

Ultrasound Signals Response Associated to Fatigue Failure Behaviour using Statistical Analysis

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Graphical abstract



Abstract

In this paper, ultrasound signals had been analysed using a statistical-based approach to evaluate and predict fatigue failure of carbon steel AISI 1045. Fatigue tests were performed according to the ASTM E466-96 standard with the attachment of an ultrasound sensor to the tested specimen. The material used in this test was the AISI 1045 carbon steel due to its extensive application in automotive and machinery industry. Fatigue test was carried out at a constant loading stress at the sampling frequency of 8 Hz. A set of data acquisition system was used to collect those fatigue ultrasound signals. All obtained data were analysed using specific software. Ultrasound signals were collected during fatigue test in order to detect any structural changes occurs during the test. Fatigue damage characteristics were observed based on the ultrasound signals characteristics and a further analysis was performed using statistical approach. The results of signals distribution, r.m.s value and energy content of the signals were discussed to correlate fatigue failure behaviour and ultrasound signals.

Keywords: Fatigue; fatigue failure; root-mean square; ultrasound

Abstrak

Kajian ini dijalankan untuk menganalisa isyarat ultrabunyi dengan menggunakan pendekatan statistik bagi menilai dan meramal kegagalan lesu keluli karbon AISI 1045. Ujikaji lesu telah dijalankan selaras dengan kaedah piawaian ASTM E466-96 dengan melekatkan sensor ultrabunyi pada spesimen ujikaji. Bahan ujikaji keluli karbon AISI 1045 telah dipilih dalam kajian ini disebabkan penggunaannya yang meluas dalam industri automotif dan perkakasan mesin. Ujikaji lesu dijalankan pada pembebanan tegasan malar dengan frekuensi persampelan 8 Hz. Satu sistem pemerolehan data telah digunakan untuk mencerap isyarat ultrabunyi. Kesemua isyarat yang dicerap telah dianalisa dengan menggunakan suatu perisian spesifik. Isyarat tersebut digunakan untuk mengesan sebarang perubahan struktur yang berlaku pada spesimen ketika ujikaji dijalankan. Ciri-ciri kerosakan lesu diperhatikan berdasarkan isyarat ultrabunyi yang di analisa menggunakan pendekatan statistik. Keputusan taburan isyarat, nilai r.m.s dan jumlah tenaga isyarat dibincangkan untuk menghubungkan antara kegagalan lesu dan isyarat ultrabunyi.

Kata kunci: Lesu; kerosakan lesu; punca min kuasa dua; ultrabunyi

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1.0 INTRODUCTION

For many structural and components, the primary mode of failure can be attributed to fatigue damage resulting from the application of repetitive amplitude loading [1]. Fatigue of structures became evident as a by-product of the industrial revolution in the 19th century. Fatigue failures were frequently associated with steam engines, locomotives and pumps. In the 19th century, it was considered to be mysterious that a fatigue fracture did not show visible plastic deformation. [2]. Thus, there were several methods and techniques have been done to detect or monitor fatigue behaviour in order to improve and enhance fatigue life of structures.

Ultrasound is one of the useful methods of materials testing. In this field, ultrasound's physical nature as a mechanical wave is used [3]. Knowledge of sound wave propagation principles in a tested medium allows for its application as a research tool. Ultrasound method is the powerful way of evaluating material degradation since the characteristics of ultrasonic wave propagation are directly related to the properties of the material. In ultrasonic, the characterizing parameters are the velocity and attenuation of the wave [4]. This wave signal will be assessed and processed to evaluate the structure or material defects. Thus, ultrasound method can be used as a tool to detect or evaluate crack initiation or crack behaviour in fatigue assessment.

This paper discusses on the application of ultrasound technique in detecting fatigue failure. The signals collected were analysed using the quadratic mean approach to find the r.m.s value in order to estimate the energy content of the ultrasound signals. These values will be correlate with fatigue failure analysis in terms of fatigue life prediction.

