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# FATIGUE PROPERTIES OF A HIGH-STRENGTH-STEEL WELDED JOINT

## UTRUJENOSTNE LASTNOSTI ZVARA VISOKOTRDNEGA JEKLA

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In addition to the strength and toughness properties, the fatigue properties of welded joints are necessary for the design of high-strength steel structures exposed to variable loading. Wöhler curves were determined for smooth tensile specimens tested with variable loading. The fatigue behaviour of a welded joint can be improved by removing the overfill; however, the fatigue properties are still lower than the values for the parent metal. Tests with pre-cracked specimens have shown the difference in the fatigue-crack growth-rate properties to be less significant than other crack parameters.

Keywords: HSLA, welded joint, low-cycle fatigue, high-cycle fatigue, crack growth rate

Utrujenostne lastnosti so potrebne poleg trdnosti in žilavosti za načrtovanje struktur iz visokotrdnih jekel, ki prenašajo spremenljivo obremenitev. Wöhlerjeve krivulje so bile določene za gladke preizkušance in spremenljivo obremenitev. Utrujenostno vedenje zvarjenega spoja se lahko izboljša z odstranitvijo nadvišenja, vendar ostanejo utrujenostne lastnosti nižje kot pri osnovnem materialu. Preizkusi na vzorcih z razpoko so pokazali, da je manj izrazita razlika v hitrosti rasti razpoke kot pri drugih parametrih razpoke.

Ključne besede: HSLA, zvarjeni spoj, malociklična utrujenost, velikociklična utrujenost, hitrost rasti razpoke

## 1 INTRODUCTION

When selecting a material for a particular application, the ease and cost of welding must be considered, and the material selected should give a welded product with adequate properties for the minimum cost. The steels developed for heavily loaded structures and their welded joints have to be resistant to variable loading, in addition to having adequate strength and toughness properties [1]. The benefits of a strength increase can be expressed in terms of reduced component dimensions, followed by a significant reduction in welded-joint cross-sections, the consumption of welding electrodes and the time necessary to produce the welded joints.

Since defects are frequently involved in welded structures, it is necessary to design against low-stress failure by fatigue. By maintaining an adequate level of control by non-destructive testing, it is possible to ensure that cracks exceeding some maximum size, as the most dangerous defects, will be avoided and the stress concentration in components be reduced as a result. This is important for the welded joints of high-strength steel that are exposed to fatigue. The data about the fatigue behaviour of HSLA steel welded-joint constituents are necessary, starting with the design stage, since the benefits gained by having a high strength could be lost under variable loading.

## 2 PREPARATION OF SAMPLES

The experiments were performed with the high-strength steel NIONICRAL-70 (NN70), with the nominal yield-stress class of 700 MPa and its welded joints, produced with metal manual arc welding (MAW). This steel is designed for the manufacturing of pressure vessels and in shipbuilding, e.g., for submarines, but is also applicabble for other heavy-duty sructures. The chemical composition and the mechanical properties are shown in **Tables 1 and 2**, respectively.

Two plates of NIONICRAL-70, 18 mm thick, were prepared by edge machining for asymmetric 2/3 X and welded in 6 passes with a Tenacito-80 electrode, which produced a slightly undermatched welded joint.

## 3 TESTING FOR FATIGUE-ENDURANCE DETERMINATION

Low-cycle fatigue initiation can be expected in the region of welded joints, because the yield stress can be achieved locally by stress concentration. The smooth specimens for testing with variable loading are presented in **Figure 1**. Four sets of smooth specimens were prepared: OM, from the parent metal and from welded samples; XN, in the as-welded condition; XB, with the overfill removed by grinding; and XO, with both sides machined to 15 mm and so the rough layer of rolling was removed together with the overfill. The specimens were

**Table 1:** Chemical composition of NIONICRAL-70 steel, *w*/%
**Tabela 1:** Kemična sestava jekla Nionicral 70, *w*/%

| C | Si | Mn | P | S | Cr | Ni | Mo | V | Al |
|---|---|---|---|---|---|---|---|---|---|
| 0.1 | 0.2 | 0.23 | 0.009 | 0.018 | 1.24 | 3.1 | 0.29 | 0.05 | 0.08 |

