Effect of Heat Treatments On Fatigue Life Of 1015 Carbon Steel

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Abstract

Fatigue is considered as the most dangerous cause of failure in industrial applications, and many of mechanical parts fail by fatigue. On the other hand, carbon steel is very important material in many industrial applications due to its properties and ability of regulating them by heat treatments, so this research investigates the effect of heat treatments on the fatigue life of carbon steel. The research material is AISI 1015 carbon steel, which is subjected to four kinds of heat treatments, annealing, normalizing, hardening and tempering into 450 ^{o}C and 650 ^{o}C respectively. Fatigue tests were done for the material before and after heat treatments. The results showed that annealing is not largely affects fatigue life, normalizing raises fatigue life into about 40%, while tempering shortens the fatigue life into about 30%. The fatigue life decreases by increasing tempering temperature.

Key words: fatigue life, 1015 carbon steel, heat treatments.

الخلاصة:

يعتبر الكلال من اكثر الاسباب خطورة في الفشل في التطبيقات الهندسية, والكثير من الأجزاء الميكانيكية تفشل بسبب الكلال. وفي الجانب الاخر, يعتبر الفولاذ الكاربوني مادة مهمة جدا في التطبيقات الصناعية بسبب مواصفاتها وإمكانية التحكم بها من خلال المعاملات الحرارية, لذلك فان هذا البحث يعمل على دراسة تاثير المعاملات الحرارية على عمر الكلال للفولاذ الكربوني. المادة المستخدمة في البحث هي الفولاذ الكاربوني 1015 حسب تصنيف AISI, و التي عرضت لاربعة معاملات حرارية هي التخمير و التطبيع و التقسية مع المراجعة الى درجتي حرارة هما ^{o}C 450 و^{o}C 650 على التوالي. ثم اجريت فحوص الكلال على عينات المادة قبل وبعد المعاملات الحرارية, وبينت نتائج الفحوصات ان التخمير لم يؤثر بدرجة كبيرة على عمر الكلال للمادة, بينما حسّن التطبيع عمر الكلال بحدود 40%, و عملت المراجعة على تقصير عمر الكلال للمادة بحدود 30%. وكان عمر الكلال ينقص كلما زادت درجة حرارة المراجعة.

الكلمات المفتاحية: عمر الكلال, الفولاذ الكاربوني 1015, المعاملات الحرارية.

Introduction And Literature Survey

Heat treating is a process utilized to change certain characteristics of metals and alloys in order to make them more suitable for a particular kind of application. In general, heat treatment is the term for any process employed which changes the physical properties of a metal by either heating or cooling. When properly performed, heat treating can greatly influence mechanical properties such as strength, hardness, ductility, toughness, fatigue resistance and wear resistance. The large number of service requirements and amount of alloys available make for a considerable variety of heat treating operations. Most carbon steels can be heat treated for the purpose of improving these mechanical properties. This is accomplished due to the heat treatment fundamentally altering the microstructure of the steel (Fastenal Engineering and Design Support, 2009).

Many attempts have been made to discuss this phenomenon. Jean (1999) describes a fatigue life prediction model accounting for high temperature applications of metallic materials. The formulation of the model is for general anisotropy and multiaxiality of loading. This phenomenological model distinguishes between an initiation phase and a propagation phase, and takes into account oxidation and creep effects on fatigue life. An application of the model is given for a coated single crystal superalloy for turbine blades. Model predictions are in good agreement with a large set of experimental data for mechanical loading including thermomechanical fatigue tests. A new experimental device, designed to produce a thermal gradient in the thickness of thin walled specimens, is also presented. This device has been used with polycrystalline and monocrystalline superalloys. Corresponding life predictions, performed by using recent anisotropic models, are presented for the single crystal superalloy.

