UNS S32205 Duplex Stainless Steel SED-critical radius characterization

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In the local strain energy density approach, the fatigue strength of notched components, like welded joints, is quantified by the value of the strain energy density averaged over a control volume of radius Rc near the singularity-dominated zone. Rc is a material dependent parameter. Unfortunately, the characterization of such parameter is far from being fast and simple because it requires different fatigue tests on notched and un-notched specimens. For this reason, a complete database of Rc values corresponding to different materials is still lacking in literature. This work is aimed at quantifying the Rc value of the SAF 2205 (UNS S32205, EN 10083-3 (steel number 1.4462)) duplex stainless steels by means of fatigue tests and metallurgical analyses.

KEYWORDS: DUPLEX STAINLESS STEEL, FATIGUE, STRAIN ENERGY DENSITY, MICROSTRUCTURE.

INTRODUCTION

The word *duplex* is Latin. It means two folds. Duplex stainless steels (DSSs) are one of the most important families of stainless steels used in important industrial applications where the requirements of excellent chemical as well as mechanical properties must be fulfilled. DSSs are used in the oil/gas, chemical, pulp and paper industries, subsea or other types of applications that are working in tough corrosive environments [1-4]. They are also used in applications such as bridges [5], wind turbines and storage tanks. Their unique properties come from the typical two-phase (namely, *duplex*) microstructure containing Ferrite and Austenite in balanced proportion. However, particular care must be taken when they undergo a heat treatment or a welding operation since a possible secondary phases precipitation will compromise their corrosion and mechanical properties [6-14]. Owing to their high proof strength, the duplex stainless steels also have very good fatigue strength [15-17]. During cyclic tensile stress testing the fatigue limit is found approximately when the maximum load in a cycle reaches the proof strength of the material. Dealing

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with notched components, like welded joints, in the past different approaches were developed to assess their fatigue strength [18-25]. Nominal stress method, structural stress methods (i.e.: spot stress) and local methods (i.e.: notch approach) heave been proposed. Among the local approaches, the notch stress intensity factor (NSIF)-based approach [26-28] models the weld toe via a sharp V-notch so that the weld toe stress is asymptotic with a singularity which follows either the linear-elastic or elastic-plastic solution according to the Willimas's [29] or Lazzarin et al. [30]'s solution, respectively. In both cases, the stress distribution along a radius r, starting from the notch tip, is represented by a straight line in a log-log plot so that the intensity of such stress distribution can be easy quantified by the NSIF parameter. Even if such local parameter is widely used in published literature to summarize the high cycle fatigue strength of welded joints having very different geometries, its major drawback is that it does not allow for a direct comparison of the fatigue strength of joints having different V-notch opening angle. This is because of rational exponents in the dimensions of NSIFs, whose value varies according to the V-notch opening angle. To overcome this limit, the fatigue strength assessments in presence of failures from the weld root and the weld toes with different opening angle can be carried out by using energy-based methods such as the J-integral approach [31] or by introducing the concept of local strain energy density (SED) [32]. In the SED approach, the fatigue strength of the welded joint is quantified by the value of the strain energy density averaged over a control volume of radius Rc near the singularity-dominated zone (Fig. 1). In recent literature, the SED criterion was also used to quantify the effect of residual stress on the fatigue strength of welded joints [33-34].

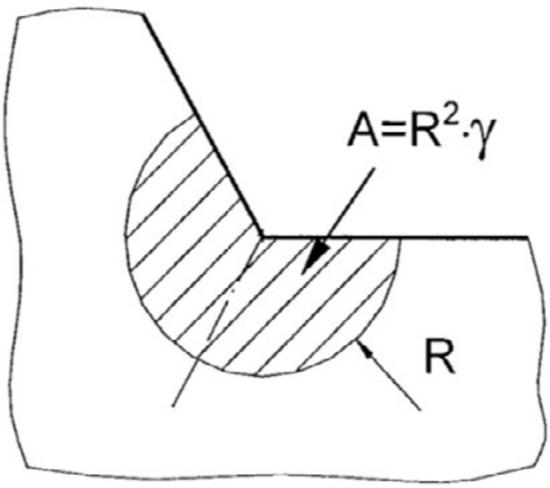


Fig.1 - Critical volume (area) surrounding the notch tip

Rc is a material parameter that was found to be equal to 0.28 mm and 0.12 mm for steel and Al-alloy welded joints, respectively. Unfortunately, the characterization of such parameter is far from being fast and simple since it requires different fatigue tests on notched and un- notched specimens. For this reason, a complete database of Rc values corresponding to different materials is still lacking in literature. This work is aimed at quantifying the Rc value of the 2205 (UNS S32205) duplex stainless steels by means of fatigue tests and metallurgical analyses.

