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MECHANICAL PROPERTIES AND CORROSION BEHAVIOUR OF 2091 SHEET MATERIAL

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Abstract

To evaluate the potential of 2091 sheet material the alloy was heat treated to three different underaged tempers. Mechanical properties were determined by tensile, fracture toughness, and fatigue crack propagation tests. Stress corrosion susceptibility and other corrosion properties were investigated. The results showed that advancing aging improves tensile and SCC properties but deteriorates fracture toughness and general corrosion behaviour.

1. Introduction

The Al-Li alloy 2091 was developed by CEGEDUR PECHINERY (tradename: CP274) to match the properties of conventional damage tolerant Al alloys like 2024-T3 or 2214-T6 [1]. Since the alloy 8090 - developed by RAE and Alcan International - in its damage tolerant version (tradename: LITAL C) also follows this goal, these two alloys can be considered as candidate materials for a good portion of future aircraft's damage tolerant structural parts.

The alloy 2091 offers a density reduction of about 8% and an increase of the specific modulus of about 15% when compared to 2XXX alloys [1]. In the course of the development of an appropriate temper for damage tolerant properties for this alloy it became evident that heat treatments had to be chosen carefully to match the properties of the conventional alloys to be replaced. Especially the fracture toughness goal made it necessary to modify the heat treatments, the trend going to stronger underaging. Similar experiences were also made by other Al-Li producers.

The purpose of the present investigation was to study how variations of the age hardening degree for underaged tempers influence the mechanical as well as corrosion properties. In some instances the results were compared to the properties of other aircraft Al alloys.

2. Experimental Procedures

1.6 mm thick 2091 sheet was supplied by CEGEDUR PECHINERY in an as-quenched and stretched condition. The fully recrystallized sheet had the composition (wt.-%) Al-2.0Cu-2.0Li-1.4Mg-0.07Zr-0.04Fe-0.03Si. The sheet was artificially aged to three aging conditions (see Table 1) all being underaged. For tensile test specimens with the gauge dimensions 25 mm long and 8 mm wide an extensometer was used to measure the elastic modulus and 0.2% yield strength. Fracture toughness and fatigue crack propagation measurements were performed on 80 mm wide and 230 mm long CCT specimens.

Texture investigations were made in the middle of the sheet on an X-ray goniometer by employing the reflection technique. Fracture surfaces were examined by SEM.

The stress corrosion cracking (SCC) behaviour in the rolling direction (RD) was investigated using bent-beam specimens with a width of 20 mm and a length in the range of 200-215 mm, depending upon the required stress. For any stress in the elastic region of the sheet material the length of the two point loaded specimens was calculated according to ASTM G 39. Below 100 MPa the loading procedure becomes unreliable, because the difference between the required specimen length and the holder span is extremely small. The strained specimens were alternately immersed in 3.5% NaCl solution for a maximum test period of 30 days. To determine the threshold stress two failure criteria were applied: macroscopic fracture and crack initiation. The latter required frequent inspections of the specimens using a light microscope at a 20-fold magnification.
The susceptibility to intergranular corrosion was investigated according to MIL-H-6088F.

The exfoliation corrosion behaviour was evaluated by performing EXCO-tests (ASTM G34-79) and intermittent acidified salt spray tests (MASTMAASIS) [2]. After various time periods of the MASTMAASIS test the weight loss of the specimens was measured after removing the corrosion products from the surface according to the cleaning procedure suggested in ASTM G1.

The pitting and rest potentials in an aerated aqueous 3.5% NaCl solution was measured potentiodynamically with a scan rate of 0.05 mV/min. Before mounted in the cell the surfaces of the specimens were ground with an 800 grit emery paper.

