Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 18
ISSUE 1-2
September–October
2006

Fatigue behaviour and energy dissipation of a nodular cast iron in ultrasonic fatigue loading

H.Q. Xue [a,b], E. Bayraktar [a,b,*], C. Bathias [a]
[a] ITMA/CNAM- Arts et Métiers, School of Mechanical Engineering, Paris, France
[b] Supmeca/LISMMA-Paris, School of Mechanical and Manufacturing Engineering, France
* Corresponding author: E-mail address: bayraktar@supmeca.fr

Received 15.03.2006; accepted in revised form 30.04.2006

Properties

ABSTRACT

Purpose: In the current research, fatigue tests of cast iron (GS51) have been conducted using the ultrasonic fatigue system and monitored by an advanced infrared imaging system in real time. Fatigue damage processes has been observed and analyzed. Furthermore, heat condition effect has been to analyze.
Design/methodology/approach: Fatigue behaviour in the very high cycle regime of 10^{10} cycles were investigated with a cast iron (GS51) under ultrasonic fatigue test system in ambient air at room temperature with a stress ratio R=-1. The influence of frequency was examined by comparing similar data generated on conventional servo hydraulic test systems. An infrared camera was also used to record specimen temperatures at various load levels caused by internal damping due to cycling at a very high frequency.
Findings: The S-N curves obtained show that fatigue failure occurred beyond 10^9 cycles, fatigue limit does not exist for the cast iron and there is no evidence of frequency effect on the test results. A detailed study on fatigue specimens subjected to ultrasonic frequency shows that the temperature evolution of the cast iron specimen is very evident, the temperature increased just at the beginning of the test, the temperature increased depending on the maximum stress amplitude.
Research limitations/implications: Ultrasonic fatigue test methodology had been applied extensively in exploring fatigue lives at very high cycle regime. However, it is a predominant problem that the thermal energy dissipation results in increasing of temperature of specimen at very high frequency fatigue experiment. In order to investigate the heat dissipation of ultrasonic fatigue specimen and understand the influence of temperature evolution on the fatigue properties, it is necessary to obtain the temperature response of vibratory specimen.
Originality/value: Early stage of damage of the cast iron which lead to crack initiation and micro crack growth are characterized by local microstructure temperature evolution, so as to understand the relationship between heat dissipation and fatigue state of material.
Keywords: Fatigue; Damage mechanism; Nodular cast iron; Thermal dissipation; Very high cycle regime

1. Introduction

In industrial applications, many components are subjected to high-frequency, low-amplitude, very high cycle loading in their working service. The high-frequency, high-cycle fatigue of the components can result in essentially unpredictable failures of the working system. In order to investigate the fatigue properties and prime causes of the components failures in very high cycles regime, ultrasonic fatigue test system had been developed and it offers an alternative testing method for generating the data necessary at very long fatigue lives[1,2].

As a result, ultrasonic fatigue test methodology had been applied extensively in exploring fatigue lives at very high cycle regime [3-6]. However, it is a predominant problem that the thermal energy dissipation results in increasing of temperature of specimen at very high frequency fatigue experiment [7-8]. In order to investigate the heat dissipation of ultrasonic fatigue specimen and understand the influence of temperature evolution on the fatigue properties, it is necessary to obtain the temperature response of vibratory specimen. Nodular cast iron (GS51) is mainly used in automobile engine components due to the combination of high strength and ductility. These materials are widely used especially in the automotive industries, for the fabrication of crankshafts, connecting rods, suspension arms, gears, etc. As a considering practical application, it should be designed to meet lifetime requirements of 10^9 or 10^{10} cycles. Thus, investigation of fatigue properties and damage mechanism of the material in very high cycle regime is necessary for significantly improving safety. In the current research, fatigue tests of cast iron (GS51) have been conducted using the ultrasonic fatigue system and monitored by an advanced infrared imaging system in real time. Fatigue damage processes has been observed and analyzed. Furthermore, heat condition effect has been to analyze. Early stage of damage of the cast iron which lead to crack initiation and micro crack growth are characterized by local microstructure temperature evolution, so as to understand the relationship between heat dissipation and fatigue state of material.

2. Experimental conditions

The material under investigation was a nodular cast iron, which has been used in automobile engine; it has not been done any additional heat treatment. The microstructure of nodular cast iron GS51, much spherical graphite are not well distributed in the microstructure, it revealed local spherical graphite gathered, and there is big difference of dimension in between spherical graphite. The nominal chemical composition and mechanical properties of the nodular cast iron GS51 is shown in Tab.1 and Tab.2 respectively [9].

