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MATERIAL SCIENCE AND NANOTECHNOLOGY

Shot peening effects on fatigue life, corrosion behavior and surface roughness of low carbon alloy steel

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Abstract. In this present study, the effect of the shot peening process on fatigue life, surface hardness and corrosion properties of a low carbon alloy steel is examined at room temperature. The research article addresses the effect of shot peening by varying the process parameters such as peening distance and pressure with amachrome as shots. The experiment is designed by means of full factorial design. The experimental result reveals that the pressure and distance are the most significant factors in the shot peening process. The results illustrate that the average pressure of 7 bar and distance of 100 mm improves fatigue life by 1.5% of unpeened material under 20 Hz frequency while corrosion resistance improves by 4% with unpeening of the low carbon alloy steel by using amachrome as a shot.

Key words: surface roughness; shot peening; fatigue life.

1. Introduction

Surface treatment and heat treatment are the universally proven techniques to improve the mechanical properties of materials by bringing changes to the surface. There are many surface treatments and heat treatments such as shot peening, roller burnishing, mechanical polishing, ball burnishing, surface coating, nitriding, annealing, normalizing, oil quenching, tempering and nitriding, improving surface properties of virgin specimen slightly or drastically [1]. For all engineering components subjected to cyclic loading, fatigue is the most important factor. The basic mechanisms leading to fatigue failure are the initiation and propagation of cracks which mostly occur on free surfaces [2]. Shot peening is a cold working method widely used in surface engineering to extend fatigue life of components. In this method, hard balls (shots) under controlled velocity impact the surface of the component. It is used in the automotive industry, e.g. on gear parts, springs and connecting rods, and in the aerospace industry on structural components of aircraft such as wing panels and gas turbine engines, blades and disks.

Industrial shot peening of low alloy steel SAE 4140, using steel shots, improves grain structure by grain refinement at different Almen intensities. This, in turn, improves corrosion resistance [3–4]. Surface modification of the Ti-6Al-4V alloy of two specimens DV and GL is performed to maintain good mechanical properties by shot peening, using micro ceramic shots. This results in good near surface hardness, residual stress and corrosion resistance [5]. Shot peening of 316 L stainless steel for different time periods of 5, 10, 15, 20, and 25 minutes improves surface hardness and fatigue resistance [6]. Shot peening of an Al7075-T6 specimen improves fatigue life by up to 350%. But it works better in the lower stress regions than in the higher stress ones [7–9]. Shot peening and ball burnishing of the Al7075-T73 aluminum alloy shows improvement in surface roughness, micro hardness and residual compressive stress, fatigue and corrosion fatigue properties. Fatigue strength and corrosion resistance of a magnesium alloy was improved by means of surface treatments [10]. Fatigue strength of low carbon alloy SAE1020 with glass microspheres shots improves in high cycle environment [11–12]

Nitriding, shot peening and pre-shot peening of 316 L stainless steel improves hardness and wear resistance by inducing compressive residual stress on the surface of the material [13]. Severe shot peening and conventional shot peening are applied to notched specimen of X70 micro alloyed steel by cast steel shots and show marginal improvement in fatigue strength in the former as compared to the latter. Pre heat treatment of SAE 4140 steel with severe shot peening using cast steel shots improves fatigue life limit of the material [14]. Fatigue life of low alloy steels improves by 11.6% and 51.3% with severe shot peening and nitriding treatment. Combination improves hardening, compressive residual stress and nitrogen diffusion. Combination technique does not improve fatigue limit.

Laser shot peening of dog bone specimen of the 7075-T7351 aluminum alloy improves fatigue strength more when compared to shot peening but it is not economical [9]. Laser shot peening increases compressive residual stress by 273 MPa and micro hardness by 30–40%, but it does not improve corrosion resistance of 316L stainless steel. Laser shock peening of interstitial free steel was subjected to different pulse energy for different lengths of time, improving tensile strength. Laser shock peening beyond 10 minutes results in melting and ablation. Laser shock peening of aluminum alloys results in suppressing crack growth rate and is also used to heal cracks in automotive applications [14]. Warm laser shot peening improves high temperature

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fatigue performance of materials [15]. Corrosion resistance and some properties of austenitic stainless steel specimen improved by inducing compressive residual stress by means of cavitating jets [16]. Shot peening is a conventional method used widely in the industry which does not affect the processing cost of components and gives better results as compared with all of the above processes.

