Study of short crack growth in shot peened 300M steel

Amrita Bag [a], Dorian Delbergue [b], Martin Lévesque [a], Philippe Bocher [b], Myriam Brochu [a]
[a] École Polytechnique de Montréal, Canada, amrita.bag@polymtl.ca; [b] École de technologie supérieure, Canada

Keywords: short crack, fatigue, shot peening, high-strength steel, crack initiation

Introduction

Shot peening can enhance the fatigue life of metals as a result of strain hardening and induced compressive residual stresses (CRS) which either delay the initiation of short fatigue cracks or cause an arrest of the already existing short cracks within the CRS layer. Some studies show that shot peening does not delay the initiation but the propagation of micro cracks and that strain hardening contributes very little in arresting cracks, as compared to crack closure by CRS[1][2]. Short crack growth (including crack initiation) has been found to account for more than 70% of the fatigue life of a component [3] and therefore could better reflect the effect of peening on fatigue life. These short cracks are usually of the order of a few micrometres to a millimetre in length and have been found to exhibit crack growth rates which are much higher than conventional long Linear Elastic Fracture Mechanics (LEFM) cracks mainly due to the absence of small scale yielding and closure observed in long cracks [4]. Short cracks can be classified into two broad types based on their size and the applied stress namely: microstructurally short cracks (MSC) or Stage I cracks and physically short cracks (PSC) or Stage II cracks as schematized in Fig.1. The MSC are usually of the order of microstructural features such as the grain diameter. They exhibit an initial accelerating–decelerating growth pattern as they advance and the crack tip plastic zone encounters microstructural barriers. Gradually, the plastic zone size increases, thus increasing the crack's resistance to the barriers. After traversing 2-3 grains [4], the effect of microstructure diminishes and crack transitions to Stage II. Its growth is then governed by Elastic-plastic Fracture Mechanics (EPFM); provided the crack is still smaller than 25 times the plastic zone size. As the crack grows further, its size exceeds this value, and after covering approximately 10 grains [4], the crack behaviour merges with that of a long LEFM crack. Shot peening has been found to primarily affect Stage I and Stage II EPFM cracks [5].

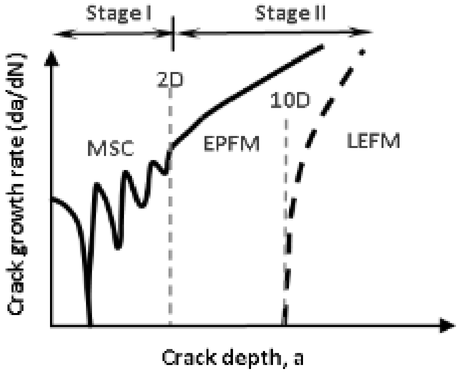

Figure 1: Crack growth rate vs. crack depth plot (log scale) for short cracks based on [4] (D= grain diameter)

Objectives

The main objective of the current work was to investigate the effect of shot peening on the short crack initiation and propagation in 300M steel, which is part of a larger objective of modelling the fatigue life of shot peened steel components. Microstructurally and physically short cracks of length ranging from 0.02mm-0.2mm have been studied in the current work.

Methodology

Hourglass specimens (Fig. 2) of 300M steel have been used to perform interrupted constant stress amplitude axial fatigue tests at R=-1 and 10Hz for two stress amplitudes: σ_{55} and σ_{64} (55% and 64% of $\sigma_{ys,0.2\%}$ respectively) . Three surface conditions have been studied in the present work, namely:

polished, as-machined and shot peened. The polished specimens were prepared by mechanically polishing as-machined specimens down to 1μm surface finish. The peening was achieved by using two types of shots namely CW14 (conditioned cut wire) and S230 (cast steel) at 8A intensity and 100% coverage. A total of 16 samples were tested; 2 samples per stress level for each surface condion. Surface crack length measurements were performed using replica technique to backtrack the initiation and propagation of short cracks in all the specimens. The resulting replicas were analysed by means of optical microscopy. Fractography analysis was performed using Scanning Electron Microscope (SEM) and Energy Dispersive Spectroscopy (EDS). Moreover, residual stresses for all surface conditions were obtained by X-ray diffraction (XRD) using a Pulstec μ-X360n apparatus equipped with a Cr-tube. To measure the through thickness residual stress profiles, thin layers of material were successively removed by electropolishing using a perchloric acid-based solution. This was performed to study the effect of peening induced residual stresses on short crack growth.

