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Determination of welding residual stress distribution in API X65 pipeline using a modified magnetic Barkhausen noise method

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Abstract

A modified magnetic Barkhausen noise (MBN) method was applied to obtain the residual stress distribution in an API X65 pipeline weldment. Different weldment microstructures affected the magnetic response and yielded different MBN values. In order to reflect the microstructural variations in the heat-affected zone (HAZ), calibration samples were extracted from four different regions: weld metal, coarse-grained HAZ (CGHAZ), fine-grained HAZ (FGHAZ), and base metal. This approach yielded that compressive residual stresses existed in the CGHAZ contrary to the tensile results using the base-metal-based calibration method. Compared with the results from the mechanical saw-cutting method, it can be concluded that the data obtained with the HAZ-based calibration method were more reliable.

Keywords: Residual stress; Magnetic Barkhausen noise; Fracture toughness; Welding

1. Introduction

Residual stresses, present in virtually all manufactured components and assembled structures, can alter a structure's load capacity when superposed upon applied external stresses. In particular, residual stresses due to welding can degrade buckling strength, brittle fracture strength, and fatigue life. It is thus important to estimate the distribution of welding residual stresses and their effects on the performance of a welded structure.

Industry has been searching for ways to measure residual stresses accurately, quickly and easily without damage to the material being tested. Several methods have been developed; however, these are either destructive or of limited capability. A less conventional approach, the magnetic Barkhausen noise (MBN) method, is of particular interest because of its potential as a non-destructive industrial tool to measure residual stress and other microstructural parameters [1–6]. The MBN method relies upon the abrupt motion of domain walls in ferromagnetic materials undergoing a change in magnetization. That is, MBN is generated by discontinuous changes in the magnetic flux density associated with the jump of domain walls between pinning sites.

Because of their sensitivity to domain configurations, MBN measurements can be used to evaluate residual stress [2–4]. Measurements of the MBN signal under applied stress indicate that it increases under applied tensile stress and decreases under compressive stress [2], i.e. a behaviour associated with an increase in the 180° domain wall population in the direction of the applied tensile strain field and a decrease under compressive strain. Since the applied strain and MBN levels are related, quantitative residual stress data can be obtained by calibrating the noise level and the absolute stress value.

In addition to being sensitive to the stress state, however, MBN is also affected by microstructure [5,6]. Therefore, for MBN to be effective in determining residual stresses in steel weldments, different microstructures must be calibrated individually. However, conventional MBN methods use only samples of weld metal and base metal for calibration, although the heat-affected zone (HAZ) microstructures change continuously from weld metal to base metal.

In this study, a HAZ-based calibration method was used to assess the effects of the microstructural variations on

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Table 1
Chemical composition and welding conditions of API 5L X65 pipeline steel

Chemical composition (wt%)					
C	Mn	P	S	Si	Fe
0.08	1.45	0.019	0.003	0.31	Bal.
Welding conditions					
Welding method	AWS	Groove shape	Heat input (kJ/cm)		
GTAW + SMAW	ER70S-G E9016-G	V	12.7–30.3		

the MBN, and the distribution of the welding residual stresses in an API X65 pipeline weldment was measured using this modified MBN method. Additionally, crack-tip-opening displacement (CTOD) tests were performed to ascertain the effect of the residual stress on the fracture performance of the weldment.

2. Experiments

The calibration sample for MBN tests is a cruciform section of API X65 pipeline, which is used as natural gas transmission pipeline in Korea. Table 1 shows the chemical composition of the base metal and the welding conditions. The pipeline wall thickness and inner diameter are 17.5 and 381 mm, respectively. Fig. 1 shows the calibration jig and sample for the MBN tests. The calibration jig has a stress-loading part and a strain-measurement system. The calibration sample is placed in the centre of the stress-loading part and loaded within elastic bending ranges. Strain gauges are attached around the test area of the calibration sample to measure the applied stress. The centre positions of the calibration sample are located in the base metal, weld metal, fusion line + 1 mm, and fusion line + 5 mm (Fig. 1(b)) so as to reflect the various microstructures of the weldment; the samples at fusion line + 1 mm and +5 mm correspond to the coarse-grained and fine-grained HAZ, respectively. Prior to MBN tests, calibration samples were heat-treated at 600 °C peak temperature, 2 h of holding time and furnace cooling to eliminate any residual stress in the samples. Then, the Barkhausen noises and applied stresses were measured and recorded.

