Hall-Effect Measurements under Alternating-Current Excitation for the Reconstruction of Obliterated Serial Numbers in Magnetic Steels

FINAL REPORT

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Executive Summary

Existing forensic techniques, employed to recover obliterated serial numbers, fall mainly into one of two categories, those requiring extensive sample preparation including the use of acid etchants, and those utilizing magnetic particles to image irregularities in surface magnetic properties. The former is time consuming and utilizes potentially harmful chemicals while the latter messy and potentially low in sensitivity. A new approach has been investigated whereby the stray magnetic field is detected using Hall or GMR (giant magnetoresistive) sensors. The component is magnetized using an electromagnetic c-core yoke. An AC approach is chosen as it enables the use of class of high-sensitivity instruments known as lock-in amplifiers. The approach has been tested on some artificial specimens and part of a real gun which has had the serial numbers removed by surface grinding. In addition to the magnetic field measurements, some studies were carried out utilizing the magnetic Barkhausen phenomena. Barkhausen measurements are known to be sensitive to stress and are therefore an appropriate choice for serial number recovery.

We conclude that the magnetic imaging approach can be significantly more sensitive (to obliterated serial numbers) than the magnetic particle approach. However, the technology is costly and data acquisition time consuming. It remains to be seen whether or not there is sufficient interest to warrant the development costs needed to transition the approach into a field-ready measurement tool.

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Introduction

The objective of this work is to develop a magnetic imaging technique for the nondestructive restoration of obliterated serial numbers in ferromagnetic metals. This can be achieved by imaging the magnetic signatures that result from residual plastic deformations. To obtain both the high sensitivity and high spatial resolution necessary for recovering the serial numbers, advanced Hall-effect sensors based on indium-antimonide technology have been utilized. By scanning the Hall sensor across the obliterated serial numbers it is possible to obtain a two dimensional image of the stray magnetic field distribution, and because of magnetoelastic coupling, this image contains information about the plastically deformed regions under the stamped characters and can therefore be used to reconstruct the serial numbers.

The technique exploits the fact that stamping of serial numbers into a metal induces plastic deformation to regions beneath the imprinted characters that remain even after the surface layer has been removed [1]. These deformed regions have magnetic properties different (lower permeability and hence a large magnetic reluctance) from those of the undamaged surroundings [2]. Under a constant applied field the spatial variations in magnetic properties disrupt the magnetic field lines, this perturbation can be detected non-destructively using magnetic field sensors. By mapping the stray field over the obliterated serial numbers it is possible to build up a two-dimensional image showing variations in the mechanical conditions. This image can be used to identify the pattern of localized material damage, from which the obliterated serial numbers can be restored.

To develop the imaging technique for restoring serial numbers, it is first necessary to implement a magnetic field sensing system capable of mapping the stray magnetic field distribution over an area large enough (typically several square centimetres) to cover the regions where the serial numbers are imprinted. The spatial resolution must be high enough (better than 0.3 mm) to reveal the imprinted characters. Commercial InSb[1] Hall-effect elements (Type HW-105) were used in this work because of their advantages over conventional sensors such as inductive coils or fluxgate magnetometers. These advantages include high field sensitivities (0.5 mV/Oe for InSb Hall sensors with a 1V supply voltage), low noise and a high signal level that minimizes the need for signal processing. In addition, the active sensor area is quite small (0.3 mm × 0.3 mm for the HW-105 device).

[1] The HW-105 Hall-effect sensor used in this work was obtained directly from Asahi Kasei Electronics, Japan.

These sensors also have low power consumption that enables integration of the devices into portable equipment. The HW-105 devices have been used in a recent study to construct sensor probes for use in a magnetic non-destructive testing system [3], and the results showed that magnetic hysteresis loop properties and Barkhausen effect signals can be imaged with a spatial resolution of 0.2 mm.

Another technique that offers some potential is that of magnetic Barkhausen emission (MBE) inspection. MBE is very sensitive to residual stress and plastic deformation and can therefore be expected to be suitable for the reconstruction of obliterated serial numbers. The challenge with MBE is minimizing the probe size in order to obtain high-resolution images.

Magnetic properties, plastic deformation and stress

Magnetic measurement techniques, such as magnetic hysteresis and Barkhausen effect (BE) measurements, are promising approaches to detecting obliterated serial numbers in magnetic materials such as magnetic steels. The techniques exploit the fact that magnetic properties of materials are dependent on both the microstructure (e.g. plastic deformation) and stress state. Magnetic hysteresis refers to the non-linear, hysteretic magnetic response of materials to an applied field. Magnetic induction of a magnetic material, when measured as a function of applied field, in general exhibits a sigmoidal shape, which can be characterized by several parameters including the coercivity, remanence, hysteresis loss and permeability, Figure 1(a). The shape of a hysteresis loop and hence its parameters are dependent on both microstructure and stress state, Figure 1(b). In general, coercivity and hysteresis loss increase whereas permeability decreases with plastic deformation. For steel which has a positive magnetostriction, both magnetic permeability and remanent induction increase with tension. The reverse is generally true for compressive stresses, Figure 2.

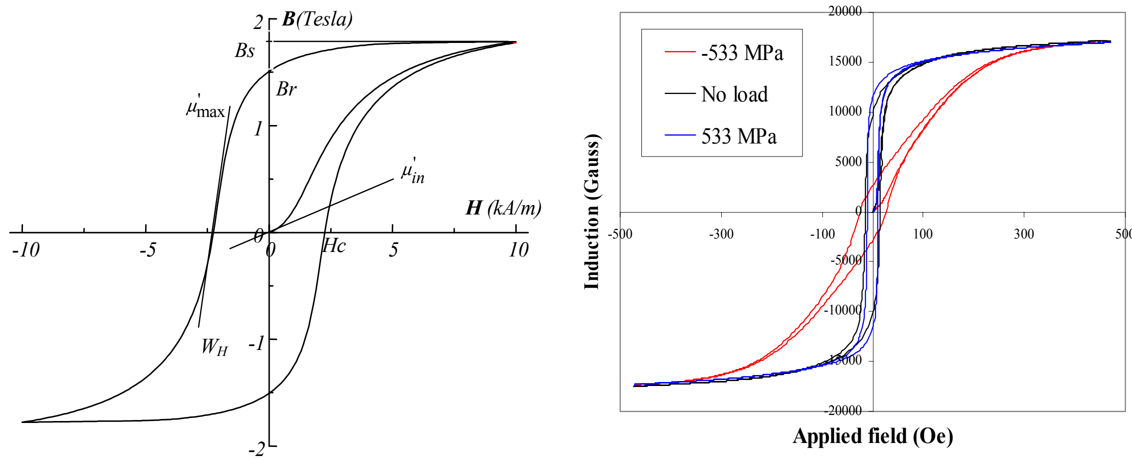

Figure 1. (a) A schematic diagram showing a hysteresis loop and the associated parameters such as the coercivity (H_c), remanent induction (B_r), the maximum permeability (μ_{max}) and initial permeability (μ_{in}). (b) Hysteresis loops measured from a 410 stainless steel for stress levels of 0 MPa, 533 MPa and -533 MPa.

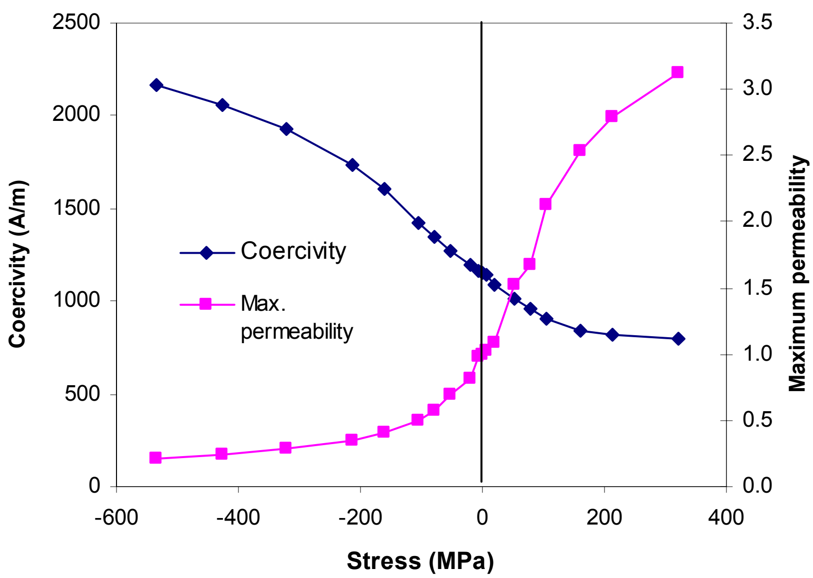

Figure 2. Dependence of coercivity and permeability of steel on applied stress.

