Influence of Lüders bands on magnetic Barkhausen noise and magnetic flux leakage signals

A. DHAR, L. CLAPHAM, D. L. ATHERTON
Department of Physics, Queen's University, Kingston, Ontario K7L 3N6, Canada
E-mail: lynann@physics.queensu.ca

Lüders bands, which occur during the onset of tensile plastic strain in most steels, are localized regions of high plastic strain within a specimen, bounded by regions that have undergone mainly elastic deformation. This study was conducted to understand the dependence of magnetic Barkhausen noise (MBN) and magnetic flux leakage (MFL) signals on Lüders banding in mild steel. MBN and MFL measurements were made on tensile samples of hot-rolled mild steel, in which Lüders bands were deliberately nucleated by applying tensile stress. The results indicate that the MBN activity increases in the region of Lüders bands. A strong magnetic anisotropy was also observed on these bands with the generation of dual magnetic easy axis. The MFL results indicate that magnetic flux leaks out into the air from regions with Lüders bands due to decreasing permeability in these regions owing to localized plastic deformation.

1. Introduction

Plastic deformation in metals and alloys sometimes occurs discontinuously in small, localized plastic zones called Lüders bands [1–4]. This phenomena is manifested by the presence of a flat serrated plastic region in the stress-strain curve, which usually shows load instabilities for which the average amplitude of stress is constant with strain. The appearance of Lüders bands and a serrated flat region in the stress-strain curve depends not only on the testing variables (strain rate, temperature) but also on also on heat treatment and microstructural parameters, such as grain size or dislocation density [1, 3].

The Lüders behavior is a plastic instability, which occurs mostly in steels containing interstitial elements, such as carbon and nitrogen, in solid solution. It is generally believed that these bands form as a result of dislocation pinning with these (carbon or nitrogen) solute atoms, although the exact mechanism of their formation has not yet been completely understood. Under tensile stress, the sample exhibits a strain localization oriented around 45° with the tensile direction, growing from one end of the sample to the other. These are often macroscopically visible and termed 'stretcher strains'. This Lüders behavior is not restricted to tensile loading, but is also observed in complex loading, leading again to stretcher strain formation. Many industrial plastic forming processes can generate these Lüders bands, consequently they can appear in many steel engineering parts subjected to plastic strain during their manufacture or while in service [1, 5].

Magnetic methods of non-destructive evaluation (NDE) are gaining recognition for the detection of defects and evaluation of intrinsic properties in steels [6–8]. Prominent among the commercially used magnetic methods for NDE of ferromagnetic materials include magnetic Barkhausen noise (MBN) and magnetic flux leakage (MFL) techniques. While MBN is used for the NDE of residual strain, thermal damage and other intrinsic properties [6, 8], MFL is primarily utilized for the detection of corrosion defects in oil and gas pipelines [6, 7]. As most of the steel products used for engineering applications are manufactured using some kind of plastic deformation processing, it is possible that Lüders bands may appear in these components. The defects which form in oil and gas pipelines during in-service aging act as stress raisers as these pipelines are operated at up to 70% of yield strength [9]; this could initiate plastic deformation in the vicinity of the defect leading to the formation of Lüders bands. Thus, in order to use MBN and MFL techniques for NDE applications in ferromagnetic materials, it is important that the effect of Lüders banding on these magnetic techniques is clearly understood.

Although there have been several investigations reported on the effect of plastic deformation on MBN activity [10–13], there is very little published work on MBN or MFL response to Lüders straining. It has recently been demonstrated that magnetic NDE techniques using SQUID have the ability to detect localized areas of plastic deformation in ferromagnetic materials [14]. The objective of the present investigation is to understand the effect of Lüders bands on MBN and MFL signals. MBN and MFL measurements have been made on hot-rolled mild steel samples, which have had Lüders bands nucleated during previous tensile straining. The results are explained in terms of the effect of localized plastic deformation on magnetic properties affecting MBN and MFL responses.

