

The Effect of Small Defects on Fatigue Life of a Low Carbon Steel

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Abstract: The effect of small surface defects on the fatigue life of low carbon steel is investigated. The experimental program consists of a set of axial fatigue tests on specimens with 0.45 mm and 0.75 mm sized circular defects. The fatigue life was reduced significantly, according to the size of the defect.

Keywords: fatigue life, small defects, low carbon steel

INTRODUCTION

Fatigue is a complex phenomenon and depends on several factors: microstructure of the material, geometry, loading, and manufacturing processes, among others (Takahashi, 2014). It can be defined as a mechanical failure that occurs due to the accumulation of damage generated by cyclic loads: local plastic deformations induce an accumulation of dislocations which evolve to cracks that lead to component failure (Dowling, 2013).

Fatigue life is significantly reduced when the material exhibits stress concentrators, such as defects, surface faults and notches (Murakami, 2002). The emergence of these in many engineering elements is unavoidable, so an appropriate understanding of their influence is necessary (Schönbaury, Yanase and Endo, 2016).

The fatigue in the presence of defects has already been studied – in the context of fatigue strength – by considering different approaches: $\sqrt{\text{area}}$ parameter (Murakami, 1983), Methods of Critical Distances (Taylor, 2008), and Gradient Criterion (Nadot, 2013). A common hypothesis applied in these theories is that the defect resembles a pre-existing crack and that the fatigue limit is determined by the limiting propagation condition (Yanase and Endo, 2014).

The fatigue process is time dependent and characterized by three stages with different characteristics: crack initiation, crack propagation and final rupture (Pilkey, 1997). In fatigue studies in the presence of defects, the crack initiation stage is an important point to understand life reduction, since up to 90% of life fatigue can be consumed by initiating a crack that will propagate and cause failure (ASM, Vol.12, 1992).

Within this setting, this work has the objective of investigating the influence of micro-defects on low carbon steel fatigue life. Differently from most of the studies reported in the literature (which addresses the problem of fatigue strength), the present study focuses on the influence of the defects on the fatigue life.

EXPERIMENTAL PROCEDURE

The material considered in this investigation is the SAE 1020 low carbon steel. The chemical composition provided by the manufacturer is described in Table 1.

Table 1 – Chemical composition of SAE 1020 steel

C (%)	Mn (%)	Si (%)	S (%)	P (%)
0.18	0.4	0.06	0.008	0.017

The specimens were machined from 5/8” cylindrical bars which were previously submitted to a normalization process – heated at 900°C for thirty minutes and cooled slowly in the open air – to relieve the residual stresses of the manufacturing process and to homogenize the grains. A monotonic tensile test was performed to obtain the Young modulus $E = 209$ GPa, the yield stress $\sigma_Y = 345$ MPa and ultimate tensile stress $\sigma_U = 415$ MPa. The measured Brinell hardness of the normalized material is 118 HB.

The fatigue specimens, illustrated in Fig. 1, have a diameter of 8 mm and a length of 40 mm in the test section.

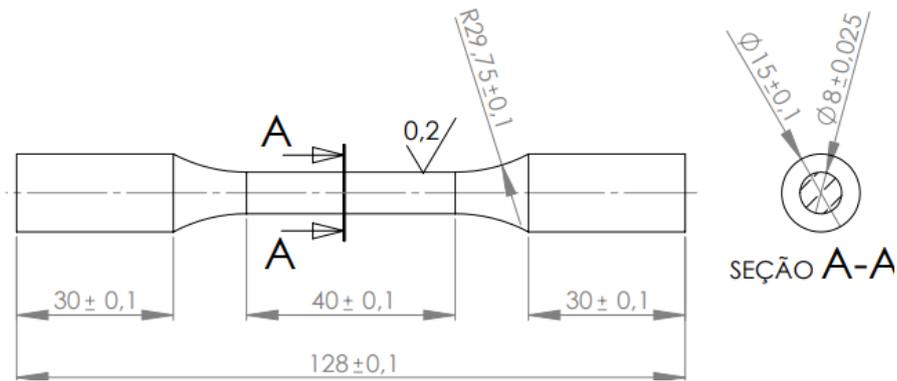


Figure 1 - Geometry of the specimens used in the uniaxial tensile-compression tests.

