Design for Structural Durability of an Hydraulic Main Valve for Mobile Applications

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Abstract

A fatigue analysis has been conducted to assess the structural durability of a valve component made of cast iron. A well-known local approach based on the linear elastic strain energy density as fatigue damage parameter has been used to account for geometrical stress concentration effects. The fatigue design curve has been calibrated on fatigue test results obtained from laboratory specimens. The theoretical estimations of the fatigue strength have been compared with results of fatigue tests on real valve components subjected to pulsating hydraulic pressure and a satisfactory level of accuracy has been obtained.

Keywords. Fatigue design, structural durability, strain energy density, finite element analysis.

1. INTRODUCTION

Hydraulic valves for mobile applications are subjected to in-service fatigue loadings owing to the time-variant pressure regimes. Given the general tendency of extending the operating pressure range, fatigue issues may become of primary concern. Therefore, this paper aims at assessing the fatigue strength of a hydraulic main valve by using a local approach based linear elastic finite element (FE) analyses and appropriate fatigue testing of laboratory specimens.

2. Theoretical Background

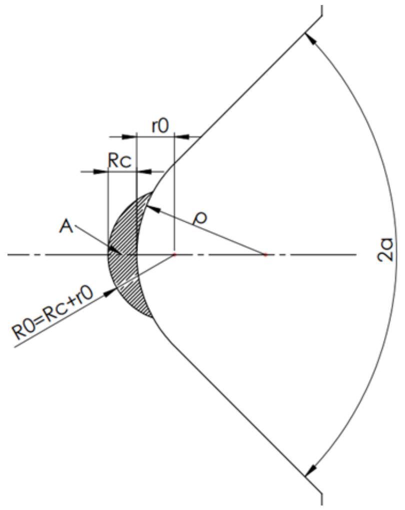

Figure 2.1. The SED approach to notch fatigue [1-3]

The linear elastic Strain Energy Density averaged in a properly defined material structural volume (i.e. the SED approach) has been selected among the local approaches available in the technical literature.
According to the approach sketched in Figure 2.1, the material fatigue strength is made to depend on the averaged SED parameter inside a structural volume having size R_c [1-3].
The SED parameter is evaluated from a linear elastic FE analysis and is compared with the fatigue design curve determined by means of fatigue tests on laboratory specimens. The size R_c of the structural volume, where the SED parameter is to be averaged, is thought of as a material property and results from the material fatigue characterisation. More precisely, R_c is found by equating the averaged SED for two different specimen's geometries at the endurance limit [1-2]. The geometrical parameter r_0 depends on the notch geometry [3].

3. Material Characterisation

Plain and notched specimens made of EN-GJS 500-7 have been prepared from separately cast Y-blocks as well as from real main valve components for evaluating the influence of the manufacturing process, as shown in Figure 3.1.

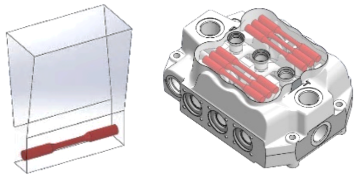

Figure 3.1. Specimens location in separately cast Y-blocks (on the left) and in real main valve components (on the right)

Results of static tensile tests are reported in Table 1. Brinell hardness resulted 224 HB and 208 HB for the Y-block and component materials, respectively.

Material	E [MPa]	$\sigma_{p,02}$ [MPa]	σ_R [MPa]	$\varepsilon_{\%,R}$ [%]
EN-GJS500-7 (Y-block)	169000	401	749	6.7
EN-GJS500-7 (component)	169000	358	593	2.7

Table 3.1. Results of static tensile tests

Fatigue tests have been performed under a nominal load ratio (i.e. the ratio between the minimum and maximum applied loads) approximately equal to zero by using a standard servo-hydraulic axial testing machine MTS Minibionix II equipped with a 15 kN load cell and a digital controller MTS Testar IIm. Load test frequencies were kept in the range 10-40 Hz. The adopted specimens' geometry included plain (Figure 3.2), bluntly notched (Fig. 3.3) and sharply notched (Fig. 3.4) specimens.

