CRACK PROPAGATION OF CORONA 5

FINAL TECHNICAL REPORT FOR THE PERIOD
September 1, 1981 through April 10, 1983

CONTRACT NO. N00019-81-C-0380

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Rockwell International
Science Center
This report includes mechanical property data for two heats of Corona-5 (Ti-4.5Al-5Mo-1.5Cr), containing 0.1 and 0.2 wt% oxygen, respectively. The materials were finish forged below the beta transus and followed by a high strength heat treatment, which produced tensile yield strengths from 132 to 162 ksi and ultimate strengths from 146 to 177 ksi. Fatigue life at 70F and 600F was found to increase with increasing tensile strength. Fatigue crack growth rate data at 70F for the various microstructural conditions were grouped into a narrow band, with the higher strength conditions slightly more resistant to crack growth than the lower strength conditions. Also included are fatigue crack growth rate data as a function of R-ratio and temperature. Fractographic observations on two high strength conditions at 70F and 600F comparing R-ratio and temperature effects are presented. A report issued by Crucible Research Center, Colt Industries for subconract effort on the effect of processing variables on grain size and mechanical properties of cold rolled Corona-5 sheet is appended.
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SECTION I

Background

Microstructural Conditions and Tensile Data
Background

The subject contract (INFLUENCE OF MICROSTRUCTURE AND INTERSTITIAL ELEMENTS ON FATIGUE CRACK PROPAGATION RATE OF CORONA-5 TITANIUM ALLOY AT AMBIENT AND ELEVATED TEMPERATURES, N00019-81-C-0380) was a follow-on contract to a program in which two heats of CORONA-5 (Ti-4.5Al-5Mo-1.5Cr) containing 0.1 and 0.2 wt% oxygen, respectively, were extensively characterized. Considerable ambient temperature tensile and FCP data was collected for the alloy. The alloy compositions, forging conditions and tensile data from the previous program are given in tables I and II. Microstructures developed are shown in Figs. 1 and 2. Fatigue crack propagation data and fractography from the previous program is compiled in Section VI for reference.
Table I
Composition and Forging Conditions for CORONA-5 Forgings

<table>
<thead>
<tr>
<th>Material</th>
<th>Al</th>
<th>Mn</th>
<th>Cr</th>
<th>Fe</th>
<th>N</th>
<th>O</th>
<th>H</th>
<th>Ti</th>
<th>°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>4.6</td>
<td>4.8</td>
<td>1.5</td>
<td>0.10</td>
<td>0.006</td>
<td>0.105</td>
<td>0.002</td>
<td>Bal</td>
<td>911</td>
</tr>
<tr>
<td>T</td>
<td>4.6</td>
<td>5.1</td>
<td>1.4</td>
<td>0.09</td>
<td>0.010</td>
<td>0.192</td>
<td>0.0009</td>
<td>Bal</td>
<td>936</td>
</tr>
</tbody>
</table>

Forging Conditions

<table>
<thead>
<tr>
<th>Designation</th>
<th>1st Upset</th>
<th>2nd Upset</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30% at $T_B + 33^\circ C$</td>
<td>35% at $T_B + 35^\circ C$</td>
</tr>
<tr>
<td>2</td>
<td>30% at $T_B + 33^\circ C$</td>
<td>35% at $T_B - 36^\circ C$</td>
</tr>
<tr>
<td>3</td>
<td>30% at $T_B - 36^\circ C$</td>
<td>35% at $T_B - 36^\circ C$</td>
</tr>
<tr>
<td>4</td>
<td>30% at $T_B + 33^\circ C$</td>
<td>35% at $T_B - 25^\circ C$</td>
</tr>
</tbody>
</table>

Die Temp: $T_B + 44^\circ C$  Die Temp: $T_B + 25^\circ C$

Table II
Fracture Toughness and Tensile Properties of CORONA-5 Forgings

<table>
<thead>
<tr>
<th>Spec No.</th>
<th>$\sigma_{0,2}$ (MPa (ksi))</th>
<th>$\sigma_U$ (MPa (ksi))</th>
<th>Elong</th>
<th>RA</th>
<th>Toughness MPa·in$^{1/2}$ (ksi·in$^{1/2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>848 (123)</td>
<td>937 (136)</td>
<td>20</td>
<td>36</td>
<td>~ 110 (~ 100)(1)</td>
</tr>
<tr>
<td>S2</td>
<td>910 (132)</td>
<td>1006 (146)</td>
<td>15</td>
<td>37</td>
<td>85 (78)(2)</td>
</tr>
<tr>
<td>S3</td>
<td>958 (139)</td>
<td>1014 (147)</td>
<td>15</td>
<td>50</td>
<td>61 (55)</td>
</tr>
<tr>
<td>S4</td>
<td>951 (138)</td>
<td>1027 (149)</td>
<td>13</td>
<td>23</td>
<td>95 (87)</td>
</tr>
<tr>
<td>T1</td>
<td>1006 (146)</td>
<td>1089 (158)</td>
<td>13</td>
<td>24</td>
<td>-</td>
</tr>
<tr>
<td>T2</td>
<td>1027 (149)</td>
<td>1103 (160)</td>
<td>15</td>
<td>22</td>
<td>-</td>
</tr>
<tr>
<td>T3</td>
<td>1034 (150)</td>
<td>1103 (160)</td>
<td>18</td>
<td>39</td>
<td>-</td>
</tr>
</tbody>
</table>

(1) Invalid $K_{IC}$: crack front curvature
(2) Estimated toughness: crack mouth displacement not recorded.
Fig. 2
Microstructural Conditions and Tensile Data

For the current program, forging material from forgings S2, S4, and T2 was subjected to a high strength heat treatment. The heat treatment used in the previous program (heat treatment A) was:

$830^\circ C/4h/air$ cool plus $593^\circ C/4h/air$ cool.

