RELATIONSHIP BETWEEN RESIDUAL SURFACE STRESS
AND FATIGUE BEHAVIOR IN HIGH STRENGTH ALLOYS

by

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Residual stress profiles and corresponding fatigue strengths exhibited by high performance steels, titanium alloys, and nickel base alloys will be presented. Surface integrity studies are summarized which define surface microstructures, residual stress profiles, and fatigue strengths associated with a wide variety of metal removal methods as well as variations in cutting conditions within these methods.

Machining conditions covered include milling, facing, grinding, ELP, EDM, and ECM. Alloys include AISI 4340, 4340 Modified, maraging steel, Ti-6Al-4V, Ti-6Al-6V-2Sn, and nickel alloys such as Rene' 80, Rene' 95, and Inconel 718.

A comparison between residual stress and fatigue strength will be made to illustrate the extent of relationship which does exist based on data available. Areas of nonconformance between residual stress and fatigue behavior as well as other significant variables that affect mechanical performance of hardware will also be discussed.
Residual stress, associated fatigue behavior and the relationship between the two are presented as follows:

Figure 1 - Residual Stress in AISI 4340 - Grinding
Figure 2 - Residual Stress in Inconel 718 - ECM
Figure 3 - Residual Stress in Inconel 718 - Grinding
Figure 4 - Residual Stress in Inconel 718 - EDM
Figure 5 - Summary of Fatigue Strengths - Ground Surfaces
Figure 6 - Summary of Fatigue Strengths - Non-Conventionally Machined Surfaces
Figure 7 - Summary of Fatigue Strengths - End Milling Surfaces
Figure 8 - Summary of Fatigue Strengths - Surface Finish Study
Figure 9 - Residual Stress vs. Fatigue - AISI 4340
Figure 10 - Residual Stress vs. Fatigue - Modified AISI 4340
Figure 11 - Residual Stress vs. Fatigue - Grade 300 Maraging Steel
Figure 12 - Residual Stress vs. Fatigue - Ti-6Al-4V, Beta Rolled
Figure 13 - Residual Stress vs. Fatigue - Ti-6Al-2Sn-4Zr-2Mo
Figure 14 - Residual Stress vs. Fatigue - Inconel 718
Figure 15 - Residual Stress vs. Fatigue - Rene' 80
Figure 16 - Residual Stress vs. Fatigue - AF 95
Figure 2
RESIDUAL SURFACE STRESS IN INCONEL 718
(SOLUTION TREATED AND AGED 44 R<sub>c1</sub>) PRODUCED BY
SURFACE GRINDING

GRINDING CONDITIONS

<table>
<thead>
<tr>
<th></th>
<th>Gentle</th>
<th>Conv.</th>
<th>Abusive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grinding Wheel</td>
<td>A46HR</td>
<td>A46KV</td>
<td>A46MV</td>
</tr>
<tr>
<td>Wheel Speed</td>
<td>2000</td>
<td>6000</td>
<td>6000</td>
</tr>
<tr>
<td>Down Feed</td>
<td>&quot;LS&quot;</td>
<td>.001</td>
<td>.002</td>
</tr>
<tr>
<td>in./pass</td>
<td>.050</td>
<td>.050</td>
<td>.050</td>
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<tr>
<td>Cross Feed</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>ft./min</td>
<td>.010</td>
<td>.010</td>
<td>.010</td>
</tr>
<tr>
<td>Table Speed</td>
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<td></td>
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<tr>
<td>ft./min</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth of Grind</td>
<td>in.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grind Fluid</td>
<td>Sulf.</td>
<td>Sol.</td>
<td>Dry</td>
</tr>
<tr>
<td></td>
<td>Oil</td>
<td>Oil</td>
<td>Oil (1:10)</td>
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</table>

EDM CONDITIONS

<table>
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<tr>
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<th>Finishing</th>
<th>Roughing</th>
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<tbody>
<tr>
<td>Frequency, kc</td>
<td>256</td>
<td>8</td>
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<tr>
<td>Amperes</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Capacitance, μfd</td>
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<td>1</td>
</tr>
<tr>
<td>Voltage</td>
<td>35</td>
<td>40</td>
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</table>

Figure 3

RESIDUAL SURFACE STRESS IN INCONEL 718
(SOLUTION TREATED AND AGED 44 R<sub>c1</sub>) PRODUCED BY
ELECTRICAL DISCHARGE MACHINING (EDM)

EDM CONDITIONS

<table>
<thead>
<tr>
<th></th>
<th>Rough EDM</th>
<th>Finish EDM</th>
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<tbody>
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<tr>
<td></td>
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</tbody>
</table>

Figure 4
SUMMARY OF FATIGUE STRENGTHS - GROUND SURFACES
Cantilever Bending, Zero Mena Stress, Room Temperature

