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EFFECT OF SHOT PEENING AT DIFFERENT ALMEN INTENSITIES ON FATIGUE BEHAVIOR OF AISI 304

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AISI 304 stainless steel is a common material that is widely used in the extensive implant industry. The failure of this material, especially in bone implant applications, is affected by its fatigue load. The purpose of the present experiment is to improve fatigue crack growth resistance and surface hardness in AISI 304 by using a shot peening metal treatment with varying Almen intensities. In this experiment, specimens of AISI 304 underwent a shot peening treatment and then subjected to surface fatigue failure. The results of this experiment show that shot peening with an Almen intensity of 0,005 achieved a 192,3 % increase in fatigue life compared to a non-treatment material, with a fatigue life of 127 700 cycles (Paris constant C, n is $1x10^{-11}$ and 3,5, respectively). The surface hardness reached HV 429,63.

Key word: AISI 304, shot peening, surface, hardness, fatigue crack growth rate

INTRODUCTION

Stainless steel 304 is one of the most widely used metals in biomaterial applications due to its good corrosion resistance and mechanical properties that make it optimal for implantation in the human body. Failure of implanted metal materials can occur in several ways, one of these ways is fatigue failure. Fatigue has been widely studied, and statistical analysis methods to describe the probability distribution of fatigue crack growth rates have been discussed [1]. The parameters of Smith, Watson, and Topper (SWT) for fatigue life were compared with the formulas of Goodman, Geber, and Solonberg's formula for G20Mn5QT Cast Steel. The results showed that the formulas of Goodman, Geber, and Solonberg were more appropriate in determining the range of fatigue limits [2]. The influence of T6 and artificial aging on fatigue was investigated in alloy A356 by subjecting a motorcycle wheel produced by centrifugal casting to rotation at 350 rpm [3].

Fatigue crack growth of Armox 500T steel has been analyzed using a uniaxial load [4]. Fatigue crack initiation, location and mechanism of fracture as a result of high-frequency loading has been studied in nodular cast iron [5].

Generally, mechanical processes that have been widely used are shot peening and roller working for generating compressive residual stresses. Shoot peening has local plastic deformation by the pressure of small balls, while roller working has local plastic deformation by the pressure of a narrow roll. Shot peening is a cold surface treatment with compressive stress induced by bombarding a metal surface layer with hard spherical particles under controlled conditions. It is widely used to improve the fatigue strength of industrial components. The effects of a shot peening surface treatment on welded metals have been studied [6-10]. The effects of Almen intensity of shot peening on fatigue strength improvement by a shot peening surface treatment have been investigated [11]. The effects of a combination of shot peening (cold working) and plasma electrolytic oxidation coating (ceramic coating) to improve the fatigue performance of 2024 T351 aluminum alloy was studied using an Almen intensity of 20 [12]. The influence of shot peening treatment on a brass alloy with varied durations (30, 60, and 120 minutes) has been discussed. The results show that fatigue life decreases after being shot peened for all sample durations. The results also showed that microstructure and surface roughness play a significant role in the effects of surface treatment by shot peening for brass alloys [13].

Optimizing the shot peening intensity to maximize the fatigue life of AISI 4340 steel has been intensively studied in quenched and tempered steels. The results have determined a specific Almen intensity able to optimize fatigue life. Fatigue value was found to increase with increasing steel strength properties up to a certain point, and then to decrease with stronger steel. This is due to an over-peening treatment, where over-peening might increase surface defects, induce relaxation of residual surface stress, and facilitate initial fatigue cracks [14] and hot tear cracks [15]. In this study, a fatigue

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analysis for AISI 304 was conducted before and after cold surface treatment (shot peening). Hardness and fatigue crack growth tests were conducted with two variations of Almen intensity, A0,003 and A0,005.

MATERIALS AND EXPERIMENTAL METHODS

A monotonic test to determine tension is easy to perform and provides information that has become conventionally accepted. However, their relation to fatigue behavior may be rather remote. Fatigue specimens were produced by a machine cutting process from AISI 304 plate according to ASTM: E647 standards, as shown in Figure 1a. The surface of the fatigue samples were grinded using SiC papers with grits of 120, 320, 500, 800, 1 000, 1 500, and 2 000, and then polished with metal autosol to ensure smoothness. The crack length was measured from one side of the specimen's surface to the initial crack on its left side. A servo-hydraulic universal testing machine with a sinusoidal load was used to investigate the fatigue life cycle of AISI 304. Stress ratio (R) and frequency (f) were set at 0,1 and 11 Hz, respectively. The stress level used was about 20 % of yield stress, *Pmax* = 225 kg and *Pmin* = 22,5 kg. Two specimens were subjected to shot peening treatment with an Almen intensity of of A0,003 and A0,005, respectively, and one sample received no treatment. The fatigue crack propagation rate (*da/dN*) of the Paris power law was determined using the following formulas:

