# THE INFLUENCE OF LOW TEMPERATURES AND STRESS CONCENTRATION ON MECHANICAL PROPERTIES AND FATIGUE STRENGTH OF THE HSLA STEELS

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## ABSTRACT

The combined effects of low temperature and material structure on mechanical properties and fatigue characteristics of the parent materials and welded joints have been considered. The results of fatigue tests with different stress ratios have been presented in the collection Goodman diagrams. Particular attention has been paid to the influence of nonmetallic inclusions on the fatigue fracture mechanisms of the HSLA steels. with Nb, V, Ni additions.

## INTRODUCTION

Fatigue and brittle fractures are the most serious causes of failures in ship structures. It is assumed that the fracture process of constructional steels is controlled by nonmetallic inclusions and microdefects [1]. The fatigue failure initiation and decohesion process of the normalized and quenched and tempered HSLA steels may be limited to the elastic-plastic behaviour around inclusions and second phase particles [2,3]. The crack tip opening displacement (CTOD) values and plastic zone radiuses are correlated with the length, shape, and distance between inclusions in range above the ductile-brittle fracture transition temperatures [4,5]. Increasing of an yield strength of quenched and tempered steels and suitable welding procedure diminish the influence of inclusions and precipitations on the fracture susceptibility of weldments. The influence of cutting and welding procedure of structural components on fatigue strength is described hereunder.

## MATERIALS AND EXPERIMENTAL PROCEDURE

The investigations of the 09G2-EH32, 15G2ANb-EH36, 15G2NNb-EH39, 15G2ANb-E460T and 10G2ANb-EH36 HSLA steels have been carried out. These steels are designed to the application in low temperatures, also for ship structures. Specimens were machined from steel plates (8-24 mm). The chemical compositions of the analysed steels are presented in Table 1.

Tabele 1. Chemical composition of the HSLA steels

| Steel | Sign. | Ingredient (wt. %) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | C | Mn | Si | P | S | Al | Nb | Cr | V | Ni |
| 09G2/A | A | .11 | 1.26 | .36 | .024 | .032 | .015 | – | – | – | – |
| 09G2/F | F | .12 | 1.40 | .30 | .016 | .015 | .03 | – | – | – | – |
| 10G2ANb | 3D | .07 | 1.35 | .36 | .007 | .009 | .015 | .030 | .08 | – | .05 |
| 10G2VNb | S | .09 | 1.34 | .29 | .013 | .015 | – | – | – | .09 | .15 |
| 15G2ANb | Z | .14 | 1.32 | .31 | .013 | .022 | .04 | .029 | – | – | – |
| 15G2ANNb | R | .16 | 1.47 | .35 | .024 | .025 | .26 | .028 | – | – | .63 |

The nonmetallic inclusion analysis has been carried out by the image analysis technique with the use of the quantimeter QTM-360B type. The nonmetallic inclusion content ,varied on the 95% confidence level as follows :

- inclusion area fraction, $A_A$ : 0.067-0.132%,
- particles per. sq. mm, $N_A$ : 55-191 $mm^{-2}$,
- mean size of inclusion, $L_2$ : 2.85-6.62 μm.

The mechanical and fatigue properties of these steels have been tested at an ambient temperature and below the null ductility temperature (NDT) on the INSTRON-1251 and MTS-810.12 universal closed-loop testing machines.

The fatigue tests were made at constant load amplitudes and stress ratios $R=\sigma min/\sigma max=-1$ and $R=+0,2$ mainly. The round (dia. 10 mm) and special shape specimens as well as rectangular ones were used. The loading frequency was chosen from 5 to 25 Hz at the number of cycles to failure up to 2 milions cycles. Low temperature tests were carried out inside a cooling tank mounted on the hydraulic actuator. As a heat transfer medium a methyl alcohol was used. Above - 73°C temperature a solide carbon dioxide and below -73°C a liquide nitrogen was immersed in the alcohol. Ultra sound fatigue tests were made on a magnetostrictional pulsator using tubular specimens (dia 8/6 mm) at resonance frequence 23 kHz and stress ratio R=-1. Tests were made at room temperature (RT), at the NDT and at the liquid nitrogen temperature. Fatigue tests of the welded joints (see Fig.1) have been carried out on the testing machines ZDM-30 and ZDM-100 type at loading frequencies from 10 to 25 Hz, at a room temperature and stress ratios R=-1 and R=0.2 mainly. The fatigue strength of butt welded joints was determined for flat not machined specimens (12x/25-100/mm) which were taken parallelly to a direction of rolling. The butt welds were manual made (MMAW) with the use of the following electrodes : EB1.55 type for 15G2ANb steel, EB3.50Ni2 type for 15G2ANNb steel and EB1.70 type for 10G2AVNb steel plates. Butt and fillet welds were made on joints of the plates with stiffeners and doublers (of 10G2AVNb and 15G2ANNb steels) both by metal active $CO_2$ - gas ($CO_2$-MAG) and submerged arc welding (SAW). The butt welds were made from both sides between plates and fillet welds were made along the longitudinal - flank - and transverse stiffeners and along the doublers on plates.

