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Design of high strength steel plate fatigue specimen for accelerated ultrasonic fatigue test

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Abstract

The demands for High Strength Steel (HSS) plate have been increased in various fields such as aerospace, automotive, plant, and marine industry to reduce the weight for increasing the fuel economy. Additionally, the parts durability which are using in those of fields is also required to be increased up to giga-cycle (10^9) regime and normally it takes very long time to check the fatigue behavior with conventional hydraulic fatigue tester. For this reason, a new accelerated fatigue test method by using ultrasonic resonance, 20kHz, has been proposed and it takes only 14 hours to reach giga- cycle regime.

The concept for accelerated ultrasonic fatigue test is using resonance and the specimen is resonating about 20 kHz frequency. The specimen will get maximum stresses on the center and maximum displacement on the end of the specimen. For this reason, the specimen has to be specially designed for each application. In this study, 590 FB(ferrite-bainite) high strength steel plate is chosen. To design the specimen, the dynamic Young's modulus measured by using PZT, Laser Doppler Vibrometer (LDV), and Digital Signal Analyzer (DSA) and the result is 221.28 GPa. By using this data, a specimen dimensions are calculated and fabricated. The fabricated specimens are tested with using ultrasonic fatigue tester. The specimens are broken in the middle, because the stress concentration. The results summarized on the infinite strength (i.e. giga-cycle) and the S-N curve of 590 FB steel. This testing method and results will be beneficial in various applications.

Keywords: Fatigue, Ultrasonic Fatigue Test, High Strength Steel, Giga Cycle Fatigue, Plate Specimen

1. Introduction

Life of mechanical parts and components is related to fatigue failure that occurs when it is repeated action of low levels of stress than the tensile strength of the material. Request life of mechanical materials and products has been increased. Recently, fatigue limit is up to more than 10^9 cycle [1]. As a result, the very high cycle fatigue area is highly interested in. Test frequency is one of the most important factor to perform the very high cycle fatigue test. The test frequency of a general hydraulic fatigue testing machine is 2~15Hz, rotary bending method and electroforce method is operating about 50~300Hz. On the contrary, ultrasonic fatigue test using 20 kHz test frequency. It can be greatly reduce fatigue testing time. That is suitable for very high cycle fatigue region experimental.

Ultrasonic fatigue test requires a resonance of the test specimen. For this reason, it is important that design of the shape of the specimen. Round bar type specimens have been studied on many previous works but only few of plate shape specimen have been researched [2,3]. The high strength steel plate are widely used in various fields such as passenger cars and pressure vessels. Very high cycle fatigue characteristic of steel plate has been studied on this paper.

In this study, the high strength steel (590 Ferrite-Bainite) plate specimen is designed and tested by using the ultrasonic fatigue testing machine. Figure 1 shows the ultrasonic fatigue testing machine. Maximum displacement exert on the end of ultrasonic fatigue specimen and maximum stress exert on the middle. The specimen resonate at a frequency of 20 kHz.

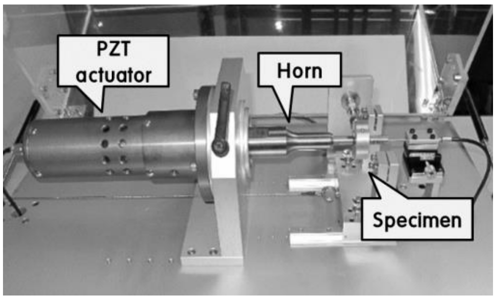

Figure 1. Ultrasonic Fatigue Tester.

2. Specimen design

2.1. Material

590 Ferrite-Bainite material thickness of 2.8mm were used in this study. 590 FB is mixed two phase materials. Ferrite showed a high strain and Bainite have high stretch-flangeability. So that have superior to the hole expandability. In addition, it is used to the wheel disk, shock absorber and arm such as to absorb the vibration damping device [4]. Ultrasonic fatigue test specimen is manufactured by the electric discharge machining (EDM) process, material composition is shown in Table 1.

