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Influence of Annealing, Normalizing Hardening Followed By Tempering And Laser Treatments on Some of The Static and Dynamic Mechanical Properties of Medium Carbon Steel

Dr. AbdulKhaliq F. Hamood* & Dr. Sanna A. hafeed**

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Abstract

This research illustrates the influence of different heat treatments on the mechanical properties such as stress-strain curves ,wear resistance and fatigue properties of medium carbon steel,. This steel was treated by annealing, normalizing, hardening followed by tempering and laser treatments. The bulk mechanical properties of ultimate ,fracture and yield tensile strength were evaluated. Surface mechanical properties of fatigue, wear resistance and hardness were evaluated as well. Microstructure of treated alloys also were inspected. Results showed that (hardened -tempered) steel had improved tensile strength, fatigue{limit, life}, wear resistance, hardness then laser surface treated alloy, then the normalized alloy came in order ,but annealed alloy had the lowest mechanical properties. Annealing caused softening and growth of alloy structure. It was found that the microstructure of treated alloy play an important role in the improvement or deterioration of bulk and surface mechanical properties and by analyzing the obtained results. For (Quenched -tempered) alloy found fine tempered martensititic structure, laser surface treated alloy had martensititic structure in the skin and ferritic- pearlitic structures in the core .Normalized alloy had ferritic-pearlitic structures, Annealed alloy had coarse ferritic- pearlitic structures

Keywords: Heat treatments, fatigue, medium Carbon Steel, quenching, normalizing, laser treatment.

أثر التلدين والتطبيع و الإطفاء المتبوع بالمراجعة والمعاملة الليزرية على بعض الخواص الديناميكية والاستاتيكية للصلب متوسط الكربون

الخلاصة

يوضح البحث الحالي أثر معاملات حرارية مختلفة على الخواص الميكانيكية مثل منحنيات الإجهاد-الانفعال،مقاومة البليان وخواص الكلال للفولاذ متوسط الكربون. لقد أجريت معاملات لهذه السبيكة بالتلدين والتطبيع والاطفاء المتبوع بعملية المراجعة لتلطيف الاجهادات المتبقية,.والاصلاد باستخدام تقنية التشعيع بالليزر. تم دراسة الخواص الميكانيكية المقترنة بالحجم الكلي للمادة والتي تضمنت مقاومة الشد القصوى،مقاومة الشد عند الكسر ، مقاومة الخضوع والسطحية متضمنة مقاومة الكلال ، مقاومة البليان ،الصلادة، كما تم دراسة البنى الدقيقة للسبيكة المعاملة. أظهرت النتائج إن الفولاذ المعامل بالاطفاء المتبوع بعملية المراجعة حقق أعلى مقاومة شد، مقاومة كلال، صلادة، و مقاومة البليان وتبعه الصلب المعامل بالاصلاد باستخدام تقنية التشعيع بالليزر ثم الصلب المعامل بالتطبيع ولكن الصلب المعامل بالتلدين أمتلك خواصا ميكانيكية أضعف حتى من السبيكة بحالتها المستلمة،وقد أعزي ذلك الى كون عملية التلدين سببت نمو الحجم

* **Materials Engineering Department, University of Technology / Baghdad**
****Applied Sciences Department, University of Technology / Baghdad**

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2412-0758/University of Technology-Iraq, Baghdad, Iraq

الحبيبي و أضعاف لتركيب الصلب.كما وجد أن نوع البنية الدقيقة للصلب المعامل يلعب دورا مهما في التحكم بالخواص الميكانيكية المقترنة بالحجم الكلي والسطحية وفي تفسير النتائج المستحصلة .الصلب المعامل بالاطفاء المتبوع بعملية المراجعة أمتلك تركيبا مكونا أساسا من المارتنسيت الناعم المراجع بينما الصلب المعامل بالاصلاد باستخدام تقنية التشعيع بالليزر أمتلك تركيبا مكونا من المارتنسيت في الطبقة السطحية ومن فيرايت مع بيرلايت في القلب، بينما الصلب المعامل بالتطبيع أمتلك تركيبا مكونا أساسا من فيريت مع بيرليت، ولكن الصلب المعامل بالتلدين أمتلك تركيبا مكونا من فيريت مع بيرليت بهيئة خشنة .