Barkhausen effect measurements detect the motion of magnetic domain walls under applied field and depend on microstructural features, such as plastic deformation around or underneath imprinted serial numbers. When a magnetic material is subjected to a time-varying magnetic field, its magnetic flux density changes in small, discontinuous steps as illustrated in Figure 3, even under the action of a continuously varying magnetic field. These changes can be detected as voltage pulses in an inductive coil which is either encircling the material or placed in close proximity to the material surface. The signals, which are called Barkhausen noise, are caused by abrupt, irreversible motion of magnetic domain walls inside the material when they break away from pinning sites (e.g. dislocations, grain boundaries or inclusions). The characteristics of Barkhausen emissions depend on the stress state and microstructure of materials (e.g. plastic deformation). For iron or steel which have positive magnetostriction, BE signal increases with tension but decrease with compression, Figure 4. Therefore BE measurements can be used for nondestructive evaluation of residual stress and microstructure in magnetic materials such as steels. The technique is primarily sensitive to the surface or near-surface material properties because the Barkhausen signals generated deep inside the material are attenuated at higher frequencies due to eddy current shielding.

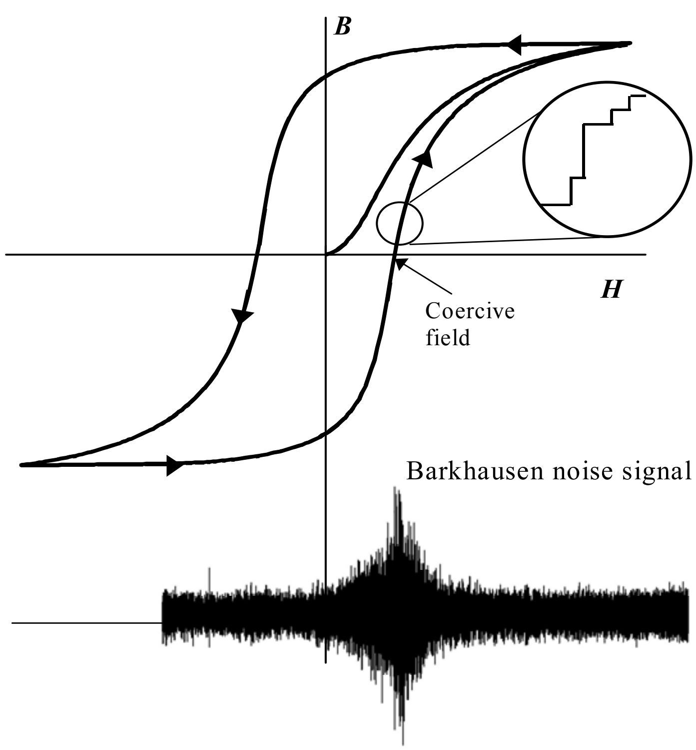

Figure 3. A schematic magnetizing curve of ferromagnetic materials showing discrete changes in magnetic flux density and emissions of Barkhausen noise signals.

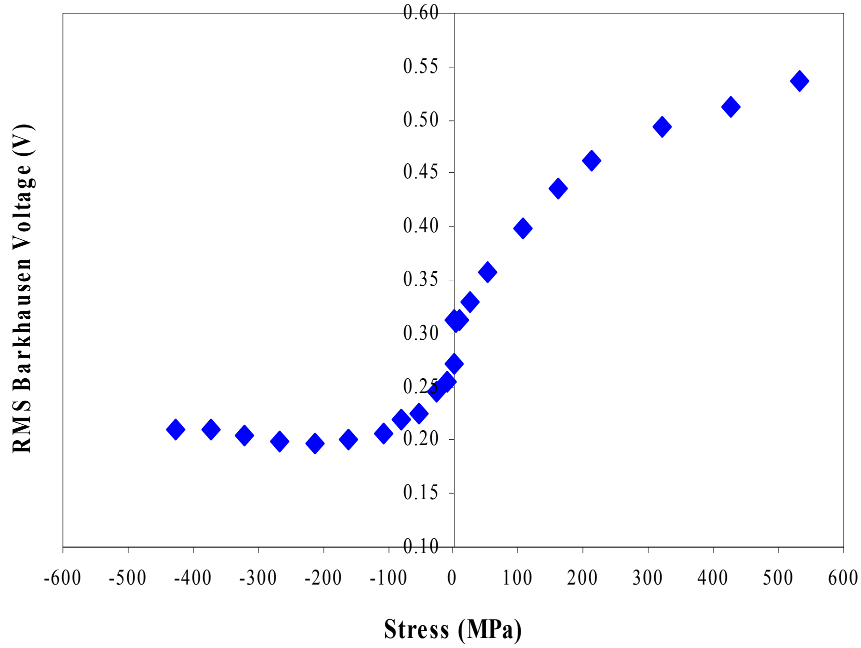

Figure 4. Dependence of the root-mean-square (RMS) values of BE signals on applied stress for a 410 stainless steel sample.

The fact that the magnetic properties of materials are sensitive to plastic deformation and stress provides the basis for a non-destructive evaluation technique for revealing obliterated serial numbers in ferromagnetic components including firearms and engine components. Stamping of serial numbers on metals induces plastic deformation to regions beneath the imprinted characters (Figure 5) that remain even after the surface layer has been removed. Such a plastic zone is surrounded by elastic material which hinders plastic flow, and is therefore under a high level of compressive stress. As a result of both plastic deformation and compressive stress the plastic zone has different magnetic properties (lower magnetic permeability and hence a large magnetic reluctance) compared with the undamaged surrounding material. If the spatial variations in magnetic properties can be detected, it should be possible to map the plastic zones associated with imprinted characters, from which the obliterated serial number could be reconstructed, although the residual plastic zones might show a more complicated pattern than the imprinted characters.

In this work two magnetic measurement techniques, namely the magnetic stray field and Barkhausen effect measurements, have been employed to detect the plastic zone around obliterated serial numbers. Magnetic stray field measurements exploit the fact that when a material is subjected to an applied field any spatial variations in magnetic permeability, such as those induced by plastic deformation, disrupt the magnetic field distribution, Figure 5. The flow of magnetic flux tends to deviate from the plastic zone because of its lower magnetic permeability (i.e. higher magnetic reluctance). This is analogous to electrical circuit in which less electrical current flows through paths with a lower conductivity. Some of the magnetic flux emanates from the plastic zone as stray field, which can be detected non-destructively using magnetic field sensors such as Hall effect devices or giant magnetoresistance (GMR) sensors.

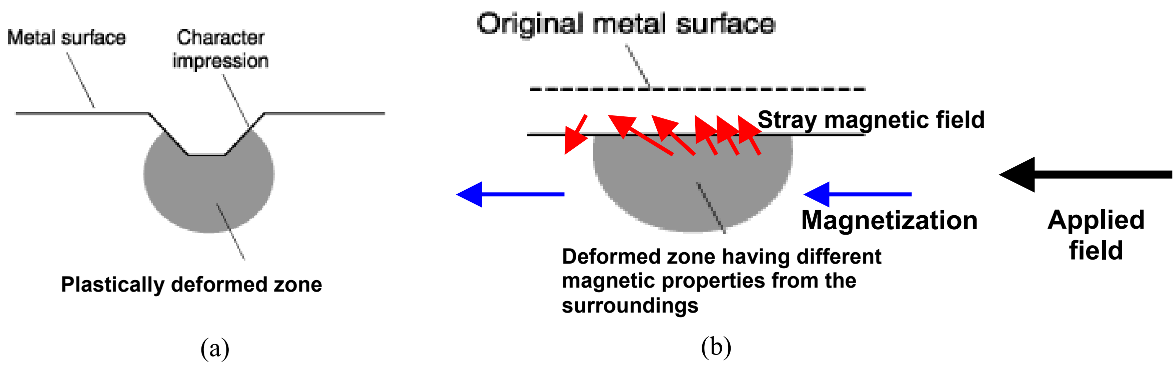

Figure 5. Stamping induces plastic deformation (a) which remains after the top surface layer is removed (b). The damaged area disrupts the magnetization which can be detected by measuring the stray field above the sample surface.

Barkhausen effect (BE) measurements offer an alternative technique for detecting residual plastic deformation around obliterated serial numbers, since the BE signal is sensitive to plastic deformation and stress. Plastic deformation reduces BE signal due to a higher density of dislocations which hinder magnetic domain walls motion. Stresses, either applied or residual, affect BE signals by means of magnetomechanical coupling. For steels which have a positive magnetostriction, the consensus is that BE signal increases with tensile stress but decreases with compressive stress, as shown in Figure 4. It is therefore expected that the regions around obliterated serial numbers would show a lower BE signal than the surrounding undamaged materials due to the combination of plastic deformation and residual compressive stress in the plastic zone.

Instrumentation development

Through prior research, magnetic measurements have been established as viable techniques for residual-stress measurements or for determining the mechanical condition of materials subjected to plastic deformation [4, 5]. Two different approaches have been used in this work, direct magnetic field imaging using a solid-state field sensor and magnetic Barkhausen imaging.

Magnetic-field imaging. In this configuration, the specimen sits between the poles of a c-core electromagnet and is magnetized with an alternating-current (AC) field, Figure 6. The AC signal is obtained from a signal generator from where the frequency can be varied from a few Hertz to up to 1000 Hertz. The signal generator's output is fed into a Kepco power supply which drives a high current through the c-core windings. A maximum current of around 10 Amps is possible.

