Nondestructive Evaluation of Cold-Rolling Reduction in SUS304 Austenitic Stainless Steel Using Eddy Current Impedance Signals

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1. Introduction

As part of ongoing research on nondestructive evaluation (NDE) techniques for assessing degradation in materials operated for extended periods under high-radiation or high-temperature environments, this study measured changes in eddy-current (EC) signals of SUS304 stainless steel as a function of cold-rolling reduction.

Cold rolling of metastable austenitic SUS304 promotes strain-induced martensitic transformation, increasing the material's relative magnetic permeability in proportion to plastic deformation and strain hardening [1-3]. Since this transformation is difficult to quantify without destructive testing, EC signals, sensitive to both conductivity and permeability, offers a promising nondestructive route to track cold-rolling reduction and, through empirical relations such as the Holloman equation, the resulting mechanical strength.

This study examines how the EC resistance (R) and reactance (X) vary with reduction ratio to identify the frequency range most sensitive for a future regression-based strength-prediction model.

2. Experimental Method

2.1 Specimens

Flat SUS304 specimens (30 mm × 10 mm × 1 mm) were cold-rolled to six nominal thickness-reduction levels: 0, 10, 20, 30, 40 and 50 %. Six specimens were prepared at each reduction level.

2.2 EC measurement setup

Figure 1 shows the experimental setup. Impedance spectra were acquired with a Keysight E4990A impedance analyzer over 20 Hz – 5 MHz (400 equally spaced points), using a 500 mV oscillator level and 8 averaging, following open/short fixture compensation. A solenoid-type probe was wound with AWG38 enameled wire (~80 turns) on a Fair-Rite #61(NiZn) ferrite core (Φ4 × 30 mm); the probe's self-resonance frequency (SRF), determined experimentally, was approximately 6.5 MHz, well above the 5 MHz upper bound of the measurement range, so SRF related signal distortion is minimized in the data.

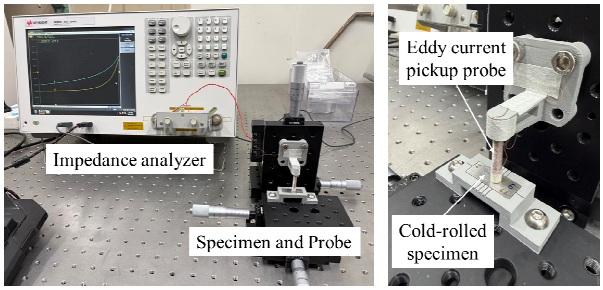


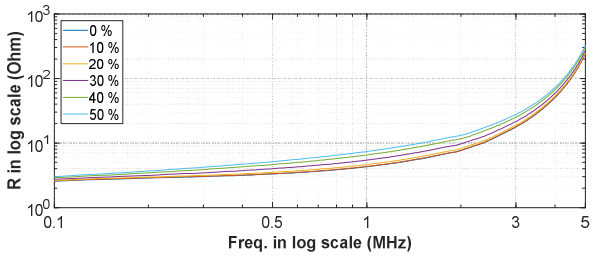
Fig. 1. Experimental setup

Signals were measured at five different points along the cold-rolling direction of each specimen. 180 EC signals (6 reduction levels × 6 specimens × 5 points) were measured in total.

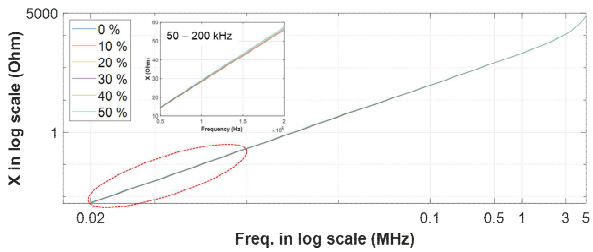
3. Results and Discussion

3.1 Impedance spectra

Figure 2 (a) and (b) show the mean resistance (R) and reactance (X), respectively, as a function of frequency for each reduction level, averaged over 30 measurements per cold-rolling level. R increases monotonically with both frequency and reduction with the largest separation between reduction levels occurring between approximately 0.5 and 3 MHz (Fig.



