The Improvement of Fatigue Strength by Edge Treatment

Paper describes a method of improving the fatigue strength of sheet material by edge treatment referred to as edge dimpling.

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ABSTRACT—This paper presents a new approach to improving the fatigue strength of sheet material by edge treatment. The improvement is achieved by inducing a compressive residual stress, by means of a mechanical procedure called edge dimpling, to a finite length along the edge.

The new technique can be utilized to increase the fatigue resistance of plates with large-scale stress concentrations such as an unstressed access-door opening into a wing structure, stress concentrations at the corners of window doublers or long, wide slots in the structures.

Experiments on 2024-T3 aluminum-alloy notched-sheet specimens indicate that edge dimpling in the notch region results in approximately 100-percent improvement in fatigue strength at one million zero to tension cycles to failure. The fatigue-strength reductions factor (FSRF) is almost halved at the same life. The FSRF tends to be constant irrespective of the fatigue life.

Introduction

Fatigue in metals is known to have two characteristics. The first being its surface nature; in most cases, fatigue cracks originate at the exposed surface. The second is its tensile nature; the fatigue cracks propagate into the material under tensile stresses.

In sheet material or components with small thickness compared to surface area, the weakest region is...
stretching of the specimen. This determines the amounts of strain at the three points and defines points $A_0$, $A_1$, and $A_2$ on the stress-strain curve. Straightening of the specimen will yield the state given by points $B_0$, $B_1$, and $B_2$ which give the values of maximum possible residual compressive stress. When the specimen is unclamped, the stresses will adjust to achieve a new balance and residual stresses will relax. Assuming that the relaxation is equal through the sheet thickness, then the final state of stress could be determined provided that the maximum possible stresses and the amount of relaxation are known. Thus, for an equal amount of relaxation strain, $\Delta e$, the final state of residual stress is determined by points $C_0$, $C_1$, and $C_2$ as shown. It can be seen that the effective value of residual compressive stress, given by $\sigma_2$, is considerably lower than $\sigma_0$ and $\sigma_1$. It can also be seen that, if the relaxation strain increases, the effective value of residual stress drops rapidly, and the greater relaxation may result in residual tensile stress at the concave side of the dimple. In the latter case, the effect of treatment will be detrimental.

The effect of bending can be eliminated by further dimpling the specimen in the opposite direction, as shown in Fig. 5. A point on the concave side during the first dimple will be on the convex side during the second dimple, and vice versa. It can be seen that this modified treatment assures a higher and more uniform residual-stress distribution throughout the thickness. This two-way or reversed edge-dimpling procedure was used in the experimental program and will be referred to, in the following context, as edge dimpling.

In selecting an optimum value of edge strain, it is helpful to consider the stages of developing residual stress with increasing edge strain. With reference to Fig. 4 and quantitative stress-strain data the following three characteristics stages, shown in Fig. 6, can be determined:

1. **Elastic stage**: in which no residual stress is left in the material after unloading and, hence, no improvement gained.

2. **Developing stage**: in which the stress develops rapidly with increasing strain. This stage is characterized by high sensitivity of stress to strain. A small error in strain will produce a large error in stress and, hence, lead to fatigue improvement with inherent possibility of much scatter.

3. **Stability stage**: in which the residual stress is high and is relatively insensitive to edge strain. This presents the useful condition of maximum fatigue improvement with minimum scatter due to dimpling.

To measure the effect of edge dimpling on the fatigue strength of sheet material, an experimental program was carried out. This program as well as the significant results are subsequently discussed.

**Experimental Program**

Of first interest is the free-edge fatigue-strength improvement due to edge dimpling. However, because it is difficult to initiate fatigue failure at a dimpled free edge in conventional fatigue specimens, edge-notched specimens were used to obtain a measure of the improvement. Therefore, the primary objective of the experimental program was to measure the improvement in the fatigue-strength reduction.
Fig. 3—Average edge strain vs. dimpling ratios

Fig. 4—Single-edge dimpling procedure

Residual stress. The latter is defined as the state of stress reached by compressing the stretched material to its original dimension (zero strain). Upon the release of the clamps, the residual stress will be of the nature shown in Fig. 2(d). Its magnitude, for a given material, will be determined by the amount of relaxation due to unclamping and the edge strain, which is related to the dimpling parameters such as: the profile of the dimpling ram, the extent of ram movement, shape and dimensions of the dimpled specimen, dimensions of the clamping system and dimpled area, and uniformity of straining.