Many researchers have noted that the shot peening treatment with steel shots of different grades improves fatigue, corrosion and some mechanical properties of the material. Some of the researchers discovered that the shot parameters such as size of the shots, peening distance, peening angle, peening pressure and shot material have an impact on improving properties of the base material. At the same time, none of the researchers has performed shot peening using amachrome balls with varying process parameters. Therefore, the objective of the study is to investigate the fatigue life, surface roughness and corrosion properties of low carbon alloy steel subjected to the shot peening process. SAE 4140 low carbon alloy steel is chosen as a base material and amachrome balls are selected as a shot material for the shot peening process under three different pressures and distances. The fatigue tests are carried out at room temperature by an axial fatigue machine. At room temperature the corrosion tests are carried out with a 3.5% NaCl solution. The results are analyzed by EDAX, SEM and a 3D surface profilometer to identify the microstructural, morphological and surface roughness of the samples.

2. Material and methods

The base material SAE4140 steel specimens used in this research are taken from a rod of 20 mm in diameter. Table 1 shows the composition of the steel. As per the ASTM E466-96 standard [17], fatigue test samples are prepared using CNC machines.

Table 1
Chemical composition of SAE4140 steel

C	Si	Mn	P (max)	S (max)	Cr	Mo
0.38–0.45	0.15–0.35	0.50–0.80	0.035	0.035	0.90–1.20	0.15–0.25

The samples are mounted onto a rotary table for shot peening treatment. They are running at 6 RPM and being peened using amachrome (the highest quality ferrite stainless) balls. Amachrome balls have the hardness of 37–45 HRC with 1–2 mm in diameter. Distance and pressure are the variable parameters in shot peening treatment. The distance is varied as 50 mm, 100 mm and 150 mm, and the pressure is varied as 6 bar, 7 bar and 8 bar.

The fatigue tests are carried out using a 250 KN MTS landmark fatigue machine. Tension-compression axial loading is applied at 20 Hz frequency and 50% of yield strength of the material. The number of cycles for all specimens needed to get fracture are tested under a constant load. Three sample for each experiments were tested and an average value is noted.

The 1.5×1 cm^2 size specimens are prepared to perform the corrosion experiments of the shot peened and unpeened materials. The corrosion tests are conducted in an NaCl solution using a direct current method. The CHI 660 C electrochemical workstation (CH Instruments, Austin, TX, USA) was used with considering $Ag/AgCl_2$ as the reference electrode and the platinum rod used as the auxiliary electrode. The specimen's surface would be exposed to the NaCl solution for corrosion rate measurement. The open-circuit potential of the specimens was measured for 30 min, after 120 min of equilibrium time. Potentiodynamic polarization tests are carried out in the solutions at room temperature using a voltage range between –1 and 0.2 V with a potential sweep rate of 10 mV s^{-1}. The experiments are designed by means of full factorial design, as shown in Table 2.

Table 2
Experimental design

S. No.	Pressure (Bar)	Distance between nozzle and work piece (mm)
1	6	50
2		100
3		150
4	7	50
5		100
6		150
7	8	50
8		100
9		150

3. Results and discussion

3.1. Fatigue. The fatigue life of SAE4140 steel is evaluated by axial push pull conditions used in industries. The results obtained showed that the shot peening process pushes the crack initiation points below the compressive residual stress zone in all the cases of carbon steel. Figure 1 shows the fatigue tests'

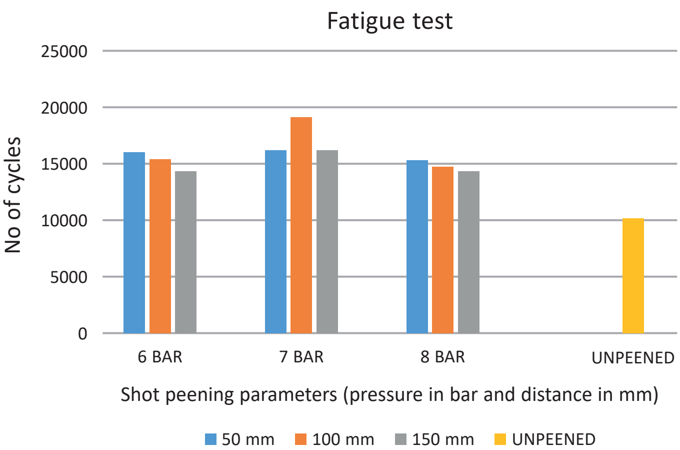

Fig. 1. Fatigue test results for various parameters

results of shot peened and unpeened specimens. The obtained results of fatigue life show that in the shot peened specimen it increased by 1.4% as compared with the unpeened specimen. Other researchers have concluded that shot peening can introduce residual compressive stress, work hardening and grain refinement, and that it postpones crack growth on the surface layers of specimens [6]. Figure 2 shows the fracture surface of specimens as identified by the scanning electron microscope.

