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Effects of Cooling Media Viscosities during the Hardening Process on the Mechanical Properties of Steel Materials

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Abstract

This study involves two parts : the first is manufacturing and testing the steel specimens without heat treatment , while the second is the treatment of the steel specimens by hardening process using different viscosity of quenching cooling oil media .At the beginning , the chemical and mechanical properties of steel specimens are measured and tested to know the mechanical properties of untreated steel specimens using tensile and hardness and fatigue testing instruments, and the microstructure photo is taken for the same specimen .The same tested procedures are followed for all the heat treated steel specimens using four types of cooling oils with different viscosities.The Four types are used with viscosities of(160,480,960 and 1540) cp for (S_1 , S_2 ,S_3 and S_4) respectively. The results show that using of cooling oils with different viscosities in the hardening process raised (ultimate and yield stresses)with(8.5,21.1)% ,(1.7,11.1)%,(0.85,1.1)%and(1.2,1.1)% for (S_1 , S_2 ,S_3 and S_4)respectively. While young modulus , elongation and reduction in area increased with values of (4,55,17.3)%, (7.7,70,30.7)%, (9.2,100,36.5)% and (10.2,100,34.15)% for S1, S2,S3 and S4 respectively. Brinell hardness also increased with (70.6,56.5,41.17and 23.5)% for(S_1 ,S_2 ,S_3 and S_4)respectively. Finally the endurance stress limit increased with (62.5,50,30 and 5)%for (S_1 , S_2 ,S_3 and S_4)respectively, and ,the best fatigue life and fatigue limit are recorded with specimen S_1 ,while the untreated specimens give the loest fatigue life and fatigue limit.

تاثير لزوجة وسط التقسية على المواصفات الميكانيكية للمعادن الحديدية

الملخص

يتضمن هذا العمل جزئين اساسين: الأول هو تصنيع وفحص عينات مصنوعة من معدن حديدي كما تم جلبة من المصدر بينما يتضمن الثاني تصنيع وفحص عينات مصنوعة من نفس المعدن لكن بعد اجراء عملية تقسية باستخدام اربعة انواع من الزيوت بلزوجة مختلفة كوسط للتبريد اثناء عملية التقسية(160, 480, 960, 1540)cp.في البدء تم تحديد الخصائص الكيمائية والميكانيكية للعينات غير المعاملة باستخدام اجهزة فحص الشد والصلادة والكلال وتم كذلك التقاط الصور المجهرية للبنية البلورية لتلك العينات غير المعاملة حراريا.تم تكرار طريقة الفحص السابقة نفسها للعينات التي

تم معاملتها حراريا باستخدام اسلوب التقسية، حيث تم تقسيم العينات المعاملة الى اربع مجاميع اعتمادا على لزوجة الزيت المستخدم كوسط للتبريد اثناء عملية التقسية.
اظهرت النتائج إن زيادة لزوجة الزيت المستخدم كوسط تبريد اثناء عملية التقسية قد ادى الى زيادة كل من اجهادي مقاومة الشد والخضوع بنسب (8.5,21.1)% ،(1.7,11.1)% ، (0.85,1.1)% ، (1.2,1.1)% لكل من S_2 , S_3 , S_1 و S_4 على التوالي بينما زاد كل من معامل المرونة ونسبة الاستطالة ونسبة النقصان في مساحة المقطع ب (4,55,17.3)% ، (7.7,70,30.7)% ، (9.2,100,36.5)% ، (10.2,100,34.15)% لكل من S1,S2,S3 و S4 على التوالي ولوحظ ايضا ان الصلادة زادت بنسبة (70.6,56.5,41.17and 23.5)% لكل من S_2 , S_3 , S_1 و S_4 على التوالي واخيرا فان اجهاد الكلال قد زاد هو الاخر بنسبة (62.5,50,30 and 5)% لكل S_2 , S_3 , S_1 و S_4 على التوالي. كذلك لوحظ إن أفضل العينات التي اعطت افضل حد للكلال وأفضل عمر هي العينات التي تم تبريد معاملتها بالزيت S_1 بينما كانت العينات التي لم تعامل حراريا هي الأسوأ.

1. Introduction

Low carbon steel has carbon content of 0.15% to 0.45%. Low carbon steel is the most common form of steel as it provides material properties that are acceptable for many applications. It is neither externally brittle nor ductile due to its lower carbon content. It has lower tensile strength and malleable. Steel with low carbon steel has properties similar to iron. As the carbon content increases, the metal becomes harder and stronger but less ductile and more difficult to be used. The heat treatment process is carried out first by heating the metal and then cooling it in water, oil and brine water[1].

The purpose of heat treatment is to modify the structure of the material and relive the stress set up in the material. This process is of interest for many fields of industries during which, the mechanical properties of metals can be improved in various ways[2]. Fatigue is the response of a material to cyclic loading. It occurs typically at stress levels that are insufficient to cause catastrophic failure under monotonic/static loading. Since between 80 and 90% of engineering failures have been estimated to occur by fatigue, it is particularly important failure mode in engineering practice. Metal fatigue is caused by repeated cycling of the load. It is a progressive localized damage due to fluctuating stresses and strains on the material. Metal fatigue cracks initiate and propagate in regions where the strain is most severe[3].

Hardening on steel materials is a very important heat treatment process during which the mechanical properties can be improved by heating the steel materials and controlling its cooling process[4].There are many different ways to perform heat treatment hardening, such as pack carburization, gas carburization, vacuum heat treatment induction heat treatment ,salt bath, oil path, water path, etc.[5]. Hardening of metals surface allows to change expensive metals to cheap ones. Improvement of surface quality allows to increase the durability of all construction. It was estimated that hardening effect depends on the residual stresses introduced applying deformation and thermal treatment regimes[6]. The success of quenching process during industrial heat treatment mainly depends on the heat transfer characteristics of the quenching medium. In the case of quenching, the scope for redesigning the system or operational parameters for enhancing the heat transfer is very much limited and the emphasis should be on designing quench media with enhanced heat transfer characteristics.[7].

Properties such as hardness, impact strength, tensile strength and fatigue bending strength of carbonitrided parts of machines depend on the proper selection of heat treatment of two main operations: austenitizing and quenching[8]. The quenching process conditions affect end-use properties such as: type and value of internal stresses, mechanical properties and the extent of hardening deformations [9]. Quench severity may be varied over a wide range from that of a slow oil to agitated water by controlling concentration, agitation and bath temperature. Some of the problems that are encountered with quench oils include: varying cooling rates, flammability, smoke and fumes. Water may also yield varying cooling rates, cracking and poor dimensional stability [10].