The weldment test samples, which are cylindrical in shape and 1.5 m long, are cut from the full pipe so as not to relax the residual stress during sampling. Samples are polished only in the testing area with 2000 emery paper. The MBN of the weldment test specimen is measured to obtain the residual stress distributions. The probe is scanned from the weld metal to the base metal at 0.5 mm intervals. MBN is automatically converted to residual stress (an average value at 0.2 mm below the surface perpendicular to the weld line) using the calibration curves. A mechanical saw-cutting method [7] was used to verify the welding residual stress distribution measured by the MBN method. As shown in Fig. 2, strain gauges were attached perpendicular to the welding direction and saw cutting was done by the procedures indicated.

To ascertain the effects of residual stress on fracture, the CTOD value of the steel weldment was evaluated using single edge-notched specimens (SENB) of thickness 12 mm. Two types of specimen are used, one as-welded and the other heat-treated. The heat-treatment conditions are again 600 °C peak temperature, 2 h holding time and furnace cooling. Notch locations of SENB specimen were varied from weld metal to base metal. Room-temperature CTOD tests were performed according to ASTM E1290 [8] using an universal tensile machine.

3. Results and discussion

The HAZ of the welded structures shows a gradient of microstructure and mechanical properties from the fusion line to the unaffected base metal. Metallographic analyses

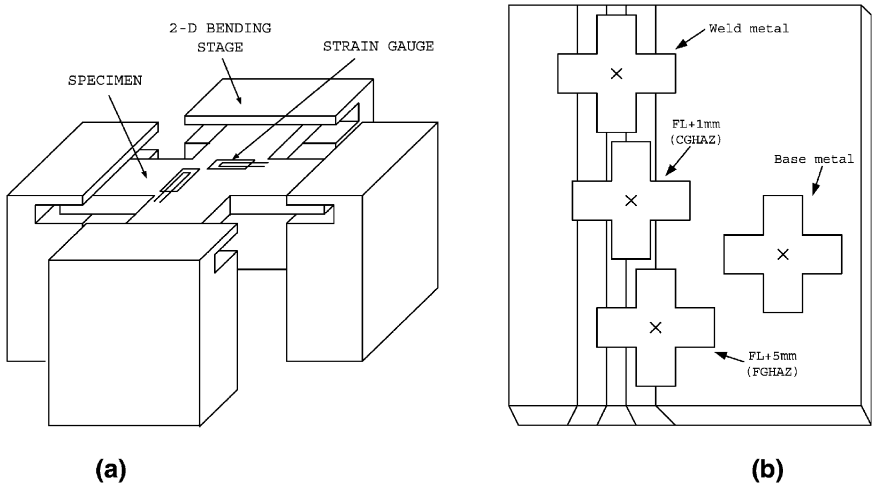

Fig. 1. (a) Calibration jig and (b) sample for MBN testing.