It is evident from the figure that superficial cracks and dimples occurred in the low carbon steel. Increasing the pressure results in reduction of superficial cracks, even though material plugging still occurred due to grain refinement of the surface layer.

According to the experimental results, it was observed that the unpeened specimens have a tough fracture on the surface and a brittle fracture in the middle. Due to shot peening, the presence of an artificial layer is clearly observed. This shows that the brittle fracture zone is shifted from the center to a position below the artificial layer. Initially the crack will occur in the subsurface layer and afterwards it propagates to the center.

Due to shot peened with amachrome material, the percentage of chromium had been increased on the surface of low carbon alloys, which increases the fatigue life and corrosion properties as found out by EDAX results and shown in Fig. 3. From the EDAX spectrum, chromium (Cr) rich phases have been identified on the surface of the low carbon alloy. The enrichment of Cr has improved the fatigue life of the low carbon alloy. Other foreign elements present in shot balls, such as Ni and Mn, had no significant influence.

3.2. Surface roughness. Figure 4 shows the surface topographies of the samples. The surface roughness of the samples is increased after shot peening [8, 11]. The shot peening effect on the samples achieves full coverage only at high pressure ranges above 7 bar. The average roughness as denoted by Ra is shown in Fig. 5. Increasing the shot pressure and shot balls sizes results in more depressions and the surface and increasing of surface roughness influences the shot peened samples. More and deeper depressions on the base material are induced by bigger shot balls at higher velocity.