2. Experimental

Tensile samples with central dimensions 250 mm × 87 mm were cut from a 2.8 mm thick hot-rolled mild steel plate in such a way that the applied tensile stress axis coincided with the rolling direction of the plate. The samples were annealed at 575°C for 1 hour and then furnace cooled to remove any residual stresses due to previous cold working. Prior to deformation the samples were ground to 1000 grit finish. The samples were subjected to uniaxial tensile deformation on a 800 kN capacity Riehle uniaxial testing machine at a strain rate of 0.1 mm/min. The strain was continued till a Lüders band nucleated near the upper yield point; this occurred at each fillet of the sample near the gripping section of the loading machine. At this point the samples were unloaded and removed for magnetic measurements. These Lüders bands, one at each end of the sample (L_1 and L_2), could be seen at about 45° to the stress axis (as shown in Fig. 1). These bands are regions of localized plastic deformation within the sample separated by a non-deformed region, which has undergone only elastic strain.

The experimental arrangement used to measure the MBN activity is shown in Fig. 2a. The samples were magnetized using a U-core ferrite electromagnet. A 12 Hz sinusoidal waveform, produced by a function generator and amplified by a Kepco Bipolar power supply, drove the exciter coil of the electromagnet. The MBN signals, detected by a high-resolution magnetic read-head placed between the pole-pieces of the electromagnet, were amplified by about 1000 times, passed through band-pass filters (2–300 kHz) and finally input into a personal computer having a resident digital oscilloscope board. The data was acquired and analyzed using LabView software. Only those voltages having amplitudes higher than a selected threshold were considered for analysis. The 'MBN_{Energy}' parameter is calculated by integrating the square of the voltage signal with respect to time.

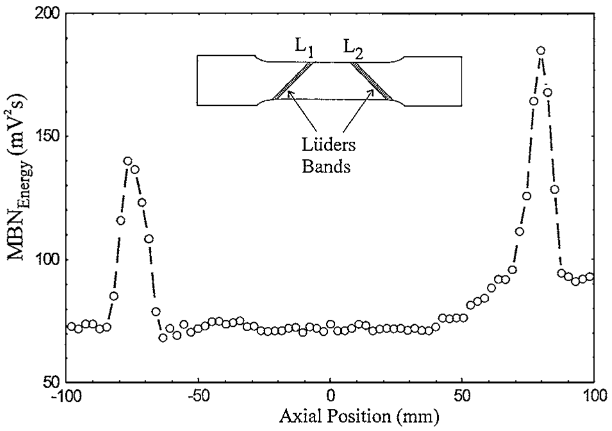

Figure 1 Variation of MBN_{Energy} along the length of the sample with the magnetization direction perpendicular to the plastic stress axis. The mild steel sample with Lüders bands is also shown.

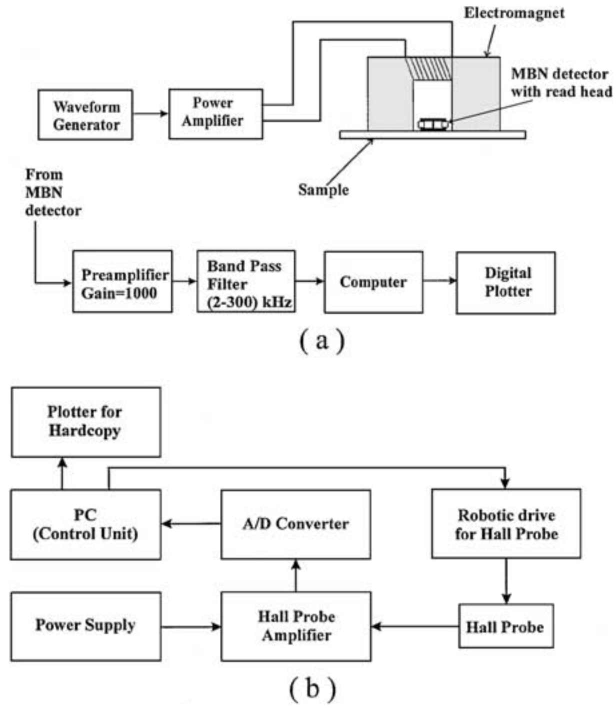

Figure 2 Experimental arrangement for the measurement of (a) MBN signals (b) MFL signals.