**Table 2:** Mechanical properties of NIONICRAL-70 steel
**Tabela 2.** Mehanske lastnosti jekla Nionicral 70

| Specimen orientation | Yield stress | Tensile strength | Elongation | Contraction | Charpy V impact energy, *E*/J | | |
|---|---|---|---|---|---|---|---|
| | $R_{p0.2}$/MPa | $R_m$/MPa | *A*/% | *Z*/% | +20 °C | –60 °C | –100 °C |
| Parallel | 780 | 820 | 19 | 66 | 126 | 117 | 93 |
| Perpendicular | 770 | 810 | 20 | 74 | 81 | 76 | 49 |

tested on a hydraulic machine, with the lower grip fixed and the upper grip oscillating with the frequency $f$ = 9 Hz to 15 Hz, depending on the maximum load in the cycle, $\sigma_g$ , at the stress ratio $R = \sigma_d/\sigma_g = 0.1$ ($\sigma_d$ is the lower stress in the cycle). Local plastic deformation ahead the crack tip is typical for crack initiation and growth in the early stage of low-cycle fatigue, followed by shear lips. But, if the frequency is low, in low-cycle fatigue of high-strength steel the fracture appearance is similar to that obtained in high-cycle fatigue, with no shear lips. In some cases the loading level was so low that the specimens did not fracture, even after more than one million cycles. As a result of this they were tested in a high-cycle regime.

For a high stress level (691 MPa), close to the yield stress (**Table 2**), the as-welded XN specimens fractured with low-cycle fatigue after only 6700 cycles. The fatigue crack initiated in the region of stress concentration, in the transition from the overfill to the heat-affected zone (HAZ), and developed through the HAZ's coarse-grain region, followed by significant contraction of the cross-section. The crack grows on both sides of the specimen, and the final fracture occurred in the weld metal in a reduced ligament size. At a stress of 415 MPa the specimen fractured after 66,300 cycles. The high-cycle fatigue crack in the third XN specimen initiated in the same region and propagated in the plane normal to the load direction, completely through the HAZ's coarse-grain region of reduced ductility. The stress level was 274 MPa and the number of cycles at fracture was 143,700. The stress concentration in the XB specimens was reduced by removing the overfill. This increased the number of cycles to fracture: (a) for stress 685 MPa to 13,700 cycles, (b) for 228 MPa to 690,800 cycles. The crack initiated in the HAZ's coarse-grain region in both low-cycle (a) and high-cycle (b) fatigue and developed mostly through the HAZ. The best results for the welded samples were obtained with machined sides of the XO specimen in the absence of the stress concentration due to geometry. The crack initiated in the weld metal's critical microstructure. In low-cycle fatigue (a) the crack developed under 45° at a load of 586 MPa, up to 49,100 cycles. In high-cycle fatigue (b) the crack path is normal to the applied load of 443 MPa, and the fracture occurred after 565,300 cycles. In some specimens the crack initiated from embedded defects.

The results are summarized in the upper part of the relationship applied load $\sigma$ vs. number of cycles $N$ (Wöhler) (**Figure 2**). The fracture stress is satisfactory for the parent metal (OM) $\sigma$ = 625 MPa and for the machined specimens (XO) $\sigma$ = 530 MPa, but the results for the XN specimens in the as-welded condition ($\sigma$ = 370 MPa) and for the XB specimens with the overfill

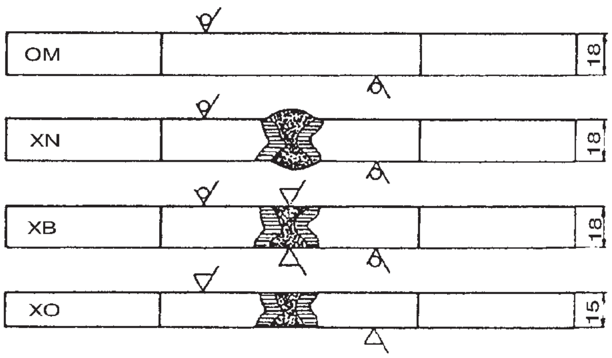


**Figure 1:** Smooth specimens for testing by variable loading
**Slika 1:** Gladki preizkušanci za preizkus pri variabilni obremenitvi