$$\left(\frac{da}{dN}\right)_a = \frac{a_{i+1} - a_i}{N_{i+1} - N_i} \quad (1)$$

$$\bar{a} = (a_{i+1} + a_i) / 2 \quad (2)$$

$$\Delta K = \frac{\Delta P}{B\sqrt{W}} \frac{(2+\alpha)}{(1-\alpha)^{3/2}} \left(0{,}886 + 4{,}64\alpha - 13{,}32\alpha^2 + 14{,}72\alpha^3 - 5{,}6\alpha^4\right) \quad (3)$$

$$\Delta P = P_{max} - P_{min} \quad (4)$$

$$\alpha = a / W \quad for \quad a / W \geq 0{,}2 \quad (5)$$

where $\bar{a}$ is average crack length and subscripts *i* and (*a+1*) represent *i*th and (*i+1*)th cycle, α is the ratio of crack length to width of the specimen, *C* and *n* are Paris constants, ΔK is the difference between stress intensity factors, *P* is load, and *W* and *B* are width and specimen thickness, respectively.

Shot peening is a cold work process in which compressive stress is induced in a metal surface by bombarding it with shot at high speed under controlled conditions. Shot peening can improve the fatigue strength of metals. In this experiment, the shot peening balls used were cast steel with a diameter of 800 μm. The air pressure ranged from 5 bars to 7 bars. The distance between the nozzle and specimen was about 10 cm. The area that received shot peening treatment included both sides of the specimen but was not its full area. The treatment only occurred in the area that would be subject to fatigue fractures. The shot peening area is shown in Figure 1b and is represented as the black section on the schematic sample.

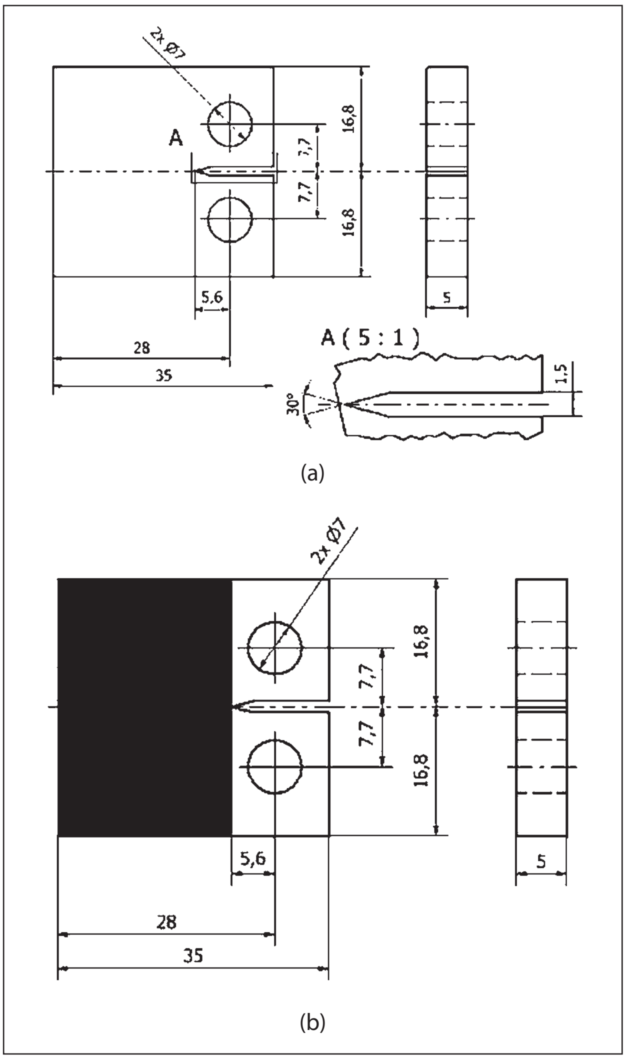

Figure 1 a) Specimens for fatigue crack growth rate test following ASTM: E647 standards, and b) the shot peened area (in mm).

Hardness testing was conducted by a Micro Hardness Tester in a transverse direction, from the shot peening surface to the middle of a cross-section of the sample. Loading was applied with 100 gr for 10 seconds at each location. Indentations were made at 25 points, with 100 μm of distance between each point in order to obtain the distribution of metal hardness from the surface to the middle of the specimen, as shown in Figure 2.

