Bending Fatigue Failures in Valve Steel

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ABSTRACT

In the present paper the effect of defects (viz. pits, gouges and oxide inclusions) will be reported. Although certain defects were uniformly distributed over the specimen surface, the majority of all fractures started in the edge region. An explanation to this behaviour is presented in terms of stress enhancement in the edge regions due to edge deflections.

INTRODUCTION

One basic requirement on flapper valve steel is a high bending fatigue strength. It has been reported previously (Johansson & Persson, 1976) that several factors influence this property. Thus, a high tensile strength and the introduction of compressive surface stresses tend to enhance the fatigue strength, while increased surface roughness and corrosion have the opposite effect. A low oxide inclusion content has, of course, a beneficial effect upon fatigue properties.

When examining flapper valves broken in service it is sometimes found that the fatigue fracture has started from a surface defect of some kind. In other cases, however, it is impossible to determine the cause and position of fracture initiation because the fracture surfaces are heavily worn. Thus, it has been considered to be of interest to perform laboratory tests in order to assess the effect of certain types of surface defects on the bending fatigue strength. The influence on impact fatigue will not be considered in this paper.

EXPERIMENTAL

The bending fatigue tests of steel strip in the present investigation were performed in so called UMG and Sonntag machines. Details concerning the experimental procedure may be found in a previous report in which also the specimen geometry used in the present work is shown (see figure 4, ref. 1).

The tested materials were SANDVIK 20C and 7C27Mo2, which are hardened and tempered steels corresponding to AISI 1095 and a modified version of AISI 420 respectively. The nominal compositions are given in table 1. Other properties which may be of interest in this context are surface roughness, hardness and residual stresses which are listed in table 2.

When nothing else is mentioned, bending fatigue specimens were blanked out of strips with the longitudinal axis parallel to the rolling direction. Experience has shown that the smoothness of the specimen edges is a critical parameter in these types of tests. Considerable care was therefore taken to prepare the edges. Thus, they were first machine ground and polished, whereas the surfaces were kept in the as-received condition.

RESULTS

In this section the effect on bending fatigue properties of certain types of defects (viz. pits, gouges, artificial surface indentations and non-metallic inclusions) will be considered. These defects are considerably larger than the small permissible irregularities arising from cold rolling and polishing of the valve steel. The existence of other types of defects (scratches, roll marks, etc.) cannot be ignored although their effect on fatigue properties will not be considered in the present paper.

3.1 Effect of Gouges

Gouges are a particular kind of surface defects created as a result of slippage between abutting turns in the strip coil. In a bending fatigue test (Series No. 1) on modified AISI 420 containing gouges, a large fraction of the resulting
fractures were associated with these defects, although exceptions could be observed. An example of a gouge leading to fatigue fracture may be observed in figure 1a. Scanning electron microscopy of the corresponding fracture surface leaves evidence that this gouge provides the initiation point (figure 1b).

How gouges on 0.40 mm (0.016") thick steel strip affect the fatigue properties is presented in figure 2. The gouge area was measured in a cross section of the strip. It may be concluded from figure 2 that there is an inverse relationship between gouge size and the number of cycles to failure. It should also be emphasized that in the present case all gouges were located to the central part of the specimens.

3.2 Effect of Pits

Pitting may be due to faults in the strip rolling process or to chemical attack on the finished material. Typically, a pit is nearly circular and rather deep (10-50\% of the diameter). An example of pits is given in figure 3.

The effect of pits on the fatigue properties of AISI 1095 (thickness 0.60 mm (0.024\"), Series 2) is shown in figure 4, where the continuous line represents the regular S-N curve for the material. The points to the left of the S-N curve represent experimental values obtained for specimens with pits of different size. The number associated with each point is the pit area in \( \mu m^2 \) measured in a cross section perpendicular to the stress axis. It is apparent from figure 4 that surface pits have a marked effect on the fatigue life. For instance, for a pit area of 150 \( \mu m^2 \) the reduction in the number of cycles to failure is roughly one order of magnitude.

