Identification of Structural Changes due to the Impact Testing of a Charpy Specimen Used for Reactor Pressure Vessel Materials Testing by Ultrasonic Analysis

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Abstract

Ultrasonic signal analysis for the broken Charpy impact specimens has been performed in order to understand the metallurgical characteristics of the specimen after impact testing. Analytical work simulating real impact testing using a finite element method (FEM) was also performed in parallel with the real ultrasonic experiment. The results showed that a longer transit time was observed near the broken area and abruptly died away from the center, and this can be correlated with the large stresses obtained from FEM analysis of the specimen.

Introduction

The integrity of a nuclear reactor pressure vessel has been achieved through various tests according to the rules and regulations, which assures the safety of nuclear power plants. One of these tests called materials surveillance testing is performed in order to evaluate the degree of degradation of a reactor vessel by measuring the change of nil-ductility transition temperature versus temperature through mechanical Charpy impact testing [1]. Although a sufficient number of mechanical test specimens have to be available in order to accurately evaluate the embrittlement effect related to reactor operation, a limited number of specimens are only available realistically, during construction due to the space limitation and thus ample information is not available for maintaining the integrity and making decisions for life extension. Due to this limited number of specimens, broken specimens, which are assumed to be metallugically, the same as unbroken specimens are sometimes reconstituted for more tests, although metallurgical changes might have already realistically occurred. In order to understand the characteristics of the specimen's inside due to impact testing, analytical work using a finite element method (FEM) can be a good tool to calculate the stresses and displacements at any point inside the specimen. Maximum and minimum stresses calculated can be used to predict the areas and locations where they exceed the allowable stress level which may lead to material deformation or failure and to extract the allowable length from a broken specimen for reconstitution. Ultrasonic testing as one of nondestructive evaluation methods can be a useful tool to measure material properties, although it has already been widely used for crack detection in structures [2-3]. Ultrasonic signals from Charpy impact test

specimen were analyzed for the ultrasonic parameters between unbroken and broken specimens. Unirradiated base and weld metal specimens kept from reactor vessel manufacturing process were used. Ultrasonic test parameter including transit time was measured at different locations. Through this analytical and experimental work, a good understanding was given for the behavior and characteristics inside the specimen due to the impact testing of the Charpy specimen

EXPERIMENT

Test specimen

The test material for this experiment is made of Mn-Mo-Ni low alloy steel and was extracted at 1/4T from the surface of the reactor vessel beltline region during reactor fabrication and machined in the form of standard Charpy impact test specimens according to ASTM E23 as shown in Fig.1 [4]. A very limited number of specimens were kept unirradiated for the reference and baseline test, while most of the specimens were inserted into the reactor vessel for continuous irradiation during operation by regulation. The chemical composition and heat treatment condition for the specimens are given in tables 1 and 2. The broken half specimens have been kept after the completion of the Charpy impact test for the unirradiated base and weld specimen for this experiment.

Transit time measurement by ultrasonics

In order to understand the change of ultrasonic characterization inside the specimen due to Charpy impact testing, an ultrasonic pulse echo data acquisition system was used. SNAP 5000 system from Ritec inc. was used as a pulser and receiver for measuring an accurate transit time. An Aerotech transducer 5.0Mhz with a diameter of 6mm was used. The dimension of the specimen was so small in depth that a delay line was attached in order to reduce the effect of the near zone. The ultrasonic signal was acquired under the same condition since the purpose of this experiment was to measure the ultrasonic signal by a direct contact method and thus constant weight was applied upon the transducer in order to maintain constant contact pressure, although it does not greatly affect the transit time measurement. Since the measurement of transit time is greatly affected by a whole range of spectrum used, continuous trials were performed in order to choose the correct frequency range that will give a linear relationship between the phase and frequency [5]. The slope between them was chosen to calculate the transit time at that location. Signal acquisition for the transit time measurement was done starting from the near end of the specimen toward the broken area through a minute movement.

