Eng. & Tech. Journal, Vol.28, No.15, 2010

The Effect of Shot Peening and Residual Stresses on Cumulative Fatigue Damage

Dr. Hussain J. M. Alalkawi *, Dr. Qusay Khalid Mohammed* & Waleed Sadun Al-Nuami*

Received on:6/5/2009
Accepted on: 16/2/2010

Abstract

A series of constant and cumulative fatigue tests under the effect of shot peening were conducted for two aluminum alloys 2024 and 5052. Three unpeed specimens were tested for each alloy under low-high stress levels (120-280 MPa) for 2024 aluminum alloy and (40-90 MPa) for 5052 aluminum alloy at room temperature and stress ratio R= -1. Other specimens were exposed to shot peening with different blasting time before the cumulative fatigue testing. It is found for 2024 Al alloy that as the shot peening time increases the cumulative fatigue life is improved but above 10 min. the life is reduced. For 5052 Al alloy the cumulative fatigue life is reduced as shot peening time increases.

Keywords: 5052, 2024 Aluminum alloy, residual stresses, cumulative fatigue damage, shot peening,

تأثير القذف بالكرات والاجهادات المتبقية على ضرر الكلال التراكمي

الخلاصة

تم إجراء مجاميع من فحوصات الكلال ثابتة ومتغيرة السعة تحت تأثير القذف بالكريات المعدنية لسبيكتين من الألمنيوم 2024 و 5052. تم فحص ثلاثة عينات غير مقذوفة لكل سبيكة تحت مستويات إجهاد واطيء- عالي (120-280 MPa) لسبيكة 2024 و(40-90 MPa) لسبيكة 5052 تحت درجة حرارة الغرفة ونسبة إجهاد R= -1 . فحصت العينات الباقية بأزمان مختلفة من القذف قبل فحص الكلال التراكمي .بينت النتائج انه كلما زاد زمن القذف تحسن عمر الكلال التراكمي و للسبيكة 2024 لكن عند أعلى من 10 دقائق فأن العمر سيقل بينما لسبيكة 5052 فأن عمر الكلال التراكمي يقل كلما زاد زمن القذف

1-Introduction

Components are regularly subjected to dynamic loads, which make them prone to fatigue failure. It is a well known fact that almost all fatigue cracks form at the surface due to a variety of surface stress concentration failures. Evidently, the control of surface initiation and growth of cracks is an effective means of enhancing the fatigue endurance of metallic components. [1-3]

The shot peening process is widely utilised for this purpose as it produces plastic deformation of the surface [3] leading to the creation of both surface work hardening and high residual compressive stresses at, or just below the surface layer [4]. The magnitude of the residual compressive

* Electromechanical Engineering Department, University of Technology/Baghdad

https://doi.org/10.30684/etj.28.15.14
2412-0758/University of Technology-Iraq, Baghdad, Iraq

stresses and the depth to which it extends beneath the surface of the component must be controlled, it becomes immediately apparent that, for shot peening to be consistently effective and reproducible, a number of parameters must be closely controlled, among those, the most important are the exposure time to the shot peening , shot speed , projection angle , dimensions, shape, nature and hardness of the shot and coverage area

The objective of the current work is to study the effect of shot peening on two aluminum alloys (2024 and 5052) with their cumulative fatigue behaviour

Shot peening is a cold working process in which the surface of a part is bombarded with small spherical media called shots. Each piece of shot striking the material acts as a tiny peening hammer, imparting to the surface a small indentation or dimple. In order for the dimple to be created, the surface fibers of the material must yield in tension. Below the surface, the fibers try to restore the surface to its original shape, thereby producing below the dimple, a hemisphere of cold-worked material highly stressed in compression. Overlapping dimples develop an even layer of metal in residual compressive stress. It is well known that cracks will not initiate or propagate in a compressively stressed zone[5]. Since nearly all fatigue and stress corrosion failures originate at the surface of a part, compressive stresses induced by shot peening provide considerable increases in part life. The maximum compressive residual stress produced at or under the surface of a part by shot peening is at least as great as half the yield strength of the material being peened. Many materials will also increase in surface hardness due to the cold working effect of shot peening. Benefits obtained by shot peening are the result of the effect of the compressive stress and the cold working induced. Compressive stresses are beneficial in increasing resistance to fatigue failures, corrosion fatigue, stress by corrosion cracking, hydrogen assisted cracking, fretting, galling and erosion caused by cavitations. Benefits obtained due to cold working include work hardening, inter granular corrosion resistance, surface texturing, closing of porosity and testing the bond of coatings [1].