In an additional investigation on the modified AISI 420 the effect of pitting on the fatigue limit at \( 2 \times 10^6 \) cycles was examined, using the stair-case method. Pitted material (typical pit size 30 \( \mu m \)) and defect free material from the same strip were tested in parallel experiments (Series 3). The resulting fatigue limits were 910 N/mm\(^2\) (132 ksi) and 710 N/mm\(^2\) (103 ksi). Although pits were uniformly distributed over the test specimen, the majority of all fatigue fractures started from pits situated near the edge, an example of which is shown in figure 5.

In order to investigate the effect of rolling direction, one batch of specimens was cut parallel to (Series 4) and another perpendicular to (Series 5) the rolling direction. The material was pitted AISI 1095 with a typical pit size of 50 \( \mu m \). Our experience is that the fatigue limit in "perpendicular" specimens is approximately 95 \% of that in "parallel" specimens. With this in mind, the stress levels chosen were 660 N/mm\(^2\) (96 ksi) and 630 N/mm\(^2\) (91 ksi) respectively and the corresponding results may be found in table 3. In both cases the life reduction due to defects was roughly one order of magnitude.

3.3 Effect of Surface Indentations

It proved rather difficult to collect a sufficient number of test pieces with "natural" defects such as pits and gouges, to allow an investigation of the effect of defect position on the fatigue life. Thus, indentations were intentionally applied to the surface by a Rockwell type of diamond with extra small tip radius (0.02 mm, 0.0008\"), an example of which is presented in figure 6. The test material used was AISI 1095 of 0.80 mm (0.031") thickness (Series 6).

Our results showed that the fatigue crack initiation always occurred in the edge region irrespective of the indentation position. Defects more than 2 mm (0.08\") from the edges failed to initiate fracture although a maximum depth of no less than 175 \( \mu m \) was used (see figure 6). By way of contrast, even comparatively small defects in the vicinity of edges served as initiation points for fatigue cracks, an example of which is given in figure 7.

Significant reductions in the fatigue life were observed when the indentations were positioned in the edge regions. For instance, at a stress amplitude of 600 N/mm\(^2\) (87 ksi) and an indentation depth of 175 \( \mu m \), the reduction was a factor of 5. It should be mentioned in this context that the fatigue limit for 0.80 mm strip thickness is 550 N/mm\(^2\) (80 ksi) under normal conditions.

It may be expected that compressive stresses created around the indentation reduce the notch effect considerably. Tempering was therefore applied to some test pieces in order to relieve these stresses. However, this treatment did not influence our test results.

3.4 Effect of Non-metallic Inclusions

It has previously been stated by Persson (1), that fatigue fractures in Sandvik valve materials are rarely initiated by non-metallic inclusions. The following examples were obtained in material discarded owing to its unacceptably high contents of large oxide inclusions. We have found that sulfides are much less harmful than oxides and are therefore not considered here. Fractography employing the scanning electron microscope showed that fatigue fracture initiation points were frequently associated with oxides. An
example of an oxide causing a fatigue fracture is given in ref. 1. Another example, where the oxide particle has fallen out is shown in figures 8a and b. The fracture surface exhibits the characteristic nature of a fatigue fracture. This is clearly imaged in figure 8a, which is a scanning electron micrograph. In a somewhat higher magnification (figure 8b), the initiation point is clearly visible as a hole.

4 DISCUSSION

The above results confirm that surface defects of various kinds may reduce the bending fatigue strength considerably. Similar conclusions may be drawn from fatigue tests under a tensile stress (2).

It is a well-known fact that oxide inclusions have a deleterious influence upon fatigue strength (e.g. ref. 2). Therefore, steel producers aim at reducing the amount of inclusions to a minimum. Our own experience of valve steel is that the content of oxides is in general too low to be responsible for fatigue fractures. It should also be noted that defects such as pits, gouges and large oxide inclusions are not permitted in valve materials delivered to the customer. The examples of defects shown here were selected only for the purpose of illustrating the importance of a proper surface finish.

In the present investigation considerable effort was made to polish the specimen edges. Nevertheless, fatigue fractures originated from the edge regions. This occurred even if deep surface indentations were applied in central parts of the specimen. This can be explained by invoking the theory of bending of plates and beams.

From elementary theory of solid mechanics (e.g. ref. 3) one finds that a beam with rectangular cross section which is subjected to bending adopts a transverse curvature which is opposite to the principal curvature (figure 9). The validity of this result may readily be checked by observing the distortion of a mirror image in a polished specimen surface subjected to bending.

