Journal of Engineering and Development, Vol. 16, No.4, Dec. 2012 ISSN 1813- 7822

Effect of Shot Peening Time on Fatigue Properties of Stainless Steel Shaft Turbine

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Abstract

The effect of different shot peening time (SPT) on the rotating bending fatigue behaviour of austenitic stainless steel TP321 was studied. The fatigue improvement with respect to the unpeened condition was discussed. Shot peening treatments employing steel balls determine a remarkable increment of the high-cycle fatigue limit of austenitic stainless steel ranging between 4% and 15% . such improvement can be essentially attributed to the compressive residual stresses deduced by the treatment in the surface layers . While the life improvement factor (LIF) was increased by a factor ranging between 1.72 to 5.3. All these improvement were happened up to 20 min shot peening time (20 SPT). Beyond this point the fatigue behaviour tends to reduce.

Key words:_ Fatigue life and Fatigue limit, Austenitic stainless steel TP321, Residual stresses, Life improvement factor (LIF) .

تأثير وقت القذف بالكريات غلى خصائص الكلال لمعدن الفولاذ المقاوم للصدأ الاوستنايتي في المحور التوربيني

الخلاصة

تـم دراسـة تـاثير زمـن القـذف المختلفـة بالكريـات علـى سلوك الكـلال الانحنـائي الـدوار لمعدن الفـولاذ المقـاوم للصـدأ الاوستنايتي . مناقشة تحسينات الكلال نسبة الى الحالة بدون القذف. معاملات القذف المستخدمة كرات فولاذية اوجدت زيادة ملحوظة لحد الكلال ذو الدورات لعالية للمعدن الفولاذ المقاوم للصدأ لاوستنايتي . هذه الزيادة تراوحت بين . (4%-15%)مثل هذه التحسينات ناتجة عن اسهام الاجهادات الضغطية المتبقية بشكل ضروري في طبقات السطح . بينما عامل تحسين العمر (LIF) ازداد بمعامل تراوح بين (1.72 الى 5.3) . جميع هذه التحسينات حدثت لحد زمن قذف 20 min (20 SPT) . بعد هذه النقطة سلوك الكلال اتجه الى النقصان .

Introduction and Literature Review

Turbine –generator shaft is often subjected to a complex transient loading. Such transient torques may initiate and propagate a circumferential crack in the shaft, the effective stress intensity factor in circumferential cracked round shafts is evaluated for a wide rang of applied loading by considering a pressure distribution between mating fracture surface [1].

The fatigue life time or load capability of a metallic component can be increased by the introduction of compressive residual stresses at the surface. The increment in the life time occurs because compressive surface residual stresses delay crack initiation, by reducing the cyclic mean stress from applied loading, and because subsurface tensile stresses slow crack growth. A variety of methods is available to introduce beneficial surface compressive residual stresses.[2]

Shot peening is a conventional and widely applied method for introducing a layer of compressive surface residual stress. In shot peening , the workpiece surface is bombarded with small spherical glass , ceramic or metallic projectiles (called shot), which creates a layer of plastic deformation . A reactionary compressive residual stress region is produced when the elastically deformed material underneath and surrounding the impacted area attempts to recover it's original geometric form. [3] **Rpoort. P. Mulltw etal [4**] investigated the corrosion fatigue of an austenitic_ferritic stainless steel under shot peening process. The air fatigue limit was only increased by 7% after shot peening, caused by work softening of the deformed surface layer. In a hot sodium chloride solution, having a pH of 2 at 80°C the corrosion fatigue limit of the steel examined was increased by 70 % compared to the electrolytically polished state. This marked increase is due to a finer surface slip distribution caused by the interaction of bulk slip with the deformed surface layer. Shot peening had also an influence on the near surface micro crack growth. The compressive residual stress field leads to some sort of crack closure effect which lowers the crack growth rate.

K.Masaki etal [5] investigated high cycle fatigue tests with four points rotating bending loading were carried out to investigate the effect of the shot peening on the fatigue properties of material austenitic stainless steel type 316L . the fatigue strength at 10^8 cycles of the non-peened and shot peening treated materials were about 180MPa , 340MPa , respectively .

R.A. Everett etal [6] investigated effects of shot peening on fatigue life and the effects of shot peening on crack growth of (4340) steel . Shot peening had a noticeable affect on crack growth life by increasing the time to failure from a factor of 2 to 4 for the lower applied stress level tests 10 MPa , or from 1.2 to 2.7 for the higher stress level 13.3 MPa .

Ralph J. Ortolano etal [7] Steam turbines designed by virtually all turbine manufacturers use shot peening and/or compression rollers to enhance fatigue life. The deformation of the metal surface not only assures that all tensile stresses have been relieved, but also that only compressive stresses are present. The result is that a significant improvement in fatigue resistance results, as well as a reduction in steady tensile stress at the surface of the metal when a load is applied

Lakhwinder Singh1 etal [8] investigated shot peening of nitrogen austenitic stainless steel increases its hardness. Endurance limit of RS561 steel improves with shot peening. Double shot peening reduces the surface roughness without significant change in residual stress. Further, increase in the fatigue strength of the material is noted with primary and secondary shot peening..

L.D. Vo1, R.I. Stephens1 etal [9]The literature review indicated shot peening of low carbon SAE 1010 cold rolled (mild) steel Weldments increased the constant amplitude R = 0 or 0.1 fatigue strength at $2x10^6$ cycles by 10 to 90% with little increase at intermediate or low cycles to failure

Katsuji Tosha etal [10] studied influences of factors such as size , velocity of particle(shot peening) also thickness, hardness and crystal phase of (work material) on surface integrity. Hardness, residual stress and crystal transformation of zone affected by shot peening are examined for a medium carbon steel (C:0.45%, 180HV) and an austenitic stainless steel (SUS304, 210HV). The result of this studding are : Residual stress distributions are divided into two types, which are S-type and C-type ("C type" which the maximum compressive stress exist on the surface.The both distributions are 'S type" where the maximum compressive stresses exist below the surface). Hardness distributions are divided into three types, which are work hadening type, non-hardening type and work softening type. Strain-induced transformation happens with shot peening. The optimum affected-layer ratio (ratio of the depth of work-hardened layer to the thickness of material), which is called "sweet zone", is from 0.3 to 0.4.

