THE EFFECT OF BLUNT NOTCHES AND SAW CUTS ON THE STATIC STRENGTH OF 2024-T3 AND 7075-T6 SHEET MATERIAL

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Abstract - Sheet specimens were produced with circular holes and slotted holes to cover a $K_t$ range from 2 to 5, while the notch root radius was 2 or 5 mm. The effect of the notches on the static net section failure stress was small, involving an average reduction at $K_t \sim 3$ of about 8 and 1 percent for 2024-T3 and 7075-T6 respectively. The trends observed can be understood qualitatively from plasticity considerations. For saw cuts, the failure stress corresponded to net section yield for the 2024-T3 alloy, while for 7075-T6 a modified Feddersen diagram represented the results quite well.

NOTATION

2a  length of saw cut or major axis of ellips

$\rho$  hole diameter

$K_c$  plane stress fracture toughness

$r_p$  plastic zone size correction

W  specimen width

$\rho$  notch root radius

$\sigma_{0.2}$  yield stress

$\sigma_U$  ultimate tensile stress

$\sigma_{nU}$  net section failure stress of notched specimen

1 N/mm$^2$  = 0.145 ksi = 0.102 kgf/mm$^2$

1 MN/mm$^{3/2}$  = 0.910 ksi $\sqrt{\ln} = 3.225$ kgf/mm$^{3/2}$
INTRODUCTION

The effect of blunt notches (holes) on the static strength of aluminium alloy sheet materials was studied in two NLR research programs. Broek and Jacobs [1] carried out a large number of tests with a notch in the center of the specimen. The main variables studied were $K_t$ and material ductility. They also compiled various data from the literature. Defining:

$$\sigma_{nU} = \text{net section failure stress of the notched specimen, and}$$

$$\sigma_U = \text{ultimate tensile strength of the material,}$$

the major observations of Ref. 1 are:

(a) $\sigma_{nU}$ can be larger than $\sigma_U$ for moderate $K_t$ values (<3).
   For larger $K_t$ values $\sigma_{nU}$ is a decreasing function of $K_t$.

(b) Low ductility materials (7075-T6) show higher $\sigma_{nU}/\sigma_U$ values than high ductility materials (see Figure 6).

(c) The effect of filling a hole with a hard driven rivet on $\sigma_{nU}$ was negligible.

Vlieger [2] considered the effect of rows of circular holes and a variety of hole patterns, both in rectangular and staggered patterns. Another variable included was the hole-edge distance. Vlieger's results confirmed the above conclusions (a) and (b). In addition he found that more holes in a row gave a slightly higher $\sigma_{nU}$ which was attributed to a biaxiality effect.

Some recent data were obtained by Clark and Morton [3] on 7075-T6 sheet specimens with a circular hole. For specimen widths of 20 and 43 mm an average value $\sigma_{nU}/\sigma_U = 1.01$ was found for $K_t$ values in the range of 2 to 2.5. This agrees with results of Refs. 1 and 2.

The present test series was primarily set up to be carried out by an IAESTE student (Aviv Akoms from Beersheba University, Israel) during a short summer period. For that reason the number of observations to be made during the tests was kept small. Specimens with high $K_t$ values were tested by Broek and Jacobs [1]. However, their specimens were small (width 25 mm) and the notch radii of the elliptical holes were also small (0.15 to 0.6 mm). Radii used in the present tests are 2 and 5 mm. The results are presented in the following sections.
MATERIALS AND SPECIMENS

All specimens were cut from sheets with a nominal thickness of 4 mm. The loading direction of the specimens was parallel to the rolling direction. The static properties of the two alloys used were (average results of 6 tensile tests).