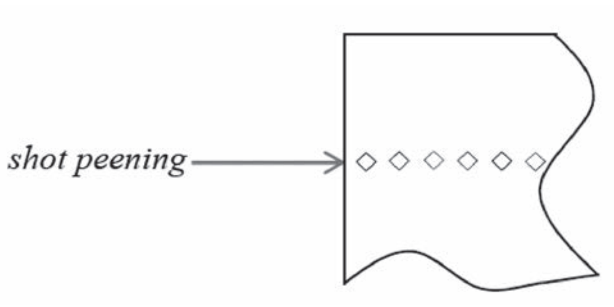

Figure 2 Surface area of the metal hardness test on the shot peening specimen

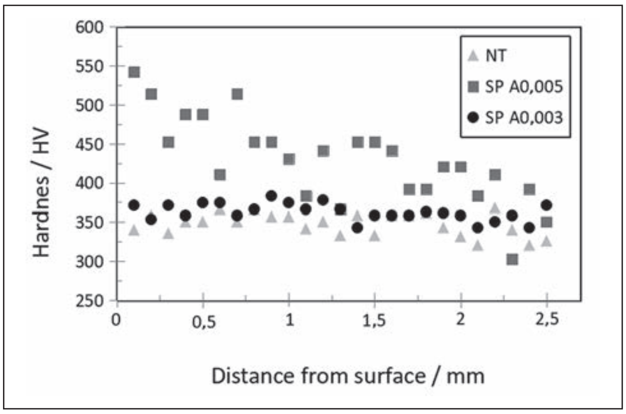

Figure 3 Vickers hardness of NT, SP A0,003, and SP A0,005 fatigue samples

RESULTS AND DISCUSSION

The Vickers hardness of the three test specimens is shown in Figure 3. The non-treatment (NT) specimen showed an HV of 346,97. The specimen subjected to shot peening with an Almen intensity of A0,005 had an average HV of 429,63, and the specimen shot peened at an Almen intensity of A0,003 had an average HV of 362,46. The results indicate that shot peening treatment can improve surface hardness. The specimen shot peened at A0,005 had the highest HV value, followed by the specimen shot peened at A0,003, and then by the NT sample.

The number of fatigue cycles the three testing samples show different characteristics, as shown in Figure 4. The numbers can be quantified: 66 400 cycles for NT, 127 700 cycles for SP A0,005 and 71 131 cycles for SP A0,003. Paris constants *C* and *n* for the three samples can be seen in Table 1.

Table 1 **Paris constants *C* and *n* of the three test samples.**

Specimen	C	n
NT	2×10^{-11}	3,6
SP A0,003	1×10^{-13}	4,7
SP A0,005	1×10^{-16}	80

The results show that a shot peening surface treatment with different Almen intensities led to the highest crack growth rate for SP A0,005, followed by SP A0,003. When compared with the non-treatment specimen, the treatment had the effect of reducing the crack propagation rate. SP A0,003 showed an insignificant reduction in the crack propagation rate. Compressive residual stress and work-hardening at the hardened surface layer was responsible for delaying fatigue crack initiation by affecting crack tip opening behavior and suppressing fatigue crack growth rate.

Figure 5 shows macro photography of the surface fatigue from the NT sample as well as from the two samples subjected to a shot peening surface treatment with two variations of Almen intensity (A0,003 and A0,005). The red ovals show the smooth fatigued area, contrasted with the usual surface roughness. The smooth fatigued area is estimated the cause of small continues dynamic load on the sample, so crack propagation increases slowly. Furthermore, the crack was a