Since the large contribution of shot peening to enhance fatigue performance is given by compressive residual stresses. It is of paramount importance to understand weather the initial residual compressive stresses remain stable throughout the service life or not. For this purpose , compressive residual stresses were modeled under different SPT. An analysis of fatigue life and fatigue limit were carried out under different SPT to evaluate the point at which the fatigue life improvement changes to the fatigue life reduction.

Experimental Work

The chemical composition of the alloy (austenitic steel A 276TP321) used in the present investigation is given in Table (1) :

Table(1):Chemical composition of (A 276TP321)wt%

Elements	C %	Si%	Mn%	Cr%	Ni%	Other elements
A276TP321 STANDARD:ASTM (VOLUME 01.03)	0.08	1.0	2.0	17-19	9-12	-
Experimental	0.07	1.2	1.56	17.11	9.03	-

The room temperature mechanical properties of material are given in table (2) with standard ASTM (VOLUME 01.03) .

Table (2): Mechanical properties of A276 TP321 austenitic steel [11].

Property	Diameter (mm)	Tensile strength nn (MPa)	Yield strength (MPa)	Elongation in (50mm)	Brinell hardness
Standard	Up to (12.70)	620	310	30%	241
Mechanical test	Up to(12.70)	610	302	26%	235

* yield strength was determined by the 0.2% offset method .

All the fatigue specimens were manufactured using programmable (CNC) (ME-310) , with minimum diameter of (6.67)mm , the test specimen is shown in figure(1):

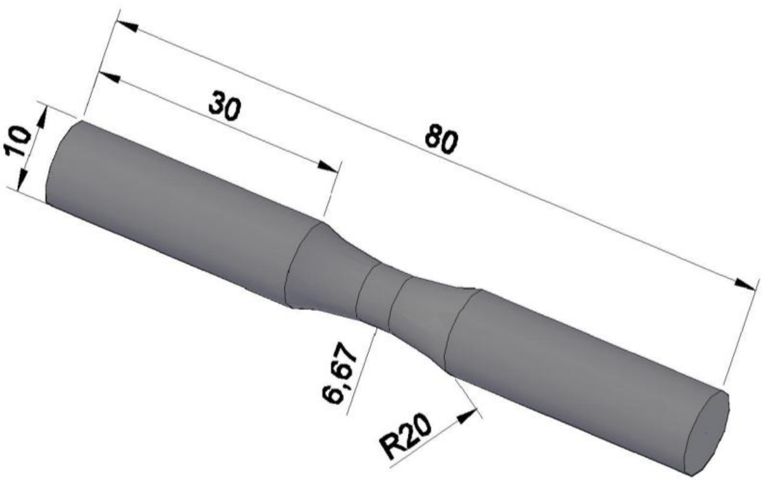


Figure (1): Geometry of fatigue specimens; dimensions,
in millimeter according to (DIN 50113) standard specification.

Shot Peening Technique

Shot peening, using spherical ball of steel of size 1mm, was done on all the fatigue specimens . The shot peening details are: 100mm stand off distance, 48-50 (HV) hardness of balls steel , 12 bar average blasting pressure , ball speed 40m/s , 100% coverage . The shot peening device used was (**shot tumblast control panel model STB-OB , machine NO. 03008 05**) type. Fig(2) shows shot peening device with the balls used.

Fatigue Testing Machine

The test series of the experimental work by Rotary fatigue bending machine in fig(3) were divided into five series ,namely . dry fatigue test (DF) and fatigue test with shot peening (SP) at (10,15,20 and 25 min) at constant amplitude stress .