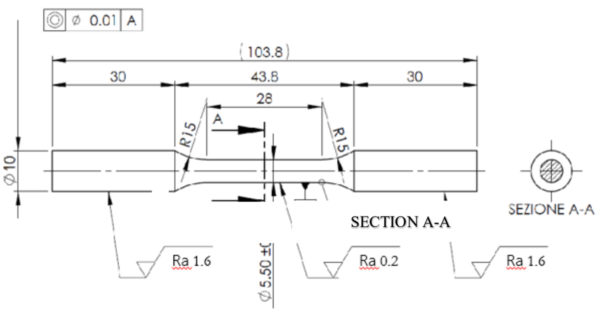

Figure 3.2. Geometry of plain specimens

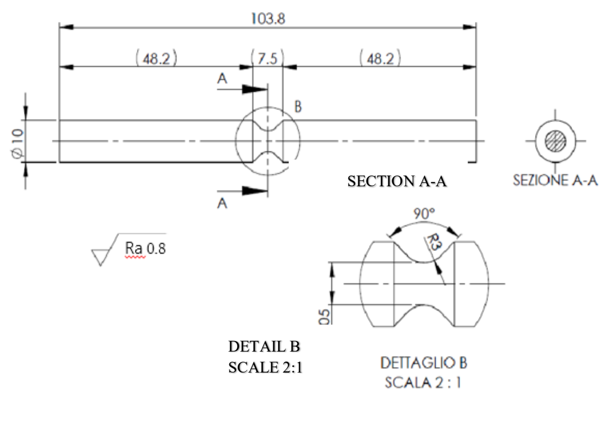

Figure 3.3. Geometry of bluntly notched specimens

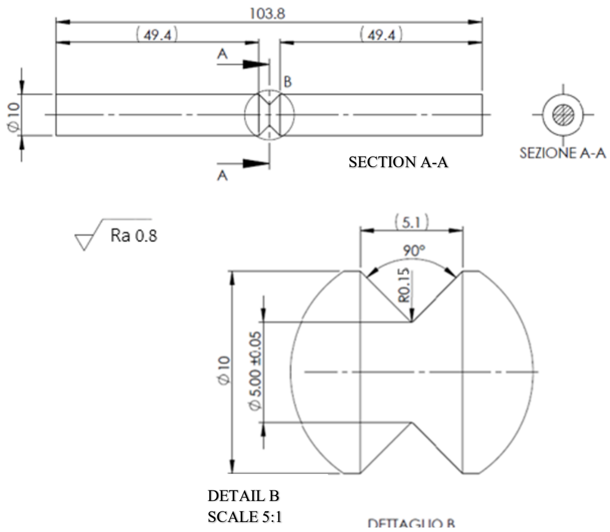

Figure 3.4. Geometry of sharply notched specimens

Short stair-case procedures were run to evaluate the endurance limit at 10 million cycles. The fatigue test results are reported in Figures 3.5-3.8 in terms of number of fatigue cycles to failure as a function of the applied nominal stress amplitude. The specimens used in the short stair-case procedure are reported with red markers, where circle markers (o) indicate the run-out test, while star markers (*) indicate the broken specimens. The microstructures are reported in Figures 3.9 and 3.10, which highlight the high pearlite content in the range 95%-97%. It was assumed that the microstructure of the specimens taken from the main valve according to figure 3.1 is also applicable to the crack initiation location, which will be commented later on.

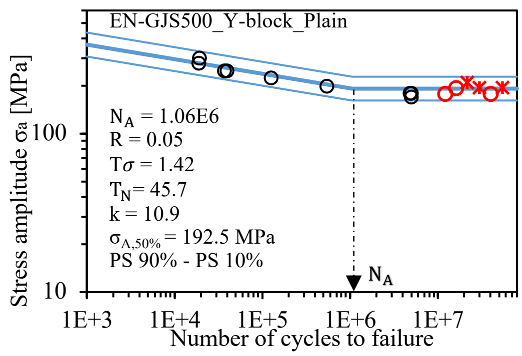

Figure 3.5. Fatigue test results of plain specimens taken from Y-block. The nominal stress is evaluated at the net-section

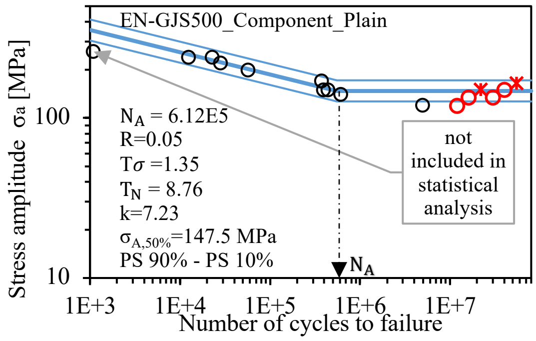

Figure 3.6. Fatigue test results of plain specimens taken from components. The nominal stress is evaluated at the net-section