THE SED CRITERION

By considering a polar coordinate system centered at the tip of a sharp V-notch (Fig. 2), the Beltrami's formulation of the strain energy is given by equation (1):

$$W(r,\theta)=\frac{1}{2E}\left\{\sigma_r^2+\sigma_\theta^2+\sigma_z^2-2\nu(\sigma_r\sigma_\theta+\sigma_z\sigma_\theta+\sigma_r\sigma_z)+2(1+\nu)(\tau_{r\theta}^2+\tau_{rz}^2+\tau_{\theta z}^2)\right\} \quad 1)$$

where E and ν are the elastic modulus and Poisson's ratio of the alloy, respectively.

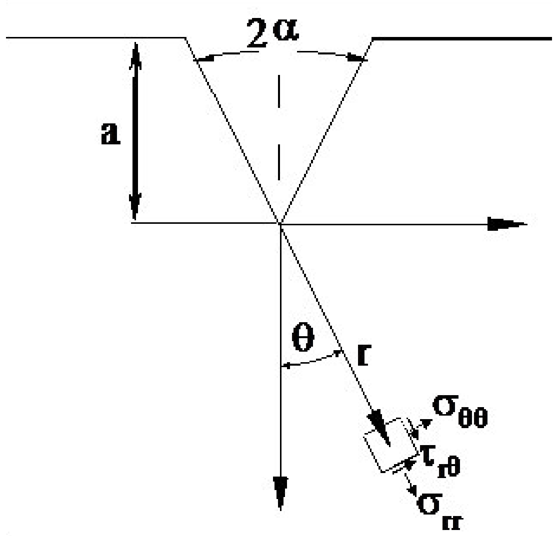


Fig.2 - Sharp v notch and polar coordinate system

Now, the stress distribution near the singularity point (Fig. 2) is given by the following equation:

$$\sigma_{ij}(r,\theta)=\frac{K_1 r^{\lambda_1-1} f_{i,j}(\theta)}{\sqrt{2\pi}} \qquad 2)$$

where K_1 is the mode I stress intensity factor (SIF), λ is the eigenvalue [9] and $f_{i,j}(\Theta)$ are angular functions. K is obtained by using the Gross and Mendelson's definition (Eq. 3)

$$K_1=\sqrt{2\pi}\lim_{r\to 0^+}\sigma_{\theta\theta}^{FEM} r^{1-\lambda_1} \qquad (r,\theta=0) \qquad 3)$$

By substituting Eq. (2) in Eq. (1), the strain energy density near the stress singularity dominated zone becomes:

$$W_1(r,\theta)=\frac{r^{2(\lambda_1-1)}}{2E}K_1^2\left\{f_{rr}^2(\theta)+f_{\theta\theta}^2(\theta)+f_{zz}^2(\theta)-2\nu[f_{rr}(\theta)f_{\theta\theta}(\theta)+f_{zz}(\theta)f_{\theta\theta}(\theta)+f_{rr}(\theta)f_{zz}(\theta)]+2(1+\nu)[f_{r\theta}^2(\theta)+f_{rz}^2(\theta)+f_{z\theta}^2(\theta)]\right\} \qquad 4)$$

According to SED criterion, the fatigue failure of notched components occurs when the strain energy density averaged over a material-dependent volume (ΔW) (Eq. 5) reaches a critical value ΔWc, typical of the material.

$$\Delta W=\frac{E(R)}{A(R)}=\frac{\int_A W\,dA}{\gamma R^2} \qquad 5)$$

The critical value is calculated according to the following equation:

$$\Delta Wc \approx \frac{\Delta\sigma_A^2}{2E} \qquad 6)$$

where $\Delta\sigma_A$ is the fatigue strength at 2 million cycles of the un-notched samples.