The higher strength heat treatment (heat treatment B) was:

$866^\circ C/4h/air$ cool plus $510^\circ C/24h/air$ cool.

In the current program two conditions of forging S2 (S2A and S.B.), a high strength condition of forging S4 (S4BB) and a high strength condition of forging T2 (T2B). Microstructures of the conditions developed are shown in Fig. 3. Tensile data for ambient and elevated temperatures are given in Table III. Ambient temperature tensile and toughness data for the four conditions are given in Table IV. Comparison of the same data with other alloys at similar strength levels are shown in Table V.
Table III
Tensile Properties of CORONA-5

<table>
<thead>
<tr>
<th>Spec. No.</th>
<th>T, °C</th>
<th>$\sigma_0$, MPa (ksi)</th>
<th>$\sigma_u$, MPa (ksi)</th>
<th>e %</th>
<th>RA %</th>
</tr>
</thead>
<tbody>
<tr>
<td>S2A</td>
<td>20</td>
<td>910 (132)</td>
<td>1007 (146)</td>
<td>15</td>
<td>37</td>
</tr>
<tr>
<td>S2-32A</td>
<td>121</td>
<td>780 (113)</td>
<td>906 (131)</td>
<td>13</td>
<td>44</td>
</tr>
<tr>
<td>S2-33A</td>
<td>121</td>
<td>790 (115)</td>
<td>914 (133)</td>
<td>14</td>
<td>44</td>
</tr>
<tr>
<td>S2-34A</td>
<td>316</td>
<td>656 (95)</td>
<td>812 (118)</td>
<td>14</td>
<td>45</td>
</tr>
<tr>
<td>S2-35A</td>
<td>316</td>
<td>644 (93)</td>
<td>812 (118)</td>
<td>14</td>
<td>50</td>
</tr>
<tr>
<td>S2B</td>
<td>20</td>
<td>1005 (146)</td>
<td>1087 (158)</td>
<td>8</td>
<td>36</td>
</tr>
<tr>
<td>S2-36B</td>
<td>121</td>
<td>858 (124)</td>
<td>995 (144)</td>
<td>12</td>
<td>32</td>
</tr>
<tr>
<td>S2-37B</td>
<td>121</td>
<td>825 (120)</td>
<td>963 (140)</td>
<td>14</td>
<td>40</td>
</tr>
<tr>
<td>S2-38B</td>
<td>316</td>
<td>698 (101)</td>
<td>869 (126)</td>
<td>14</td>
<td>55</td>
</tr>
<tr>
<td>S2-39B</td>
<td>316</td>
<td>662 (95)</td>
<td>846 (123)</td>
<td>14</td>
<td>57</td>
</tr>
<tr>
<td>T2B</td>
<td>20</td>
<td>1120 (162)</td>
<td>1221 (177)</td>
<td>7</td>
<td>22</td>
</tr>
<tr>
<td>T2-32B</td>
<td>121</td>
<td>903 (131)</td>
<td>1023 (148)</td>
<td>12</td>
<td>39</td>
</tr>
<tr>
<td>T2-33B</td>
<td>121</td>
<td>960 (139)</td>
<td>1101 (160)</td>
<td>10</td>
<td>29</td>
</tr>
<tr>
<td>T2-34B</td>
<td>316</td>
<td>740 (107)</td>
<td>936 (136)</td>
<td>10</td>
<td>44</td>
</tr>
<tr>
<td>T2-35B</td>
<td>316</td>
<td>723 (105)</td>
<td>913 (132)</td>
<td>12</td>
<td>54</td>
</tr>
<tr>
<td>S4B</td>
<td>20</td>
<td>983 (142)</td>
<td>1099 (159)</td>
<td>9</td>
<td>33</td>
</tr>
<tr>
<td>S4-34B</td>
<td>121</td>
<td>847 (123)</td>
<td>981 (142)</td>
<td>11</td>
<td>38</td>
</tr>
<tr>
<td>S4-35B</td>
<td>121</td>
<td>890 (129)</td>
<td>1006 (146)</td>
<td>11</td>
<td>32</td>
</tr>
<tr>
<td>S4-36B</td>
<td>316</td>
<td>702 (102)</td>
<td>875 (127)</td>
<td>13</td>
<td>52</td>
</tr>
<tr>
<td>S4-37B</td>
<td>316</td>
<td>694 (101)</td>
<td>876 (127)</td>
<td>14</td>
<td>53</td>
</tr>
<tr>
<td>COND</td>
<td>$\sigma_{0.2}$ (MPa, ksi)</td>
<td>$\sigma_{u}$ (MPa, ksi)</td>
<td>ELONG %</td>
<td>RA %</td>
<td>TOUGHNESS $\sigma_{\gamma}$ (MPa $\cdot$ m$^{1/2}$, ksi $\cdot$ in.$^{1/2}$)</td>
</tr>
<tr>
<td>------</td>
<td>-------------------------</td>
<td>-------------------------</td>
<td>---------</td>
<td>------</td>
<td>---------------------------------------------------------</td>
</tr>
<tr>
<td>S2A</td>
<td>910 (132)</td>
<td>1006 (146)</td>
<td>15</td>
<td>37</td>
<td>85 (78)</td>
</tr>
<tr>
<td>S2B</td>
<td>1005 (146)</td>
<td>1087 (158)</td>
<td>8</td>
<td>36</td>
<td>73 (66)</td>
</tr>
<tr>
<td>S4B</td>
<td>983 (142)</td>
<td>1099 (159)</td>
<td>9</td>
<td>33</td>
<td>97 (88)</td>
</tr>
<tr>
<td>T2B</td>
<td>1120 (162)</td>
<td>1221 (177)</td>
<td>7</td>
<td>22</td>
<td>49 (45)</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{0.2}$ (ksi)</td>
<td>$\sigma_U$ (ksi)</td>
<td>e (%)</td>
<td>RA (%)</td>
<td>$K_{IC}$ (ksi $\sqrt{in}$)</td>
</tr>
<tr>
<td>---------------------</td>
<td>----------------------</td>
<td>------------------</td>
<td>-------</td>
<td>--------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>Su = 145 ksi</td>
<td>132</td>
<td>142</td>
<td>15</td>
<td>47</td>
<td>69</td>
</tr>
<tr>
<td>Ti-6Al-4V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CORONA-5</td>
<td>132</td>
<td>146</td>
<td>15</td>
<td>37</td>
<td>85</td>
</tr>
<tr>
<td>Su = 160-165 ksi</td>
<td>155</td>
<td>165</td>
<td>10</td>
<td>20</td>
<td>30 est</td>
</tr>
<tr>
<td>Ti-6Al-4V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CORONA-5</td>
<td>144</td>
<td>158</td>
<td>9</td>
<td>34</td>
<td>88</td>
</tr>
<tr>
<td>Ti-10V-2Fe-3Al</td>
<td>150</td>
<td>160</td>
<td>8</td>
<td>15</td>
<td>74 est</td>
</tr>
<tr>
<td>Su = 180 ksi</td>
<td>162</td>
<td>177</td>
<td>7</td>
<td>22</td>
<td>45</td>
</tr>
<tr>
<td>CORONA-5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ti-10V-2Fe-3Al</td>
<td>170</td>
<td>180</td>
<td>10</td>
<td>20</td>
<td>49 est</td>
</tr>
</tbody>
</table>