(a) Resistance change



(b) Reactance change with 50 – 200 kHz inset

Fig. 2. R and X spectra by cold rolling reduction for the SUS304 specimens

2(a)). In contrast, change of X according to reduction levels is smaller than that of R; the inset in Fig. 2(b) (50 – 200 kHz) reveals a small but consistent upward shift of X with increasing reduction, most visible at the lower end of the frequency range.

3.2 Sensitivity to Cold-Rolling Reduction

To quantify sensitivity, R and X were evaluated at five representative frequencies (100 kHz, 500 kHz, 1 MHz, 2.5 MHz, and 5 MHz) and expressed as percentage change relative to the unrolled (0%) baseline (Fig. 3). At 50% reduction, ΔR reaches +72.3% at 1 MHz, compared with only +17.2% at 100 kHz. ΔX, by contrast, is largest at 100 kHz (+3.2% at 50% reduction) and decreases at higher frequency, remaining below 1.5% above 1 MHz. This contrasting frequency dependence — R most sensitive near 1-1.5 MHz, X most sensitive at lower frequency — is consistent with the eddy-current response of a specimen whose relative magnetic permeability increases with martensite fraction: increasing permeability reduces the electromagnetic skin depth, concentrating induced eddy currents near the specimen surface and increasing the associated resistive loss (R) more strongly than the reactive term (X) once the skin depth becomes small relative to the 1 mm specimen thickness at MHz frequencies. Table I summarizes ΔR and ΔX at each reduction level for two representative frequencies.

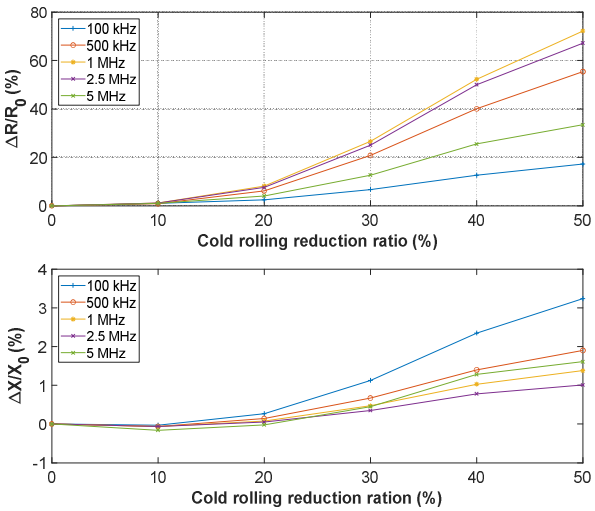


Fig. 3 Relative change in resistance (top) and reactance (bottom) according to cold rolling reduction ratio at several frequencies

Table I. ΔR and ΔX relative to 0 % reduction

Red. (%)	ΔR @ 100 kHz	ΔX @ 100 kHz	ΔR @ 1 MHz	ΔX @ 1 MHz
10	0.8	0	1.2	-0.1
20	2.3	0.3	8.2	0.1
30	6.6	1.1	26.8	0.5
40	12.5	2.4	52.4	1.0
50	17.1	3.2	72.5	1.4

4. Conclusions

Eddy-current resistance (R) increases by up to 72% at 50% cold-rolling reduction in SUS304, with maximum sensitivity near 1-1.5 MHz, making it a strong candidate indicator for nondestructive assessment of cold work. Reactance (X) changes are much smaller (< 3.5%) and are most pronounced at lower frequency (100 kHz), the opposite trend from R. Measurement repeatability (< 1% variation in R) supports the robustness of these trends. The 1-1.5 MHz band is recommended for a future regression-based model of reduction ratio, remaining safely below the probe's self-resonant frequency of 6.5 MHz. Future work will incorporate SUS316 as a nonmagnetic control, correlate the impedance signal with tensile properties (yield and ultimate tensile strength) through an empirical strain-hardening relation, and develop a Gaussian Process Regression model using the full R and X spectra with group-wise (specimen-level) leave-one-out cross-validation.

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