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Influence of Bainitic Transformation on Fatigue Behaviour of Medium Carbon Steel

F. F. Osasere Orumwense[1], Okeoghene Henry Emonena[2], Segun Afokhainu Agbadua[3, *]

[1]Department of Mechanical Engineering, University of Benin, Benin City, Nigeria

[2]Direct labour Agency, Asaba, Nigeria

[3]National Engineering Design Development Institute, Nnewi, Nigeria

Email address:

vc@uniben.edu (F. F. O. Orumwense), ena_hen@yahoo.com (O. H. Emonena), afokhainu@yahoo.com (S. A. Agbadua)

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Abstract: This paper examines the behavior of medium carbon steels subjected to a bainitic transformation. The compositional analysis was performed to ascertain the percentage of carbon in the as-received materials. The specimens were machined to a precise gauge length and exposed to various bainitic transformation temperatures. Fatigue test was also performed with the use of Avery Dennison and bending stress was obtained using the curve supplied with the machine. The medium carbon steel specimens were austenitized at 900°C and then transformed into bainite at 200, 300 and 400°C for one hour and also at 300°C for periods of 20, 40, 60, 80, 100, 120 and 140 minutes to obtain various bainitic transformation microstructures. The results from the machine were converted to Mega Pascal (MPa) and the values used to plot S-N curves and fatigue behavior for the specimens at various bainitic transformation temperatures at different times were established. It was discovered that bainitic transformed medium carbon steel showed improved fatigue behavior.

Keywords: Isothermal Heat Treatment, Bainitic Transformation, Bainitic Microstructures

1. Introduction

Bainite originally was described as consisting of only two distinguishable microstructures upper and lower bainite. Upper bainite consists of lathe with carbides at the lathe boundaries. Lower bainite consist of plates or lathe containing arrays of carbides that form at 60°C to the plate axis. In the 1960s, it was discovered that when certain low-carbon, low-alloy steels were transformed by continuous cooling to ambient temperature (as opposed to an isothermal transformation) the morphology of the bainite microstructure that formed was different from the classical upper and lower bainite. Two class of “non-classical” bainite were identified: carbide free acicular and granular bainite (the name being descriptive of the microstructure). Which microstructure formed depended on the cooling rate from the austenitization temperature [2]. However, for carbon steels and most of the alloys steels pearlitic and bainitic bays in the time, temperature, transformation curves overlap and austenite transforms to pearlite or martensite depending on the cooling rate. In such steels, bainite cannot be produced by continuous cooling. It can be formed by cooling austenite isothermally at a sufficiently high rate so that its transformation to pearlite is suppressed. The properties of bainitic steels are believed to depend on the crystallographic texture that develops as a consequence of transformation from austenite. This can be clearly understood from the concept of bain strain. The Bain strain is the pure part of the lattice deformation which for displacive transformation in steel converts austenite into ferrite or martensite. During the Bain strain, no plane or direction is rotated by more than 11^0. This defines the Bain region [3].

Bainite refers to a mixture of ferrite and carbide. This ferrite-carbide mixture has a basic difference with respect to pearlite. It is not lamellar in nature but rather dispersed. It has similar microstructure to martensite.

There are few studies of fatigue phenomena in bainitic steels because they have not had many structural applications when compared with martensitic alloys. Notable exceptions are the creep resistant alloys used in the power generation industry, where high cycle fatigue is an issue for rotating parts and thermal fatigue resistance becomes important for plant designed to operate intermittently. Fatigue crack propagation in hydrogen-containing environments (chemical or coal conversion plant and pressure vessel) can be life limiting and so there are more studies in this area for bainitic alloys. Sub-surface fatigue caused by rolling-contact stress can similarly limit the life of rails in the transportation industries [3]. Bainitic transformation of steel which is also known as austempering consists of heating steel to above the austenitizing temperature and then quenched in a salt bath maintained at a constant temperature above Ms point within the bainitic range (200 to 400°C in general) [2]. The steel is quenched and maintained at a constant temperature in the bath itself till all the austenite is transformed into bainite. Also, the distribution of carbide is on a finer scale. Hence higher magnifications than those required for resolution of pearlite are required to resolve the bainite which is formed within the temperature range stated above.

The concept of bainitic transformation is now being used in the development of new high strength steels with strength and toughness combination which match or exceed more expensive alloys at a lower cost. Medium carbon steels are heat treatable steels used for the production of machine parts such as bolts, crankshafts, gears and railroads [1]. These steel parts are constantly subjected to fatigue loading; hence the need to improve on their fatigue strength became necessary.

A material subjected to a repetitive or fluctuating stress will fail at a stress much lower than that required to cause fracture on a single application of load. Failures occurring under conditions of dynamic loadings are called fatigue failures, presumably because it is generally observed that these failures occur only after a considerable period of service. Fatigue has become progressively more prevalent as technology has developed a greater amount of equipment such as automobiles, aircraft, compressors, pumps, turbines etc subjected to repeated loading and vibration. Until today it is often stated that fatigue accounts for at least 90% of all service failures due to mechanical causes [1]. The following are the basic factors necessary to cause fatigue failure;

i) Tensile stress of sufficiently high value
ii) Large enough variation or fluctuation in the applied stress
iii) Sufficiently large number of cycles of the applied stress.