The linear and area MBN measurements were made using an automated MBN scanner. This scanning unit consists of stepper motors to control the X and Y movements of the U-core electromagnet/read-head arrangement. The scanner is controlled by LabView software, which controls the X-Y movement of the MBN detector and also acquires the MBN data at equally spaced points along a linear direction or in a defined area on the sample surface. Angular MBN measurements were made on a different MBN set-up by rotating the electromagnet in 10° angular increments around a fixed axis location, through 360°. Angular MBN data is usually displayed in a polar form and the maximum of the MBN_{Energy} corresponds to the magnetic easy axis direction of the sample. This angular MBN technique has been used extensively to determine the easy axis of magnetization in ferromagnetic materials [15, 16]

MFL measurements were made by magnetizing the sample with permanent magnets and using steel plates to couple the magnetic flux into the sample. The samples were magnetized in the direction of the plastic stress. The leakage flux was detected using a Hall probe sensor positioned between the two arms of the magnetizer. The Hall probe sensor position is scanned using a simple computer controlled stepper motor system obtained from a modified digital plotter. The pen of the digital plotter is replaced by a plastic robotic arm, on which the Hall probe is mounted. The main unit of the data acquisition and control system is a personal computer with data acquisition board, as shown in Fig. 2b. It controls the Hall probe scanning system and reads the output from the Hall probe amplifier. The signal from the Hall probe is read into the PC via an A/D converter. During data acquisition, the flux density at each point is recorded along with the position coordinates of the Hall probe. Thus surface or contour plots

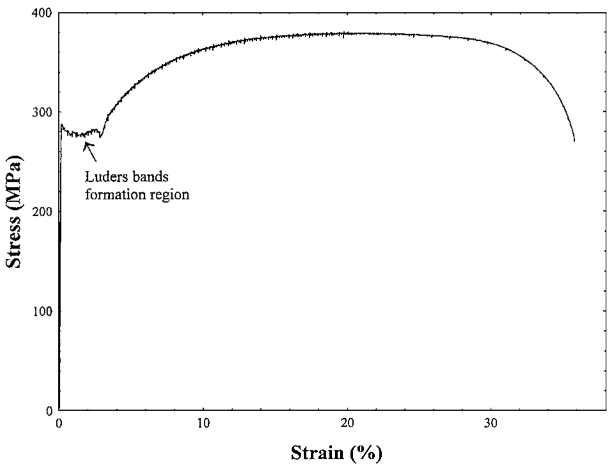

Figure 3 Tensile stress-strain curve of the hot-rolled mild steel sample, clearly showing the Lüders straining region.

can be generated showing the leakage flux distribution over the area scanned by the Hall probe.

3. Results and discussion

Fig. 3 shows the tensile stress-strain curve of the sample used in the present investigation, clearly showing the Lüders banding region. This region is characterized by a relatively flat portion on the stress-strain curve just past the upper yield point where serrated yielding takes place due to nucleation and propagation of Lüders bands. After these Lüders bands have propagated the entire length of the sample, the stress increases in the usual manner due to strain hardening. In the present investigation, in order to understand the effect of Lüders bands on MBN and MFL signals, all the magnetic measurements were made on samples with only a single Lüders band nucleated at each end of the sample near the fillet (Fig. 1), where the initial stress concentration occurs when tensile stress is applied.

