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MATERIAL ASPECTS OF IMPACT FATIGUE OF VALVE STEELS

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INTRODUCTION

Fractographic studies of service failures of compressor valves showed that the mechanical limitations of the material are primarily associated with the conditions which prevail above the valve seat (1–3). Impact stresses induced when the valve component hits the seat or valve stop were analysed and several investigators indicated that despite the fracture occurrence, the calculated or measured stresses were lower than fatigue strength of the valve material (3–6). Presented study was conceived to determine the applicability and the limitations of the valve material fatigue strength at impact loading. Beside impact fatigue, a tensile fatigue test was performed. Two standard high-strength valve steels were tested, UHB 20 and UHB Stainless 716, the first one was hardened and tempered to tensile strengths of 1 400 – 2 300 MPa (200 – 330 ksi). The fractographic features that allow distinction between various loading modes are discussed. Using the Weibull concept of critically stressed volume an attempt is done to estimate the magnitude of impact stresses in the tested specimens.

TESTING PROCEDURE

In order to simulate the dynamic performance of compressor valves the testing was made in a special testing equipment, Fig. 1. The specimen, dimension 100 x 20 x 0.38 mm, see Fig. 2, was operated by short-duration compressed air pulses generated by a fluidic device. The reed was repeatedly lifted from and struck against the seat. The operating frequency was 250 Hz which is equivalent to the specimen natural frequency. When the reed hits the seat, the impact intensity was detected by a piezoelectric accelerometer. The calibration of accelerometer, see Appendix, was made according to ref (6) where more details on testing apparatus are given. Impact intensity is the accelerometer signal, unit is m/s². In agreement with published data, no units were specified in the present paper. The testing equipment was stopped by optical fracture detector when a small fragment was torn off. Some constructional modifications were made to enable the continuous monitoring of the impact intensity.

Tensile fatigue testing was done on a high-frequency Amcal pulsator, Type 2HFP, testing frequency 70 – 90 Hz, maximum load 20 000 N. The pulsator works on the resonance principle and is equipped with an electromagnetic system which provides the driving force. Specimen shape is shown in Fig. 3.

Fig. 1 - Impact fatigue testing equipment.

The specimens were blanked from the strip parallel with the rolling direction, the edges were ground and polished. No surface preparation was made.

The impact and tensile fatigue tests were carried out at a room temperature of about 20°C in a dry, non-corrosive atmosphere. The fatigue limits at 10⁷ loading cycles were determined according to stair-case method (7). The fatigue limit is defined as impact intensity or tensile stress amplitude at which 50% of the specimens failed within 10⁷ cycles. The experimental scope comprised 30 specimens. To plot S-N curves, additional 50 specimens were tested.
Fig. 2 - Broken impact specimens. An early stage (left) and late stage of impact fracture (right).

Fig. 3 - Tensile fatigue specimen.

MATERIALS

Two standard hardened and tempered valve steels were used, UHB 20 and UHB Stainless 716, strip thickness 0.18 mm (0.015 in). The strip materials originating from two different heats were tested for each grade. The chemical composition is given below:

Table 1 - Chemical composition.

<table>
<thead>
<tr>
<th>Grade UHB</th>
<th>wt %</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td></td>
<td>1.01</td>
<td>.25</td>
<td>.45</td>
<td>.14</td>
</tr>
<tr>
<td></td>
<td>heat A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>1.00</td>
<td>.20</td>
<td>.39</td>
<td>.16</td>
</tr>
</tbody>
</table>
| Stainless 716 |    | .38 | .33| .45| 13.3| 1.02
|            | A    |    |    |    |    |
|            | B    | .37 | .41| .48| 13.5| 1.00|

Static tensile properties and hardness of test materials:

Table 2 - Tensile properties and hardness.