The different factors affecting dimpling can be expressed in terms of three non-dimensional parameters which will be used to determine the average or mid-thickness edge strain. These are:

1. The dimpling–thickness ratio, $R_t$, which is defined as the ratio of the extent of ram movement, $d$, to the material thickness, $t$,

$$R_t = \frac{d}{t}$$

2. The dimpling–span ratio, $R_s$, which is defined by the ratio of the extent of ram movement, $d$, to the span, $2b$,

$$R_s = \frac{d}{2b}$$

The two ratios are related by

$$R_t = \frac{2b}{t} R_s$$

3. The dimpling constant, $K$, which relates the dimensions of the clamping system and the material thickness;

$$K = \frac{r_1 + r_2 + t}{2b}$$

where, $r_1$ is the radius of dimpling ram, $r_2$ is the radius of all fillets of the clamps, and $t$ is the material thickness.

The derivation of the relation between these parameters and the average edge strain can be found in the Appendix and is represented graphically in Fig. 3.

The process of dimpling, described above, is accompanied by biaxial bending which is unfavorable for two reasons:

1. The plastic strain, and consequently the stress, throughout the thickness will not be uniform. This requires three-dimensional stress analysis and complicates the determination of residual stress.

2. The effective value of residual compressive stress (which is the minimum value of the distribution throughout the thickness) will be lower due to bending effects. Hence, a lower improvement of fatigue resistance is expected. This effect becomes more pronounced as the material thickness increases.

The effect of bending is illustrated on the stress–strain diagram, Fig. 4. Subscripts 0, 1 and 2 are used to designate points on the neutral axis, the concave side in contact with the ram, and the convex side of the specimen, respectively. The strain distribution due to bending is superimposed on the uniform
the edge. The additional presence of geometrical concentrations at the edge will greatly aggravate the fatigue situation and result in a condition which requires treatment. This treatment may include the reduction of the effective tensile stresses through the introduction of residual compressive stresses. These stresses, in the critical areas, will improve the fatigue resistance by:

1. lowering the actual stress-concentration effect, thus delaying the crack initiation;
2. reducing the effective tensile stresses, thus lowering the rate of crack propagation. Moreover, it is possible that fatigue cracks may not even start at the treated area.

Several approaches have been proposed for inducing favorable residual stresses around small-scale stress concentrations in plate material such as holes and cutouts; one of these is the coining technique. Coining, in early experiments, was done by pressing a concentric groove with sufficient force to create plastic flow around the opening to be treated. The technique has been refined by Speakman and it is currently used for treating holes and slots in plates of up to 0.0-in. thickness. Coining procedures have been reported to improve the fatigue life of test specimens of various aircraft materials by a factor of approximately four.

Recently, Shewchuk and Roberts have developed a new method for improving the fatigue strength of loaded holes in sheet and thin plate materials. Their method, illustrated in Fig. 1, consists of locally dimpling the material centering around the intended hole location, thus producing tensile plastic strain. The process is completed by flattening the dimple and drilling the hole so that the region around the hole is under residual compressive stress. They conducted experiments on 2024-T3 aluminum-alloy specimens which indicated fatigue-strength improvement factors of approximately 2.1 and 3.4 at 200 kilocycles and 2 million cycles to failure, respectively.

Very little work has been reported on edge treatment of large-scale stress concentrations. Phillips reported brief experiments on edge-rolled coining. He pressed a groove parallel to the edge on specimens of 7075-T6 aluminum alloy. The specimens were V-notched and tested in axial tension fatigue. His results indicate varying improvements in fatigue life for different conditions of preparation and testing. Except for some practical applications in use, no further work has been done on edge coining.

This paper describes a new method of improving the fatigue strength of sheet material by edge treatment. The treatment, limited to a short length of the edge, will be referred to as edge dimpling.