The surface finish is a parameter that has a considerable effect on the fatigue strength of a part. All the shot peening parameters modify the surface finish of the machine element depending on the improvement in the fatigue strength required and the surface finish tolerances that have to adhere to one or other of the parameters [5].

Residual stresses are those stresses remaining in part when all manufacturing operations are completed, and with no external load applied. These residual stresses can be either tensile or compressive. In most applications for shot peening, the benefits obtained is the direct result of the residual compressive stress produced.

Residual compressive stress has four important characteristics:

1- The stress measured at the surface.
2- The maximum value of the compressive stress induced, which normally is highest just below the surface.
3- The depth of the compressive stress is the point at which the compressive stress crosses over the neutral axis and becomes tensile.
4- The offsetting tensile stresses in the core of the material balance the surface layer of compressive stress so that the part remains in equilibrium maximum tensile stress must be allowed to become large enough to create early internal failures. [1]

2- Experimental Details

2-1Materials

Materials used in this work are two aluminum alloys; 2024, and 5052.The Aluminum alloy 2024, the first heat – treatable alloy discovered (duralumin), still finds wide application for many general engineering and aircraft structural purpose in the form of forgings, extruded bars and section sheets, plates , tubes and rivets. This alloy possesses considerably higher strength than other Aluminum alloys but it has a much lower corrosion resistance due to high copper content. The alloy has good fracture toughness and finds usage for service at temperature up to 120 ^oC. [6]

The Aluminum alloy 5052 provides good resistance to stress corrosion in marine atmospheres and has good welding characteristics. Notably, this class of alloy have been widely used in low temperature applications, which satisfy the most severe requirements of liquefied fuel storage in aircrafts and transportation at cryogenic temperature. [7]

Chemical analysis of the alloys was carried out at Scanning Center of geological survey and mining using X-rays method. The result are summarized in table (1)

2-2 Mechanical Properties

Mechanical tests of the alloys were conducted at the center of standardization and quality control. The tensile test was done using instron 225 testing machine that has a maximum capacity of 150 kN. Four specimens have been taken from the received round bar of diameter (ϕ = 16 mm). Shapes and dimensions were taken according to German engineering standard (DIM 50123). The obtained values are shown in table (2)

2-3 Fatigue specimens and testing

The materials 5052 and 2024 were received in the form of rolled rods. To get perfect dimensions of a fatigue specimen and to avoid mistakes, an accurate profile should be attained. All specimens were manufactured using programmable CNC lathing machine by writing a suitable program from the profile of specimen on an edge of metallic plate. Then, all the specimens were machined, corresponding to that profile by copy machining. During manufacturing of specimens, careful control was taken into consideration to produce a good surface finish and to minimize residual stresses. The test specimen is shown schematically in figure (1).

A rotating bending fatigue – testing machine was used to execute all fatigue tests, with constant and variable amplitude, as illustrated in figure (2)

The specimen was subjected to an applied load from the right side of the perpendicular to the axis of specimen, developing a bending moment. Therefore, the surface of the specimen is under tension and compression stresses when it rotates. The bending stress (σ_b) is calculated using the relation:

$$\sigma_b = \frac{P * 125.7 * 32}{\pi d^3} \quad .. \quad (1)$$

where P is the load measured in Newton (N),the force arm is equal to 125.7 mm and d is the minimum diameter of the specimen in mm. The test machine is Avery 7305 type which is shown in Fig.(3)

2-4 Shot Peening Specifications

The peening operation was performed in a special apparatus (Shot Tumblast control panel model STB-OB). The ball material was cast steel with an average ball size of diameter 0.6 mm and a Rockwell hardness of (48-50 HRC). The pressure is about 12 bars resulting in ball velocities of nearly 40 m /s .The distance of shot peening process is 20 mm.

3- Results and discussions

3-1 2024 Cumulative Fatigue Damage

Six unpeened specimens were tested under low-high cumulative fatigue damage (120-280 MPa for 2024 alloy and 40-90MPa for 5052 alloy) at room temperature and stress ratio R = -1. The number of rotating cycles at each stress was 10^5 cycles for the 2024 alloy and 3×10^4 cycles for 5052 alloy. The results are given in table (3)

Specimens were exposed to shot peening with different blasting time (1,2,3,4,5,6,7,8,9,10 and 15) minutes as shown in Table (4)

In the case of 2024 alloy, the effect of shot peening on fatigue property is most pronounced under conditions of cumulative high cycle fatigue. i.e low to high loading as shown in Fig. (4). The reason for this is that probably because the surface layers of 2024-Al-alloy are heavily deformed during shot peening, and this will stop fatigue cracks following the slip planes and hence prevents the faceted fracture surface. The effect of the time of shot peening has a limit value of 10 minutes above which the fatigue life is reduced [8] [9].