2.2. Dynamic Young's modulus

The measurement of the dynamic Young's modulus is required for the fatigue test specimen design and stress calculation. Dynamic young's modulus was measured by a piezoelectric element, OFV-352 Laser Doppler Vibrometer (LDV) and HP-35670A Digital Signal Analyzer (DSA). Dynamic Young's modulus of 590 FB steel plate is 221.28 GPa

Table 1 Chemical compositon of 590 FB.

element	C Max.	Mn Max.	Si Max.	P Max.	S Max.	Fe
Wt. %	0.090	1.550	0.150	0.030	0.003	balance

2.3. Steel plate specimen design

Deformation and stress occurs at the specimen during ultrasonic vibration. The specimen assumes a one-dimensional wave equations to obtain deformation and stress value. If the gravity ignore to thin plate, the primary wave equation is as follows. In the Equation (1), u is displacement along x, E and ρ the Young's modulus and mass density, t is time.

$$\mathrm{E}\frac{\partial^2 u}{\partial x^2} = \rho\frac{\partial^2 u}{\partial t^2} \qquad (1)$$

Boundary condition is displacement becomes the maximum from both ends of the specimen. First mode resonance length l consist of frequency f, dynamic Young's modulus E_d and ρ.

$$l = \frac{1}{2f}\sqrt{\frac{E_d}{\rho}} \qquad (2)$$

Reducing the cross-sectional area of the central portion in order to generate a stress concentration in the ultrasonic fatigue specimen. Wave equation is considered the cross-sectional area S (x).

$$\rho S(x)\frac{\partial^2 u}{\partial t^2} = \frac{\partial f}{\partial x}, \qquad f = E_d S(x)\frac{\partial u}{\partial x} \qquad (3)$$

E_d of the wave equation obtained by the above experiment. Sectional area of the plate specimen is divided into two parts. Figure 2 is dimension of ultrasonic fatigue test specimen. L_1 is parallel section, L_2 changes the exponential profile at the middle of specimen. Function y is profile of specimen, R_1 and R_2 are shown in Figure 2.

$$\begin{gathered} \mathrm{y(x)}=R_2, \qquad L_2 < |x| \le L \\ \mathrm{y(x)}=R_1\exp(2\alpha x), \qquad |x| \le L_2 \\ \alpha = \frac{1}{2L_2}\ln\left(\frac{R_2}{R_1}\right) \end{gathered} \qquad (4)$$

The length of the plate specimen is equal to the resonant wavelength for the maximum stress acting in the middle. The length L_1 can be determined by applying the boundary condition that the displacement is continuous and differentiable over the distance L_2 from the center of the plate specimen. [1]

$$\begin{gathered} L_1 = \frac{1}{k}arctan\frac{1}{k}\{\beta coth(\beta L_2) - \alpha\}, \\ \beta = \sqrt{\alpha^2 - k^2}, \qquad k = \frac{\pi}{l} \end{gathered} \qquad (5)$$

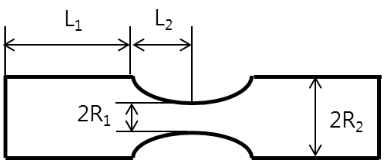

Figure 2. Dimension of ultrasonic fatigue test specimen.

3. Result

590 FB steel plate specimen is tested by ultrasonic fatigue tester with stress ratio "–1", at the 20 kHz testing frequency in room temperature. Figure 3 (a) is pre-plate ultrasonic fatigue test specimen. As it predicted, the failure occurred in the middle of the specimen as the figure 3 (b). Figure 4 is S-N curve of 590 FB steel plate. Fatigue test results are shortest fatigue life 7.34×10^4 cycle at 540 MPa and most long fatigue life 1.41×10^9 cycle at 460 MPa.

(a) Before (b) after

Figure 3. Ultrasonic fatigue test specimen .

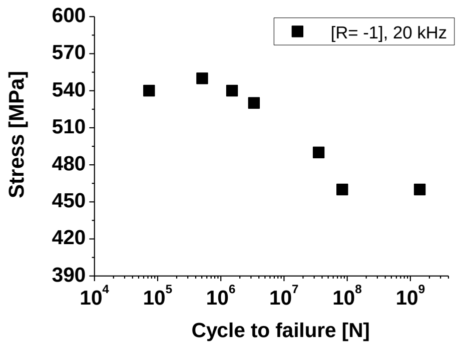

Figure 4. S-N curve of 590 FB .

4. Conclusion

In this study, specimen is designed for ultrasonic fatigue test and to find out very high cycle fatigue properties of 590FB steel plate. Ultrasonic fatigue test specimen is designed by measuring dynamic Young's modulus and existing theoretical formula for resonance at a particular frequency. Designed specimen resonate at 19.914 kHz, it is close to 20 kHz. When 460 MPa stress exert on 590FB steel plate, fatigue failure occurred at giga-cycle.

The specimen design and fatigue test have a meaningful result. It is expected to be easier to find very high cycle fatigue testing data of plate steel material that widely used in industries

Acknowledgements

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