<table>
<thead>
<tr>
<th>Alloy</th>
<th>( \sigma_{0.2} ) (N/mm(^2))</th>
<th>( \sigma_U ) (N/mm(^2))</th>
<th>Elongation, gage length 50 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>2024-T3 Al clad</td>
<td>385.1</td>
<td>481.4</td>
<td>17.9 %</td>
</tr>
<tr>
<td>7075-T6 Clad</td>
<td>470.5</td>
<td>531.8</td>
<td>9.7 %</td>
</tr>
</tbody>
</table>

The dimensions of the specimens are shown in Figures 1, 2 and 3 for specimens with circular holes, slotted holes and saw cuts respectively. The \( K_t \) values for the holes were obtained from Peterson's book [4]. For the circular holes Peterson presents the well-known Howland data. The slotted hole was considered to be an elliptical hole with the same major axis \((2a)\) and the same tip radius \( \rho \). For an infinite sheet:

\[
K_t = 1 + 2 \sqrt{\frac{a}{\rho}}
\]

Finite width correction factors are presented by Peterson (Ref. [4], Fig. 131), which are calculated results of Isida.

The total length of all specimens was 300 mm, which left a length between the clamping edges of about 220 mm. All holes were drilled and reamed, while the specimen edges were contour milled. Specimens with a width up to 40 mm were directly clamped between the grips of the testing machines. Specimens with a width of 100 mm were provided with a row of three bolt holes at each end. Clamping then occurred in a fork. For some specimens this resulted in clamping failures, which was solved in subsequent tests by either bonding reinforcing strips on the specimen ends or producing specimens with wider ends (160 mm, 5 bolt holes at each end). Saw cuts (Fig. 3) were produced by first drilling a small hole (diameter 1mm) in the center of the specimen and sawing by hand employing a fret saw.
TESTS AND RESULTS

All specimens were pulled in tension until failure occurred. This was done in a 200 kN Amsler machine with MTS closed loop control equipment. Stroke control was used in all tests. In most cases four identical specimens were tested.

For one out of each four specimens it was tried to get some indications about the occurrence of net section yield just before failure. For this purpose a strain meter (COD-type) with a gage length of 4 mm was attached to one edge of the specimen. This was done in the minimum section. The output of the strain meter and the load cell of the testing machine were fed into an X-Y plotter. The $\epsilon_{\text{edge}} - P$ records revealed some non-linearity in most experiments. This is insufficient information to indicate plastic yielding at the specimen edge. Because it turned out to require more accurate measurements to establish whether $\sigma_{0.2}$ was exceeded at the specimen edges, some qualitative results will be summarized only:

- A considerable amount of plastic deformation at the specimen edge was found only in the specimens with a small width (15 and 20 mm), which had the lowest $K_t$ values.
- Absence of plastic deformation at the edges was observed for 7075-T6 specimens with saw cuts.

Failure loads of all specimens have been compiled in table 1, where average results are given also. The average net section failure stress ($\sigma_{nU}$) was calculated by employing net section dimensions as they were measured. Values of $\sigma_{nU}$ are shown in Figures 1, 2 and 3, and they have been plotted in Figures 4 and 5. The average trends of Figure 4 is shown again in Figure 6 for comparison with results of Broek and Jacobs [Ref. 1]. In Figure 5 for the saw cut specimens $\sigma_{nU}$ is compared to $\sigma_{0.2}$. For 2024-T3 the difference between $\sigma_{nU}$ and $\sigma_{0.2}$ is small indicating that net section yield was approximately obtained. However, for 7075-T6 this does not apply.
Fractography

As a first impression all fracture surfaces were largely macroscopic shear failures, which are typical for static failure of sheet material. Usually single shear occurred, but double shear failures were observed on several specimens, also starting in that way at the notch root. It is therefore thought that the initiation of the failure occurred in the notch root at mid thickness. Moreover, at the notch root a considerable amount of plastic thickness reduction was easily observed with a magnifying glass.

Small ridges in the width direction, located in the center of the thickness, suggested a narrow band of macroscopically flat tensile failure. These ridges were observed on 7075-T6 specimens, but they were hardly visible on 2024-T3 specimens.