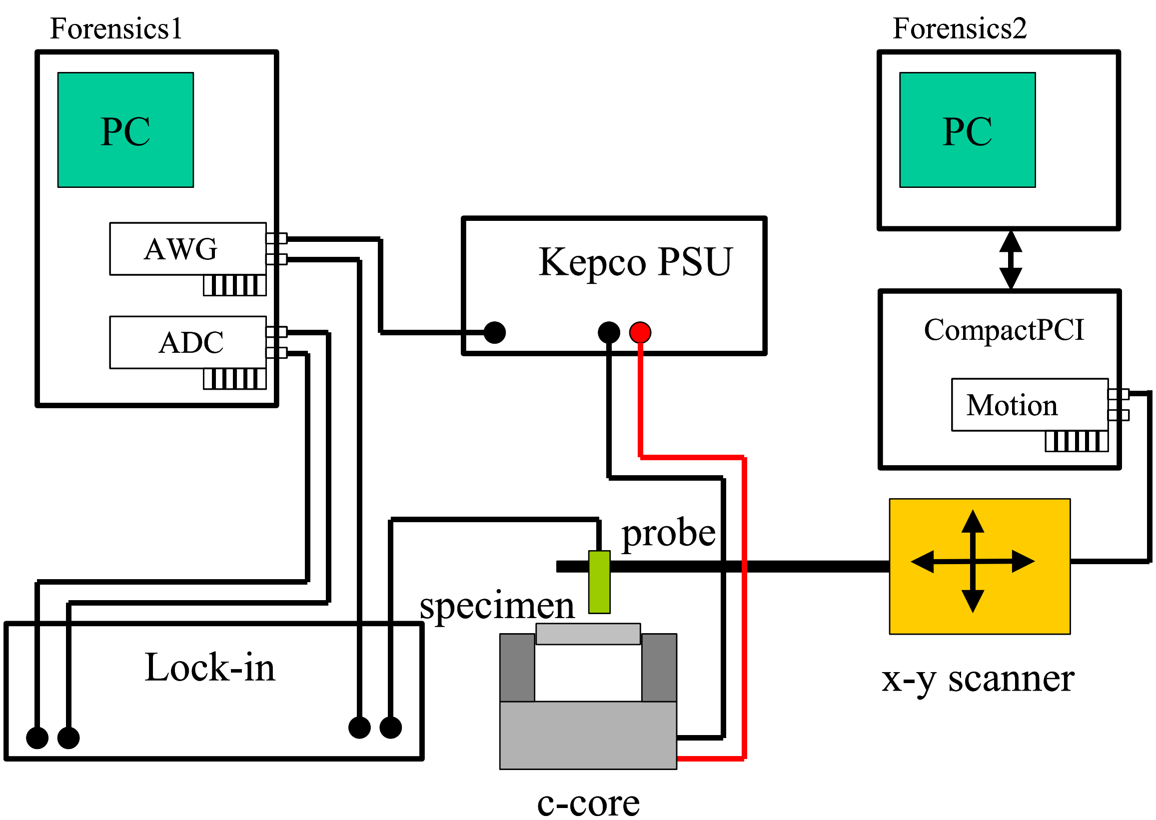

Figure 6. Major components of the new magnetic imaging system.

In order to build up an image of the scattered field from a magnetized specimen it is necessary to scan a solid state field sensor (a Hall device, for example) over the surface of the specimen while acquiring readings. This is achieved by mounting the Hall device on an x-y linear motion stage sitting just above the specimen. The Hall device is mounted on a cantilever to ensure consistent surface contact, Figure 7. Typically, Hall sensors have better performance when operated in constant-current mode. The HW-105A device used in this study could operate at around 1 mA and so a simple transconductance amplifier circuit was built to provide this supply. A Hall device typically has two outputs, in fact, each output is either side of semiconductor chip across which the Hall [6] voltage is developed. For this reason, it is important that neither output is grounded, the two outputs must instead be amplified differentially. This is actually achieved by using an EG&E lock-in amplifier which provisions for differential inputs. The lock-in amplifier is a very sensitive instrument and the perfect choice for the detection of small AC signals. The lock-in requires a reference signal which must be at the same frequency as the Hall signals but can be of much greater amplitude. The signal generator’s output, used to drive the c-core electromagnet, is a suitable reference source. The lock-in provides two output signals, the magnitude of the Hall signal component that is in phase with the reference and that which is quadrature to the reference signal. Alternatively, this information may be output as a resolved magnitude and a phase angle. It is important to look at both outputs, for a given frequency, material type and serial number indentation depth the required response may be split asymmetrically between the two output channels.

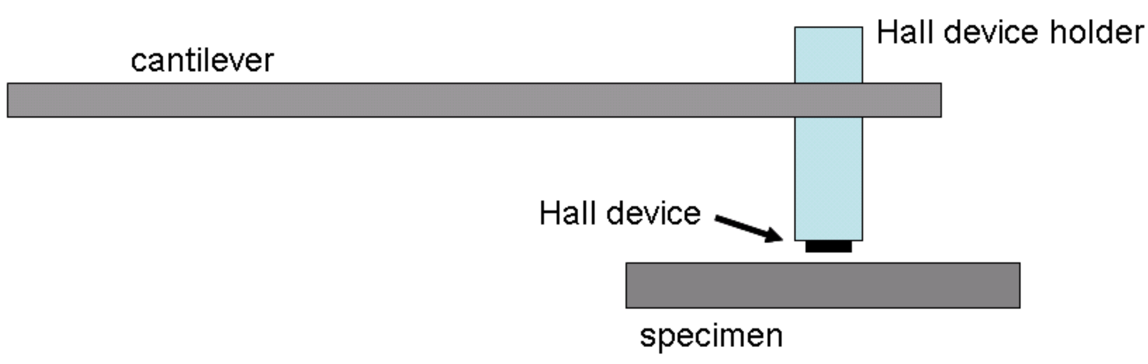

Figure 7. The Hall (or GMR) sensor is mounted onto a cantilever to ensure consistent contact with the specimen.

A computer controlled measurement system has been implemented that controls the *x-y* motion stage for positioning the Hall sensor, and acquires and digitizes signals from the lock-in amplifier's two output channels. The system is based on the National Instruments PXI system whereby data-acquisition and control cards are housed in a separate card cage connected to a computer via a high-speed fiber-optic link. The system is capable of performing a raster scan over the surface of a flat specimen while acquiring Hall-effect voltage measurements. The size and pitch of a scan is selectable at run-time as is the number of measurements (for averaging purposes) and sampling rate. The averaged measurements are then stored to two separate disk files representing the in-phase and quadrature components of the signal respectively. These disk files are essentially area-scans showing the normal component of the leakage field as a function of sensor position.

GMR Arrays. Part of this research aims to investigate some of the more practical aspects to implementing field-capable magnetic imaging systems. The problem with single sensor Hall-based systems is that automated 2-D scanning is required and the process is slow. One-dimensional arrays of sensors could speed up analysis since only line scan is required and potentially lead to hand-held devices. Giant magneto-resistive (GMR) sensors offer more sensitivity than most standard Hall sensors although using them is not always as convenient. One must pay careful attention to absolute field levels and apply bias currents to obtain linear sensor operation and to avoid saturating the devices. The Minnesota-based company, NVE Corp, produce a GMR array consisting of 16 elements with 15 and 5 um separations between two sensor elements. There are only minor differences in the way GMR versus Hall-effect signals must be processed and so it is possible to develop electronics to handle both types of sensor. To take full advantage of an array of GMR sensors it is necessary to detect the signals from each individual sensor simultaneously. This might mean the need for sixteen separate lock-in amplifiers which would be very unreasonable and costly. Instead, detection can be carried out using a simple demodulator circuit which can be duplicated many times for a much lower cost. Figure 8 shows the basic design for a single channel. The Hall device or GMR output is first amplified and fed into an AD734 demodulator integrated circuit. A sample and hold configuration is used that enable the circuit output to be nulled at any time. This useful feature allows for the subtraction of background field. The final output is filtered to remove ripple and fed into the A/D converter. Note, Figure 8 provides only a single channel, two such circuits would be required to obtain both the in-phase and quadrature signals from a GMR sensor element. The full (single channel) circuit diagram is shown in Appendix C.

