Evaluating the Reliability of a Nondestructive Evaluation (NDE) Tool to Measure the Incoming Sheet Mechanical Properties

Fernando J. Alamos, Jiahui C. Gu, and Hyunok Kim

Abstract Today, the automotive OEMs and part suppliers are increasing their material suppliers globally. Therefore, the same grade steels are supplied by different steel mills and batch conditions to meet this requirement. However, the variation of the incoming mechanical properties can significantly influence the stamping quality associated with necking, wrinkling, and cracking. This increases the overall manufacturing costs and lowers productivity. Nondestructive evaluation (NDE) tools have become useful to reduce this uncertainty by measuring incoming mechanical properties. The measured data can be used during production in a feed-forward control to select the optimal process parameters or as forming process parameter optimization using simulations. A detailed evaluation of a 3MA (micromagnetic, multiparametric microstructure, and stress analysis) Fraunhofer IZFP's device and its viability of implementations in a production environment is introduced. The 3MA equipment was incorporated into an industrial flexible robot and a practical calibration procedure was developed and validated for Bake-Hardening (BH) 340 steel.

Keywords Nondestructive evaluation tool · 3MA · Mechanical properties · Sheet metal forming

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1 Introduction

The manufacturing industry is recently experiencing a global scale transformation. This new industrial revolution, often called Industry 4.0, is driven by connectivity, intelligence, and automation [1]. In sheet metal forming, the increased part complexity and emerging high-strength light sheet materials often increase technical challenges associated with the variation of formability and process robustness. To overcome these challenges, smart machines, intelligent systems, and the use of big data have become essential for factories to become more efficient and productive.

Today, the automotive OEMs and part suppliers are globally resourcing various sheet materials from different suppliers considering the geographical distribution of the plants. The same grade steels are supplied by different steel mills and batch conditions to meet this requirement. However, there is significant uncertainty in the incoming material properties of the sheet materials. These uncertainties affect the part quality associated with necking, wrinkling, and cracking, increasing drastically the production cost [2–4]. Nondestructive evaluation (NDE) tools have become useful to reduce this uncertainty by inspecting the incoming coil material properties in production. In several sheet metal forming applications, NDE tools were used to measure incoming mechanical properties, which allows adjusting forming process parameters based on the measured data.

NDE tools have been used in deep drawing of kitchen sink production [5–8]. An eddy current NDE sensor was used to measure the yield strength, tensile strength, uniform elongation, total elongation, and grain size of the incoming material, and a laser triangulation sensor was used to measure the sheet thickness. The measured data was used in simulations to generate the metamodels to determine the process window and as input for a feed-forward control to select the optimal process parameters during production, improving part quality and reducing failure during small-batch productions.

Other studies have used a commercial NDE equipment 3MA (micromagnetic, multiparametric microstructure, and stress analysis), developed by Fraunhofer IZFP to determine the material properties, grain size, and residual stress of strip coils, reporting an important variation in the material properties across same coils [4, 9, 10]. Increased variation in the yield strength, from 160 to 200 MPa, has been reported for an interstitial-free steel-string coil by Wolter et al. [4]. Kim et al. [3] used the 3MA equipment to determine the mechanical properties of the incoming blanks for a sheet forming process to determine the effective servo press parameters to improve part quality and minimize failure. The study showed a good correlation between the measurements from the sensor and the tensile testing results and proposed to use a Machine Learning algorithm instead of a feed-forward control to predict the most effective parameters during the drawing process.

The application of NDE tools has a huge potential in production for the metal forming industry. 3MA has been used to measure mechanical properties in many applications; however, this tool needs to be further improved for practical applications. For example, the calibration procedure recommended by the manufacturer does not guarantee accurate measurement data of 3MA. Therefore, in this study, a practical calibration procedure was developed and validated for Bake-Hardening (BH) 340 steel. The viability of implementations of 3MA equipment was demonstrated with an automated flexible robot to emulate the production conditions.

2 Approach

In this study, the performance of the automation of a commercial NDE tool, 3MA, integrated with an industrial robot was evaluated. 3MA can measure different properties of ferromagnetic materials by correlating the measured magnetic properties, which are related to the microstructure of the material. Figure 1 illustrates the relationship among microstructure, magnetic properties, and mechanical properties. The batch-to-batch production variation in steel mills varies the microstructure which results in variation of both magnetic and mechanical properties.