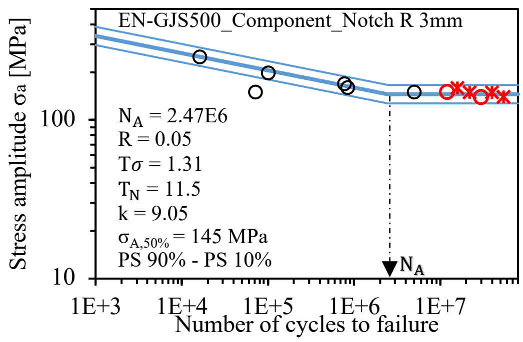

Figure 3.7. Fatigue test results of notched specimens (R=3 mm) taken from components. The nominal stress is evaluated at the net-section

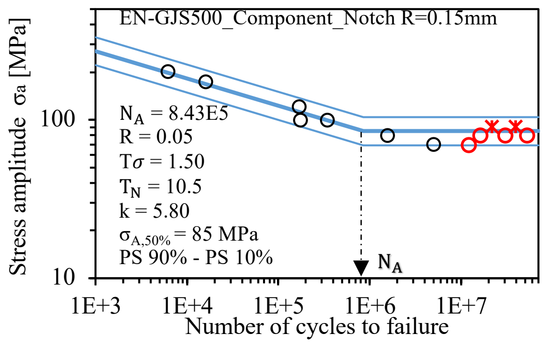

Figure 3.8. Fatigue test results of notched specimens (R=0.15 mm) taken from components. The nominal stress is evaluated at the net-section

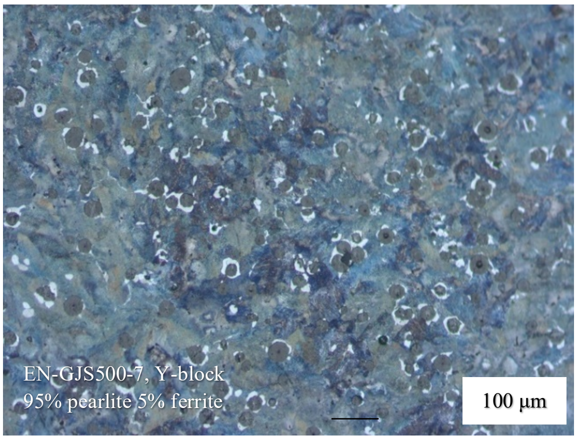

Figure 3.9. Microstructure of the cast iron material from the Y-block

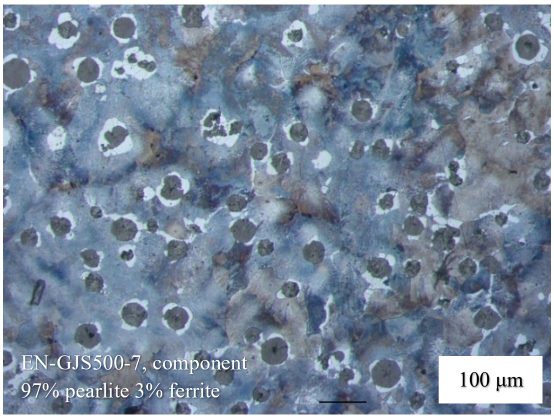

Figure 3.10. Microstructure of the cast iron material from the component

4. FE ANALYSIS OF THE VALVE COMPONENT

Linear elastic finite element analyses have been performed in parallel to evaluate the local stresses and assess the fatigue strength. Figure 4.1 reports the geometry of the GJS 500-7 cast component investigated.

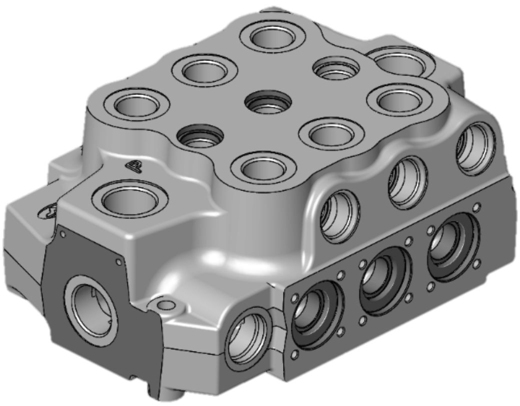

Figure 4.1. Geometry of the cast component investigated

The applied boundary conditions included the internal hydraulic pressure, the force applied by the caps (Figure 4.2) and the tightening forces applied in the threaded connections along with the fixed holes through which the component was constrained to the test bench (Figure 4.3).