Introduction:

The failure of engineering materials is almost undesirable event for several reasons; these include human lives those are put in jeopardy, economic losses, and the interference with the availability of products and services. Even though the causes of failure and the behavior of materials may be known, prevention of failures is difficult to guarantee. The usual causes are due to selection of improper materials and processing and inadequate design of the component or its misuse. It is the responsibility of the engineer to anticipate and plan for possible failure and, in the event that failure does occur, to assess its cause and then take appropriate preventive measures against future incidents[1].

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 a 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. The process of fatigue consists of three stages: 1. Initial crack initiation, 2. Progressive crack growth across the part, and 3. Final sudden fracture of the remaining cross section[2].

The influence of heat treatment on fatigue life for various types of steels has appeared in numerous publications. It has been found that the majority of the work has focused upon modifying the surface properties either by heat treatment such as carburizing, nitrocarburizing, laser beam treatments, shot penning surface-treated steels or by depositing a thin layer to enhance either the corrosion-fatigue or contact-fatigue lives[3]. Low power laser beam treatment has been also used to a certain extent as a localized hardening heat treatment method. Martensite formation due to high cooling rate was the result of this treatment which enhanced the fatigue properties, wear resistance and hardness. This is due to the transformation of residual compressive stresses at the surface[4]. In addition, laser beam cladding has not only improved the fatigue resistance of an alloy steel but also forms a heat, corrosion and wear resisting layers [5]. But this was accompanied with large scatter in fatigue life results and crack growth rates due to some defects such as voids found in the cladded layer. However, fewer defects significantly led to more strengthening[6].

Because of increasing demands imposed on high-performance materials and the disastrous and costly results of component failures, the need for fracture and fatigue research has gained significance and importance. So, too, has the need for designers and engineers to gain an understanding of the fundamental principles of failure investigation and analysis, and the fracture mechanics and fatigue of steels that are widely used in industry. These steels are specifically carbon and alloy steels which are mainly characterized by durability which is perhaps the most significant attribute an industry can possess. Industrial examples that require high durability and long fatigue life are: Bolts, Connecting Rods, Hydraulic Clamps, Heavy duty Shafts, Bearings, Gears, Conveyor Rolls, Hydraulic Shafts, Axles, Couplings, etc [7].

The fatigue properties of metals are quite structure-sensitive. However, at the present time there are only a limited number of ways in which the fatigue properties can be improved by metallurgical means. By far the greatest improvements in fatigue performance results from design changes, which reduces stress concentration and from the use of beneficial compressive residual stress, rather than from a change in material. Nevertheless, there are certain metallurgical factors, which must be considered to ensure the best fatigue performance from a particular metal or alloy[8].

Fatigue tests designed to measure the effect of some metallurgical variable, such as special heat treatments, on fatigue performance are usually made with smooth, polished specimens under completely reversed stress conditions. It is usually assumed that any change in fatigue properties due to metallurgical factors will also occur to about the same extent under more complex fatigue conditions, as with notched specimens under combined stresses[9].

Fatigue properties are frequently correlated with tensile properties. In general, the fatigue limit of cast and wrought steels is approximately 50 percent of the ultimate tensile strength. The ratio of the fatigue limit (or the fatigue resistance at 10^6 cycles) to the tensile strength is called the fatigue ratio. However, the greater structure sensitivity of fatigue properties, compared with tensile properties, is shown in tests comparing the fatigue limit of plain carbon eutectoid steel heat-treated to coarse pearlite and to spheroidite of the same tensile strength. Even though the steel in the two structural conditions had the same tensile strength, the pearlitic structure resulted in a significantly lower fatigue limit due to the higher notch effects of the carbide lamellae in pearlite[10].

Surface deterioration is also important in engineering practice; it is often the major factor limiting the life and the performance of machine components. Wear may be defined as unintentional deterioration resulting from use or environment. It may be considered essentially a surface phenomenon. Wear is one of the most destructive influences to which metals are exposed, and the importance of wear resistance needs no amplification[11].

Research Aim:

This research aims to study the effect of various heat treatments { hardening followed by tempering, laser surface treatment, normalizing and annealing} on the stress –strain curves ,fatigue properties (live, limit),wear resistance of medium carbon steel. Also, the aim of this work is to gain a full understanding to the correlations between fatigue life, mechanical properties, micro structure. In addition to wear resistance as another objective in this research.

Experimental part Material

In the present work a medium Carbon Steel was selected ,then chemical analysis will be employed in order to ascertain the steel type that had to be used in this research , the obtained chemical composition in wt.% given in Table (1) .This steel was a bar with (16 mm dia.) received from general company for mechanical industries in alascindarea city ,this steel is widely used in industry and is mainly characterized by good properties which perhaps the most significant attribute that an industry can possess. May be normally used in rotating parts {axels, crank shafts and gears}.