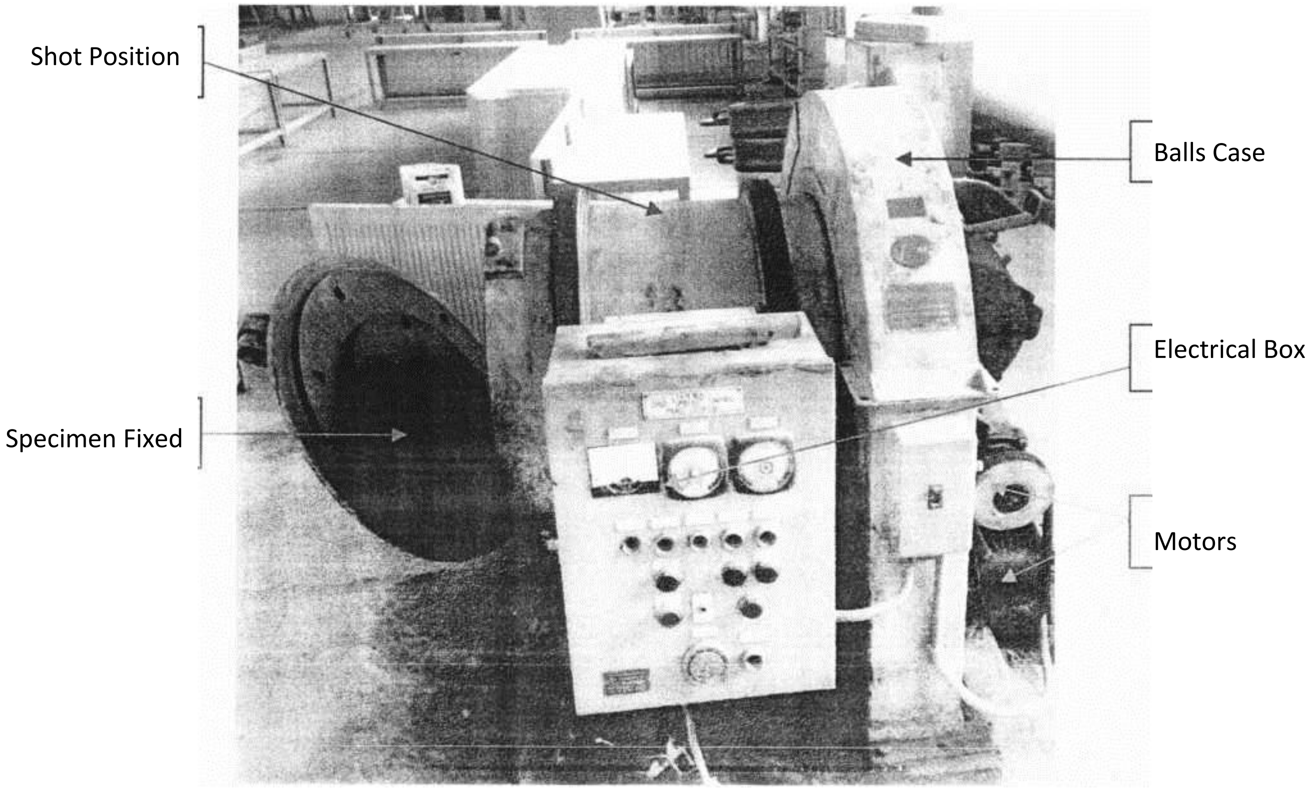


Fig (2): Shot Peening Device

Test Procedure

Constant fatigue tests were conducted in laboratory air (approximately 25-30% relative humidity)at room temperature on PUNN rotary fatigue bending machine with a stress ratio of (R= -1) . The cycle frequency was 25 Hz, The speed rotating used (6350 cycle/min).

First Series: (15) specimens were tested to establish the basic S-N curve (fatigue only). The results of this series are illustrated in table (3).

Table (3): Basic S-N fatigue tests

specimens	Stress applied (MPa)	N_f (cycles)
A1,B1,C1	400	980,1000,1200
A2,B2,C2	350	2900,3000,3150
A3,B3,C3	300	10000,11000,12200
A4,B4,C4	275	72000,77000,83000
A5,B5,C5	250	427000,433000,439600