In addition there are lists of other variables such as stress concentration, corrosion, temperature, overload, residual stress, metallurgical structure that tend to alter the condition for fatigue. It is usually found that the onset of fatigue failure originates at surface irregularities arising from poor workmanship, material defect and geometric or strain discontinuities. This is because any change in section such as a hole, a change in shaft diameter, a groove, a keyhole, a material defect or even a tool mark gives rise to a concentration of stress [1]. below are fatigue behavior of a material;

The fatigue life of a material increases as the applied stress decreases.

a) There is marked scatter in any one stress test.
b) The fatigue limit for steels is empirically found to be about 0.4 times the ultimate tensile strength as conventionally determined
c) The life is not greatly affected by the frequency of application of the stress [1].

Though fatigue life can be addressed by care in design, fabrication and maintenance and proper selection of materials, it could be enhanced further by the use of phase transformation mechanisms that could lead to the development of other steel products like bainitic steels with better fatigue resistance.

Fatigue failure which was recognized long ago has become a major source of concern in modern technology as it accounts for most of the failures due to mechanical causes and it occurs without warning with dire consequences. Failure analysis of rails has demonstrated that fatigue crack propagation and fracture is one of the major reasons of broken rail derailment and other severe accidents [4]. Other area where fatigue poses a great threat is in automobiles, compressors, aircrafts, pumps and turbines. Early efforts to mitigate its effects were more in the use of more expensive alloys to strengthen the steel besides proper design and fabrication rather than phase transformation methods that could lead to the development of other steel products like bainitic steel with better fatigue resistance. Bainite structures exhibits a good combination of strength and toughness. Accordingly, it attracts more attention. However, the development of bainite steel was limited due to the complicated technique of isothermal treatment. Pickering and Irvine invented an air cooled low carbon bainite steel of Mo-B series in the late 1950's [5]. Many researchers have since been working on the bainitic transformation of steels and its improved properties and the development of new materials for specific application. M. Takahashi et al [6] developed a model on bainitic transformation to address; (i) the quantitative estimation of mixed microstructures of bainitic ferrite, austenite and martensite, (ii) the prediction of the onset of carbon precipitation during bainitic reaction

The aim of this work is to determine the influence of bainitic transformation on the fatigue behaviour of medium carbon steel and establish an understanding of the strengthening mechanism of medium carbon steels against fatigue using the bainitic transformation method as a veritable alternative to the use of more expensive alloys and to obtain information that might lead to a better understanding of the effect of various soaking times at a fixed bainitic transformation temperature of the medium carbon steels on their fatigue resistance.

2. Materials and Methods

2.1. Materials

2.1.1. Steel Specimen

Medium carbon steel was sourced from the market and the materials supplied in the form of hot-rolled bars. The compositional analysis was carried out at Obafemi Awolowo

University (OAU) Material Science and Engineering Laboratory and the composition is shown in Table 1.

Table 1. *Chemical composition of medium carbon steel.*

C	Si	S	P	Mn	Ni	Cr	Mo	V	Cu
0.2790	0.1570	0.0303	0.0089	0.7299	0.1194	0.1505	0.0137	0.0001	0.1494
W	As	Sn	Co	Al	Pb	Ca	Zn	Fe	
0.0001	0.0007	0.0087	0.0096	0.0071	-0.0014	-0.0001	0.0021	98.3342	

2.1.2. Fatigue Testing Machine (Avery Dennison7305 Model)

The fatigue testing machine used is Avery Dennison is designed to apply reverse loads with or without an initial static load. Grips are provided for torsion tests and for bend tests on flat specimens. Extra grips may be provided for bending tests on round specimens or for combined bending and torsion tests on round specimens. The load is imposed at one end of the specimen by an oscillating spindle driven by means of a connecting rod, crank and double eccentric. The eccentric is adjustable to give the necessary range of bending angle. The load is measured at opposite end of the specimen by means of a torsion dynamometer and the angle of twist is registered on dial gauges. Three dynamometers are supplied and calibration curves are provided giving the relationship between dial gauge reading and imposed torque. Initial static loads can be applied by rotating the dynamometer housing in its bearing by means of a pair of adjusting screws. The revolution counter fitted to the motor records the number of stress cycles to failure. When the specimen breaks the machine is stopped automatically by cut out switches. The dynamometer housing is adjustable along the length of the bed to accommodate varying length of torsion specimen.

2.1.3. Furnace (Carbolite Muffle Furnace)

The furnace used is carbolite muffle type of furnace which has a thermocouple pyrometer attached to it for reading the temperature range.

2.1.4. Acuscope Camera

The camera has a magnification of X 400. It was used to snap the specimen in order to reveal the microstructure.

2.2. Methods

2.2.1. Bainitic Transformation Process

The medium carbon steel specimens were heated to an autenitizing temperature of 900°C for one hour and then quenched in a salt bath to the bainitic transformation temperature range of 200 – 400°C. Thereafter, the specimens were cooled to room temperature. Three bainitic transformation temperatures were used; 200, 300 and 400°C at a fixed transformation period of one hour and transformation periods of 20, 40, 60, 80, 100, 120 and 140 minutes were selected at a fixed transformation temperature of 300°C. Ten sets of eight specimens each were soaked in the salt bath maintained at transformation temperatures and periods as specified above to enable transformation to bainite.