Specimens Manufacturing

Machining of tensile ,fatigue and wear specimens to standard dimensions and then manually grounded using SiC abrasive paper to a 1000-grade finish., and also few additional specimens for microscopic and hardness testing. Specimens were cut to dimensions of approximately {(20×10mm) for wear, (10×10mm) for microstructure and hardness}, and tensile test Specimens in conjunction with the relation (A=5D) as in fig.(1a.) and then manually grounded using SiC abrasive paper to a 600-grade finish, and fatigue test specimens as in fig.(1b.) and then manually grounded and polished using different grades of SiC abrasive paper until approaches to a 1000-grade finish.

Specimens Classification and Treatments

Specimens then classified to four categories each of which has -{one specimen for tensile test according to ASTM E 8 ,eight specimen for fatigue test according ASTM E 466 (this does assist drawing the S-N curve), one specimen for wear test, the another specimen for microstructure and hardness }- and each corresponds to the specified heat treatment -{accomplished in amuffle –furnace(size two) gallen camp}- which includes [full hardening of the section (water quenching) followed by tempering, Partial hardening of the section (laser surface treatment) normalizing, and annealing] with the steps as illustrated in Table (2).

Tests Microstructure and Hardness Testing

Microstructure across the whole section was analyzed using optical microscopy (OM) (Hitachi S-2400) and hardness testing by using {Digital microhardness tester No. 924 ,Hvs-1000} according to test method of Vickers Hardness Testing (ASTM E 92) was employed in order to determine the obtained phases and the variation in hardness to assure that the heat treatment has been done as planned and to be compared with the original alloy.

Tensile Test

The tensile strength values were measured using computerized tensile testing device -{Microcomputer controlled electronic universal testing machine ,model (WOW-50E class 1,serial No. 0465, made in peoples republic of china }-. By inspecting tensile specimen through the application of different vertical tensile forces until the fracture , and determine the (ultimate ,yield, fracture) tensile strength, elongation for each heat treated sample according to test method of tension testing of ASTM A 370, E 8 .

Fatigue Test

Th Fatigue testing used in a rotating-bending fatigue testing machine with the specification of { fatigue testing machine gunt Hamburg, 2800 rpm ,spanning voltage 230 V , frequency 50Hz ,Normal power 0.4 Kw and fabrication No.188630} , and performed at room temperature and a stress ratio of R= - 1 (tension–compression) ISO 1143, 1975 and ASTM E 468. The stresses in this type of testing are predominantly elastic, and stress levels are below the yield strength of the selected alloy. Test results were plotted as (semi-logarithmic) S-N curve for each type of heat treatment.

Wear Test

The wear testing in which the results of wear resistance values were measured by dry siding wear test using pin on disc wear testing device according Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus (ASTM G 99) .{ This testing device consist of a motor with a constant rotation velocity, arm for fixing the sample after connection by the carrier and making it in a horizontal manner touching with balance as aid . ,sample was touching the disc during rotation under the effect of vertical specified load. wear rates for the treated samples were calculated by the weighter methods which includs the measuring of the sample weight after and before test by using sensitive apothecaries weighed from mettler (AE200) type with (0,0001) gm accuracy ,and then wear rates were calculated using the following equation}.

Wear rate (W.R) in gm/cm $= \frac{\Delta W}{S.D} = \frac{WO - W1}{\{\left(\frac{\pi DN}{1000}\right) \times t\}}$

Volumetric Wear rate $(W.R)_V$ in $cm^2 = \frac{Wear\ rate\ (W.R)\ gm/cm}{\rho\ \left(\frac{gm}{cm3}\right)}$

ΔW:Weight loss after test (gm).

S.D: Sliding distance (cm).

Wo: Initial weight before test (gm).

W1 : Final weight after test (gm).

D: Diameter of sample trajectory (16cm).

N: Number of rotation per minute. (420 rpm).

T: Sliding time (30min.).

After obtaining the full results, then Evaluation of heat treatments which gave the highest results ,from the studied properties points of view and studying the correlations between them.

Results and Discussion

Microstructure investigation:

The microstructural study of microstructure images captured by optical microscopy , revealed that the quenched and tempered structure is homogeneous fine-laths of tempered martensite Fig. 2(Image4), whereas, the laser surface treated structure consist of fine-laths of tempered martensite at the surface skin only ,but the internal layers consist of grains of ferrite and pearlite Fig. 2(Image5,6), whereas, the normalized structure consists of fine grains of ferrite and pearlite , Fig. 2 (Image3) , and annealed structure was coarse-grains of ferrite and pearlite Fig. 2(Image2).