Fig. 1 shows the variation of MBN_{Energy} along the gauge length of the sample with the magnetization perpendicular to the plastic stress direction. It is evident from this figure that the MBN_{Energy} exhibits a sharp increase at the two opposite ends of the sample in the region of Lüders bands. This figure indicates that the increase in MBN activity is only confined to the Lüders band regions where the plastic deformation is localized; regions remote from this band show a lower but relatively constant MBN_{Energy} response. An increase in MBN activity due to Lüders straining has also been observed earlier by other workers [17, 18]. This increase in the MBN_{Energy} has been attributed to the introduction of dislocations on plastic deformation [12, 19]. These dislocations form effective pinning centers for domain wall motion, which can be subsequently unpinned by the applied time-varying magnetic field. This leads to increasing interaction between domain walls and pinning sites, which results in an increase in MBN signals [12, 13].

In order to understand the variation of MBN activity around the Lüders band, area scans of MBN_{Energy} were made over a (50 mm × 30 mm) region above the Lüders bands. Fig. 4a and b shows the surface and contour plots, respectively, of the MBN_{Energy} variation over the Lüders band (L_1), with magnetization direction perpendicular to the plastic stress axis. It is clear from this figure that the MBN_{Energy} increases in the region of Lüders band. The increase in MBN_{Energy} is confined to the region of Lüders bands; away from the Lüders bands the MBN_{Energy} shows almost a flat response, characteristic of the undeformed region. The MBN response to the Lüders band in Fig. 4 suggests that the band appears to be at an angle of about 45° to the direction of tensile plastic stress, which is typical for the formation of Lüders bands [1, 3]. Fig. 5a and b show the surface and contour plots, respectively, of the MBN_{Energy} over the Lüders band (L_1), with magnetization direction parallel to the plastic stress axis. This MBN response is similar to that in Fig. 4, for magnetization direction perpendicular to plastic stress axis, except that the magnitudes of MBN_{Energy} shown in Fig. 5 are much lower. Comparison of the magnitudes of MBN_{Energy} in Figs 4 and 5, with different magnetization directions, indicates that the MBN activity is dependent on the direction of magnetization thereby suggesting some magnetic anisotropy induced by the localized plastic strain in the region of the Lüders bands. As the material is plastically deformed, the introduction of dislocations causes complete magnetic domain reorganization in the system. The directional order produced by the movement of isolated dislocations during plastic slip, introduces magnetic anisotropy in the deformed regions [19, 20]. The anisotropy, resulting from localized plastic deformation, creates changes in the domain wall configuration and also alters the distribution of pinning sites in the ferromagnetic system. Both these affect the MBN activity significantly.

Fig. 6 shows the polar plots of the angular dependence of MBN_{Energy} on both the regions of Lüders bands (L_1 and L_2) and on the undeformed region in the center of the sample. (It should be noted that the large difference in the magnitude between these MBN_{Energy} results compared to those in Fig. 1 and Figs 4 and 5 is due to the different MBN set-up employed for angular and linear/area MBN scans). The angular MBN technique has earlier been successfully utilized for the determination of the easy axis of magnetization in polycrystalline steels, with the magnetic easy axis being the direction of highest MBN_{Energy} [15, 16]. It is evident from Fig. 6 that at the undeformed region in the center of the sample, the MBN_{Energy} shows no angular dependence indicating that the undeformed (elastically strained and then unloaded) regions on the sample exhibit no magnetic anisotropy. However, magnetic anisotropy is induced in the regions of Lüders bands due to localized plastic straining, as is evident from the shapes of the MBN angular dependence curves for the two Lüders bands in Fig. 6. This figure clearly indicates that in all the angular orientations, the MBN_{Energy} is higher on both the Lüders band regions as compared to the undeformed regions in the center of the sample. Both the Lüders bands exhibit similar angular dependence of MBN_{Energy} except that the magnitude of MBN_{Energy} for one of the bands (L_2) is slightly higher than the other (L_1). This figure also indicates that each Lüders band region exhibits two maxima in their angular dependence of MBN_{Energy},