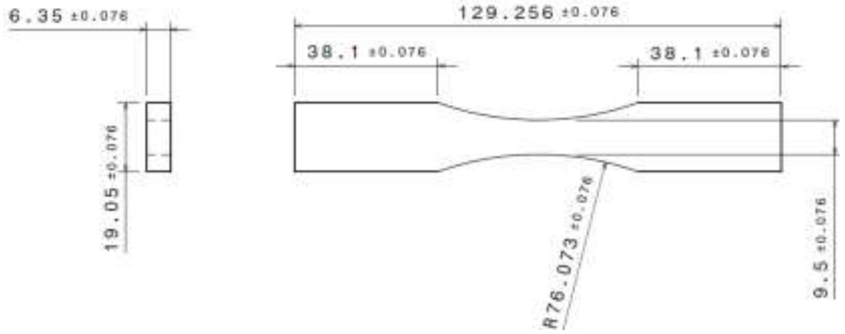

Figure 2: Hourglass flat specimen dimensions (in mm)

The total fatigue life of a component (N_t) can be divided into three basic stages given by: $N_t = N_i + N_p + N_{LC}$, where N_i= crack initiation life, N_p= short crack propagation life, N_{LC} = long crack propagation life. In the present study, we will investigate the effects of shot peening on the crack initiation and short crack growth regime durations. Here, crack initiation has been quantified by the number of cycles required to grow a crack of 0.02mm which is comparable to the average grain diameter of the material, D = 23μm. Short crack propagation ranges between 0.02mm to 0.2mm. The basis of these assumptions will be discussed later in the section “Crack growth rate results”.

Results

Average fatigue life

The average fatigue lives presented in this paper are normalised by the average fatigue life (N_t) of polished specimens as shown by the ordinate legend of Fig.3.

At σ_{55}, fatigue life of polished (100%) and as-machined specimens (99%) are similar whereas the fatigue lives of CW14 and S230 peened specimens (84%) are about 16% lower.

At σ_{64}, best fatigue life was given by CW14 peened specimens (117%) which was 17% higher than the baseline polished specimens. The S230 peened (74%) and the as-machined (43%) specimens had 26% and 57% lower lives as compared to the polished specimens respectively.

Thus, shot peening is found to improve fatigue life only in case of the high stress amplitude (σ_{64}) and the CW14 peened specimens showed better life than those with the S230 peening condition. At σ_{55}, both conditions showed similar lives, shorter than the as-machined specimens.