Sudhakar et.al (2000) studied Dual phase steel which was intercritically annealed at different temperatures from fully martensitic state to achieve martensite plus ferrite, microstructures with martensite contents in the range of 32 to 76%. Fatigue crack growth was carried out as per ASTM standards E 647 to evaluate the potential of the steels. The crack growth rates (*da/dN*) at different stress intensity ranges were determined to obtain the threshold value of stress intensity range. Crack path morphology was studied to determine the influence of microstructure on crack growth characteristics. These rates decreased and threshold values increased with increase in vol.% martensite in the steel. This is attributed to the lower carbon content in the martensite formed at higher intercritical annealing temperatures, causing retardation of crack growth rate by crack tip blunting and/or deflection. Results indicate the possibility that the steels may be treated to obtain an excellent combination of strength and fatigue properties.

The effects of tempering temperatures of range 30 to 600°C on the fatigue properties of AISI 410 Stainless Steel Rods were experimentally investigated and presented by A.J. Alawode et.al (2008). Fatigue limit was found to decrease with increase in tempering temperature; at 10^7 cycles to failure, the fatigue strength of non-corroded as-received specimen increased from 310 to 520 MPa due to tempering. at fatigue stress of 550 MPa, the fatigue life of non corroded as received specimen was elongated from $10^{3.8}$ to $10^{3.7}$ cycles to failure after quenching, while tempering as-quenched specimen at 400 and 600°C caused its fatigue life to be shortened to $10^{4.8}$ and 10^4 cycles to failure, respectively.

Experimental Work

The experimental work started with selecting material for tests by examining its chemical composition and mechanical properties, then processing some heat treatments on it, so its mechanical properties were testes again after each heat treatment. Finally, constant amplitude fatigue test was achieved for each heat treated specimen.

Material

The selected material for the experimental work is 1015 carbon steel as AISI designation. The standard and experimental chemical composition in percentage weight (%wt) of the selected material is shown in Table (1).

Table (1) Standard and experimental chemical composition of 1015 AISI carbon steel (%wt).

Element	C	Mn	P	S	Fe
Standard Composition(Engineering Handbook, 2004)	0.14	0.6	0.04	0.05	Rem.
Experimental Composition	0.13	0.4	0.03	0.05	Rem.

Mechanical Properties before Heat Treatments:

Pretest of static properties was performed by axial tensile test, this was at room temperature (approximately 30^{o}C) by universal testing machine (WP 300) shown in Fig. (1) in Laboratory of Metals in Mechanical Techniques Department/Technical Institute in Karbalaa.

Fig.(1) universal testing machine (WP 300).

The specimens were prepared for these tests according to the testing machine requirements (WP 300) for Din 50125 standards as shown in Fig (2). Table (2) shows the tensile properties from these tests with the standard values of the alloy at room temperature. Each value is an average of two tests.

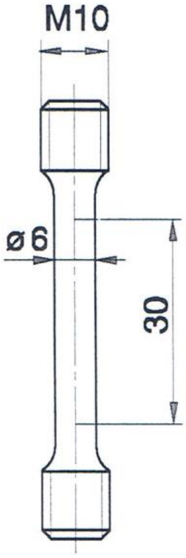

Fig.(2) tensile test specimen

Table (2) Mechanical properties of 1015 carbon steel before heat treatment.

Property	Yield stress σ_y (MPa)	Ultimate stress σ_u (MPa)	Elongation %	Modulus of elasticity, *E* (MPa)	Hardness (HB)
Standard values(Gandy, 2007) (Room Temp.)	165	310	30	550	120
Experimental values (Room temp.)	158	290	28	564	143

Heat Treatments

Many heat treatments were selected to be applied in the investigation work to allow studying be more efficient and clear. These were annealing, normalizing, hardening and tempering.

Special furnace shown in Fig.(3) was used to cover all treatments, which are processed in Laboratory of Metals in Mechanical Techniques Department/Technical Institute in Karbalaa.

Fig.(3); Heat treatment furnace (LapTech).

Annealing was achieved by heating the specimens gradually to the austiniting temperature, 870 ^oC (Brook, 1996), then holding them at this temperature for about one hour, then leaving them to cool inside the furnace until reaching room temperature (30 ^oC).