The 3MA equipment uses a combination of a field harmonics, eddy current, Barkhausen noise, and incremental permeability analysis [11]. Figure 2 shows how the 3MA probe was mounted to a FANUC LR Mate 200iD/4S industrial robot with a fixture. A batch of BH340 steel with 0.75 mm thickness was used throughout this study. The BH340 steel samples were obtained from two different coils (labeled as HA and HB) of the same mill, to consider variations of the sheet mechanical properties. All blanks were cut to the same size of 508 × 508 mm. Ultimate tensile strength (UTS), yield strength (S_y), and total elongation (e_{tot}) were the measured material properties throughout this study. The automated 3MA equipment integrated with a FANUC flexible robot was first calibrated and then validated for both HA and HB materials individually.

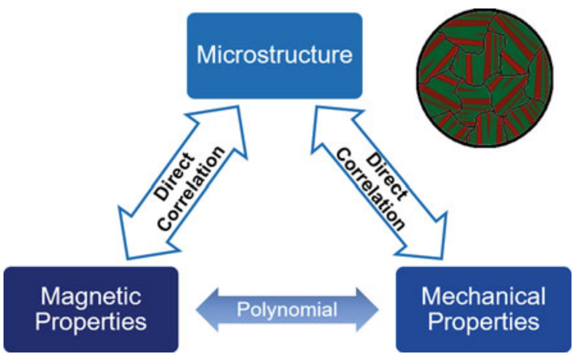

Fig. 1 Principal of 3MA measurement of magnetic properties and its correlations with mechanical properties. (Color figure online)

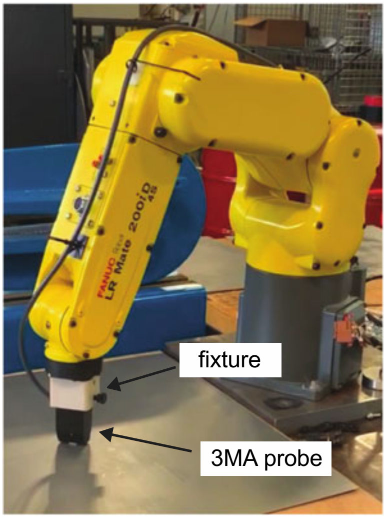

Fig. 2: 3MA probe attached to a FANUC industrial robot. (Color figure online)

2.1 Calibration Procedure

The 3MA equipment is calibrated with tensile test data. The magnetic parameters measured with the 3MA equipment and the tensile testing results of the specimens (UTS, S_y, and e_{tot}) are stored in the same database. Then calibration functions are determined using regression analysis to correlate the magnetic properties to each tensile property. The calibration functions for each tensile property have the following form:

$$y = a_0 + a_1 x_1 + a_2 x_2 + \cdots + a_n x_n \tag{1}$$

where y is the target property, a_i $(i = 0 \ldots n)$ are the computed regression coefficient, and x_i are the 3MA-measured magnetic parameters.

For the calibration of the system, first, 50 tensile specimens for BH340 were drawn on different blanks. The blanks were randomly selected from different batches and different locations to have a representative and broad sampling size. Two sets of tensile specimens were marked at 0°, 45°, and 90° with respect to the rolling direction of the coil, as showed in Fig. 3a, to account for the anisotropic properties of the blank. The gauge area of the specimens was 12.5 mm wide and 50 mm long. The length of area reduction was 57 mm. Second, the automated 3MA-robot system was used to take 40 measurements in four different locations of the specimen (Fig. 3b). The following precautions should be carefully executed for measurement:

- The contacting surface of the 3MA probe needs to be parallel with respect to the blank surface because the measurement is sensitive to contacting angle variation.

