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Comparison of Different Techniques for Measurement of Cold Work in Mild Steel

B. P. Badgujar*, S. K. Jha** and G. L. Goswami*,†

Abstract There are various Non-Destructive Evaluation (NDE) techniques used for measurement of residual stresses in material, such as magnetic methods, X-ray diffraction, Ultrasonic velocity measurement etc. The capabilities, applications and limitations of these techniques for evaluation of cold work / plastic deformation were studied and compared. Mild steel plates were subjected to different degree of cold deformation and were analyzed by Magneto-mechanical Acoustic Emission (MAE), Barkhausen Noise (BN) and magnetic properties (hysteresis loop parameters analysis). Further, these specimens were analyzed by X-ray diffraction and ultrasonic velocity measurements. The microhardness measurement and microstructure studies of these cold worked plates were also carried out. The results of all these studies and comparison of different techniques are discussed in this paper.

Keywords: NDE, magneto-mechanical acoustic emission, MAE, cold work, residual stress, X-ray diffraction, magnetic properties

1. Introduction

There is increasing interest for nondestructive inspection of steel components for detection of defects and for evaluation of plastic deformation and residual stresses. Different NDT techniques are used for residual stress analysis of steel, like magnetic methods, ultrasonic velocity measurements, X-ray or neutron diffraction, optical and thermal techniques etc. The capabilities, applications and limitations of these techniques are different. Each technique has its own advantage and limitations and hence needs evaluation & comparison.

The magnetic methods utilize the inherent ferromagnetic properties of steel for nondestructive evaluation; the changes in magnetic properties observed are easily measurable. The magnetic methods include, Magneto-mechanical Acoustic Emission (MAE), Barkhausen noise magnetic properties (hysteresis loop parameter analysis) measurement. When a magnetic field affects a ferromagnetic material, magnetic-domain walls move, and the size and shape of domains change as well. Magnetization of ferromagnetic material is not a reversible process along the magnetization curve due to formation of magnetic domains. Because of irreversibility of the process, the hysteresis shows a non-uniform dependence on magnetization, magnetic flux density, and magnetic field strength. When the magnetic saturation is reached, all of the domains are field oriented. The number and size of magnetic domain depends on numerous factors such as magnetization scheme, intensity and frequency of applied field, residual stress, cold deformation, microstructure etc.

Magneto-mechanical Acoustic emission (MAE) signals are elastic waves generated during a

Received: September 30, 2002. Accepted: November 15, 2002. * Laser Processing & Advanced Welding Section, Bhabha Atomic Research Centre, Trombay, Mumbai ** Atomic Fuels Division, Bhabha Atomic Research Centre, Trombay, Mumbai, 400 085, India. † Corresponding author : goswami@apsara.barc.ernet.in

hysteresis sweep in a ferromagnetic material. During the magnetization process the motion of non-180° domain wall mainly gives MAE signals (Ono, 1986). Therefore, the MAE signals characteristics will depend on all the parameters that will affect number, size and rotation of magnetic domains. The depth of penetration of the MAE is many times larger in comparison with other technique (Shibata and Ono, 1981). The Barkhausen noise is caused by sudden irreversible motion of magnetic domain walls when they break away from pinning sites due to change in magnetic field. BN is strong when motion of 180-degree domain wall is involved. The magnetic properties like coercive force (Hc), remanence (Br), hysteresis area, etc. were measured on mild steel plates of different degree of cold work.

X-ray diffraction is matured and widely used technique for assessing residual stress. The basis of measurement in diffraction methods is that, when a metal or the polycrystalline material is placed under stress, the resultant elastic strain causes changes in inter planar atomic plane spacing. Through the knowledge of change in interplanner spacing in terms of peak shift, the stresses can be calculated. The limitations of this technique is that, it reveals only the surface stress distributions, as the penetration of X-ray is limited to depth of order of ten microns in steels. Also material and source related problems give errors in the measurements (Venkatraman et al., 2001).

Ultrasonic methods utilize the sensitivities of the velocity of ultrasound waves travelling through a material to stress level within it. The velocity of ultrasonic wave in a material is altered by presence of stresses. The change in velocity is very less in most of the cases. This technique allows only a characterization of macro residual stresses over a large volume of material and measurements are sensitive to the texture of material(Venkatraman et al., 2001).