The specimens with saw cuts showed some differences. Necking was much less and the initial part of the failure occurred as a flat tensile failure with increasing shear lip formation at the sheet surfaces after further crack extension.
DISCUSSION

The blunt notch effect

The present results clearly confirm the trends from earlier work by Broek and Jacobs, see the comparison in Figure 6. Figure 4 suggests a scatter band with a width of about 3 to 8% of the failure stress. The scatter between identical tests (see table 1) is significantly smaller. The difference between the maximum and minimum result of similar tests is in the order of 1% as an average. Consequently the scatter band in Figure 4 cannot be due to test scatter. It should be attributed to geometry effects. Unfortunately there are no clear indications of certain trends. Data compiled in Ref. 1 give a weak indication of a small size effect, lower \( \sigma_u \) values being obtained for larger specimens. This is somewhat confirmed in the present test series (compare the data in Figure 1 for \( K_t = 2.74 \), \( d = 4 \) mm and \( d = 10 \) mm).

From a technical point of view scatter as observed in Figure 4 seems to be fully acceptable. Further improvement of our understanding should start with more detailed observations about how failure does occur and to see which failure criterion can be applicable. The present fractographic observations suggest that the failure mechanism is qualitatively similar to the mechanism in unnotched specimens. However, initiation in a notched specimen starts at (or close to) a free surface, whereas it starts in the center of the cross section for an unnotched specimen. This is an essential difference. Necking and biaxiality aspects further complicate comparisons between different types of specimens.

On the other hand, one might hope that finite element calculation can throw some more light on plastic deformations around blunt notches. However, it should not be overlooked that local deformations involved can no longer be considered as small deformations. Relevant calculations will be difficult. Fortunately the problem does not seem to be urgent from a technical point of view.
As shown by Figure 4 all specimens with holes failed at stresses well above the yield stress of the material, up to $K_t \sim 5$. Apparently the material is very tolerant towards blunt notches. It is of some technical significance that the 7075 alloy is more notch tolerant than the 2024 alloy. For $K_t = 3$ the net section failure stress of 2024-T3 has dropped with about 8 percent (Fig. 6), whereas for the 7075-T6 material the drop is no more than about 1 percent. Actually it is not too surprising that $\sigma_{nU}/\sigma_U$ can be so close to 1 and even larger than 1 [5]. The ultimate tensile strength $\sigma_U$ is derived from the maximum load ($P_{\text{max}}$) in a tensile test and the original specimen cross section. However, at $P_{\text{max}}$ failure does not occur; necking starts which causes a plastic instability. Failure occurs after further plastic deformation at a lower load, but a higher true stress (based on the instantaneous cross section). In a notched element, necking at the notch root does not cause a plastic instability and a further increase of load on the specimen is possible. A fully plastic net section can then be obtained. Plastic contraction in the sheet thickness direction was observed but in the width direction it will be restrained by material outside the minimum section. As a consequence higher stresses can be transmitted. It then may occur that $\sigma_{nU} > \sigma_U$, especially if a sufficiently homogeneous stress distribution has been obtained. A more homogeneous distribution should be expected for the low strain hardening material 7075-T6 as compared to the less strain hardening material 2024-T3. This explains why the former alloy is more tolerant to blunt notches than the latter one, in spite of its lower ductility (see also the discussion by Broek in [1]).

The effect of cracks (saw cuts)

The results of the specimens with saw cuts have been replotted in a residual strength diagram, see Figure 7. A comparison is made also here with the net section yield criterion ($\sigma_{\text{net}} = \sigma_{0.2}$) which gives a reasonable result for the 2024-T3 alloy, but not for the 7075-T6 alloy. The four data points for 7075-T6 include only one point ($2a_0 = 25 \text{ mm}$, $\sigma_c = 308.7 \text{ N/mm}^2$), which gives a valid result according to the Feddersen
concept ([6], $2a < \frac{W}{3}$, $W =$ full width, and $\sigma_c < \frac{2}{3} \sigma_{0.2}$). For this data point $K_c$ has been calculated. However, contrary to the Feddersen concept the width correction has not been dropped. Actually it is difficult to understand why Feddersen dropped that correction, because it is unrealistic and unnecessary. Moreover omitting the width correction factor introduces the problem of obtaining the residual strength diagram for large values of the crack length. Feddersen solved this by adopting a tangent line going to $\sigma_c = 0$ at $2a = W$.