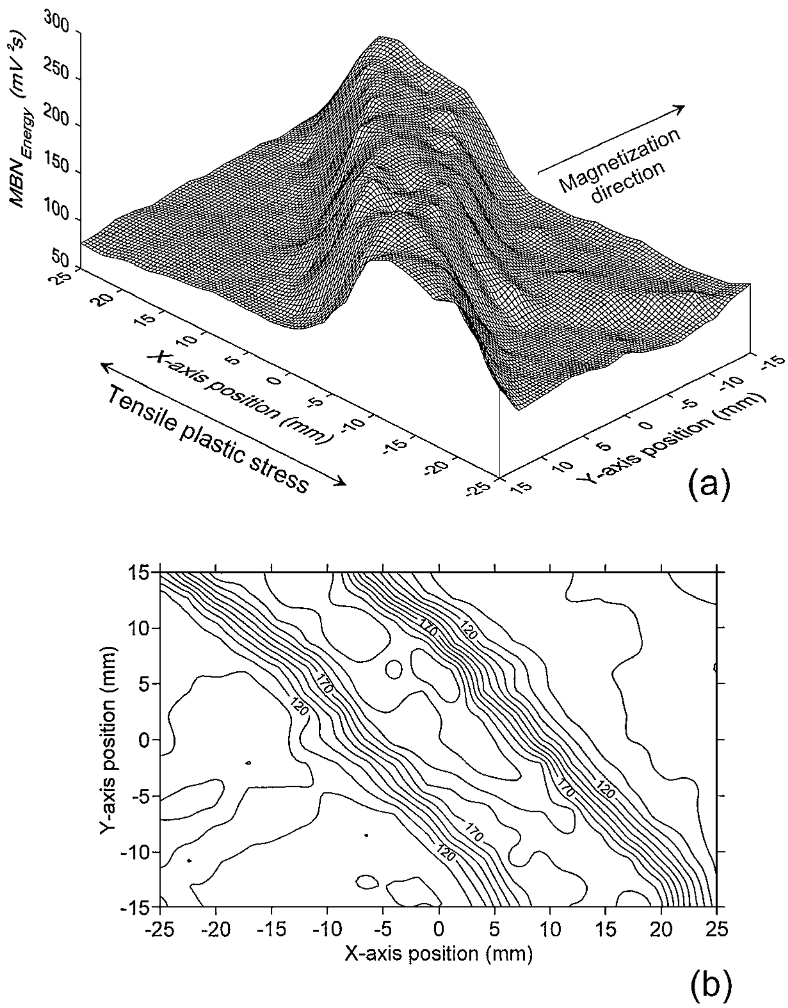

Figure 4 MBN_{Energy} patterns in the region of Lüders band (L_1), for magnetization direction perpendicular to the stress axis (a) surface plot, (b) contour plot.

thereby suggesting the existence of dual magnetic easy axis in both these Lüders band regions. From the angular position of the maximas of MBN_{Energy} in this figure it is apparent that, for both the Lüders band regions, the two magnetic easy axes are mutually perpendicular to one another. Thus the Lüders straining, due to localized plastic deformation, introduces a magnetic anisotropy with dual magnetic easy axis mutually perpendicular to one another. It is generally accepted that the primary mechanism of microscopic deformation in the Lüders band is shearing with some amount of grain rotation at a macroscopic level [3]; this plastic deformation gives rise to residual stresses [14, 19, 20] in the region of Lüders bands. As the plastic deformation in Lüders bands is primarily by shearing, the distribution of surface residual stresses is expected to be rather complicated. Nevertheless, the presence of dual magnetic easy axes in the Lüders band regions, as observed in the present study, indicates a biaxial tensile residual stress distribution in this region. Biaxial magnetic anisotropy has also been observed in several ferromagnetic materials after plastic tension [20]. However, more precise techniques such as, X-ray diffraction or neutron diffraction are required to characterize the exact residual stress distribution in the region of these bands.