Components of machines, vehicles and structures are frequently subjected to cyclic loads, which, in some cases, may lead to their failure due to fatigue. Fatigue cracks in these components may usually be initiated in geometrical features, which cause local stress concentrations, in most cases at the surface. Thus, it is well known that the fatigue life of a machine component depends strongly on its surface layer condition. Fatigue crack nucleation and propagation, in most cases, can be attributed to surface integrity, which includes surface roughness, structure and stress conditions of the surface layer. The importance of surface integrity increases with increasing loads, temperature and frequency[11]. Fatigue strength is one of the most important mechanical properties [12]. Durability and reliability of machine parts is often defined by their fatigue strength, since most of them are loaded with dynamic, repeating or variable loads and the main type of failure is metal fatigue. Failure of fatigue usually starts on the metal surface.This is related to the fact that the most intensive fatigue plastic deformation occurs in the surface of one grain thickness metal layer [13]. The choice of surface treatment method is determined by properties and microstructure of a material, as well as the purpose and working conditions of material of the parts. Very often the optimum treatment is a combination of several methods, which enables to obtain the required properties (high fatigue strength, wear, etc.)[14]. Hardening the steel materials is the most satisfactory means of increasing the fatigue life. This increase in life is attributed to the compressively stressed case on the surface of the piece[15].In this paper the effects of cooling media during hardening process on the mechanical properties of steel material will be studied using different petroleum oils with different viscosities .

3-EXPERIMENTAL PART

3-1- Materials and Processing

36 ASTM E8 steel specimens were manufactured for destructive tensile and hardness tests . According to ASTM E8 Standard Test Methods for Tensile Testing of Metallic Materials[16] . as shown in figure(1)

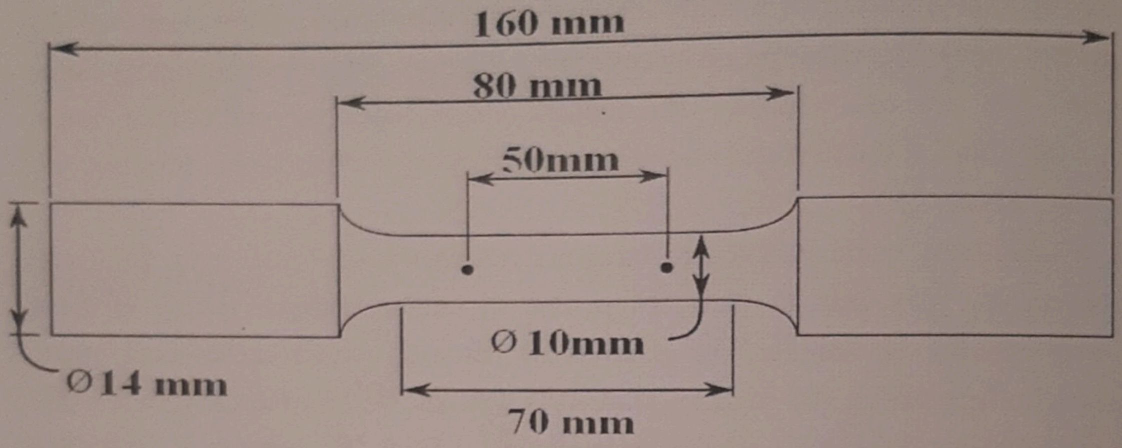


Fig.(1) Tensile test specimen according to ASTM E8

The chemical composition of the specimen material is tested at the laboratory of the Specialized Institute for Engineering Industries (SIEI) as shown in table (1).

Table (1) The Chemical composition of the specimen material

sample	C%	Si%	Mn%	P%	S%	Cr%	Mo%	Ni%	Cu%	V%	Fe%
shaft	0.18	0.177	0.474	0.006	0.014	0.039	0.003	0.051	0.087	0.001	balance

3-2 Hardening Heat Treatment

The general approach of this work is to find the effect viscosity of cooling media during hardening heat treatment process on the mechanical properties of the steel. The hardening process is done after knowing the chemical composition of the specimen material by using table (1). The hardening temperature is chosen according to the carbon percent in the steel which is (0.18) ,during which the hardening temperature is(30-50) °C above upper critical temperature (point) (A3 line) [17].

The testing specimens are classified to Five groups: the first of which is without heat treatment and the other four groups are full hardening and then cooling the specimens in petroleum oil with different viscosities (SAE(10,30,60and 90),(160,480,960 and 1540)cp .The oil viscosities are measured at the laboratory of the Specialized Institute for Engineering Industries (SIEI).Table (2) shows the tensile specimens classification according to type of heat treatment and viscosities of cooling media.

Table (2) Tensile and hardness test specimen with and without heat treatment (hardening process)

No of group	Type of Heat Treatment	Specimen Symbol	Cooling media(oil) viscosity	Specimens Diameter (mm)	Original Length (mm)	Hard. Tem. °C
1	Steel without Treating	S_0	---	10.1	50	---
2	hardening	S_1	160	10	50	900
3	hardening	S_2	480	9.9	50	900
4	hardening	S_3	960	10	50	900
5	hardening	S_4	1540	10	50	900

The hardening process are done using equipment and furnaces of the metallurgy laboratory in the materials engineering department at Al-Mustansiriyah University .

3-3 Test Procedure

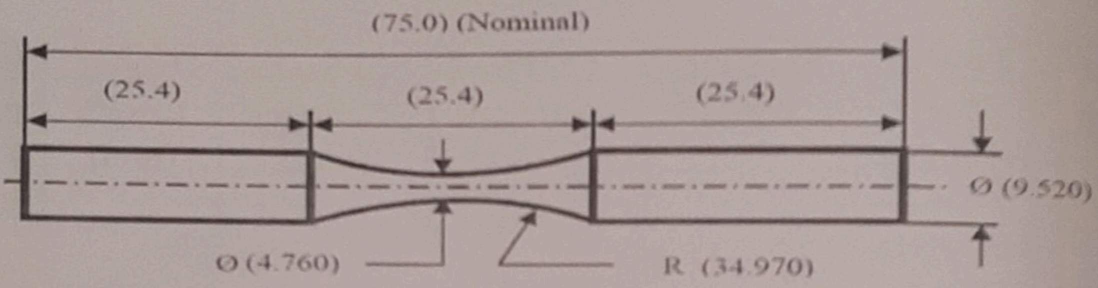
The INSTRON tensile is used for the destructive tensile test for all specimens for each heat treatment type. This test were done at the metallurgy laboratory in the materials engineering department at the Technology University .