After machining, the specimens were polished with 220, 400, 600, 800 and 1200 grit papers. This procedure resulted in a surface roughness less than $0.2\mu\text{m}$, as recommended by ASTM E606 / E606M (2012).

The small surface defects were drilled in a machining center and their dimensions were measured using a confocal microscope applying a 200X magnification. Table 2 lists the diameters and depths of the defects. Figure 2 shows the top image of two defects, together with their profiles.

Table 2 - Dimensions of the holes obtained

	Diameter (mm)	Depth (mm)
CP1	0.75	0.65
CP2	0.75	0.64
CP3	0.42	0.42
CP4	0.42	0.42

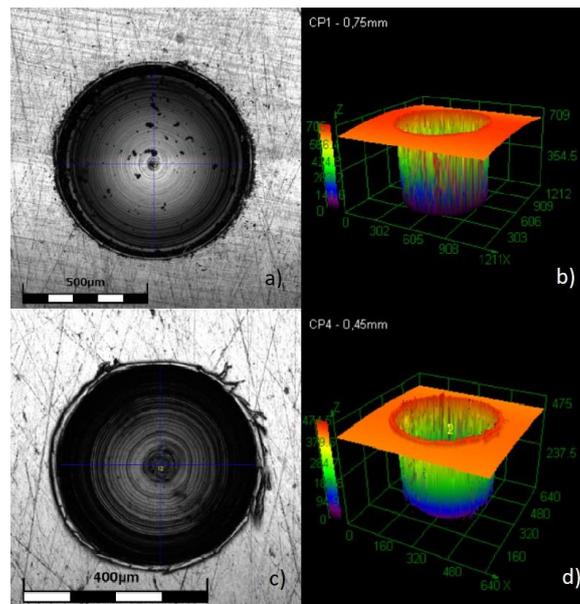


Figure 2 - a) View of the finished hole $\varnothing = 0.75$ mm and $h = 0.65$ mm and b)3D image of $\varnothing = 0.75$ mm. c) View of the finished hole $\varnothing = 0.45$ mm and $h = 0.42$ mm and d)3D image of $\varnothing = 0.45$ mm

Mechanical fatigue tests were performed using a MTS810 TestFrame uniaxial servo-hydraulic machine, with load capacity of $\pm 100\text{KN}$. The uniaxial tests were controlled by force, with stress ratio $R = -1$.

RESULTS AND DISCUSSION

The fatigue tests with specimens with smooth surfaces and with defects were performed considering loading frequencies between 1 and 10 Hz. Stress amplitudes and corresponding number of cycles to failure are presented in Table 3 and Fig. 3.

Table 3 - Synthesis of the experimental results generated by fatigue testing

Specimen Type	Identification	f (Hz)	σ_a	N_f
Smooth	1020ND02	1.0	229	35029
	1020ND03	1.2	198	94430
	1020ND04	1.8	188	112564
	1020ND05	4.0	174	293782
	1020ND06	10.0	159	1722105
	1020ND07	5.0	209	27528
	1020ND09	8.0	167	1139052
0.45mm defect	1020H04-01	1.8	188	43991
	1020H04-02	4.0	174	113409
	1020H04-03	10.0	229	12708
	1020H04-04	10.0	198	34774
	1020H04-05	10.0	159	904545
	1020H04-06	10.0	209	21943
	1020H04-07	10.0	167	429244
0.75mm defect	1020H07-01	1.8	188	26600
	1020H07-02	4.0	174	119086
	1020H07-03	5.0	229	5118
	1020H07-04	5.0	198	19863
	1020H07-05	5.0	159	396657
	1020H07-06	5.0	209	13645
	1020H07-07	10.0	167	297784