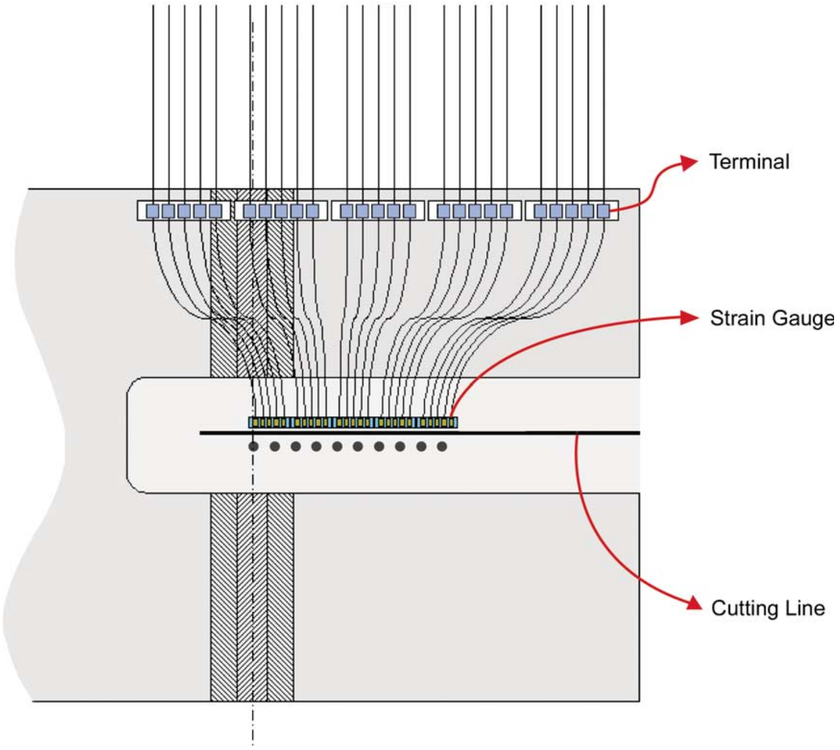

Fig. 2. Schematic diagrams of mechanical saw-cutting methods.

of the HAZ reveal four characteristic regions [9,10]: coarse-grained, fine-grained, intercritical, and subcritical regions, as determined by the peak temperature to which the region was exposed during the weld thermal cycle. We studied the coarse-grained HAZ (CGHAZ) and fine-grained HAZ (FGHAZ) regions because of their distinct differences from the base metal in microstructure and mechanical properties. Fig. 3 shows the microstructures of

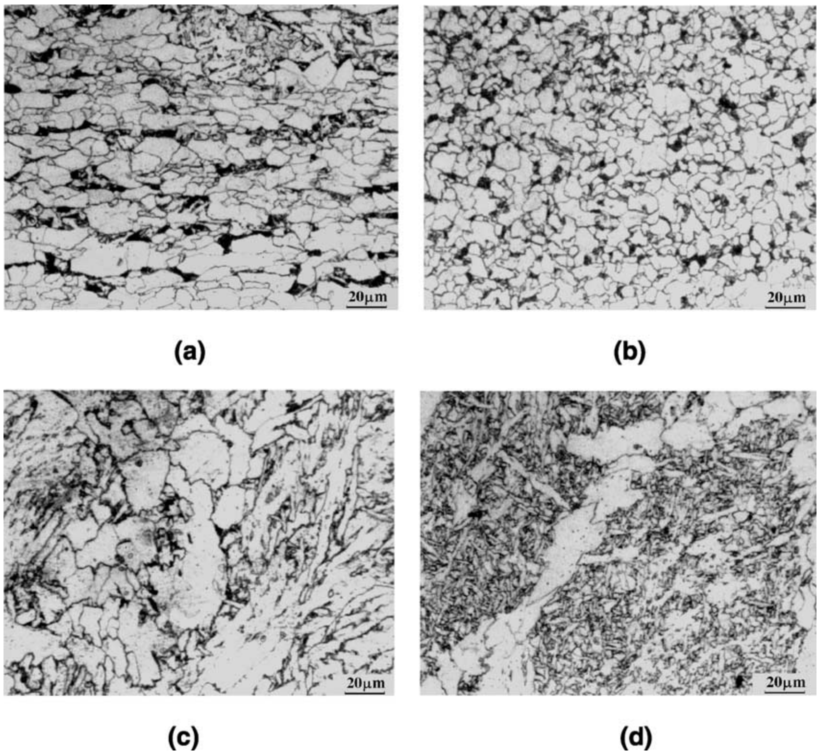

Fig. 3. Sample microstructures: (a) base metal, (b) FGHAZ, (c) CGHAZ, and (d) weld metal.

the base metal, FGHAZ, CGHAZ, and weld metal. The base metal microstructure is an elongated ferrite–pearlite structure with average grain size 10 μm, whereas that of the weld metal displays a typical solidification structure of ferrite with carbides on its grain boundaries. Coarse ferrite and grain-boundary carbides caused by the weld thermal cycle are observed in the CGHAZ. Carbides, mainly upper bainites and martensite islands, reduced the toughness of the CGHAZ by acting as a local brittle zone [11]. However, the FGHAZ had a uniform fine ferrite–pearlite structure with average grain size 2–3 μm.