<table>
<thead>
<tr>
<th>Grade UHB</th>
<th>Tensile strength</th>
<th>Yield strength</th>
<th>Elong.</th>
<th>HV 100 N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MPa/m²</td>
<td>MPa/m²</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>UHB 20</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1220</td>
<td>1200</td>
<td>7.0</td>
<td>385</td>
<td></td>
</tr>
<tr>
<td>1430</td>
<td>1370</td>
<td>5.5</td>
<td>440</td>
<td></td>
</tr>
<tr>
<td>1680</td>
<td>1600</td>
<td>4.5</td>
<td>505</td>
<td></td>
</tr>
<tr>
<td>1930</td>
<td>1730</td>
<td>4.0</td>
<td>560</td>
<td></td>
</tr>
<tr>
<td>1960</td>
<td>1850</td>
<td>3.5</td>
<td>565</td>
<td></td>
</tr>
<tr>
<td>2240</td>
<td>2050</td>
<td>2.0</td>
<td>635</td>
<td></td>
</tr>
<tr>
<td>Stainless 716</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1860</td>
<td>1500</td>
<td>6.5</td>
<td>570</td>
<td></td>
</tr>
<tr>
<td>1920</td>
<td>1510</td>
<td>6.0</td>
<td>570</td>
<td></td>
</tr>
</tbody>
</table>

S-N DIAGRAMS

The impact testing results of UHB 20 and UHB Stainless 716 are shown in Fig. 4 and 5. In both cases the fracture probability for 10, 50 and 90 % are given. At 10⁷ impact cycles S-N curves become asymptotic. The stainless steel exhibited higher impact fatigue strength compared with UHB 20. It should be emphasised that tested valve steels exhibited a low scatter.

Fig. 4 - S-N curves for UHB 20, UTS 1930 MPa/m² (280 ksi), impact loading.

Fig. 5 - S-N curves for UHB Stainless 716, UTS 1860 MPa/m² (270 ksi), impact loading.

To make sure that there is a significant difference between the measured impact fatigue intensity of UHB 20 and UHB Stainless 716, the results were treated statistically. The method proposed by Welch-Aspin adopted for the stair-case procedure was used (8). The results of this calculation show that there is a difference between the mean values on the confidence level of 99.5 %. It was therefore concluded that the impact fatigue strength of UHB Stainless 716 is higher than that for UHB 20 on the significance level of 0.5 %. Many practical applications proved that UHB Stainless 716 ex-
Hibbitt superior impact fatigue stress compared with the carbon steel.

It is known that crack initiation stage takes the main part of the total fatigue life in high-strength materials exposed to dynamic loading (1, 9, 10). The initiation stage depends on stress field intensity at the tip of the crack or defect. In practice, whenever the stresses exceed the yield strength of the material a region of plasticity is developed near the crack tip. An estimate of the size of this zone, Fig. 6, for plane stress condition prevailing in valve strip material (1, 9) may be obtained from (10)

\[ r_y \approx \frac{1}{2\pi} \frac{K^2}{\sigma_{YS}^2} \quad \text{eq. 1} \]

- \( r_y \): plastic zone radius
- \( K \): stress intensity factor
- \( \sigma_{YS} \): yield strength

![Diagram of plastic deformation at the crack tip](image)

Fig. 6 - Onset of plastic deformation at the crack tip.

The effective crack length will be the initial crack length plus the plastic zone radius. The samples of both materials possess the similar external (flatness, straightness, surface and edge finish) and internal properties (carbide size, microinclusion size and content, tensile strength). The difference in yield strength can be roughly attributed to the differences in some structural parameters. It should be noted that at tensile testing of the fatigued tensile samples (10^7 loading cycles, stress amplitude 600 ± 600 MN/m², 87 ± 87 ksi) the changes in tensile and yield strength were smaller than 5% compared with the initial values, see Table 2. Furthermore, no structural changes were found due to impact loading of high-strength strip materials (6). Using \( K_{\text{ep}} \)-values determined for UHB 20 and UHB Stainless 716 with UTS ~ 1 000 MN/m², 87 and 131 MN m⁻³/² respectively (9), the plastic zone radius will be 0.4 mm in carbon steel and 1.2 mm in stainless steel. Considering that the "true defect size" is the same, one can expect, that due to significantly larger plastic zone in UHB Stainless 716 the fatigue crack initiation at certain stress level will be more retarded in this material than in UHB 20. This is the probable explanation to the superior impact fatigue strength exhibited by valve steel UHB Stainless 716.