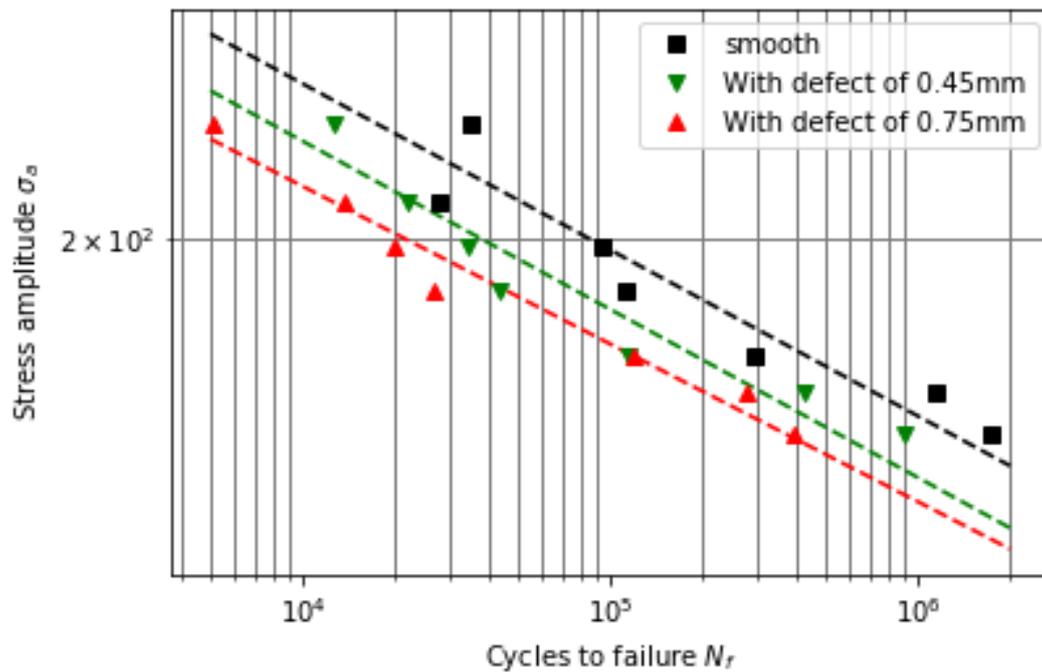


Figure 3 – S-N curve of SAE 1020 steel

From the experiments, the fatigue strength coefficient for the smooth specimens is $\sigma_f' = 555$ MPa and the fatigue strength exponent is $b = -0.0848$. For the specimens with $\varnothing 0.45$ mm defects, the fatigue parameters are $\sigma_f' = 524$ MPa, and $b = -0.0858$ while, for the specimens with $\varnothing 0.75$ mm defects, the fatigue parameters are $\sigma_f' = 472$ MPa and $b = -0.0805$.

Quantitative analyzes show that specimens with defects of $\varnothing 0.45$ mm showed a reduction between 48% and 60% in fatigue life when compared to those found in smooth specimens. For higher stress amplitudes, life reduction due to the defect was correspondingly higher. The same tendency is observed for the $\varnothing 0.75$ mm defect, where the fatigue life reduced between 50% and 85%.

When comparing the two types of defects it is noted that the lives resulting from specimens with defects $\varnothing 0.75$ mm defects are about half of the ones exhibited by specimens with $\varnothing 0.45$ mm defect.

Fracture surfaces reveal the initiation and propagation of cracks and the possible causes of failure. In faults due to fatigue, fracture surfaces usually present three characteristic zones: one for the beginning of the crack, another associated with crack propagation and the last one created during the final rupture (Lee et al, 2005). Figure 4 presents a surface with three characteristic zones for the smooth specimens. The crack initiation zone is generally a point on or near the surface of the mechanical element, where the cyclic deformation is very high or where defects are located. This zone has characteristic marks on the fracture surface, such as river and radio lines (ASM, Vol.12, 1992).

In an overview of the fracture surface, the three types of specimens (smooth and two with different sizes defects) show river marks that converge to the same location, indicating the point where the initiation of the crack occurred. In specimens with defects it is possible to notice that the river marks converge to the defect at a point near the surface, as indicated in Fig. 5a.