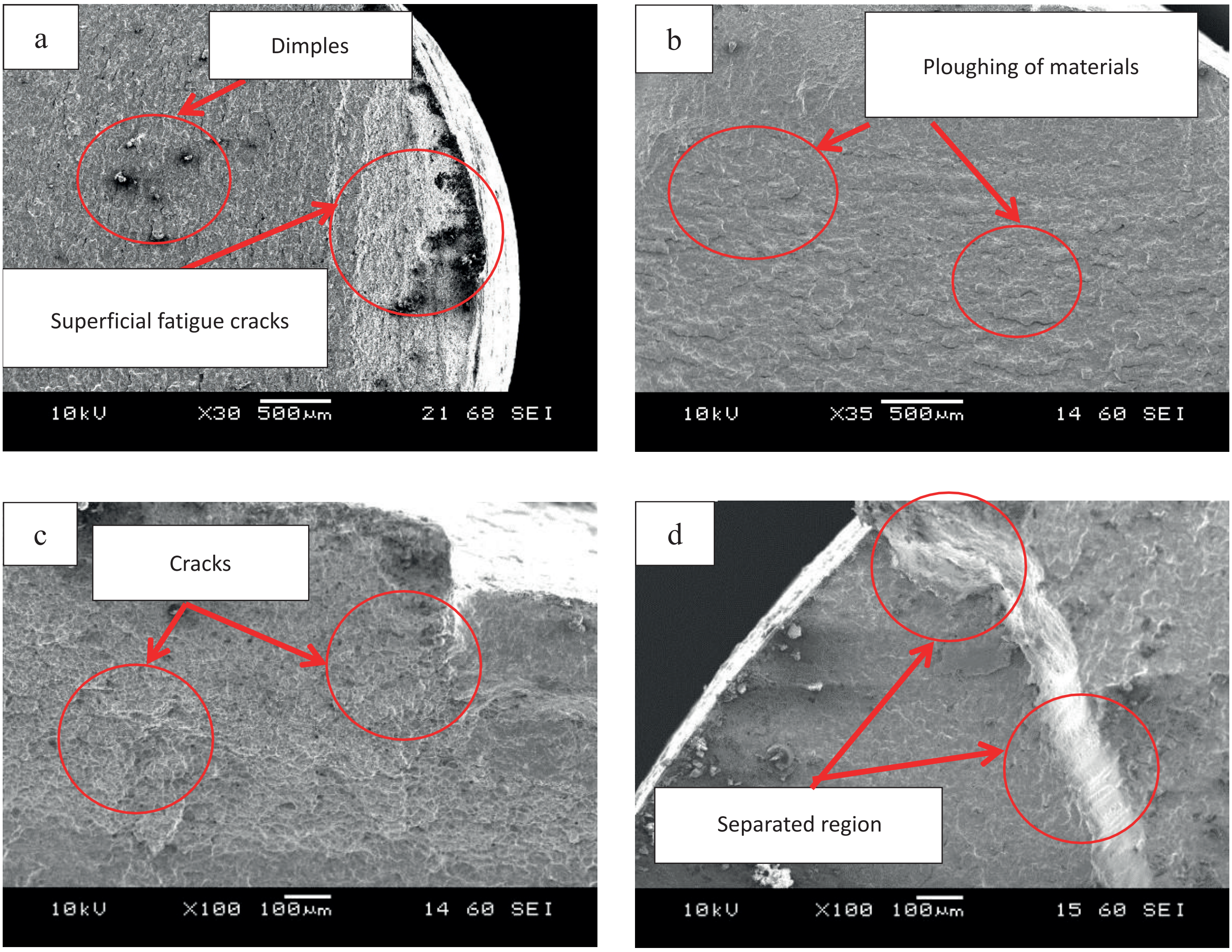

Fig. 2. SEM images of fatigue cracks for various parameters such as a) 6 bar, b) 7 bar, c) 8 bar and d) unpeened material