Brinell hardness tests are performed according to ASTM E-92 at the laboratory of Specialized Institute for Engineering Industries (SIEI)). The principle of the test is the subjected force by hardness steel ball will(D=5mm),then the Brinell hardness will be calculated by measuring the diameter of the indentation at the specimen surface. The Brinell hardness can be measured by using the following equation :

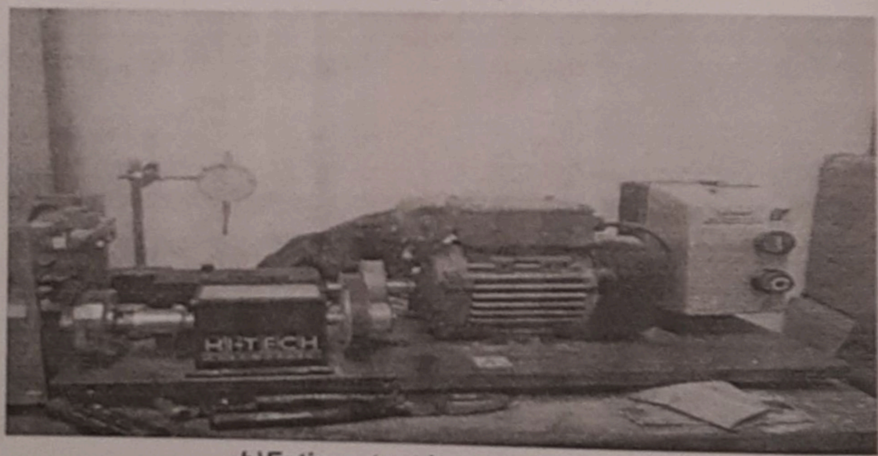
$$BHN = HB = \frac{P}{\pi D t} = \frac{2P}{\pi D\left[D-\sqrt{(D^2-d^2)}\right]} \quad (1)$$

The Fatigue test procedure depend on the mechanical properties of the material. The fatigue tests are performed at room temperature using a rotating–bending fatigue testing machine at a rotational speed of 3000 rpm and a stress ratio of R= - 1. The maximum stress amplitude is calculated according to the relation: σmax= Mc/ I where, M is the bending moment at the critical section of the specimen , c is the maximum distance from center line of the specimen and I is the moment of inertia of a round cross section.

A Fifty specimens are needed to complete fatigue test for each Heat treatment type using HI-TECH fatigue device as it is shown in Fig.(2). All specimens are tested using fatigue instrument at the metallurgy laboratory in the Mechanical Engineering Department at Al-Mustansiriyah University by HI-TECH device.



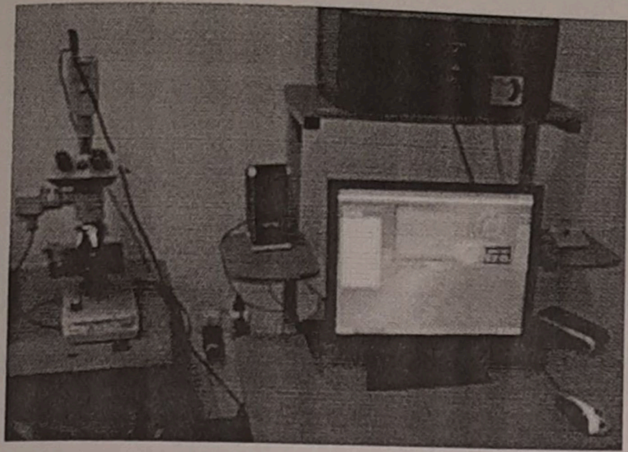
a) Fatigue specimens



b)Fatigue test instrument

Fig. (2) HI-TECH fatigue device used for fatigue test for all specimens

Finally The microstructure of all specimens were photoset using a digital microscope at the metallurgy laboratory in the mechanical engineering department at Al-Mustansiriyah University as it is shown in figure(3)



Fig(3) Digital microscope used for photoset the microstructure of all specimens

4-Result, Discussion and Conclusion

4-1- Tensile Test Results

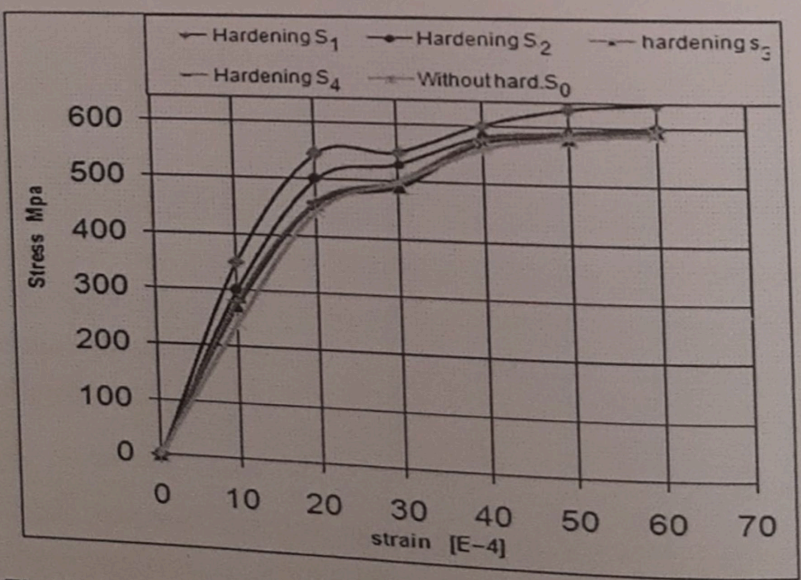
The results data from stress- strain curve for all tested specimens are recorded in table(3) ,and shown in figure(4).These results show that using cooling oil with different viscosities in hardening process will raise (ultimate and yield stresses) with(8.5,21.1)% ,(1.7,11.1)%,(0.85,1.1) %and(1.2,1.1)% for (S_1 , S_2 ,S_3 and S_4) respectively.While (young modulus,elongation and reduction in area) is increased with(4,55,17.3)%, (7.7,70,30.7)%,(9.2,100,36.5)% and (10.2,100,34.15)% for (S_1 ,S_2 ,S_3 and S_4) respectively .

