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Comparison of Fatigue Characteristic for AISI 1039 Steel with Surface Treatment

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ABSTRACT

Wear and fatigue resistance in steel components used in various industries can be improved by surface treatments. Coatings systems which are used for improving the mechanical properties, generally, decreased the components fatigue life due to micro cracks, that propagate through the substrate , it is possible to improve the fatigue resistance of a component by the application of shot peening treatment, whose compressive residual stresses delay or eliminate the initiation and propagation of fatigue cracks. The aim of this study is to obtain the fatigue limit of untreated, shot peened, and hard chromium coating of medium carbon steel AISI 1039 and comparison between them. Fatigue tests were carried out using small samples with 4 mm diameter, with hard chromium layer of (47.1) µm thick. Rotating-bending fatigue test was carried out on samples after shot peening with steel balls of about 20 minutes peening time. Experimental results showed that hard chromium electroplating decreased the fatigue life and fatigue limit in comparison with the uncoated steel. As the highest thickness for coating was 23µm. On the other hand, Shot peening Results indicated that the fatigue strengths of samples are increased and the highest fatigue limit was (298.566Mpa) after treated the samples by shot peening for 20 minutes.

Keywords: *shot peening, fatigue, AISI 1039 medium carbon steel, chromium coating*

الخلاصة:

مقاومةالكلالو البليفيمركباتالفولاذالمستخدمهفيالصناعاتالمختلفهيمكنتحسينهاباستخدامالمعاملاتالسطحيهومنهذهالمعاملاتاستخدامطرقالطلاءللفولاذلتحسي
نالخواصالميكانيكيهوبصورهعامهتقليلعمرالكلالللجزءالمعدنييعزبالوجودالشقوقالصغيرهالتيتتكونعسطحالجزءوتمتدالبكلالمادهمحدثهفشلفجائيللمعدنبد
ونانذارمسبقايضايمكنتحسينمقاومهالكلالباستخدامالشوتبيننكوالتيمنخلالهاتعملاجهاداتالضغطعلىتاخيراوالغاءتكونونموشقوقالكلال .انالهدفمنهذاالعملهوها
يجادحدالكلالللفولاذالمتوسطالكاربونالغيرمعاملوايجادهللفولاذالمطليبالكرومالمصلدلمده 20 دقيقهوللفولاذبعداجراءالشوتبيننكلمده 20
دقيقهومقارنهحدالكلالالناتجمنكلمجموعة.
فيهذاالبحثاجريفحصالكلالباستخدامعيناتصغيرهمنالفولاذبقطر 4 ملموتمطلاءهبالكرومالمصلدلمده 20
دقيقه.ايضاتماجراءفحصالكلالللفولاذبعدعمليةالشوتبيننكلمده 20 دقيقهوذلكبضرببالمعدنبكراتصغيرهمنالفولاذ.
اظهرتالنتائجالعمليهانالطلاءبالكرومالمصلديعملعلىتقليلعمرالكلالوحدالكلالمقارنهمعالفولاذالغيرمعاملمنجانباخراظهرتالنتائجانعمليهالشوتبيننكادتالىزيا
دهعمرالكلالوتحسينمقاومهالمعدنللكلالمقارنهمعالفولاذالغيرمعاملوالفولاذالمطليبالكرومالمصلد.

I. INTRODUCTION

Steels are the most important group of engineering materials as they have widest diversity of application than any other engineering materials. Furthermore, plain carbon steels are widely used for many industrial applications and manufacturing on account of their low cost and easy fabrication [1]. Medium-carbon steels have a carbon content of 0.29 to 0.60 wt. %. They balance ductility and strength and has good wear resistance; used for large parts, forging, and automotive components [2]. Metals when subjected to repeated cyclic load exhibit damage by fatigue which this failure may be defined as the most common types of fractures in machines and probably constitute about 90% of all fractures, Fatigue fractures can develop at a stress level below the yield strength [3]. A metal's fatigue strength will be less than its yield strength, as determined in a tensile test.