Normalizing was achieved as annealing (Brook, 1996) except that the cooling to room temperature was achieved in outside air.

Hardening (Krauss, 1990) was existed by quenching the specimens in water, then two tempering treatments were processed (Krauss, 1990), first was tempering quenched specimens to 450 ^oC, and second was tempering the rest quenched specimens to 650 ^oC.

Mechanical Properties after Heat Treatments:

After each heat treatment, the specimens that specialized for tensile test were subjected again to tensile test by the WP 300 tester to find the yield limit and ultimate strength of the material and how they effected by the heat treatment, then the predicted fatigue limit, the maximum stress below which the specimen can theoretically endure and infinite of number of stress cycles (Alawode *et al.*, 2008), was determined by the following equation(Khurmi & Gupta, 1990):

$$\sigma_e = 0.5\sigma_u \ldots\ldots\ldots(1)$$

where σ_e is the endurance fatigue limit, and

σ_u is the ultimate strength of the material.

Table (3) shows the ultimate and predicted endurance limit for the material after each heat treatment, while Fig.(4) shows the stress-strain diagram for the treated specimens.

Table (3) ultimate and predicted endurance limit for 1015 carbon steel before and after heat treatment.

Treatment	σ_u (Mpa)	σ_e (MPa)
Without heat treatment	310	155
Annealing	375	187.5
Normalizing	432	216
Hardening and tempering for 450 ^oC	456	228
Hardening and tempering for 650 ^oC	386	193

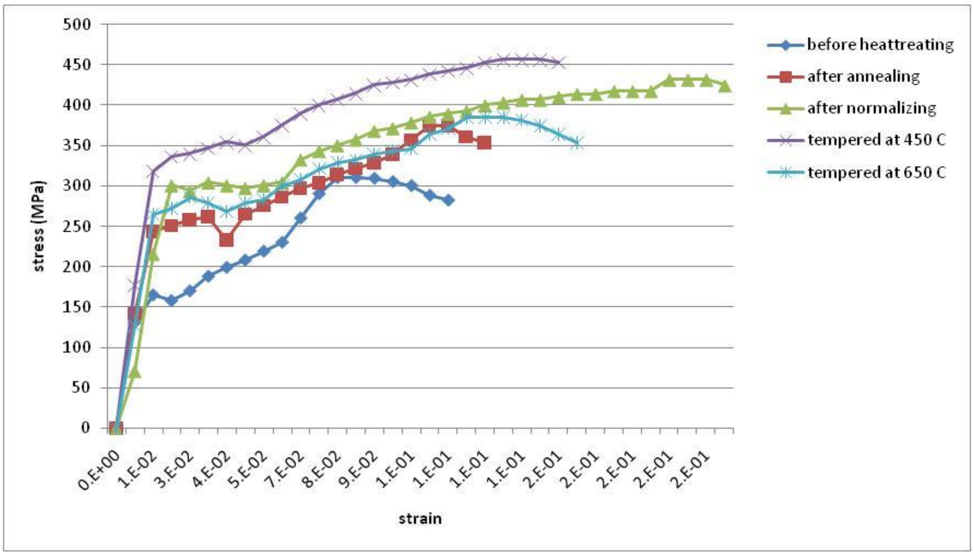

Fig.(4) stress-strain diagram for the 1015 carbon steel before and after heat treating.

Fatigue Test:

The specimens were prepared to conform a standard E 466 as in Fig.(5), then subjected to constant amplitude fatigue tests at room temperature. The tests were achieved by fatigue machine made locally by the Technical Institute In Karbalaa/ Mechanical Techniques Department, which is shown in Fig. (6). This machine working by completely reversed stress amplitude with zero mean stress, rod specimen. A revolution counter was fitted to the machine motor to record number of cycles when specimen is fractured. The applied stresses were calculated as described by Mahir (2009).