The fatigue test was carried out with the use of Avery Dennison testing machine (Avery model 7305). The machine was set up according to laid down procedures and the specimen securely held in place in the machine by grips provided for round specimens. The initial reading of the revolution counter was taken. The bending moment was measured by means of a torsion dynamometer which measured the load imposed at the opposite end of the specimen and the calibration curves that are provided with the dynamometer which gives the relationship between dial gauge reading and imposed torque. The machine was then switched on and allowed to run until the specimen breaks and the machine stopped automatically by means of cut-out switches. The final reading of the revolution counter was taken and the process repeated for all the specimens.

The bending stress was calculated using the following equation;

$$\sigma_s = \frac{32 \times P \times L}{\pi d^3} \quad (1)$$

Where σ is the stress, M_{max} is the maximum bending moment (Nm). W is the section modulus (mm^3), P is the applied load (N). L is the moment of length and d is the diameter of the test specimen.

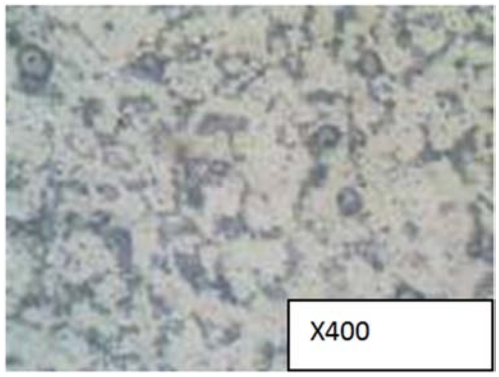

Fig. 1. *As-received Medium Steel.*

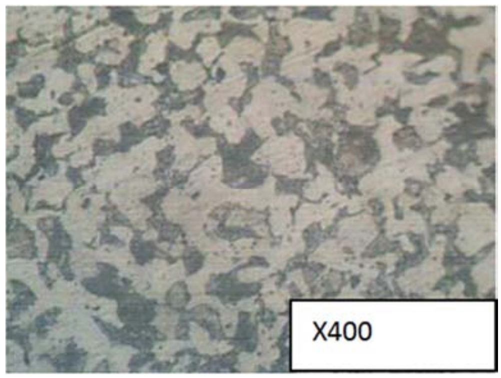

Fig. 2. *Bainitic Steel at 400°C for 60mins.*

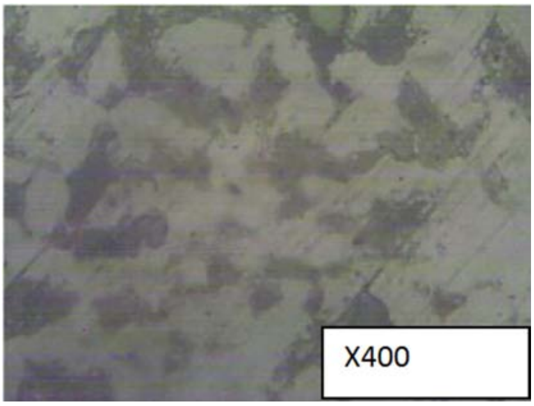

Fig. 3. *Bainitic Steel at 300°C for 20 mins.*

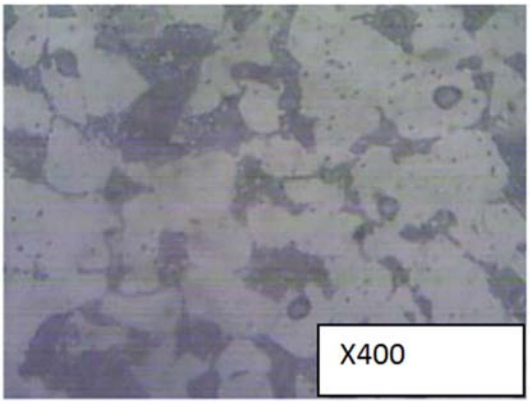

Fig. 4. *Bainitic Steel at 300°C for 40 mins.*

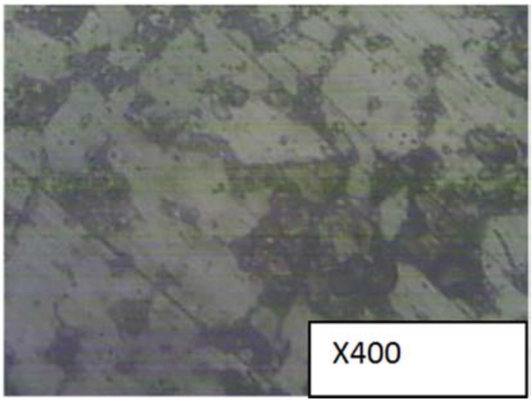

Fig. 5. *Bainitic Steel at 300°C for 60mins.*

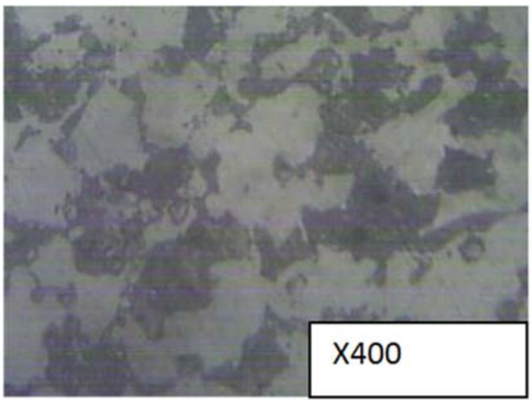

Fig. 6. *Bainitic Steel at 300°C for 80mins.*

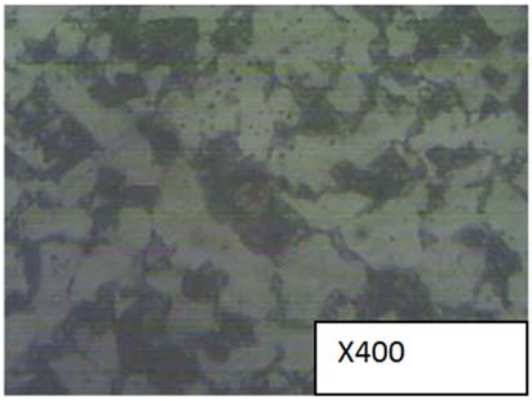

Fig. 7. *Bainitic Steel at 300°C for 100mins.*

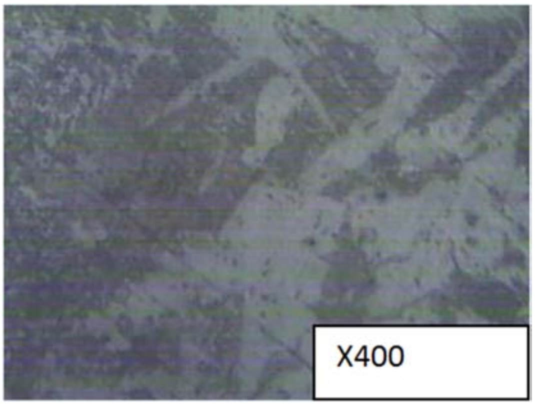

Fig. 8. *Bainitic Steel at 300°C for 120mins.*

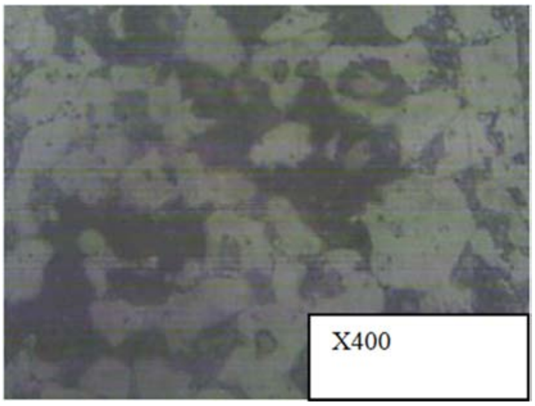

Fig. 9. *Bainitic Steel at 300°C for 40mins.*