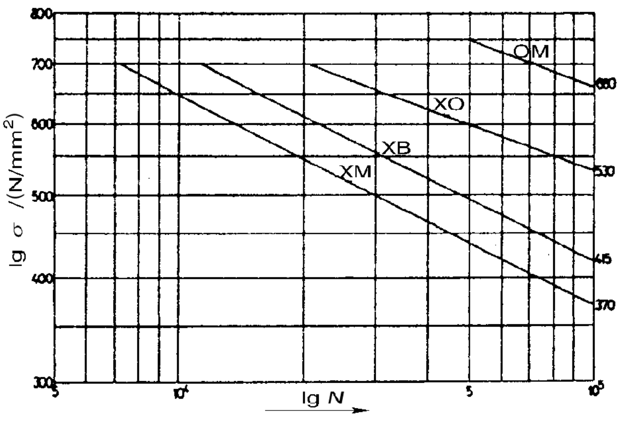


**Figure 2:** Upper part of the relationship applied load $\sigma$ vs. number of cycles $N$
**Slika 2:** Zgornji del odvisnosti obremenitev – število amplitud

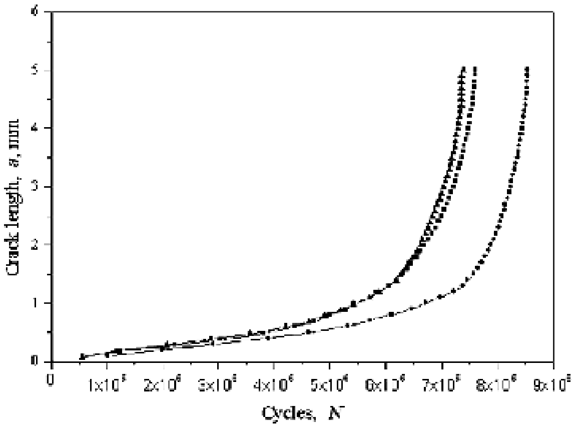


**Figure 3:** Crack length *a* vs. number of cycles *N* for parent metal (right), weld metal (in the middle) and HAZ (left)
**Slika 3:** Odvisnost dolžine razpoke – število ciklov za osnovni material (desno), deponirani material (sredina) in HAZ (levo)

ground away ($\sigma$ = 415 MPa) are not acceptable. This is confirmed by the value of the coefficient $m$ – the Wöhler curve slope in the initial part, up to 100,000 cycles, which is 5.90 for the OM specimens, 5.80 for the XO specimens, 4.23 for the XB specimens and 4.17 for the XN specimens. The recommended design values are 5 to 7 [2].

## 4 TESTING OF FATIGUE-CRACK GROWTH RATE

Welded structures can contain small pre-existing cracks, which will propagate under repeated loads up to the size critical for fracture. Since in this case the zone ahead of the crack tip, exposed to the cyclic plasticity, is small, a plane-strain state is formed, even for a small thickness, and generally the data obtained with small specimens can be applied.

The testing of the fatigue-crack growth rate is performed using the ratio $R$ = 0.1, with precracked SE(B) specimens (width $W$ = 16 mm, thickness $B$ = 12 mm, span $S = 4W$) of parent metal, weld metal and HAZ, on a CRACKTRONIC dynamic testing device. The number of cycles was registered for each 0.1 mm of crack growth, as presented in the crack length $a$ vs. number of cycles of $N$ relation (**Figure 3**). The curve on the right-hand side is for the parent metal, the middle