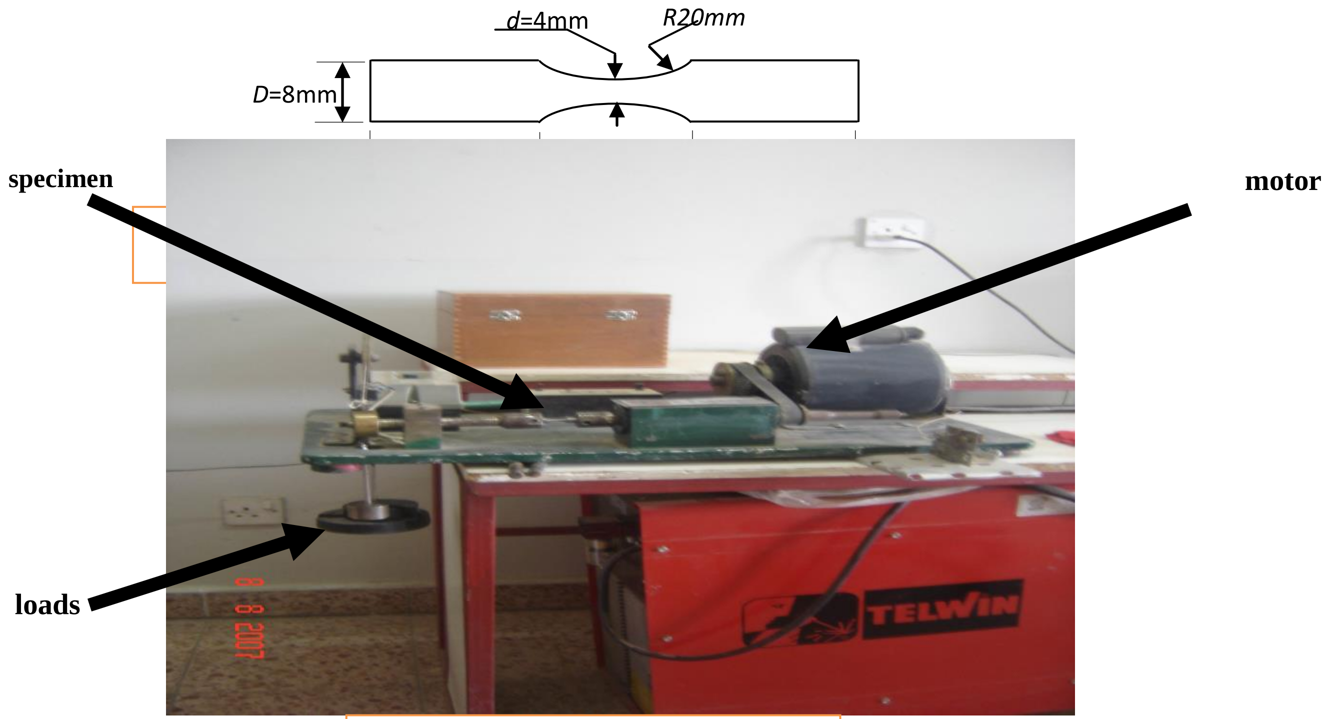

Fig. (6) Fatigue Testing Machine.

The applied stresses were selected to be under and equal to the ultimate stress of the specimen for each treatment.

Results And Discussion

The resulted readings from fatigue tests are shown in figures (7) to (11) as Stress-Number of Cycles curves (S-N), while Fig.(12) shows the comparison in S-N curves between all tests.

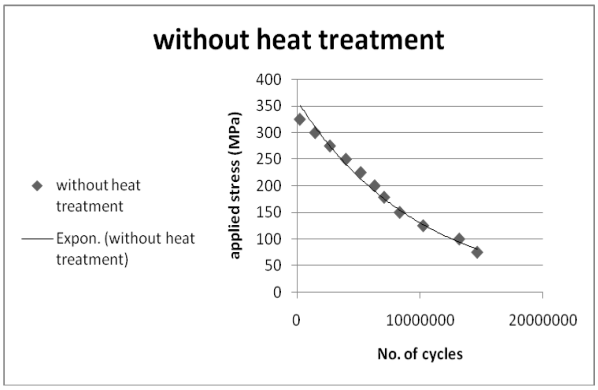

Fig. (7) S-N curve for 1015 carbon steel before heat treatment.