REFERENCES:

1. AFML-TR-78-68
2. TIMET BULLETIN
SECTION II

Fatigue Life Data

The following S-N curves are included:

A. S-N, 700°F, k = 1
   S1, S2A, S2B, S3, S4A, S4B, T2

B. S-N, 700°F, k = 2.55
   S1, S2A, S2B, S3, S4A, S4B, T2

C. S-N, 600°F, k = 1
   S1, S2A, S2B, S3, S4A, S4B, T2

D. Comparison plot for three strength levels of CORONA-5

E. Data normalized to ultimate tensile strength for S2k,
   S4B, and T2B
S1 Series (Kt = 1)

\[ \begin{align*}
\text{Smax (ksi)} & \quad \text{Nf (cycles)} \\
\triangle & \quad \text{S1 (Kt = 1)}
\end{align*} \]
S3 Series (Kt = 1)

$\Delta$ S3 (Kt = 1)
S4A Series (Kt = 1)

Diagram showing the relationship between $S_{max}$ (ksi) and $N_f$ (cycles) for S4A (Kt = 1).
T2B Series (Kt = 1)

\[ S_{\text{max}} \text{ (ksi)} \]

\[ S_{\text{max}} \text{ (MPa)} \]

\[ N_f \text{ (cycles)} \]
S1 Series \( (K_t = 2.55) \)

\[ \begin{align*}
\text{Smax (ksi)} & \quad \text{Nf (cycles)} \\
\triangle S1 \ (K_t = 2.55) \\
\end{align*} \]
S2A Series (Kt = 2.55)

\[ S_{\text{max}} \text{(ksi)} \]

\[ S_{\text{max}} \text{(MPa)} \]

\[ N_{f} \text{ (cycles)} \]

\[ N_{f} \text{ (cycles)} \]

\[ \Delta \text{ S2A (Kt = 2.55)} \]
S3 Series (Kt = 2.55)

![Graph showing fatigue life and stress amplitude relationship for the S3 series with Kt = 2.55. The graph plots Smax (ksi) against Nf (cycles).]
S2A Series (Kt = 1, 600F)
T2B Series (Kt = 1, 600F)

\[ S_{\text{max}} \text{ (ksi)} \]

\[ N_f \text{ (cycles)} \]

\[ S_{\text{max}} \text{ (MPa)} \]
SECTION III

Fatigue Crack Propagation Data

The following data is versus BLT at 100 psi and includes:

A. 70°F, Dry Air, R=0.30
   S2-24A (S2A), S2-34 (S2A), S4-7 (S4A), L-31 (L31)

B. 70°F, Dry Air, R=0.45
   S2-36 (S2A), S2-38 (S2A), S4-24 (S4A), L-31 (L31)

C. 250°F, Dry Air, R=0.45
   S2-40A (S2A), S2-38 (S2A), S4-24 (S4A), L-31 (L31)

D. 600°F, Dry Air, R=0.45
   S2-42A (S2A), S2-43 (S2A), S4-24 (S4A), L-31 (L31)

E. Comparison plots as a function of 1) microstructural condition, 2) R-ratio, and 3) temperature.
CORONA-5, S2-37
R = 0.08  FREQ = 20 Hz
LAB AIR AT 70F(21C)  6-11-82
PLOT OF DA/DN VS. DELTA-K (ENGLISH)

CORONA-5, S4-33
R = 0.08 FREQ = 20 Hz
LAB AIR AT 70F(21C) 12-APR-8

DA/DN
(inches/cycle)

1E-03

1E-04

1E-05

1E-06

1E-07

1E-08

1E-09

1E-00 1E 01 1E 02

DELTA-K
(ksi/sqrt(inches))
CORONA-5, T2-31
R = .08  FREQ = 20 HZ
LAB AIR AT 70F(21C)  JUN-15-8
CORONA-5, S2-36
R = 0.3  FREQ = 20 Hz
LAB AIR AT 70F(21C)  27-MAY-1
FLOT OF DA/DN VS DELTA-K (ENGLISH)

CORONA-5, S4-34
R = 0.3 FREQ = 20 HZ
LAB AIR AT 70°F (21°C) 9-MAR-82

DA/DN
(inches/cycle)

1E-03
1E-04
1E-05
1E-06
1E-07
1E-08
1E-09

1E 00
1E 01
1E 02

DELTA-K
(ksi × sqrt(inches))
CORONA-5, S4-36
R = .3  FREQ = 20 Hz
LAB AIR AT 250F(121C)  26-JAN

DA/DN
(inches/cycle)

DELTA-K
(ksi x sqrt(inches))
CORONA-5, T2-36
R = .3  FREQ = 20 HZ
LAB AIR AT 250F(121C)  7-FEB-
PLOT OF DA/DN VS. DELTA-K (ENGLISH)

CORONA-5, S2-42A
R = .3 FREQ = 20 HZ
LAB AIR AT 600F (316C) 28-JAN

DA/DN
(inches/cycle)

1E-03
1E-04
1E-05
1E-06
1E-07
1E-08
1E 00 1E 01 1E 02

DELTA-K
(inches/sqrt(inches))
PLOT OF DA/DN vs DELTA-K (ENGLISH)

CORONA-5, S2-43
R = .3  FREQ = 20 HZ
LAB AIR AT 600F (316C)  01-FEB

DA/DN
(inches/cycle)

1E-03

1E-04

1E-05

1E-06

1E-07

1E-08

1E-09

1E 00  1E 01  1E 02

DELTA-K
(ksi/sqrt(inches))
PLOT OF DA/DN vs DELTA-K (ENGLISH)

CORONA-5, S4-37
R = 0.3  FREQ = 20 HZ
LAB AIR AT 600F (316°C)  2-FEB-

DA/DN
(inches/cycle)

1E-03
1E-04
1E-05
1E-06
1E-07
1E-08
1E-09

DELTA-K
(ksi x sqrt(inches))

1E-00
1E 01
1E 02
PLOT OF DA/DN vs. DELTA-K (ENGLISH)

CORONA-5, T2-35
R = 0.3  FREQ = 20 HZ
LAB AIR AT 600°F (316°C)  07-FEB

DA/DN
(inches/cycle)

DELTA-K
(ksi*sqrt(inches))
CORONA-5, FN OF MICRO, LAB AIR AT 70F, R = 0.08, 20 Hz

\( \frac{d\alpha}{dN} \) (in/CYCLE)

\( \Delta K \text{(ksi} \sqrt{\text{in})} \)

Symbols:
- S2A
- S2B
- S4B
- T2B
CORONA-5, S2A AS A FN OF R, LAB AIR AT 70F, 20HZ

\[
\begin{align*}
\Delta & \quad S239A \quad R = 0.08 \\
\triangledown & \quad S230 \quad R = 0.3
\end{align*}
\]
CORONA-5, S2B AS A FN OF R, LAB AIR AT 70F, 20 Hz

\[ \frac{da}{dN} (\text{in/CYCLE}) \]

- \( \Delta R = 0.08 \)
- \( \triangledown R = 0.3 \)

\[ \Delta K (\text{ksi} \sqrt{\text{in}}) \]

Graph showing the relationship between \( \frac{da}{dN} \) and \( \Delta K \) with data points for different values of \( R \).
CORONA-5, S4B AS A FN OF R, LAB AIR AT 70°F, 20Hz

$\Delta$ S433 $R = 0.08$

$\nabla$ S434 $R = 0.3$

$\text{DELTA}-K = \text{KSI} \times \sqrt{\text{INCH}}$
CORONA-5, T2B AS A FN OF R, LAB AIR AT 70F, 20 Hz

\[ \Delta R = 0.08 \]
\[ \nabla R = 0.3 \]
CORONA-5, S2A AS A FN OF T, LAB AIR, R = 0.3, 20 Hz