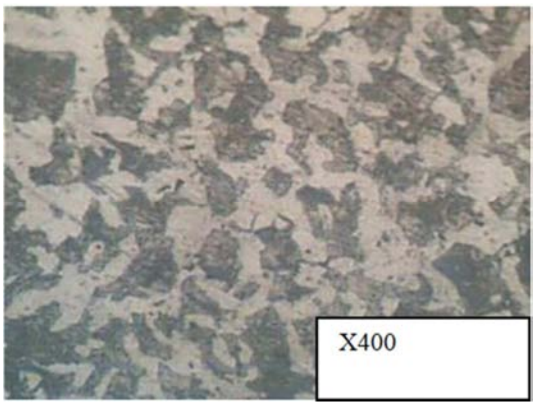

Fig. 10. *Bainitic Steel at 200°C for 60mins.*

2.2.2. Metallography

The specimens were prepared for examination under the microscope by cutting the specimens, carefully removing the disturbed layer and then rubbing the surface with successively finer abrasives until a smooth polished surface was obtained free from disturbing effects from the cutting and grinding.

Grinding was carried out with the aid of emery clothes of 240, 320, 400 and 600grit while the polishing was carried out, firstly, with the aid of emery cloth and silicon carbide of 1μm and finally, with emery cloth and silicon carbide of 0.5 μm. Etching was done with the use of Nital (2%) and photomicrograph acuscope camera was used to examine the microstructure at magnification of 400.

3. Results and Discussions

3.1. Fatigue Resistance

The medium carbon steels used in this research work were isothermally transformed into bainitic steel from the austenitizing temperature. Isothermal transformation is the main stage at which the bainitic transformation occurs. The time and temperature of isothermal transformation are the factors that affect the amount of bainitic transformation that occurs in the matrix. The two step reaction that takes place at this stage has an important influence on the fatigue behaviour of the medium carbon steel.

Firstly, the austenite (γ) decomposes into ferrite (α) and high carbon austenite. The morphology and relative amount of bainitic ferrite formed during this first reaction are largely determined by the isothermal transformation temperature and time

The isothermally transformed medium carbon steel samples were subjected to fatigue test using the Avery Dennison fatigue testing machine and the graphs of stress against the number of cycles to failures were plotted for each of the transformation times and temperatures stated earlier as shown in Fig. 11 – 21.