In the calculation of $K_c$ the Irwin plastic zone correction has been included. The relevant equations are:

$$K_c = C \sigma_c \sqrt{\frac{\pi}{2} \left( a + r_p^* \right)}$$  \hspace{1cm} (1)

Width correction:  
$$C = \sqrt{\sec \left( \frac{\pi}{W} \left( a + r_p^* \right) \right)}$$ \hspace{1cm} (2)

Plane stress plastic zone size correction [7]:  
$$r_p^* = \frac{1}{2\pi} \left( \frac{K_c}{\sigma_{0.2}} \right)^2$$ \hspace{1cm} (3)

Combining these equations with an elimination of $K_c$ leads to:  
$$r_p^* = \frac{1}{2} \left( \frac{\sigma_c}{\sigma_{0.2}} \right)^2 \left( a + r_p^* \right) \sec \left( \frac{\pi}{W} \left( a + r_p^* \right) \right)$$ \hspace{1cm} (4)

$r_p^*$ has to be solved from Eq. (4) by iteration. $K_c$ is then calculated with equation (3). The result thus obtained was $K_c = 75.8$ MN/m$^{3/2}$ which seems to be the correct order of magnitude for a plane stress situation [6, 7]. The $\sigma_c$ - a relation for a constant $K_c$ is obtained from Eqs. (1)-(3).:
\[ \sigma_c^2 = \frac{K_c^2 \cos \left[ \frac{\pi \left\{ a + \frac{1}{2\pi} \frac{K_c}{\sigma_{0.2}} \right\}^2}{W} \right]}{\pi \left\{ a + \frac{1}{2\pi} \frac{K_c}{\sigma_{0.2}} \right\}^2} \]  

(5)

This equation was used to draw the line \( K_c = 75.8 \text{ MN/m}^{3/2} \) in Figure 7. (In view of the plastic zone correction it does not go through \( \sigma_c = 0, \, 2a = W \). The data point for \( 2a = 50 \text{ mm} \) is accurately on this curve. The data points for \( 2a = 4 \) and 10 mm are below the curve. For this \( 2a - \) values \( \sigma_c > 2/3 \sigma_{0.2} \) and here a tangent line as proposed by Feddersen [Ref. 7] was drawn. The two upper data points are close the tangent line.

Acknowledgement

Part of the tests were carried out by Aviv Akons (student from the Bersheeba University, Israel).
CONCLUSIONS

1. The effect of blunt notches on the static failure stress of sheet specimens of 2024-T3 and 7075-T6 was found to be relatively small in the $K_t$ range from 2 to 5. At $K_t \sim 3$ the net section failure stress ($\sigma_{nU}$) of 2024-T3 was about 8 percent lower than the tensile strength ($\sigma_Y$). For the 7075-T6 material the reduction was only 1 percent, which implies that this alloy was even less sensitive to blunt notches than the more ductile 2024-T3 alloy. The trends found were in good agreement with earlier work.

2. The results imply that both sheet materials are very tolerant towards blunt notches as far as static strength is concerned. Qualitatively this can be understood from plasticity considerations.