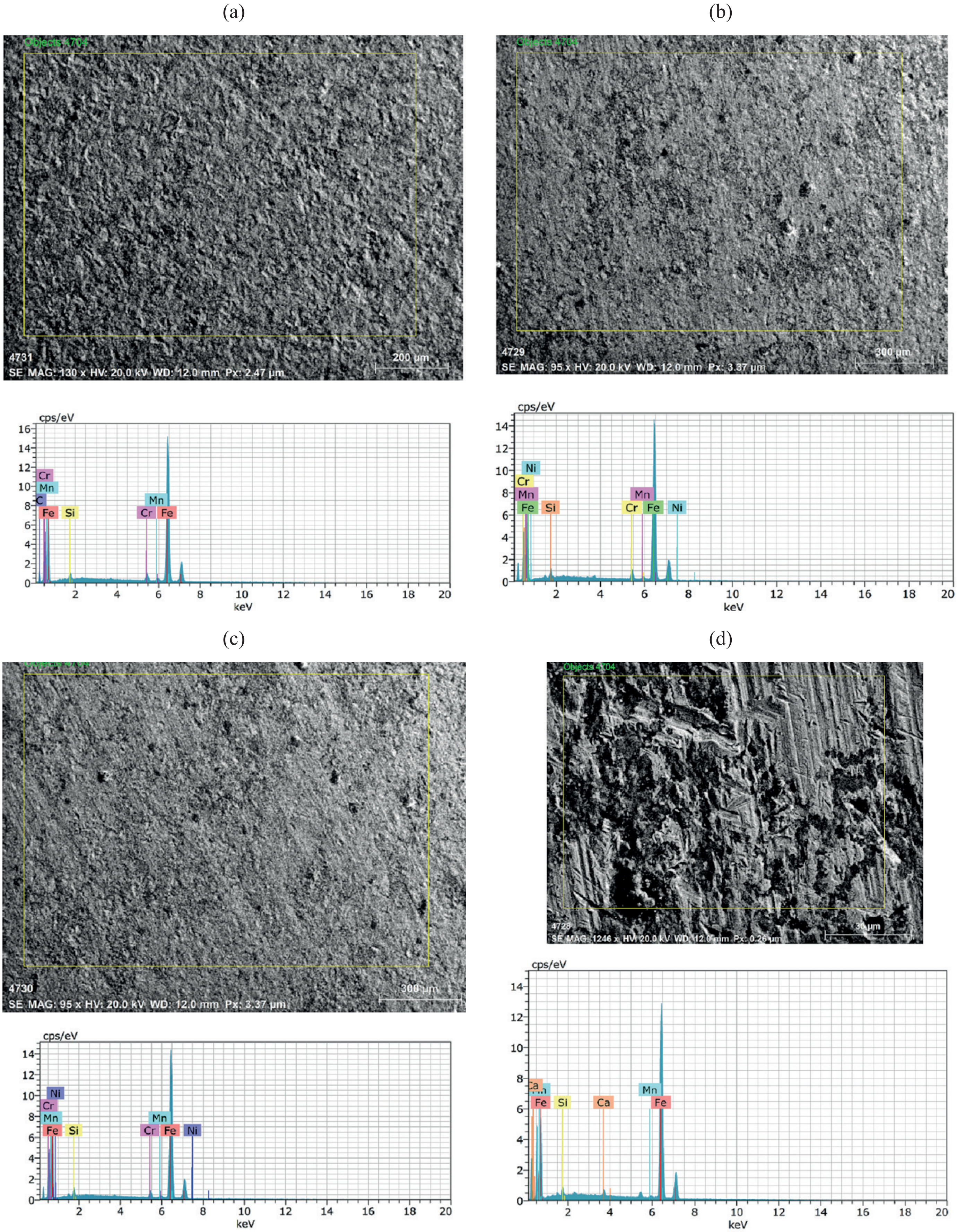

Fig. 3. EDAX results for various parameters such as a) 6 bar, b) 7 bar c) 8 bar and d) unpeened material