3. Results and Discussion

3.1 Tensile Properties and Fracture Behaviour

The tensile data of specimens tested in the rolling direction (RD) are given in Table 1 for the three 2091 tempers chosen in this investigation. For comparison values for 2024-T3 clad sheet are also included. The 2091 results clearly show an 8% higher Young's modulus compared to 2024. The 0.2% yield and ultimate tensile strength values are increasing with advancing artificial aging. Only a small difference was found between the low (12h 135 °C) and the medium temper (12h 150 °C). The ductility is always sufficiently high. All tensile test results match well the properties of 2024-T3. It should be mentioned that even after 100h aging at 150 °C the alloy is still below peak strength, i.e., the highest aging chosen in this investigation (100h 150 °C) still represents a strongly underaged temper.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Aging Treatment</th>
<th>E [GPa]</th>
<th>YS [MPa]</th>
<th>TS [MPa]</th>
<th>EI [%]</th>
<th>Kc [MPa · m^1/2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2091</td>
<td>12h 135 °C</td>
<td>78.2</td>
<td>355</td>
<td>455</td>
<td>16.3</td>
<td>56.5</td>
</tr>
<tr>
<td></td>
<td>12h 150 °C</td>
<td>78.2</td>
<td>365</td>
<td>460</td>
<td>16.1</td>
<td>56.5</td>
</tr>
<tr>
<td></td>
<td>100h 150 °C</td>
<td>78.2</td>
<td>390</td>
<td>492</td>
<td>14.4</td>
<td>40.0</td>
</tr>
<tr>
<td>2024</td>
<td>T3</td>
<td>72.4</td>
<td>365</td>
<td>458</td>
<td>20.5</td>
<td>----</td>
</tr>
</tbody>
</table>

Table 1. Mechanical properties of the three different 2091 tempers compared to 2024-T3.

![Figure 1](image1.png)

It is reported in the literature that Al-Li sheet material often reveals a pronounced anisotropy of tensile properties with respect to RD which is due to a strong crystallographic texture [3 to 6]. To study this effect for the alloy 2081 additional tensile tests were performed on specimens with a variety of angles with respect to RD, and also for different aging treatments. The yield strength and elongation profiles for 2091 (100h 150 °C) are plotted in Figure 1 and compared to the conventional high strength Al alloys 2024, 7075 and 7475 as well as to the Al-Li alloy 8090. 2091 reveals a profile with a yield strength minimum and an elongation maximum at 60 degrees off the RD. Similar but more pronounced profiles have been found for 8090 sheet (Figure 1) [3 to 6]. Looking at the {111} pole figure of the 2091 sheet (Figure 2) and comparing it to the respective pole
it is evident that the alloy investigated here exhibits a stronger texture than 2024. The texture of 8090, however, is much more pronounced. The latter is partly due to the unrecrystallized grain structure of the 8090 sheet investigated, but the behaviour of 2091 confirms the general tendency of Al-Li alloys to exhibit a stronger crystallographic texture compared to conventional alloys. The degree of age hardening only shifts the 2091 profiles but does not influence the shape of the curves.

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![Figure 2. (111) pole figure of 2091.](image)

SEM investigations of the fracture surfaces of broken tensile specimens exhibit a transgranular dimple and slip band fracture for the lowest temper (12h 135 °C), Figures 3a and 3b. Large dimples with broken particles were seldom found. This is due to the very low Fe and Si content and therefore very low volume fraction of constituent particles in comparison to 2XXX and 7XXX alloys. Specimens with the highest temper (100h 150 °C) reveal a predominantly intergranular fracture mode (Figures 3c and 3d) although the ductility for this temper is also high (Table 1). At high magnification slip steps are visible on the grain boundary surfaces indicating that plastic deformation has taken place within the matrix (Figure 3d). The medium temper (12h 150 °C) already shows a mixture of transgranular and grain boundary fracture.

The grain boundary failure mode seems to be an inherent matter of artificially aged Al-Li containing Al alloys. It is assumed that this fracture mode is mainly due to a segregation of Li or trace elements like Na to the grain boundaries, or that the grain boundary particles of equilibrium phases are responsible for the intergranular fracture. The mechanism which causes the drastic change in fracture mode in the present work is a matter of further investigation.

### 3.2 Fracture Toughness and Fatigue Crack Propagation

The fracture toughness measured for the three 2091 tempers is included in Table 1. It should be mentioned that the values are relatively low because of the small CCT specimens employed. There is no difference between the two 12h tempers, but the fracture toughness drops strongly for the 100h 150 °C condition.

It is known that generally the fracture toughness decreases with increasing age hardening degree. Additionally, Al-Li alloys tend to have reduced toughness when the fracture mode changes from transgranular to intergranular. Both arguments contribute to the drastic drop in fracture toughness found for 2091 (Table 1).