Graph showing da/dN (in/CYCLE) vs. ΔK (ksi √in) for different temperatures: △ 70°F, ▲ 250°F, □ 600°F.
CORONA-5, S2B AS A FN OF T, LAB AIR, R = 0.3, 20 Hz
CORONA-5, S48 AS A FN OF T, LAB AIR, R = 0.3, 20 Hz
CORONA-5, T2B AS A FN OF T, LAB AIR, R = 0.3, 20 Hz

\[ \frac{da}{dN} \text{ (in/CYCLE)} \]

\[ \Delta K \text{ (ksi} \sqrt{\text{in})} \]

\[ \Delta 70^\circ F \]
\[ \nabla 250^\circ F \]
\[ \Box 600^\circ F \]
SECTION IV

Fractography

Fractographic comparisons of two high strength conditions, S4K and T2B at 700°F and 600°F; and comparison of R-ratio and temperature effects on the fractography of T2B are included.
70°F

$\Delta K = 5 \text{ ksi} \cdot \text{in}^{1/2}$

T2B

S4B
ΔK = 5 ksi \cdot in^{1/2} \hspace{1cm} ΔK = 10 ksi \cdot in^{1/2}

R = 0.3

R = 0.08

20 \mu m
T2B

$\Delta K = 5 \text{ ksi} \cdot \text{in}^{1/2}$
600°F

\[ \Delta K = 5 \text{ ksi} \cdot \text{in}^{1/2} \]

T2B

S4B
SECTION V

Sheet Rolling Study

The report issued by Crucible Research Center, Colt Industries for their subcontract effort, "CORONA-5 Coil Process Evaluation", is included in its entirety.
ABSTRACT

Results of an investigation to evaluate the effect of processing variables on grain size and mechanical properties of cold rolled CORONA 5 sheet are presented. Within the range of variables investigated (hot rolling temperature, inter-anneal cold reduction and annealing temperature), properties are relatively insensitive to the processing variations. Final grain size is affected only by hot rolling temperature and mechanical properties are affected only by final annealing temperature.
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<td>Distribution</td>
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I. Introduction

CORONA 5 (Ti-4.5Al-5Mo-1.5Cr) is an alpha-beta alloy which has attractive properties in heavy sections as well as thin gage sheet. In heavy section, fracture critical applications CORONA 5 is a good candidate because of its high fracture toughness. In sheet applications requiring superplastic forming and diffusion bonding, CORONA 5 has several advantages in that it is easy to process to sheet form, it can be superplastically formed at lower temperatures than the commonly used Ti-6Al-4V alloy, and it can be heat treated to high strength levels. An earlier program demonstrated that CORONA 5 is more amenable to coil sheet processing than the Ti-6Al-4V alloy. This work also showed that CORONA 5 has good room temperature formability. Objective of the present program is to determine to what extent processing variables affect grain size and mechanical properties of the sheet.
II. Experimental Results and Discussion

A. Materials

The standard grade CORONA 5 starting stock for the program was obtained in the form of 3-inch (76mm) thick plate. Table I gives the chemical analysis of this plate. The plate was produced under an earlier NAVAIR program. To eliminate the effects of prior hot working, the plate was beta annealed before hot rolling under the current program.

B. Processing

The beta annealed 3-inch (76mm) plate was cut into two sections and one section hot rolled from the beta field and one section hot rolled from the alpha-beta field. After hot rolling, sections of each hot band were cold rolled to 0.060-inch (1.5mm) sheet by four separate cold reduction cycles. A flow chart for the processing is shown in Figure 1. Descriptions of the hot and cold rolling follow.

1. Hot Rolling

The plate to be hot rolled from the beta field was heated to 1800F (980C) and unidirectionally rolled to 0.170-inch (4.3mm) hot band without reheating. The rolling was accomplished in 19 passes with a total time of 90 seconds from the furnace to completion of rolling. Approximate temperature of the hot band on the final pass was 1300F (705C). The hot band had a good surface and a small amount of edge cracking up to 0.120-inch (3mm) deep.

The alpha-beta rolled material was heated to 1650F (900C) and rolled to 0.170-inch (4.3mm) hot band in two cycles. Two cycles were required to prevent excessive cooling of the material in
the final stages of rolling. After reaching temperature initially the plate was rolled from 3-inch (76mm) thick to 0.750-inch (19mm) thick in 12 passes. Time for rolling was 70 seconds and the plate finished at about 1350F (730C). The plate was then reheated to 1650F (900C). Final rolling to 0.170-inch (4.3mm) hot band was done in 7 passes with an elapsed time of 40 seconds. Finishing temperature was about 1280F (695C). Surface of the hot band was uniform and the edges were free of cracking.

2. **Cold Rolling**

The beta rolled and alpha-beta rolled hot bands were cut into panels and unidirectionally cold rolled, maintaining the same direction as in hot rolling, to 0.060-inch (1.5mm) thick sheet. Each hot band was cold rolled via four cold reduction/annealing cycles as outlined in Figure 1. After cutting, the panels were annealed at either 1300F (705C) or 1500F (815C) for 5 minutes and air cooled. Annealed panels were then descaled by grit blasting and pickled in nitric-hydrofluoric mixed acid to remove the oxygen enriched surface layer of metal. The anneal, grit blast, and pickle were repeated after each cycle of cold rolling. In general, the cold rolling went well. Same edge trimming of the sheet was required to remove minor edge cracking.