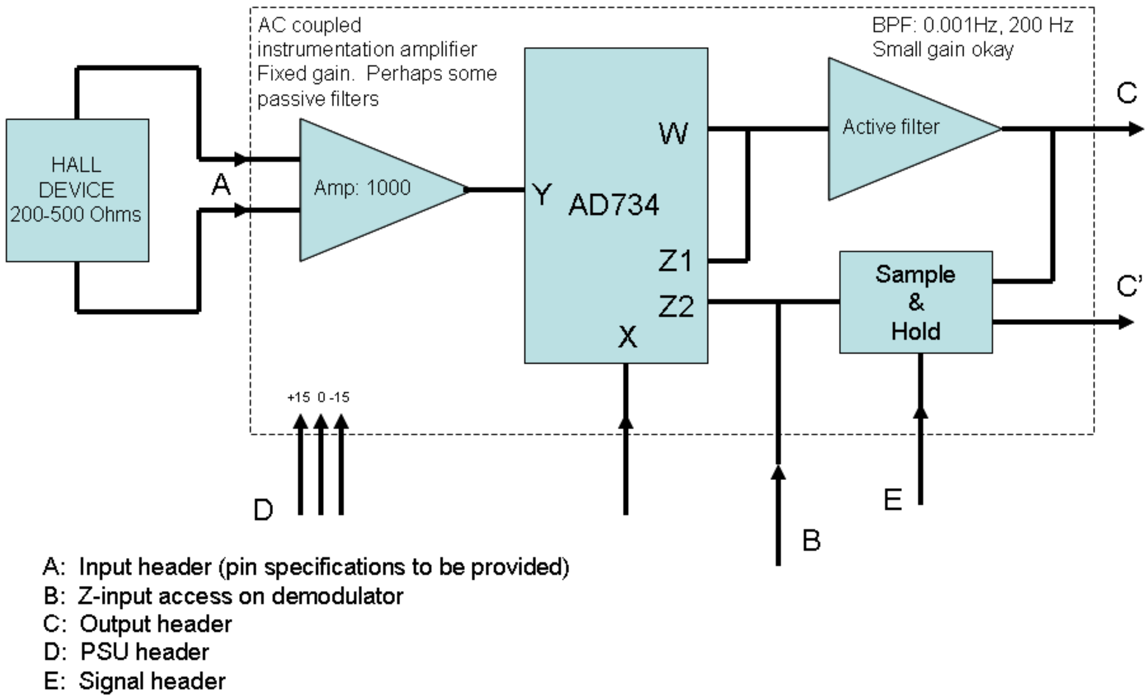

Figure 8. Single channel demodulator circuit. Two such circuits are required to provide the in-phase and quadrature signals.

Barkhausen system. The Barkhausen effect system is shown in Figure 9. It consists of a portable stepper-motor driven x-y scanning frame (Model: XT-3600 Plus, Xactec Corp.) and a signal processing module which are controlled using a personal computer. During the scanning process the sample under test remained stationary while a sensor probe was raster scanned over the sample surface. The minimum step size is 0.025 mm and the largest scan size is 250 mm by 250 mm. A specially designed manipulator was used to ensure repeatable coupling between the sensor probe and the sample.

An integrated magnetic probe was constructed to measure both magnetic hysteresis and Barkhausen signals. The schematic diagram of the sensor probe is shown in Figure 10. The sensor consists of an electromagnet for applying a magnetizing field to the test specimen. Magnetic induction signals were detected using an inductive coil, while the tangential magnetic field at the sample surface was measured using a InSb Hall effect element (Model: HW-302B, Asahi Kasei Electronics, Japan) which offered a higher field sensitivity (7 mV/Oe/V) than GaAs Hall elements (30 μV/Oe/V). The outputs of both the flux coil and the Hall effect element were amplified by factors of $\times 12$ and $\times 20$ respectively using wide-band differential amplifiers to improve the signal-to-noise ratio.

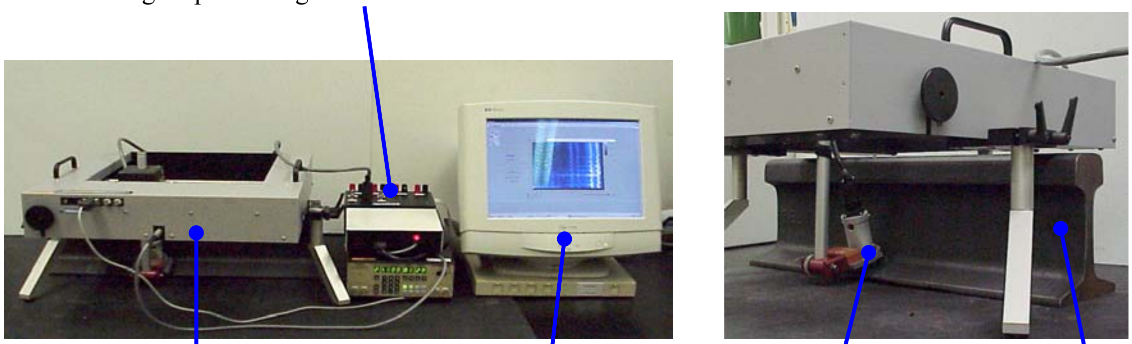

Figure 9. (a) The magnetic scanning system. (b) Scanning in progress.

An induction coil wound on a ferrite core with a sharpened tip was used for detecting Barkhausen effect signals emanating from the sample surface. The induction coil sensor output was first amplified (voltage gain = 40 dB) and then filtered using a high-pass filter (cut-off frequency = 20 kHz) to remove the low-frequency components. The filtered signal was further amplified by 30 dB and was then low-pass filtered (cut-off frequency = 99 kHz) to reduce the electronic noise. The filtered Barkhausen effect signals were acquired at a sampling rate of 200 kHz into a personal computer using a 4-channel, 12-bit analog-to-digital (A/D) converter capable of sampling data at up to 10 MHz.

The functionality of the magnetic scanning system derives largely from the computer software package. Several routines were incorporated into the software for measuring BE signals while scanning a sample. They provide the users complete control of the scanning processing (e.g. scan size and step size), measurement conditions (e.g. waveform, amplitude and frequency of magnetizing field signal), signal processing (e.g. filter settings) and data acquisition and analysis (e.g. sampling rate). The Barkhausen effect routine allows users to specify the measurement conditions such as the excitation field signal, filter settings (passband and voltage gain), sampling rate and number of magnetization cycles of data acquisition. It also determines the root-mean-square (rms) values of the acquired BE signals for constructing images of the sample surface (Figure 11), and performs fast Fourier transform (FFT) on the data.

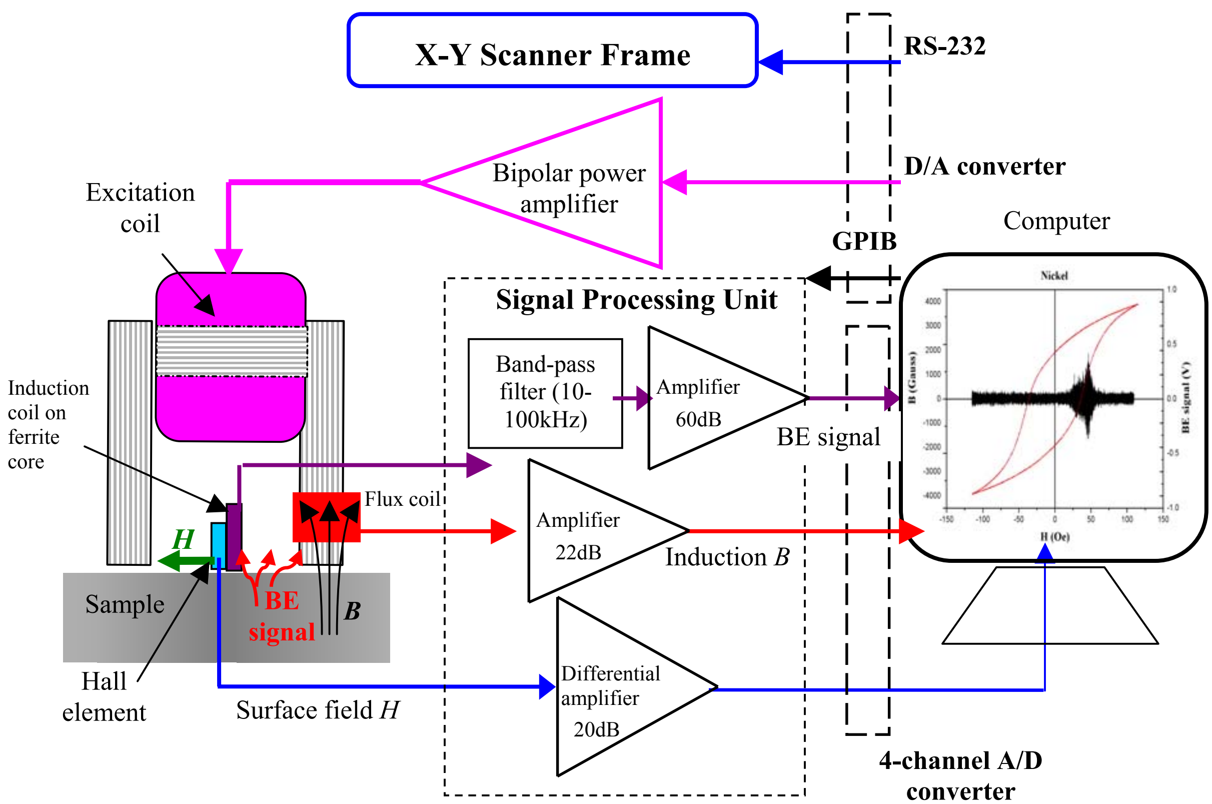

Figure 10. Schematic diagram of the magnetic imaging system.