In the present studies, mild steel plates were subjected to different degree of cold deformation. These plates were analyzed by Magneto-acoustic emission (MAE), Barkhausen Noise (BN) and magnetic property measurement. These plates were also analyzed by X-ray diffraction and ultrasonic velocity measurement. Further, microhardness measurement and microstructure studies of these cold worked plates were done. Out of above-mentioned techniques, the magneto-acoustic emission (MAE) method is found suitable for characterization of cold work in large-scale production, due to its speed. The results of all these analysis are discussed in this paper.

2. Experimental

2.1. Specimen preparation:

During this investigation, mild steel plates of initial thickness 5.2 mm were heated upto 825°C, soaked for half-an hour and then furnace cooled, so that similar heat treatment can again be given to sheets after intermediate rolling to different thickness and before final rolling to 2.0mm thickness. The mild steel plates of 5.2 mm thickness, after initial heat treatment were rolled to various thickness ranging from 2.0 mm to 3.9 mm. Out of the two plates of 2.0 mm thickness, one was heated 825°C and furnace cooled to simulate 0 % cold work and other plate was not subjected to any treatment to retain 62 % cold work. All other plates were heated upto 825° C, soaked for half-an-hour and then furnace cooled to achieve the starting microstructure. Afterwards, all these plates were rolled into uniform thickness of 2.0 mm to introduce various degrees of cold work, i.e. 12 %, 25 %, 37 %, and 48 %.

2.2. Measurement by magnetic methods

The measurement system is a PC based analyzer consisting of main unit, transient recorder card, excitation head, and acoustic sensor with preamplifier. The excitation head contains "C" type yokes of dimensions 7x9mm each and the excitation coil has 4mm diameter with 260 number of turns. It also contains Barkhausen coil kept in middle of yokes and has 0.05mm diameter with 350 number of turns. The main unit drives the excitation electromagnet and selects, amplify and filters the signal. The system has a capability to measure characteristics of MAE and BN like RMS, Peak-to-peak voltage & area. The system also can measure various hysteresis loop properties like coercive force (Hc), remanence (Br), area of hysteresis etc. It is possible to change the excitation waveform (sine, triangular or square), excitation current and excitation frequency (10 to 100Hz).

During MAE measurements, acoustic signals were recorded by a 30 kHz resonant AE sensor with 40-dB amplifier and band pass filter of frequency 15-50 kHz. The sensor was mounted on each plate, keeping the distance between magnetization head and AE sensor same. Based on earlier studies excitation current and excitation frequency were kept at 2.5 A and 20 Hz respectively. MAE signals were recorded for all plates having various degree of cold deformation and each signal was analyzed for peak-to-peak voltage, RMS voltage level and area. During BN measurements, excitation current and excitation frequency were kept at 1.0 A and 20 Hz respectively and each BN signal was analyzed for peak-to-peak voltage, RMS voltage level and area. For measurement of magnetic properties, excitation current and excitation frequency were kept at 2.5 A and 10 Hz respectively and various hysteresis loop properties like coercive force (Hc), remanence (Br), area of hysteresis were measured on plates having different degree of cold work. During all these measurements the position of excitation head was kept at the center of each plate and sine waveform was used.

2.3. Other Techniques

X-ray diffraction profiles were recorded for all plates having various degree of cold deformation using Cu Kα radiation. For all measurements, diffraction profile was recorded in 10° - 70° 2θ range at the recording speed of 0.02 degree per second. The recording time for each measurement was 1500 seconds.

The ultrasonic velocity was measured on specimens with different degree of cold work using 5 mm diameter, 10 MHz ultrasonic transducer and oil was used as a couplant. The velocity measurement was done using longitudinal waves by CL 204 equipment. The measurements were taken at three different locations on each plate and average ultrasonic velocity was calculated.

For micro-hardness measurement, the surface of each plate was ground and well polished. Hardness measurement was done on surface of specimens having different degree of cold deformation, using Galileo micro hardness-tester at load of 500 gm. The hardness value was obtained by the averaging of three measurements taken on each cold worked specimen. The mild steel plates of 0 %, 37 % and 62 % cold worked were prepared for metallography to study the microstructure.