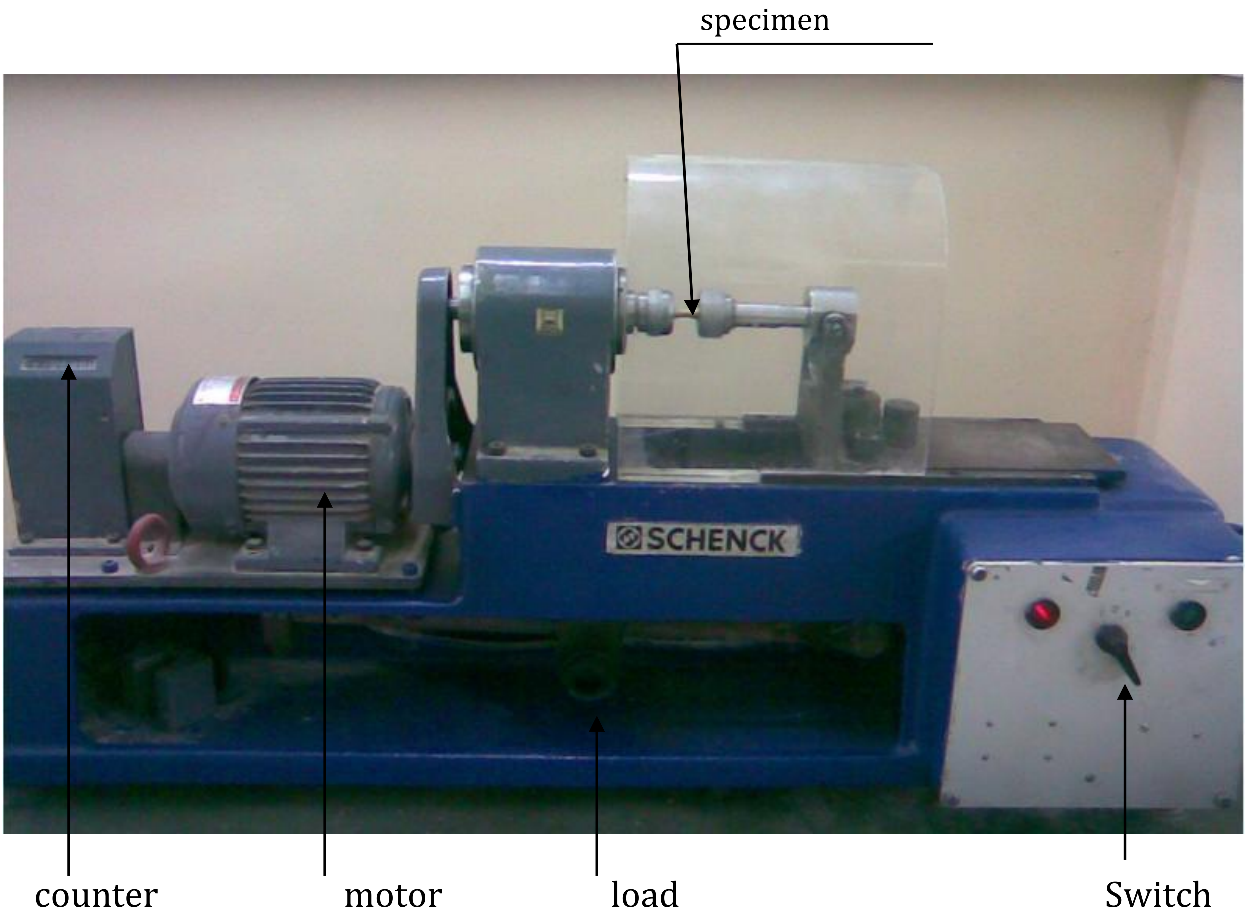


Figure (3): PUNN Rotary fatigue bending machine

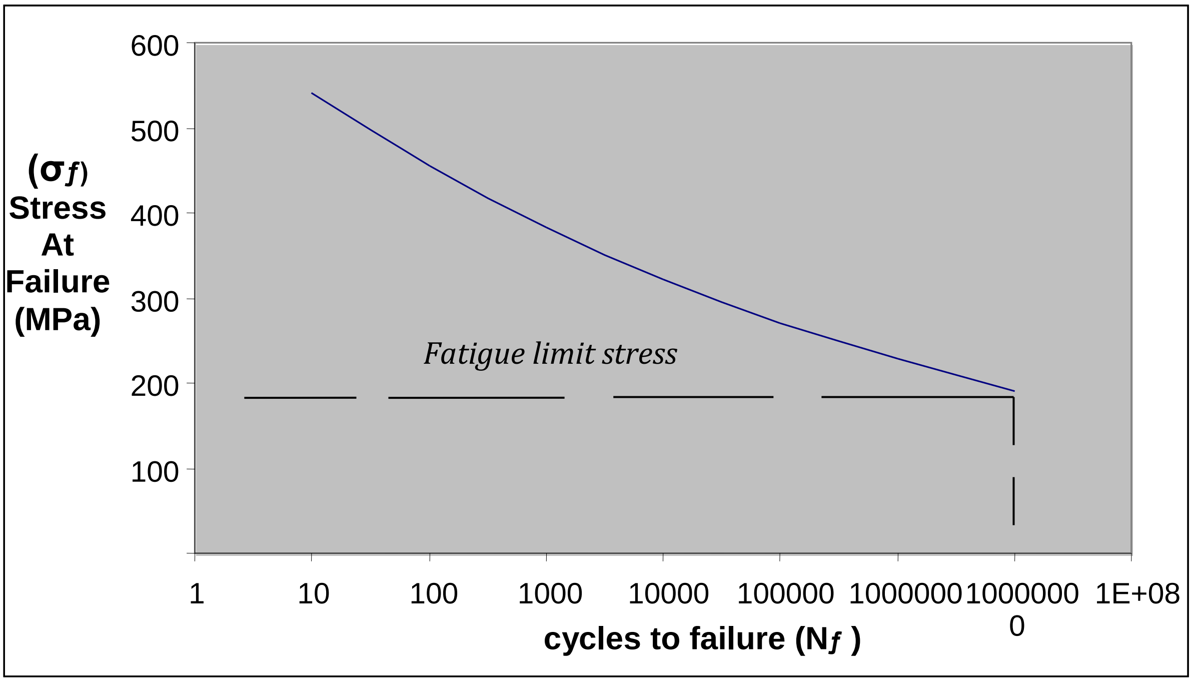
The fatigue behavior of the above alloy at constant amplitude stresses can be described by the Basquin formula as $\sigma f = 642(Nf)^{-0.075}$. This equation gives fatigue limit of (191 MPa) at 10^7 cycles.

Second series : This group (15) specimen are selected to investigate the effect of (10 min sp) on the behavior of constant S-N curve , the results are shown in table (4):

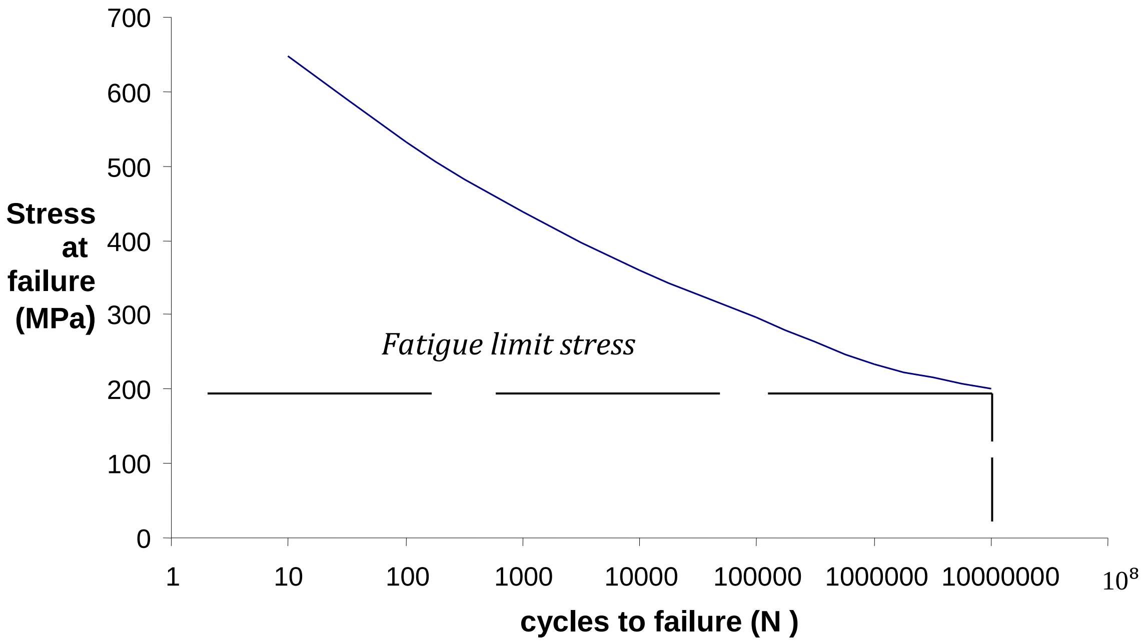
Table (4): Constant stress fatigue at 10 min shot peening (SPT 10)

Specimens	Stress applied (MPa)	Nf (cycles fatigue)
A6,B6,C6	500	810,1000,1200
A7,B7,C7	400	1900,2000,2150
A8,B8,C8	350	2870,3000,3400
A9,B9,C9	300	28700,30000,31800
A10,B10,C10	250	852900,950000,1012000

The deduced relation for the same material used at (10 min sp) may be described by the relation $\boldsymbol{\sigma} f = 787(\mathrm{N}f)^{-0.085}$. This equation gives 200 MPa fatigue limit at 10^7 cycles.