The CAD model of the valve component was imported in Ansys Mechanical environment and meshed by running the free mesh generation algorithm using 10-node, second order tetrahedral finite elements. The element size of 1.5 mm was properly selected after a convergence analysis and a picture of the adopted mesh is reported in Figure 4.4.

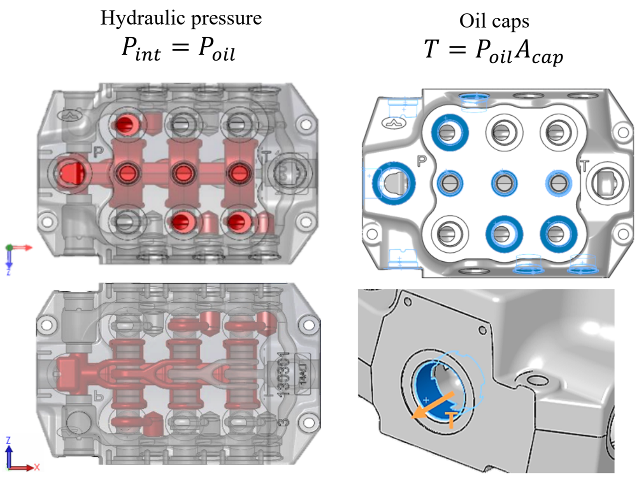

Figure 4.2. Boundary conditions applied to the valve component (hydraulic pressure and caps)

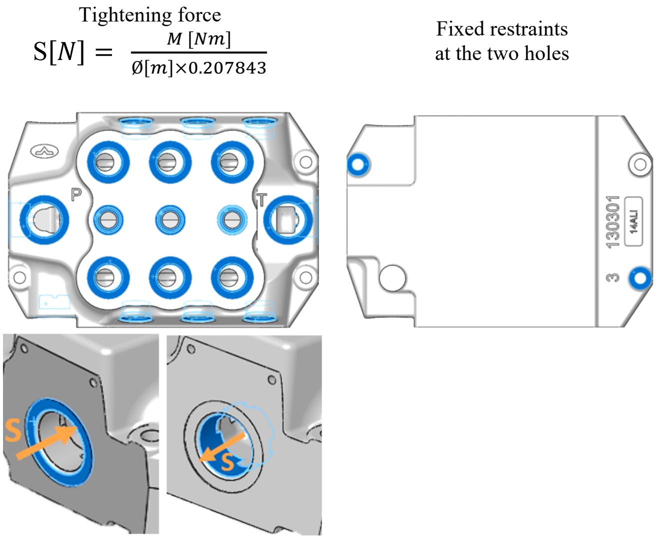

Figure 4.3. Boundary conditions applied to the valve component (tightening forces and constraints)

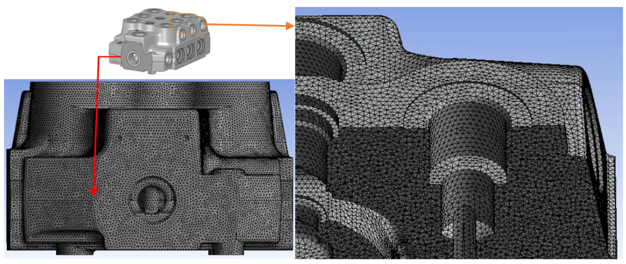

Figure 4.4. Adopted FE mesh of 10-node tetrahedral finite element in Ansys Mechanical environment (22 million degrees of freedom)

Linear elastic FE analyses were performed and a general view of the Von Mises stress distribution evaluated by applying an hydraulic pressure of 500 bar is reported in Figure 4.5.