Analysis by finite element method

Two-dimensional triangular meshes were applied to the unbroken Charpy specimen in order to simulate Charpy impact testing [6]. Modeling was performed on the specimen with a rectangular shape. The model of the specimen with a total length of 55mm and depth of 10mm, having a notch at the bottom center has 302 triangular meshes. No differences were given between the base and weld metal in modeling since the detailed microscopic metallurgical constant was not considered as an input for the model. Stress free boundary conditions and free movement at the bottom edge were assumed. Impact load was also assumed to apply at the top center. Stresses were calculated at each mesh from the displacement at each node of each triangular element.

Table 1. Chemical composition(wt%) of the specimen

Element	C	Si	Mn	P	S	Mo
Base	0.16	0.17	1.28	0.006	0.005	0.48
Weld	0.06	0.37	1.68	0.007	0.008	0.55
Element	Ni	Cr	Cu	Al	Co	Fe
Base	0.71	0.17	0.06	0.011	0.012	Bal.
Weld	0.58	0.03	0.04	0.004	0.011	Bal.

Table 2. Heat treatment of the specimen

Material	Temperature	Time	Cooling method
Base Metal	Austenizing(871 ^{o}C)	4 hr	Water-quenched
	Tempered(663 ^{o}C)	4 hr	Air-cooled
	Heating : 595 ^{o}C Holding : 595 ^{o}C Cooling : 310 ^{o}C	15 ^{o}C/hr 6 hr 10 ^{o}C	Air-cooled
Weld Metal	Post weld , Stress relief Heating : 595 ^{o}C Holding : 595 ^{o}C Cooling : 310 ^{o}C	15 ^{o}C/hr 6 hr 10 ^{o}C	Air-cooled

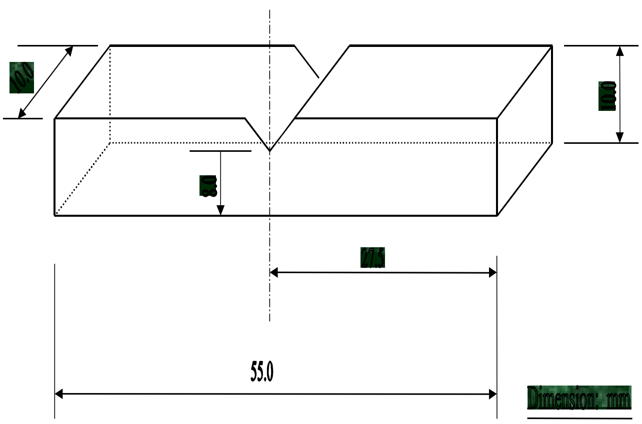

Figure 1. Charpy impact test specimen

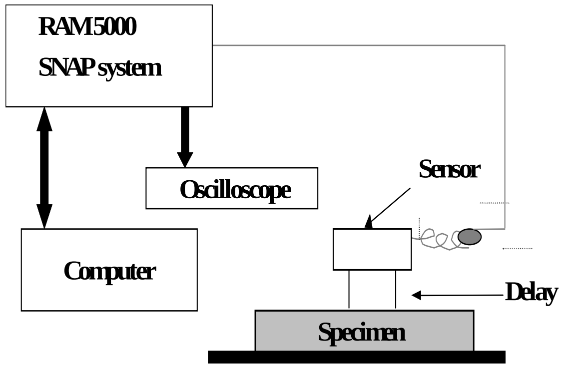

Figure 2. Experimental set-up for acquiring signals

RESULTS AND DISCUSSION

Characteristic evaluation by ultrasonics

Ultrasonic signal acquisition and analysis for the broken Charpy impact specimen was performed. Fig. 3 shows a typical ultrasonic signal acquired from the specimen by a transducer. Signals 1 and 2 represent the front and back surface of the delay line and 3 and 4 are the signals from the front and back surface of the specimen. The signal from 3 to 4 acquired from the back surface of the specimen was gated and then continually Fourier transformed in order to achieve a relationship between the phase and frequency and finally the slope, transit time between front and back surface of the specimen was calculated within acceptable frequency range.