Figure(4): Basic dry fatigue S-N curve



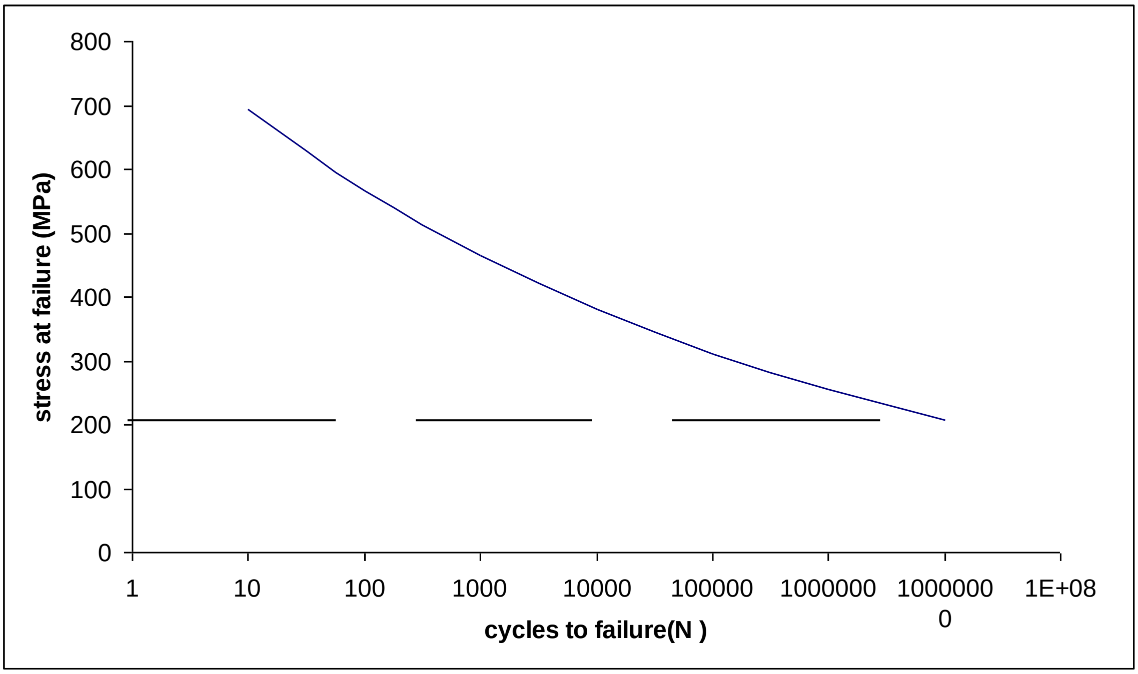
Figure(5): Basic SPT10 S-N curve

Third Series: 15 min. SP was shot peened of (15) specimen to know the behavior of constant S-N curve. The results are tabulated in table (5).

Table (5):Constant stress fatigue with shot peening 15min. (SPT 15) .

Specimen	Stress applied (MPa)	Nf (cycles)
A11,B11,C11	500	1920,2000,2100
A12,B12,C12	400	2870,3000,3300
A13,B13,C13	350	7050,7500,8100
A14,B14,C14	300	219800,222000,226600
A15,B15,C15	250	1270000,1300000,1336000

The deduced relation for the same material used at (15 min sp) may be described by the relation Is $\boldsymbol{\sigma}f = 847(\mathrm{N}f)^{-0.087}$. this equation shows 208 MPa fatigue limit at 10^7 cycles .