**Edge Treatment by Edge Dimpling**

Edge dimpling is a mechanical method of producing a controllable gradient of plastic strain and, hence, residual stress, in a finite length of the free edge of sheet metallic material. The procedure of edge dimpling is illustrated in Fig. 2. The material is first clamped as shown in plan and profile in Fig. 2(a). Figure 2(b) shows the dimpling action and the resulting edge dimple. Figure 2(c) illustrates the flattening process which places the dimple region in a state of compressive in-plane stress. The straightening movement of the ram must be a distinct distance beyond the zero line to compensate for the elastic springback. The resulting stress distribution in clamped specimens will be the maximum possible re-
TABLE I—NOMINAL CHEMICAL AND MECHANICAL PROPERTIES OF 2024-T3 ALCALD ALUMINUM-ALLOY SHEET

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Chemical Properties</td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td>4.5%</td>
</tr>
<tr>
<td>Mg</td>
<td>1.5%</td>
</tr>
<tr>
<td>Mn</td>
<td>0.6%</td>
</tr>
<tr>
<td>Nominal Mechanical Properties</td>
<td></td>
</tr>
<tr>
<td>Ultimate Tensile Strength</td>
<td>65,000 psi (450 MPa)</td>
</tr>
<tr>
<td>Yield Strength</td>
<td>45,000 psi (312 MPa)</td>
</tr>
<tr>
<td>Hardness (Rockwell E)</td>
<td>90-100</td>
</tr>
<tr>
<td>Percent Elongation (2 in. G.L.)</td>
<td>18</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>$10.6 \times 10^6$ psi (7.3 $\times 10^4$ MPa)</td>
</tr>
</tbody>
</table>

factor, $FSRF^*,$ which could be obtained in an edge notched specimen by edge dimpling the notch region prior to notching. Three series of S-N fatigue tests were performed using three kinds of specimens — notched, dimpled-notched and plain.

All fatigue testing was zero to tension and was performed on a Sonntag-Baldwin fatigue-testing machine model SF-1-U at a test frequency of 1800 cpm. Failure was characterized by complete rupture at the section; the upper test limit was 10 million cycles. The material used for specimens was 2024-T3 alclad aluminum alloy. The nominal chemical composition and mechanical properties are given in Table 1. The specimens, as shown in Fig. 7(a), were nominally 0.050 in. thick and were oriented in the direction of rolling. Stress concentration was produced by a 90-deg Vee notch with notch radius of 0.005 in. (0.125 mm) and notch depth equal to the thickness. For the reference S-N curve which was obtained using plain specimens, it was necessary to modify the gripping area, as shown in Fig. 7(b), to eliminate premature failure at the grips. To show that the modification did not influence test results, several comparative tests were performed using both types of notched specimens. These tests indicated no significant differences due to specimen type.

The dimpling operation was performed on an apparatus shown in Fig. 8. The design provides a constant span and width of dimpled area while the extent of ram movement is variable. The dimpling ram is equipped with two replaceable contoured dimpling heads designed to permit a gradual strain gradient in the dimple region.

Before proceeding with the primary experimental program, it was necessary to determine the value of edge strain which gives the greatest fatigue improvement. Series 1 tests were carried out for that purpose.

Thirty specimens were used, with edge strains ranging from 0 to 2.25 percent. The specimens were notched and tested to failure in zero to tension fatigue with a maximum stress level of 23 ksi (162 MPa). The test results in Figs. 9 and 10 indicate increasing fatigue improvement as the average edge strain is increased. It can also be seen that the rate of improvement decreases with increasing edge strain. Although the theoretical limit of improvement, for a given specimen, is governed by the maximum possible residual stress which can be generated, the practical upper limit was determined by the value of edge

* $FSRF$ is the ratio of the fatigue strength of a member or specimen with no stress concentration to the fatigue strength of a specimen with stress concentration.

Fig. 7—Types of fatigue specimens

Fig. 8—Dimpling apparatus
strain for which the dimple region could be flattened without causing local buckling. Accordingly, the value of 2-percent edge strain was selected for the primary fatigue-strength tests, Series 2, 3 and 4. The exact residual-stress distribution for this value of edge strain is a subject of continuing research by the authors.

Test Series 2, 3 and 4 were carried out to obtain S-N fatigue curves for notched, dimpled-notched and plain specimens, respectively. Each series contained a minimum of five different stress levels with a minimum of five specimens at each stress level. The experimental results of the three series are shown in Fig. 11.

Discussion of Results

The results of Test Series 2, 3 and 4 are fitted to three S-N curves shown in Fig. 12, according to the general mathematical expression:

\[ S = S_o + A (N + B)^{-m} \]  

where \( S \) = the fatigue strength, ksi  
\( N \) = fatigue life, Kc,  
\( S_o \) = the fatigue strength corresponding to infinite number of cycles, ksi,  
\( A, B \) and \( m \); parameters.