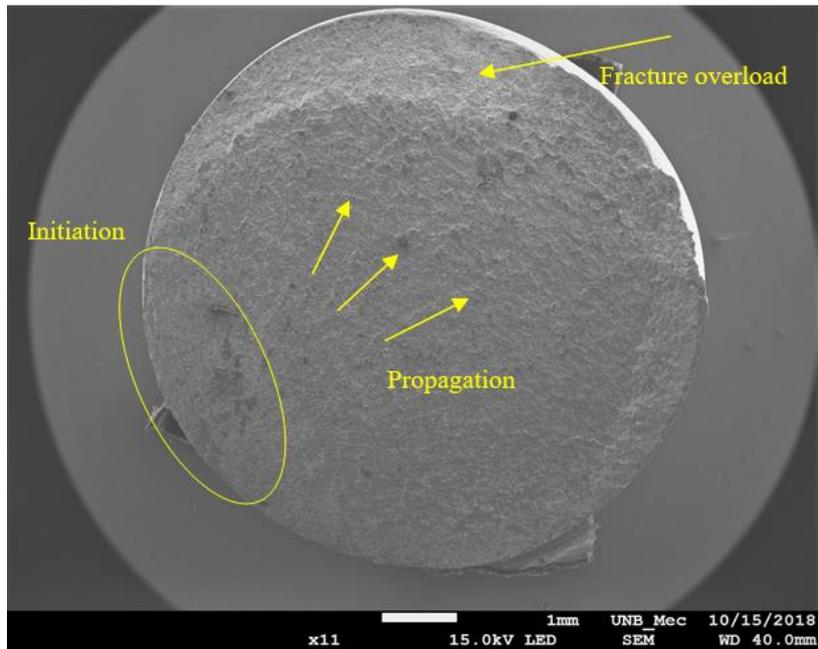


Figure 4 - Surface of fracture of smooth specimens. MEV. 11x

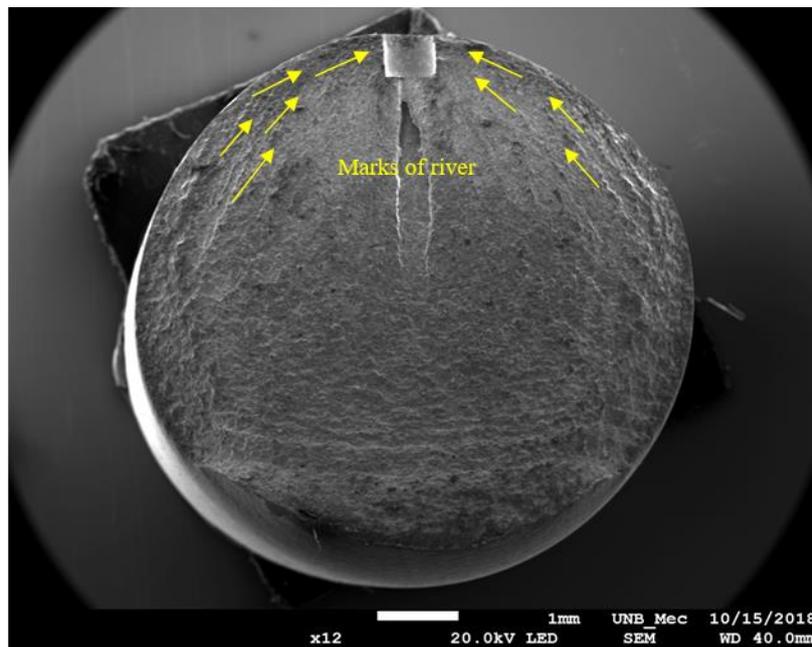


Figure 5 – a) Marks of river of specimens with defects \varnothing 0.75 mm. MEV. 12x.

It can be observed, in Fig. 6, the striations characteristics of the fatigue process, while the final fracture zone in Fig. 7 presents dimples, characteristics of a ductile fracture.