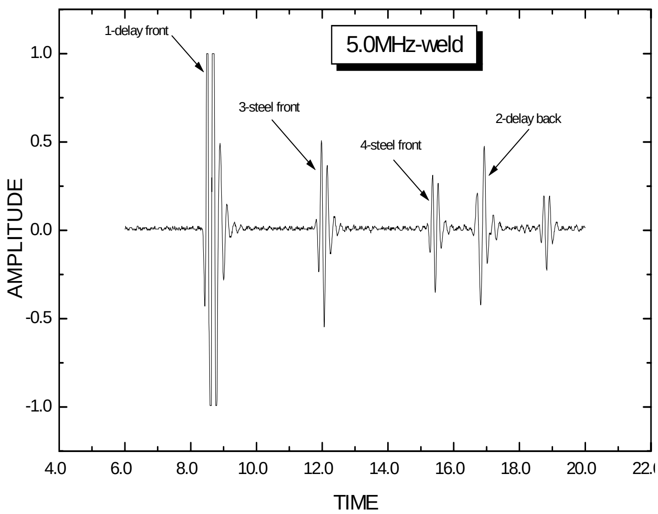

Figure 3. Typical ultrasonic signal from specimen

An ultrasonic evaluation was conducted for the signals acquired from the Charpy impact test specimens made of the same material representing the base and weld metal of the reactor vessel. The evaluation was performed for the unirradiated specimen and the relationships between the transit time and the location from the end of the specimen toward the broken area for the specimen being tested and the notched center for the unbroken specimen. These results are shown in Figs. 4 and Fig. 5. One can see from these figures that the transit time for the specimen does not change much from the left end of the specimen to a certain location for both the broken specimen as well as the unbroken specimen, although transit time in the broken specimen becomes slightly higher compared to the unbroken specimen and then suddenly jumps in the broken specimen compared to the unbroken specimen for both the base and weld metal. This jump in the base metal was higher than in the weld metal. Such jump in the different metals may not be interpreted from the effect generated by a microstructural defect and it may be just related to the material testing itself. The only concern considered is how far the jump lasts from the notched center and if the jump is related to the metallurgical changes due to material testing within the targeted area. Such question has to be answered through more research and various experiment