Fig.(5) shows that the tensile strength of the specimens decreases with increasing viscosity of cooling oils used during hardening process .The same behavior will be noticed with yield stress relationship as it is shown in fig. (6) .This is because the quenched and tempered microstructure is predominantly tempered martensite which give the maximum yield and ultimate stresses. While values of Young's modulus ,elongation, reduction in cross sectional area will be increases with the increasing of the viscosity of cooling oils used during hardening process as it is shown in table(3) and figures (7 and8) respectively .The reason for this behavior is that when manufacturing the specimen (untreated specimens S_1 which is a steel without heat treatment), the internal crystal will be deformed due to the work hardening and the hardening process using oils with different viscosity as cooling media will lead to a quenching with low cooling rate .This process will be the optimum solution to resolve the internal deformation energy in the steel crystals through rising the hardening temperature to (900) °C and this will help the specimen to return to its original state during which the hardening temperature will help deposition of the ferrite from the austenite and cementite and the quenching using cooling oils will insure deposition to a homogeneous tempered martensite .This microstructure has the highest mechanical properties specially with hardening process S1 in comparison to the other microstructures as it is shown in fig.(9,10,11,12,13) that show the shape of the internal microstructure of S_0,S_1 ,S_2 ,S_3 andS_4 respectively.

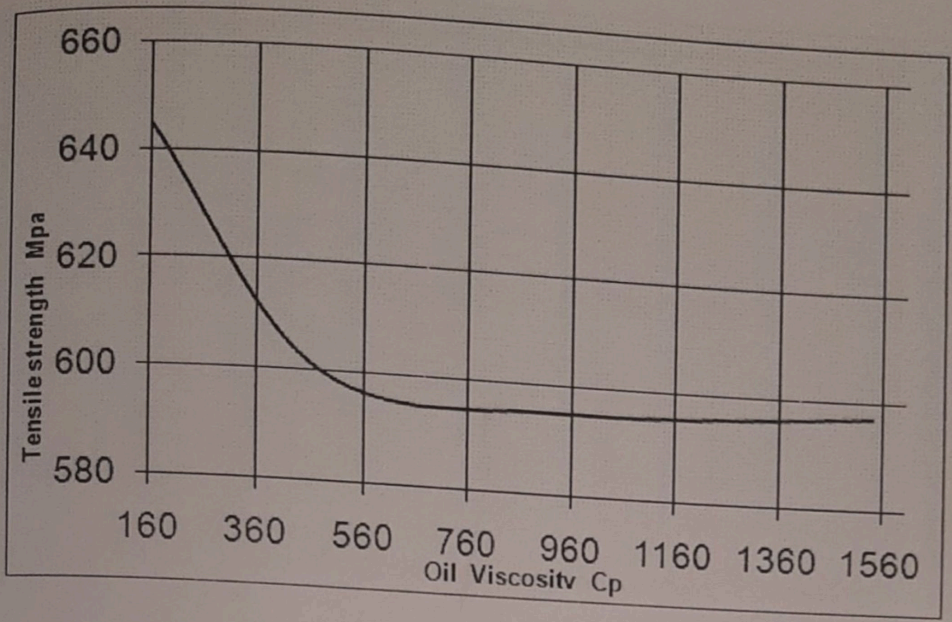
The microstructures of the untreated specimans S0 is consisted mainly from ferrite , austenite and cementite phases shown in fig(9) ,While The hardening process will insure deposition to a tempered martensite as shown in The microstructures of heat treated specimen S_1 Fig(10).

Table (3) resulted data for all testing specimens

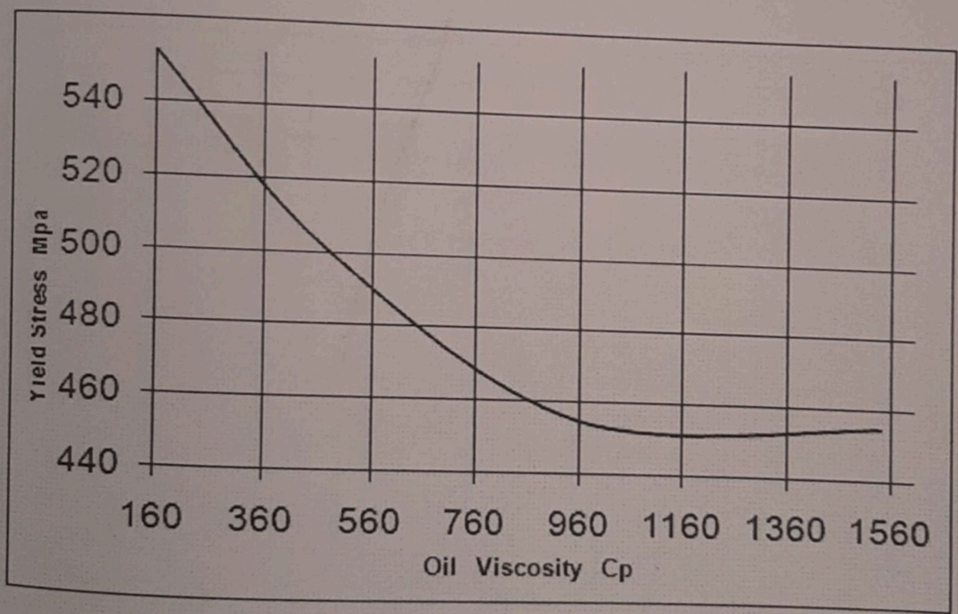
Group No.	Specim. symbol	Origin D.mm	Gage Length mm	σ_Y Mpa	σ_{Ult} Mpa	El%	R.A %	E Gpa
1	S_0	10.3	50	450	590	20%	52	195
2	S_1	10	50	545	640	31%	61	203
3	S_2	10	50	500	600	34%	68	210
4	S_3	9.90	50	455	595	40%	71	213
5	S_4	10	50	455	597	40%	70	215