C. **Characterization**

1. **Microstructure**

The microstructure of the CORONA 5 was examined on the L-S plane at several stages in the processing. Figure 2 shows the microstructure of the 3-inch (76mm) plate after beta annealing. The
as-hot rolled microstructure of the 0.170-inch (4.3mm) hot band is shown in Figure 3. Microstructure of the material rolled from above the beta transus is fine grained with some banding which appears to be a result of prior beta grain orientation. The material rolled from below the beta transus is somewhat coarser and contains elongated primary alpha platelets.

Figure 4 shows the microstructures of the two hot bands after annealing at 1300F (705C) and 1500F (815C). The annealing treatments produced a slight coarsening of the structures but are not significantly different from the hot rolled structures.

Figures 5 through 12 show the microstructures of the cold rolled sheet after processing to an intermediate stage of 0.105-inch (2.6mm) thick. For the alpha-beta rolled material, the higher annealing temperature and greater cold reduction per cycle tended to produce more refinement of the primary alpha and homogenization of the structure. The beta rolled material showed very little effect of cold reduction per cycle. Comparing the two annealing temperatures shows a slightly coarser structure after the higher temperature anneal.

Final microstructures of the 0.060-inch (1.5mm) sheet are shown in Figures 13 and 14. The structure of the alpha-beta rolled material annealed at 1300F (705C) and given four cycles of 20% cold reductions and anneals shows very little change over the hot rolled structure. The other three conditions (Figure 13) show a substantial amount of refinement of the primary alpha and are generally similar to one another.
Microstructures of the beta rolled material, Figure 14, are all essentially the same at finished size with the higher temperature anneal showing a slightly coarser structure. Comparing the alpha-beta rolled sheet with the beta rolled sheet shows the structures are similar except for the presence of residual primary alpha in the alpha-beta rolled sheet.

2. **Grain Size**

Grain size measurements were made on the 0.060-inch (1.5mm) sheet after annealing four hours at 1650F to produce complete recrystallization of the structure. The recrystallized microstructures are shown in Figure 15. Average grain size for all grains was determined as well as individual alpha and beta grain sizes. These results are given in Table II. The results show an effect of hot rolling temperature but no effect for annealing temperature or cold reduction per cycle on grain size. Grain sizes for the beta rolled material are about 1 μm smaller than the alpha-beta rolled material reflecting the smaller as-hot rolled grain size in the beta rolled material.

3. **Mechanical Properties**

Tensile properties were determined on the annealed hot band and cold rolled plus annealed 0.060-inch (1.5mm) sheet. Bend ductility was also determined on the cold rolled sheet. Tensile properties of the hot band are given in Table III. Hot rolling temperature has very little effect on the properties. Annealing temperature has a significant effect with strengths about 20ksi (138MPa) lower for the higher temperature 1500F (815C) anneal. In all cases,
directionality is relatively high with about a 30ksi (207MPa) difference between longitudinal and transverse yield strengths. Neither hot rolling temperature or annealing temperature appear to have an effect on tensile ductility.

Tensile properties of the 0.060-inch (1.5mm) sheet are given in Table IV. The tensile and yield strengths of the sheet are basically the same as the hot band for a given annealing temperature, although the sheet tends to have somewhat higher ductility. Inter-anneal cold reduction has very little effect on the properties. The amount of directionality in the sheet is changed very little from the hot band. Bend ductility of the sheet is highest in material annealed at 1500F (815C). Annealing temperature is the only parameter which has a measurable effect on bend ductility.
III. Conclusions

1. A very fine grain size can be produced in CORONA 5 sheet by conventional processing. Within the scope of this program the only parameter which affects grain size is hot rolling temperature. Hot rolling from above the beta transus temperature resulted in a finer grain size than hot rolling from below the beta transus.

2. Room temperature tensile properties and bend properties are not affected by any of the hot or cold processing variations examined under the program. Only final annealing temperature had a significant effect on properties.

Prepared by:

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Research Engineer

Approved by:

J. H. Moll
Technical Director
P/M & Titanium

E. J. Dulis
President
V. References


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<th></th>
<th></th>
<th></th>
<th></th>
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<th>Beta Transus F (C)</th>
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<tr>
<td>Al</td>
<td>Mo</td>
<td>Cr</td>
<td>Fe</td>
<td>C</td>
<td>N</td>
<td>O</td>
<td>H</td>
<td>Ti</td>
</tr>
<tr>
<td>4.4</td>
<td>5.1</td>
<td>1.46</td>
<td>.20</td>
<td>.065</td>
<td>.011</td>
<td>.174</td>
<td>.0056</td>
<td>Bal. 1720 (940)</td>
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TABLE II
Grain Size of 0.060-inch (1.5mm) CORONA 5
Cold Rolled Sheet Annealed 4 hours at 1650F (900C)