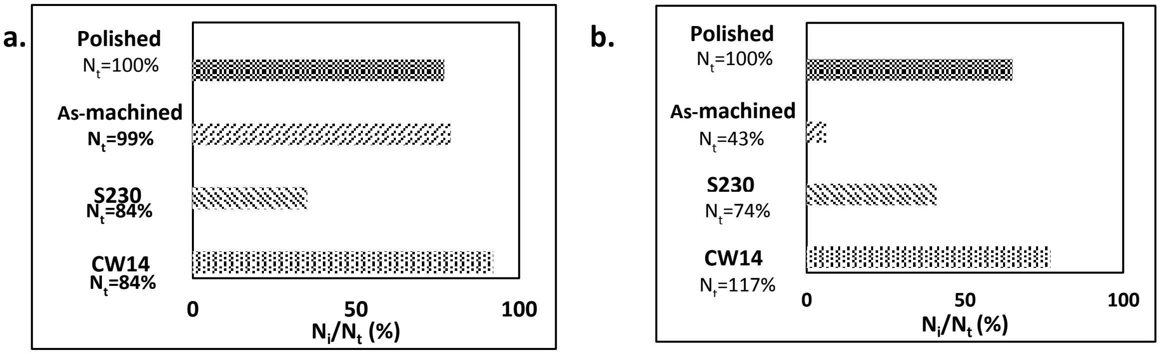

Figure 3 : Ratio of crack initiation life (N_i) to total fatigue life (N_t) at a. σ_{55} b. σ_{64}

Effect of peening on crack initiation

For a given surface condition, the abscissa of Fig.3 depicts the ratio of crack initiation life to the fatigue life (N_i/N_t), in order to analyze the effect of shot peening on specific damage mechanisms.

Investigating the percentage of total fatigue life (N_t) occupied by crack initiation (N_i), it was observed that it accounts for about 35-92% of N_t at σ_{55}. A higher N_i/N_t ratio resulted in a higher overall fatigue life; except in case of CW14 peened specimens, which in spite of having the highest N_i/N_t, did not have the highest fatigue life (Fig.3a). In case of CW14 peened specimens, most of the life was dominated by crack initiation, while in S230 peened specimens, crack initiation occurred relatively early and most of the life was spent in propagation of a short crack. Fatigue lives of both the peening conditions were however very close. At σ_{55}, for both the peening conditions, the cracks initiated at the surface on the specimen edge. The as-machined and the polished specimens were subjected to subsurface crack initiation at non-metallic inclusions mainly composed of Al, Mg, O and Ca (Fig.4a). The size of the inclusions (represented as square root of the inclusion area [6]) was in the range of 1-28 μm and they were situated within a depth of 0.03mm from the surface.

In case of σ_{64}, N_i/N_t was highest in CW14 peened specimens followed by polished, S230 peened and as-machined specimens (Fig.3b) which was consistent with the decreasing order of their fatigue lives. The polished specimens had crack initiation at inclusions similar to the ones tested at σ_{55}. All crack initiations except for polished specimens started at the surface on the specimen edge (Fig.4b).

This confirms that shot peening with CW14 delays crack initiation at the higher stress amplitude, σ_{64}. In general, peening with CW14 seems to increase the cycles to crack initiation more than S230 peening at both stress amplitude, reflected by the higher N_i/N_t ratios of CW14 peened specimens compared to S230 peened ones (Fig.3).

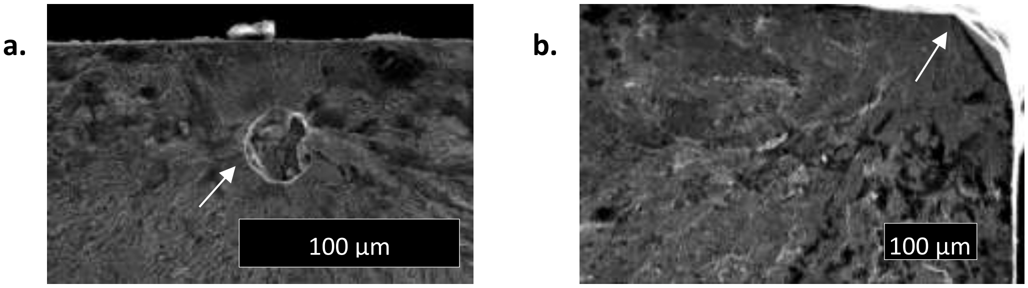

Figure 4: Crack initiation (red arrow) a. at an inclusion in a polished specimen at σ_{55}, b. at the edge in a peened specimen at σ_{64}

Short crack growth rate results

It is evident from the aforementioned results at σ_{55}, that the fatigue lives of both peening conditions are similar although the N_i/N_t ratio of CW14 peened specimens is almost 3 times that of the S230 peened ones. This could indicate that peening with S230 affects the short crack propagation more than crack initiation, contrary to CW14 peening condition. Therefore it is necessary to investigate how the different peening conditions affect short crack growth as compared to the unpeened conditions.

