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Non-Destructive Evaluation of Ion-Nitrided And Carbonitrided Layers on BH11 and D2 Tool Steels: Eddy Current Testing and Barkhausen Noise Methods

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***Abstract* — This paper systematises the destructive reference characteristics of ion-nitrided and carbonitrided layers on BH11 (4CrSMoVSi, VS4659) and D2 (Cr12MoV) tool steels produced in glow-discharge plasma at 550 °C and ~400 Pa, and investigates their suitability for calibrating and validating non-destructive testing (NDT) methods. Two principal NDT techniques are examined—eddy current testing (ECT) and the Barkhausen noise method (BNM)—whose complementary depth sensitivity enables simultaneous estimation of effective case depth (δ, 55–145 µm) and surface hardness (1150–1300 $HV_{0.1}$). Concrete calibration procedures, an integrated inline station concept, and a validation strategy including statistical process control (SPC) are proposed. Multi-frequency ECT (50–200 kHz) proves most sensitive to total diffusion-zone depth, while BNM (50–200 Hz magnetisation) captures near-surface hardness changes. A combined data-fusion model reduces MAE in δ estimation to ±10–15 µm and provides reliable OSZ classification (accuracy > 92 %).**

***Keywords* —Barkhausen noise; eddy current testing; ion nitriding; nitrocarburising; non-destructive testing; tool steels.**

I. Introduction

Ensuring high quality of machine-building components is closely linked to improving their reliability and service life, which are to a large extent determined by the wear resistance of the materials. Among chemical-heat treatment processes, ion nitriding and carbonitriding occupy a prominent place as primary methods for surface hardening of steels [1], [2], [3]. Both processes predominantly increase surface hardness and wear resistance of the treated parts, during which only nitrogen, or simultaneously carbon and nitrogen, diffuse into the surface layer.

The fundamental objective of both processes is the formation of a thin but exceptionally hard and wear-resistant surface layer composed of a compound zone (white layer) and a gradually declining hardness diffusion zone [1], [2]. The quality of the nitrided or carbonitrided layers is determined by three key parameters: surface hardness ($HV_{0.1}$), effective case depth (δ, defined per DIN 50190-3 as the depth at which hardness drops to HV_{n0es} + 50), and compound layer thickness (OSZ) [4].

Conventional measurement of these parameters requires destructive metallographic preparation and microhardness profiling—a procedure incompatible with serial production. This has driven growing interest in NDT methods capable of replacing or supplementing destructive measurements [5] – [7]. Among the most promising are ECT and BNM, whose complementary sensitivity to electrical conductivity, permeability, and microstructural state makes them well-suited for characterising diffusion layers on tool steels [8] – [11].

The present work systematises destructive reference data for ion-nitrided and carbonitrided layers on BH11 and D2 steels, proposes concrete calibration and validation procedures for ECT and BNM, and presents a combined data-fusion model for simultaneous estimation of δ and surface hardness, together with an integrated inline NDT station concept for production control.

II. Materials And Experimental Methods

A. Materials

Two widely used tool steels were investigated: BH11 (4CrSMoVSi, VS4659) for hot-work deformation, and D2 (Cr12MoV) for cold-work tooling. The high chromium content of D2 (≈11.5 % Cr, 1.46 % C) impedes nitrogen diffusion, resulting in shallower but harder layers compared with BH11.

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B. Treatment Regimes

Two surface-treatment processes were applied in a glow-discharge plasma reactor at 550 °C and ~400 Pa: (i) ion nitriding (IA) in pure NH_3 atmosphere for 1, 2, 4, and 6 h; (ii) ion carbonitriding (ICN) in NH_3/Ar/CO_2 atmosphere for 4 h. Temperature and pressure were maintained within ±5 °C and ±10 Pa.

C. Treatment Regimes

After treatment, specimens were cross-sectioned, polished to 0.05 µm finish, and etched with 3 % Nital. Microhardness profiles ($HV_{0.1}$, 100 gf, 10 µm step) were measured with a calibrated Vickers indenter. Effective case depth δ was determined per DIN 50190-3; OSZ was measured metallographically at ×1000 (10 measurements/specimen).

TABLE 1 SUMMARY OF DESTRUCTIVE PARAMETERS FOR EACH TREATMENT REGIME

Steel	Process	Time (h)	δ (µm)	$HV_{0.1}$
BH11	IA	1–2	55–65	1150–1180
BH11	IA	2–4	85–95	1180–1230
BH11	IA	4–6	130–145	1200–1250
BH11	ICN	3–5	90–120	1220–1280
D2	IA	1–2	50–60	1200–1250
D2	IA	2–4	75–90	1230–1280
D2	IA	4–6	110–125	1250–1300
D2	ICN	3–5	80–110	1260–1300
Note: D2 produces shallower layers due to high Cr content impeding N diffusion.				