Gentle
Conventional
Abusive

Endurance Limit, ksi for $10^7$ cycles

Figure 5
SUMMARY OF FATIGUE STRENGTHS -
NON-CONVENTIONALLY MACHINED SURFACES
Cantilever Bending, Zero Mean Stress, Room Temperature

- [ ] Finishing
- [x] Roughing

<table>
<thead>
<tr>
<th>Method</th>
<th>Material</th>
<th>STA</th>
<th>$R_c$</th>
<th>Endurance Limit, Ksi for $10^7$ cycles</th>
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</thead>
<tbody>
<tr>
<td>EDM</td>
<td>Inconel 718</td>
<td>44</td>
<td></td>
<td>Denotes fatigue strength level due to gentle grinding</td>
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<tr>
<td>EDM</td>
<td>AF 95</td>
<td>50</td>
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<tr>
<td>ECM</td>
<td>Ti-6-6-2</td>
<td>42</td>
<td></td>
<td></td>
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<tr>
<td>ECM</td>
<td>Inconel 718</td>
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<td>CHM</td>
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Figure 6
SUMMARY OF FATIGUE STRENGTHS - END MILLED SURFACES

Cantilever Bending, Zero Mean Stress, Room Temperature

- Gentle
- Abusive

<table>
<thead>
<tr>
<th>Material</th>
<th>Endurance Limit, ksi for 10^7 cycles</th>
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<tbody>
<tr>
<td>4340 Q&amp;T, 50 Rc</td>
<td>~60</td>
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<tr>
<td>300 M' Steel Q&amp;T, 53 Rc</td>
<td>~60</td>
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<tr>
<td>Grade 300 Maraging Steel 54 Rc</td>
<td>~80</td>
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<td>Ti-6-2-4-2 STA, 36 Rc</td>
<td>~80</td>
</tr>
<tr>
<td>Ti-6-6-2 STA, 42 Rc</td>
<td>~80</td>
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</table>

Denotes fatigue strength level due to gentle grinding

Figure 7
SUMMARY OF FATIGUE STRENGTHS - SURFACE FINISH STUDY

4340 Steel, Quenched and Tempered, 50 Rc
Ti-6-6-2 Solution treated and Aged 42 Rc
Inconel 718 Solution treated and Aged 44 Rc

- Gentle
- Abusive

<table>
<thead>
<tr>
<th>Surf. Fin. AA</th>
<th>4340 Grind</th>
<th>4340 Transverse Grind</th>
<th>4340 Longitudinal Grind</th>
<th>Ti-6-6-2 End Mill</th>
<th>Inconel 718 Turning (Facing)</th>
<th>Inconel 718 Turning (Facing)</th>
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<tr>
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<td>128</td>
<td>97</td>
<td>125</td>
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</table>

Endurance Limit, ksi

Figure 8
RELATIONSHIP BETWEEN PEAK RESIDUAL STRESS
AND ENDURANCE LIMIT FOR AISI 4340
QUENCHED AND TEMPERED, 50 R_c

ENDURANCE LIMIT - KSI

Figure 9
RESIDUAL STRESS VS. FATIGUE BEHAVIOR
OF MODIFIED 4340 (53 Rc) COMPARED TO AISI 4340 (50 Rc)

Figure 10
RESIDUAL STRESS VS. FATIGUE BEHAVIOR
OF GRADE 300 MARAGING STEEL
(54 R_c) COMPARED TO AISI 4340 (50 R_c)

Figure 11
RELATIONSHIP BETWEEN PEAK RESIDUAL STRESS AND ENDURANCE LIMIT FOR BETA ROLLED TITANIUM 6A1-4V

Figure 12
RESIDUAL STRESS VS. FATIGUE BEHAVIOR
OF Ti-6Al-2Sn-4Zr-2Mo, (36 $R_c$)

Figure 13
RELATIONSHIP BETWEEN PEAK RESIDUAL STRESS AND ENDURANCE LIMIT FOR INCONEL 718 (SOLUTION TREATED AND AGED, 44 R_c)

As Machined

As Machined + Peened

As Machined + Post Heat Treatment

Machined as Solution Treated Followed by Aging in Vacuum

Figure 14
RESIDUAL STRESS VS. FATIGUE BEHAVIOR OF RENE' 80 (AS CAST, 38 R_c)

Figure 15
RESIDUAL STRESS VS. FATIGUE BEHAVIOR
OF AF 95 (50 R_c)

CONVENTIONAL GRIND

ABUSIVE GRIND

FINISHING EDM
ROUGHING EDM

STANDARD ECM
OFF-STANDARD ECM

2 POINTS

GENTLE GRIND

COMPARATIVE BEHAVIOR OF INCONEL 718

Figure 16