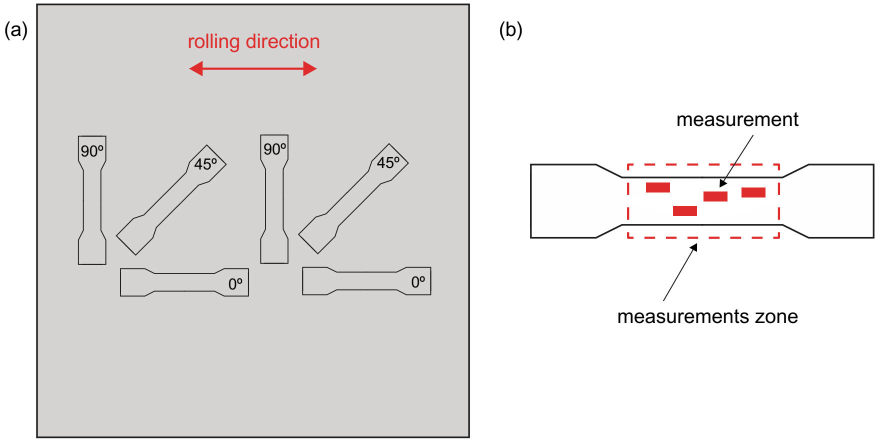

Fig. 3 **a** Layout of the tensile specimens on a blank. **b** Randomly selected four locations with the tensile gauge range for 3MA measurements. (Color figure online)

- The contact force on the probe with the sample should not exceed 15 N; therefore, the robot can be programmed to apply the same contact.
- To avoid edge effects, the 3MA measurement location should have at least 50 mm offset distance from the blank edges.

Third, the specimens were cut and tensile tested following the ASTM E-8 standard. UTS, S_y, and e_{tot} were the measured tensile properties. Finally, calibration functions were used to correlate the 3MA NDE measurements and the tensile testing data. The coefficient of determination (R^2) and the root mean square error (RMSE) values were minimized to find the most reliable regression coefficients a_i in the calibration functions.

2.2 *Validation of the Calibration Function*

To validate the effectiveness of the automated 3MA-robot system after calibration, multiple blanks were randomly selected for the BH340-HA and BH340-HB steel. For each blank, nine measurements were taken at three different positions with the automated 3MA-robot system and direction with respect to the rolling direction (0°, 45°, and 90°). Figure 4 shows the measurement locations for a blank. In addition, all the measurements were repeated by manually holding the 3MA probe to compare the manually measured 3MA data with the automatically measured data and evaluate the effectiveness of the automated system.

An analysis of variance (ANOVA) and a Tukey test were performed to statistically quantify the difference between the mechanical properties measured using the automated 3MA-robot system, the manually handled 3MA equipment, and the

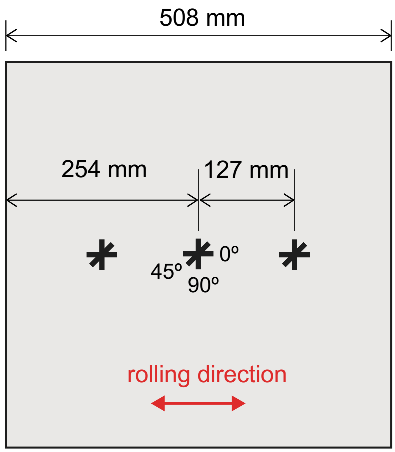

Fig. 4 Nine measurements on each blank for validation at three different locations, 0°, 45°, and 90° with respect to the rolling direction. (Color figure online)

tensile testing results. The results were analyzed with a 95% confidence interval. The ANOVA test compares the similarity of two data sets. Two data sets are significantly different if p-values are lower or equal to 0.05. The assumptions of independence of cases, homoscedasticity, and normality of the residuals were checked. The Anderson–Darling test was used to verify the normality of the residuals. For the cases where the assumption of normality of the residual was invalid, a Kruskal–Wallis nonparametric test was performed, and the p-values were compared with the results from the ANOVA test. The results using both tests gave similar p-values; consequently, the assumptions are satisfied and the standard ANOVA analysis was considered satisfactory [12].