Table 2. Mechanical properties of the investigated materials.

| Material | Test temp. K | Temp. NDT K | Yield streng. $\sigma_{YS}$, MPa | Tensile streng. UTS, MPa | Elon-gation $A_5$ % | Fatigue streng. $\sigma_{tc}$, MPa | Factor n $MPaK^{-1}$ |
|---|---|---|---|---|---|---|---|
| 09G2-EH32 | 293 | 208 | 352 | 489 | 35,0 | 260 | -0,46 |
| 10G2ANb -EH36 | 293<br>203 | 228 | 376 | 502 | 33,0 | 256<br>280 | -0,27 |
| 10G2VNb -EH36 | 293<br>173 | 218 | 413 | 537 | 28,2 | 360<br>393 | -0,28 |
| 15G2ANb -EH36 | 293<br>228 | 228 | 405 | 560 | 25,5 | 275<br>303 | -0,44 |
| 15G2ANb -E460T | 293<br>213<br>153<br>77 | 198 | 475<br>533<br>621<br>921 | 586<br>673<br>739<br>979 | 27,8<br>28,3<br>32,0<br>20,0 | 312<br>330<br>360 | -0,53<br>- |
| EB3.50Ni2 /welded 15G2ANb-E460T | 293<br>213<br>153<br>77 | | | 579<br>668<br>741<br>983 | | 193 | |
| 15G2ANNb -EH39 | 293<br>213<br>173<br>133<br>77 | 213 | 463<br>558<br>638<br>691<br>922 | 615<br>716<br>786<br>833<br>1000 | 28,9<br>27,5<br>27,5<br>30,1<br>22,3 | 296<br>312<br>343<br>-<br>360 | -0,34 |

The weld rainforcement causes a shape discontinuity and stress concentration in the transition zone from the weld face to the parent material. The influence of the butt joint shape is determined by the notch radius and by the angle θ between a

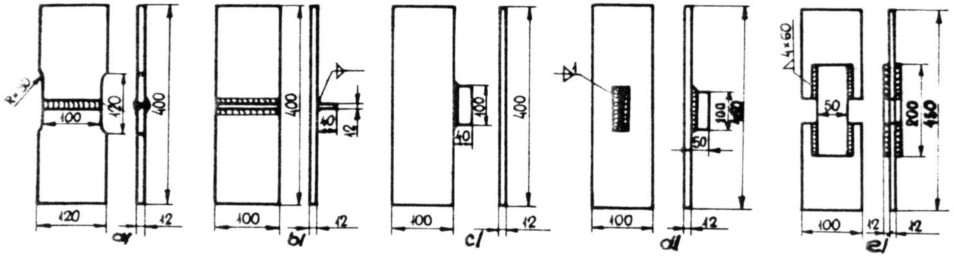

Fig. 1. The specimens with butt welds made from both sides between plates (a) fillet welds made on the transverse stiffener (b) - on the flank stiffener (c) - on the longitudinal stiffener (d) and along doublers on plates (e).