Radial MFL measurements were performed in the region (40 mm $\times$ 40 mm) over the Lüders band so that the Hall probe sensor detects the component of the leakage flux normal to the surface of the sample. Fig. 7 shows the surface and contour plots of radial MFL signals in the region of Lüders band (L_1) at a flux density of 1.7 T. It is clear from this figure that the flux leaks out of the sample at one edge of the Lüders band, and reenters the sample at the opposite edge of this band. The leakage of the flux is confined to the region of Lüders straining, which is the region of localized plastic deformation. In the undeformed regions away from the Lüders bands the MFL signal is almost zero. The surface plot in Fig. 7 indicates a slight non-zero background in the MFL pattern, which arises as a result of the fringing field between the sample and the magnetic poles. In the region of the Lüders band the permeability of the sample decreases sharply due to localized deformation [11]; implying that this region has high magnetic reluctance. The magnitude of the MFL signals from the Lüders band region can be interpreted in terms of modifications of the flux density paths in the sample and the degree to which flux remains in the steel sample or is forced out into the air due to changes in permeability. The magnitude of leakage flux from the Lüders bands would likely depend on the ratio of permeability of the plastically strained (Lüders band) to the unstrained regions of the sample.

These results suggest that, in non-destructive inspection of oil and gas pipelines using the MFL technique,

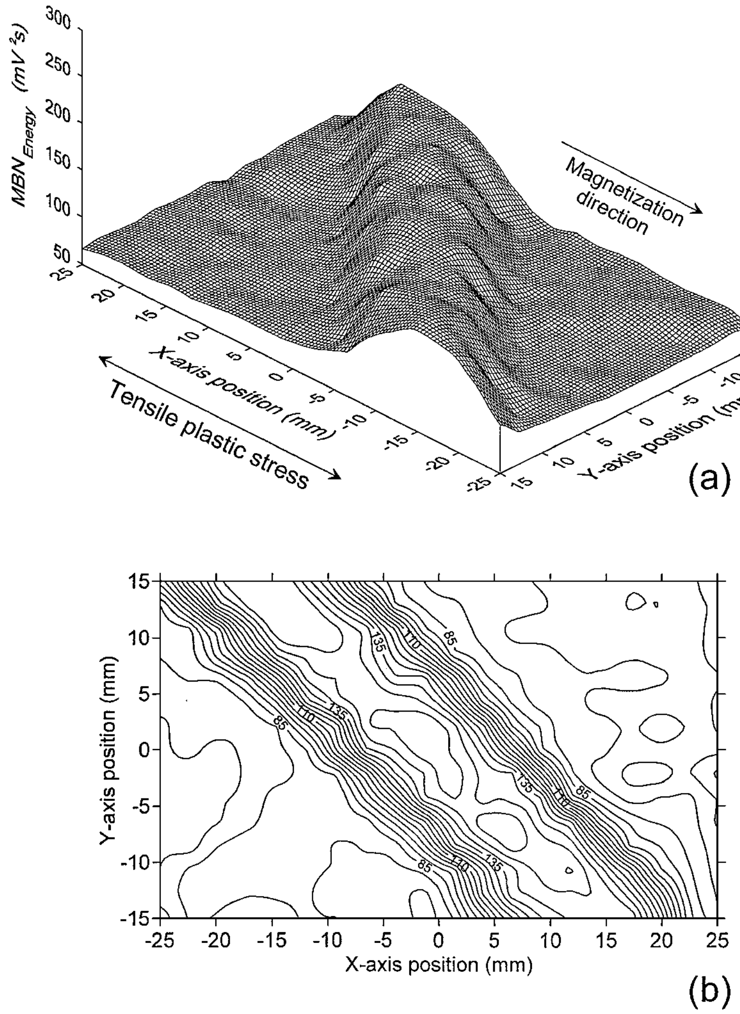

Figure 5 MBN$_{Energy}$ patterns in the region of Lüders band (L_1), for magnetization direction parellel to the stress axis (a) surface plot (b) contour plot.