For the 5052 alloy, the results are summarized in table, (5) and (6).

The results of table (6) indicate that increasing shot peening time causes damage in the material structure and reduces the fatigue lives. This can be explained by the high roughness of shot peening surfaces, i-e the effect of shot peening increase the roughness which enhances an important stress concentration in different regions of the surface. As a consequence, it leads to a rapid propagation of cracks in these regions of the surface [3,10]. This behaviour is illustrated in Fig.(5).

3-2 Constant amplitude fatigue tests

Table (7) gives the preliminary results for 2024 and 5052 aluminum alloys

Fig.(6) shows the fatigue behavior of the two aluminum alloys for the unpeened condition. The behavior may be described by the S-N curve equations as:

$$s_f = 685 * N_f^{-0.115} \quad \ldots(2)$$

for 2024 Al-alloy

$$s_f = 526 * N_f^{-0.155} \quad \ldots(3)$$

for 5052 Al-alloy

3-3 Residual Stresses

Shot peening is an effective way of strengthening and pre-stressing elements for cars , aircrafts , ships , etc. The residual compression stress in the metal layers near the surface increases their lifetime [11] , and as a result the surface state, the stress intensity and the affected depth can vary with respect to the applied shot-peening parameters, i.e time of shot peening, surface, coverage, and shot size [12,13]. The residual stresses were estimated experimentally based on the preliminary results of the S-N curve equation. Tables (8) and (9) give these results.

* The residual stresses were calculated using the S-N curve equation $s_f = 685 * N_f^{-0.115}$

The variation of residual stresses with time of shot peening is shown in figure (7)

According to figure (4) , an increase of fatigue life is noticed , in the range from 1 min to 10 min of shot peening. This improvement is due to the formation of a hard layer on which compressive residual stresses exist. However fatigue life drops suddenly at 15 min of shot peening. At 15 min of shot peening the material becomes brittle. As a result, it can be said that shot peening time has a threshold value beyond which a deleterious effect will appear. [14]. For the case of high loading, the maximum value of fatigue life is attained at 6 min of shot peening then the fatigue life decreases. Fig.(7) indicates that the compressive residual stresses increase with the peening time until 10 min and at 15 min it becomes tensile stresses. This behaviour agrees with Refs. [15,16].

*The residual stresses are calculated using the S-N curve equation $s_f = 526 * N_f^{-0.155}$

Shot peening caused deleterious effect in the 5052 alloy. Shot peening created high stress concentrations that exists on specimen surface and tensile residual stress increases when the peening time increases. Thus fatigue life of 5052 Al-alloy specimens has decreased due to shot peening by creation of compressed rough surface i-e tensile residual stresses. These results are similar to those found by Mohamed. [17]

Conclusions

1- Cumulative fatigue life of 2024 Al-alloy is increased by shot peening. The shot peening time has a limit value, about 10 min, below it the fatigue life is increased and above it the effect is inversed.

2- Improvement in fatigue life of 2024 Al-alloy is due to the formation of a hard layer on which compressive residual stresses exist.

3- Cumulative fatigue life of 5052 Al-alloy is reduced due to shot peening and the high tensile residual stresses developed.

References

[1] Jack Champaigne "Shot peening overview" Electronics Inc. 2000.

[2] K.J. Miller "Materials Science perspective of metals fatigue resistance" Material Science and Technology, Vol. 9 pp 453-462, 1993.

[3] G. Nachman "Shot peening –past, present and future" 7^{th} conference on shot peening (ICSP-7) Warsaw, Poland, 1999.

[4] N.Rajesh and N. Ramesh Babu "Empirical Modelling of water jet peening of 6063-T6 Aluminum alloy" IE(I) Journal –PR, Vol.86, pp 220-228, 2005.

[5] M.Suraratchai, J.Limido, C.Mabru, R. Chieragatti "Modelling the influence of machined surface roughness on the fatigue life of Aluminum alloy" International Journal of fatigue 30 (2008) 2119-2125.

[6] Wail Rasheed Al Naimy "Cumulative multixial fatigue damage on aircraft alloy 2024-T4 under complex loading" M.Sc. thesis, university of Technology 1997.

[7] R.J. Bucci "Selecting Aluminum alloys to resist failure by fracture mechanisms" Int. J. fracture Mechanics Vol. 12 , pp. 407- 441, 1979.