**EFFECT OF TENSILE STRENGTH ON IMPACT AND TENSILE FATIGUE LIMIT**

The effect of mechanical properties on valve material fatigue response was examined. Simultaneously with impact fatigue experiment, the tensile fatigue was performed on UHB 20. The number of loading cycles was 10^7 at both loading modes. The results are presented in Fig. 7.

![Graph showing impact and tensile fatigue limit](image)

Fig. 7 - UHB 20, impact and tensile fatigue (\( R = 0 \)) limit for 10^7 loading cycles vs tensile strength. The scatter corresponds to the standard deviation.

The tensile fatigue limit increases linearly with the increased tensile strength up to ~ 1 700 MN/m² (250 ksi) while for impact fatigue limit the linear relationship was documented over the whole investigated tensile strength range, 1 400 – 2 300 MN/m² (200 – 330 ksi). This difference in fatigue behaviour is believed to be dependent mainly on the difference in the critically stressed volume. By critically stressed volume is understood the volume of the material subjected to at least 95% of the maximum stress (11). The critically stressed volume is smaller in the impact samples than in tensile fatigued samples, compare Fig. 3 and 12. Assuming, that potential crack
initiation sites are randomly distributed, the probability \( P \) to find one or more initiation sites in the stressed volume yields the Poisson distribution (12)

\[
P = 1 - e^{-NV}
\]

\( \text{eq. 2} \)

- \( N \) number or potential initiation sites in the stressed volume.
- \( V \) stressed volume.

It is well established that the higher tensile strength gives the higher notch effect for the existing defects. Consequently, with increased tensile strength the critical defect size in material decreases and number of potential initiation sites \( N \) increases. For a given probability \( P \), the smaller stressed volume \( V \) allows the higher tensile strength which can explain the different behaviour of valve steel material at repeated tensile and impact loading.

Presented relationships between fatigue limit and tensile strength are in a good agreement with established knowledge concerning the fatigue behaviour of the high-strength materials. Compared with the published results (6) exhibited tested material a very low scatter. Generally, a large experimental scatter in fatigue data gives a low statistical significance and makes often the reasonable evaluation of the basic material properties such as composition, tensile strength, surface condition etc., with respect to the material fatigue response impossible.

An attempt was done to determine the impact fatigue strength for strip material with UTS 1 220 MPa (177 ksi), HV 365, which is lower than min. tensile strength for standard valve steels. The pronounced groove formation in the sample surfaces contacting the valve seat was detected. The groove formation was attributed to the plastic deformation and wear. The cracking started at deep wear marks. It was stated, that fatigue behaviour of the soft material, where impact induced stresses cause predominantly the plastic deformation of the exposed volume, differs strongly from the valve material with tensile strength of 1 400 - 2 300 MPa (200 - 330 ksi), see below.

**FRACTOGRAPHY**

A large number of fractured specimens, see Fig. 2, was examined in a scanning electron microscope. A typical appearance of impact fatigue fracture is, that small fragments are torn off from the edges. The primary fatigue cracks were radially oriented. In all cases the initiation on the surface near the edges was found. The initiated cracks were created by circumferential (tangential) stresses indicating the opening mode. The initiation was observed both on the upper and impact surface.

The subsequent impact fracture formation is illustrated in Fig. 8. The initial fracture stage is shown in Fig. 8a. Fig. 8b, c demonstrates the fragment immediately before tearing. Note the pronounced plastic deformation of the surface during this stage. The appearance of the edge after fragment torn off is visible in Fig. 8d. It is important to know, that the fragment or chip formation in this study is attributed to the final fracture and not to the initiation stage. The mixture of the radial crack growth and edge tearing gives the late fracture stage, exhibited by broken samples, fig. 8e, f. The initiation of the primary fatigue cracks is visible on both fractographs. No stress raisers were detected, which indicates the necessity of the high stresses governing the impact fracture. The location of the primary fatigue cracks was on the surface outside the contact ring between specimen and seat.