The fatigue resistance of each of the medium carbon steel samples transformed into bainitic steel at varying transformation times and transformation temperatures was also determined from Fig. 11- 21 and plotted as shown in Figs. 22 and 23. It is seen from the graph of fatigue resistance against transformation temperature (Fig. 23) that the resistance of the samples increased with increase in transformation temperature due to upper bainite structure obtained at elevated transformation temperature. At elevated temperature within the bainitic range, there is rapid growth of bainite and partitioning of carbide into the residual austenite. The essential thing to be considered in increasing bainite content in the matrix is the temperature at which transformation occur.

The isothermal transformation of the medium carbon steel samples from the austenitizing temperatures to the bainitic temperature range leads to the decomposition of the austenite (γ) to ferrite (α) and carbon-enriched austenite (τ_{HC}). The growth of upper bainite at higher transformation temperatures leads to the partitioning of carbon into the residual austenite. And since the rate of partitioning of carbon into retained austenite in upper bainite is slow as compared to the growth of bainite, fatigue resistance is improved as retained austenite which tends to martensite when cooled to room temperature is detrimental to fatigue life of the medium carbon steel. But at lower transformation temperatures some of the carbon precipitates from supersaturated ferrite and the rest are partitioned into the residual austenite. The growth of bainite at lower transformation temperatures is slower as compared to the rate of carbon precipitation hence fatigue resistance is low as compared to that at elevated temperatures as shown in Fig. 22. The second stage of the reaction shows that the transformation process is a function of time. Higher bainitic transformation temperatures resulted in increase in the fatigue resistance as shown in Fig. 21. This is due to the fact that as the transformation time increases, the second stage reaction which leads to the decomposition of carbon enriched austenite progresses leading to the production of more bainite in the matrix while reducing the austenite content in the matrix. Retained austenite is undesirable since it tends to martensite on cooling which is detrimental to fatigue resistance.

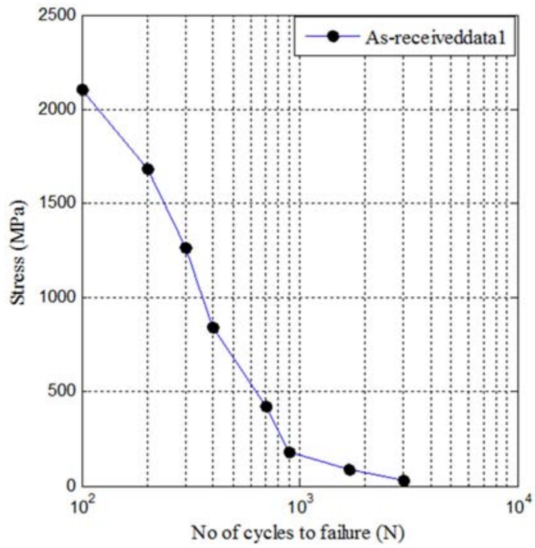

Fig. 11. *Fatigue Resistance (MPa) against Number of Cycles to Failure (N) of As-received.*

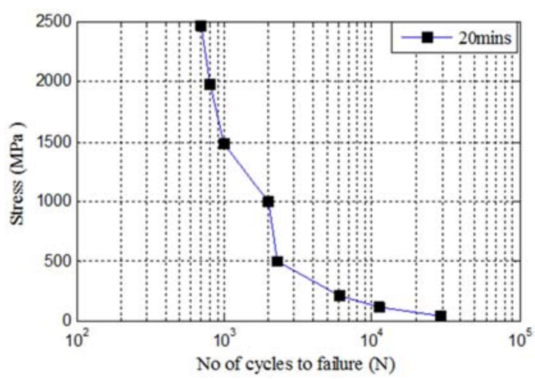

Fig. 12. *Fatigue Resistance (MPa) against Number of Cycles to Failure (N) at fixed Temperature of 300°C and varying Bainitic transformation time (20 minutes).*

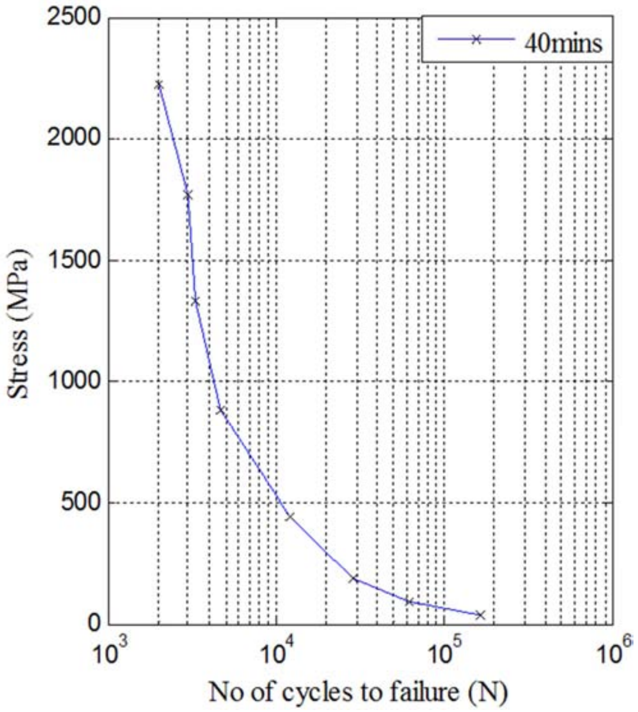

Fig. 13. *Fatigue Resistance (MPa) against Number of Cycles to Failure (N) at fixed Temperature of 300°C and varying Bainitic transformation time (40 minutes).*