Table 1.
Chemical composition of nodular cast iron GS51 (mass%)

Material	C (%)	Si (%)	Mn (%)	Cu (%)	Mg (%)
GS51	3.65	2.49	0.5	0.7	0.04

Table 2.
Mechanical properties of nodular cast iron GS51

E_d/ (GPa)	σ_y/ (MPa)	UTS/ (MPa)	A/ (%)	ρ/ (kg/m^3)	HV30
169	460	795	9	7100	265

Fatigue tests were conducted on cylindrical dog-bone specimens, all fatigue loading was controlled by inputting vibration amplitude. In order to monitor the damage progression and temperature evolution over the entire fatigue test, ultrasonic fatigue tests were conducted without cooling. The specimens of the cast iron, which were used for ultrasonic fatigue testing, was designed with 20 kHz longitudinal resonance frequency, the resonance length of ultrasonic fatigue specimen was calculated by analytic or numerical method in detail [2,10], the geometry and displacement-stress distribution of the fatigue vibration specimen is shown in Figure 1.

Ultrasonic frequency involves the heat generated by internal friction of material. So, the effect of temperature evolution on the fatigue properties of material should be concerned, and therefore temperature measurements were taken at various stress level during testing. In the present study, an advanced, high-speed, and high-sensitivity infrared imaging system was used to record the temperature changes during ultrasonic fatigue test.

3. Results and discussion

3.1. High-cycle fatigue properties

The stress versus fatigue life (S-N) curves including results obtained at 35 Hz and 20 kHz with stress ratio R=-1 in air and room temperature, are shown in Figure 2. The general trend of the S-N data was that the fatigue life increased with decreasing the applied maximum stress level. Although it has the higher scatter of the fatigue data, the fatigue strength determined from ultrasonic testing was consistent with conventional testing in the data scatter band. The difference of fatigue strength between $7x10^5$ and 10^{10} cycles is 25 MPa for stress ratio *R*=-1.

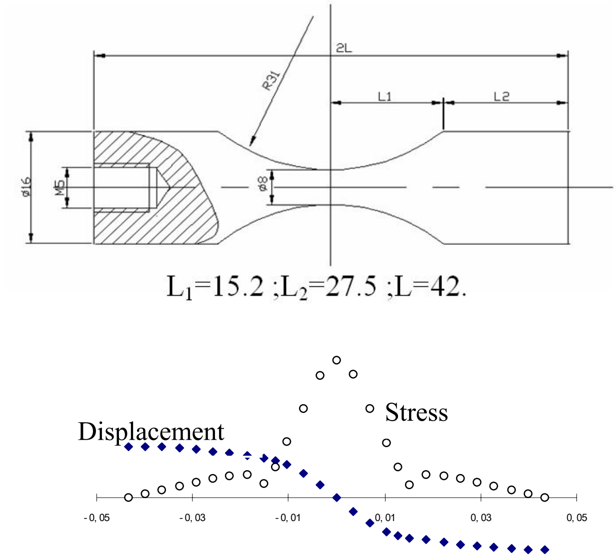

Fig. 1. Geometry and displacement-stress field along the nodular iron GS51 specimen

3.2. Thermal behaviour

It was found that the temperature of the specimen subjected to cyclic deformation rose due to heat generated, and a greater increase in the temperature at the high frequency, specially at an ultrasonic frequency was observed [7, 11]. Figure 3 illustrates the type of temperature distributions in the gage-length section of the cast iron specimen during ultrasonic fatigue testing with an R ratio of –1 at a frequency of 20 kHz with an applied maximum stress of 120 MPa after 10^7 cycles. It is noted that the temperature is heterogeneous along the axis of the specimen and is maximal at the centre of the gage length of the specimen, with the highest temperatures occurring at the high strain location. This temperature field can be explained by the heterogeneity of the solicitation (strain and stress) and by the thermal losses related to conduction along the axis of the specimen.

Figure 4 shows the temperature variation at the centre of the specimen according to the cycle number for two different stress levels. It can be also highlighted a fast increase in the temperature at the beginning of test followed by a stabilization corresponding to a balance between the mechanical energy dissipated into heat and the energy lost by convection and radiation at the specimen surface and by conduction inside the specimen. Thus, this increase in temperature is directly related to the mechanical energy dissipated into heat. Although stress in the specimen is lower than the elastic limit, the dissipated energy comes from internal material damping and the local plastic deformation at the microscopic scale.