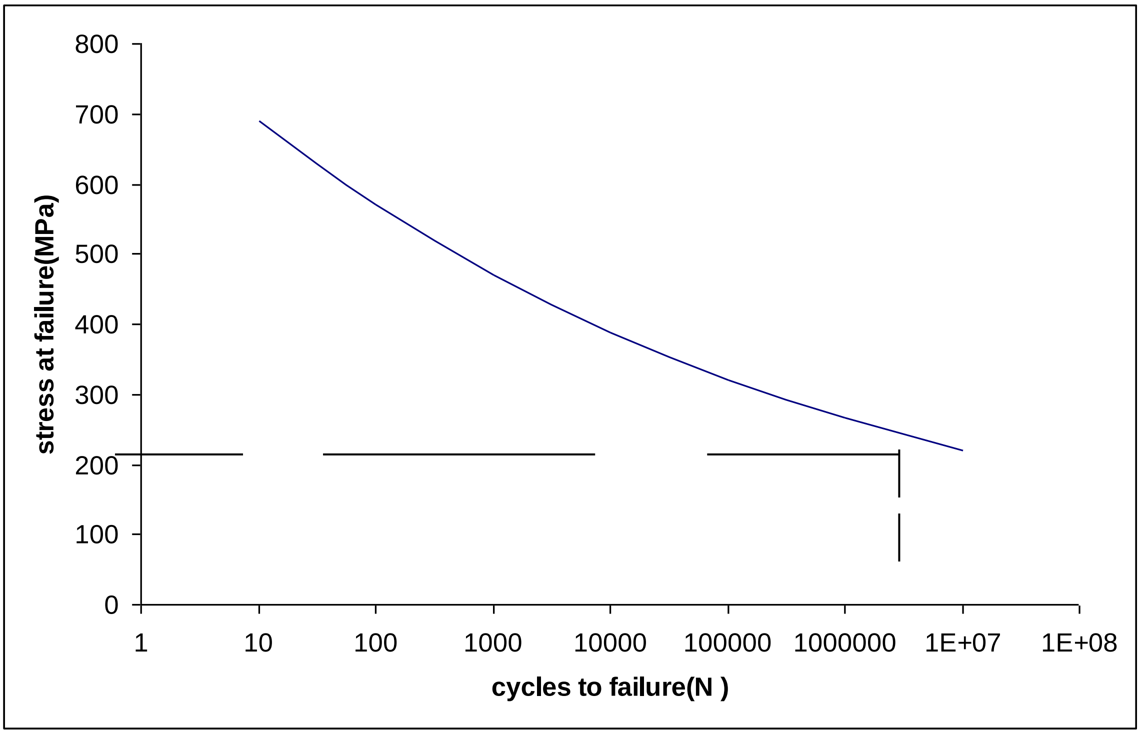


Figure(6): Basic 15 min sp S-N curve (SPT 15)

Fourth Series : This group (15) specimen were selected in order to tested the effect of (20 min SP) on the behavior of constant S-N curve. The results are tabulated in table (6).
The deduced relation for the same material used at (20 min sp) may be described by the relation is $\boldsymbol{\sigma}f = 836(\mathrm{N}f)^{-0.083}$. this equation showed that the fatigue limit at 10^7 cycles is (219 MPa) .

Table (6): Constant stress fatigue with shot peening at 20min (SPT 20).

Specimen	Stress applied (MPa)	N*f* (cycles)
A16,B16,C16	500	2250,2500,2800
A17,B17,C17	400	3350,3500,3800
A18,B18,C18	350	9600,10000,11200
A19,B19,C19	300	328900,340000,362800
A20,B20,C20	250	2108000,2169000,2205000



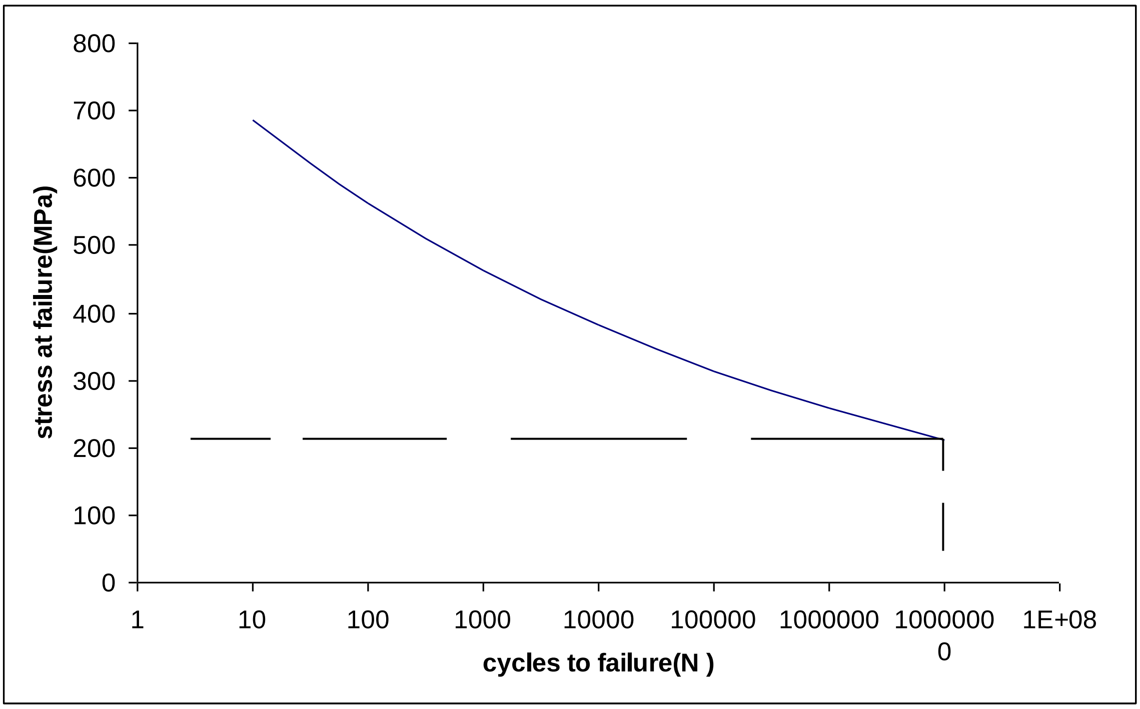
Figure(7): Basic 20 min sp S-N curve (SPT 20) .

Fifth Series: This group (15) specimen were selected in order to tested the effect of (25 min sp) on the behavior of constant S-N curve. The results are tabulated in table (7).

Table (7): Constant stress fatigue with shot peening at 25min (SPT 25).

Specimens	Stress applied (MPa)	N*f* (cycles)
A21,B21,C21	500	1820,2000,2200
A22,B22,C22	400	2800,3000,3310
A23,B23,C23	350	6800,7000,7150
A24,B24,C24	300	233800,240000,248900
A25,B25,C25	250	1553000,1521000,1498000

The deduced relation for the same material used at (25 min sp) may be described by the relation is $\boldsymbol{\sigma} f = 834(\mathrm{N}f)^{-0.085}$. This equation showed that the fatigue limit at 10^7 cycles is (212MPa) .



Figure(8): Basic 25 min sp S-N curve (SPT 25) .

Results Analysis and Discussion

Compressive Residual Stresses

Inducing compressive residual stresses in the surfaces of materials, is one of the most widely used surface engineering techniques in improving the fatigue limit and fatigue life. Shot peening is one of the best methods of inducing the compressive residual stresses. The residual surface compressive stresses reduce the possibility of properties fatigue crack by reducing the peak applied tensile stress. The localized plastic flow at the surface , resulting in the shot peening process , causes work hardening of the surface , general roughening of the surface a long with generation of the compressive residual stresses [12][13] . All of these factors can be expected to affect both the fatigue limit and fatigue life.
The variation of fatigue limit with SPT can be seen in table (8) and Fig.(9) .