The endurance limit is the limiting value of stress below which a material can presumably endure an infinite number of stress cycles [4]. The fatigue failure occurs after four different stages, namely: Crack initiation at points of stress concentration, Crack growth, Crack propagation, and Final rupture [5].
Shot peening is one of the most common surface treatments to improve the fatigue strength of the metallic products. Such treatment involves blasting the surface of the products with steel or glass shots at high Velocity [6]. Shot peening is a very effective way to relieve tensile stress built up in the manufacturing process and to produce very high compressive residual stress near the specimen's surface. Both fatigue limit and fatigue life can be greatly increased. The effect of shot peening is a critical issue for the damage tolerance design and analysis and needs to be carefully investigated [7].
Increasing the wear, tear and corrosion resistance of many aeronautical components steel is obtained through a hard chromium superficial treatment. Systems of superficial coatings, which improve these properties, reduce the fatigue life of these components drastically due to the coating cracks starting and penetrating through the substrate. The result of crack propagation in the substrate, implicates in a reduction of the useful life of a component. Experiments with hard chrome electroplated high strength steels showed that despite of an increasing in wear, tear and corrosion resistance, a reduction of the fatigue strength, when compared with uncoated material, was observed [8].
The main objective of this research is to find the fatigue limit of untreated, shot peened, and hard chromium coating medium carbon steel AISI 1039 by using superficial treatments like the electro deposition method and shot peening process.

Some research significance which is somewhat similar to this subject shown below:
(Bruce D. et al.) : Studied Validation of HVOF Thermal Spray Coatings as a Replacement for Hard Chrome Plating on Hydraulic/Pneumatic Actuators. All fatigue specimens were fabricated from round bar taken from the same heat treating lot for each material. They found the fatigue performance of the HVOF coatings was equal or superior to that for EHC. The only spalling seen with HVOF coatings (other than one sample with WC/Co Cr at run out) was for Cr3C2/Ni Cr at high stress. Other HVOF coatings developed circumferential cracks at high cycles. This type of coating cracking has been observed to occur in HVOF coated landing gear without causing deleterious performance results, such as leakage, corrosion or seal damage. [9]

(Padilha, R.Q. et al.) : Studied the influence of electroless nickle interlayer thickness on fatigue strength of chromium-plated AISI 4340 steel. Specimens were prepared from bars with approximate diameter of 14.4 mm and length of 6 m, with hardness equal to 23 HRc. Samples were submitted to heat treatment, to reach hardness of 38-42 HRc and 49-53 HRc, respectively. After final preparation, specimens were subjected to a stress relieving heat treatment at 190 oC for 4 hours to reduce residual stresses induced by machining. Rotating bending fatigue tests were conducted using a sinusoidal load of frequency 50 Hz and load ratio R= -1, at room temperature, considering as fatigue strength the complete specimens fracture or 107 load cycles. Twelve groups of fatigue specimens were prepared to obtain S-N curves for rotating bending fatigue tests, They found from comparison between curves the effect of hard chromium electroplating on the fatigue strength reduction of AISI 4340 steel, for hardness equal to 39 HRc and 52 HRc and also S-N curves indicate the importance of the electroless nickel underlayer as a barrier to crack propagation. [10]

(Valdas Kvedaras et al.) : Showed Fatigue Strength of Chromium-Plated Steel. In this research The specimens were prepared from this material and had minimal diameter of 7.52 mm and gauge length of 20 mm. The surface of specimens was grinded. The fatigue tests were carried out by rotating-beam fatigue machine (MUI-6000) with frequency of load alternation 3000 cycles/min. The hardness was measured by microhardness testing tester (PMT-3). The cross-sectional micrographs were ex-amined using optical microscope "Neophot". The micro-structure has been developed by etching polished surface with 3 % nitric acid solution in ethanol. The testing was done at room temperature. The results of experimental investigations have shown, that after pyrolytic chromium-plating the fatigue strength of investigated steel can be improved as well as considerably worsened. [11]