3. The effect of saw cuts on the residual strength of the same materials was in agreement with net sections yield for the 2024-T3 alloy. For the 7075-T6 alloy (thickness 4 mm, plane stress) a modified Feddersen diagram was applicable. The modification consisted of introducing the width correction and a plastic zone correction. The lower tangent line is no longer necessary, but the upper tangent line has to be maintained.
REFERENCES


Figure 1: Specimens with circular holes.
Figure 2: Specimens with slotted holes.
Figure 3: Specimens with saw cuts.
Figure 4: Static strength of hole-notched specimens.
Figure 5: Residual strength of specimens with saw cuts.
Figure 6: Comparison of the average trend of the present test series with results of Broek and Jacobs (Ref. 1)
Figure 7: Residual strength diagram for the specimens with saw cuts.
## Table 1: Test Results

<table>
<thead>
<tr>
<th>Type of notch</th>
<th>Width (mm)</th>
<th>Alloy</th>
<th>Failure load (kN)</th>
<th>Net area((^*)) (mm(^2))</th>
<th>Average failure stress (N/mm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>All specimens</td>
<td>Average</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20 10</td>
<td>2024 7075</td>
<td>18.9/19.1/19.0/19.1 22.2/22.1/22.1/22.2</td>
<td>19.03 22.15</td>
<td>39.5 40.3</td>
</tr>
<tr>
<td></td>
<td>40 10</td>
<td>2024 7075</td>
<td>54.6/54.7/54.4/54.5 64.0/64.2/64.3/64.35 64.1</td>
<td>54.55 64.5</td>
<td>118.5 121.2</td>
</tr>
<tr>
<td></td>
<td>40 4</td>
<td>2024 7075</td>
<td>64.1/64.0/64.15 75.3/76.2/76.1</td>
<td>64.1 75.9</td>
<td>141.2 145.3</td>
</tr>
<tr>
<td></td>
<td>100 10</td>
<td>2024 7075</td>
<td>152/153/151.8/153.4/153.5 186/187.1/187.0</td>
<td>152.7 186.7</td>
<td>354.0 361.4</td>
</tr>
<tr>
<td></td>
<td>100 4</td>
<td>2024 7075</td>
<td>164.2/161.2/162.9/163.4 197.2/199.0/197.6/196.9</td>
<td>162.9 197.7</td>
<td>379.0 386.5</td>
</tr>
<tr>
<td>Slotted hole</td>
<td>100 25</td>
<td>2024 7075</td>
<td>130.7/128.3/129.9/130.2 156.1/155.4</td>
<td>129.8 155.75</td>
<td>296.2 303.0</td>
</tr>
<tr>
<td></td>
<td>(p=25)</td>
<td>2024 7075</td>
<td>88.2/87.8/87.6/87.9 104.8/104.6/104.5/104.8</td>
<td>87.9 104.7</td>
<td>197.5 202.2</td>
</tr>
<tr>
<td></td>
<td>(p=15)</td>
<td>2024 7075</td>
<td>123.6/124.8/121.9/124.8 154.1/154.5/153.9</td>
<td>123.8 154.2</td>
<td>295.9 303.1</td>
</tr>
<tr>
<td></td>
<td>(p=2)</td>
<td>2024 7075</td>
<td>83.0/85.4/85.2 103.6/103.0/103.1/103.2</td>
<td>84.5 103.2</td>
<td>197.2 202.3</td>
</tr>
<tr>
<td>Saw cut</td>
<td>100 4</td>
<td>2024 7075</td>
<td>150.1/149.8/150.0/150.7 187.7/184.3/185.3/185.6</td>
<td>150.15 185.7</td>
<td>375.6 386.6</td>
</tr>
<tr>
<td></td>
<td>10 2024</td>
<td>7075</td>
<td>141.5/144.6/137/142.2 168.0/169.0/169.0/169.1</td>
<td>141.4 168.9</td>
<td>354.0 363.8</td>
</tr>
<tr>
<td></td>
<td>25 2024</td>
<td>7075</td>
<td>114.7/116.0/114.2/115.3 125.2/124.8/125.6/122.4</td>
<td>115.0 124.7</td>
<td>295.5 301.4</td>
</tr>
<tr>
<td></td>
<td>50 2024</td>
<td>7075</td>
<td>74.1/73.9/72.6/74.1 78.1/77.7/79.2/79.2</td>
<td>73.7 78.55</td>
<td>197.0 202.0</td>
</tr>
</tbody>
</table>

(*) Calculated with as measured dimensions