Table (8): Fatigue limit at different shot peening time (SPT)

SPT (min)	Fatigue limit at 10^7 (MPa)	S-N curve equation
0	191	$\boldsymbol{\sigma} f = 642(\mathrm{N}f)^{-0.075}$
10	199	$\boldsymbol{\sigma} f = 787(\mathrm{N}f)^{-0.085}$
15	208	$\boldsymbol{\sigma} f = 847(\mathrm{N}f)^{-0.087}$
20	219	$\boldsymbol{\sigma} f = 836(\mathrm{N}f)^{-0.083}$
25	212	$\boldsymbol{\sigma} f = 834(\mathrm{N}f)^{-0.085}$

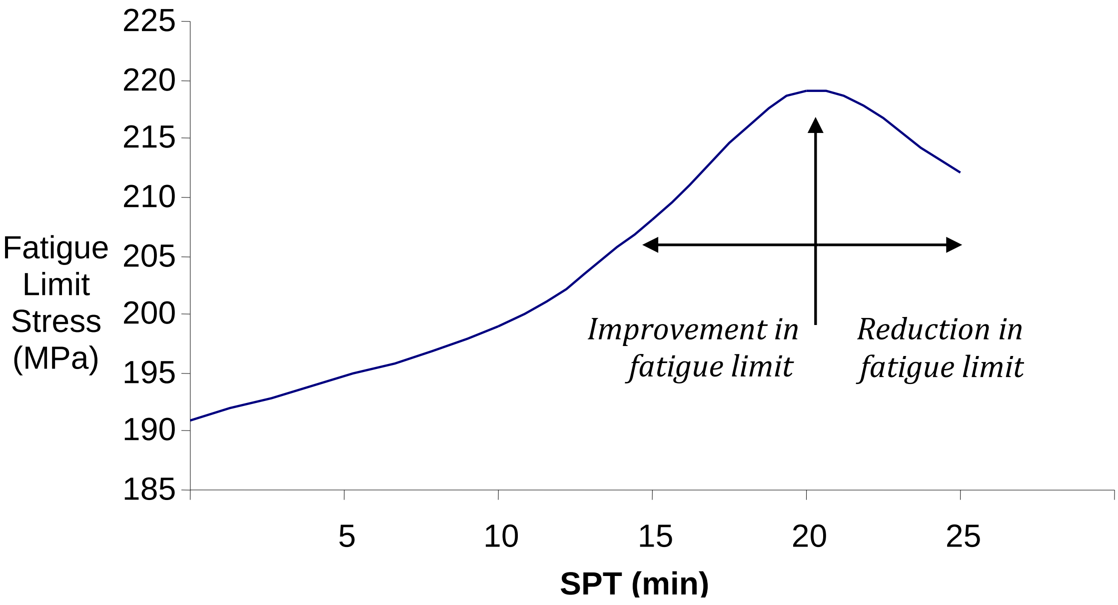


Figure (9): The effect of shot peening time (SPT) on the fatigue limit .

The deduced relation between the fatigue limit at 10^7 cycles and shot peening time (SPT) may be described by the equation $\boldsymbol{\sigma} f.\ L = 144(SPT)^{0.139}$ upto 20 SPT . After that the fatigue limit reduces when SPT increases. The influence of shot peening on fatigue limit may be explained as follows. The shot peening may be expected to give rise to similar effects on the surface as that of localized plastic flow causing work hardening, and generation of compressive residual stresses. At a particular SPT value, the effect of residual stress and work hardening would balance the effect of surface roughening. Hence, shot peening would not have any effect on the fatigue limit and fatigue life at all .However, above this value of SPT, adverse effect of roughening and / or surface cracking would dominate leading to reduction in fatigue limit and fatigue life. [12] [14]
The compressive residual stress, created at the surface of the specimens can be illustrated in table (9) and Fig. (10) at different SPT .

Table (9): The compressive residual stress (CRS) at different shot peening time(SPT) .

CRS(MPa)					
10^3	10^4	10^5	10^6	10^7	Cycle fatigue / SPT(min)
0	0	0	0	0	0
56	38	25	15	9	10
82	58	40	27	17	15
89	67	51	38	28	20
82	59	42	30	21	25

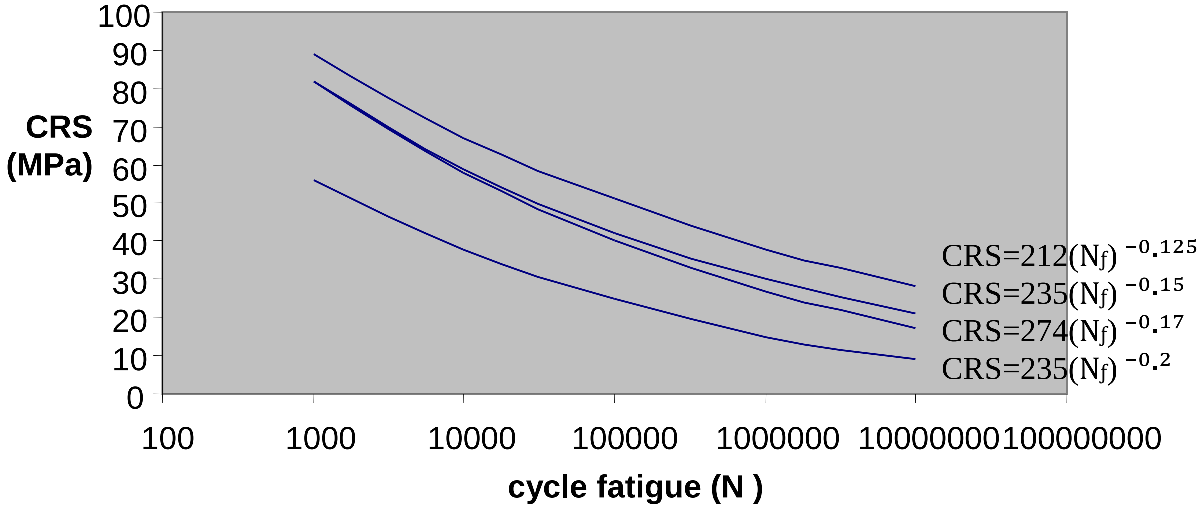


Figure (10): The variation of CRS at the specimen surface with number of fatigue cycles at different SPT