The aspect ratio (a/c) or the ratio of crack depth, a to surface crack length c has been calculated for cracks upto 0.8mm in length. Owing to the complex shape of the dominant crack, the calculation of a/c is based on measurements from semi/quarter elliptical shaped secondary cracks that were found on the fracture surface of the specimens tested at σ_{64}. The a/c value was found to be always equal to 1 for a < 0.8mm. No secondary cracks were observed on the fracture surface of specimens tested at σ_{55}. However, the dominant crack morphology of the specimens was similar at both stress amplitudes. Therefore, the same a/c ratio of 1 was used for specimens tested at σ_{55}.

In the current study, the smallest crack depth detected in the replicas corresponds to 0.02mm. Therefore, N_i was defined as the number of cycles required to reach this size. In case of unpeened specimens, no clear transition from Stage I to stage II was observed due to lack of data. Therefore, based on the predictions of Taylor and Knott [4], the upper limit for Stage I cracks was fixed at 0.05mm (2D) and that for Stage II EPFM cracks at 0.2mm (10D).

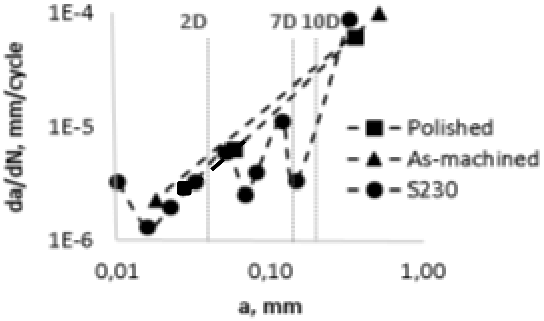

Figure 5: Crack growth rate vs. crack depth plot (log scale) for polished, as-machined and S230 peened specimen at σ_{55} (Dotted lines are joining experimental points to help visualize acceleration and deceleration)

At σ_{55}, the Stage I propagation rates of polished as-machined and S230-peened specimens were very similar as depicted in Fig.5. However, the transition of MSC to EPFM cracks was delayed in S230 peened specimens to 7D as compared to unpeened specimens (2D). Crack growth was retarded at grain boundary barriers till it reached a size of 0.16mm (7D). As a result, the EPFM crack propagation rates were 2-4 times lower than the unpeened specimens at the barriers. No observations could be made for CW14 peened specimens due to lack of data.

At σ_{64}, the propagation rates of CW14 peened specimens at the end of Stage I (a=2D) were similar to the as-machined specimens and S230 peened specimens as shown in Fig.6. However, as the cracks transitioned to Stage II, the crack growth rates in unpeened specimens began to increase monotonically as expected, except for the peened specimens, where the crack growth rates dropped. In CW14 peened specimens, the decrease in crack propagation rates was gradual which delayed the transition of MSC to EPFM cracks. The crack traversed 5 grains instead of 2 grains before switching to Stage II. In S230 peened specimens, crack growth rates after crossing 2 grains decreased by 3-4 times. The growth rates continued to drop until the crack reached a size of 0.07mm (3D) and then accelerated upto 0.12mm (5D). After 5D, however, the crack growth rates of all conditions were quite similar.

CRS and surface roughness results

The measured residual stress profiles for all surface conditions are presented in Fig.7. The surface roughness of all the samples (except polished) was measured using a roughness profilometer. Table 1 provides the data for surface CRS, depth of CRS, mean roughness parameter R_a, total fatigue life, N_t (%) and the crack initiation sites at σ_{55} and σ_{64} for all tested conditions. It can be seen that the maximum CRS was same for both S230 and CW14 peened specimens followed by as-machined and finally polished specimens. The CRS was however deeper in S230 peened specimens than the CW14 peened. The surface roughness was highest for the CW14 peening condition, followed by S230 peening condition and finally as-machined. Taking into account all these parameters, the effect of peening on short crack growth and the resulting influence on fatigue life will be discussed below.