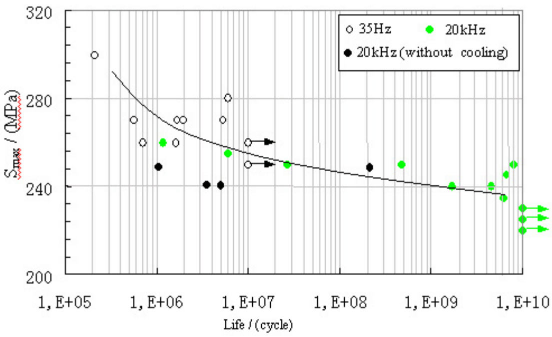

Fig. 2. *S-N* curve tested at 35Hz and at 20 kHz with a *R*=-1 in air at room temperature

a)

b)

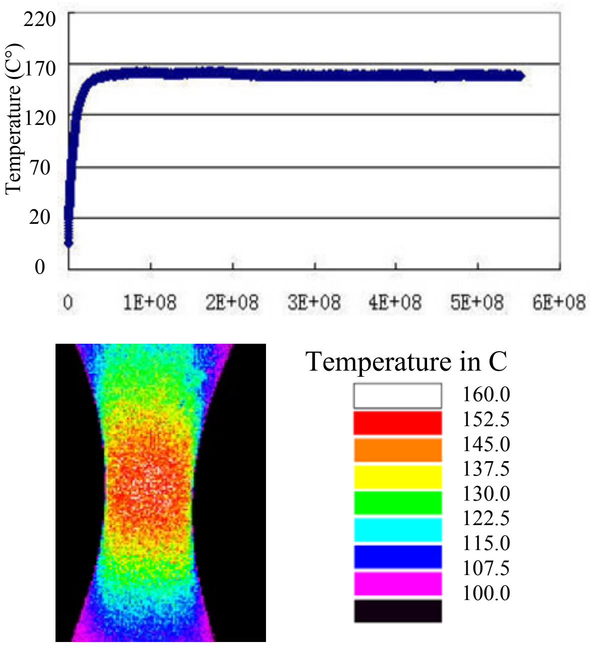

Fig. 3. Temperature changement in nodular cast iron GS51 during the fatigue test (a); Temperature field in the specimen gage for GS51 after10^7 cycles and with a stress amplitude of 120MPa (b)

Figure 4 also shows the influence of the stress on the temperature evolution. The increase in maximum specimen temperature is related to the maximum stress, the higher the stress is, the larger the increase of temperature is. We can also notice that same stress amplitude of 260 MPa for the cast iron GS51 generates a more significant increase in the temperature. In the case of the cast iron, indeed, the stress amplitude of 260 MPa corresponds to 55% of the cast iron GS51 yield strength. It is seen that the increase in the temperature is rather related to the amplitude ratio of the constraint by the elastic limit. As a further check on the effect of cooling air on the temperature distribution in the testing specimen, temperature distribution of tested specimen without cooling and with cooling was compared.

Figure 5 shows the results of temperature distribution in the gage length section of another cast iron specimen with the similar physical properties and chemical composition [10].

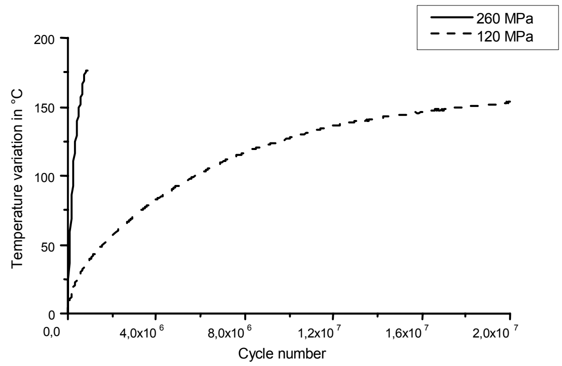

Fig. 4. Temperature variation at the centre of the specimen; GS51

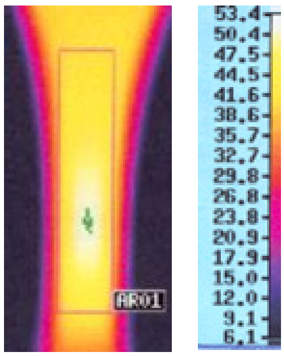

Fig. 5. Temperature field in the ultrasonic fatigue specimen and with a stress amplitude of 320MPa and R=0

It can be found that compressed cooling air is very effective in ultrasonic fatigue test to decrease the temperature of specimen. The temperature decrease not only in the longitudinal of specimen but also in the radial of specimen, in the gage section of specimen, temperature decrease obviously from the centre to surface, the maximum temperature is in the centre of specimen. There is a single hot spot in the gage section. Compared with the specimen tested at 20 kHz and without cooling, it approaches an equilibrium (steady-state) temperature in a lower cycles, and the equilibrium temperature decrease evidently.