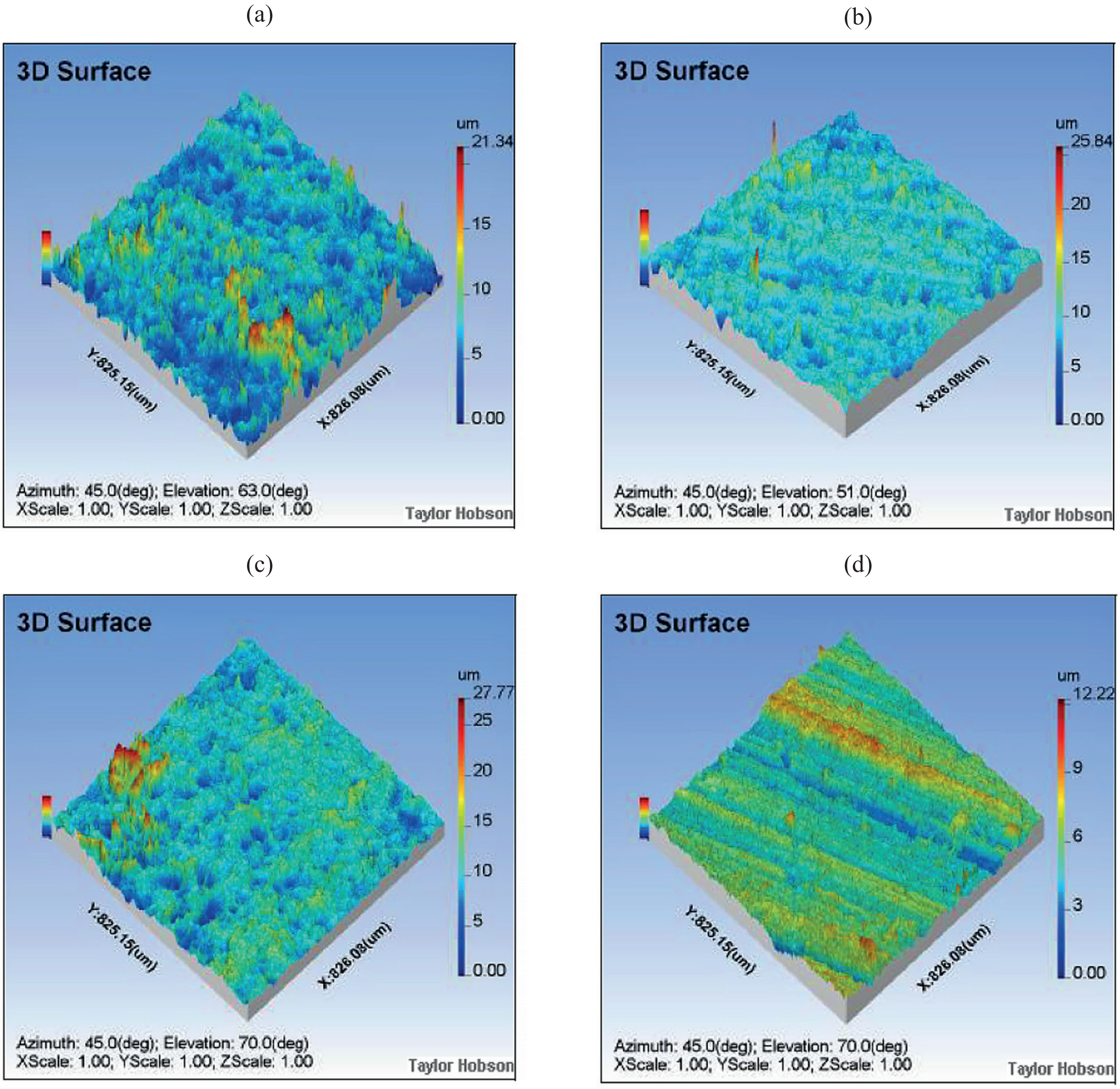

Fig. 4. Average area roughness for various process parameters such as a) 6 bar, b) 7 bar c) 8 bar and d) unpeened material

Figure 5 shows that shot peening produces high surface roughness as compared to the base material at different pressure ranges. Shot peening is one of the mechanical surface treatments which changes the surface and sub-surface of materials, and roughness values increase after treatments. It is observed from Fig. 5 that the 7 bar pressure and 150 mm distance sample has a smooth surface finish when compared to other shot peened samples. However, the number of fatigue cycles is reduced with high surface roughness. Most previous studies suggest that high surface roughness is reduced by surface treatment methods applied to decrease surface roughness of the treated samples to removing a thin layer of the material by abrasive grinding, electro polishing and by double-shot peening.

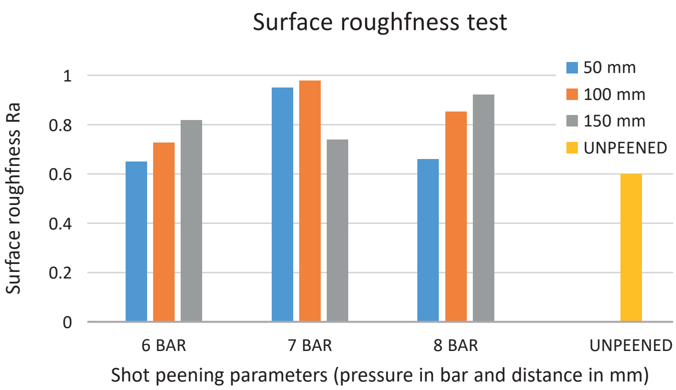

Fig. 5. Roughness vs. parameters

3.3. Corrosion. The specimen was a SAE4140 plate, the reference electrode was standard Ag/AgCl, the counter electrode is platinum wire. The working electrode is dipped in the salt solution for 30 mins by running the CH1660C Electrochemical Workstation Beta application after the time bound open circuit potential (OCP) and Tafel plot graph obtained for the specimen. The shot material, amachrome, contains 18% chromium. The 7 bar pressure and 100 mm distance peened sample gets the highest open circuit potential. The unpeened sample is at its most active potential value when compared to peened samples. Figure 6 shows the curves of the Tafel plot of the specimens under various conditions. The Ecorr values are noted, directly proportional to the corrosion rate of the material [18, 19]. The peened samples have good desirable Ecorr values as compared to the unpeened sample. Also, 7 bar pressure and 100 mm distance sample peened sample showed the maximum corrosion resistance [20]. This proves that the shot peening parameters play an important role in the improvement of material properties. Additionally, the Icorr values are examined. The highest anodic Icorr value found in the unpeened sample is 50.2 $\mu A/cm^2$. An i mmense dynamic region is presented in unpeened samples. This shows that the lowest corrosion resistance is found in the unpeened sample. The values of Icorr varied progressively from sample 1 to 9, and for 7 bar pressure and 100 mm distance sample the peened sample it stood at 15 $\mu A/cm^2$.

The 7 bar pressure and 100 mm distance shot peened sample has lower corrosion rates (miles per year – mpy), i.e. 61.1 mpy whereas the unpeened specimen had the fastest rate of 241.3 mpy. The shot peening distance and pressure plays a major role in improving the corrosion rate of the samples.

4. Conclusions

- Fatigue life of shot peened material increased significantly, by 1.4% of unpeened material. Shot peened specimens have a lower crack growth rate value when compared to unpeened specimens.
- The fatigue life varied based on the shot peening parameters of distance and pressure. A maximum life of 19,122 cycles was obtained for the 7 bar and 100 mm distance sample.
- The shot peening process increases surface roughness value, which results in reducing the fatigue life cycles. The mean surface roughness values of samples with 7 bar pressure have 0.98 and the remaining ones have the value below 0.85.
- Shot peening induced chromium phases on the surface of the low carbon alloy steel. This results in reduction of the corrosion rate. The corrosion rate of the 7 bar pressure and 100 mm distance shot peened sample is 61.1 mpy, whereas the unpeened specimen had the fastest rate of 241.3 mpy.

