

Magnetic easy axis development in steel—the influence of manufacturing

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Oil and gas pipelines often display a bulk magnetic easy magnetization direction, and this may influence results obtained during magnetic nondestructive evaluation. The origin of this magnetic easy axis is not well known. Earlier work [L. Clapham, C. Heald, T. Krause, and D. L. Atherton, *J. Appl. Phys.* **86**, 1574 (1999)] speculated that it was a result of residual stresses introduced during pipeline manufacturing, specifically cold bending. This article reports a study in which a magnetic Barkhausen noise technique is used to follow the development of a magnetic easy axis in a steel plate sample subjected to progressive amounts of cold bending. © 2000 American Institute of Physics. [S0021-8979(00)04816-7]

The most cost-effective inspection methods for oil and gas pipelines are based on the magnetic flux leakage (MFL) technique, where the pipe wall is magnetized to near saturation and defects cause the flux to “leak” into the air where it is detected by inductive coils or Hall probes. The MFL signal is used to determine defect depth, however it is sensitive not only to defect depth but also inspection tool speed, pipe wall stress, and pipe wall magnetic behavior. The last parameter is the subject of this communication.

Steel pipelines often exhibit a bulk magnetic easy axis in the pipe axial direction.¹ Although traditionally magnetic easy axes have been associated with crystallographic texture, our recent work¹ has shown that the pipeline easy axis is associated not with texture but with the effect of cold work during the manufacturing process. Specifically, we speculated that the pipeline magnetic easy axis was created by residual compressive stresses produced during the cold bending stage of processing. In the present study we investigate this hypothesis by examining magnetic easy axis development in a steel sample subjected to progressive cold bending.

Bulk magnetic anisotropy can be effectively characterized using a surface magnetic Barkhausen noise (MBN) technique. In the “angular dependent” MBN method the MBN signal is measured as a function of the angle of the applied magnetic sweep field to a reference direction. This method has been used successfully to determine the magnetic easy axis in 3% Si–Fe laminates² and pipeline steels.³ Figure 1 shows angular MBN results for a typical steep pipe. The MBN_{energy} term is the voltage signal squared, and is used to characterize the MBN measurement at a given sample location. The elongation of an angular MBN_{energy} plot in a certain direction has been shown to correspond to a magnetic easy axis.² Figure 1 illustrates a typical axial magnetic easy axis result at a pipe wall outside surface. In contrast, hot rolled steel plate typically exhibits no magnetic easy axis.³

During pipe forming, a steel plate is cold bent into a circular cross section. In the present study a sample of steel plate of dimensions 645 mm×128 mm×3 mm was progressively bent into an arc, with MBN measurements made after each bending stage. Bending was done along the long axis of

the plate (645 mm) which is equivalent to the “hoop” direction in a pipe. The short axis (128 mm) was correspondingly labeled the “axial” direction. In addition to angular MBN, linear MBN scans of the sample were conducted in which the magnetic sweep field was aligned in a constant direction with the magnet moved along a linear trajectory. The magnetic anisotropy was characterized by the MBN_{energy} ratio, which is the ratio of the MBN_{energy} in the axial direction to that in the hoop direction, or

$$MBN_{energy} \text{ ratio} = \frac{MBN_{energy}(\text{axial})}{MBN_{energy}(\text{hoop})}. \quad (1)$$

Prior to bending, the plate sample exhibited no magnetic easy axis, i.e., the MBN_{energy} ratio was approximately to one.

Cold bending was achieved by feeding the sample lengthwise through sets of parallel bending rollers. Figure 2(a) shows (in cross section) the roller configuration. Roller C can be adjusted to alter the degree of bending in the sample. Figure 2(b) shows the cross section of the sample after bending, with the parameter “z” indicated. Only two progressive bending stages (z=12 and 36 mm) were possible before the MBN magnet began losing surface contact due to the sample curvature, however results from these two stages were sufficient to draw some important conclusions.

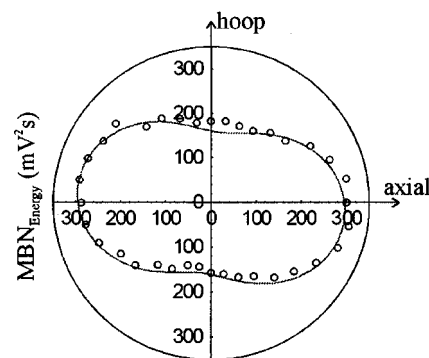


FIG. 1. Angular MBN_{energy} results for the outside surface of a typical axially welded pipeline sample.