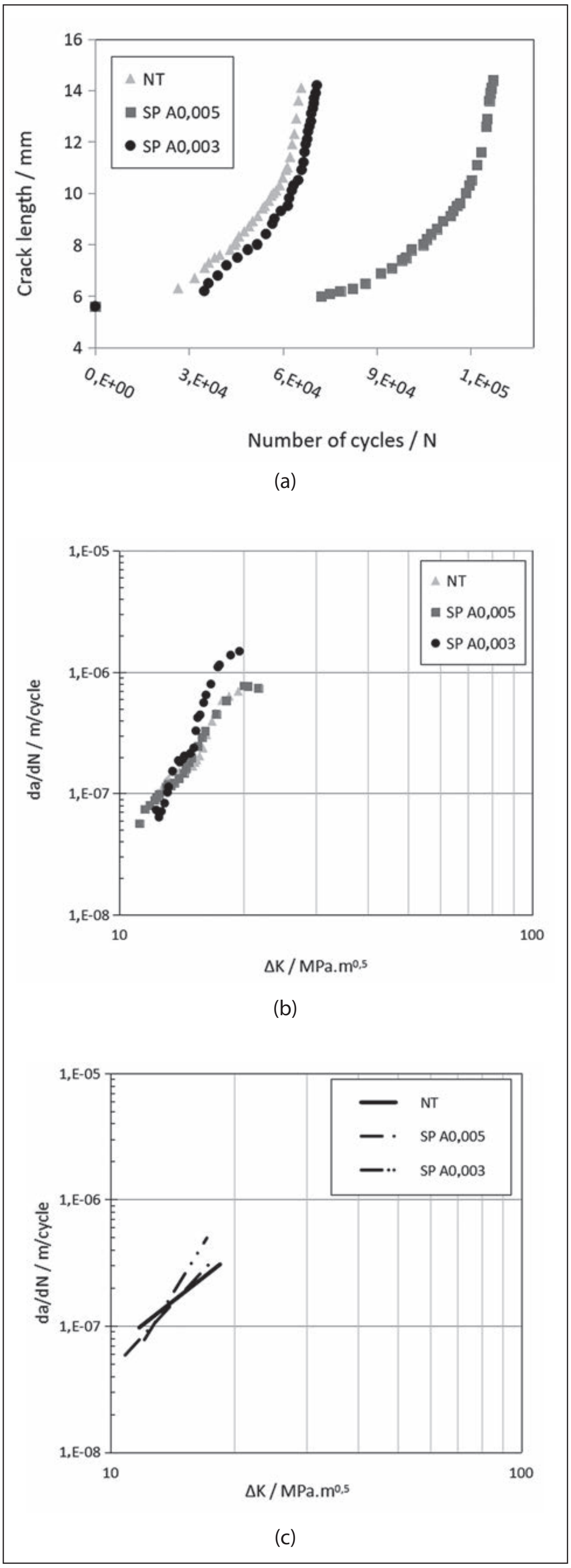

Figure 4 a) Correlation of crack length with number of cycles, b) Plot of *da/dN–ΔK*, and c) Trend line of *da/dN–ΔK*.

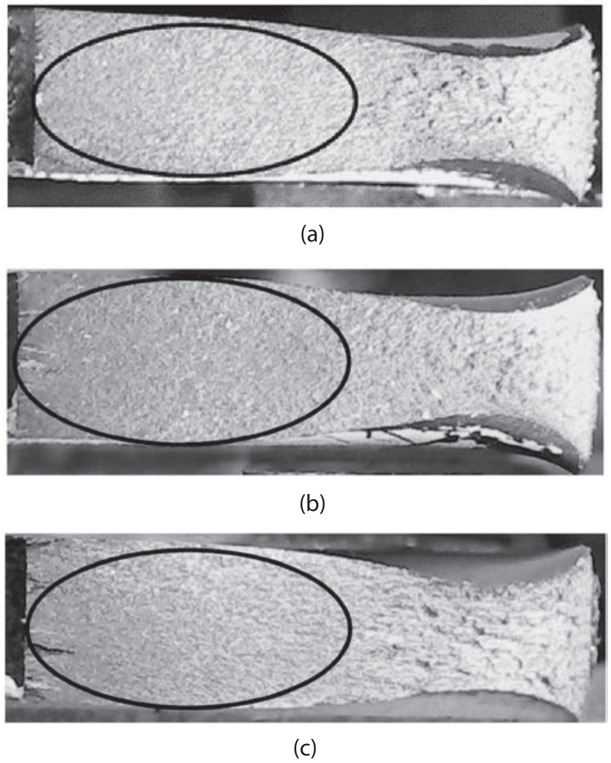

Figure 5 Fractography of fatigue samples, a) NT specimen, b) SP A0,003, and b) SP A0,005

continuation of brittle crack from a notch on the fatigue sample at the last stage in the sample before fracture. This can be seen in the rough area of the sample (shown in the right area in Figure 5). The characteristics of a brittle fracture include a relatively rough fracture surface, due to the sample receiving a shock load after a dynamic load.

CONCLUSIONS

This experiment studied the effects of shot peening with two different Almen intensities on the fatigue limit of AISI 304 plate. The findings and conclusions of this study are that shot peening can improve surface hardness. Compressive residual stress and work-hardening at the hardened surface layer was responsible for delaying fatigue crack initiation and suppressing the fatigue crack growth rate. The sample SP A0,005 showed the highest surface hardness, with a surface hardness and fatigue propagation characteristic of HV 429,63 and 127 700 cycles, respectively. It also had good fatigue crack growth characteristics, according to the Paris constants C and n.

Acknowledgments

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Note: The responsible English translator is Peter D’Auria - the Language Center, Syiah Kuala University, Indonesia