Fig(4) Stress-Strain relationship for all type of specimens



Fig(5) Tensile strength- cooling media(oil) viscosity relationship



Fig(6) Yield stress - cooling media(oil) viscosity relationship

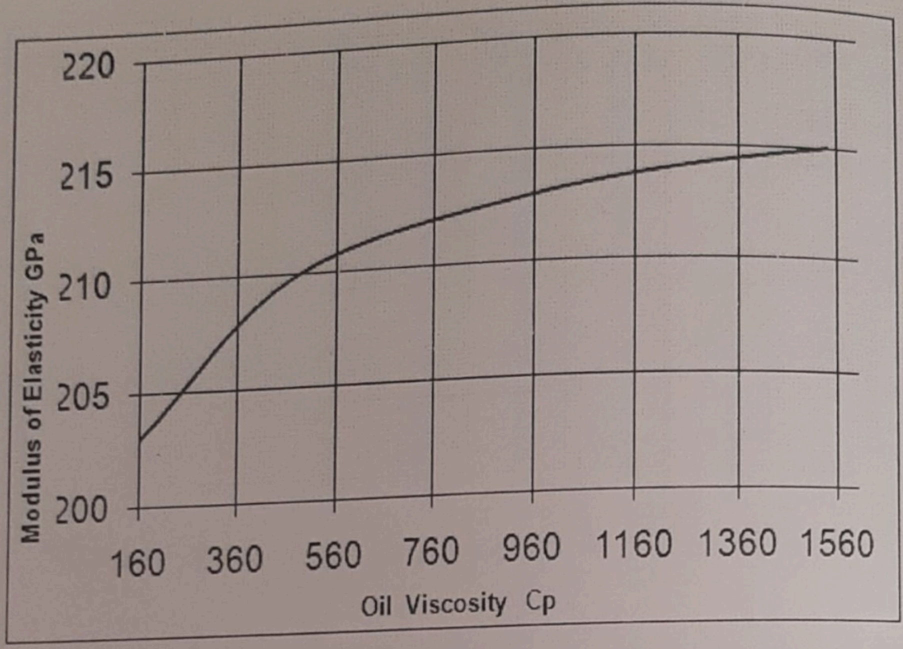


Fig (7) Modulus of Elasticity - cooling media (oil) viscosity relationship

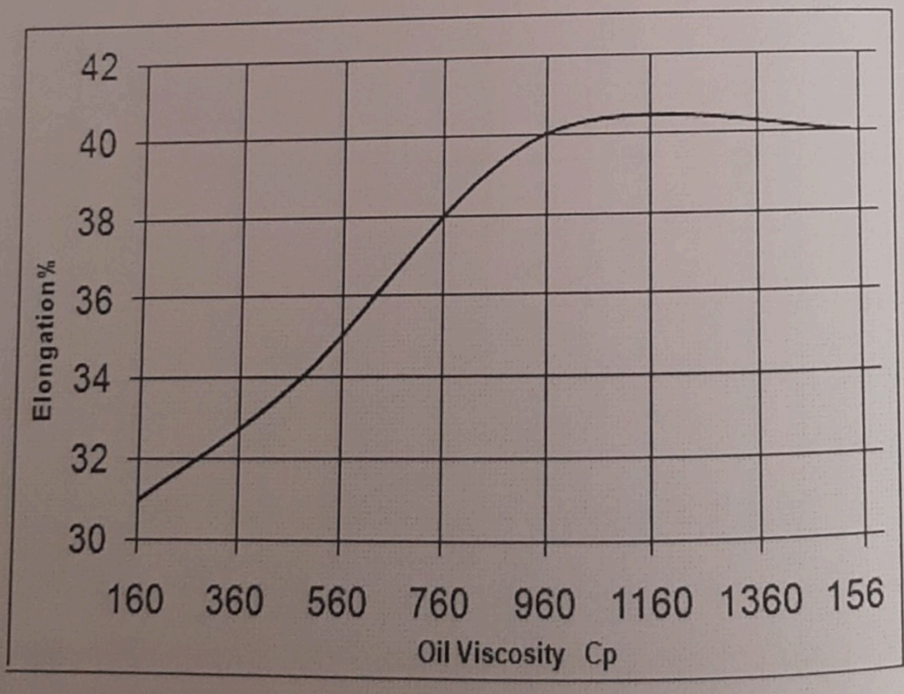
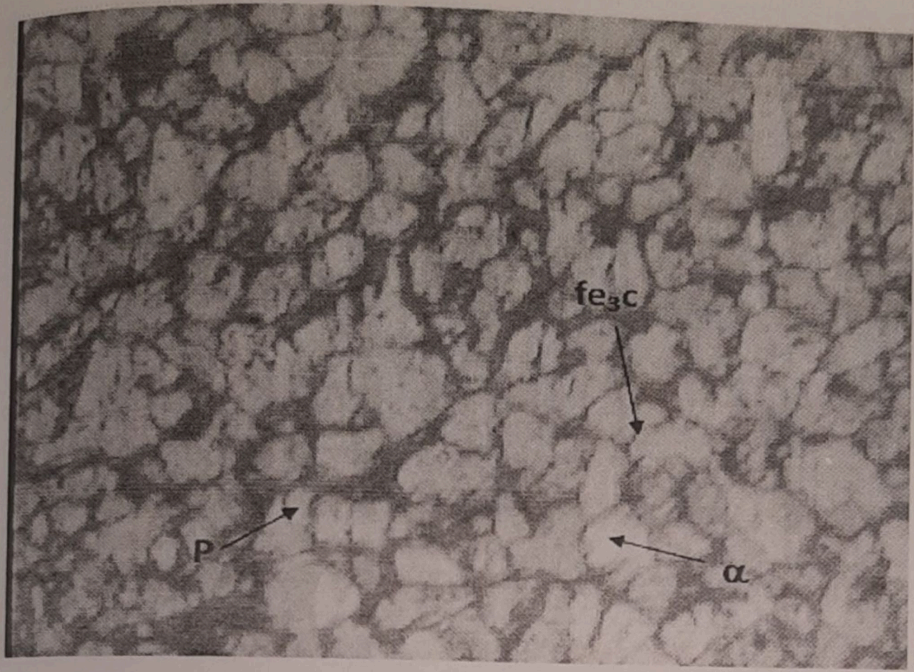
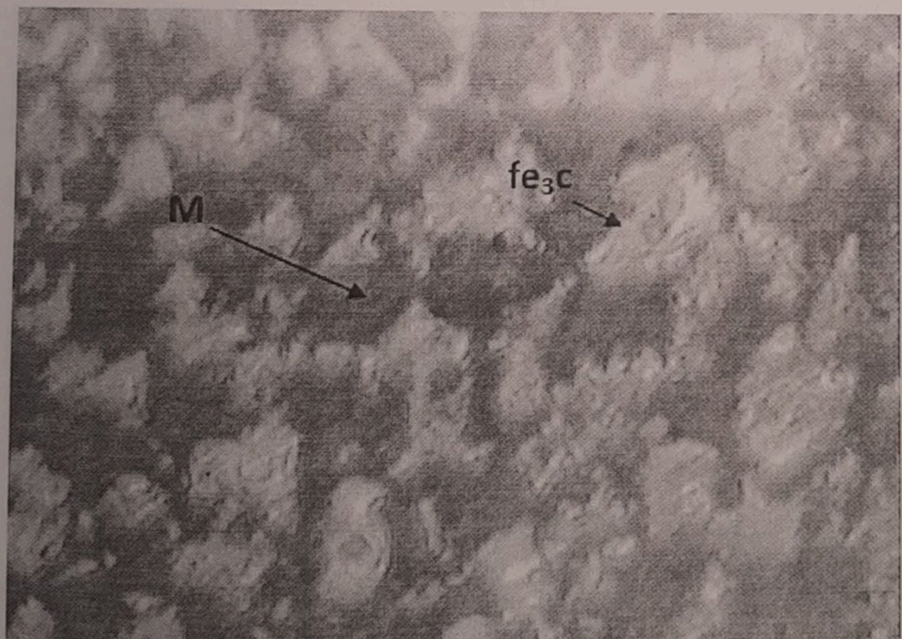