Figure 4 shows the results of the fatigue crack propagation tests for the three 2091 tempers. Nearly no difference between the various conditions was found for low and intermediate crack growth rates. This is expected since the fatigue crack path for all tempers is predominantly a transgranular slip band fracture mode. At high growth rates, however, the 100h 150 °C temper is inferior (Figure 4). This is consistent with the fracture toughness results in Table 1, since for $K_t$ the same ranking is observed. At high fatigue crack growth rates the fracture modes approach those observed in a fracture toughness test.
Figure 3. Fracture surfaces of 2091 tensile specimens artificially aged 12h at 135 °C (a and b) or 100h at 150 °C (c and d).

Figure 4. Fatigue crack propagation behaviour of the three tempers of 2091.
3.3 Stress Corrosion Cracking Behaviour

As found in the bent-beam stress corrosion tests the alloy 2091 in the low and medium temper is susceptible to stress corrosion cracking in RD. In Table 2 the threshold stresses for the three tempers are listed. The values are determined using both, the crack initiation and the macroscopic fracture as failure criteria. According to the crack initiation criterion all bent-beam specimens in the two 12 hours tempers stressed to 100 MPa and higher have failed. A macroscopic fracture threshold stress of 150 MPa was measured for the alloy aged 12h at 135 °C, whereas the threshold stress increases to 200 MPa when the material was aged 12h at 150 °C. In the temper 100h at 150 °C the sheet material is less susceptible to SCC. Up to stresses of 300 MPa which corresponds to 75% of 0.2% proof stress no crack initiation was observed. At 330 MPa and above specimens with a crack initiated by SCC failed macroscopically during the test time. The results indicate that with advancing aging the SCC resistance increases. For comparison the threshold stresses of 2024-T3 unclad sheet are also given in Table 2. Up to 350 MPa the latter material did not fail within 30 days. Crack initiation was observed at stresses of 200 MPa and higher. For longer immersion times the surfaces of the specimens were covered with corrosion products and the first crack was difficult to detect. Therefore the crack initiation threshold stress of the unclad 2024-T3 sheet material is possibly lower than indicated in Table 2.

<table>
<thead>
<tr>
<th>Material</th>
<th>Temper</th>
<th>Threshold Stress [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2091-CP274</td>
<td>12h/135 °C</td>
<td>Crack Initiation &lt; 100</td>
</tr>
<tr>
<td>2091-CP274</td>
<td>12h/150 °C</td>
<td>&lt; 100</td>
</tr>
<tr>
<td>2091-CP274</td>
<td>100h/150 °C</td>
<td>300</td>
</tr>
<tr>
<td>2024-T3, unclad</td>
<td></td>
<td>Fracture 150</td>
</tr>
<tr>
<td>2024-T3, unclad</td>
<td></td>
<td>&gt; 350</td>
</tr>
</tbody>
</table>

Table 2. Thresholds (bent-beam specimens) of 2091 in different tempers and of unclad 2024-T3 in RD regarding different failure criteria, tested in 3.5% NaCl in alternate immersion for 30 days.

In Figure 5 the fracture surface of a bent-beam specimen aged 12h at 135 °C is shown. The SCC induced fracture is entirely intergranular, whereas the fracture mode is transgranular when the specimens in the same temper are tensile tested in an inert environment (Figure 3a and 3b). This change in the fracture mode may be caused by hydrogen embrittlement as proved by preexposure corrosion tests. Specimens aged 12h at 135 °C were 300h and 400h immersed continuously in 3.5% NaCl solution and then immediately tensile tested in inert environment with a strain rate of $5 \cdot 10^{-7}s^{-1}$. The fracture mode than was also predominantly intergranular. This corrosion induced transition from transgranular to intergranular fracture can be explained by hydrogen absorbed during precorrosion.

Figure 5. Fracture surface of a 2091 bent-beam specimen aged 12h at 135 °C tested in 3.5% NaCl under alternate immersion.
3.4 Localized Corrosion Behaviour

After immersion in an aqueous solution of 57 g/l NaCl and 10 ml/l H2O2, according to MIL-H-6088F pitting was observed. The susceptibility to pitting decreases with increasing aging. In the metallographic cross section of the specimens of all three heat treatments additional to pitting intergranular corrosion was observed, up to 250 μm deep.