2.0 MATERIALS AND METHOD

2.1 Materials

The AISI 1045 carbon steel is a medium carbon steel with great strength and hardness. AISI 1045 steel is used extensively by all industry sectors for applications requiring more strength and wear resistance than the typical applications of low-carbon mild steel, including axles, bolts, connecting rods, hydraulic clamps and rams, shafts, and spindles [5]. It has been selected for this experiment due to its low cost and various applications in most

engineering fields and machinery tools. Figure 1 shows the dimensions of flat rectangular tensile specimens, which were used as a test specimen.

2.2 Tensile Testing

Monotonic tests were performed at room temperature using a 100 kN servohydraulic test system with computer control [6], as shown in Figure 2(a). Monotonic tensile tests were performed according to the ASTM standard E08 [7] to obtain the main mechanical properties of the AISI 1045 carbon steel specimen, which will be used to determine the load value in the cyclic test. [8]. The tensile specimens were machined in order for them to be in a received (flat) condition. Data on load and extension at a given strain rate were obtained during the test. The dimensions of the specimens before and after the tensile test were also recorded. These data were analysed to determine the yield strength, tensile strength, elongation, and reduction in area. Standard procedures to determine these values are described in ASTM E8 [7].

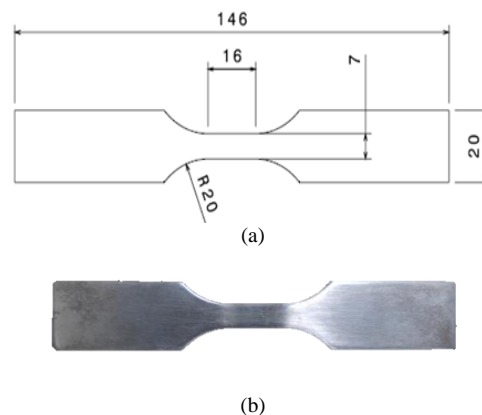


Figure 1 Specimen used for the test; (a) dimension, (b) geometry



Figure 2 (a) 100 kN servo-hydraulic universal testing machine used for the test of the flat specimen, (b) 250 kN servo-hydraulic universal used for the cyclic tests

2.3 Cyclic Testing

From the stress–strain curve measured by the tension test, the maximum stress (σ_{max}) of the cyclic tensile test in the fatigue test is determined in Table 1. A specimen is subjected to constant load as the input of machine, 85% of the ultimate strength of this as-received material. The value of applied stress is 690 MPa with its equivalent load of 14 kN. The test was performed at cyclic tensile stress ratio ($\sigma_{min}/\sigma_{max}$) of -1 and frequency of 8 Hz

[9] using the 25 kN servohydraulic universal testing machine as shown in Figure 2(b). Constant loadings of 690 MPa and the frequency were chosen due to time constraint and the capability of the data acquisition system. An ultrasound sensor 20–450 kHz was attached to the specimen that connected to ultrasound data acquisition system. Ultrasound signals were collected at the sampling frequency of 200 kHz. This sampling frequency was chosen based on the capability of the ultrasound sensor to record the data. The tests were performed according to the ASTM

E466-96, which is based on the stress control procedure. The process flow of the experimental method is shown in Figure 3.

2.4 Signal Analysis

The Quadratic Mean will calculate the root-mean-square (r.m.s.) value, which is the 2nd statistical moment is used to quantify the overall energy content of the signal. For discrete data sets, the r.m.s. value is defined as in Eq. 1:

$$r. m. s. = \left\{ \frac{1}{n} \sum_{j=1}^n x_j^2 \right\}^{1/2} \quad (1)$$

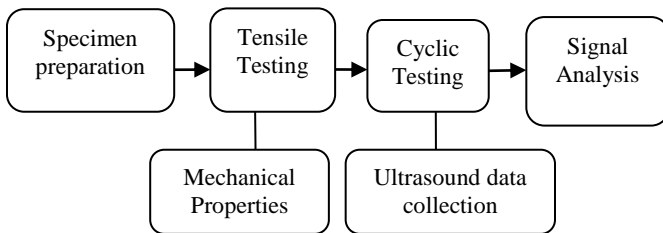


Figure 3 Process flow of the experimental method

Table 1 Room temperature tensile properties of the AISI 1045 Carbon Steel

Maximum Load [kN]	17
Ultimate tensile strength [MPa]	811
Yield strength [MPa]	421
Modulus [GPa]	196
Room temperature [°C]	27