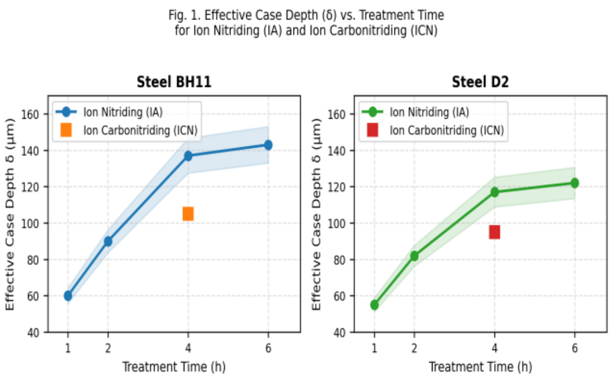

Fig. 1. Effective case depth (δ) vs. treatment time for ion nitriding (IA) and ion carbonitriding (ICN) on BH11 (left) and D2 (right).

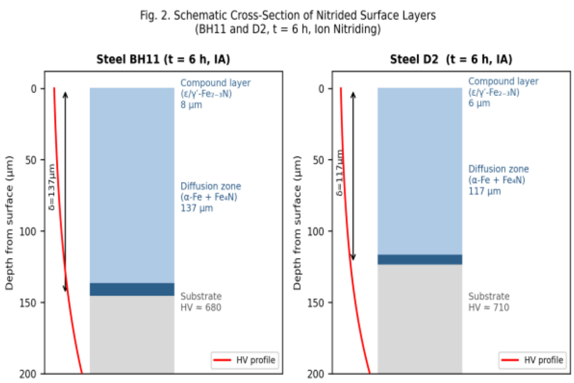

Fig. 2. Schematic cross-section of nitrided surface layers on BH11 and D2 (t = 6 h, ion nitriding), showing compound layer, diffusion zone, and HV profile.

III. PHYSICAL PRINCIPLES OF NDT METHODS

A. Eddy Current Testing (ECT)

ECT exploits the variation of electrical impedance Z in a coil placed near a conductive specimen. Thepenetration (skin) depth is given by:

$$\delta_{skin} = (\pi\ f\ \mu_0\ \mu_r\ \sigma)^{-1}{}_{,}{}^{2} \tag{1}$$

where f is frequency, $\mu_0\mu_r$ is permeability, and σ is electrical conductivity. For δ = 55–145 µm and typical nitrided-steel properties (σ ≈ 2.5 MS/m, μ_r ≈ 50–100), the required frequency range is 50–200 kHz [11], [12]. The normalised impedance change $|\Delta Z/Z_0|$ increases monotonically with δ, providing the basis for calibration.

B. Barkhausen Noise Method (BNM)

Two BNM measures burst-like magnetic flux changes (Barkhausen events) that occur when domain walls are pinned by lattice defects, precipitates, and grain boundaries during low-frequency magnetisation cycling (50–200 Hz). BN-RMS is inversely correlated with surface hardness: higher dislocation density and nitride precipitate density in harder layers increase pinning and suppress BN-RMS [6] – [7], [12] – [13]. BNM is primarily sensitive to the near-surface zone (< 0.3 mm), complementingECT.

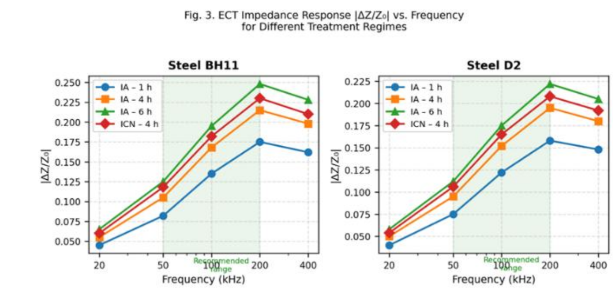

Fig. 3. ECT impedance response $|\Delta Z/Z_0|$ vs. frequency (20–400 kHz) for different treatment regimes on BH11 (left) and D2 (right). Shaded band: recommended calibration range.