3.3. Fatigue damage processes

Materials do not behave in a perfectly elastic manner even at very low stress. Inelasticity is always present under all types of loading. Under cyclic loading conditions, due to the presence of inelasticity, the stress-strain curve is no longer a single valued function but forms a hysteresis loop. The area enclosed by the hysteresis loop is the energy absorbed, which is the damping energy. The damping energy will be converted into heat, and eventually, dissipate through the material. Jiang [8] had tested one kind of alloy at frequency of 20Hz and 1000Hz respectively, and got the result that the damping energy could depend on the rate and amplitude of cyclic loading. That is, the accumulation of irreversible plastic strain continued until the mean strain reached a certain value depending on the applied maximum stress level, and the hysteresis loop remained at a typical shape and size. In the tension –compression, high cycle fatigue test, the temperature evolution corresponded to the change of the stress-strain state. It has been experimentally found that the stored energy was only a small amount of dissipated energy. Hence, almost all the irreversible mechanical energy due to the inelastic deformation will be converted into heat. The temperature evolution show the change of the stress-strain behaviour. The temperature of cast iron specimen tested at frequency of 20 kHz increase evidently, it shows that there is much more accumulation of irreversible plastic deformation for the materials tested at very high frequency.

Figure 5 illustrates the temperature evolution of the variation in temperature at the point where the temperature is maximal during the fatigue rupture of the cast iron GS51. For stress amplitudes of 260 MPa, The failures were obtained at the levels of 1.1×10^6 cycles. All of the specimens tested here illustrated that the local temperature increases sharply just before the specimen fatigue fracture. Thus, the failure is preceded by a damage phase where the temperature increases locally.

4. Conclusions

Fatigue properties in very high cycle regime were obtained for cast iron at 20 kHz frequency, the fatigue strength decreased as the applied stress levels increased. Comparing with the fatigue test results obtained at 35Hz tests, there is no frequency effect. The thermography detection has been applied to observe the fatigue damage processes of cast iron GS51. The relationship between the temperature evolution and fatigue damage were analysed, the heat dissipation behaviour of the cast iron is depend on not only the amplitude of cyclic loading but also the loading frequency. Temperature increase at ultrasonic frequency was considerably higher than that at 20Hz. The study of fractography showed that fatigue crack initiation site from the surface graphite, void or subsurface void for the cast iron GS51, fatigue crack initiation site is predominated from the subsurface microstructure defect under lower maximum cyclic stress. Temperature evolution reflect the heat dissipation process, due to the damage phase occurred in the microstructure of the cast iron GS51, local temperature increase sharply in the fatigue test specimen, it also reflected the micro crack growth processes. Micro crack growth life is only a very small part of the total fatigue life for specimen with very long fatigue life.

References

[1] C.J. Bathias: Ni, Determination of fatigue limit between 10^5 and 10^9 cycles using an ultrasonic fatigue device, Advances in fatigue lifetime predictive techniques, ASTM STP 1211, M. R. Michell and R. W. Landgraf eds., Vol. 2, 141-152, ASTM Philadelphia,1993

[2] H.Q. Xue, H. Tao, C. Bathias The Analysis of Specimen Design for Fatigue Test at Ultrasonic Frequency. "The 3rd International Conference on Very High Cycle Fatigue", Tokyo, Japan, Sept. 2004.

[3] Q.Y. Wang, J.Y. Berard, Rathery, C. Bathias: High –cycle fatigue crack initiation and propagation behaviour of high–cycle spring steel wires. Fatigue Fract Eng Mater Struct 1999; 22(8):673-7

[4] C. Bathias, How and why the fatigue S-N curve does not approach a horizontal asymptote. International journal of fatigue, 2001,23(1):143-151

[5] H. Mayer, M. Papakyriacou, B. Zettl, S.E. Stanzl-Tschegg: Influence of porosity on the fatigue limit of die cast magnesium and aluminium alloys. International journal of fatigue, 2003(25):245-256

[6] E. Bayraktar, C. Bathias, H. Xue, Tao Hua: On the giga cycle fatigue behaviour of two-phase ($\alpha_2+\gamma$) TiAl alloy. International Journal of Fatigue, No.12, 2005

[7] G.H. Norbert, Meyendorf, H. Rosner, V. Kramb, S. Sathish. Thermo-acoustic fatigue characterization. Ultrasonics, 2002(40):427-434

[8] L. Jiang, C.R. Brooks, P.K. Liaw, H. Wang: High-frequency metal fatigue : the high-cycle fatigue behavior of ULTIMET alloy. Materials science & engineering A, 2001(A314):162-175

[9] I. Marines, Exploration de la fatigue des métaux au-dela du milliard de cycles. Ph.D thesis, ITMA/CNAM, Paris France, 2004

[10] X. Kong, K. Saanouni, C. Bathias: On the fatigue at very high frequency, part 1:Theoretical and variation formulation. Journal of Engineering Materials and technology, 1991,113:205-209

[11] A.L. Audenino, V. Crupi, E.M. Zanetti, Correlation between thermography and internal damping in metal. International journal of fatigue, 2003,(25):343-351

[12] Q.Y. Wang: Etude de la fatigue gigacyclique des alliages ferrous. Ph.D thesis, Ecp, 1998