Sample Preparation

A number of laboratory samples were made out of 1”×1.5”×0.25” cold-rolled plain carbon steel blocks which were indented with different characters. The details are given in Table 1. One sample was stamped with the letter “I” in the center, and was then milled at an inclined angle to remove part of the stamped letter, Figure 12(a). Another set of two samples were stamped with the letter "V". The initial thickness of the samples was first measured. They were then indented and the indentation depth was measured using an atomic force microscope. The samples indented with the letter "V" were ground until the characters became invisible, Figure 12b, and their final thickness was measured in order to determine the amount of material removed below the indentation, Table 1. A more realistic specimen (in the form of a shotgun part) was also included in the study. The manufacturer's name, Remington, was removed by surface grinding prior to magnetic imaging.

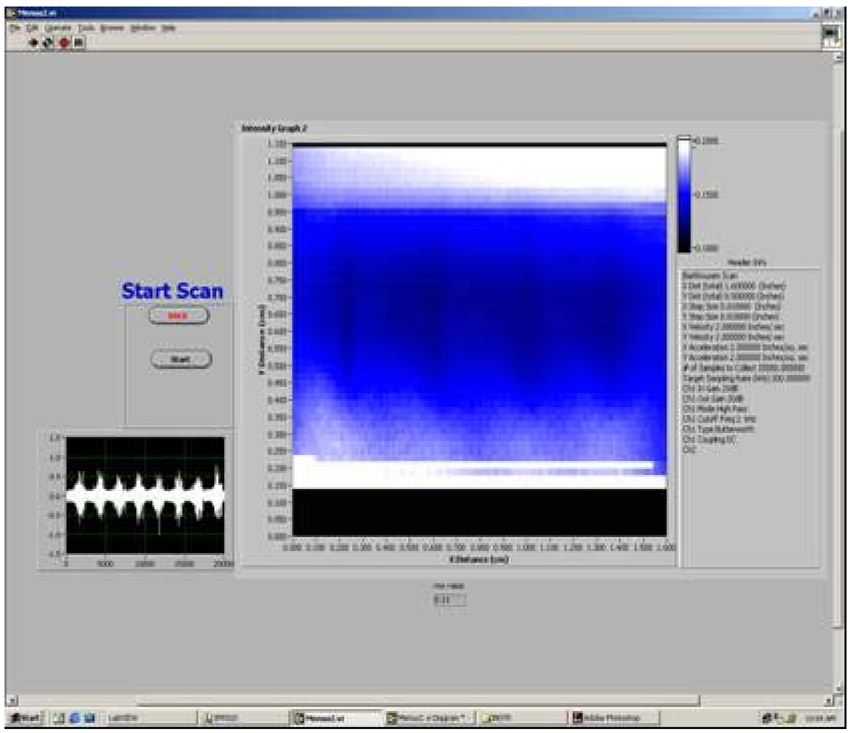

Figure 11. Software interfaces of the Barkhausen effect measurement routine showing the acquired BE signals (insets) and the corresponding two dimensional images (in blue) obtained from the sample indented with 4 I's.

A final specimen, identified as 4I, consisted of a set of four single-line indentations, made using a range of load conditions, in a piece of 1018 steel bar stock. The surface of the specimen was then ground down such that the shallowest indentation was completely removed and the remaining three indentations were partially obliterated.

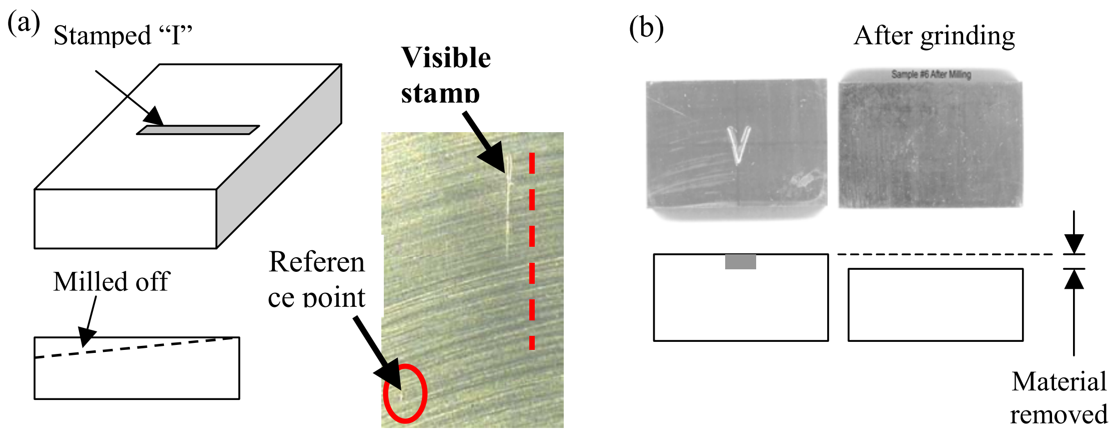

Figure 12. (a) Schematic diagram showing the steel samples stamped with the letter "I". (b) Photograph of the sample after milling; around one-half of the visible stamping has been milled away. The original stamp length is shown by the red dashed line. The reference point (circled in red) was used as a scan origin. (b) photographs of the samples stamped with "V" before and after grinding.

Table 1. Indentation information pertaining to specimens 'I' and 'V'.

sample	indentation	indentation depth (mil)	material removed (mil)
1	letter 'I'	variable	50 % of visible
2	letter 'V'	11.9	none
3	letter 'V'	16.6	16.6

Table 2. Thickness of material removed = Initial thickness – Final thickness at specimens' center

Initial thickness (mil)	Final thickness (mil)	Material removed (mil)
235.5	223.7	11.8

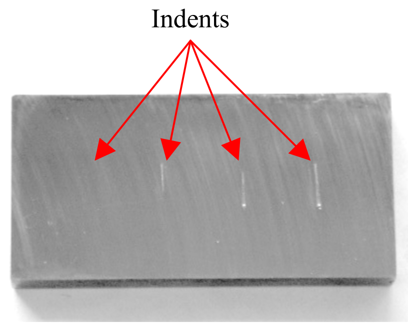

Figure 13. 1018 steel block stamped with 4 I's to different depths, with the one on the right being the deepest. The stamps have been partially removed by grinding to different extents. The spacing between the stampings is 0.4".

Analysis

Some basic signal processing algorithms have been implemented to remove offsets and trends in the Hall-response signals. These algorithms are necessary so that small signal variations due to obliterated serial numbers are not masked and overwhelmed by large background signals. These algorithms included a simple linear regression tool to operate on scan lines parallel with the field direction.

A number of more advanced analysis procedures were attempted but perhaps the simplest and most successful of these was a spatial band-pass filter. There are two factors that complicated visualization of the magnetic images. Firstly, a complicated stray-field pattern can overwhelm the small perturbations in the field due to remnants of the serial numbers. Secondly, background noise and random fluctuations in magnetic field properties produce high-spatial frequency effects. Both of these effects can be minimized through the appropriate use of a spatial band-pass filter.

The peaks approach is another technique that works well for larger serial numbers by exploiting the dipole nature of the magnetic response. If the applied field is normal to the particular feature of a serial number then a magnetic scan in the field direction will yield first a positive and then a negative response. At the center of the feature the magnetic field gradient will be zero. This symmetry can be exploited fairly easily to produce a refined serial number image. In the case of small serial numbers, the symmetry can be broken by the combined response from other parts of the serial number in which case the approach may not be as accurate.

The gradient approach is useful when there are edges perpendicular to the direction of the applied field. The slope of the magnetic field image is obtained in directions both parallel and perpendicular to the direction of the applied field. Edges perpendicular to the applied field direction show up very clearly in the field derivative in this direction. The field derivative calculated in the perpendicular direction can be used to determine (physically) where a particular edge or feature starts or stops.

Results

Specimen I. Figure 15 shows the magnetic response of the 'I' specimen and a reconstruction using the peaks approach. The results demonstrate that the technique can detect serial numbers that have had at least 0.0023" of additional material removed after they are no longer visible. The reconstruction demonstrates how effective the peaks approach is for relatively simple images.

Specimen V. Figure 16 shows a reconstruction carried out on magnetic data from the "V" specimens. Due to convergence of the two sides of the "V" and the fact that the relatively soft steel led to a spatially large region of plastic deformation, the peaks method was not found to give the best results. Instead the magnetic image was band-pass filtered and displayed as a black-and white image in Matlab. This was found to give the most accurate representation of the original serial number.

Shotgun specimen. Part of a real shotgun (manufactured by Remington) was scanned, Figure 17. The resulting images offer some clue at to the original text but do not produce the crystal-clear images observed with the magnetic particle method.