(Gejza Rosenberg et al.) : Studied effect of shot peening on fatigue properties of steel in different structural states. In this work, there are presented results of tests on smooth samples as well as on samples with stress concentrator (a drilling hole, size d = 4mm). The expectations, that shot peening of flat steel samples improves resistance to fatigue failure, were approved by all tested structural states by all tested structural states. The tests on samples with the drilled hole showed, that effect of shot peening on fatigue properties may be negative, if the hole was drilled after shot peening of surface of samples. [12]

(Voorwald et al.) : Investigated the influence of shot peening in chromium-electroplated AISI 4340 steel fatigue life and the influence of different shot materials, this is, steel and ceramic shots. It was observed that peened chromium electroplated AISI 4340 steel presented around 100% of recovering in fatigue limit in both peening condition. It is also possible to observe the great decrease in fatigue strength due to chromium coating, around 47%. Fatigue limit for base material is 800 Mpa while fatigue strength for coated material is 420 MPa and the shot peeing increased fatigue strength of base material. Peening using ceramic shots presented a lower scatter than peening with steel shots. [13]

(B. GÖLGELİ and K. GENEL) : Showed Fatigue strength improvement of a hard chromium plated AISI 4140 steel using a plasma nitriding pre-treatment.in this research test specimens of 4-mm diameter had been plasma nitrided at 510°C for 4, 8 and 12 h. It was found that HC-plated specimens with a coating layer of 23 ± 2 μm thickness showed approximately 33% reduction in fatigue strength when compared to quenched and tempered (Q&T) specimens. An application of the PN pre-treatment before the plating process was effective in improving the fatigue performance of HC-coated steel. An improvement of 71% in the fatigue strength of pre-treated specimens was recorded as compared with the specimens, which were HC plated only. The results also indicated that prolonged nitriding time did not cause better improvement in the fatigue performance. [14]

II. MATERIAL SELECTION AND EXPERIMENTAL PROCEDURES

In this research work the medium carbon steel (AISI 1039) has been used, and the chemical composition of this material in weight percentage associated with the American standard is signified in table 1:

Table 1: The chemical composition analysis.

	C%	Si%	Mn%	P%	S%	Fe%
STANDARD: 1039 ASTM	0.36-0.44	0.4	0.7-1	≤ 0.040	≤ 0.050	98.47-98.94
Experimental	0.390	0.173	0.796	0.009	0.022	Bal.

The mechanical properties of this alloy are: (179) HRC, yield strength of 510 MPa, ultimate tensile of 605 MPa. The application of medium carbon steel include automotive parts, connecting rods, gears, shafts, Axles, bolts, studs, rolls, pins, spindles, crank shaft, torsion bars, ratchets, rams, sockets, worms, light gears, guide rods, and hydraulic clamps.
Firstly the stress relief processes were carried out by placing all samples in the electric furnace at 200 C0 for a period of 4 hours.

2.1. Tensile test specimen:

The specimen for tensile test were prepared from the base metal after the stress relief process by dimensions according to ASTM, as shown in figure (1), and the tensile test was carried out with WDW 2000 model No. M 353 tensile device.