[8] P. Arker, J.Lu , J. Favenot "Effect of Glass Beads Nature ,Manufacturing and ageing on the behaviour of shot peened Aeronautical materials" 4^{th} International Conf. on shot peening (ICSP-4) Tokyo, Japan 1990

[9] A.Dorr, L.Tillmann and C.Wagner "Effect of Shot peening on residual life of fatigue Pre-damaged 2024 Al." 6^{th} International Conf. on shot peening (ICSP-6) San Francisco ,USA , 1996

[10] H.Woylfahrt "The influence of the peening conditions on the resulting distribution of residual stress" 2^{nd} International Conf. on shot peening (ICSP-2) Chicago, USA, 1984.

[11] Mitar M., Nebojsa, I, Zoran, C. and Milos, J. "Residual Stresses in shot peening of AlMg 4.5Mn alloy" Material in Technologies, pp. 128-133 ,36 (2002).

[12] R.Fathallah,H. Sidhom,G. Lnglebert,L.Castex "Phenomenological approach to the effects of the exposure time on the shot peening residual stresses"

ICRS-5 Linkoping (1997), Proc.107-114.

[13] A. Piarrt-Garot, A. Lodini, T.M. Holden, R.Rpggc,C. Braham "Stress measurement in shot-peened plates by neutron and X-rays diffraction", ICRS-5, Linkoping (1977), proc. 244-249.

[14] E.R. Rios and P. Mercier "Short crack growth behaviour under variable amplitude loading of shot peened surfaces" Int. J. fatigue Fract. Engng. Mater. Struct. Vol.19 No. 23 pp 175-184 1996.

[15] Al-Alkawi Mohamed , H.J. Marib R.A. Fatin Abdull N. "Shot Peening Treatment as Barrier to Fatigue Crack Propagation in Pure Shear " Al-Taqani Journal to be published (2009)

[16] Al-Alkawi Mohamed ,H.J. , Al-Jubory K. Hamid, Alsalihy Huda, A. "Fatigue damage accumulation behaviour of 2024 Al-alloy under the effect of shot peening time" Engineering and Technology Journal Vol. 25 No.5 , pp. 44-58, 2007.

[17] Al-Alkawi Mohamed ,H.J ,Al-Awsi Mohamed, Q.K., Al-Asadi Abbas A., "Influence of Shot Peening on 70/30 brass Residual Stresses using Plasticity Theory" to be published in Engineering and Technology journal (2009).

Table (1) Chemical Composition of Aluminum alloys

Material	Chemical Composition (wt %)							
	Cu	Mg	Mn	Zn	Si	Fe	Ni	Al
2024	4.0	0.244	0.43	0.43	0.12	0.28	0.1	Remainder
5052	0.024	2.351	0.015	0.019	0.132	0.308	-	Remainder

Table (2) Mechanical Properties

Aluminum Alloys	sy (MPa)	su (MPa)	Elongation %	HB (kg/mm^2)	E GPa	G GPa
2024	352	502	15.4	117	80	30
5052	100.5	195.5	13.33	45	79	29

Table (3) Low-high cumulative fatigue tests of unpeened specimens, 2024 alloy.

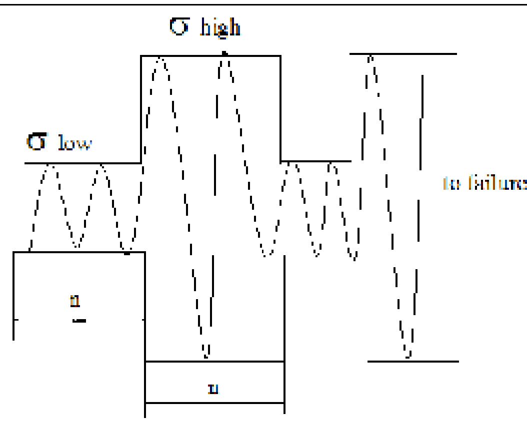
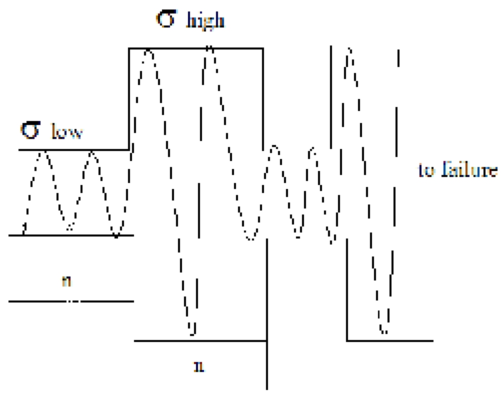
Specimens No.	N_f (cycles)	Loading Programe
1 2 3	506880 496610 478980 Nf (average) = 494157	 σ_{low} =120 MPa σ_{high} = 280 MPa $n = 10^5$ cycles $stressratio R = \frac{\sigma_{min}}{\sigma_{max}} = -1$ room temperature