It is clear that , for a given fatigue life , 10^3 or 10^4 …atc , the CRS increases with increase SPT Up to 20 SPT value . But for a given value of SPT , increasing the fatigue life , reducing the CRS . This may be to the relaxization of CRS when the fatigue life increases resulting reduction in CRS[12].

Fig(11) shows the beneficial effect of (SP) in inducing the CRS upto 20 SPT value. After that the CRS will reduced due to dominate roughening surface or surface cracking leading to reduction in CRS [13] .

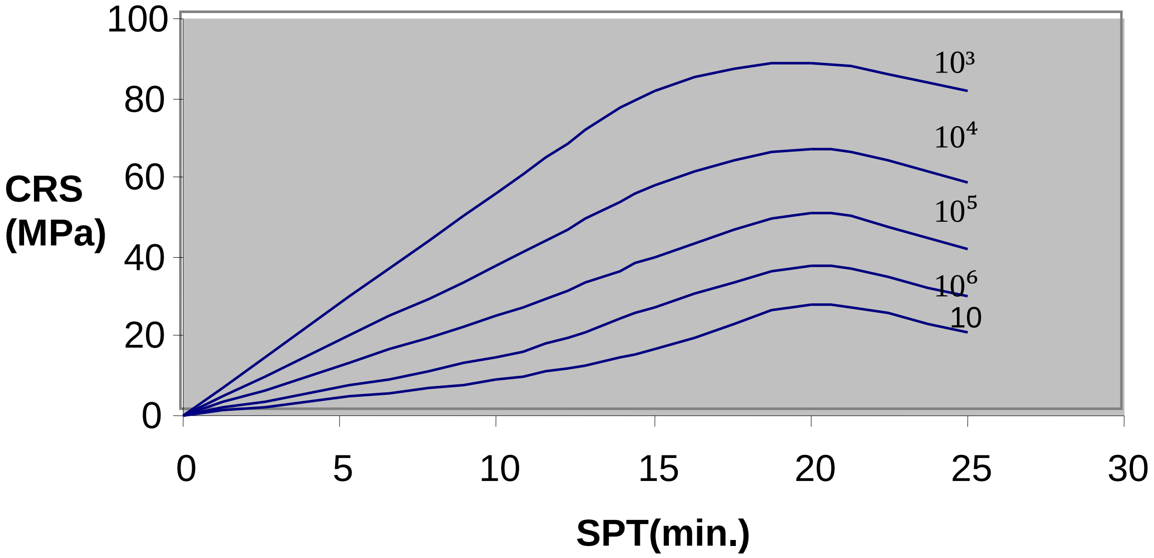


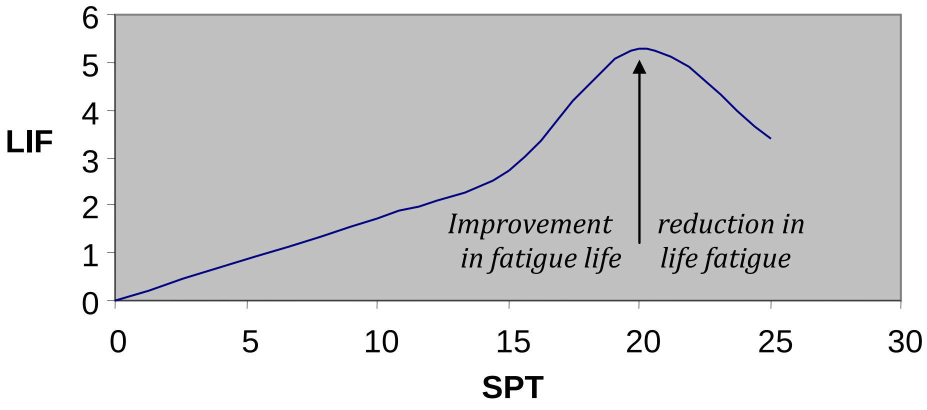
Figure (11): Effect of shot peening time(SPT) with CRS at different fatigue cycles

Life Improvement factor (LIF)

The life improvement factor (defined as N*f* peened/ N*f* unpeened) was calculated for all the condition of shot peening and the result are shown in table (10) , [12] .

Table (10) Life improvement factor at different SPT

SPT(min.)	(LIF) Life improvement factor
10	1.72
15	2.72
20	5.3
25	3.4



Fig(12) LIF against SPT of stainless steel

Fig(12) shows the variation of LIF with SPT. It is clear that the peak value of LIF is occurred at 20 SPT . At this value of SPT the maximum beneficial effect of SP in enhancing the fatigue life is clearly evident , at low stress levels . Beyond 20 SPT the beneficial effect decreases and the effect of SP is detrimental, i.e increasing SPT more than (20 min.) increasing the detrimental effect due to SP process [12].

Conclusions

1. Shot peening significantly increased the fatigue life by a factor of 1.72 at 10 SPT , 2.72 at 15 SPT and 5.3 at 20 SPT .
2. Beyond 20 SPT the LIF reduced and the fatigue life clearly less than the fatigue life at 20 SPT .
3. Max. increase in fatigue limit occurred at 20 SPT. This increase is about 15% compared to unpeened fatigue limit.

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