3.0 RESULTS AND DISCUSSION

Fatigue test was performed with an ultrasound sensor attached to the specimen. Ultrasound responses were collected throughout the fatigue test in every five minutes interval. This is

due to limitation of hardware which can only record the data maximum up to 10 000 data in 0.05 seconds. Therefore, until the specimen breaks, there were 20 groups of data collected in which every groups contains 10 000 data.

Figure 4 shows three groups of data which have highest response values compared to others.

The highest amplitude in each group is 0.0304, 0.0272 and 0.0304 respectively. Those signals were analysed using root mean square (r.m.s) which is used to quantify the overall energy content of the signal. The energy content will be discussed to correlate with the fatigue failure behavior.

Graphs in Figure 5 presents the r.m.s values and energy content versus no. of cycles. The r.m.s values were obtained for all the 20 groups of data from the initial until the end of the test. Generally, both graphs display quite a same trend of graph which is keep increasing till failure. At early stage of test, the r.m.s value seems to be relatively constant until the seventh value of r.m.s. At this point, the r.m.s value suddenly increase to 5.87×10^{-3} (peak 1), then decreased back to 3.61×10^{-3} , after that increase again to 5.61×10^{-3} (peak 2). Then, the graph was going down and slowly increased until failure occurs. At peak 3, the r.m.s value is 6.33×10^{-3} slightly before the specimen breaks. The same explanation goes for graph energy versus no. of cycles. At first peak, the energy content is 34.58 J which at this point the specimen may have internal structural changes (i.e; crack initiation) due to its abrupt changes. At point 2, the energy content keep increase which is 34.20 J but slightly lower than the first point. This may due to crack propagation occur at point 2, as crack propagation may have slightly lower energy to break the atomic bonding rather than to initiate the crack. While at point 3, the signals contain the highest energy which is 42.15 J, and the specimen fails. Highest energy occurs at this point since more energy required to break the specimen.

Figure 6 compares the r.m.s values and energy content in a graph. Both graphs present almost the same peak point at the three significant points throughout the test. As both r.m.s and energy values keep increasing from the start to the end of test, those the three highest peak points indicate that there will be activities occur within those points. It may represent the fatigue failure process (initiation, propagation and failure) as both graphs shows considerable data to explain and correlate the ultrasound response towards fatigue failure behaviour.

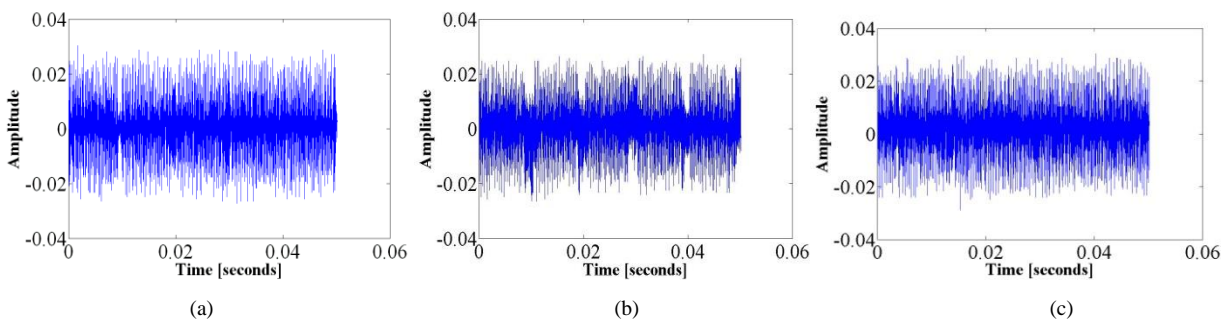


Figure 4 Three groups of the highest ultrasound response to the fatigue test; (a) signals group 1, (b) signals group 2 and (c) signals group 3