Table (4) Low-high fatigue tests of peened specimens of 2024 alloy at

ecimens No.	Time of shot peening (min)	N_f (cycles)	Loading Programe
1	1	496824	
2	2	527920	
3	3	626427	
4	4	767211	
5	5	811720	
6	6	844270	
7	7	856721	
8	8	921728	
9	10	987215	σ_{low} =120 MPa σ_{high} = 280 MPa stress ratio $R = \frac{\sigma_{min}}{\sigma_{max}} = -1$ room temperature $n = 10^5$ cycles
10	15	67250	

different peening time

Table (5) Low-high cumulative fatigue tests of unpeened specimens

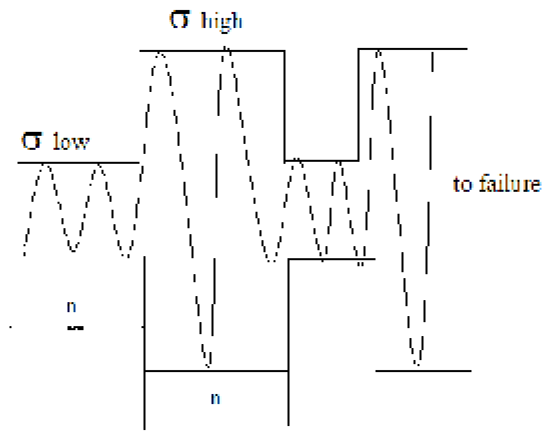
Specimens No.	N_f (cycles)	Loading Programe
1	208860	
2	198980	
3	197280	
	Nf (average) = 201707	σ_{low} =40 MPa σ_{high} = 90 MPa stress ratio $R = \frac{\sigma_{min}}{\sigma_{max}} = -1$ room temperature n = $3*10^4$ cycles

Table (6) Fatigue tests of 5052 Al-alloy at different shot peening time

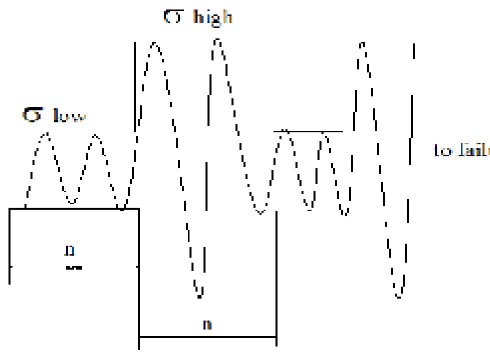
Specimens No.	Time of shot peening(min)	N_f (cycles)	Loading Programe
1	1	207222	 σ_{low} =40 MPa σ_{high} = 90 MPa stress ratio $R = \frac{\sigma_{min}}{\sigma_{max}} = -1$ room temperature $n = 3*10^4$ cycle
2	2	197250	
3	3	198821	
4	4	188251	
5	5	177260	
6	6	158556	
7	7	140661	
8	8	90880	
9	10	44650	
10	15	38660	

Table (7) Results for 2024 and 5052 Aluminum alloys

Aluminum2024 alloy			Aluminum5052 alloy		
Specimen No.	Stress amplitude (MPa)	N_f (cycles)	Specimen No.	Stress amplitude (MPa)	N_f (cycles)
1	130	1486721	1	60	810670
2	150	206727	2	65	668207
3	220	120611	3	70	500676
4	250	3600	4	75	329600
5	300	1660	5	80	210600
6	320	780	6	85	90600
			7	90	87600

Table (8) Shot peening residual stresses due to shot peening in 2024 Al alloy

Specimen No.	Time of shot peening (min)	Nf (cycles)	Nf cycles without shot peening	Residual stress (MPa) *
1	1	496824	494157	-0.0937
2	2	527920	=	-1.147
3	3	626427	=	-4.08
4	4	767211	=	-7.48
5	5	811720	=	-8.413
6	6	844270	=	-9.059
7	7	856721	=	-9.299
8	8	921728	=	-10.49
9	10	987215	=	-11.6
10	15	67250	=	39.1 (tensile

				residual stress)