Hardness

The effect of different selected treatments on the hardness were illustrated in fig.(4).also Table 3 presents the effect of different heat treatments on the hardness and other studied mechanical properties .Hardness results showed a fascinating improvement for the quenched and tempered alloy , the laser surface treated alloy and the normalized alloy respectively, Annealed alloy revealed deterioration in its value .The improvement in hardness of quenched and tempered alloy is attributed to the formation of fine hard –brittle martensite – observed by microstructure examination-,this phase was created as a result of rabid quenching from the austenitic region . The improvement in hardness of the laser surface treated alloy will be attributed to the rapid heating and cooling caused by laser surface treatment, whereas, the improvement in hardness of normalized alloy will be attributed to the accelerated cooling in still air ,which is activate the formation of fine grins , and the deterioration in hardness of annealed alloy will be attributed to the slow furnace cooling, which was activate the grain growth and formation of fine microstructure .

Tensile strength

The effect of different selected treatment on the stress-strain curves were illustrated in fig.(3).also Table 3 presents the effect of different heat treatments on the tensile and other studied mechanical properties. Tensile properties(Ultimate tensile strength, yield strength, fracture strength) showed a fascinating improvement for the quenched - tempered alloy ,this behavior will be attributed to the role of hardening effect which was ensured by hardness inspection{percent of hardness increment is 116.5% }, residual stresses due to rapid quenching from a high temperature (austenite region) to room temperature (cold water bath) and formation of hard fine laths of martensite along the full cross sectional area of treated alloy as revealed by microstructural study as in Fig. 2(Image4). whereas, the laser surface treated showed less fascinating improvement ,this behavior will be attributed to the role of hardening effect which was ensured by hardness inspection{percent of hardness increment is 75%}, compressive residual stresses due to rapid quenching from a high temperature (austenite region) to the room temperature (still air) and formation of hard fine laths of martensite at the surface skin only ,but the internal layers consist from grains of ferrite and pearlite, as reveled by microstructural study as in Fig. 2(Image5,6). The normalized alloy come in the third order in the improvement behavior this will be attributed to the role of hardening effect which was ensured by hardness inspection{percent of hardness increment is 20%},and microstrucrtre refining of ferrite and pearlite as reveled by microstructural study as in Fig. 2 (Image3) this increases the grain boundary area and the energy required to produce failure . Annealed alloy showed deterioration in tensile properties compared with the alloy in as received conditions this will be attributed to the role of grain growth which was revealed by microstructural study as in Fig. 2 (Image2),but also obvious fascinating improvement in fracture strain ,elongation which indicates an increment in ductility and machinability properties .

Fatigue Properties

The effect of different selected treatment on the fatigue properties (live .limit, strength, S-N curves) will be illustrated in fig.(5).Also Table 3 present the effect of different heat treatments on the experimental, theoretical, fatigue limit and other studied mechanical properties. Quenching - tempering treatment resulted in longest fatigue life and increment in fatigue limit when compared with laser surface treatment ,normalizing and annealing treatments respectively. This is seems to be due to full martensitic microstructure type as in Fig. 2(Image4) within which crack propagates during the entire fatigue life., whereas, the laser surface treated structure consists of fine-laths of tempered martensite at the surface skin only ,but the internal layers consist of grains of ferrite and pearlite as in Fig. 2(Image5,6). The normalized structure consists of fine grains of ferrite and pearlite, Fig. 2 (Image7) Annealed structure was coarse-grains of ferrite and pearlite as in Fig. 2 (Image3).The homogeneous tempered martensite has the highest fatigue properties with respect to the other microstructures, this is in conjunction with the improvement in tensile and yield strengths as in Table 3. This will be attributed to the fact that homogeneous structures results in homogeneous slip deformations so that local concentration of plastic deformations are avoided, thus causing dislocation across-slip more difficult [12].The improved fatigue properties of the laser surface treated structure which consists of fine-laths of tempered martensite at the surface skin only ,will be attributed to the fact of martensite formation accompanied with volume increase [13]. This leads to residual compressive stresses which relatively makes the crack spend more energy to grow and consequently hinders an initiated crack to propagate. The improved fatigue properties of the normalized structure is due to fine ferritic pearlitic structure, in conjunction with increment of grain boundary area, which represents an obstacles against the fatigue crack propagation, and increment of fatigue live. Annealing treatment results in lowest fatigue properties due to the soft coarse ferritic pearlitic structure in which ferrite grains dominate, as seen in Fig. 2 (Image2). Within the stages of crack initiation and propagation, the soft ferrite grains are deformed heavily by forming fine and uniform slip bands [14] thus encouraging fatigue cracks to initiate at slip bands rather than at the ferrite-pearlite interface,