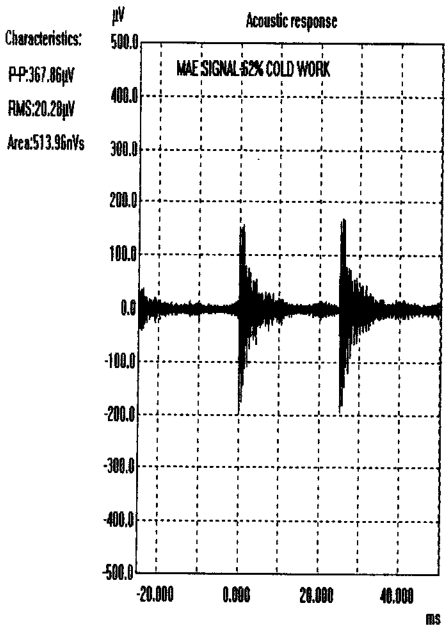

Fig. 1 Typical MAE Signal for 62% Cold Worked Mild Steel Specimen

3. Results & Discussion

Fig. 1 shows raw MAE signal recorded for 62% cold worked specimen. Figures 2, 3 & 4 show the effect of cold deformation on RMS, peak-to-peak voltage level and the Area of MAE signal. It is seen that as degree of cold work increases the values of RMS, Peak-to-peak voltage level and area of MAE signal decreases (Badgujar et al., 2000). The decrease was found to be uniform in case of all MAE parameters studied. These changes in RMS values, Peak-to-peak voltage level & area can be attributed to changes in dislocation density and grain size due to cold work.

Table I show the results of various Barkhausen noise (BN) parameters studied on specimens with different degree of cold work. The Peak-to-Peak voltage, RMS and the area of BN signal do not show well-defined trend with degree of cold work.

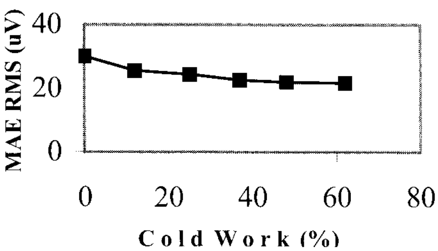

Fig. 2 Effect of RMS on degree of cold work

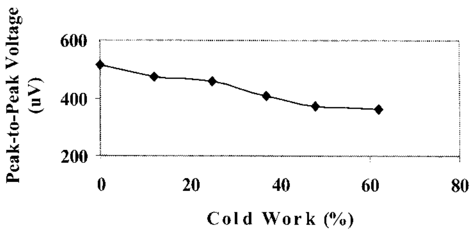

Fig. 3 Effect of Peak-to-Peak voltage on degree of cold work

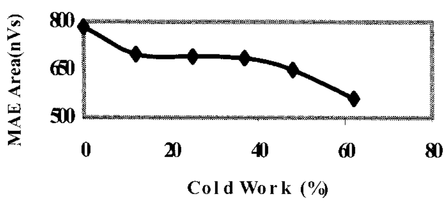

Fig. 4 Effect of MAE area on degree of cold work

Table 1 Barkhausen Noise (BN) parameter values for various degree of cold work

Serial NO.	% Cold Work	Peak-to-Peak voltage (mV)	RMS (μV)	Area (μVs)
1	0	8.25	777	58.5
2	12	14.69	1160	63.2
3	25	16.88	1490	104.0
4	37	20.32	1440	98.9
5	48	20.09	1520	104.6
6	62	14.38	1190	82.7

Out of the various hysteresis loop parameters measured from B-H curve, the variation of coercive force (Hc) with degree of cold work is shown in Fig. 5. The coercive force shows increasing trend with degree of cold work. The coercivity is property of ferromagnetic material, which depends upon stress conditions, dislocation density, microstructure, hardness, grain size etc. The increase in Hc values with degree of cold work is because of increase in dislocation density, as Hc is directly proportional to the square root on dislocation density. The higher dislocation densities are associated with larger degree of plastic deformation (Bhattacharya, 2001). Fig. 6 shows variation of remanence (Br) with degree of cold work. The remanence (Br) or retentivity values decreases with increase in degree of cold work, as retentivity and coercivity are inverse to each other. Cold work does not have appreciable effect on saturation magnetic induction (Bs) and area of hysteresis.