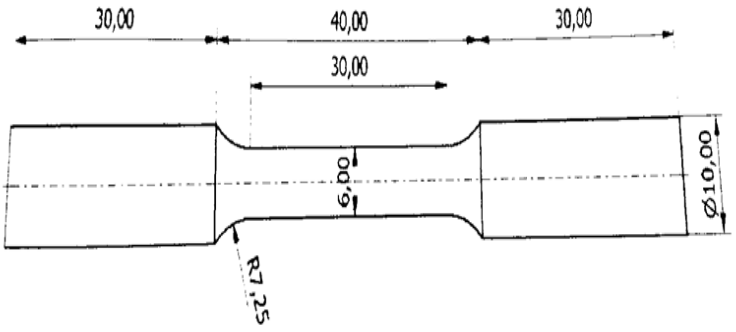


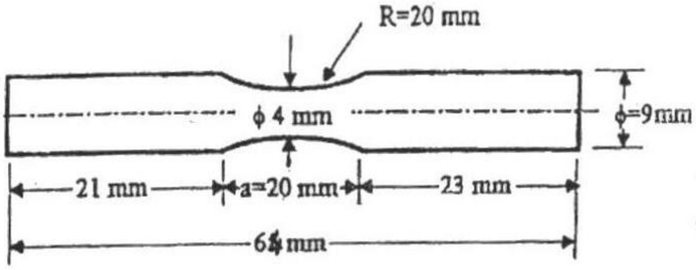
Fig (4-2) Tensile test specimen with dimensions in (mm)

Figure 1: Tensile test specimen with dimension in mm.

2.2. Roughness test:
Surface roughness was measured for the specimens used in this research by using the surface roughness measuring device (pocket surf) , and the surface roughness values was (0.44) µm.

2.3. Hardness test:
The Brinell hardness values of specimens were carried out for untreated , shot peened and coated with hard chromium by using 412A/413A INNOVA TEST Micro hardness device.

2.4. Fatigue test:



The samples were prepared by using conventional lathe (Harrison600, M350, EW700) and get the dimensions of the fatigue specimens with accordance to the standard dimension of the (HSM20 alternating bending fatigue machine) as shown in figure (2)

Figure 2: Rotating bending fatigue testing specimen.

Three groups of fatigue specimens were prepared to obtain S –N curves for bending fatigue tests:
- Specimens of base alloy.
- Specimens of base alloy with conventional hard chromium electroplating.
- Specimens of base alloy peened with steel shots.

2.5. Shot peening process:

Shot peening technique was done by using spherical ball of steel of diameter 1mm and carried out on ten samples of fatigue specimens, the standoff distance are 100:1 mm, 12 bar Average blasting pressure and the rest condition summarized in table (2). The shot peening device used was shot tumblast control panel model STB-OB, machine NO.03008 05 types.

Table 2: Shot peening condition

Coverage (%)	Shot size (mm)	Shot hardness ((HRC	Ballspeed (m/s)
100	1.3-1	50-48	40

2.6. Electroplating with hard chromium process:

Generally accepted as a critical step in most electroplating processes, surface preparation of metals prior to the metal electroplating is done in order to give maximum bond of the plated coating to the substrate and prepare apart for subsequent finishing electroplating. Surface preparation include the following steps [15]:

1- Alkaline cleaners: These cleaners are largely intended to neutralize acidic species and soften the water to prevent formation of insoluble calcium and magnesium soaps. Sodium hydroxide is the most important alkali in cleaners, and in this step the samples immersing in hot solution of (75gm/l) NaOH holding with 3 minutes at 50 C.0
2- Water rinsing.
3- Immersing in dilute H2SO4 acid bath holding with 1 minute at room temperature, in order to remove contaminants, oxides and rust from the outer layer of the metal.
4- Water immersing.

The electro coating cell consists of Chrome Chemical Bath, Anode, Cathode potentials, part to be coated, Heaters, rectifiers & Electrical control systems. Initially the bath has to be heated up to the required temperature. Cathode potential has to be connected to the part to be deposited and anode electrode has to be connected to the + potential .Before starting the process the part should be thoroughly cleaned and it should be ensured that it is free from all kinds of surface marks/defects. Then deposition of hard chrome deposit is started by separation of ions from the chemical bath due to the flow of current to the part to be deposited. The amount of current flow and the duration of process will vary depends upon size of the component [16].

The conventional hard chromium electroplating was carried out from a chromic acid solution with 250 g/l of CrO3 and 2.5 g/l of H2SO4, at 50-55 ºC, with a current density from 30 to 46 A/dm2, and speed of deposition equal to 25 µm/h. A bath with catalyst based on sulphate was employed. Also the coating was done on ten specimen within 20 minutes plating time, so the coating layer was (47.1) µm.