This general expression of the power function has been used extensively. A computerized least-squares method based on median lives was used to determine the best-fitting curves.

The results indicate a considerable improvement in fatigue strength. The improvement in the strength of notched specimens by dimpling is plotted against the fatigue life in Fig. 13. The improvement in strength increases with the increase of fatigue life (or the decrease of fatigue load) and appears to reach a peak value at a life longer than ten million cycles. The fatigue strength is almost doubled at this life. However, as the fatigue life decreases, the strengthening effect of dimpling is reduced to about 60 percent at 100 kilocycles. Less strengthening effect is expected for lower-cycle fatigue tests due to the redistribution of residual stresses by plastic flow at higher loads.

The improvement may be expressed in terms of the decrease in the fatigue-strength reduction factor due to dimpling, as shown in Fig. 14. This decrease approaches the 50-percent figure at one million cycles to failure. Examination of the curves indicates that the FSRF after dimpling tends to be constant and shows very little variation with fatigue life.

It should be noted that higher ratios of improvement are expected in structural parts as the rigidity of the body will prevent local buckling and, thereby, allow residual stresses to be much closer to the maximum possible values. Furthermore, it should be possible to extend the technique, using a suitable continuous edge-treatment process, to the treatment of long, free edges.
Conclusion

The following conclusion can be drawn:
1. Edge dimpling significantly improves the edge-notch fatigue strength of 2024-T3 aluminum-alloy sheet under zero-to-tension loading.
2. The fatigue-strength reduction factor of the dimpled specimens tends to be constant regardless of fatigue life.

Acknowledgment

The research described was supported by the National Research Council of Canada through Operating Grant No. A 4131 to J. Shewchuk. The authors wish to extend their gratitude for the assistance.

References


Fig. 11—Results of fatigue testing

Fig. 12—Best-fitting S-N curves based on median analysis
APPENDIX

Derivation of Average Edge Strain-Dimpling Relation

With reference to Fig. 15, the strain (at mid-thickness) along the neutral axis can be calculated as follows:

The mid-thickness length for the half span, \( b \), after elongation:

\[
b + \Delta b = \overline{AB} + \overline{BC} + \overline{CD}
\]

\[
= \left[ (r_1 + t/2) \theta \right] + \left[ b \sec \theta \right] - \left[ (r_2 + t/2) \theta \right]
\]

\[
= b \sec \theta + (r_1 + r_2 + t) (\theta - \tan \theta)
\]

The elongation is:

\[
\Delta b = b (\sec \theta - 1) + (r_1 + r_2 + t) (\theta - \tan \theta)
\]

The strain is then:

\[
\varepsilon = \frac{\Delta b}{b}
\]

\[
= (\sec \theta - 1) + \left( \frac{r_1 + r_2 + t}{b} \right) (\theta - \tan \theta)
\]

But from eq (4), the dimpling constant, by definition, is

\[
K = \frac{(r_1 + r_2 + t)}{2b}
\]  (4)

\[
\varepsilon = (\sec \theta - 1) + 2K(\theta - \tan \theta)
\]  (5)

This equation gives the average strain in terms of \( K \) and the angle \( \theta \). Next, we have to find the \( \theta \) as a function of nondimensional dimpling parameters. On the other hand:

\[
d = \overline{AB} + \overline{BE} + \overline{CD}
\]

\[
= \left[ (r_1 + t/2) (1 - \cos \theta) \right] + \left[ b \tan \theta \right] - \left[ (r_3 + r_2 + t) \sin \theta \tan \theta \right]
\]

\[
+ \left[ (r_2 + t/2) (1 - \cos \theta) \right]
\]

\[
= (r_1 + r_2 + t) (1 - \sec \theta) + b \tan \theta
\]

Substituting for \( d \) in eq (2):

\[
R_6 = \frac{d}{2b} = \left( \frac{r_1 + r_2 + t}{2b} \right) (\sec \theta - 1) + \frac{1}{2} \tan \theta
\]

\[
R_b = \frac{1}{2} \tan \theta - K(\sec \theta - 1)
\]  (6)

Substituting for different values of \( \theta \) in eqs (5) and (6) the relation between the dimpling-span ratio and resulting strain can be determined. The relation between \( R_b, R_6 \) and \( \varepsilon \) is plotted in Fig. 3 for the dimensions used in the design of dimpling apparatus.