These microstructural factors affected the magnetic response and yielded different MBN values. In order to reflect the various microstructures in the HAZ, we used a HAZ-based calibration method. The weldment microstructure is taken as consisting of four different parts: weld metal, CGHAZ, FGHAZ, and base metal. Thus four calibration samples were cut from the pipeline weldment so that the centre position of each calibration sample was located at each microstructure (Fig. 1(b)). Fig. 4 shows the applied strain versus magnetic values obtained for the base metal, weld metal, CGHAZ, and FGHAZ. With these curves, the residual stress in the API 5L X65 pipeline weldment was measured directly using magnetic probes. The HAZ region was divided into two separate CGHAZ and FGHAZ regions on the basis of the etched microstructures. From fusion line to fusion line + 3 mm, we used the calibration sample at fusion line + 1 mm (CGHAZ) and its magnetic properties; the measured magnetic values for the calibration sample at fusion line + 5 mm (FGHAZ) were used from fusion line + 3 mm to fusion line + 7 mm.

For comparison with conventional methods, which use the base metal as the calibration sample for the HAZ region, the residual stress was also obtained using only two calibration samples; the results are shown in Fig. 5. In the HAZ regions, the two methods yielded different results: the conventional, two-calibration-sample methods (called ‘base-metal-based calibration’) found tensile residual stress in the HAZ region near the weld metal, while the stress was

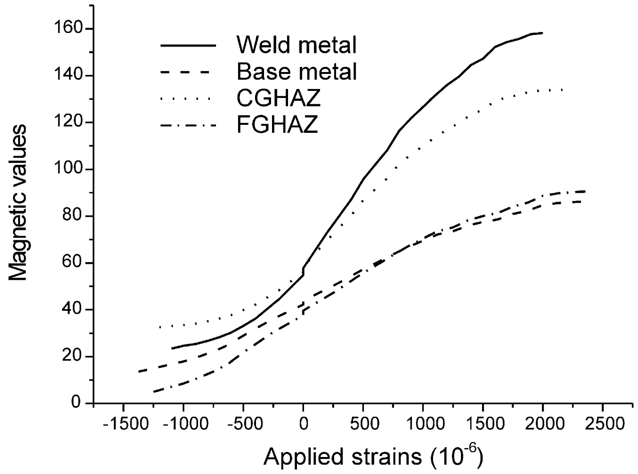

Fig. 4. Applied strains versus magnetic values.

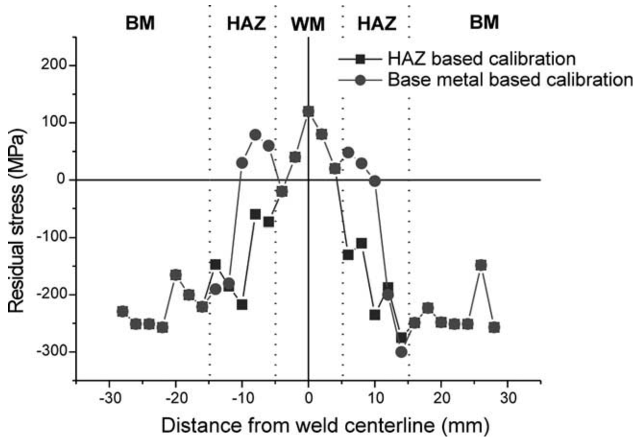

Fig. 5. Residual stress distributions obtained by MBN methods (WM: weld metal, BM: base metal).

identified as compressive when the HAZ-based calibration method was used. This difference arises from the variations in the HAZ microstructures. That is, the magnetic response calibrated by the base-metal microstructure seems not to take into account the effects of the grain coarsening and grain-boundary carbides in CGHAZ. These residual stress distributions obtained from the MBN method are compared with the mechanical cutting method in Fig. 6. To eliminate the thermal problems generally involved in specimen cutting, mechanical saw cutting was performed. The welding residual stresses, which reflect the relaxation of the residual stresses by the cutting, are easily calculated from the measured strains. The distribution is similar to the results using the HAZ-based calibration method, thus validating our new proposed calibration method for MBN methods.

The total residual stress distribution near the weldment is an equilibrium state of tensile and compressive residual stresses: a high tensile stress exists in the vicinity of the weld line, while the outer region is in compressive residual stress. As solidification commences at the weld metal, tensile stresses begin to appear in the weld metal that, upon