The exfoliation corrosion behaviour of the 2091 alloy in all three tempers is shown in Table 3 as determined by the EXCO test and compared with the results of unclad 2024-T3 sheet material. The susceptibility of 2091 to exfoliation corrosion is more severe in the aging condition 100h 150 °C compared to the more underaged conditions. After 96h immersion time for the latter tempers an EA/EB exfoliation rating was observed, whereas in the 100h 150 °C heat treatment the rating is EB/EC which is one degree higher. The unclad 2024-T3 sheet material is less susceptible to exfoliation corrosion. Only the degree P/EA was determined.

<table>
<thead>
<tr>
<th>Material</th>
<th>Temper</th>
<th>Exposure Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>24h 48h 72h 96h</td>
<td></td>
</tr>
<tr>
<td>2091-CP274</td>
<td>12h/135 °C</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td>12h/150 °C</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td>100h/150 °C</td>
<td>N</td>
</tr>
<tr>
<td>2024</td>
<td>T3, unclad</td>
<td>N/P</td>
</tr>
</tbody>
</table>

Table 3. Visual assessment of exfoliation corrosion according to ASTM G34-79.

In the MASTMAASIS test the exfoliation corrosion of 2091 was less severe as compared with the results of the EXCO test. After five weeks exposure period in the salt spray chamber a P/EA exfoliation rating was determined for the three heat treatments. The corrosion attack was different for all aging conditions but the classification in the ASTM G34-79 standard is too rough to discriminate between these various degrees of attack. However, the difference in the exfoliation corrosion behaviour is better characterized by weight loss measurements (Figure 6). After four and five weeks exposure time the weight loss is higher in the 100h 150 °C heat treatment as compared with that in the two other aging conditions. In both exfoliation corrosion tests the same performance of 2091 in all three tempers was found, i.e. the susceptibility increases with increasing aging. Up to now, results of marine exposure experiments are not available. Therefore, a comment on the significance of both test methods for service behaviour is actually not possible.

In Table 4 the pitting and rest potentials of 2091 for all tempers in aerated 3.5% NaCl solution are given compared with those of conventional Al alloys. With increasing aging pitting and rest potentials of 2091 are shifted in negative direction. There was no significant difference to the pitting potentials of conventional alloys.
Table 4. Pitting and rest potentials in aerated aqueous 3.5% NaCl solution (pH = 6) potentiodynamically measured with a scan rate of 0.05 mV/min.

<table>
<thead>
<tr>
<th>Material</th>
<th>Temper</th>
<th>Pitting Pot. mV (SCE)</th>
<th>Rest Pot. mV (SCE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2091-CP274</td>
<td>nat. aged</td>
<td>-653</td>
<td>-655</td>
</tr>
<tr>
<td></td>
<td>12h/135 °C</td>
<td>-684</td>
<td>-687</td>
</tr>
<tr>
<td></td>
<td>12h/150 °C</td>
<td>-689</td>
<td>-691</td>
</tr>
<tr>
<td></td>
<td>100h/150 °C</td>
<td>-755</td>
<td>-756</td>
</tr>
<tr>
<td>2024</td>
<td>T351</td>
<td>-618</td>
<td>-620</td>
</tr>
<tr>
<td>7010</td>
<td>T7651</td>
<td>-748</td>
<td>-749</td>
</tr>
</tbody>
</table>

4. Summary and Conclusions

- Increased aging of underaged tempers of 2091 leads to a change in fracture mode (transgranular = > intergranular)
- Decrease in fracture toughness
- Increase in SCC resistance
- Drop in uniform and exfoliation corrosion resistance

- The fatigue crack propagation behaviour at low and medium growth rates is not influenced by the aging treatments performed in this study.
- Increased corrosion attack and reduced SCC susceptibility with advancing aging confirm the experience that both phenomena go into opposite directions.
- The drop of rest and pitting potential with increased artificial aging indicates an increasing electrochemical activity of the material.
- In the more underaged tempers stress corrosion cracks propagate probably as a result of hydrogen embrittlement.

The present results revealed that for the development of an appropriate heat treatment to meet damage tolerant requirements for 2091, both, mechanical and corrosion properties have to be carefully balanced.

5. References