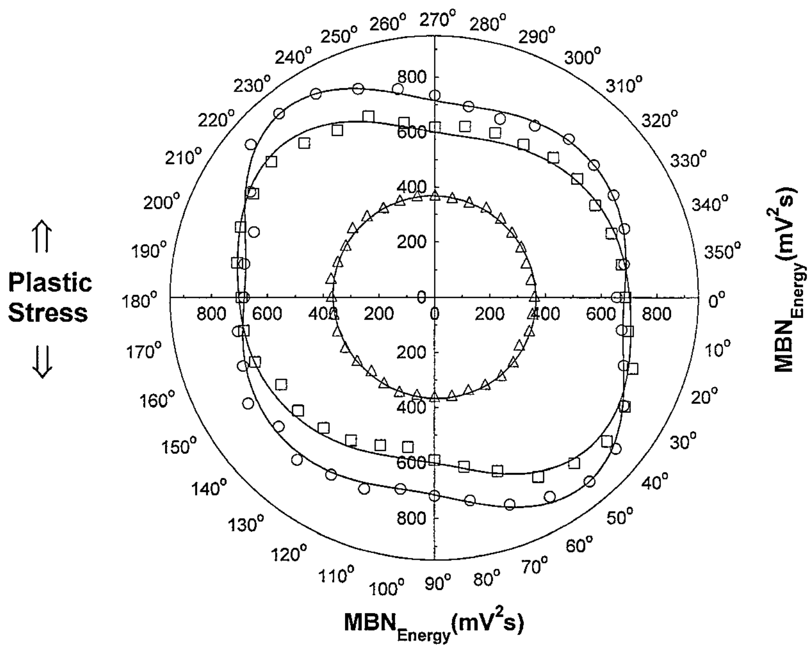

Figure 6 Polar plots of MBN$_{Energy}$ variation with magnetizing angle at different positions on the sample: (△) undeformed region in the center of the sample; (□) Lüders band L_1; (○) Lüders band L_2.

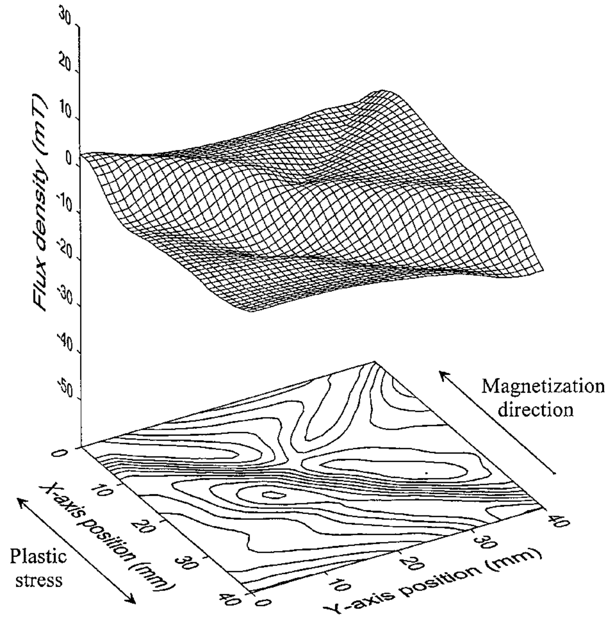

Figure 7 Surface and contour plots of radial magnetic leakage flux density field over the Lüders band L_1, with a flux density of 1. 7 T in the plate.

the MFL signals could be significantly modified due to the presence of Lüders bands in the test specimen, due to plastic deformation during manufacturing or while in service. This could seriously affect the accuracy of defect evaluation using MFL techniques.

4. Conclusions

Magnetic NDE techniques, such as MBN and MFL, are able to detect Lüders bands in ferromagnetic materials. The MBN activity was found to increase in the regions of Lüders band due to localized plastic deformation, which introduces a strong magnetic anisotropy in the region of these bands. The MFL results indicate that the magnetic flux leaks out of the sample in the region of Lüders band, likely due to the decrease of permeability caused by localized deformation in that region. These results suggest that the effect of Lüders banding should be considered while using magnetic NDE techniques for steel structures and components, which may exhibit Lüders banding due to plastic deformation.

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