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**Fig. 8** - (a) Initial fracture stage. (b) Fragment immediately before tearing, note the plastic deformation of the surface (c). (d) Fragment torn off from the edge. (e,f) A late fracture stage, the arrows show the initiation of the primary fatigue cracks outside the contact ring.
It can be seen that in this zone no mechanical loads due to the impact can be expected. This indicates that initiated cracks were created by stress waves induced by impact. The fracture occurrence is similar to the fractographic analysis of failed compressor valves (1).

The initiation stage takes the main part of the fatigue life. The growth of the initiated cracks is very fast and leads to the sudden final fracture. Depending on the stress system exposed to the samples due to the flexural and torsional vibrations resulting in the oblique impact on the seat the growing crack can propagate in two directions, namely in the radial direction, which is the initial direction and perpendicular to it, Fig. 8f, 9. The pictures indicate that near the surface the circumferential (tangential) stress component is dominating. With increasing depth below the surface the stress component in thickness direction can influence the crack growth, see the "stair-case pattern", Fig. 9. The resulting fracture is oriented approx. 45° to the surface.

The crack extension during one loading cycle was estimated to $10^{-2}$ - $20\ \mu m$, Fig. 9, which is very large compared with conventional stable crack growth. A detailed fractograph show that the crack propagates due to the microvoid coalescence, Fig. 10. The duration of the stress pulses resulting from the stress wave propagation can be approximated to $10^{-8}$ sec, see ref (1) where more details are given.

It is well known that high-strength materials are notch sensitive. Moreover, the fractographic observations show clearly that at impact loading the surface and edge are exposed to the highest stresses. This emphasizes the importance of the surface conditions. An attempt with coarse ground specimens showed that fatigue cracking at the initial stage was strongly influenced by surface stress raisers. At fractographic analysis of broken impact samples of UHB 20 and UHB Stainless 716 no evidence of fatigue crack initiation below the surface was found. It was stated that initiation stage is similar to fatigue behaviour of high-strength material at other loading modes.

![Fig. 11 - Initiated fatigue crack propagates along the surface defects.](image)

CALCULATION OF MAXIMUM IMPACT STRESSES

From a statistical viewpoint, the larger the volume of material experiencing maximum stress, the greater the probability of finding a weak point that would lead to more rapid failure, see even eq. 2. It was demonstrated by Weibull (13), that the size effect in fatigue at equal fracture probability levels can be expressed by

$$\sigma^m \cdot V = \text{const} \quad \text{eq. 3}$$

$\sigma$ fatigue limit
m material constant
V critically stressed volume

There are only a few determinations of m of current interest, since most investigations concern less sophisticated materials than high-strength valve steel. Available data show, that a value of m between 20 - 30 is valid for this type of steel (11, 14).

The ratio between the fatigue limit of two specimens with different stressed volumes derived from eq. 3 is

$$\frac{\sigma_1}{\sigma_2} = \left(\frac{V_2}{V_1}\right)^{1/m} \quad \text{eq. 4}$$

The critically stressed volume for the tensile fatigue specimen is $70\ mm^2$, Fig. 3. Based on fractographic analysis the stressed volume of impact loaded specimen was assessed to be between 1.5 - 4.5 mm², see Fig. 12. Hence

$$\frac{\sigma_1}{\sigma_2} = 1.13 \pm 0.06 \quad \text{eq. 5}$$
maximum impact stress, $10^7$ loading cycles.

The values for $\sigma_2$ above UTS 1 680 MN/m$^2$ (245 ksi) were calculated by extrapolation from the linear relationship given in Fig. 7. The estimated impact stresses corresponding to the 50% probability of fracture are summarized in Table 3.