<table>
<thead>
<tr>
<th>Condition</th>
<th>Mean Linear Intercept</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Alpha(^a) ((\mu m))</td>
</tr>
<tr>
<td>Hot Roll 900C + Anneal 705C &amp; CR20% 4 cycles</td>
<td>3.0 ± 0.8</td>
</tr>
<tr>
<td>Hot Roll 900C + Anneal 705C &amp; CR37% 2 cycles</td>
<td>3.1 ± 0.6</td>
</tr>
<tr>
<td>Hot Roll 900C + Anneal 815C &amp; CR20% 4 cycles</td>
<td>2.6 ± 1.0</td>
</tr>
<tr>
<td>Hot Roll 900C + Anneal 815C &amp; CR37% 2 cycles</td>
<td>3.2 ± 0.8</td>
</tr>
<tr>
<td>Hot Roll 980C + Anneal 705C &amp; CR20% 4 cycles</td>
<td>2.8 ± 0.3</td>
</tr>
<tr>
<td>Hot Roll 980C + Anneal 705C &amp; CR37% 2 cycles</td>
<td>2.3 ± 0.2</td>
</tr>
<tr>
<td>Hot Roll 980C + Anneal 815C &amp; CR20% 4 cycles</td>
<td>2.1 ± 0.1</td>
</tr>
<tr>
<td>Hot Roll 980C + Anneal 815C &amp; CR37% 2 cycles</td>
<td>2.3 ± 0.6</td>
</tr>
</tbody>
</table>

\(^a\) Mean linear intercept determined from the relationship described by Underwood\(^3\) where:

\[
\text{Mean Intercept Length Phase A} = \frac{1}{N_{LA}} \left(1 - \frac{V_{V/A}}{N_{LA}}\right)
\]

\(N_{LA} = \text{Phase A grains per unit length}\)

\(V_{V/A} = \text{Volume fraction phase A}\)

\(^b\) Mean linear intercept of all grains determined by counting number of grain boundary intercepts per unit line length and dividing line length by number of intercepts.
### TABLE III

Tensile Properties of Annealed CORONA 5
Hot Band (Heat R52071)

<table>
<thead>
<tr>
<th>Hot Rolling Temperature F (°C)</th>
<th>Anneal Temperature F (°C)</th>
<th>Test Direction</th>
<th>Tensile Strength ksi (MPa)</th>
<th>Yield Strength 0.2% Offset ksi (MPa)</th>
<th>Elongation (%)</th>
<th>Reduction of Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1650 (900)</td>
<td>1300 (705)</td>
<td>L</td>
<td>166.8 (1149)</td>
<td>161.7 (1114)</td>
<td>10.5</td>
<td>33.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>T</td>
<td>191.5 (1319)</td>
<td>189.3 (1304)</td>
<td>10.5</td>
<td>21.9</td>
</tr>
<tr>
<td>1650 (900)</td>
<td>1500 (815)</td>
<td>L</td>
<td>144.2 (993)</td>
<td>137.7 (949)</td>
<td>10.5</td>
<td>24.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>T</td>
<td>171.3 (1180)</td>
<td>168.3 (1159)</td>
<td>9.5</td>
<td>28.5</td>
</tr>
<tr>
<td>1800 (980)</td>
<td>1300 (705)</td>
<td>L</td>
<td>163.0 (1123)</td>
<td>159.4 (1098)</td>
<td>4.5&lt;sup&gt;c&lt;/sup&gt;</td>
<td>39.1</td>
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<tr>
<td></td>
<td></td>
<td>T</td>
<td>198.5 (1368)</td>
<td>196.9 (1357)</td>
<td>4.5&lt;sup&gt;c&lt;/sup&gt;</td>
<td>18.9</td>
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<tr>
<td>1800 (980)</td>
<td>1500 (815)</td>
<td>L</td>
<td>143.9 (991)</td>
<td>142.8 (984)</td>
<td>9.0</td>
<td>33.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>T</td>
<td>174.4 (1202)</td>
<td>172.0 (1185)</td>
<td>8.5</td>
<td>25.1</td>
</tr>
</tbody>
</table>

<sup>a</sup>Samples annealed 5 minutes at indicated temperature and air cooled.

<sup>b</sup>L = longitudinal
T = transverse

<sup>c</sup>Fracture near edge of gage section.
TABLE IV
Tensile and Bend Properties of Cold Rolled
CORONA 5 Sheet (Heat R32071, 0.060-inch thick)

<p>| Hot Rolling | Inter-annal | Anneal | Test | Tensile Strength | Yield Strength | Elongation | Reduction of Area | Minimum Bend |
| Temperature | Cold Reduction | Temperature | Direction | ksi (MPa) | 0.2% Offset ksi (MPa) | (%) | (%) | R/t |</p>
<table>
<thead>
<tr>
<th>(°C)</th>
<th>(%)</th>
<th>(°C)</th>
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<th></th>
<th></th>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>1650 (900)</td>
<td>20</td>
<td>1300 (705)</td>
<td>L</td>
<td>169.2 (1166)</td>
<td>157.2 (1083)</td>
<td>11</td>
<td>35.5</td>
<td>4.2</td>
</tr>
<tr>
<td>1650 (900)</td>
<td>37</td>
<td>1300 (705)</td>
<td>L</td>
<td>173.4 (1195)</td>
<td>163.2 (1124)</td>
<td>9</td>
<td>38.1</td>
<td>6.8</td>
</tr>
<tr>
<td>1650 (900)</td>
<td>20</td>
<td>1500 (815)</td>
<td>L</td>
<td>152.3 (1049)</td>
<td>138.8 (956)</td>
<td>13</td>
<td>32.3</td>
<td>3.6</td>
</tr>
<tr>
<td>1650 (900)</td>
<td>37</td>
<td>1500 (815)</td>
<td>L</td>
<td>153.7 (1059)</td>
<td>140.8 (970)</td>
<td>16</td>
<td>29.7</td>
<td>5.7</td>
</tr>
<tr>
<td>1800 (980)</td>
<td>20</td>
<td>1300 (705)</td>
<td>L</td>
<td>169.4 (1167)</td>
<td>162.5 (1120)</td>
<td>8</td>
<td>36.1</td>
<td>3.5</td>
</tr>
<tr>
<td>1800 (980)</td>
<td>37</td>
<td>1300 (705)</td>
<td>L</td>
<td>171.6 (1196)</td>
<td>165.8 (1142)</td>
<td>6</td>
<td>37.6</td>
<td>5.6</td>
</tr>
<tr>
<td>1800 (980)</td>
<td>20</td>
<td>1500 (815)</td>
<td>L</td>
<td>152.8 (1053)</td>
<td>142.2 (980)</td>
<td>12</td>
<td>28.0</td>
<td>4.7</td>
</tr>
<tr>
<td>1800 (980)</td>
<td>37</td>
<td>1500 (815)</td>
<td>L</td>
<td>152.8 (1053)</td>
<td>142.4 (981)</td>
<td>14</td>
<td>34.8</td>
<td>6.8</td>
</tr>
</tbody>
</table>