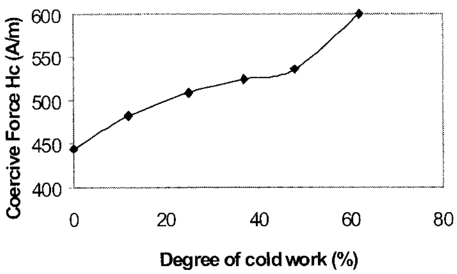

Fig. 5 Variation of coercive force with degree of cold work

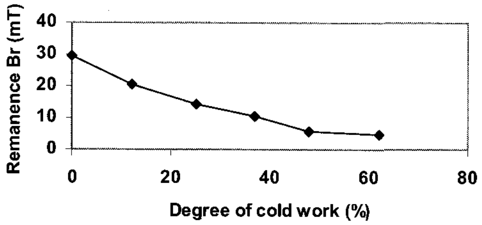

Fig. 6 Variation of remanence with degree of cold work

From the X-ray diffraction profiles recorded on specimens for various degree of cold work, the values of Full Width at Half Maximum (FWHM) were calculated for {110} peaks. Fig. 7 shows variation of FWHM with degree of cold work. As a metal is plastically deformed, the dislocation density increases, reducing crystallite (coherent domain) size and increasing the average microstrain. The reduced crystallite size and increased microstrain both produced a broadening of diffraction peaks (Vincent et al., 2000).

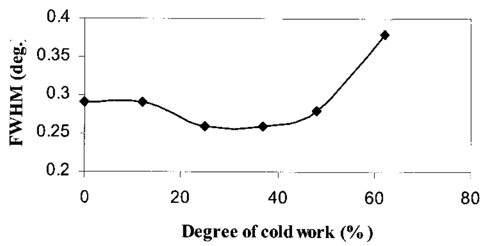

Fig. 7 Variation of Full Width at Half Maximum (FWHM) with degree of cold work

The effect of degree of cold work on hardness is shown in Fig. 8. The hardness values are increasing with degree of cold work, 112 VHN for annealed (0 % cold work) to 209 VHN for 62 % cold work. This increase in hardness values with degree of cold work is due to the increase in dislocation density and changes in microstructure.

Table-II shows the average ultrasonic velocity values for different degree of cold work. It is observed that the change in average ultrasonic velocity between annealed and 62% cold worked specimen is about 0.9 percentage only and thine on thin plates.

Table 2 Ultrasonic velocity values for various degree of cold work

Serial NO.	% Cold Work	Ultrasonic Velocity (m/sec)	Average Ultrasonic Velocity (m/sec)
1	0	5987, 5964, 6003	5985
2	12	5981, 5981, 5966	5976
3	25	5920, 5922, 5971	5938
4	37	5945, 5926, 5952	5941
5	48	5937, 5937, 5938	5937
6	62	5916, 5946, 5930	5931

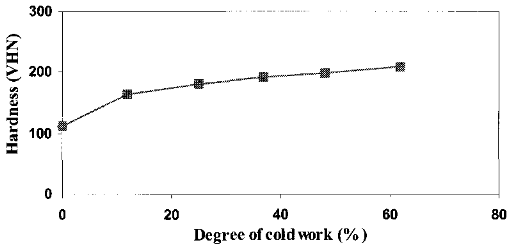

Fig. 8 Variation of hardness with degree of cold work

Fig. 9 (a), (b) & (c) shows the optical photographs of mild steel for specimens cold worked at 0 %, 37% and 62% respectively. Fig. 9 (a) shows equiaxed grain structure for annealed mild steel specimen. However elongated grain structure in the rolling direction was seen for specimens cold worked at 37% & 62% as shown in Figs. 9 (b) and 9 (c). The increase in the hardness and coercive force values with degree of cold work is also due change in microstructure of mild steel because of cold deformation.

4. Conclusions

Out of different methods for measurement of cold work / plastic deformation, X- ray diffraction is a matured technique, but it reveals stresses limited to depth of order of ten microns. The average ultrasonic velocity was not found varying appreciably with degree of cold work. On the other hand, the magnetic methods such as Magneto mechanical-Acoustic Emission (MAE) and magnetic properties measurement are found to be more suitable for cold work / plastic deformation analysis in ferromagnetic materials. The RMS, peak-to-peak voltage level and MAE signal area decreases with degree of cold work. Out of various hysteresis loop parameters, the coercive force (Hc) is increasing with degree of cold work due increase in dislocation densities and remanence (Br) values found decreasing with degree of cold deformation. Thus, the magnetic methods have high potential for cold work analysis due to high depth of penetration during measurement and high speed. These methods are more suitable for large-scale production, as the changes recorded in these methods are large compared to other methods.

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