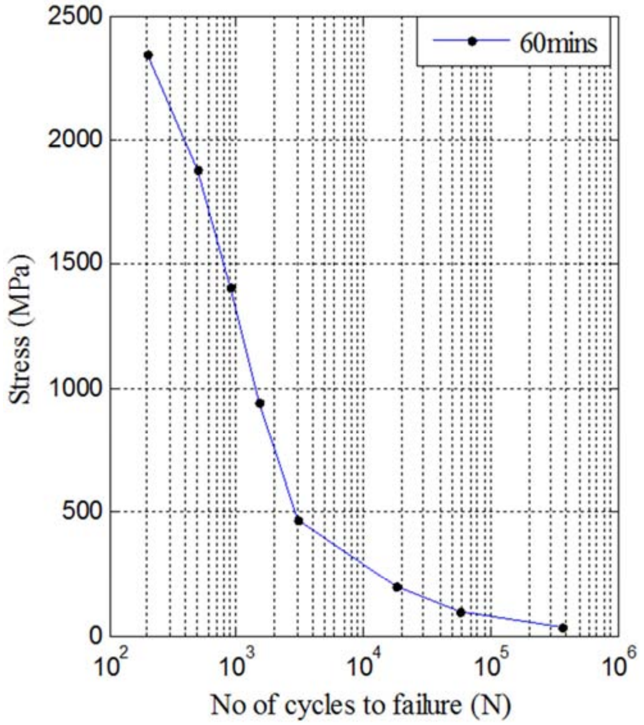

Fig. 14. *Fatigue Resistance (MPa) against Number of Cycles to Failure (N) at fixed Temperature of 300°C and varying Bainitic transformation time (60 minutes).*

3.2. Microstructural Examination of the Specimens

The properties of bainitic steels are believed to depend on the crystallographic texture that develops as a result of transformation from austenite. An important characteristic is the nature and extent of carbide precipitation in the matrix. Fig. 1 is the microstructure of as –received and Fig. 2- 10 shows the microstructure of the bainitic steel at bainitic transformation temperatures of 300°C and 400°C for a period of one hour. At 300°C transformation temperature (Fig. 3-10), there is a higher presence of carbide as compared to that at 400°C transformation temperature (Fig. 2), and this is due to carbide precipitation from the supersaturated ferrite and the slow growth rate of bainite at 300°C as compared to 400°C transformation temperature.

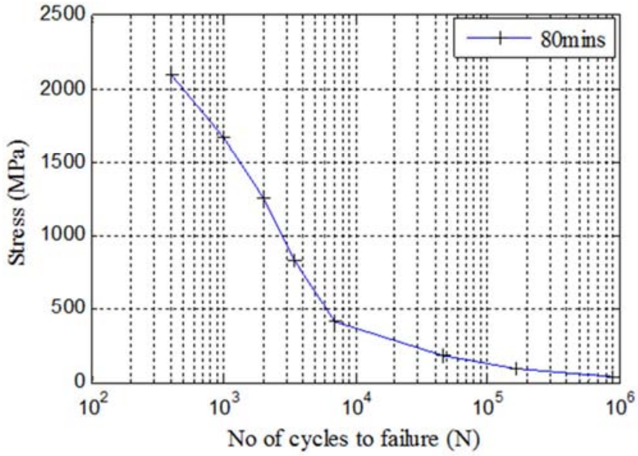

Fig. 15. *Fatigue Resistance (MPa) against Number of Cycles to Failure (N) at fixed Temperature of 300°C and varying Bainitic transformation time (80 minutes).*

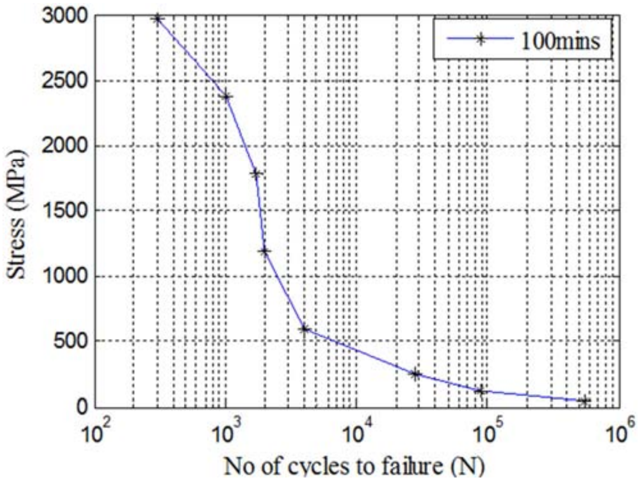

Fig. 16. *Fatigue Resistance (MPa) against Number of Cycles to Failure (N) at fixed Temperature of 300°C and varying Bainitic transformation time (100 minutes).*

At the upper bainitic temperature of 400°C (Fig. 2) the microstructure of the ferrite matrix is coarse as compared to lower bainite obtained at lower transformation temperature of 300°C (fig. 8) which is finer. This is due to the rapid growth of bainite at that elevated temperature as compared to the growth at lower temperature and high precipitation of carbide from the matrix.