Wear rate

Wear rates for quenching and tempering treatments indicate lower values ,that's in conjunction with improvement in wear resistance ,this behavior coincides with surface hardness improvement (this improvement behavior is correlated to the formation of hard fine martensite ,this mind is correlated with V.F. Siva et. Al [13] when they studied the influence of retained austenite on short fatigue crack growth and wear resistance of case carburized steel and attributed to the improvement of wear resistance to the formation of hard phases [13]. The laser surface treated alloy showed a similar behavior ,this was be attributed to the mind that wear resistance depends only on the skin properties, this mind is correlated with Fly et. al , when they studied the low power laser heat treatment to improve fatigue life of low carbon steel [4] . The normalized structure shows a lower values ,that's in conjunction with improvement in wear resistance , this behavior coincides with surface hardness improvement (this improvement behavior correlates to the refining effect) this behavior was in conjunction with researcher A.fawzy mind when he Studded the pack cementation effect on the wear properties of medium carbon steel[15]. Annealed alloy results in highest wear rate and deterioration in wear resistance due to the soft coarse ferritic pearlitic structure and decrement of hardness values.

Conclusions

1. In this research for the selected alloy the hardening - tempering treatment gives the superior tensile properties, fatigue properties wear resistance , hardness compared to laser surface ,normalizing and annealing respectively.
2. The microstructural study revealed martensite formation along the cross-sectional area of hardened –tempered alloy, but for laser surface treated ,it revealed this phase at the skin only.
3. Annealing treatment gives an obvious deterioration in all mechanical properties.
4. Annealing, normalizing treatment give no change in phases ,but caused a change in their grain size ,so that the variation in grain size caused change in mechanical properties .
5. Full phase transformations resulted due to hardening - tempering treatment ,although laser surface treatment gave a partial(surface) phase transformations .
6.There is an obvious correlation between hardness valued and fatigue strength.
7. Improvement in fatigue strength for hardened –tempered, laser surface treated, normalized ,and deterioration for annealed conditions .
8.The improvement in tensile properties may represent a good criteria for fatigue strength improvement.

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Table (1) Chemical composition of materials (wt %).

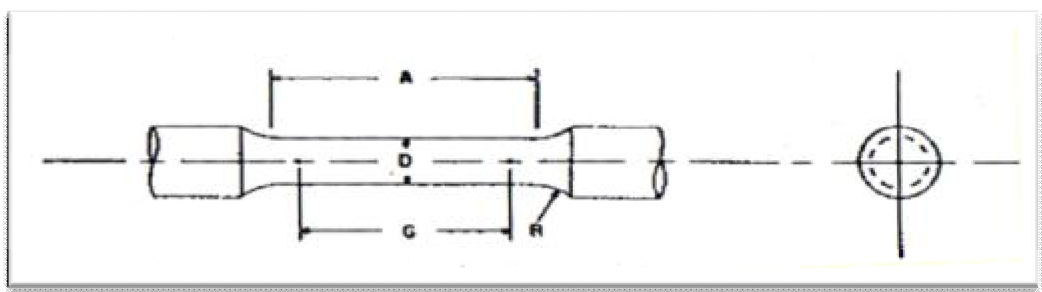
Ingredient	C	P	Si	Ni	Mn	Cr	Mo	V	Cu	W	Ti	Mg	Fe
Percentage	0.45	0.0158	0.4	0.101	0.311	0.05	0.09	-	-	-	-	-	98.1

Table (2) Heat Treatment procedures applied to the selected steel alloy.

Treatment type	**Full Annealing**	**Normalizing** Grin refining	**Water Quenching followed by Tempering** {Bulk Hardening}	**Laser surface treatment** {partial hardening}
Treatment conditions	1.Austenitize at 800 °C and hold for 1 hour. 2. furnace cooling.	1. Austenitize at 800 °C and hold for 15 minutes. 2. still air Cooling.	1. Austenitize at 800 °C hold for 15 minutes. 2. Quench in water. 3. Temper by reheating at 200 °C for 1 hour. 4. cooling in a furnace.	1. laser irradiation using 1000mJ for 1sec with 8 pulse for each 1mm zone.