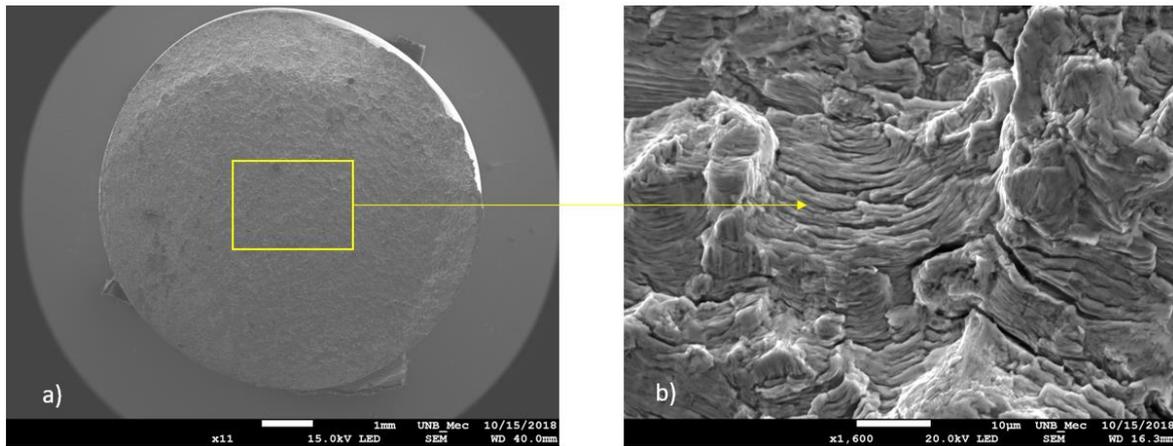


Figure 6 - a) Surface of fracture of smooth specimens. b) Increased image of the crack propagation region showing fatigue striations. MEV.1600x

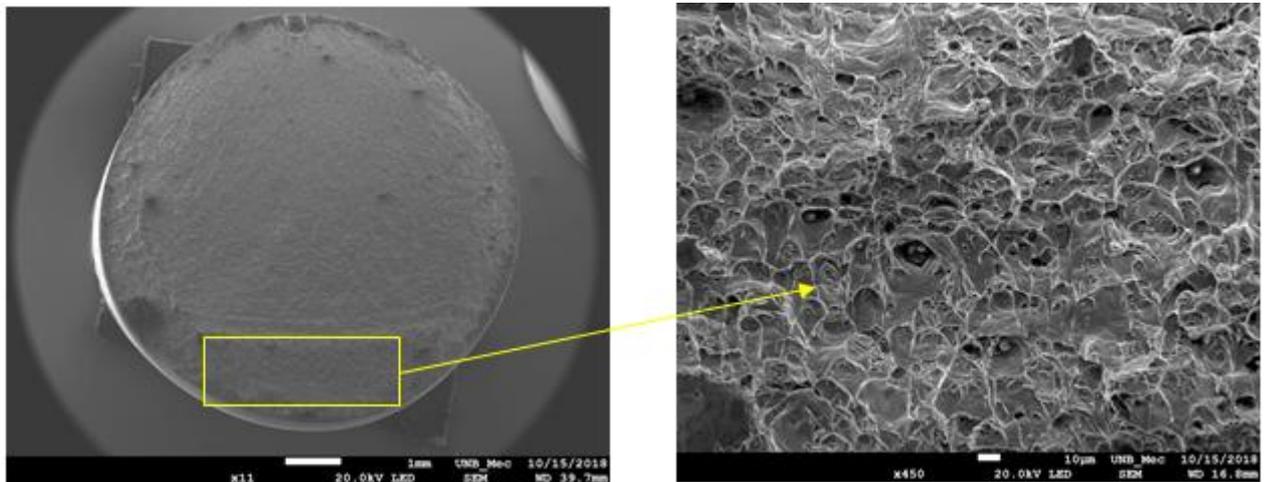


Figure 7 – a) Surface of fracture of specimens with defect of \varnothing 0.45 mm. MEV. 11x. b) Dimples found in the final fracture region. MEV. 250x.

CONCLUSION

This study contributes to the knowledge on the fatigue in the presence of small defects in the sense that it focuses on fatigue life, whereas most of the studies on the subject focus on fatigue strength. It shows that small defects can reduce the fatigue life by factor-of-two in the case of the smaller defect and by a factor-of-four in the case of the larger defect. Further, the larger the stress amplitude, the larger the reduction in fatigue life produced by the defect of a given size. The results obtained in this study will subsidize the proposition of a mechanical model for the estimation of the fatigue life in the presence of small defects. Additional analysis of the crack surfaces is required to determine in detail the locus and the orientation of the crack nucleation.

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