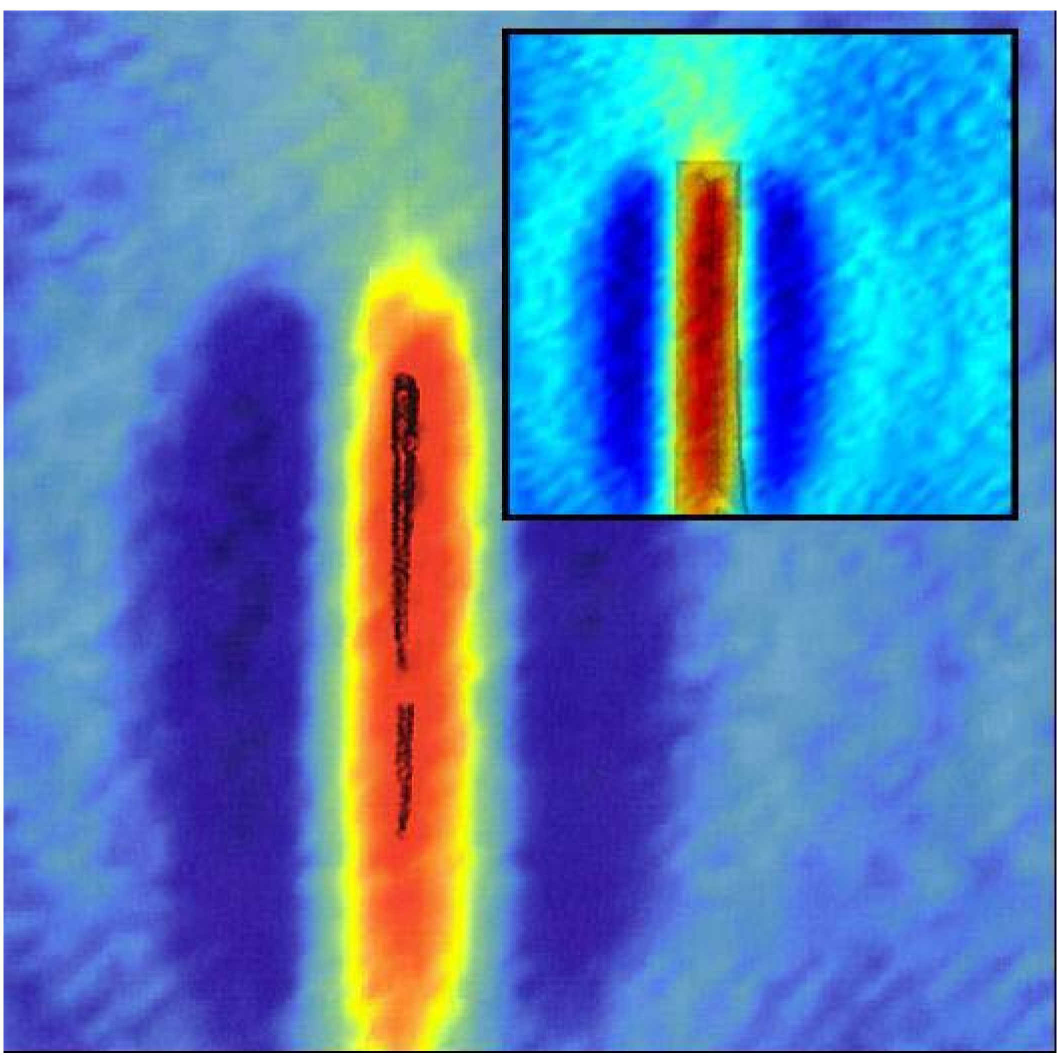

Figure 15. Magnetic image of the "I" specimen with the reconstructed indication shown in red and remaining visible indentation in black. Inset: The reconstructed image with the original indentation superimposed.

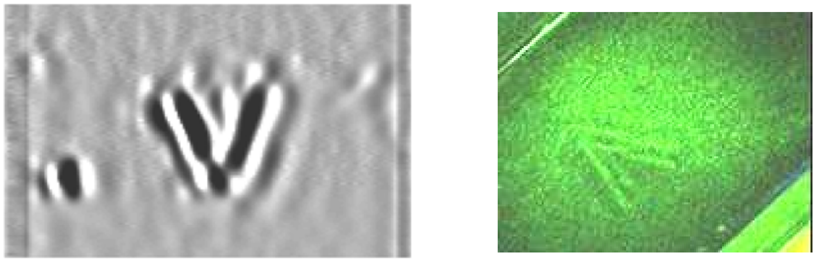

Figure 16. LEFT: Reconstructed image of the letter "V" following a Hall-device scan. RIGHT: Reconstruction of the same character using fluorescent magnetic aerosol particles following magnetization of the part in a high-current DC coil.

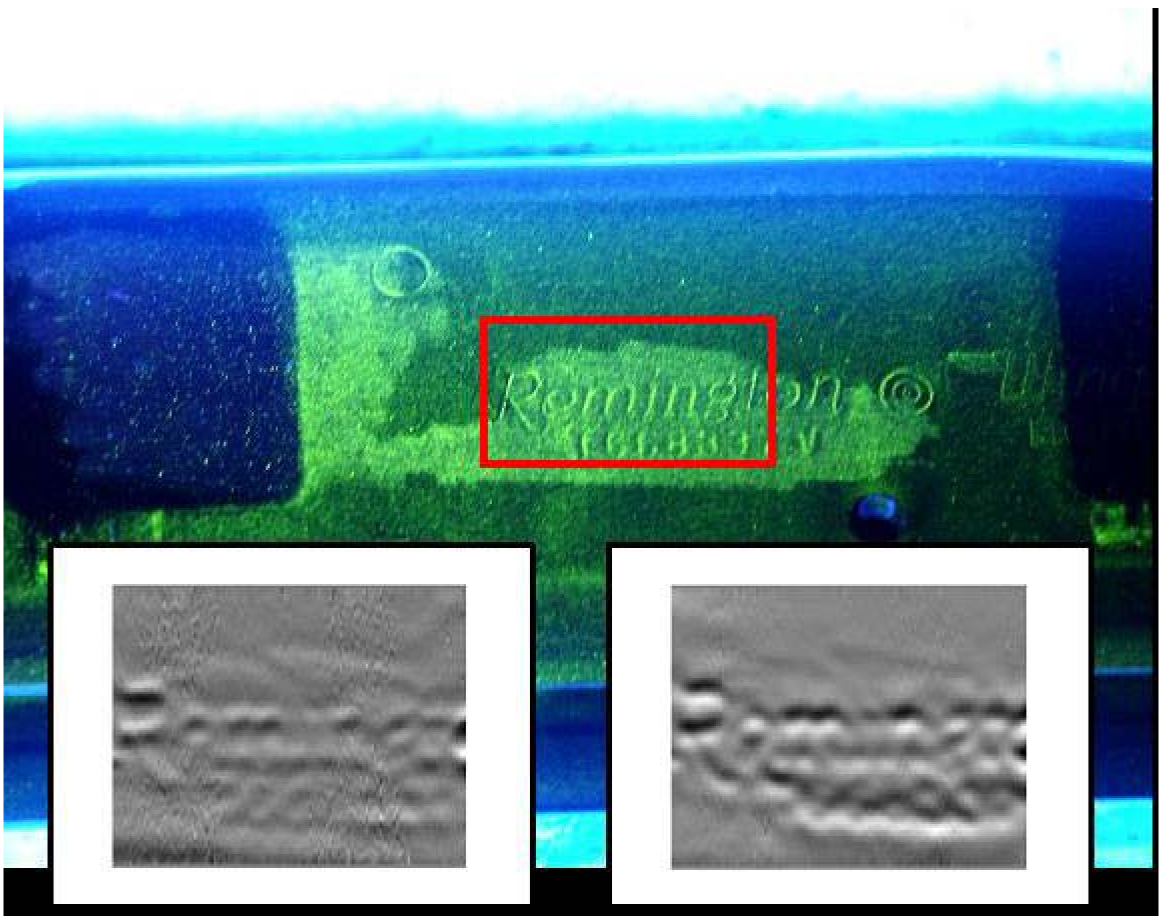

Figure 17. MAIN IMAGE: The manufacturer's name reconstructed using a magnetic particle solution. INSETS: Reconstruction of the same character using magnetic imaging .

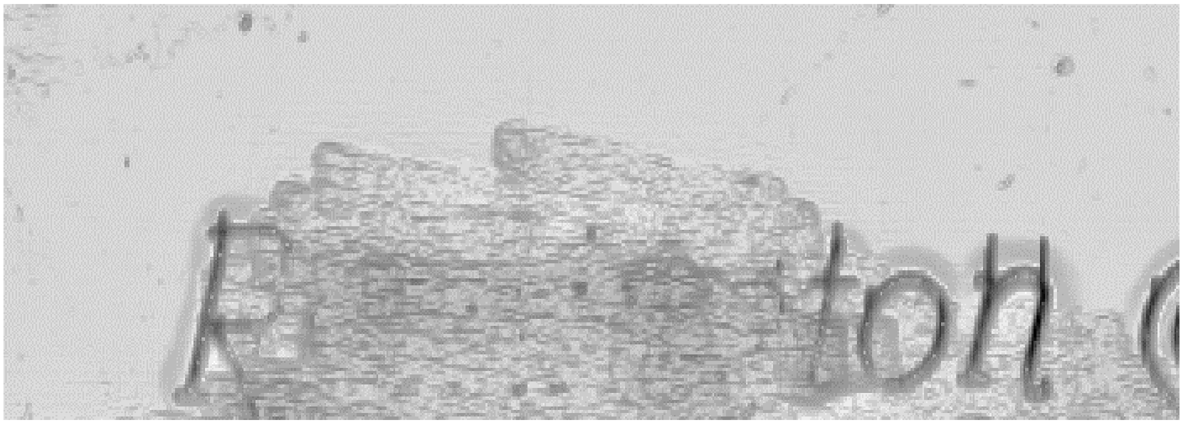

Figure 18. Surface profile scan of the Remington shotgun specimen obtained using the LaserScan instrument from Solarius, Inc. These results show that parts of the serial number are truly obliterated from a visual perspective and that one has no choice but to resort to magnetic or microstructural techniques.