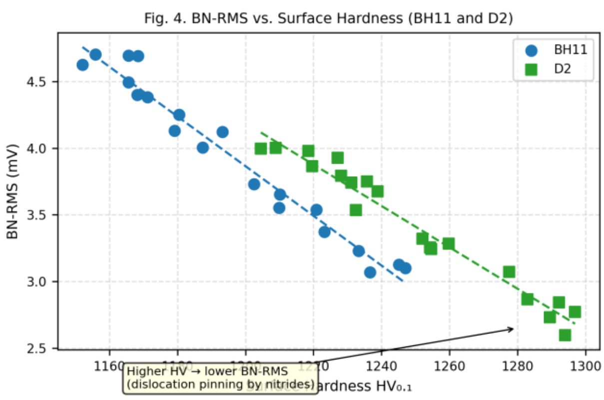

Fig. 4. BN-RMS vs. surface hardness $HV_{0.1}$ for BH11 and D2 steels with inverse correlation and regression lines.

IV. Eddy Current Calibration Protocol

A calibration matrix is constructed from 6–10 specimen groups, each defined by a unique steel/regime combination. For each group, 3–5 specimens are fully characterised destructively (δ, $HV_{0.1}$, OSZ) and the remainder reserved for NDT validation. ECT measurements are performed at five frequency steps: 20, 50, 100, 200, and 400 kHz.

The extracted features at each frequency are the real and imaginary components of $|\Delta Z/Z_0|$ and the phase angle $\Delta\varphi$. A multiparametric linear regression model for δ estimation is:

$$\delta = a_0 + a_1|\Delta Z/Z_0|_{50} + a_2|\Delta Z/Z_0|_{200} + a_3\Delta\varphi + a_4\cdot \mathrm{SteelID} \quad (2)$$

Model coefficients a_i are determined by least-squares fitting to the destructive reference data. Cross-validation on reserved specimens yields MAE(δ) ⩽ ±10–15 µm for δ ⩽ 150 µm. OSZ classification (thin: < 3 µm; medium: 3–6 µm; thick: > 6 µm) achieves accuracy > 90 % using the 200 kHz amplitude threshold [14], [15], [16].

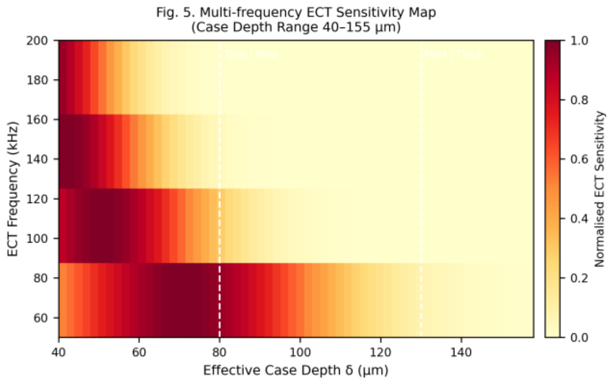

Fig. 5. Multi-frequency ECT sensitivity map: normalised sensitivity to effective case depth (40–155 µm) vs. frequency (50–200 kHz). OSZ class boundaries shown as dashed lines.

V. Combined ECT + BNM Data-Fusion Programme

The complementary sensitivities of ECT (depth) and BNM (near-surface hardness) motivate their combination in a unified data-fusion model. The input feature vector is:

$$x = [|\Delta Z/Z_0|_{50}, |\Delta Z/Z_0|_{100}, |\Delta Z/Z_0|_{200},$$

$$\Delta\varphi, \text{BN-RMS}, \text{BN}_{peak}, \text{BN}_{env}, \text{SteelID}] \quad (3)$$

Table 2 Summary of Destructive Parameters for Each Treatment Regime

Parameter	ECT	BNM
Primary sensitivity	Case depth (δ)	Near-surface hardness (HV)
Frequency range	50–200 kHz	50–200 Hz (magnetisation)
Output quantity	$\lvert\Delta Z/Z_0\rvert$, $\Delta\varphi$	BN-RMS, peak position, envelope
Expected MAE	±10–15 µm (δ)	±20–25 HV

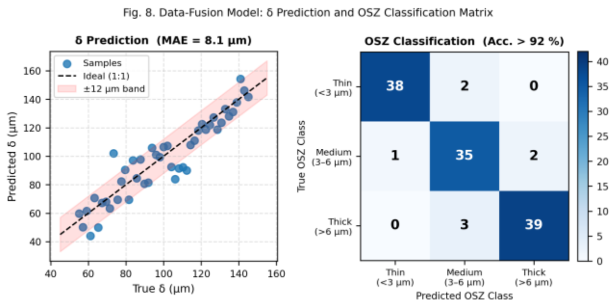

Fig. 6. Data-fusion model performance: (left) predicted vs. true δ with MAE; (right) OSZ classification confusion matrix (accuracy > 92 %).