Table (9) Residual Stresses due to shot peening in 5052 Alloy

Specimen No.	Time of shot peening (min)	Nf (cycles)	Nf (cycles) without shot peening	Residual stress (MPa) *
1	1	207222	201707	-
2	2	197250	=	0.28
3	3	198821	=	0.182
4	4	188251	=	0.857
5	5	177260	=	1.6
6	6	158556	=	3.01
7	7	140661	=	4.556
8	8	90880	=	10.423
9	10	44650	=	20.86
10	15	38660	=	23.12

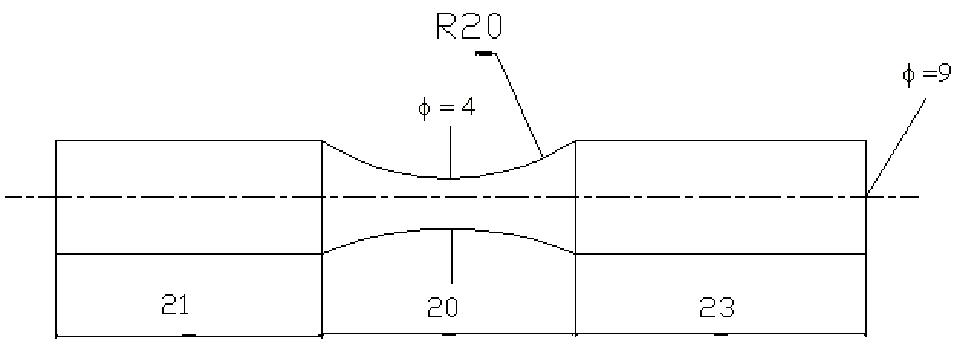


Figure (1) Test Specimen(all dimensions in mm)