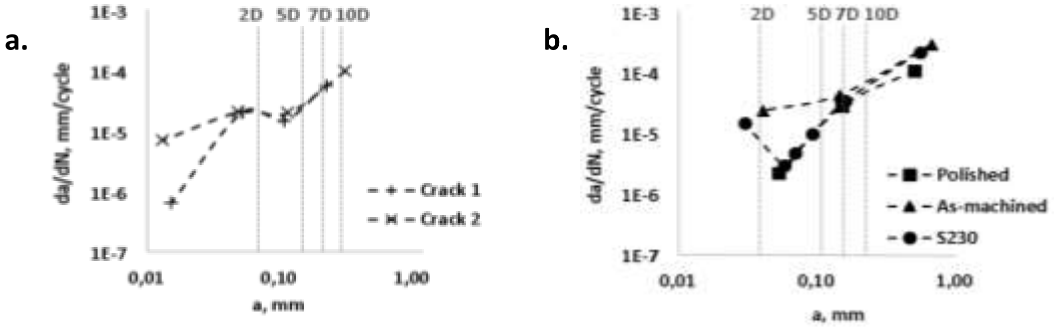

Figure 6: : Crack growth rate vs. crack depth plot (log scale) for a. CW14 peened specimen , b. polished, as-machined and S230 peened specimen at σ_{64}

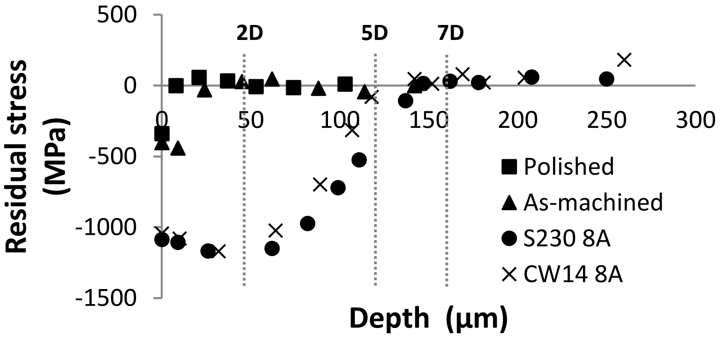

Figure 7: XRD residual stress profiles for polished, as-machined and peened specimens

Table 1: Compressive residual stress, roughness, fatigue life and crack initiation site data for all tested conditions

Condition	Surface CRS (MPa)	CRS depth (µm)	Ra (µm)	N_t % (σ_{55})	Crack initiation site (σ_{55})	N_t % (σ_{64})	Crack initiation site (σ_{64})
Polished	-404	8	--	100	Subsurface	100	Subsurface
As- machined	-441	24	0.29 ±0.06	99	Subsurface	43	Surface
S230 8A	-1080	150	0.82 ±0.04	84	Surface	74	Surface
CW14 8A	-1044	125	1.23 ±0.01	84	Surface	117	Surface

Discussion

In general, a competition between the detrimental effect of roughness and the beneficial effect of CRS was observed and could be related to the resulting trend in fatigue life.

At σ_{55}, highest fatigue life is given by polished and as-machined specimens. The low roughness in the case of polished and as-machined specimens coupled with the CRS resulted in subsurface crack initiation, and hence, a high N_t. In case of peened specimens, the higher roughness overcame the effect of high surface CRS, causing surface rather than subsurface crack initiations. It is however interesting to note that, in spite of having the highest roughness, the CW14 peened specimen had the highest crack initiation life and fatigue life similar to S230-peened ones. Nevertheless, in S230-peened specimens, the in-depth CRS seemed to delay the transition of Stage I to Stage II cracks (Fig.5), although it did not improve the overall fatigue life. Therefore, peening did not prove beneficial for fatigue life at the lower stress amplitude (σ_{55}).