Now, by solving the integral in Eq. (5), and considering only the mode I, Eq. (5) becomes:

$$\Delta\bar{W} = \frac{e_1}{E}\left[\frac{\Delta K_1}{R^{1-\lambda_1}}\right]^2 \quad 7)$$

where R is the control volume radius and e1 is a shape function that depends on the notch angle (2α, Fig. 2) and Poisson's ratio according to the following relation:

$$e_1 = -5.373 \cdot 10^{-6}(2\alpha)^2 + 6.151 \cdot 10^{-4}(2\alpha) + 0.1330 \quad 8)$$

Finally, by equating Eq. (7) with Eq. (6), the critical radius expression is obtained:

$$Rc = \left(\frac{\sqrt{2e_1}\,\Delta K_{1A}^{FEM}}{\Delta\sigma_A}\right)^{\frac{1}{1-\lambda_1}} \quad 9)$$

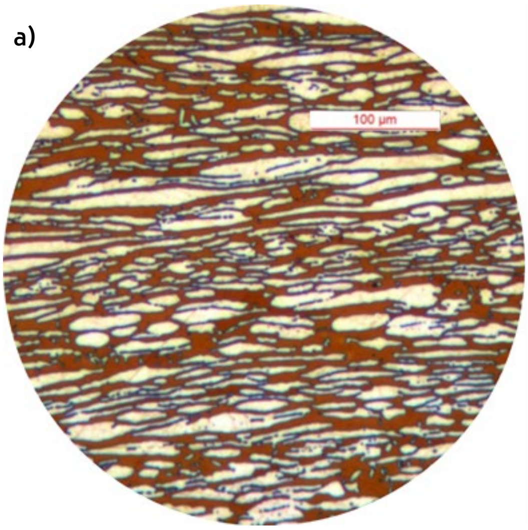
In Eq. (9) ΔK_{1A}^{FEM} is the fatigue strength at 2 million cycles of notch specimens in terms of SIF amplitude obtained by imposing in the numerical model of the notched sample the corresponding remotely applied amplitude coming from experiments; $\Delta\sigma_A$ is, as always, the fatigue strength at 2 million cycles of the un-notched samples.

MATERIALS AND METHODS

The measured chemical composition of the SAF 2205 DSS (obtained with the Optical Emission Spectrometer) and its microstructure are shown in table 1 and fig. 3, respectively.

Tab.1 - Measured chemical composition of the DSS UNS S32205 (EN 10083-3, steel number 1.4462) (wt%)

C	Mn	Ni	Cr	Mo	N	Fe
0.059±0.003	1.74±0.006	4.77±0.02	22.35±0.01	3.11±0.01	-	Bal

a) 

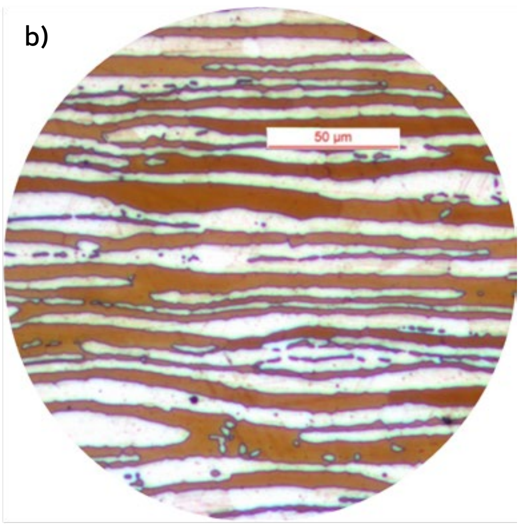
b) 

Fig.3 - Microstructure of DSS UNS S32205 (Ferrite phase: dark; Austenite phase: white): a) transversal section, b) longitudinal section

The raw material was received in form of pieces cut from hot rolled sheets conventionally used for pipes production. A sufficient balanced ratio between ferrite and austenite was observed in the as-received material (57.8/42.2). Fig. 4 shows the geometry of notched and smooth samples used in the fatigue tests with the indication of the minimum guaranteed surface roughness values. The V-notch opening angle was 90°. In particular the V-notch radius (Fig. 5) was carefully measured with a stereoscope on 20 samples. A mean value of 0.25±0.03 mm was found.