Interestingly, there is some banding apparent in the images that probably corresponds to regions having different magnetic properties. This banding appears to affect the image quality with higher image contrast being observed in regions having the more grainy bands. It is possible that some kind of surface normalization treatment, shot peening for example, could be used to improve the whole image. A profile scan of the shotgun specimen is shown in Figure 18.

Specimen 4I. The raw (unprocessed) magnetic scan obtained from the 4I specimen is shown in the upper portion of Figure 19. Simple bandpass filtering yields strong indications as shown in the lower portion of Figure 19. The gradient method was used very effectively with this data (as shown in Figure 20) and even the completely obliterated indentation is clearly visible. A surface profile was obtained from the 4I specimen, Figure 21, in order to determine actual levels of physical surface distortion. Figure 21 shows that the fourth indentation was completely removed by grinding, the middle two were partially removed and the first indentation was largely unaffected. In all four cases, the magnetic images (as processed using the gradient approach) were found to accurately recover the length of the original indentations; even in the case of the completely obliterated fourth indentation. Magnetic imaging performance was compared with the fluorescent magnetic particle method[2], Figure 22. Despite every effort to obtain good magnetic particle results,

[2] Work performed by D. Utrata, Center for Nondestructive Evaluation, Iowa State University.

the technique was found to be significantly less sensitive than the Hall-based magnetic approach.

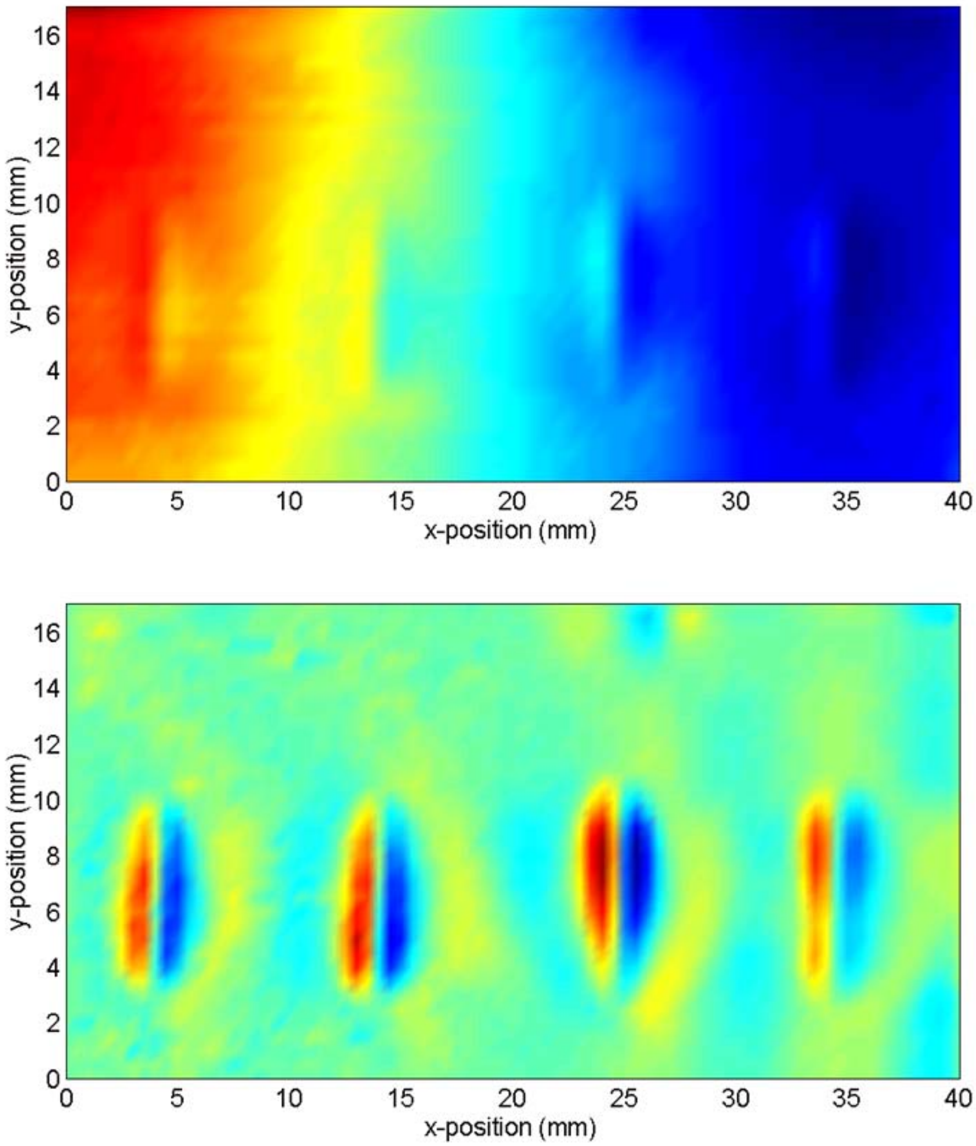

Figure 19. Raw magnetic image data (top) and following background suppression (bottom). The four indentations are clearly visible.

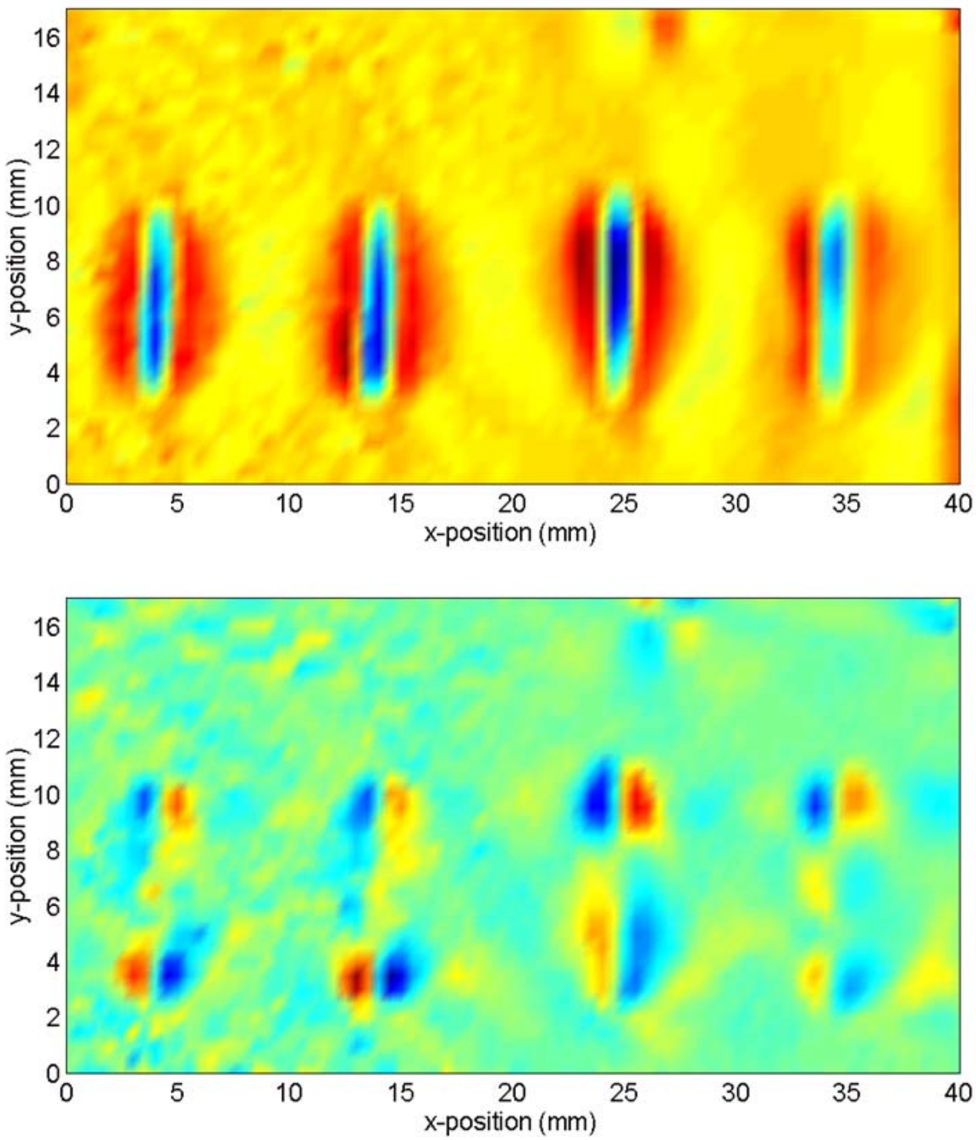

Figure 20. Magnetic image gradient in the x- and y-directions (top and bottom respectively). The fourth indentation clearly shows up on the right-hand-side of the image.