The fatigue properties are indeed influenced by the matrix microstructure of the medium carbon steel especially the amount of bainite and retained austenite in the matrix. This is because fatigue crack propagate as damage is accumulated during the cyclic straining of the material at the crack tip. It is natural to expect metastable austenite in the vicinity of the crack tip to transform into martensite leading effectively to an increase in the strain hardening rate. A high strain hardening rate leads to more rapid crack propagation because the ability of the material to accommodate plastic strain then becomes exhausted more readily. The formation of hard martensite in a ductile matrix also decreases the strain preceding fracture. Higher presence of carbide and retained austenite which tends to martensite on cooling is detrimental to fatigue properties hence fatigue is enhanced at higher transformation temperatures as against lower transformation temperature.

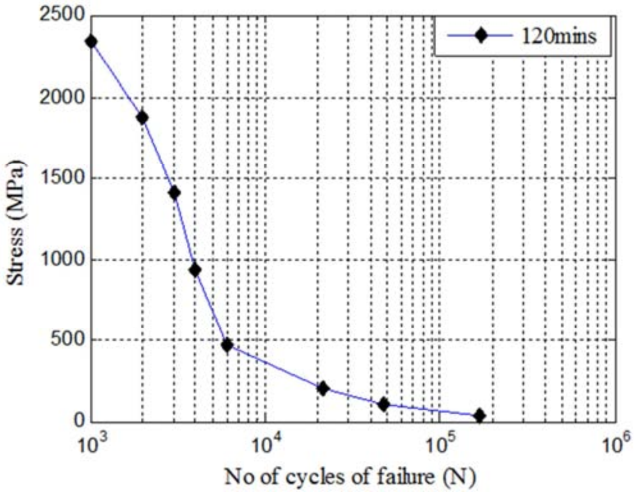

Fig. 17. *Fatigue Resistance (MPa) against Number of Cycles to Failure (N) at fixed Temperature of 300°C and varying Bainitic transformation time (120 minutes).*

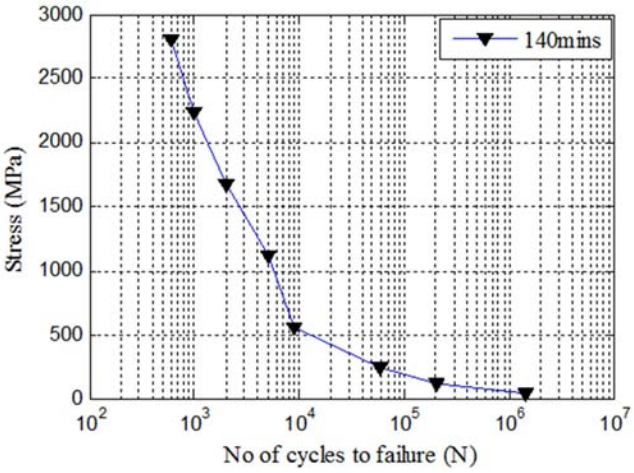

Fig. 18. *Fatigue Resistance (MPa) against Number of Cycles to Failure (N) at fixed Temperature of 300°C and varying Bainitic transformation time (140 minutes).*

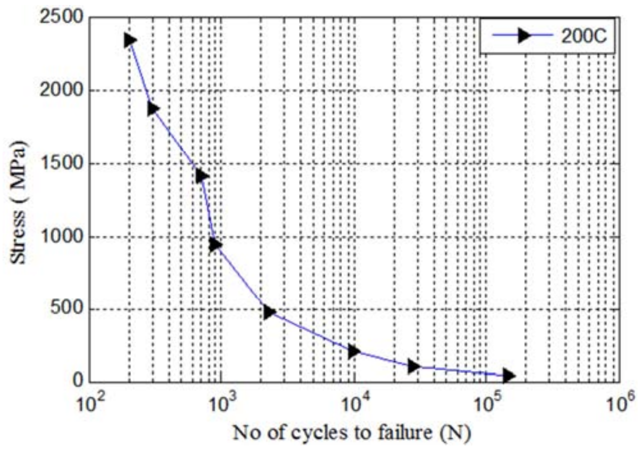

Fig. 19. *Fatigue Resistance (MPa) against Number of Cycles to Failure (N) at fixed time of one hour and varying Bainitic transformation Temperature of 200°C.*