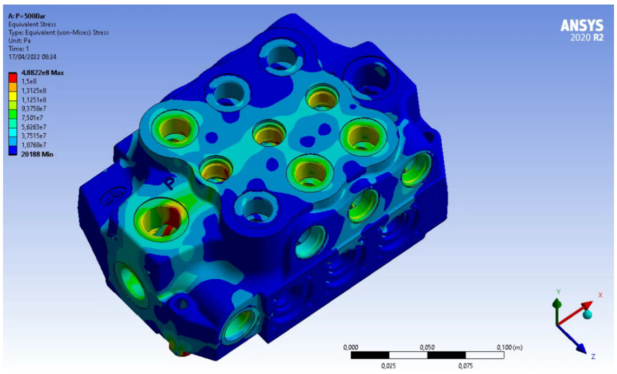

Figure 4.5. Von Mises stress distribution with 500 bar internal hydraulic pressure

5. FATIGUE TESTS OF REAL VALVE COMPONENTS

With the task to carry out fatigue tests in parallel with standard material specimens, 20 samples of a main valve block were manufactured. Walvoil's commercial product SDM140/3 was chosen: a GJS500 cast block weighing 16,5 kg. The complicated internal circuit was only partially pressurised (Fig. 5.1 and 5.2), in order to maximise the deformation and to replicate the worst stress typologies and distribution that the product can face in field applications.

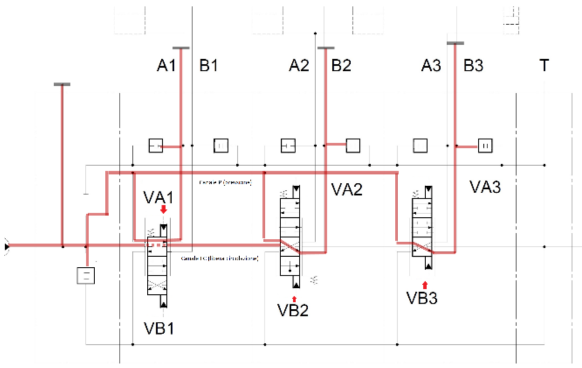

Figure 5.1. Hydraulic test schematic

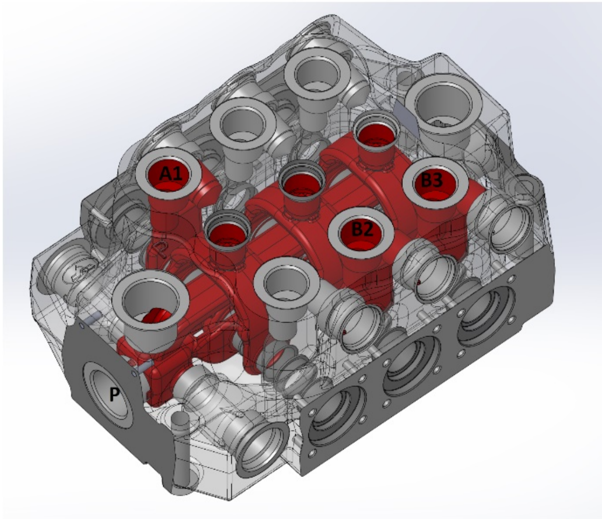

Figure 5.2. Pressurised circuit in cast samples

Up to five different test rigs have been used in parallel, with over 9 months of total bench time to apply altogether more than 50 million pressure cycles to the samples. A meaningful test set up is shown in Figure 5.3, while pressure variation during a test is represented in Figure 5.4.