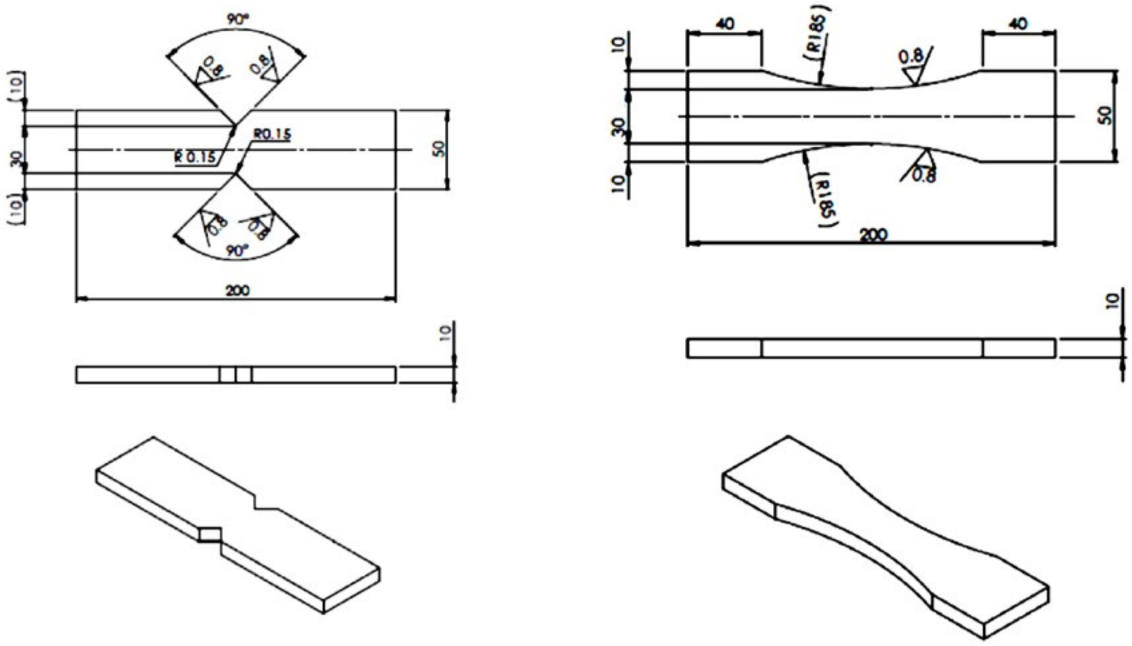


Fig.4 - Geometry of the specimens used in fatigue tests.