The electro deposition shown in figure (3) below:

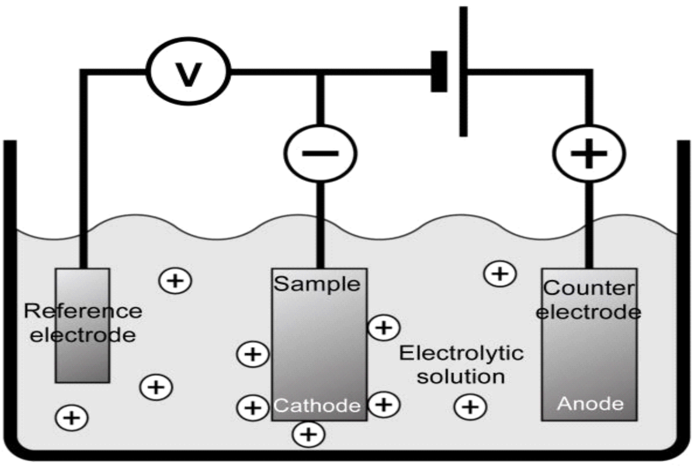


Figure 3: Electro deposition cell.

2.7. Metallurgical examination :

For microstructure examination, surface of specimens were grounded by using (60, 120, 320 , 1200 , and 2000) sic emery papers. Polishing was performed using alumina slurry with particle size of 7µm. The polished samples were cleaned by water and alcohol and then dried. The polishing and grinding processes were carried out by using MP-IS metallurgical preparation grinder /polish NO.1226. Samples were etched using etching solution contains 2% Nitric acid and 98% Methyl alcohol.

Finally, each sample was then observed and photographed at a magnification of 200X by using EMIJI microscope.
The broken samples were examined by using scanning electron microscope TESCAN, VEGA 3 LMU with OXFORD EDX detector (INCA XMAW20) device in order to determine the beginning of the crack , its propagation and the microstructure.

2.8. Condition of the specimens:

Three groups were used in the presented research, each group contain ten samples of the tested steel and the conditions for these groups illustrated in the table (3) below:

Table 3: Condition of the groups used in this research.

Group of the specimen	Condition
A	Untreated or dry Med. Carbon steel
B	μm thickCoating with hard Cr 47.1
C	Min. shot peened steel 20

III. RESULTS AND DISCUSSIONS

In this research work, the mechanical properties of medium carbon steel AISI 1039 has been investigated. It can be seen from the figure (4) the microstructure of this alloy after the stress relief process for 4 hour at 200C0 in electric furnace. The microstructure of this alloy consist of two phases pearlite (dark region) and ferrite (white region). The hardness value of this steel was (105.63) HRC, this value was less than the hardness value for the same steel before the stress relief due to eliminate the dislocations lines and remove the stresses, which may be exist in the structure of steel (as received).

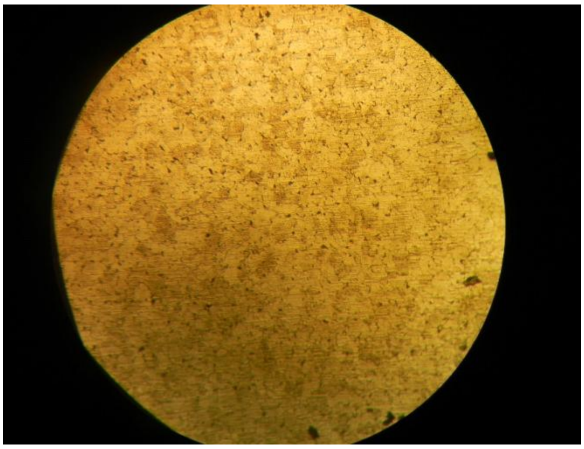


Figure 4: The microstructure for medium carbon steel AISI 1039 after stress relief at 200C0 for 4 hours, magnification (200X).