When the beam is thick, i.e. when the thickness (t) is comparable to the width (w), the upper surface becomes approximately a saddle surface. For thin beams or plates (t ≪ w) the elementary theory is no longer valid. An attempt to extend the classical theory in such a way that also thin beams could be dealt with was made by Ashwell (4). The essential results of this work may be discussed with reference to figure 10. Here, the distance of the centre line from the x-axis (y) is plotted as a function of position (x). The relation between the dimensionless quantities y/t and x/w depends only on the dimensionless quantity w²/t and on the Poisson's ratio, ν. As a matter of fact it is the transverse contraction determined by ν which causes the transverse curvature.

From figure 10 we observe that there is a pronounced deflection of the beam in the edge region. When w²/t is large, i.e. when the plate is thin, it may be observed that the deflection of the cross section is confined to the edge region whereas the centre remains virtually flat. It is expected that the upward deflection in the edge region will enhance the tensile stresses which arise in the upper edges (see figure 9, arrowed).

The values of our test specimens generally lie in the ranges t = 0.25-0.80 mm (0.01-0.03"), w = 15-20 mm (0.6-0.8") and R = 50-80 mm (1.95-3.15"). These values yield a result of w²/t in the interval 3.5-32 (cf figure 10). The maximum deflection occurs at the outermost edges and is -0.1t irrespective of the value of w²/t. This deflection will inevitably cause an increase in tensile stress in this region, which we may estimate to 5-10 %. Measurements of the transverse curvature employing a Talysurf tester give results in agreement with theoretical predictions. Furthermore, we find that the minimum transverse radius is -250 mm (9.8") close to the narrowest part of the UMG trapezoidal bending fatigue specimen when the longitudinal bending radius is 80 mm (3.15"). This is consistent with a Poisson ratio (ν) of -0.30. Indeed, this method may be used to determine ν.

For a fatigue limit of 850 N/mm² (123 ksi), which is obtained for SANDVIK 7C27Mo2 (see ref. 1) and was calculated neglecting edge deflections, the transverse bending implies that the true stress in the edge region may be as high as -940 N/mm² (136 ksi). It may be inferred from these considerations that stress enhancement due to edge deflections cannot be neglected in a proper stress analysis. However, incorporating this effect in a quantitative manner demands the use of for instance FEM (finite element method), an investigation which will be undertaken in the near future.

5 CONCLUSIONS

(1) The results support he view that a proper surface finish is essential in preventing fatigue failures in valve steel. The size of the defects investigated is comparable to the typical size of oxide particles responsible for fatigue fractures in these materials (cf. ref. 2).
(ii) Virtually all bending fatigue fractures originate from the specimen edge region. This effect has been attributed to the stress enhancement which occurs in the vicinity of edges as a result of transverse bending.

REFERENCES


Table 1

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Table 3

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Figure 1a
Modified AISI 420. A gouge causing premature fatigue fracture. 50x

Figure 1b
Fatigue fracture surface. Initiation point at the gouge shown in figure 1a. 90x SEM

Figure 2
Modified AISI 420. The effect of gouge size (cross section area) on the fatigue life.

Figure 3
A pit in modified AISI 420. 90x

Figure 4
AISI 1095. The effect of pits on the fatigue life. The numbers refer to the pit cross section area in \( \mu \text{m}^2 \).

378
Figure 5
AISI 1095. A fatigue fracture originating from a pit (arrowed). 7x

Figure 6
AISI 1095. A fatigue fracture which has started in the edge region. Note that the fracture is not caused by the 175 \mu m deep surface indentation in the centre. 4.5x

Figure 7
AISI 1095. Close to the edges of the specimen there are two 35 \mu m deep indentations associated with the fatigue fracture. 4.5x

Figure 8a
A fatigue fracture which has initiated at an oxide particle. 150x SEM
Figure 8b
Enlargement of the fracture initiation point. 960x SEM

Figure 9
Illustration of the shape of a thick strip subjected to bending. Principal curvature 1/R. Transverse curvature 1/r.

tensile stresses

Figure 10
Distortion of the cross section in bent strips for various values of w^2/Rt.