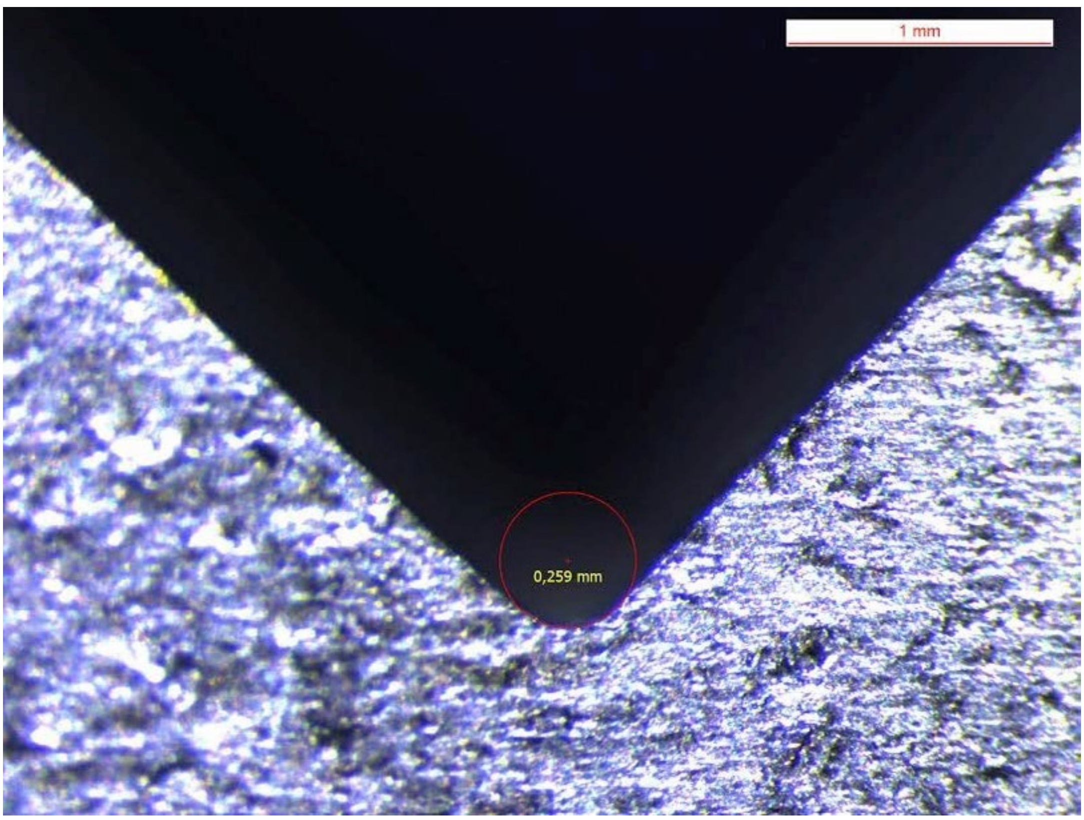


Fig.5 - Stereoscope macrograph of the notch tip

Fatigue life tests were carried out at room temperature using a universal MTS machine (250 kN), a uniaxial tension with a frequency of 15 Hz and a load ratio R=0.
In order to calculate the SIF value corresponding to the fatigue strength at 2 million cycles, a numerical model was developed with Ansys code. By taking advantage of the load as well as geometry symmetry, only one fourth of the specimens was modelled using 1552 PLANE 183 elements under plain strain condition. With the aim to capture the asymptotic stress feature, a very fine mesh was used in the stress singularity-dominated zone. The smallest element size was 0.0002 mm (Fig. 6).

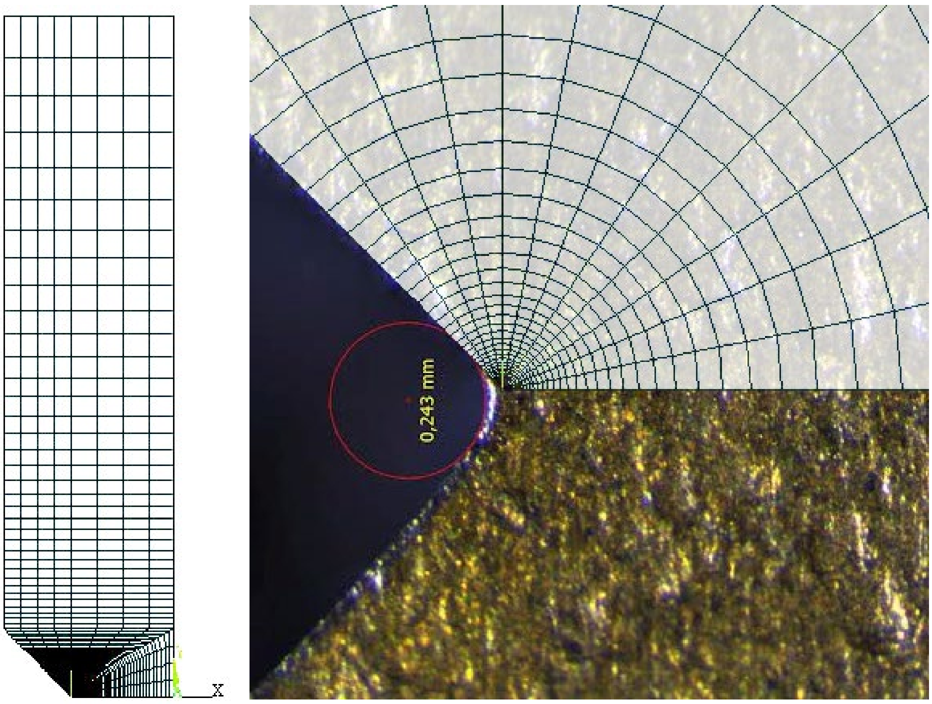


Fig.6 - Mesh used in the numerical model with a detail of the stress singularity-dominated zone.