3.1 Tensile test:

It can be seen from the figure (5) the stress-strain diagram for this alloy, It can be remarked that the ultimate tensile strength was (755) Mpa and yield strength was (675) while the percentage of elongation was (16) %.

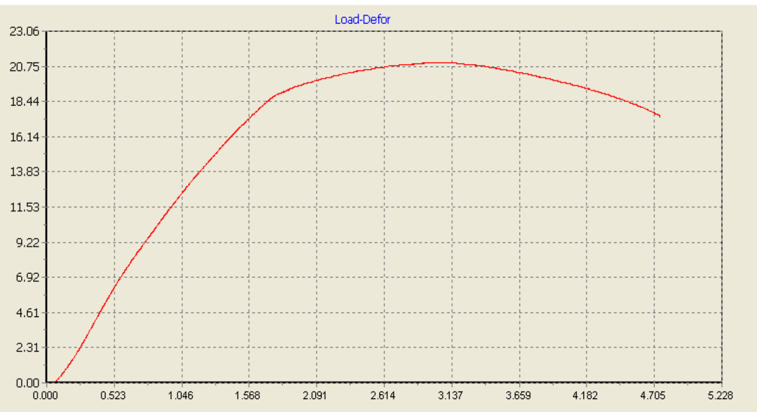


Figure 5: stress-strain diagram for medium carbon steel AISI 1039 after stress relief for 4 hours at 200C0.

3.2. Fatigue test:
Rotating bending fatigue test were performed by using fatigue testing machine of type (HSM20).

3.2.1 Group A: Fatigue test of dry medium carbon steel:
Ten samples were prepared for fatigue test at room temperature, the surface roughness of these samples were (0.44) µm. The stresses were applied in the range of (398-179.1) Mpa.
The results of dry steel are listed in table (4):

Table 4: Fatigue test results of dry steel.

Sample	(MPa)Stress	(No. of cycles (RPM
A1	398	97872
A2	358.28	103253
A3	318.47	112546
A4	238.8	137248
A5	218.94	158356
A6	199	207989
A7	194	234835
A8	189	321498
A9	184.1	465831
A10	179.1	1046478

The S x N curves of the rotating bending fatigue tests for dry steel group shown in figure (6).
This group contain ten samples of AISI 1039 medium carbon steel and submitted to hard chromium coating with 20 minutes plating time, so the thickness of this layer was (47.1) µm.
The chrome layer contraction during the electroplating process generates high equi biaxial tensile stresses in the coating and compression stresses in the substrate. So, in the coating with simple hard chrome layer, the "benefit" given to the substrate is counteracted by the micro cracks density contained in the coating, which when submitted to the tensile residual stresses action in addition to external loads, propagates and reduces the life fatigue of a component.

Figure 6: The S-N Curve for medium carbon steel AISI 1039 after stress relief at 200C0 for 4 hours.

From this group (dry medium carbon steel AISI 1039) it is observed that the fatigue limit of AISI 1039 steel was at 179.1 MPa.

3.2.2 Group B: Fatigue test of 20 minutes shot peened medium carbon steel AISI 1039.
The results of the fatigue test of 20 minute shot peening medium carbon steel are listed in the table (5).

Table 5: Fatigue test results at 20 minutes shot peening.

Sample	(MPa)Stress	(No. of cycles (RPM
B1	398	1841929
B2	378.18	2784363
B3	358.28	3939675
B4	338.37	5490174
B5	328.423	6274839
B6	318.47	7045021
B7	313.495	7483264
B8	308.519	8089411
B9	303.54	8735476
B10	298.566	10496873

The S x N curves of the rotating bending fatigue tests for 20 minutes shot peening group shown in figure (7) below:

Figure 7: The S-N curve for shot peened medium carbon steel AISI 1039.