VI. Combined Inline NDT Station For Production Control

The proposed integrated inline NDT station is positioned after the washing/cooling stage, before final finishing operations. Hardware components include: a multi-frequency ECT module (50, 100, 200 kHz), a BNM system (e.g., Stresstech Rollscan series [17]) with constant-pressure spring-loaded probe, a PLC/PC-based data-acquisition and fusion unit, and a pneumatic accept/reject sorter.

Measurement cycle time is 1–3 s per part, enabling throughput of 30–60 parts/min. All measurements are logged to a database, and Shewhart control charts for δ and BN-RMS provide early warning of process drift. Daily verification against reference standards is incorporated into the station routine.

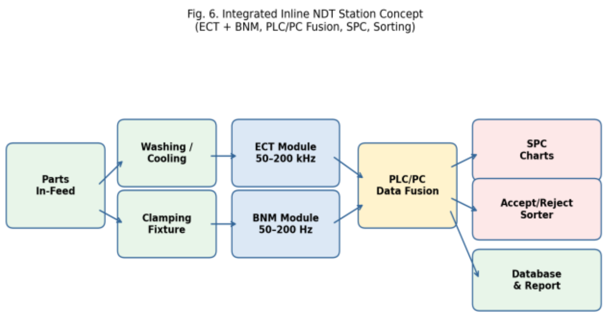

Fig. 7. Concept of the integrated inline NDT station combining ECT and BNM modules with PLC/PC data fusion, SPC charts, and accept/reject sorting.

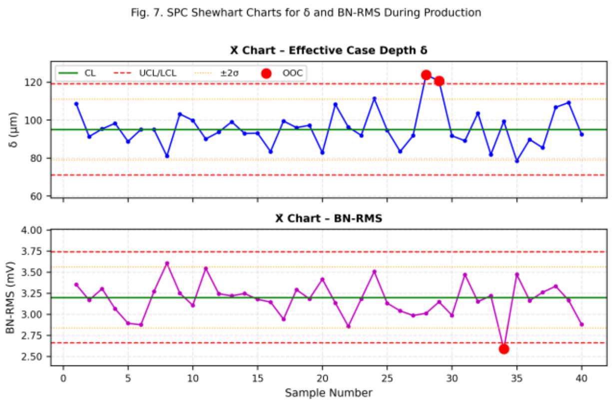

Fig. 8. SPC Shewhart $\bar{X}$ charts for δ (top) and BN-RMS (bottom) during production. Out-of-control points highlighted in red.

VII. Limitations And Future Work

The present study has the following limitations to be addressed in future work:

• The calibration and fusion model are based on destructive reference data; direct ECT and BNM measurements on the same specimens are required to populate the full calibration matrix and establish confidence intervals for δ and OSZ.

• The model has been validated for δ = 55–145 µm. Extension to deeper layers (δ > 150 µm) will require lower ECT frequencies or supplementary ultrasonic surface-wave methods (Rayleigh waves, > 10 MHz) [5], [6], [11].

• Confidence intervals for δ and HV predictions are not yet established; a bootstrap uncertainty quantification study is planned.

• Extension to other tool steels (H13, M2, PM steels) and alternative surface treatments (plasma nitriding at different temperatures, gas nitriding) is envisaged.

VIII. Conclusions

1. Ion nitriding and carbonitriding of BH11 and D2 steels at 550 °C in glow-discharge plasma produce well-defined surface layers with δ = 55–145 µm and $HV_{0.1}$ = 1150–1300, controllable through gas atmosphere composition and treatment duration.

2. Multi-frequency ECT (50–200 kHz) is most sensitive to total diffusion-zone depth δ, while BNM (50–200 Hz magnetisation) predominantly reflects near-surface hardness changes—the two methods are complementary.

3. The combined ECT + BNM data-fusion model achieves MAE(δ) < 12 µm, MAE(HV) < 25 HV, and OSZ classification accuracy > 92 %, meeting requirements for reliable production-line quality control.

4. The proposed integrated inline NDT station enables 100 % inspection at 30–60 parts/min with SPC-based early warning of process drift.

5. Full realisation requires a complete NDT calibration matrix combining destructive and non-destructive measurements on identical specimens—the logical next step of the present investigation.

IX. Aknowledgments

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