Fig (8) Elongation % - cooling media(oil) viscosity relationship



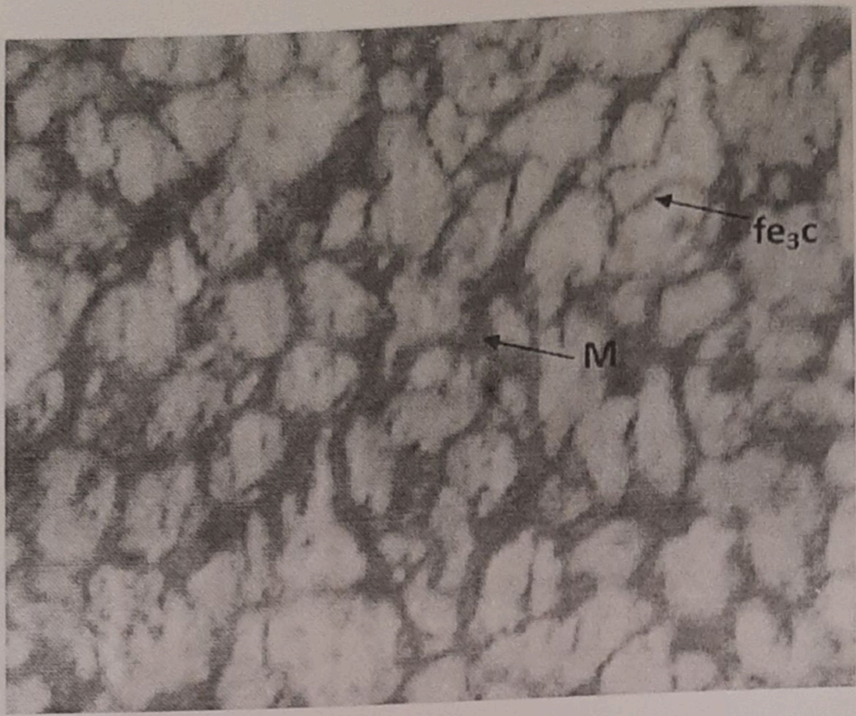
Fig(9):Internal Microstructure for Untreated steel specimen(S_0) X200

α: Ferrite, M= Martenstie, P= Pearlite



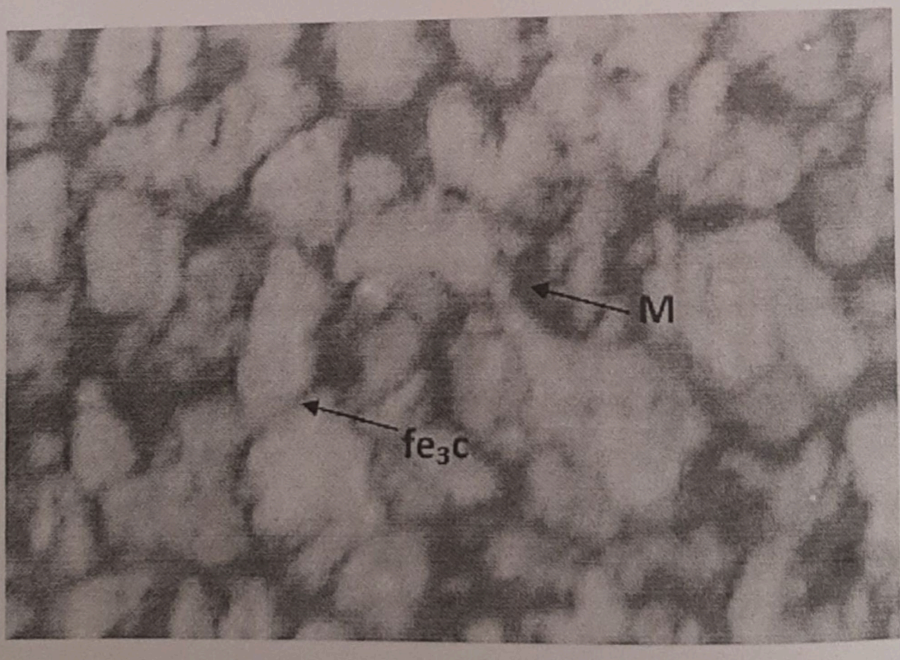
Fig(10):Internal Microstructure for hardening steel specimen using cooling oil viscosities of 160 cp (S_1) X200

α: Ferrite, M= Martenstie, P= Pearlite



Fig(11): Internal Microstructure for hardening steel specimen using cooling oil viscosities of 480 cp (S_2)X200

α: Ferrite, M= Martenstie, P= Pearlite



Fig(12): Internal Microstructure for hardening steel specimen using cooling oil viscosities of 960 cp (S_3)X200