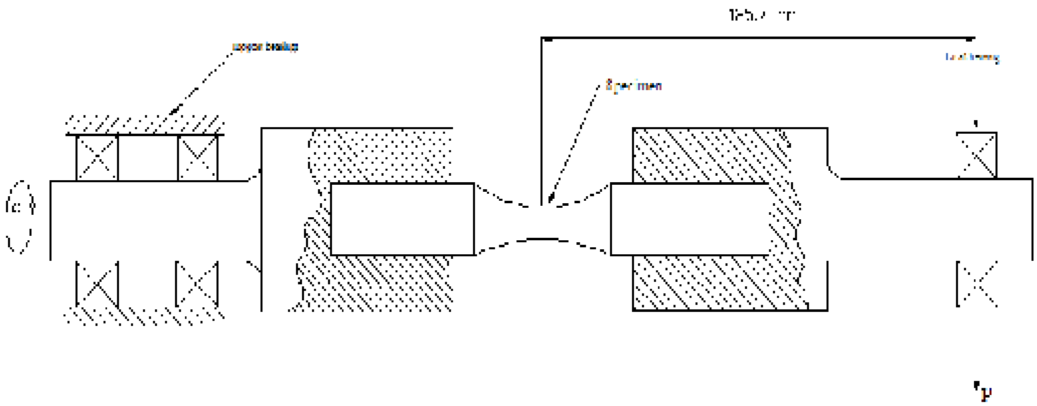


Figure (2) Schematic diagram for rotating bending fatigue test machine

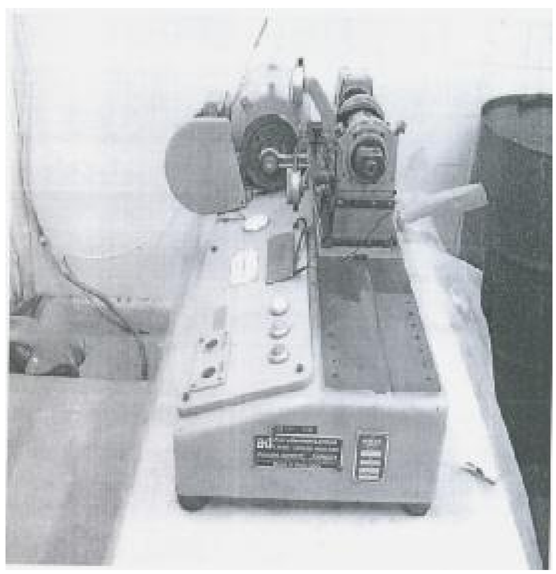


Figure (3) Side view of Avery 7305 Fatigue testing Machine

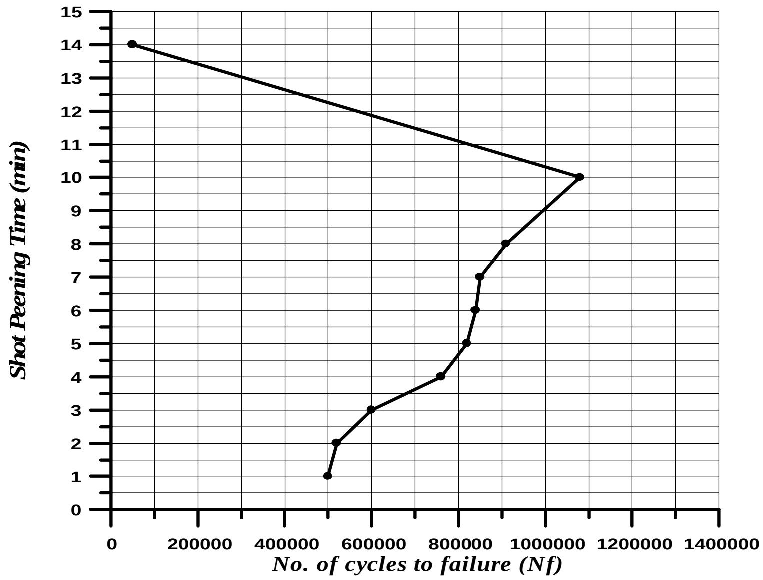


Figure (4) the effect of shot peening time on cumulative fatigue life at failure (Nf) for 2024 Al-alloy

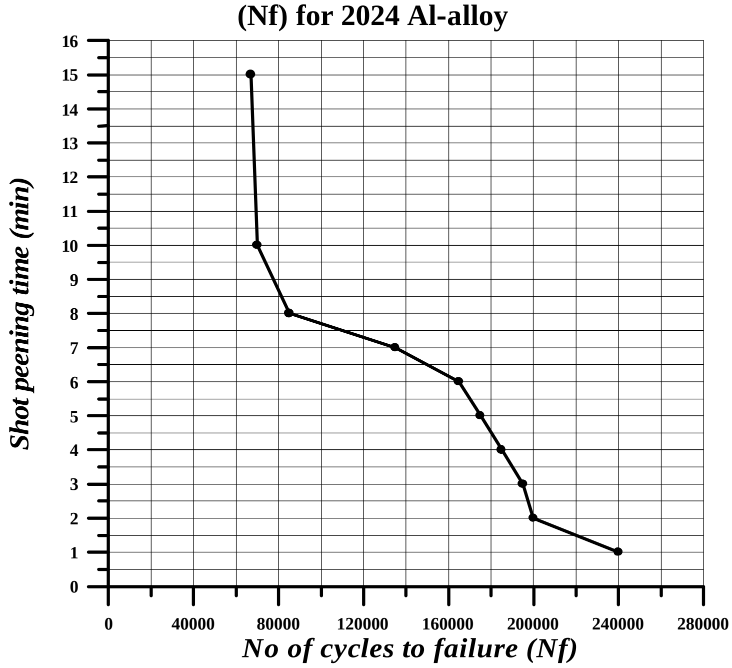


Figure (5) the effect of shot peening time on cumulative fatigue life at failure (Nf) for 5052 Al-alloy