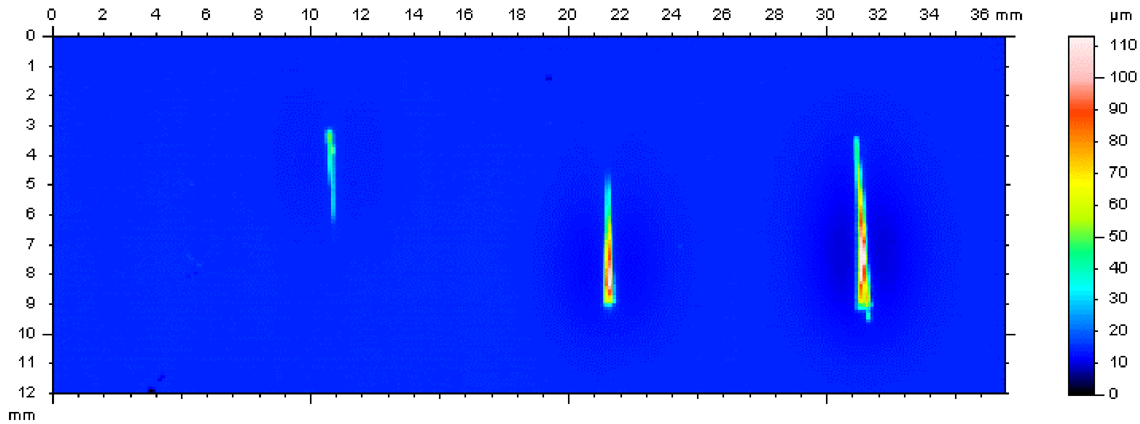

Figure 21. Scan obtained using a Solarius LaserScan optical profilometer. The fourth indentation should be on the left-hand-side of the image but is not visible due to the fact that all visible surface distortion was removed.

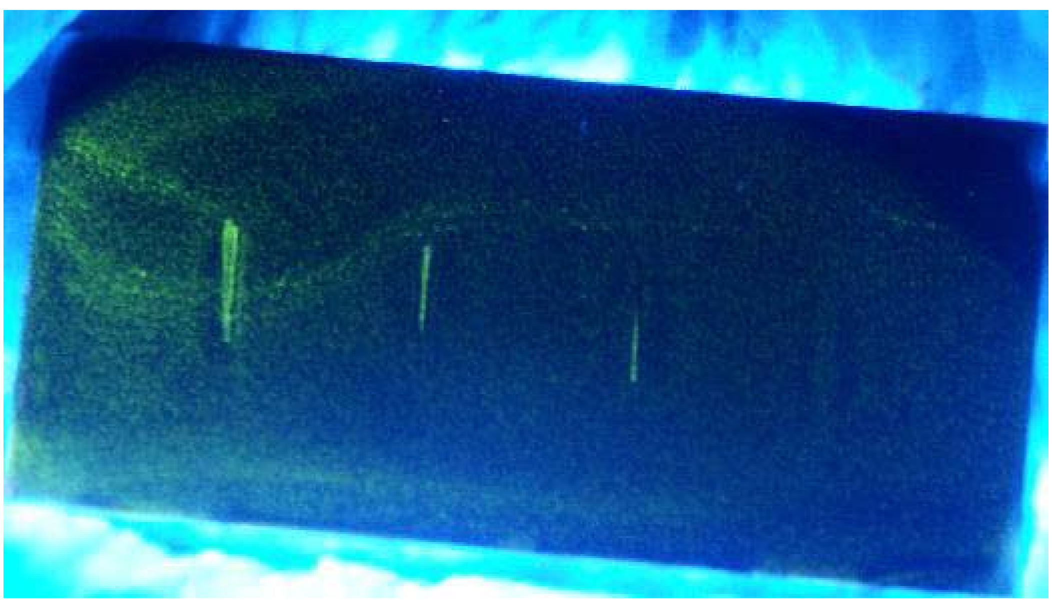

Figure 22. Despite every effort to obtain good results using the fluorescent magnetic particle approach, the fourth indentation was not visible.

SUMMARY

Results to date demonstrate the potential of the Hall-device based magnetic imaging system for serial number reconstruction. Issues remain with the ability to resolve serial numbers that are close together. One way to improve results would be to use a Hall device with a smaller active area such as 50 by 50 µm. There is a banding effect observed in Figure 6 in which some regions of the specimen exhibit better contrast than others. This is perhaps due residual magnetization or surface stress. The origin of the banding should be investigated in order that images of consistent contrast can be produced. The finding that magnetic imaging could sometimes reveal removed serial numbers when magnetic particle inspection cannot raises the need of further studies to identify key factors that determine the sensitivity of both techniques.

ACKNOWLEDGEMENTS

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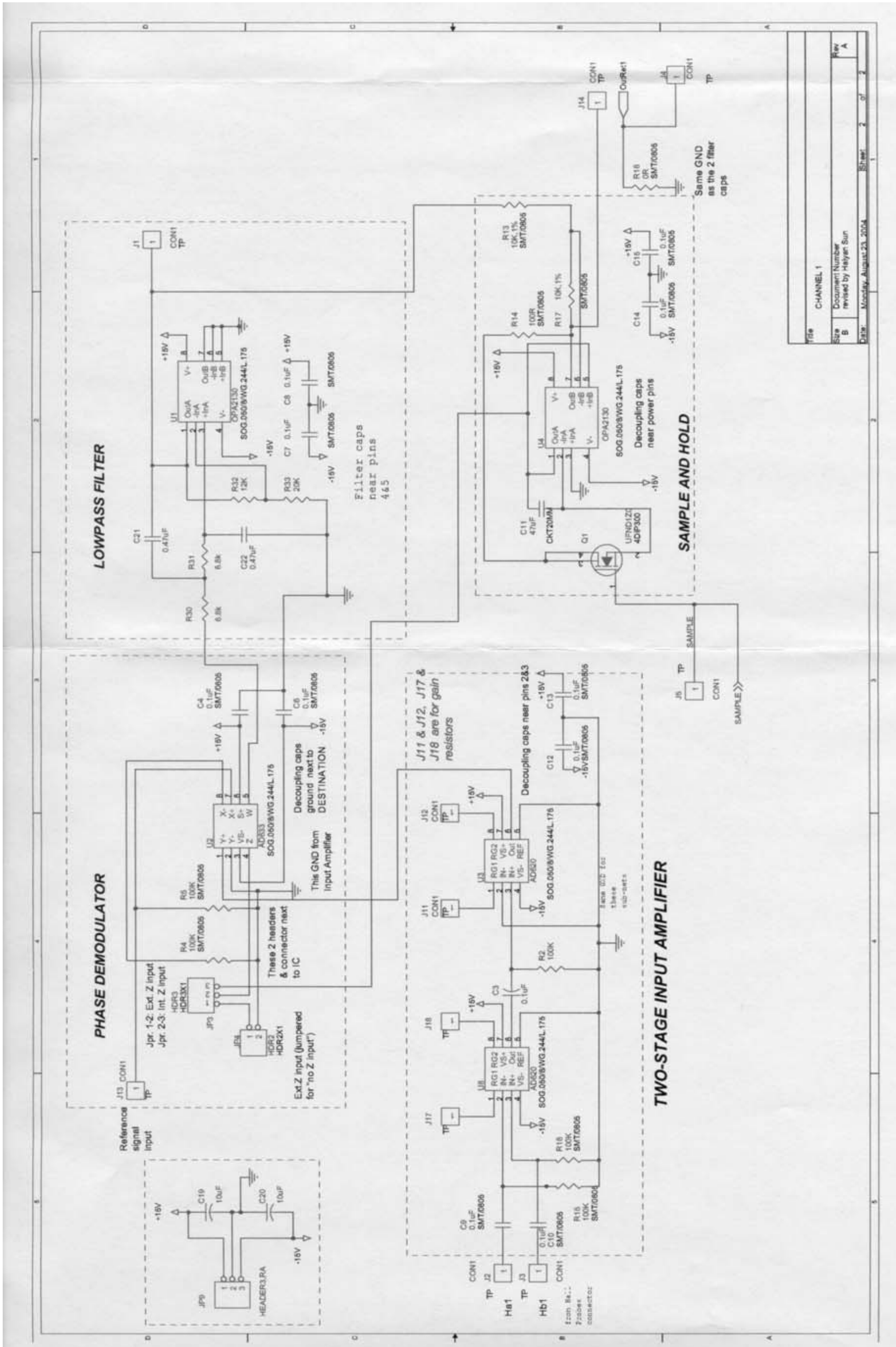
APPENDIX A: Array circuit diagram



LOWPASS FILTER
PHASE DEMODULATOR
TWO-STAGE INPUT AMPLIFIER
SAMPLE AND HOLD
Filter caps near pins 4&5
Decoupling caps near power pins
These 2 headers & connector next to IC
Jpr. 1-2: Ext. Z input
Jpr. 2-3: Int. Z input
Ext.Z input (jumpered for "no Z input")
Reference signal input
This GND from Input Amplifier
Decoupling caps ground next to DESTINATION
J11 & J12, J17 & J18 are for gain resistors
Decoupling caps near pins 2&3
Same GND as the 2 filter caps
CHANNEL 1
revised by Haiyan Sun
Monday, August 23, 2004