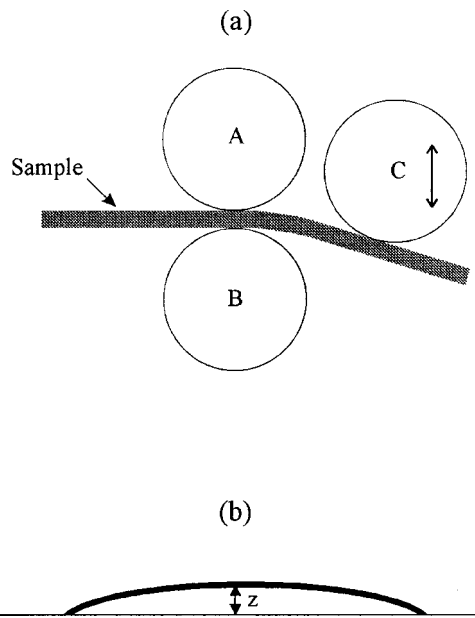


FIG. 2. (a) roller configuration in the bending apparatus (cross section), (b) cross section after bending with parameter z indicated.

Figure 3 shows results of linear scans along the pipe wall external surface. Scans are along the hoop direction of the sample, with the MBN magnet oriented in the axial direction. Scans for the flat sample and samples bent to $z=12$ (radius of curvature $r=17.3$ m) and 36 mm ($r=5.8$ m) are shown. A clear increase in axial MBN signal is seen with increasing deformation. Figure 4 shows results of additional linear scans along the sample axial direction, with a hoop-oriented MBN magnet. Here many points overlap so only results from the flat sample and the $z=36$ mm sample are shown.

Finally, calculations of MBN_{energy} ratio were made for each bending stage, using the average of the linear MBN signals in the axial direction (Fig. 3), and the hoop direction (Fig. 4). A graph of the MBN_{energy} ratio is shown as a function of z in Fig. 5.

The results of Figs. 3–5 clearly indicate that cold bending of the steel sheet samples produces a magnetic easy axis in the direction transverse to bending. This confirms our earlier speculation¹ that the axial magnetic easy axis in pipe-line results from the cold bending process. The evolution of

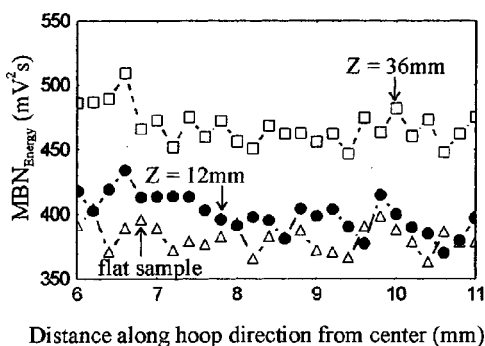


FIG. 3. MBN_{energy} results for a scan along the hoop direction. MBN magnet is oriented in the axial direction. Data is shown for the flat sample (Δ), at $z=12$ (\bullet) and 36 mm (\square).

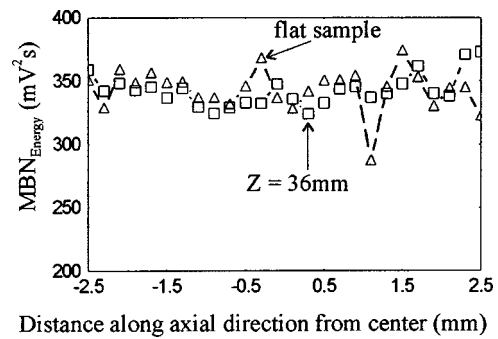


FIG. 4. MBN_{energy} results for a scan along the axial direction. MBN magnet is oriented in the axial direction. Data is shown for the flat sample (Δ) and $z=36$ mm (\square).

this easy axis is explained as follows. Bending produces significant plastic tensile strain the hoop direction, and when the external bending load is released, the outer wall surface adopts a state of *residual elastic hoop compression*.⁴ Concurrent work⁵ on these materials has shown that MBN is highly sensitive to elastic, yet relatively insensitive to plastic strain, therefore the elastic component will determine the magnetic behavior. Hoop elastic compression is expected to create fewer 180° domain walls (which generate MBN) in the hoop direction and correspondingly more of these walls in the axial direction, the result being a magnetic easy axis in the axial direction.⁶

The results of this study yielded an unexpected result. It was earlier believed that the residual hoop compression both reduced the MBN signal in the hoop direction and increased it in the axial direction. The present study indicates that this is not the case; although the hoop compression increases the MBN signal in the axial direction it decreases it only slightly in hoop direction. This result implies that minor modifications to the existing theory⁶ are required; however more importantly it will be useful in determining the influence of more complex defect-induced stress patterns on MFL signals.

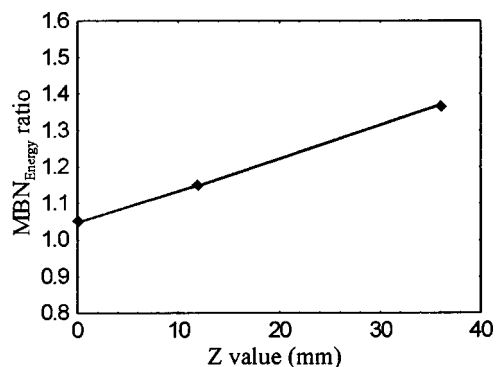


FIG. 5. MBN_{energy} ratio vs z value. In this case the MBN_{energy} values used in Eq. (1) are calculated from an average of data values shown in the scans of Figs. 3 and 4.

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