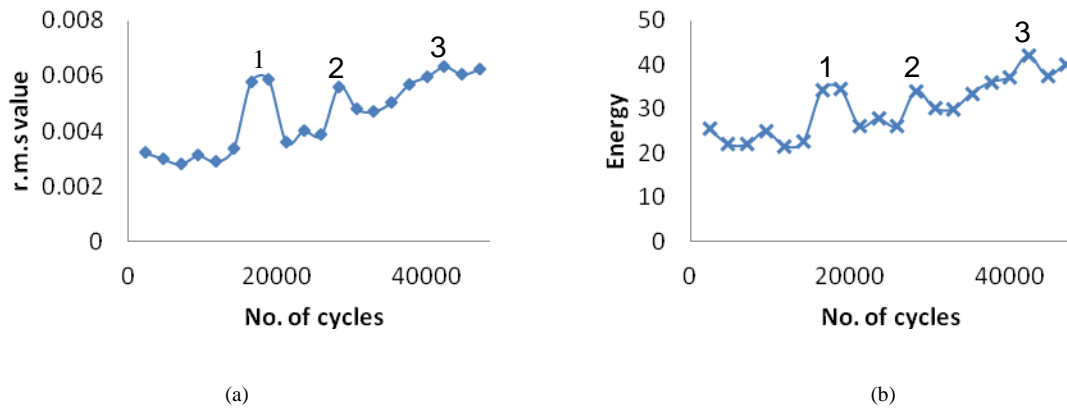


Figure 5 r.m.s and energy values towards fatigue failure collected every 5 minutes; (a) r.m.s values and (b) energy content of the signals

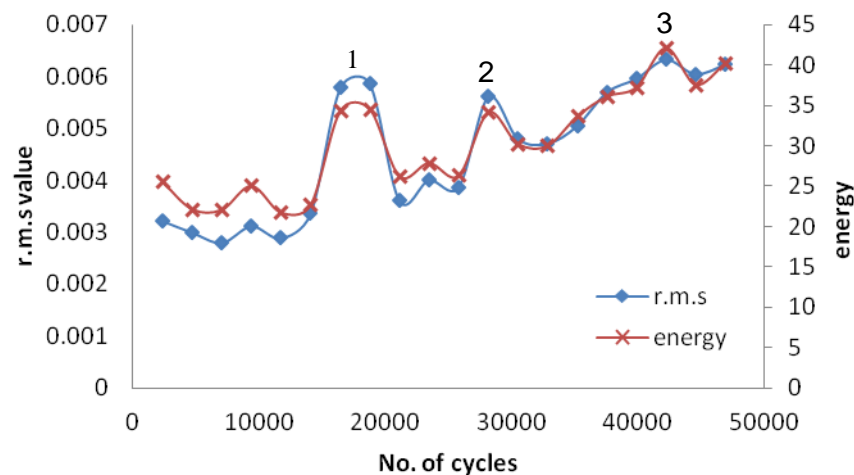


Figure 6 Comparison of r.m.s and energy values at three high peaks towards fatigue failure

4.0 CONCLUSION

This paper discussed on observation of ultrasound response associated to fatigue failure behaviour. From the fatigue test performed, there were 20 groups of ultrasound signals recorded and 3 groups which has highest amplitude has been found to be the main finding. The three groups give the highest r.m.s and energy values. The r.m.s values are 5.87×10^{-3} , 5.61×10^{-3} and 6.33×10^{-3} while the energy values are 34.58 J, 34.20 and 42.15 J for those three peaks respectively. Those three peaks are significant in describing fatigue failure behaviour throughout the test. At those peaks, there may have certain activity (structural changes) which contributing to fatigue failure, therefore highest signal response obtained at each peak. Thus, it can be concluded that ultrasound signals can be used as fatigue assessment tool in observing fatigue failure behaviour. However, there should be more signals and analysis technique performed to ensure the main cause affecting signal response changes (correspond to fatigue failure) other than explained above.

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