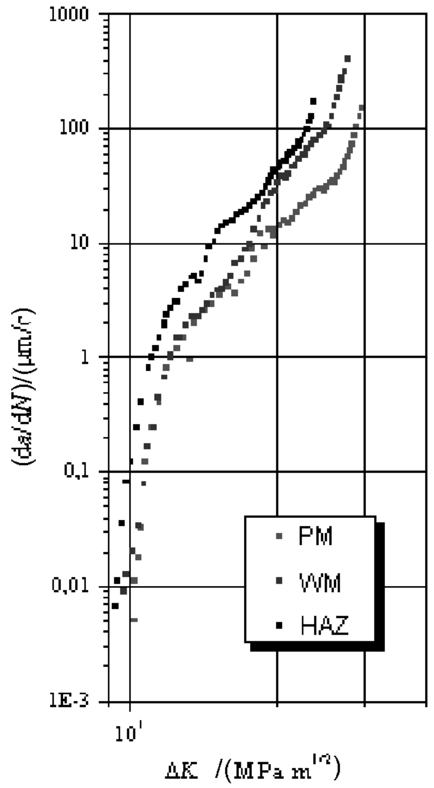


**Figure 4:** Diagram d$a$/d$N$ – $\Delta K$
**Slika 4:** Odvisnost d$a$/d$N$-$\Delta K$

curve is for the weld metal, and the curve on the left-hand side is for the HAZ. From these curves the data necessary for Paris law are derived:

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C(\Delta K)^{\mathrm{m}} \qquad (1)$$

Here, d$a$/d$N$ is the crack size $a$ growth per unit cycle, $N$ is the cycle number, $C$ and $m$ are constants obtained from experiments and given in **Table 3**, $\Delta K = K_{\max} - K_{\min}$ is the stress-intensity factor range in the loading cycle.

The obtained relationships d$a$/d$N$ vs. $\Delta K$ are given in **Figure 4**. It is interesting that the difference in the fatigue threshold value, the value of the stress-intensity factor range, $\Delta K_{\mathrm{th}}$, at which existing crack will not grow, is not significant: for the parent metal it is 10.22 MPa m$^{1/2}$, for the weld metal it is 9.11 MPa m$^{1/2}$ and for heat-affected zone it is 8.51 MPa m$^{1/2}$.

**Table 3:** The values for parameters $C$ and $m$ in the Paris equation
**Tabela 3:** Vrednosti parametrov $C$ in $m$ v Parisovi enačbi

| Specimen | $C$ | $m$ | Specimen | $C$ | $m$ |
|---|---|---|---|---|---|
| Parent metal | | | HAZ | | |
| I | $3.98 \cdot 10^{-14}$ | 4.139 | I | $1.90 \cdot 10^{-20}$ | 10.259 |
| II | $1.67 \cdot 10^{-13}$ | 3.765 | II | $4.63 \cdot 10^{-12}$ | 2.667 |
| Weld metal | | | III | $2.90 \cdot 10^{-16}$ | 6.403 |
| I | $8.38 \cdot 10^{-15}$ | 4.798 | IV | $7.87 \cdot 10^{-13}$ | 3.560 |
| II | $3.30 \cdot 10^{-19}$ | 8.462 | V | $1.48 \cdot 10^{-16}$ | 6.505 |
| III | $7.93 \cdot 10^{-15}$ | 5.078 | VI | $1.74 \cdot 10^{-14}$ | 4.929 |

## 5 CONCLUSIONS

The importance of reducing the stress concentration for fatigue life can be easily seen from **Figure 3**. The critical load for $N = 10^5$ cycles for the smooth parent-metal specimen is 625 MPa, reduced in the machined specimen of the welded joint to 530 MPa, with the overfill ground away it is reduced to 415 MPa, and down to 370 MPa in the as-welded condition.

In regime I the crack-growth rate is low since the threshold for the crack $\Delta K_{th}$ is approached. In regime II the Paris law is obeyed, while in regime III the crack-growth rate increases above that predicted by the Paris relation.

The fatigue resistance of the weld metal and the HAZ is reduced, compared to the parent metal, and this has to be taken into account when a welded structure is designed with high-strength steel.

### Acknowledgement

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