Table (3) Mechanical properties of selected steel measured after different treatments.

Mechanical properties		Vickers Hardness	Fracture Tensile Strength (MPa)	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	F.l experimental (MPa)	F.l predicted (MPa)	Elongation	Fatigue Ratio	F.l Percentage of improvement	Fatigue live equation
Selected Treatment	As received	200	427	555	467	190		17	34.2	-------	$\sigma= 3542.Nf^{-0.22}$
	Full Annealing	164	315.5	519	313	170		43	32.7	-10%	$\sigma= 2265.Nf^{-0.2}$
	Normalizing	240	583	707	501	220		14	31.1	16%	$\sigma= 5078.Nf^{-0.24}$
	Water Quenching followed by Tempering	**433**	**1033**	**1069**	**906**	**288**		**12**	**27**	**34%**	$\boldsymbol{\sigma= 5918Nf^{-0.24}}$
	Laser surface treatment	350	710	882	624	235		18	25	24%	$\sigma= 3991Nf^{-0.22}$



D:cross sectional diameter=**4**, **G**:gage length =**16**, **A**; length of reduced section =**20**, **R**; radius of fillet=**0.08** , all dimensions in mm and the samples must obey to this relation (**A=5D**).

Figure (1a.)Show the shape &dimension of tensile sample test according ASTM A370,E 8

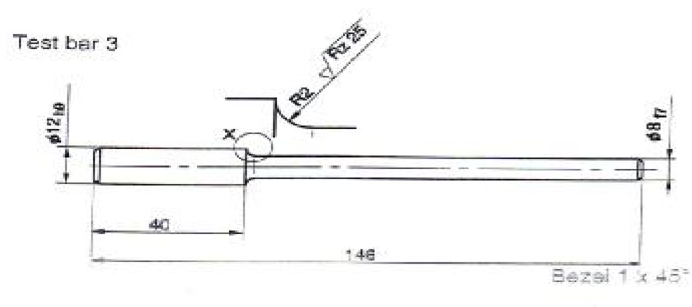
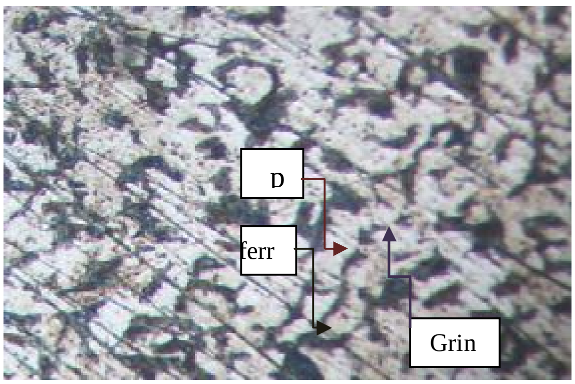


Figure (1b.) Show the shape &dimension of Fatigue Sample test according ASTM E 468.



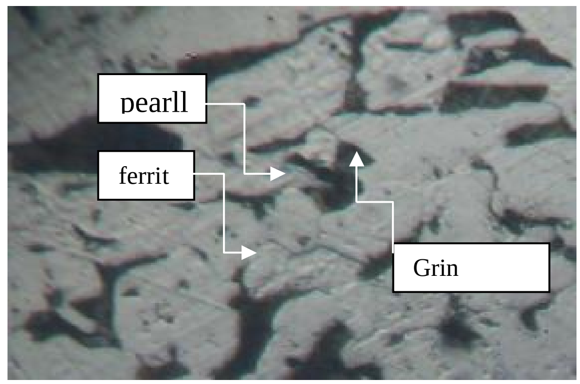
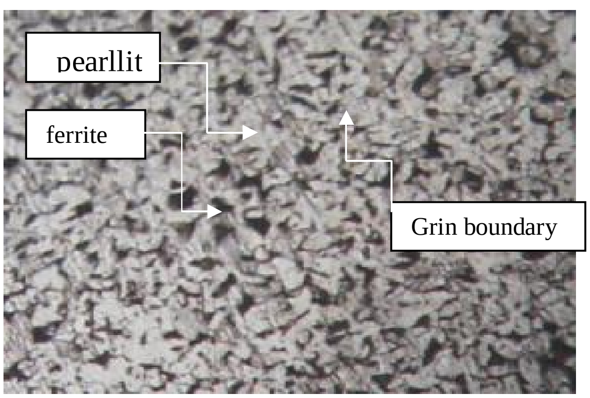


