table>

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**CONVENTIONAL GRINDING**

**ABUSIVE GRINDING**

**GENTLE GRINDING**

#### DEPTH BELOW SURFACE - INCHES

**FIGURE 25**

---

**FIGURE 28**
RESIDUAL SURFACE STRESS IN INCONEL 718
(SOLUTION TREATED AND AGED, 44 Rc) PRODUCED BY
ELECTROCHEMICAL MACHINING (ECM)

ECM CONDITIONS

- ABUSIVE ECM
- GENTLE ECM

Voltage Applied to Finish Surface: 20 / 20/2
Current, amps (start/finish): 1300/2500 / 1300-2500/15
Feed Rate, in/min: .045 / .045/0
Electrolyte Pressure, psig: 175/185 / 175/190
Outlet (start/finish): 70/35 / 70/40
Electrolyte Temperature, °F: 105 / 100
Bottom Gap, in.: .005 / .009/.050

FIGURE 27

RESIDUAL SURFACE STRESS IN INCONEL 718
(SOLUTION TREATED AND AGED, 44 Rc) PRODUCED BY
ELECTROPOLISHING (ELP)

ELP CONDITIONS
- As ELP
- ELP After Solution Treat
- Only Followed by Aging
- ELP and Shot Peening
  (Level I)

Solution - Ethylene glycol - 75% (by wt)
Sulfuric Acid - 25% (by wt)
Hydrofluoric Acid - 1% (by wt) of total volume

Temperature - 180 ± 3 °F
Current Density - 5-6 amperes/sq. in.
Agitation - Continuous mechanical
Machining Removed - .003-.004 in./side

SHOT PEENING CONDITIONS (LEVEL I)
Shot Size - S110
Intensity - .006-.008 A
Coverage, % - 300
Shot Hardness, Rc - 50-55

FIGURE 28