Table 3 - Estimated maximum impact stress

<table>
<thead>
<tr>
<th>Tensile Fatigue limit</th>
<th>Impact Max. tensile stress</th>
<th>Estimated Max impact stress</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P 50 %</td>
<td>P 50 %</td>
</tr>
<tr>
<td></td>
<td>MN/m$^2$</td>
<td>MN/m$^2$</td>
</tr>
<tr>
<td>1430</td>
<td>1050</td>
<td>1.09</td>
</tr>
<tr>
<td>1650</td>
<td>1160</td>
<td>1.20</td>
</tr>
<tr>
<td>1930</td>
<td>1220</td>
<td>1.31</td>
</tr>
<tr>
<td>1960</td>
<td>1180</td>
<td>1.32</td>
</tr>
<tr>
<td>2240</td>
<td>1210</td>
<td>1.41</td>
</tr>
</tbody>
</table>

Estimated maximum impact stresses are high compared with material ultimate tensile strength. Even fractographic studies documented the necessity of high stresses responsible for the initiation of the fatigue cracks since no stress raisers were detected.

CONCLUSIONS

- The valve steel UHB Stainless 716 exhibited a higher impact fatigue strength than UHB 20. Both materials showed a very low scatter in presented fatigue data. For compressor valve applications, where the severe impact loading is expected, the UHB Stainless 716 should be selected.

- The differences between tested grades can be attributed to the fatigue crack initiation stage. This stage takes the main part of the total fatigue life of dynamically loaded high-strength materials. The plastic zone size occurring at the crack tip was much larger in stainless steel which leads to the retarded initiation stage.

- The impact fatigue strength is strongly dependent on the static mechanical properties of valve steel. The linear relationship was documented for the range of 1 400 - 2 300 MN/m$^2$ (200 - 330 ksi).

- Extensive fractographic studies showed, that impact fracture initiates entirely on the surface. The identical behaviour was detected at analysis of service compressor valve failures. The crack initiation below the surface was not found.

- The primary fatigue cracks were radially oriented and located outside the contact ring with the seat where no mechanical loads due to the impact can be expected. This leads to an assumption that detected fatigue cracks were created by propagating stress waves.

- Based on the fractographic observations, the duration of the stress pulses governing the crack initiation and crack propagation in laboratory testing equipment was approximated to $10^{-6}$ sec. The similar results were found on service valve failures.

- Using the Weibull's concept of critically stressed volume, the maximum impact stresses were calculated. The determined stresses are high compared with the valve material tensile strength. This is in accordance with the fractographic studies indicating the necessity of the high stresses in order to initiate fatigue fracture since no stress raisers were detected in impact loaded specimens.

APPENDIX

The accelerometer was calibrated with a steel ball falling freely from different heights. The momentum $p$, immediately before the first seat contact is

$$p = mv$$

where

- $m$ mass of steel ball 2.04 g
- $v$ impact velocity $\sqrt{2gh}$
- $g$ acceleration of gravity
- $h$ height
The result of calibration is shown in Fig. 13, where impact intensity $a$ measured by Uddeholm and impact intensity $a_{\text{ref}}$ (6) is plotted. Comparison between $a$ and $a_{\text{ref}}$ is illustrated in Fig. 14, where the straight line was fitted by the least square method

$$a_{\text{ref}} = 0.44a + 0.42 \quad \text{eq. 7}$$

stand dev 0.045

corr coef 0.997

In Fig. 14, the impact velocity of the specimen immediately before contact with the seat vs impact intensity is also shown.

The continuous monitoring of the impact intensity during fatigue was made by recording the damped accelerometer signal $a_D$. The relation between $a$ and $a_D$ was determined by simultaneous measurements. For each $a_D$ value the corresponding $a$ was recorded by the peak detector, Fig. 15. The relation between $a$ and $a_D$ was found

$$a = 1.61a_D + 0.45 \quad \text{eq. 8}$$

stand dev 0.047

corr coef 0.997

Eq. 7 and 8 give

$$a_{\text{ref}} = 0.71a_D + 0.62 \quad \text{eq. 9}$$

Fig. 13 - Calibration of accelerometer with steel ball.

Fig. 14 - Impact intensity $a_{\text{ref}}$ versus measured impact intensity $a$.

Fig. 15 - Measured impact intensity $a$ versus $a_D$.

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