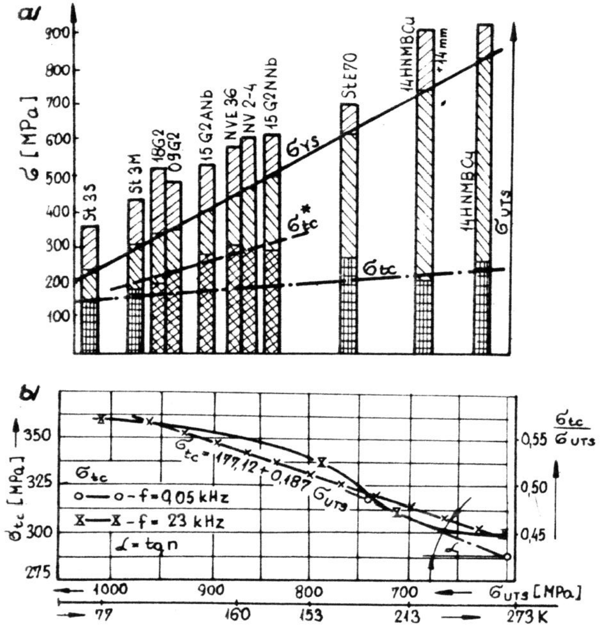

Fig. 2. Yield strength $\sigma_{YS}$ of HSLA steels and fatigue strength $\sigma^*_{tc}$ (R=-1) for grinded specimens and $\sigma_{tc}$ for specimens with scale at number N=2 $10^6$ cycles (a) and relationship between ultimate tensile strength $\sigma_{UTS}$ and fatigue strength $\sigma_{tc}$ of 15G2NNb steel at low temperatures(b).

tangent to the reinforcement bead and the plate surface. In some publications that angle is used in formulas defining the stress concentration factors [6]. Thin foils and fracture specimens were prepared for electron microscope observations (TEM and SEM). The foils were examined in the BS-540 (TESLA) microscope. All fatigue fractures have been analysed with the use of the microscanner (SEM) BS300 type.

## FATIGUE TEST RESULTS AND DISCUSSION

The investigation results of mechanical and fatigue properties of HSLA steels and welded joints (MMAW) are given in Table 2. The factors $n=(\sigma_{tc\ NDT} - \sigma_{tc\ RT})/(NDT-RT)$ have been determined from the above results. Where the $\sigma_{tcNDT}$ and $\sigma_{tcRT}$ - is the tension-compression stress amplitude at stress ratio R=-1, and at the NDT and RT temperatures, respectively. Without exception, the alloys showed a decrease of the fatigue strength and tensile strength with the increasing test temperatures. The 20-30% decrease of the fatigue strength $\sigma_{tc}$(R=-1) was followed by 50% decrease of the yield strength of the HSLA steels in temperature range from NDT or 77K to RT. In equation from a ultimate tensile strength $\sigma_{UTS}$ determined experimentally at correlation factor wefficient r = 0,9967 is given by :

$$\sigma_{UTS} = 2232 - 283\ \mathrm{LnT} \qquad (1)$$

and a yield strength $\sigma_{YS}$ at r = 0,993 is given by equation :

$$\sigma_{YS} = 2352-333\ \mathrm{lnT} \qquad (2)$$

where T : test temperature from 77 K to 293 K. The results of tensile and fatigue tests of HSLA steels are comparised in Fig.2. The increase of the yield strength of the HSLA steel from 250 to 700 MPa is accompanied by the increase of the fatigue strength ca-10%. The relationship between $\sigma_{tc}$ and $\sigma_{UTS}$ varies in the range from 0,575 to 0,425 at temperatures from 77K to 293K (Fig.2b). These values are higher for grinded specimens than for specimen with scale. The results of fatigue tests of weldments and HSLA steel plates at stress ratio R=-1 and R=0,2 and $N=2*10^6$ cycles are presented in Tables 3 and 4. Average fatigue test results and S-N curves of the MMAW, SAW and $CO_2$-MAG butt welded joints with toes of welds for the 10G2AVNb steel (Fig.3b) and for 10G2AVNb, 15G2ANNb, 18G2AV and St3S steels joints made by $CO_2$-MAG welding are comparised in Fig.3a.