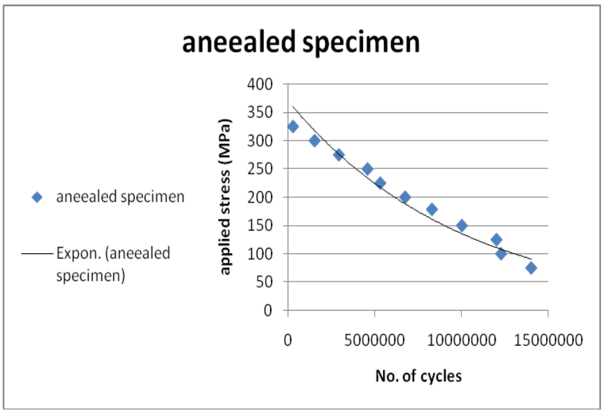

Fig. (8) S-N curve for 1015 carbon steel after annealing.

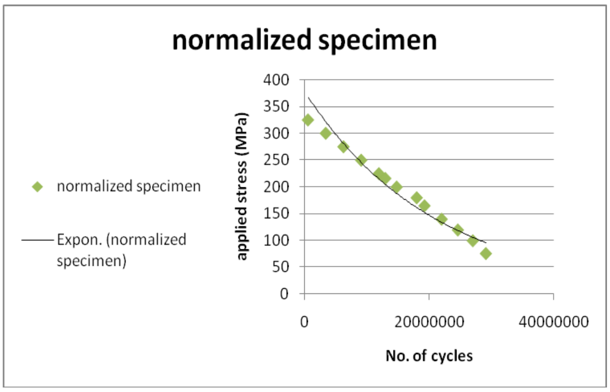

Fig. (9) S-N curve for 1015 carbon steel after normalizing.

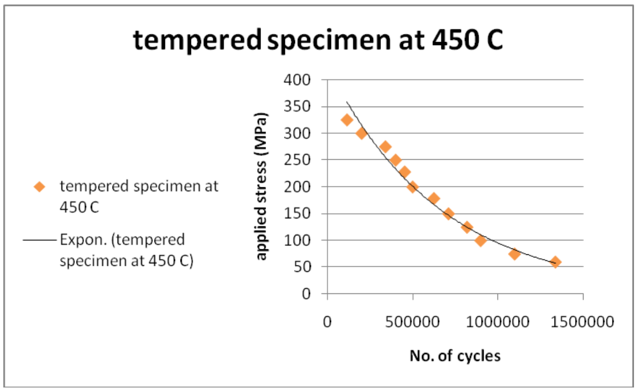

Fig. (10) S-N curve for 1015 carbon steel after tempering to 450°C

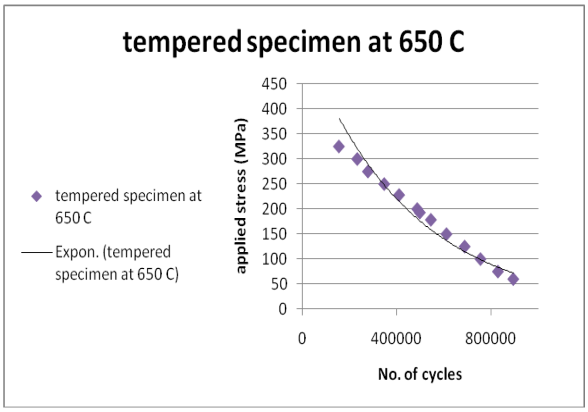

Fig. (11) S-N curve for 1015 carbon steel after tempering to 650 °C.