Note: Test results are average of two tests.

*Sheet annealed 5 minutes at indicated temperature and air cooled.

| L = longitudinal |
| T = transverse |

| R = Die radius |
| t = Sheet thickness |
Figure 1. Flow chart for processing of cold rolled CORONA 5 sheet to evaluate the effect of hot rolling temperature, inter-anneal cold reduction, and annealing temperature on grain size and properties.
Figure 2. Microstructure of CORONA 5 3-inch (76mm) plate after beta annealing at 1750F (955C).
Figure 3. Microstructure of 0.170-inch (4.3mm) CORONA 5 hot band as hot rolled.
Figure 4. Microstructure of 0.170-inch (4.3mm) thick hot band after annealing at 1300°F (705°C) and 1500°F (815°C) for 5 minutes and air cooling.

500X
Figure 5. Microstructure of alpha-beta rolled hot band annealed at 1300°F (705°C) and given two 20% cold reductions to 0.105-inch (2.6mm) thick. 500X

Figure 6. Microstructure of alpha-beta rolled hot band annealed at 1300°F (705°C) and given one 37% cold reduction to 0.105-inch (2.6mm) thick. 500X
Figure 7. Microstructure of alpha-beta rolled hot band annealed at 1500°F (815°C) and given two 20% cold reductions to 0.105-inch (2.6mm) thick. 500X

Figure 8. Microstructure of alpha-beta rolled hot band annealed at 1500°F (815°C) and given one 37% cold reduction to 0.105-inch (2.6mm) thick. 500X
Figure 9. Microstructure of beta rolled hot band annealed at 1300°F (705°C) and given two 20% cold reductions to 0.105-inch (2.6mm) thick. 500X

Figure 10. Microstructure of beta rolled hot band annealed at 1300°F (705°C) and given one 37% cold reduction to 0.105-inch (2.6mm) thick. 500X
Figure 11. Microstructure of beta rolled hot band annealed at 1500°F (815°C) and given two 20% cold reductions to 0.105-inch (2.6mm) thick. 500X

Figure 12. Microstructure of beta rolled hot band annealed at 1500°F (815°C) and given one 37% cold reduction to 0.105 inch (2.6mm) thick. 500X
Figure 13. Microstructure of 0.060-inch (1.5mm) CORONA 5 cold rolled sheet produced from hot band rolled from below the beta transus. 500X
Figure 14. Microstructure of 0.060 (1.5mm) CORONA 5 cold rolled sheet produced from hot band rolled from above the beta transus. 500X
Figure 15. Microstructure of 0.060-inch (1.5mm) CORONA 5 sheet after annealing 1650F (900C) 4 hours for determination of recrystallized grain size. 500X
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SECTION VI

Fatigue Crack Propagation Data and Fractography from Previous Program

Miscellaneous FCP data and fractography from the previous program are included for comparison with the current data.
\[ \Delta K = 22 \text{ MPa} \cdot m^{1/2} \]

LA(20): \( \frac{da}{dN} = 3 \times 10^{-4} \text{ mm/CYCLE} \)

NaCl(1): \( \frac{da}{dN} = 1 \times 10^{-4} \text{ mm/CYCLE} \)
T1: $8 \times 10^{-6}$ mm/CYCLE

T2: $2 \times 10^{-6}$ mm/CYCLE

$\Delta K = 6.5 \text{ MPa} \cdot \text{m}^{1/2}$
S1: \( \frac{da}{dN} = 9 \times 10^{-6} \text{ mm/CYCLE} \)

T1: \( \frac{da}{dN} = 4 \times 10^{-5} \text{ mm/CYCLE} \)

\( \Delta K = 10 \text{ MPa} \cdot \text{ m}^{1/2} \)
S1(20H): \( \frac{da}{dN} = 2 \times 10^{-6} \text{ mm/CYCLE} \)

S1(300H): \( \frac{da}{dN} = 1 \times 10^{-5} \text{ mm/CYCLE} \)

\[ \Delta K = 7 \text{ MPa} \cdot \text{m}^{1/2} \]
CORONA-5, FORGING S2
LAB AIR, 10-20 Hz, R = 0.3
Ο 20 ppm HYDROGEN
X 100 ppm HYDROGEN
+ 300 ppm HYDROGEN