Table 3. Estimation of the fatigue strength $\sigma_t(R=0,2)$ and fatigue life of the welded joints (RWO- controlled rolling (CR) and annealed - and CR normalized steel plate).

| Steel type/ (heat treat.) | Specimen/welding method | Regression line equation | $\sigma_t$ MPa |
|---|---|---|---|
| 15G2ANb-EH360 | ‡12•50 SAW (grinded surface) | σ=846,8-85,766 lgN | 295 |
| 15G2ANb/NVA-360 | ‡12•40 MMAW | σ=479,6-49,279 lgN | 155 |
| 15G2ANb/NVA-360 | ‡20•30SAW | σ=710,8-81,449 lgN | 195 |
| 15G2ANNb-D420 | ‡12•50 SAW | σ=400,8-74,766 lgN | 190 |
| 15G2ANNb-D420 | ‡20•30 SAW | σ=1100,9-144,83 lgN | 195 |
| 15G2AVNb/RWO/ | ‡8•50(with scale) | σ=903,6-87,190 lgN | 350 |
| 15G2AVNb/RWO/ | ‡8•75 MMAW | σ=552,1-55,918 lgN | 195 |
| 15G2AVNb/RWN/ | ‡12•75 SAW | σ=761,3-95,318 lgN | 155 |
| 15G2AVNb/RWO/ | ‡24•75 SAW | σ=402,3-37,117 lgN | 165 |
| 15G2AVNb/RWN/ | ‡8•80 trans.stiff weld joint MMAW | σ=924,6-128,049 lgN | 120 |
| 15G2AVNb/RWN/ | ‡8•80 long stiff. weld joint MMAW | σ=444,8-52,182lgN | 130 |
| 15G2ANb-E460T | ‡16•47(with scale) | σ=905,2-84,212lgN | 340 |
| 15G2ANb-EN460T | ‡16•47 MMAW EB3.50Ni2 | σ=1095,7-151,58lgN | 145 |

Machined or at the θ = 150 - 180° joints have greater fatigue strength.

Table 4. Estimation of the fatigue life and fatigue strength $\sigma_{tc}$ (R=-1) of the weldments and HSLA steel plates

| Steel type/ heat treatment | Specimen type | Regression line equation | $\sigma_{tc}$ MPa |
|---|---|---|---|
| 10G2AVNb/RWO/ | ‡8•50transverse | σ=513,3-51,461 lgN | 190 |
| 10G2AVNb/RWO/ | ‡8•75 SAW | σ=361,6-40,031 lgN | 110 |
| 10G2AVNb/RWN/ | ‡12•75 SAW | σ=312,7-33,659 lgN | 97 |
| 10G2AVNb/RWO/ | ‡8•75 MMAW | σ=461,8-56,854 lgN | 100 |
| 10G2AVNb/RWN/ | ‡8•80 trans.stiff weld joint MMAW | σ=421,3-39,884 lgN | 170 |
| 10G2AVNb/RWN/ | ‡8•80 long.stiff. weld joint | σ=291,7-33,904 lgN | 77 |
| 15G2ANNb-3390 | ‡12•50 SAW | σ=480,4-58,223 lgN | 115 |
| 15G2ANNb-D420 | ‡20•30 SAW | σ=728,4-92,050 lgN | 160 |
| 15G2ANb-NVE36 | ‡20•20 SAW | σ=315,6-29,190 lgN | 127 |
| 10HNAP | Φ7,5 long.tubular | σ=638,5-50,867 lgN | 305 |
| 10G2VNb/RWO/ | ‡ =//= | σ=406,8-6,2361 lgN | 368 |
| 15G2ANNb-EH390 | ‡ =//= | σ=289,6-11,664 lgN | 297 |
| 15G2ANb-NVE360 | ‡ =//= | σ=289,2-12,651 lgN | 289 |
| 10G2NNb/RWO/ | ‡ =//= | σ=572,4-34,600 lgN | 275 |
| 10G2NNb/RWN/ | ‡ =//= | σ=541,6-32,504 lgN | 291 |

The machined or oxyfuel cutting cause lower increasing of the fatigue strength than the structural and technological postweld notches.