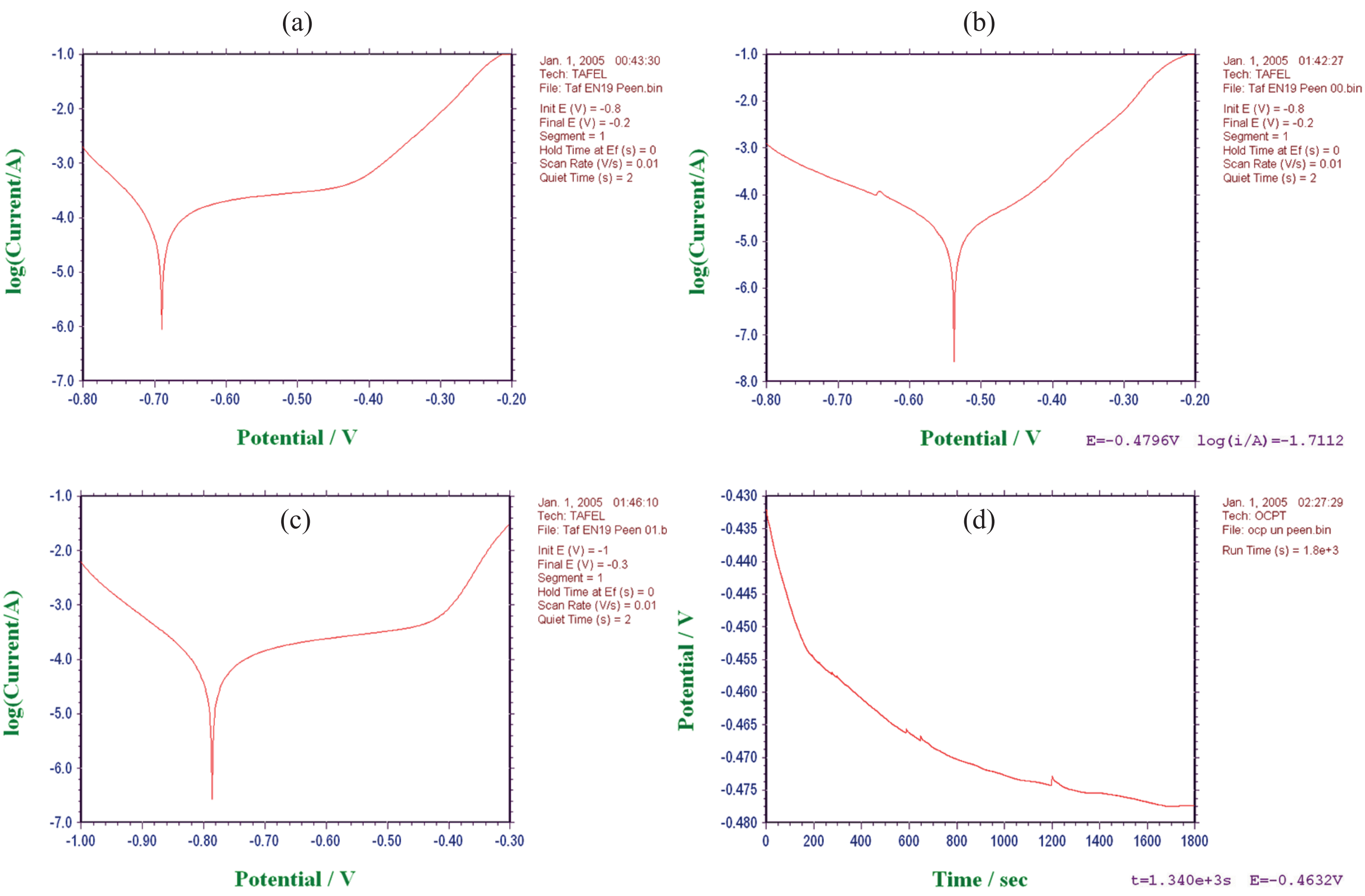

Fig. 6. Tafel plot for various process parameters such as a) 6 bar, b) 7 bar c) 8 bar and d) unpeened material

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