Image (1) As received condition X50 , **Image (2) annealed condition X50**



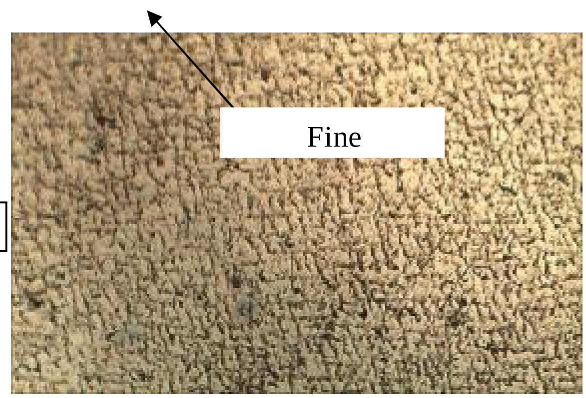


Image (3) Normalized X50 **Image (4) Quenched + Tempered X200**

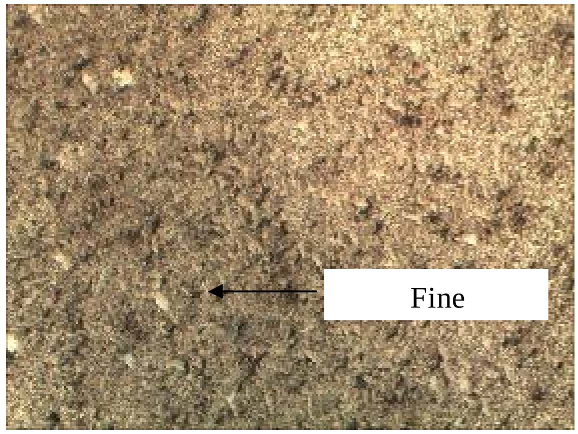


Image (5) laser surface treated core X50 **Image (6) laser surface treated case X200**

Figure (2) Microstructures images illustrate the created phases for selected various heat treatments to the medium carbon steel.

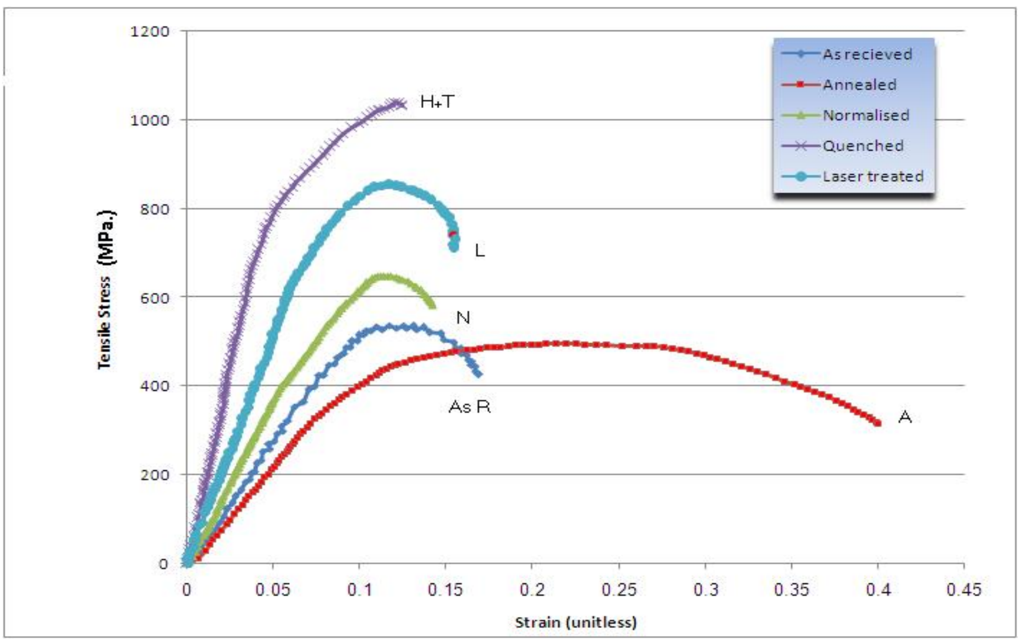


Figure (3) Stress –Strain curves for selected various heat treatments to the medium carbon steel.