Goodman diagrams of HSLA steels after various heat treatments

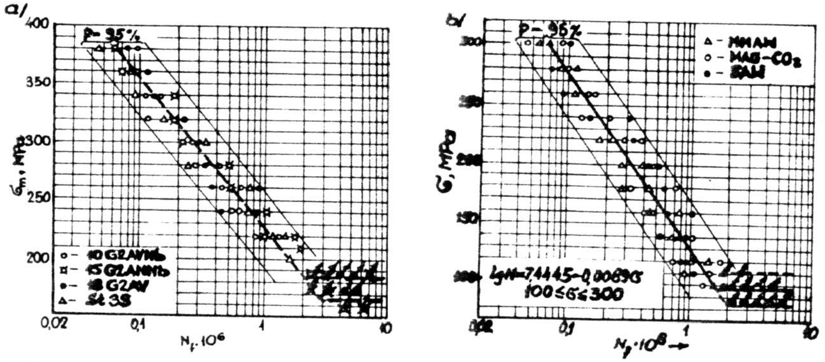

Fig.3. S-N curves of $CO_2$-MAG butt welded joints of 10G2AVNb, 15G2ANNb, 18G2AV and St3S steels (a) and S-N curves of MMAW, $CO_2$-MAG and SAW butt welded joints 10G2AVNb steel plates (b) with toes of welds at stress ratio R=0,2.

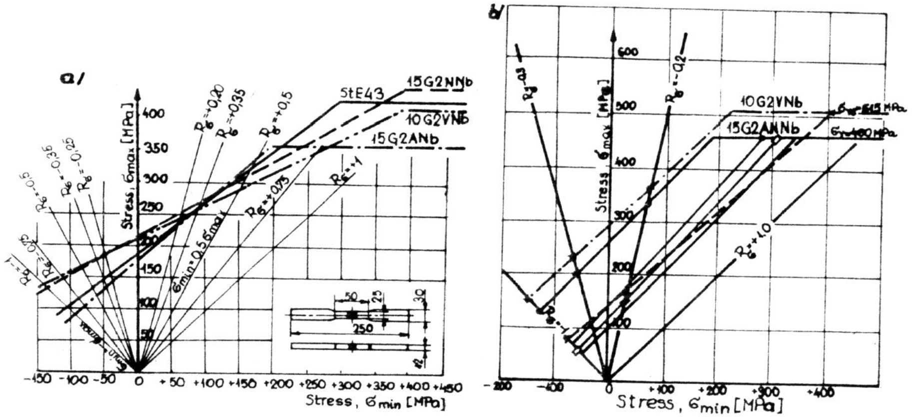

Fig.4. Goodman diagramms of butt welded joints ($CO_2$-MAG) at the fatigue life N = 2 $10^6$ cycles. StE43, 10G2ANNb, 15G2ANNb and steel plates (a) and for 10G2AVNb steel ● - parent material with scale, RWO. ● - parent material, RWN x-the butt weld trans. MMAW RWN, o - the butt weld trans. SAW RWN, θ - longitudinal stiffener MMAW RWN, Δ - butt weld SAW RWN (b).

and welded joints are showed in Fig.4. The results of fatigue testing of the 10G2AVNb steel plates and weldments with stiffeners are summarized in Table 5. Factors β-1, β0.2 indicate the relationships between the fatigue strength of parent material and that of welded joints. The biggest factors β are for from specimens with longitudinal stiffeners and with doublers on the face plates. Welding methods influence slightly the fatigue strength of welded joints with toe of welds. Machined and grinded or remelted toes butt welds result in much higher fatigue strength of weldments. The test results indicate on the limited range of application of high strength steels for high cycle service conditions.

## FRACTOGRAPHIC OBSERVATIONS

The fatigue fracture have been examinated with the use of microscanner. It has been confirmed that the inclusions situated at the specimen surface act frequently as crack initiators and may arrest the propagating crack (particurlarly when front lines of propagating crack meet inclusions e.q. sulphides along their full length) (Fig.5-7)

The fatigue strength level decisively depends on the yield and tensile strength of the matrix. The influence of inclusions is limited to the range of temperature in which metal exhibits good plasticity. Variations of fatigue strength may be ascribed to the influence of the numbers and sizes of the inclusions. Randomizing of test results below NDT leads to the conclusion that influence of inclusions on fatigue cracking is smaller at low temperature. Fig.5d shows a SEM photograph of a typical fatigue fracture surface with the crack origin and with an untypical complex fatigue lamellar fracture initiatiors (particulary around the fatigue crack tip) is very probable and may cause the incubation and growth of elougated lamellar discontinuities. The fatigue behaviour and crack nucleation at various low temperatures (NDT - see Table 1, 77K) were photographed. Some examples cracks are arrested on the boundary between the matrix and an inclusion. Next, the decohesion occurs