At σ_{64}, highest fatigue life is given by CW14 peened specimens followed by polished, S230 peened and as-machined specimens. In polished specimens, in absence of surface defects, crack initiation occurred at subsurface inclusions, and crack initiation was delayed to a greater extent than in as-machined or S230 peened specimens (which were affected by competition between the roughness and CRS). In as-machined specimens, the CRS was not deep enough to affect the short crack propagation rates, therefore the effect of roughness dominated. In S230 peened specimens, the Stage I cracks decelerated while travelling in the region of maximum CRS (1.5D-3D) as shown in Fig.6b, which led to a better fatigue life compared to as-machined specimens. On the contrary, in CW14 peened specimens, in spite of the high roughness, crack initiation was delayed. A small amount of crack deceleration occurred between 2D and 5D (Fig.6a), which corresponds to the crack growing deeper into the material from a region of maximum CRS to gradually diminishing CRS. Afterwards, crack growth accelerated at around 0.12mm (or 5D), which corresponds to the end of the CRS layer in CW14 peened specimens (Fig.7). It should be noted that, after reaching a length of 0.05mm (2D), the cracks in CW14 peened specimens had growth rates higher than those of the S230 peening condition which gradually became similar at around 7D. This suggests that S230 peening is more effective in delaying crack propagation compared to CW14 peening, and that the higher fatigue life in CW14 peening condition at σ_{64} is caused primarily by delayed crack initiation.

Conclusion

Study of short crack behaviour is instrumental in revealing the effect of peening on specific damage mechanisms governing fatigue life. From the present work, the following conclusions can be drawn:

- In general, there seems to be a competition between the detrimental effect of roughness and the beneficial effect of CRS depending on the applied stress. At low stress-high roughness conditions (peened specimens), effect of roughness dominates over CRS, causing surface crack initiation; while in case of low stress-low roughness conditions (unpeened specimens), CRS dominates leading to subsurface crack initiation. At high stress, CRS effect dominates over roughness.
- Higher the N_i/N_t, higher is the fatigue life, irrespective of the stress amplitude (except CW14 at σ_{55}).
- Peening is nevertheless beneficial only for the high stress amplitude (σ_{64}). Of the 2 peening conditions, CW14-8A gave a higher fatigue life at σ_{64} by delaying both crack initiation and short crack propagation. S230-8A condition was found to affect short crack propagation at both σ_{55} and σ_{64} although it did not improve the fatigue life.

References

[1] Liu, W., Dong, J., Zhang, P., Zhai, C., & Ding, W. (2009). Effect of shot peening on surface characteristics and fatigue properties of T5-treated ZK60 alloy. Materials Transactions, 50(4), 791-798.
[2] Guagliano, M., & Vergani, L. (2004). An approach for prediction of fatigue strength of shot peened components. Engineering Fracture Mechanics, 71(4), 501-512.
[3] Kitagawa, H., & Takahashi, S. (1976). Applicability of fracture mechanics to very small cracks or the cracks in the early stage. In Second International Conference on Mechanical Behavior of Materials. ASM, Metals Park, Ohio. 1976, 627-631.
[4] Taylor, D., & Knott, J. F. (1981). Fatigue crack propagation behaviour of short cracks; the effect of microstructure. Fatigue & Fracture of Engineering Materials & Structures, 4(2), 147-155.
[5] Miller, K. J. (1993). Materials science perspective of metal fatigue resistance. Materials Science and Technology, 9(6), 453-462.
[6] Yukitaka, M., & Masahiro, E. (1983). Quantitative evaluation of fatigue strength of metals containing various small defects or cracks. Engineering Fracture Mechanics, 17(1), 1-15.