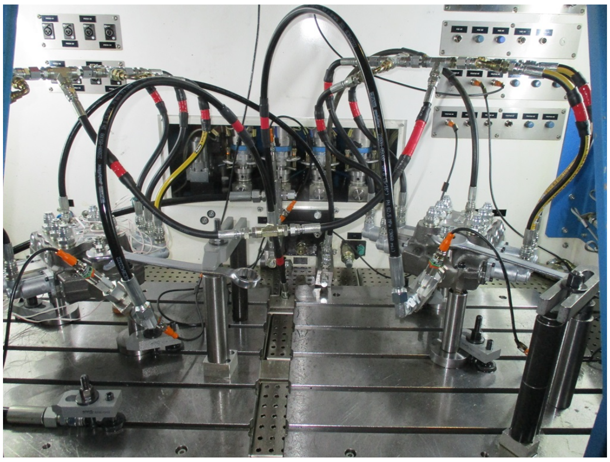

Figure 5.3. Set up of one of the tests

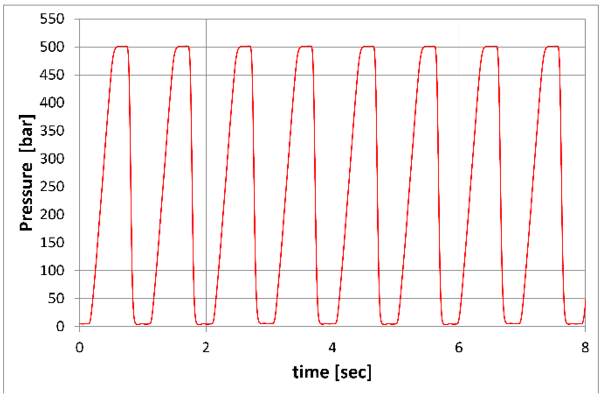

Figure 5.4. Pressure variation during a 500 bar test

Due to high tensile strength of cast material, the breaking of the samples occurred at higher than expected number of cycles. The earliest rupture happened after 1,2 million pulses at 500 bar, while both samples tested at 380 bar broke just after passing 8,6 million cycles. With the aim to shorten the test time, the lower side of 12 samples was milled for a depth of 12 mm, leaving wall thicknesses ranging between 0,90 and 1,95 mm (measured after their breakage). The geometry of the modified component is reported in Figure 5.5.

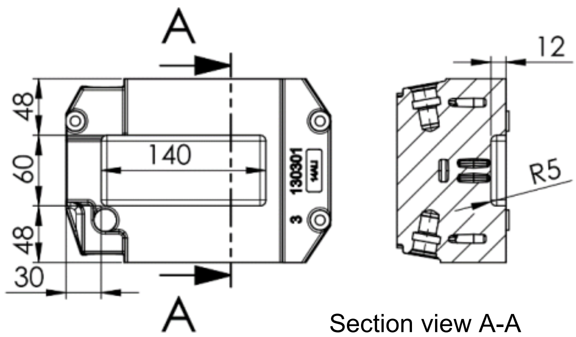

Figure 5.5. Geometry of the modified valve component

These modified samples showed much shorter fatigue lives, ranging from a minimum of 1.556 cycles of the earliest rupture at 500 bar to the latest happening at 235.000 cycles at 260 bar, while both samples tested at 220 bar were considered run-out after surviving over 9 million cycles. All results are summarized within the semi-logarithmic graph of Figure 5.6, where the blue dots represent the fatigue lives of whole casting and the red dots regard the samples with milled surface (labelled with material residual thickness).

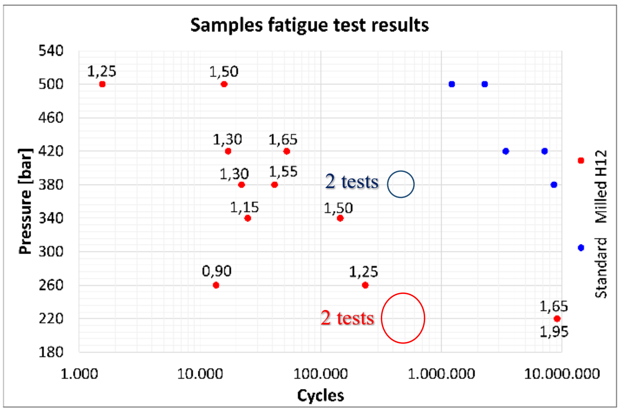

Figure 5.6. Fatigue test results on cast samples

In the six standard castings the fatigue crack always propagated from bottom part of section ports (A1 in one case, between B2 and B3 in the other five cases, Figures 5.2 and 5.7), while in the twelve samples with lowered thickness the crack always initiated at the "Y" duct of the P line near to the machined surface (Fig. 5.8).

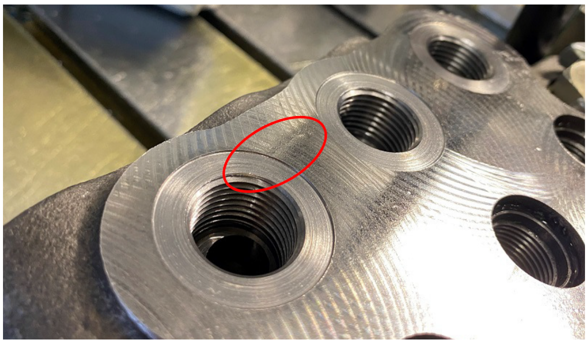

Figure 5.7. Crack on sample 002, between ports B2 and B3, after 8.613.179 cycles at 380 bar