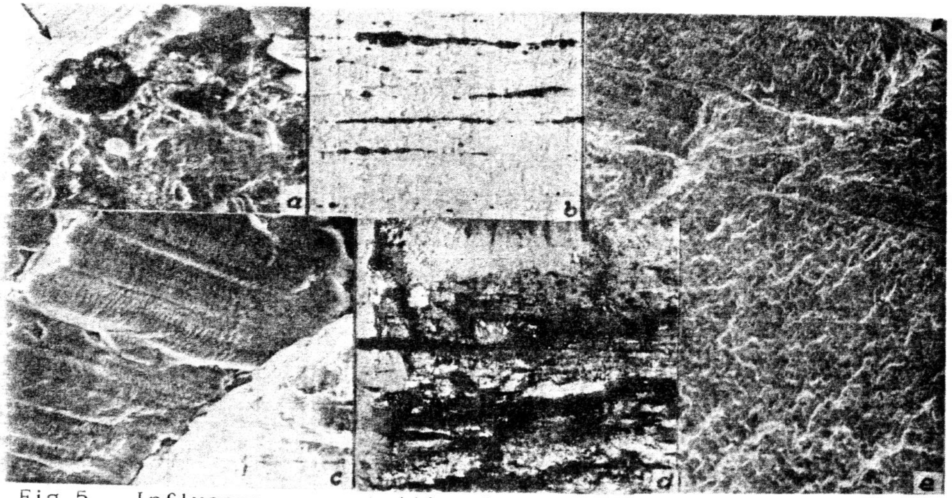

Fig.5. Influence nonmetallic inclusions on the fatigue crack iniciations (a,e) and fatigue crack arrest (c,e) and activated fatigue - lamellar deep crack (e,d) in HSLA steel plates at room temperature.

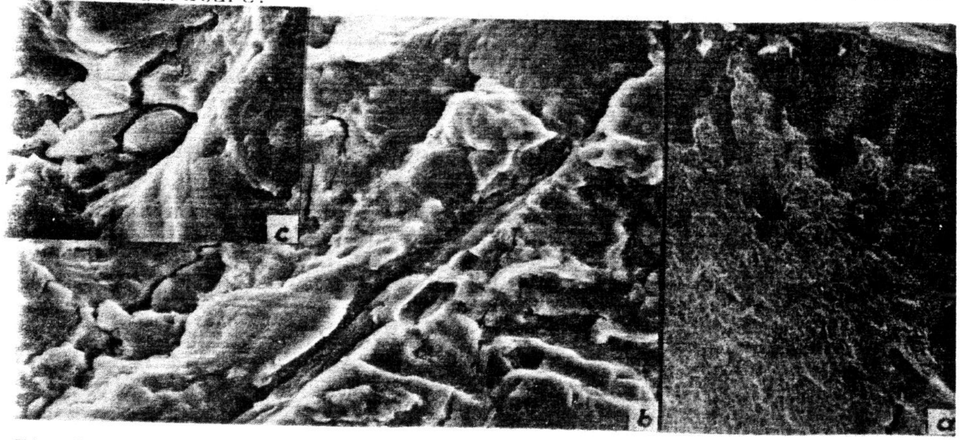

Fig.6. Example of fatigue crack starters and low cycle fatigue crack below NDT. Crack growth rate $5\ 10^{-8}$ mm/cycles.

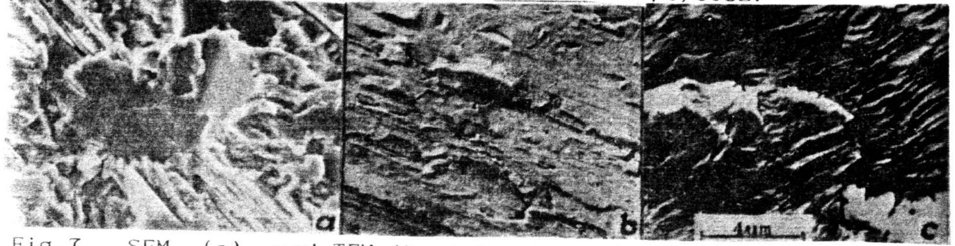

Fig.7. SEM (a) and TEM (b,c) fractographs of fatigue fracture surface at 77 K.

and the crack propagation in the matrix is restored. The test results at temperatures below NDT also indicate that the influence of inclusions on fatigue cracking is insignificant. The prevailing cracking is insignificant and that the prevailing fatigue mode is a brittle fracture with some tracks of intergranular cracks.