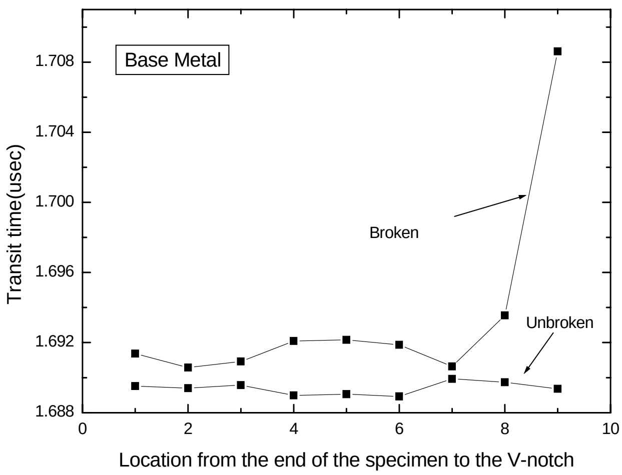

Figure 4. Transit time variation versus sensing location on base metal specimen

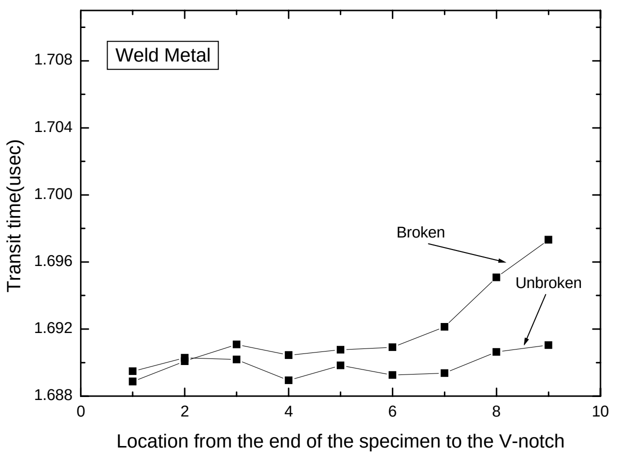

Figure 5. Transit time variation versus sensing location on weld metal specimen

Analytical evaluation by FEM

Stress-max and stress-min. at each mesh were calculated from the nodal point displacement by a finite element analysis and the results are shown in Figs. 6 and 7. In these figures, horizontal axis shows the total number of nodal points lengthwise and the vertical axis indicates the stress-max. and stress-min. respectively. The unit in the vertical axis is in N/m^2 and 2.09E+09 N/m^2 was used as the Young's modulus. One can see that there are many lines, which denotes a stress value from just below the top surface depth-wise to the bottom of the specimen. The areas where peaks are observed in the figures are the centers of the specimen. One may notice that stress-max and min. occur near the center notched area of the specimen and died away sharply as we move towards the end of the specimen. Such a phenomenon was also observed in the transit time measurement shown in Figs. 4 and 5, where it was greater near the center area and died away easily. One may also easily expect failure to occur near the center notched area, where the stress-max and min. exceed a certain range, the Young modulus, for example.

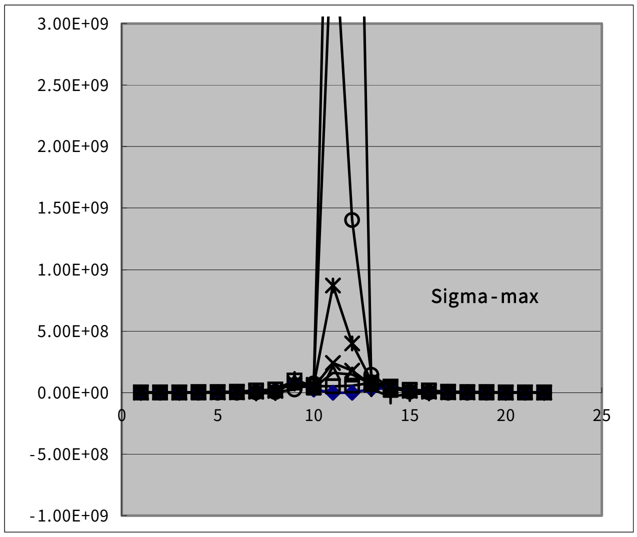

Figure 6. Stress-max. distribution versus nodal point location in lengthwise on base metal specimen

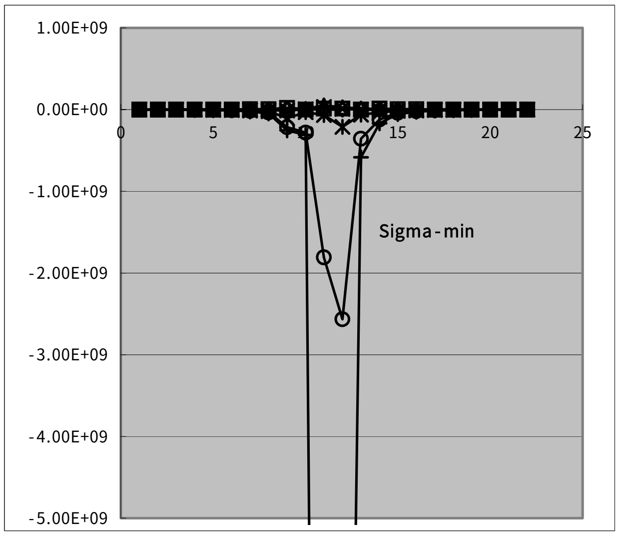

Figure 7. Stress-min. distribution versus nodal point location in lengthwise on weld metal specimen

Conclusions

Ultrasonic transit time variation was measured for broken base and weld Charpy impact test specimens in order to see if there were any metallurgical changes due to the impact testing. Analytical work by modeling a real impact testing using a finite element method (FEM) analysis was also performed in parallel with a real ultrasonic experiment. The results showed that a longer transit time was observed near the broken area and then abruptly died away from the center, and this can be correlated with the large stresses obtained from the FEM analysis for the specimen, where a large stress distribution was also observed near the center notched area and died away as soon as we move away toward the end of the specimen.

This study suggests that an adequate metallurgical understanding must be given to the reuse of the area subjected to impact testing, especially from a broken half specimen. More scientific research is needed for a specimen embrittled by neutrons in a nuclear reactor vessel [7].

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