RESULTS AND DISCUSSION

Figs 6 and 7 show the results of fatigue tests carried out on smooth and notched samples, respectively. As expected, a significantly reduction of the fatigue strength is observed for the notched specimens compared to that of the smooth ones. Considering a survival probability of 50%, the fatigue strength at 2 million cycle the notched samples is 83 MPa against a value of 424 MPa measured with smooth samples. In both cases, a very low dispersion of results is observed, which prove the soundness (defects-free) of the as-received alloy.

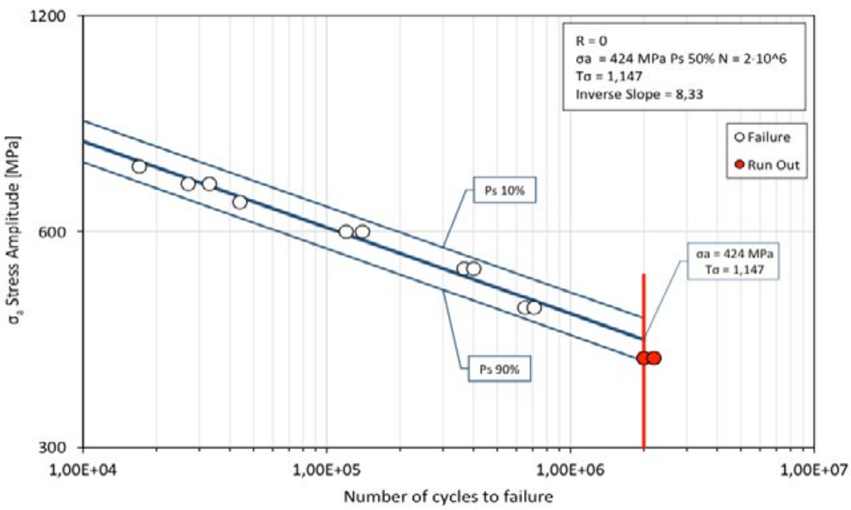


Fig.7 - S-N curve of 2205 DSS, smooth sample

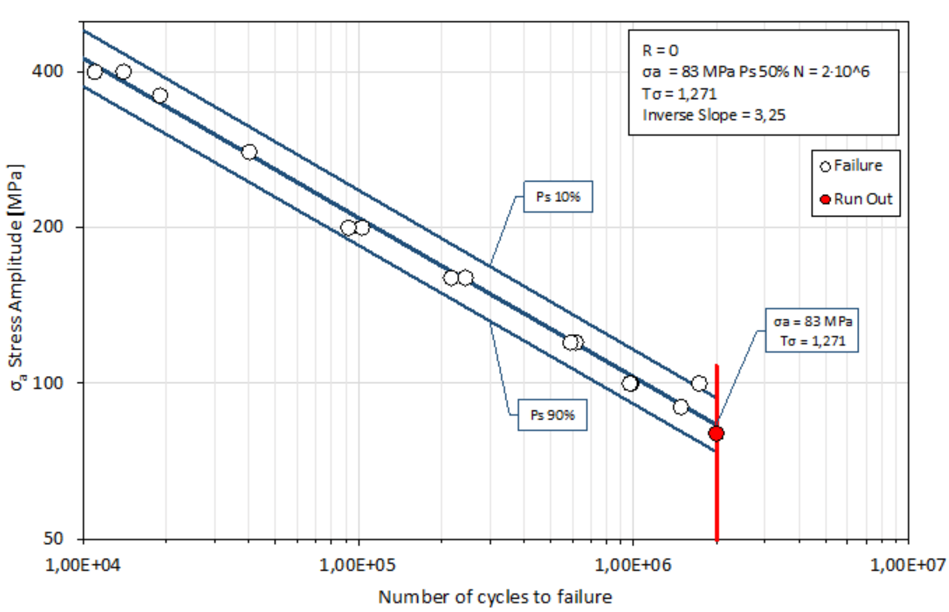


Fig.8 - S-N curve of 2205 DSS, sharp V-notched sample

The stress distribution along the notch bisector obtained via numerical simulation is shown in Fig. 9. In particular, it is obtained by using the remotely applied stress amplitude of 83 MPa (i.e., the fatigue strength at 2 million cycle of notched samples). The singularity grade is found to be -0.457 while the NSIF amplitude (ΔK_1) obtained using Gross and Mendelson's definition (Eq. (3)) is 522 MPa mm$^{0.456}$.