This group was tested with 20 minutes shot peening, the diameter of steel balls used was 1mm. From Fig (6), it can be observed the excellent recuperation on fatigue strength of the group submitted to shot peening pretreatment. It is well known that the process induces compressive residual stresses at the surface and subsurface, in a depth which depends on the intensity, size, material and hardness of the shot and percentage of recovering. The compressive residual stresses arises as a result of the resistance of the adjacent area of the material to the plastic deformation caused by the shot, which act arresting or delaying the cracks nucleation/propagation

3.2.3 Group C Fatigue test of medium carbon steel coated by hard chromium layer with (47.1) µm thick:
The results of the fatigue test of steel coated with hard chromium are listed below in table (6):

Table 6: Fatigue test results of 20 min. hard Cr coating

Sample	(MPa)Stress	(No. of cycles (RPM
C1	199	36543
C2	179	54364
C3	159.235	365154
C4	139.33	1142582
C5	129.378	1625395
C6	119.42	2417483
C7	109.4	4304340
C8	104	6745216
C9	99.52	8754198
C10	94.546	12730200

The S x N curves of the rotating bending fatigue tests for steel group which coated with hard chromium shown in figure (8).

Figure 8: The S-N Curve for medium carbon steel AISI 1039 coated by hard chromium layer with (47.1) µm thick.

From Fig. (9) it can be remarked the S-N curves for medium carbon steel AISI 1039, first curve for steel without any surface treatment, the second for steel treated with shot peening process while the third one for steel coated with hard chromium. It was observed that shot peeing improved the fatigue strength of steel. More over the former presented a higher fatigue limit of 298.566 MPa against 179.1 MPa of untreated steel while hard Cr coating reduced the fatigue strength of base materials due to high residual tensile stress and micro cracks that may be exist in coating layer so it presented a lower fatigue limit of 79.61 MPa against 179.1 MPa of untreated steel.
However, the peening treatment with steel shots, presented good results, it will be increasing the fatigue strength of AISI 1039 steel up to levels of base steel. In this situation, the compressive residual stress field induced on material surface due to shot peening treatment acted decreasing the harmful effects of micro cracks in chromium layer.
In all situations presented, the influence of chromium or shot peening is more significant in high cycle fatigue tests than in low cycle fatigue tests. High stress on low cycle causes crack propagation so fast after crack nucleation, no matter whether the specimen is the base material or electroplated or peened. In samples without shot peening or chromium it is natural that the crack beginning comes from the surface. Chromium layer acts as an artificial surface for the samples and this surface is full of micro cracks that quickly propagates under high stress.
The residual tensile stresses induced a fast crack propagation, no matter if the crack is come from chromium layer or surface defects.
In chromium electroplated samples submitted to high cycle fatigue tests or lower stresses, it is not necessary a nucleation of a crack from surface as chromium layer provides several micro cracks. The nucleation phase of fatigue crack is skipped and the fatigue process go straight to second phase, this is, propagation, reducing the time needed to lead the component to failure. Lower stresses do not surpass the compressive residual stress field on peened specimens allowing shot peening treatment to act as a barrier to crack propagation, delaying the second phase of fatigue process. These mechanisms illustrate how Cr decreases fatigue life of AISI 1039 steel when chromium electroplated and how shot peening treatment increases its fatigue life.

Figure 9: S-N comparative curves.

IV. CONCLUSION

Based on the results obtained from experimental work for three groups of medium carbon steel AISI 1039 the conclusions can be illustrated below:

1- Experimental results indicate a significant reduction in AISI 1039 steel fatigue strength when coating the steel with hard chromium.
2- Hard chromium electroplating causes residual tensile stresses which leading to fast crack propagation so the fatigue strength decreased.
3- The compressive residual stress field induced on material surface due to shot peening treatment delaying the cracks nucleation/propagation so there is an improving in fatigue strength for steel.
4- Hardness values and fatigue strength increased with treated the steel by using shot peening process.

5- Shot peening treatment give good results by increasing the fatigue limit of steel in which fatigue limit in this work was 298.566 MPa.

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