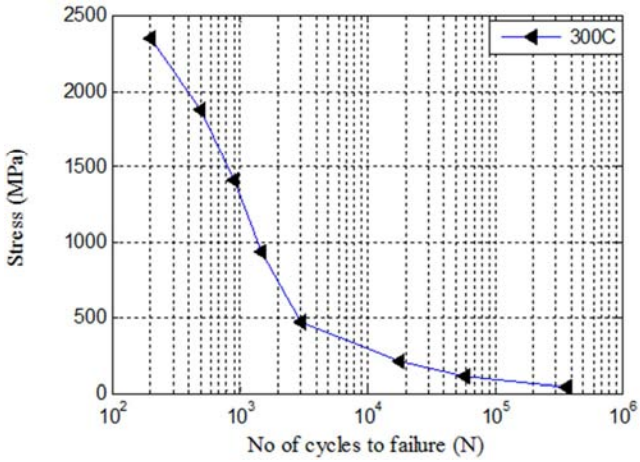

Fig. 20. *Fatigue Resistance (MPa) against Number of Cycles to Failure (N) at fixed time of one hour and varying Bainitic transformation Temperature of 300°C.*

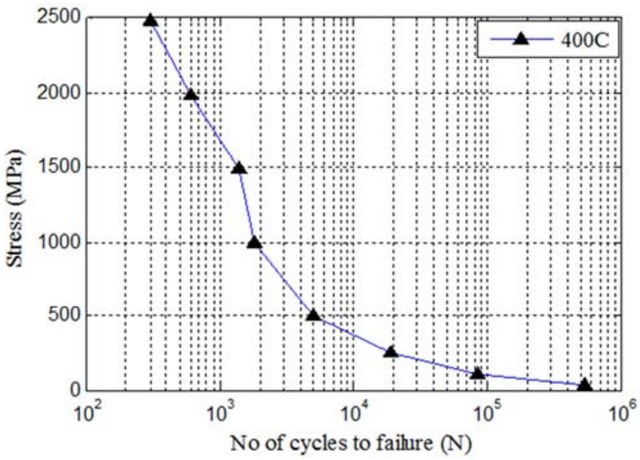

Fig. 21. *Fatigue Resistance (MPa) against Number of Cycles to Failure (N) at fixed time of one hour and varying Bainitic transformation Temperature of 400°C.*

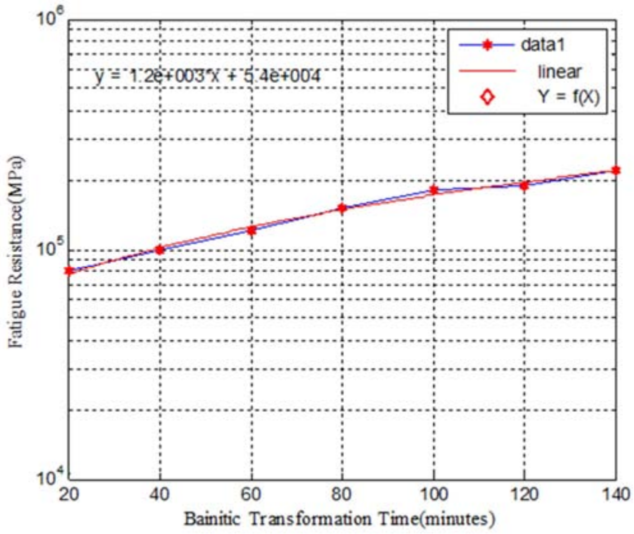

Fig. 22. *Fatigue Resistance (MPa) against Bainitic Transformation Times at Fixed Bainitic Transformation Temperature of 300°C.*

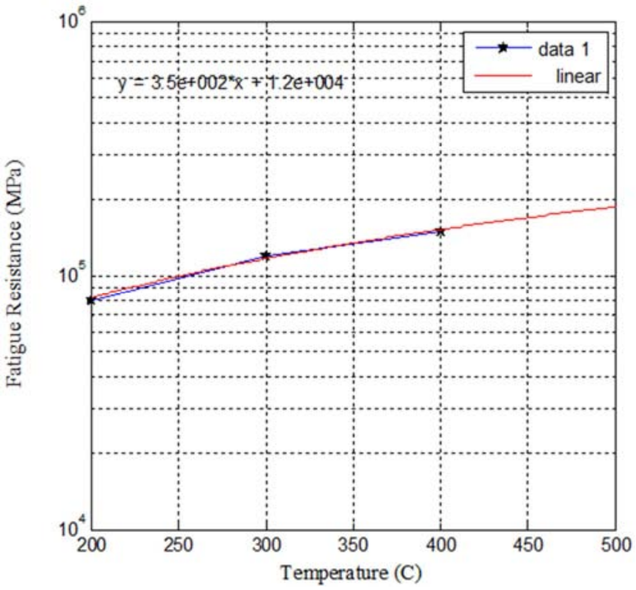

Fig. 23. *Fatigue Resistance (MPa) against Bainitic transformation Temperature at a fixed Bainitic transformation time of hour.*

4. Conclusions

It was observed that at 400°C transformation temperature the ferrite matrix was coarser while at 200°C transformation temperature the ferrite matrix was finer. A higher presence of carbide was observed at 200°C transformation temperature while at 300°C transformation temperature a mixed microstructure was seen.

Fatigue resistance was also observed to increase with increase in transformation temperature and time. Higher presence of carbide and retained austenite is detrimental to fatigue properties and it might therefore be concluded that the presence of austenite is not beneficial to the fatigue properties. [3]

Medium steel transformed at 400°C at low transformation time shows better fatigue properties.

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