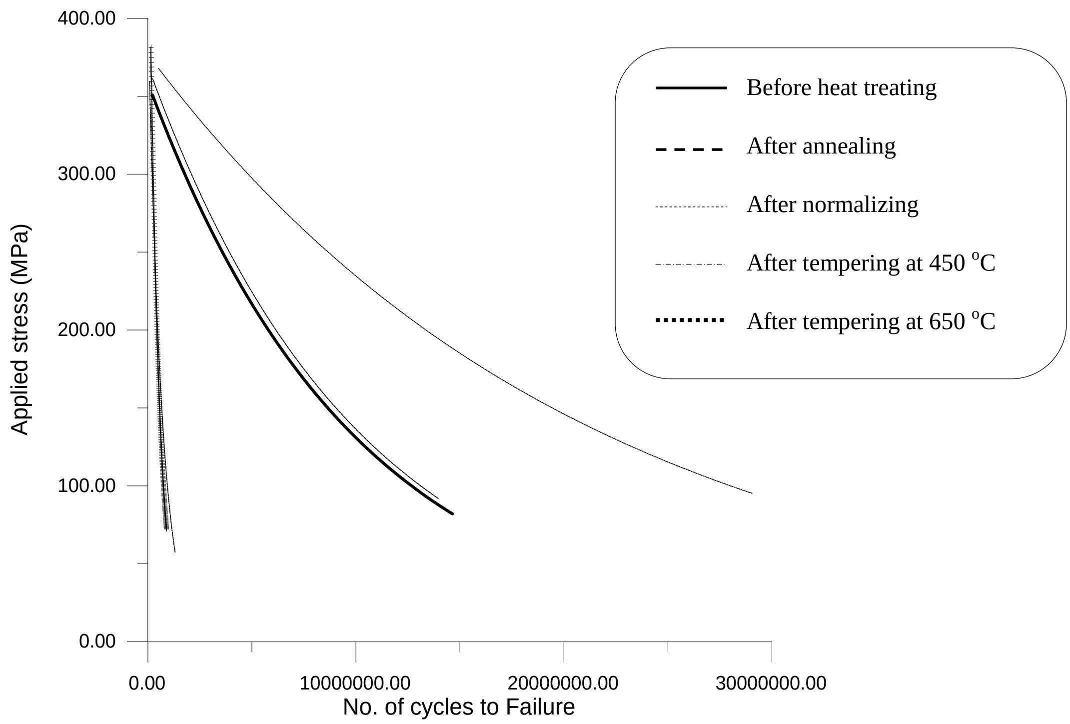

Fig. (12); S-N curve for 1015 carbon steel before and after heat treating

The above S-N curves can be described by the following Eqns;

Without heat treating: $\sigma = 359.403 N^{-10^{-7}}$ ……..…(2)

For annealing: ………(3)

For normalizing: $\sigma = 391.33 N^{-1.1\times10^{-7}}$ ………(4)

For tempering at 450 ^{o}C: $\sigma = 410.433 N^{-5\times10^{-8}}$ ……..(5)

For tempering at 650 ^{o}C $\sigma = 434.697 N^{-1.5\times10^{-6}}$ ………(6)

$\sigma = 559 N^{-2.27\times10^{-6}}$

where; σ is the applied stress in (MPa) and N is the number of cycles to failure.

Thus, the fatigue life for the material can be predicted by substituting the endurance limit value in Table (3) in the above Eqns., the results are listed in Table (4).

Table (4) predicted fatigue life of 1015 carbon steel before and after heat treatment.

Treatment	**σ_u (Mpa)**	**Fatigue life (cycles)**
Without heat treatment	155	3.6×10^{7}
Annealing	187.5	3.3×10^{7}
Normalizing	216	6.4×10^{7}
Hardening and tempering for 450 ^{o}C	228	2.4×10^{6}
Hardening and tempering for 650 ^{o}C	193	1.7×10^{6}

From the above table it seems that annealing has no clear effect on fatigue life, and the reason may refers to the original selected material, which may not be subjected to any work hardening before, so annealing did not affect its properties.

Normalizing is the large positive effecter in this work, so it raises fatigue life to about 40%, while it was about 34% in Zabett *et al.*, (2008) work. Normalizing causes significant transformation from austenite into perlite and ferrite (Celik *et al.*, 2009), which improving the material strength, so the fatigue limit is improved, too. Also, normalizing is considered as no-rabid hardening treatment, so it prevents creation of micro cracks as it may happen in high cooling rate treatments (Gandy, 2007).