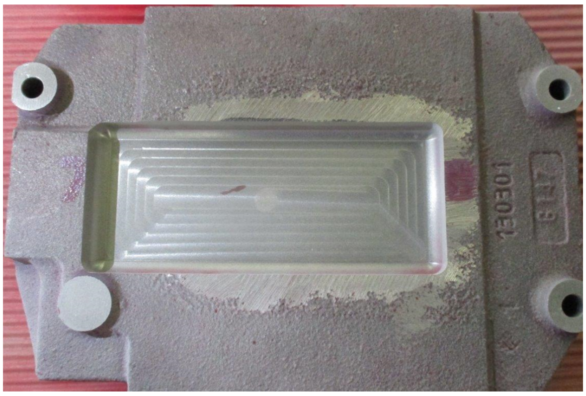

Figure 5.8. Crack on sample 010 with reduced thickness, after 15.888 cycles at 500 bar

6. FATIGUE LIFE ESTIMATIONS AND COMPARISON WITH EXPERIMENTAL RESULTS

The control volume of the EN-GJS500-7 material from cast component was determined by equating the SED values at the endurance limit relevant to the two notched specimens (R=3 mm and R=0.15 mm, respectively) [1-3]. The resulting structural control volume R_c was 0.121 mm. The size of the structural volume takes into account the material microstructure [1, 2, 4]. After calibrating the structural volume, the notched specimens' results could be plotted in the same fatigue scatter band, as reported in Figure 6.1.

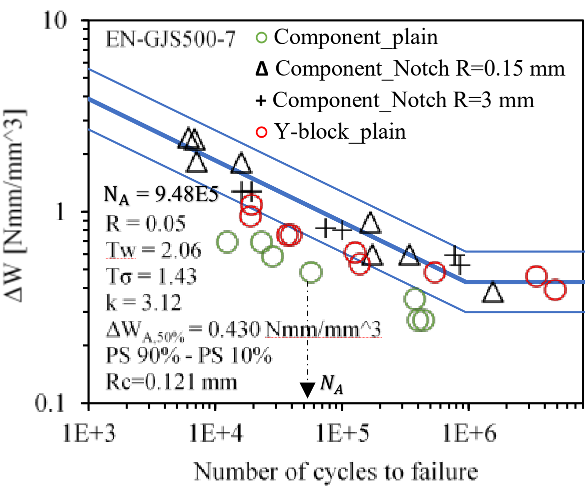

Figure 6.1. Summary of notched fatigue results in terms of averaged SED

According to the SED approach, all geometrical effects are included in the fatigue design curve reported in Figure 6.1. Therefore, the SED was evaluated in the structural volumes located at the crack initiation locations, which led to fatigue failures according to previous Figures 5.7 and 5.8. Figures 6.2 and 6.3 report the control volume at the crack initiation location of the original valve component (Figure 5.7), where the adopted element size is 0.015 mm, and of the component with milled surface (Figure 5.8), where the element size is 0.035 mm, in order to increase the mesh density inside the control volume and guarantee convergence. A transition zone having size approximately equal to 5 mm was created around the control volume and outside this zone the element size was 1.5mm as shown in the previous analysis.

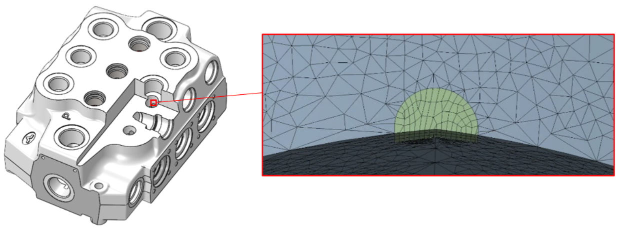

Figure 6.2. Control volume for the averaged SED evaluation at the crack initiation point between ports B2 and B3 (Figures 5.2 and 5.7) of the original valve component.

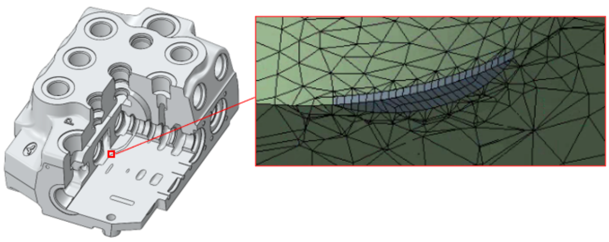

Figure 6.3. Control volume for the averaged SED evaluation at the crack initiation point of the valve component with milled surface (Figure 5.8).

Finally Figure 6.4 reports the comparison between the fatigue design scatter band calibrated on laboratory specimens (Figure 6.1) and the experimental test results on valve components (previously reported in Figure 5.6).