α: Ferrite, M= Martenstie, P= Pearlite

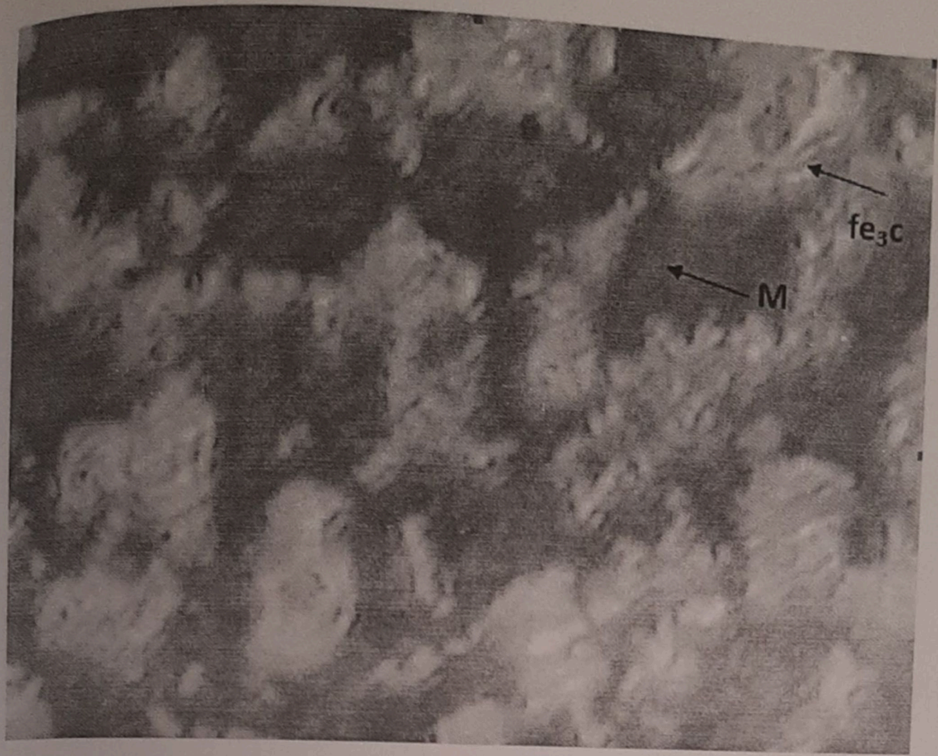


Fig. (13)): Internal Microstructure for hardening steel specimen using cooling oil viscosities of 1540 cp (S_4)X200

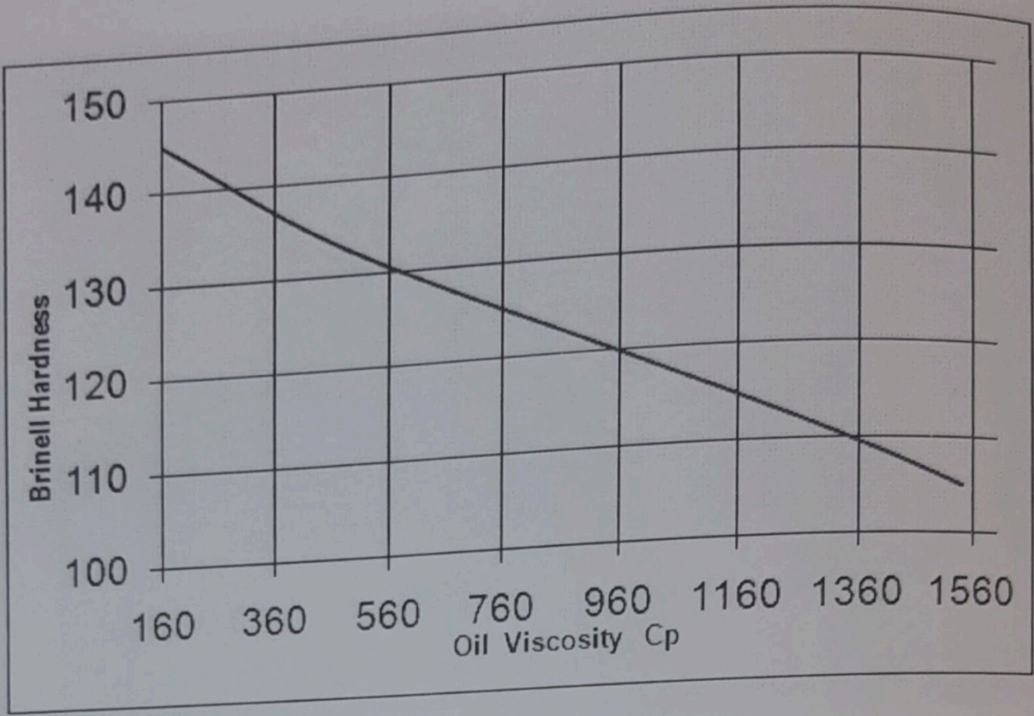
α: Ferrite, M= Martenstie, P= Pearlite

4-2 Hardness Result

The Brinell hardness can be determined and listed in table 4 .Fig.(14) shows that the Hardness decreased with the increasing viscosity of cooling oils used during hardening process. The Brinell hardness increases with (70.6,56.5,41.17and 23.5)% for(S_1 , S_2 ,S_3 and S_4) respectively.

Table (4) shows the Hardness from heat treatment group.

Specimen symbol	HB	σ_{Ult} Mpa
S_0	85	590
S_1	145	640
S_2	133	600
S_3	120	595
S_4	105	597



Fig(14) Brinell hardness against cooling media(oil) viscosity

4-3 Fatigue Testing Result

Fig.(15) shows the fatigue endurance limit against fatigue life in cycle for four types of oil viscosities used as a cooling media during the hardening process in comparison to specimens without heat treatment .The figure shows that the best fatigue life and endurance limit are recorded with specimens S_2 ,while the untreated specimens give the worst fatigue life and endurance stress limit. The figure shows that the endurance limit will be increased with increasing the viscosity of cooling oils used during hardening process. The increased percent of endurance limit will be (62.5,50,30and5)%for (S_1 , S_2 ,S_3 and S_4) respectively.

This behavior can be understood based on the fact that homogeneous structures results in homogeneous slip deformations so that local concentration of plastic deformations are avoided, thus causing dislocation cross-slip more difficult [18]. Another reason for this superior fatigue property may be due to the oil quenching that occurred with this treatment. With such steel materials , oil quenching results into martensite formation with its accompanying volume increase [19]. This may lead to residual compressive stresses which relatively makes the crack spend more energy to grow and consequently hinders an initiated crack to propagate.