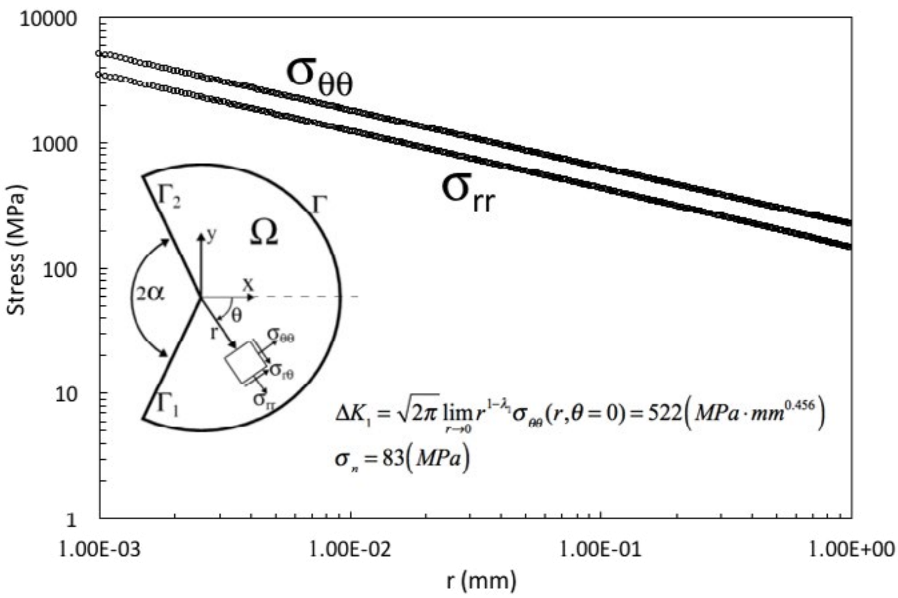


Fig.9 - Stress distribution along the notch bisector

Now, using Eq. (9) and the above described numerical and experimental results, the Rc values was found to be 0.456 mm:

$$Rc = \left(\frac{\sqrt{2e_1}\Delta K_{1A}^{FEM}}{\Delta\sigma_A}\right)^{\frac{1}{1-\lambda_1}} = \left(\frac{\sqrt{2\cdot 0.145}\cdot 522}{424}\right)^{\frac{1}{1-0.544}} = 0.456\ \text{mm} \quad 10)$$

It is observed that UNS S32205 DSS Rc value is different from that of both structural steels (0.28 mm) and aluminium alloys (0.12 mm). These last two values were obtained by using a lot of fatigue test data (900) found in literature about arc-welded joints made out of structural steels and aluminium alloys, respectively. Details can be found in reference [35]. It is pointed out that different values of Rc might characterise welded joints obtained from high-power processes, in particular from automated laser beam welding [36]; this is because of the different microstructure induced by high power density processes compared to those induced by conventional arc welding operations. This proves that Rc is a material parameter which value depends on alloy's microstructure.

CONCLUSIONS

DSSs correspond to a little but very important family of steels used in offshore, nuclear or solar power applications. Fatigue life estimation of DSS notched components is for this reason of fundamental importance in mechanical design. In recent years, the strain energy density approach was proved to be a powerful method for static and fatigue life assessment of notched components but it requires the critical radius to be characterized for each material by using fatigue tests on both notched and smooth samples. In this work such parameter was fully quantified for the UNS S32205 DSS grade. It was found to be equal to 0.456 mm. The obtained results are thought to be extremely useful for the future application of the SED approach to the fatigue assessment of notched as well as welded components made out of DSS.

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