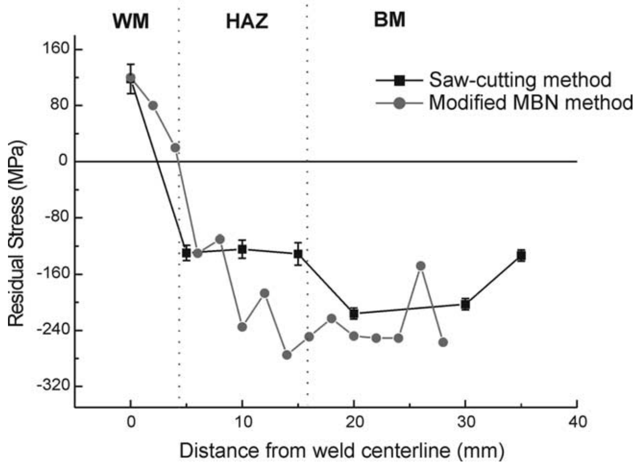

Fig. 6. Residual stress distributions obtained by saw-cutting methods.

cooling to ambient temperature, build up to the residual stress pattern [12]. Thus the maximum tensile residual stress, of magnitude as much as 35% of the weld metal yield strength, was found at the weld centre line. In the HAZ region, the welding residual stress changed from tensile to compressive stress, and the welding residual stress in the base metal reached one half of the base metal yield strength.

The tensile residual stress found in the weld metal is undesirable since tensile stress is one of the primary initiators of brittle fracture and stress-corrosion cracking in butt-welded pipes [13]. The residual stresses combined with applied stresses have a profound effect on the fracture behaviour of a welded joint and thus on the in-service performance of the welded structure. Because of tensile residual stress, both the applied stress level in the structures and the apparent fracture toughness decrease. Moreover, the tensile residual stress is confined to the weld metal, which was the weakest region in this steel weldment (Fig. 7). Therefore, the effect of the welding residual stress on the fracture performance of the steel weldment must be carefully examined. On the other hand, compressive residual stresses in the HAZ and base metal are beneficial to the fatigue life and fatigue strength of butt-welded joints [14].

Fig. 7 shows the results of a CTOD test for the specimens as-welded and after heat treatment. For the tensile-stressed zone, i.e. in the weld metal, CTOD increased due to heat treatment, resulting from relaxation of the residual stresses. Otherwise, CTOD decreased in the region of compressive residual stress, i.e. in the HAZ and base metal. We can expect that CTOD in weld metal could be recovered with the appropriate heat treatment, which can eliminate the detrimental effects of welding residual stress. However, the fracture response of weld metal did not totally recover to the base metal level. In other words, weldment fracture is affected not only by welding residual stresses but also by other factors such as weld metal mismatch and microstructural changes [11,15]. Nevertheless, the experimental results described above provide a means for correlating the MBN with the HAZ microstructure and for eliminating the microstructural effects by means of newly proposed methods of calibration in MBN.

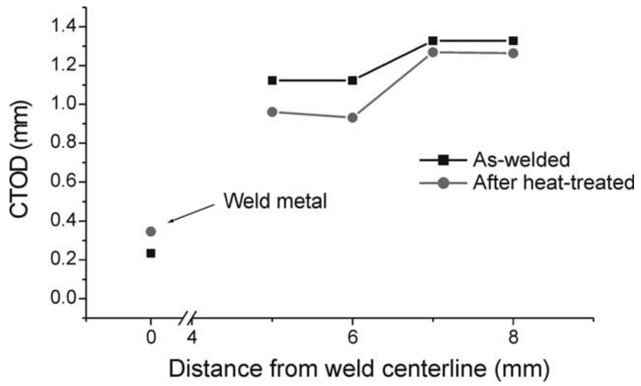

Fig. 7. CTOD for as-welded and heat-treated specimens.

4. Conclusions

A modified MBN method was used to evaluate the distribution of welding residual stresses in API X65 pipeline weldments. It was found that

(1) Different weldment microstructures affected the magnetic response and yielded different MBN values. MBN methods were modified using HAZ-based calibration methods to assess the effects of microstructure and were compared with the conventional method using a base-metal-based calibration.
(2) The maximum tensile residual stress found at the centreline of weld was as much as 35% of the weld metal yield strength. On the other hand, the HAZ and base metal showed compressive welding residual stress.
(3) Experimental results have revealed that compressive residual stresses existed in the CGHAZ contrary to the tensile results in the conventional method. Comparing results with those from the mechanical saw-cutting method, it can be concluded that the data obtained with the HAZ-based calibration method were more reliable.
(4) CTOD tests for the as-welded and heat-treated specimens revealed that the tensile residual stress in this pipeline weldment lowered the CTOD at fracture and vice versa.

Acknowledgements

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