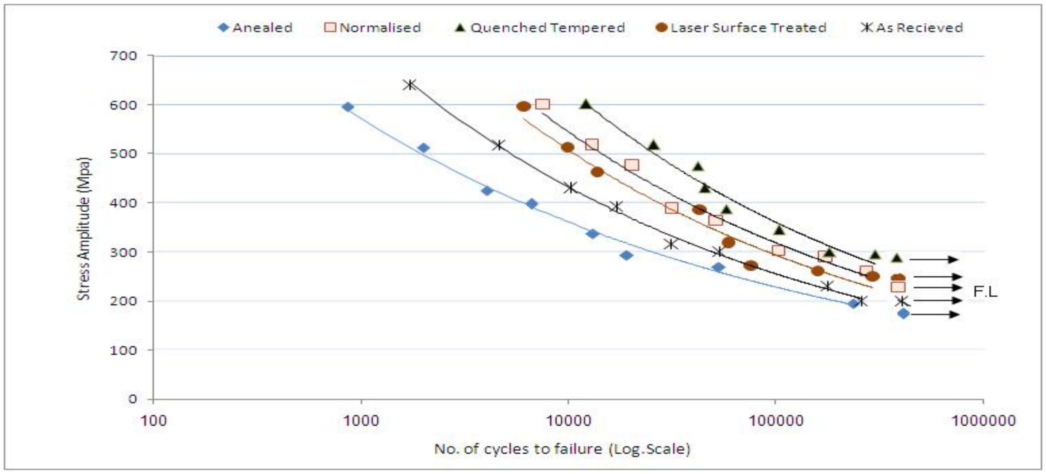
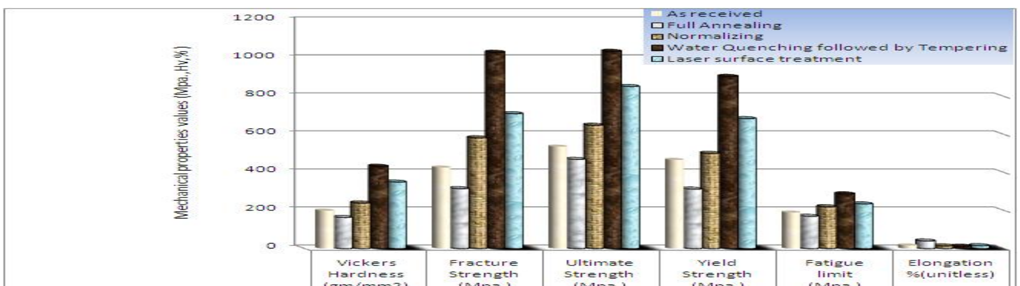
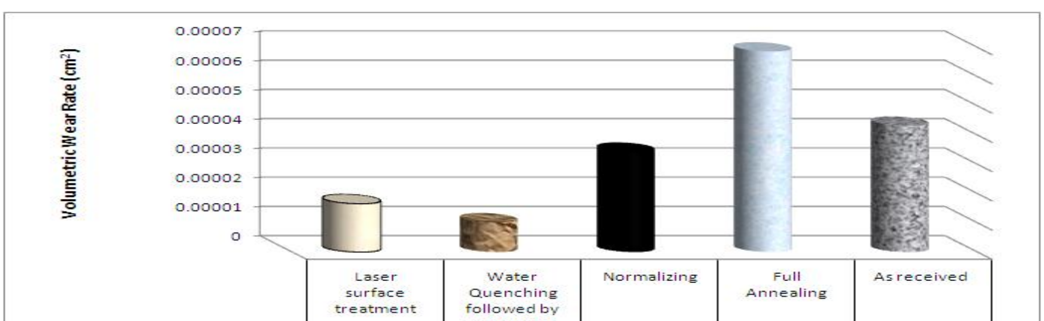


Figure (4) Block diagram show the variation of mechanical properties with selected various heat treatments to the medium carbon steel.



	Vickers Hardness (gm/mm2)	Fracture Strength (Mpa.)	Ultimate Strength (Mpa.)	Yield Strength (Mpa.)	Fatigue limit (Mpa.)	Elongation %(unitless)
As received	200	427	536.75	467	190	16.87
Full Annealing	164	315.5	469.4	313	170	40
Normalizing	240	583	649	501	220	14.21
Water Quenching followed by Tempering	433	1033	1038	906	288	12.49
Laser surface treatment	350	710	853	684	235	15.4

Figure (5) (semi –log.)Stress-No. of cycles to failure (S-N) curve for selected various heat treatments to the medium



	Laser surface treatment	Water Quenching followed by Tempering	Normalizing	Full Annealing	As received
Volumetric Wear Rate	1.65184E-05	1.01652E-05	3.43075E-05	6.8615E-05	4.3202E-05

Treatment condations

Figure (6) Variation of wear rate for selected various