Table.5. Results of the fatigue tests of the 10G2AVNb steel

| Specimen type/ welding procedure | Fatigue strength $\sigma_{t0,2}$MPa | | | | Fatigue strength $\sigma_{tc}$MPa | | | |
|---|---|---|---|---|---|---|---|---|
| | $N=10^5$ | $N=10^6$ | $N=2*10^6$ | $\beta_{0,2}$ | $N=10^5$ | $N=10^6$ | $N=2*10^6$ | $\beta_{-1}$ |
| Parent material<br>•machined edges<br>•oxyfuel-cut.<br>•oxyfuel - cut edges/grinded | 470<br>-<br>- | 389<br>342<br>289 | 350<br>280<br>249 | -<br>1,6<br>1,45 | 289<br>-<br>- | 260<br>-<br>- | 190<br>-<br>- | -<br>-<br>- |
| Butt w. joints with toes of welds<br>• MMAW<br>• $CO_2$-MAG<br>• SAW | 295<br>382<br>378 | 218<br>180<br>188 | 195<br>159<br>165 | 1,80<br>2,12<br>2,10 | 185 | 120 | 100 | 1,9 |
| Butt w. joints without toe weld<br>• MMAW<br>• $CO_2$-MAG<br>• SAW | 410<br>415<br>438 | 335<br>310<br>323 | 315<br>260<br>268 | -<br>1,34<br>1,33 | 218<br>-<br>- | 188<br>-<br>- | 168<br>-<br>- | - |
| Specimens with trans stiffener<br>• MMAW<br>• $CO_2$-MAG<br>• SAW | 288<br>275<br>298 | 180<br>198<br>292 | 130<br>169<br>188 | 2,5<br>2,6<br>1,8 | 230 | 185 | 170 | 1,1 |
| Specimens with long.stiffener<br>• MMAW<br>• $CO_2$-MAG<br>• SAW | 198<br>199<br>198 | 139<br>143<br>141 | 130<br>144<br>141 | 2,7<br>2,4<br>2,55 | 125 | 87,5 | 77,5 | 2,5 |
| Doublers on the face plate<br>• MMAW<br>• $CO_2$-MAG<br>• SAW | 226<br>228<br>220 | 127<br>130<br>128 | 98<br>100<br>99 | 3,57<br>3,5<br>3,53 | - | - | - | - |

MMAW - manual metal arc welding, SAW - submerged arc welding
$CO_2$-MAG - metal active $CO_2$ gas welding
$\sigma_{t0,2p}, \sigma_{tcp}$ - fatigue strength of parent material (R=0.2, R=-1)
$\sigma_{t0,2w}, \sigma_{tcw}$ - fatigue strength welded joint testing 15G2VNb steel $\beta_{-1}=\sigma_{tcp}/\sigma_{tcw}$ , $\beta_{0,2}=\sigma_{t0,2p}/\sigma_{t0,2w}$

## CONCLUSIONS

1. The fatigue tests of HSLA steels at temperatures ranging from NDT or 77K to 293 K indicate :

- 20-30% decrease of the fatigue strenth $\sigma_{tc}$ (R=-1) and 50% decrease yield strength $\sigma_{YC}$,

- decrease of the quasi-cleavage fracture parts,

2. nonmetallic inclusions act frequently as fatigue crack initiators at the specimen surface at ambient temperature or as crack arresting obstacles.

3. The influence of inclusions on a fatigue cracking is smaller at low temperatures and lower the stress level.

4. Increasing the yield strength of the HSLA steels from 250 700 Mpa causes small increase of the fatigue strength (ca 10%).

5. The fatigue strengths of the welded joints with toes of welds influence slightly by welding procedures.

6. Machined and grinded or remelted toes of the butt welds cause higher fatigue strength of weldments.

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