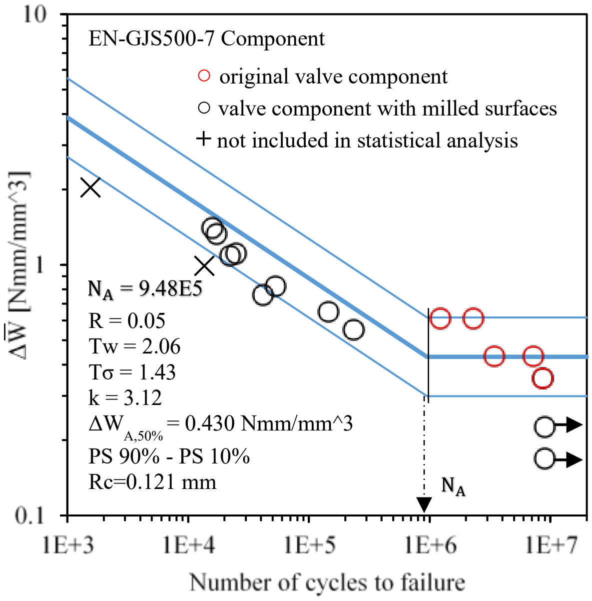

Figure 6.4. Comparison between the fatigue design scatter band calibrated on laboratory specimens (Figure 6.1) and the experimental test results on valve components

It is worth mentioning that failure initiated from an as-cast surface both in the original valve component and in component with milled surface. Conversely, the design scatter band calibrated on specimens (Figure 6.1) accounts only for geometrical effects in fatigue with machined surfaces. Therefore, the scatter band reported in Figures 6.1 and 6.4 should be downgraded to include the surface roughness effect. In a previous investigation, a downgrading factor of 1.4 was found on plain specimens tested in push-pull fatigue [5]. However, it is expected that the downgrading effect found on plain specimens is not fully effective when notched components are considered, as it is the present case.

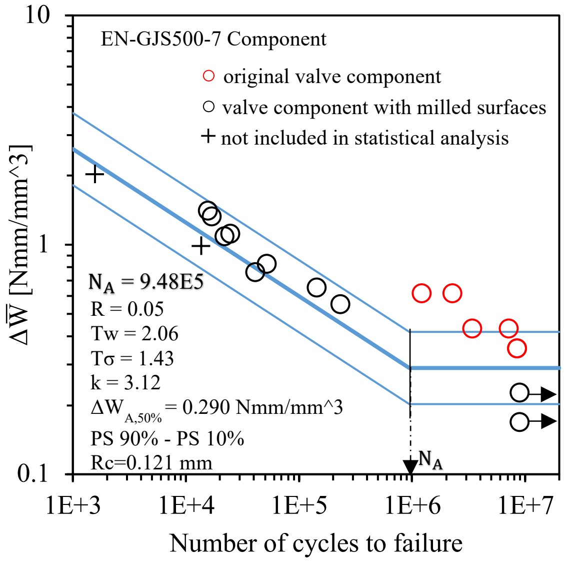

Figure 6.5. Comparison between the fatigue design scatter band calibrated on laboratory specimens (Figure 6.1) and the experimental test results on valve components with surface roughness effect

Due to the lack of knowledge regarding the partial surface roughness effect, the downgrading factor 1.4 valid for push-pull fatigue has been updated for the case of tension-tension (R=0.05) fatigue in terms of energy ($K^2_{L,R0.05} = 1.22^2$=1.48) and has been fully applied to the fatigue design scatter band reported in Figures 6.1 and 6.4. Results are reported in Figure 6.5. The design fatigue curves reported in Figure 6.5 can be used to assess the fatigue life of valve components, all geometrical effects being included in the evaluation of the averaged SED.

7. CONCLUSIONS

Fatigue strength assessment of a valve component made of EN-GJS500-7 spheroidal cast iron have been performed. The local approach based on the linear elastic strain energy density has been applied to synthesize the fatigue strength of notched specimens taken from the component itself. By so doing a fatigue design curve able to unify the geometrical stress concentration effects has been determined and subsequently it has been used to assess the fatigue strength of the real valve components, which have been tested under pulsating pressure in dedicated test benches. The comparison between the estimated and the experimental fatigue strength was satisfactory.

8. ACKNOWLEDGMENT

C2MacGroup is gratefully acknowledged for financial support.

9. REFERENCES

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