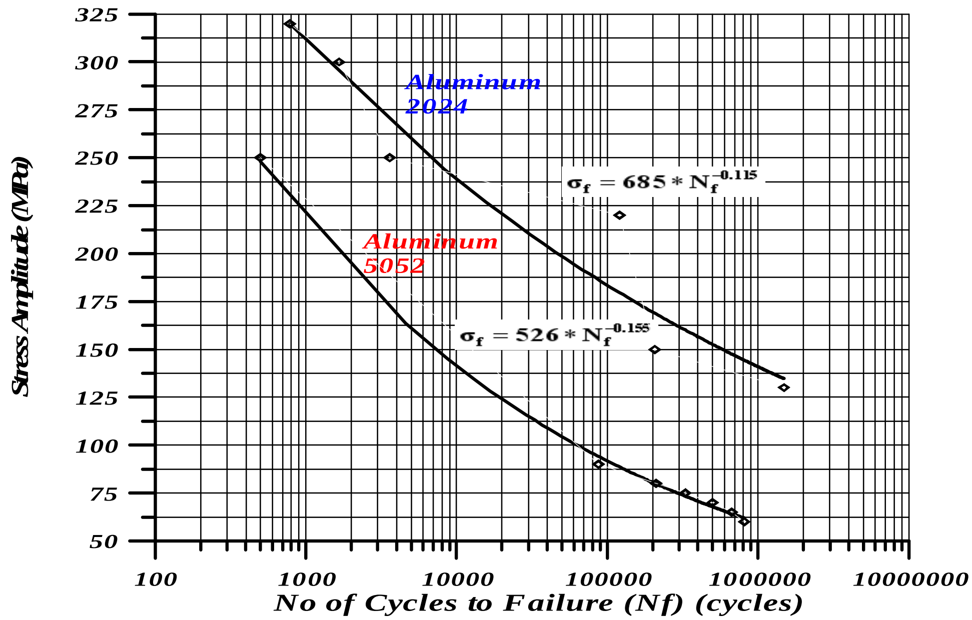


Figure (6) S-N curve of 2024 and 5052 Al-alloy without peening

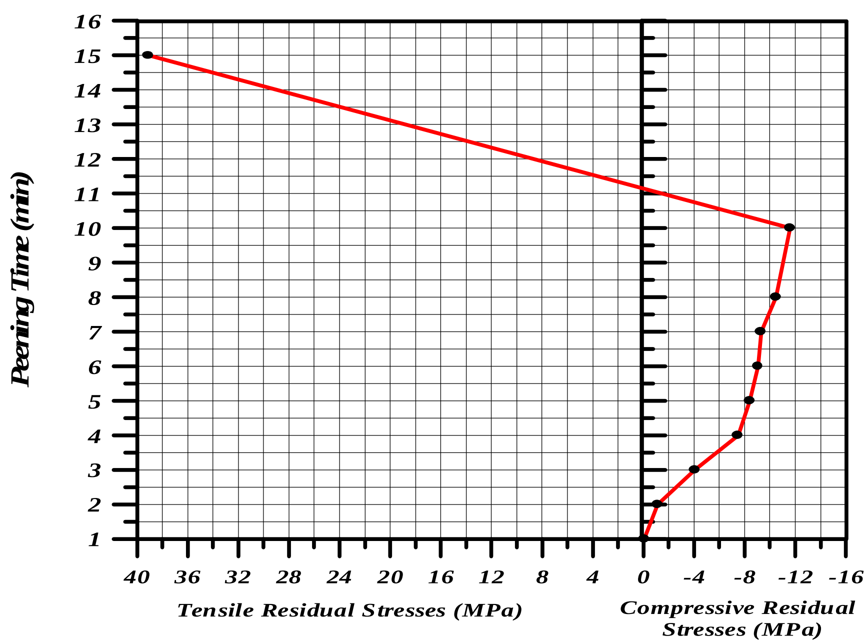


Figure (7) Peening time verses residual stresses in 2024 Al-alloy

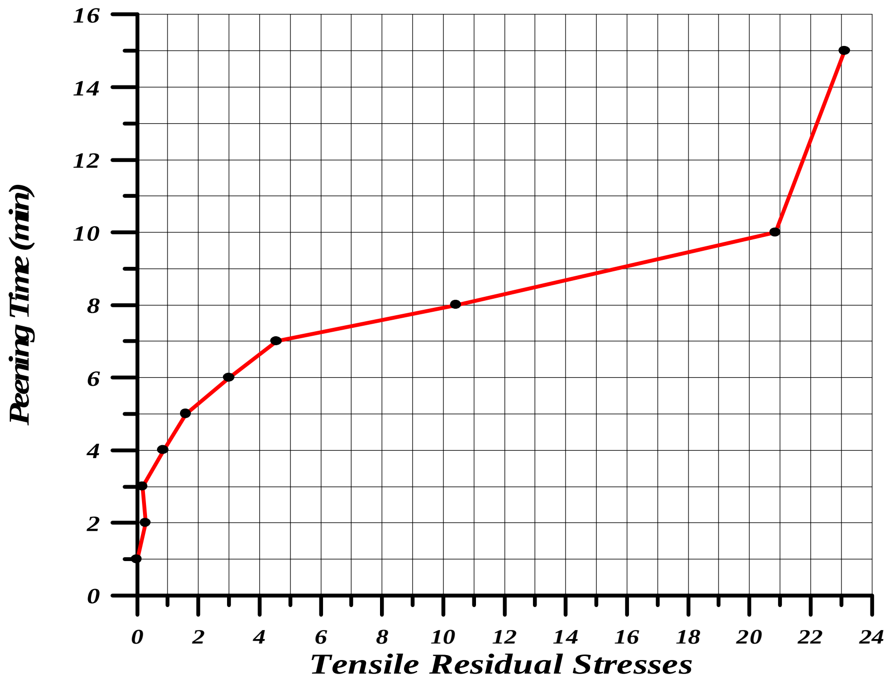


Figure (8) Variation of tensile residual stresses with peening time for 5052 Al alloy