Normalizing treatment homogenizes and refines the microstructure and softens the steel. Homogenization and microstructure refinement improve mechanical properties and prevent distortion or cracking of parts with complicated shapes during hardening, while softening reduces machining costs. If the part does not need machining, and has a simple shape, normalizing treatment may be eliminated from the process to decrease manufacturing costs. For this decision, the effect of normalizing on the mechanical properties of the part should be considered with an emphasis on the fatigue life of the parts(Zabett *et al.*, 2008).

Quenching and tempering treatments reduced the fatigue life in large degree, and the predicted fatigue life of 1015 carbon steel is shortened in about 30% when the tempering temperature was increased into about 200 ^{o}C. This reduction can be accepted if compared with Alawode [4] result, which was about 22%. The declining in fatigue life could be attributed to the stress concentration effect of thin carbide films that are formed during the tempering of martinsite, which is formed by quenching(Alawode *et al.*, 2008).

This investigation did not consider effect of microstructure and grain size on the fatigue life, so it is recommended to be a subject of future study.

Conclusions

The following conclusions can be drawn from this investigation concerning effect of heat treatments on fatigue life of 1015 carbon steel:

1. Annealing does not affect fatigue life largely, especially when the research specimen is not worked hardly before or keeps any residual stresses.

2. Normalizing increases fatigue life by forming strong structure with perlite and ferrite. It gave the best results in this investigation.
3. Hardening and tempering shortens fatigue life largely due to thin films of carbides formed during tempering martensite.
4. Increasing in tempering temperature causes more decreasing in fatigue life.

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References

Fastenal Engineering and Design Support, www.fastenal.com, 2009.

Jean-Louis Chaboche, " **Fatigue Life Prediction of Single Crystals for Turbine Blade Applications**", *International Journal of Damage Mechanics*, Vol. 8, No. 4, pp. 404-427 (1999), France.

Sudhakar K V and E S Dwarakadasa, "**A Study on Fatigue Crack Growth in Dual Phase Martensitic Steel in Air Environment**", *Bull. Mater. Sci.*, Vol. 23, No. 3, pp. 193–199, 2000.

Alawode, A.J. ; M.O. Akomolede and A.O. Agbanigo, " **Effects of Tempering Temperatures and Corrosion on the Fatigue Behaviours of AISI 410 Stainless Steel Rods**", *journal of engineering and applied sciences*, Vol. 3, No. 5, pp. 390-395, 2008.

"**Engineering Handbook**", Industrial Press Inc., New York, 2004.

Gandy, D. "**Carbon Steel Handbook**", Electric Power Research Institute, Final Report, March 2007.

Brooks, C. R., "**Principles of the Heat Treatment of Plain Carbon and Low Alloy Steels**", ASM International, Materials Park, OH, 1996.

Krauss, G., "**Steels—Heat Treatment and Processing Principles",** ASM International, Materials Park, OH, 1990.

Khurmi R. S. and J. K. Gupta, **"A Text Book of Machine Design",** 10th Edition, Eurasia Publishing House (Pvt) Ltd, 1990.

Mahir H. Majeed, " ***Accumulated Damage in Fatigue-Creep Interaction of Aluminum Alloy 2024 T4***", *University* of Technology, Iraq, Ph D. Thesis, p 44-45, 2009.

Zabett, A.; R. Irankhah, M. Miri Disfani, I. Zohur Karimi, M. Hashemi**, "FATIGUE LIFE OF FORGED, HARDENED AND TEMPERED CARBON STEEL WITH AND WITOUT NORMALIZING",** Ferdowsi University of Mashad, Iran, 2008.

Celik, O.N.; H. Gasan, M. Ulutan , M. Saygin, " **An investigation on fatigue life of borided AISI 1010 steel**"; *Journal of Achievements in Materials and Manufacturing Engineering*, vol. 32, ISSUE 1, January 2009.