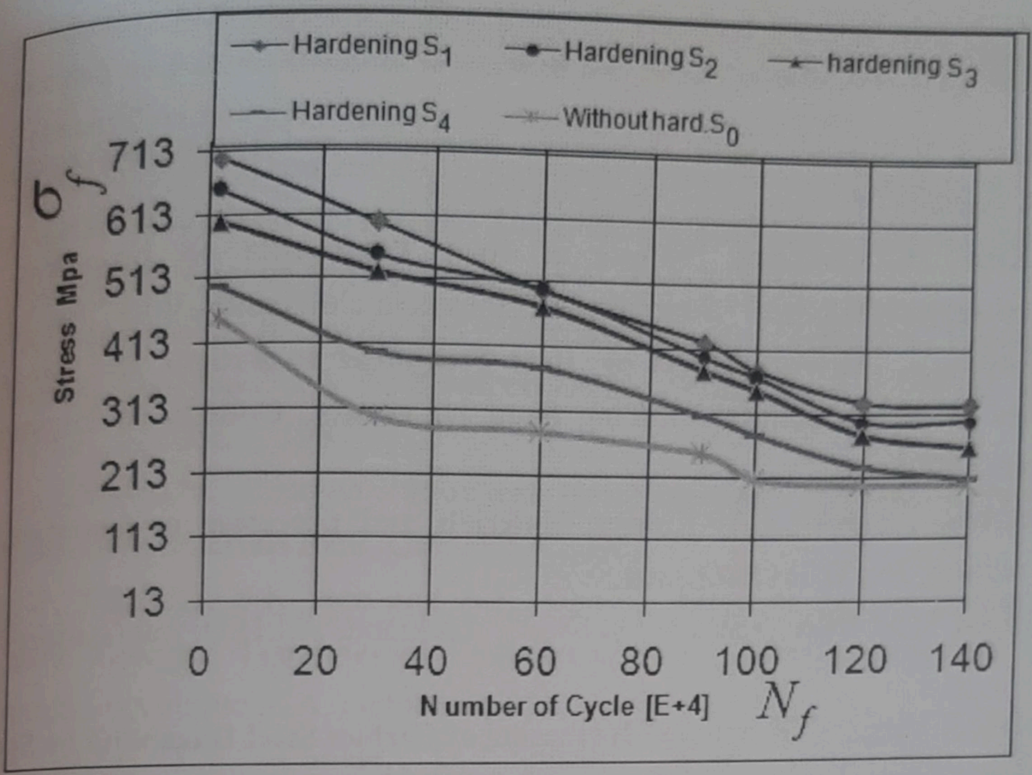


Fig. (15) S-N curve for all tested specimens.

4-4 Conclusion

1- Using cooling oil with different viscosities in hardening process will raise (ultimate and yield stresses) with((8.5,21.1)%, (1.7,11.1)%, (0.85,1.1)% and (1.2,1.1)% for (S_1 , S_2 ,S_3 and S_4) respectively.

2- Using cooling oil with different viscosities in hardening process will increase (young modulus , elongation and reduction in area) with(4,55,17.3)%, (7.7,70,30.7)%, (9.2,100,36.5)% and (10.2,100,34.15)% for (S_1 , S_2 ,S_3 and S_4) respectively.

3- The Brinell hardness increased with (47.2,23.1,17.9and 11.8)% for(S_1 ,S_2 ,S_3 and S_4) respectively.

4- The endurance stress is increased with (62.5,50,30and5)%for (S_1 , S_2 ,S_3 and S_4) respectively.

5-The best fatigue life and endurance stress limit are recorded with specimens S_1 ,while the untreated specimens give the worst fatigue life and endurance stress limit.

References

[1]T.V Rajan, C.P Sharma" **Heat Treatment: Principles and Techniques**",Journal of National Institute of Technology,Vo.l3,No.2,2008

[2]Y. ZaiXian ,H. QuiNgan "**Effects of Heat Treatments on properties and Microstructure of H13 Steel** ",Journal of Northeastem University ,Vol17,No.2,1996.

[3]M. El Rayes, S. Darwish "**Effect of Heat Treatment on Fatigue and Toughness Properties of Steel**", Journal of King Saud University, College of Engineering ,Vol.5,No.2,2006

[4]E.P. Degrmo, J.Black ,R.A. Kohser."**Materials and processes in manufacturing** ",Eight edition, Jon Wiley&sons,Inc,1999

[5]S. Nicholson "**The Heat Treatment of Steel**". Auckland, A.I.D.D, publication, L. R. 2, 1967.

[6]V. Čiuplys, J. Vilys, V. Kvedaras" **Increasing of Carbon Steel Durability by Surface Hardening**", Journal of Materials science (MEDŽIAGOTYRA). Vol. 16, No. 1. 2010.

[7]G. Ramesh and N. Kotekar Prabhu "**Review of thermo-physical properties, wettingand heat transfer characteristics of nanofluids and their applicability in industrial quench heatTreatment**",Ramesh and Prabhu Nanoscale Research Letters 2011.

[8]M. Przyłęcka1, W. Gęstwa1 and G. E. Totten," **Use of Aqueous Polymer Quenchants for Hardening of Carbonitrided Parts**", Committee of Scientific Investigations publication, Poznań University of Technology, LLC, Seattle, WA USA;2005.

[9] B.Lišèiæ, H.M. Tensi and W.Luty"**Theory and Technology of Quenching**",Springer-Verlag, 1992.

[10] M.Przyłęcka And W. Gęstwa "**The Modeling Residual Stresses of Carbonitriding Chromium and Chromium-nickel Steels After Quench Hardening in Different Quehching Mediums**", 3dr International Conference On Quenching And Control Of Distortion ASM , Praga ,Czechy, 1999.

[11] K. S. Lopes, W. F. Sales and E. S. Palma" **Influnceof Machininh parameters on Fatigue Endurance Limit of AISI4140 Steel**", Fundação de Amparo à Pesquisa de Minas Gerais publication , PUC Minas – Brazil,2009.

[12] Y. Akiniwa, S. Tschegg , S. Mayer, H. Wakita and M. Tanaka" **Fatigue Strength of Spring Steel Under Axial and Torsional Loading in the Very High Cycle Regime**", International Journal of Fatigue ,Vol.3,N0.30, 2008.

[13] V. F. Terentjev "Fatigue of Metallic Materials'. Moscow,Nauka Conference (in Russian), 2002.

[14] I. Pariente, M.Guagliano " **The Role of Residual Stresses and Surface Work Hardening on Fatigue ΔKth of a Nitrided and Shot Peened Low-Alloy Steel Surface & Coatings Technology**" Journal of Fatigue ,Vol.13,No.4 2008.

[15] L.R.Singhi, R.A. Khan and M.L. Aggarwal" **Effect of Shot Peening on Hardening and Surface Roughness of Nitrogen Austenitic Stainless Steel**" ,International Journal of Engineering Science and Technology Vol. 2,No.5, 2010.

[16] American Soscietyof Testing and Materials,"**Standard Methods of Tension Testing of Metallic Materials,**" ASTM Standard E8-82, Annual Book of ASTM Standards, Vol. 03.01, Section 3, 1983.

[17]J. L. Dossett,H. E.Boyer "**Practical Heat Treating**", Second Edition, ASM International, Materials Park, Ohio, USA,2006

[18]0.P. P. Talukdar, S.K. Sen and A.K. Ghosh, "**Effect of Fatigue Damage on the Dynamic Fracture Toughnes of En-8-Grade Steel**", Metallurgical and Materials Transactions,volume 32A, October 2001.

[19]V.F. Siva, L.F. Canale, D. Spinelli, W.W. Bose-Filho, and O.R. Crnkovic,"**Influence of Retained Austenite on Short Fatigue Crack Growth and Wear Resistance of Case Carburized Steel**", Journal of Materials Engineering and Performance, Volume 8,No.5, 1999.