3 Results

3.1 Tensile Testing Results

The detailed tensile testing results are summarized in Table 1. The results show an important variation in the mechanical properties between BH340-HA and -HB batch materials. The BH340-HB steel is stronger and less ductile than the BH340-HA steel. The average UTS is at least 10 MPa higher and the yield strength (S_y) is at least 12 MPa higher for BH340-HB than BH340-HA for all three orientations with respect to the rolling direction. The average total elongation (e_{tot}) is around 2% less ductile for BH340-HB than BH340-HA. The tensile testing results also showed a significant variation in the mechanical properties within the same coil. For example, for BH340-HA, the $S_{y\_90^\circ}$ standard deviation (SD) is 8.83 MPa and the range is 27 MPa, which is 17.2% of the measured value. For $e_{tot\ 90^\circ}$, the SD is 9.3% and the range is 27.3% of the measured value. Moreover, for some cases, a large variation

Table 1 Tensile testing results for BH340-HA and BH340-HB steels for 0°, 45°, and 90° orientations

Material variation	Property	UTS (MPa)			S_y (MPa)			e_{tot} (%)		
	Angle (°)	0	90	45	0	90	45	0	90	45
BH340-HA	Mean	340.8	341.4	344.1	227.2	233.5	233.5	39.98	39.26	38.95
	St. dev.	9.1	9.0	9.3	8.8	8.4	7.0	2.88	3.64	3.26
	Range	32.0	33.0	34.0	39.0	27.0	28.0	8.60	10.70	10.40
BH340-HB	Mean	350.9	354.6	355.1	241.2	246.2	245.3	37.29	35.71	36.06
	St. dev.	4.6	7.2	7.2	3.7	9.4	4.9	2.48	3.34	3.23
	Range	16.0	20.0	21.0	16.0	38.0	16.0	8.20	9.60	10.10

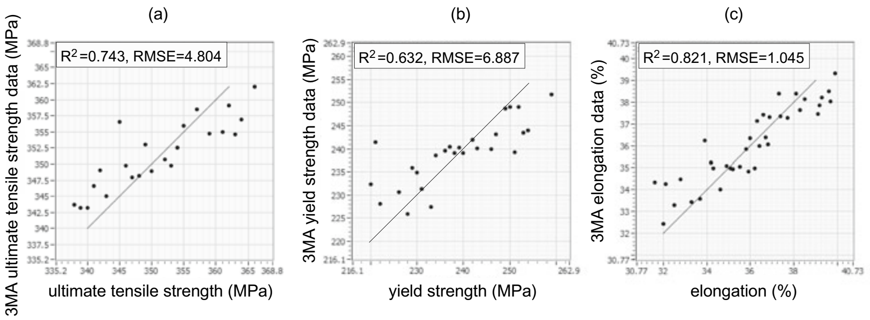

Fig. 5 Calibration correlation plots for UTS **a**, S_y **b**, and e_{tot} **c**

on the material properties was found in the same blank. For example, for a single BH340-HA blank, the values of two different specimens in the rolling direction were 354 and 340 MPa for UTS, 243 and 222 MPa for S_y, and 39.2 and 37.7% for e_{tot}.

3.2 Calibration Model Results

The correlation plots between the 3MA-measured data and the tensile testing properties (ultimate tensile and yield strength, and elongation) are shown in Fig. 5. The manufacturer suggests a model correlation higher than 80%; however, the R^2 values for S_y and UTS were lower than 80%. The correlation was 63.2% for S_y but the RMSE was 6.89 MPa, which is only 2% of the mean value and within the coil specification (6–40 MPa). The UTS model shows a correlation of 74.3%, although the RMSE was 4.8 MPa, which is lower than the 3MA manufacturer specifications (8–40 MPa) [11]. For e_{tot} the correlation is 82%. Therefore, the regression polynomial equations used for the calibration are considered acceptable for the tensile properties. Nevertheless, further tests with 3MA and subsequent statistical analysis were conducted to increase the accuracy of the calibration and the system.

3.3 Validation of the Calibration Function

To prove the repeatability of the automated 3MA-robot system, the same point of the blank, in the same direction, was measured three times. The results showed a consistent value for the same location of the blank. The higher percent deviation (PD) was 1.2% for UTS, 1.4% for S_y, and 3.7% for e_{tot}. All of the results showed a lower PD than specified by the manufacturer [11].

An ANOVA test was performed to quantify the accuracy of the calibration model of the 3MA measurements. The ANOVA test evaluates how similar two different

Table 2 ANOVA p-value results between the 3MA-measured data from the sheet blanks concerning the tensile testing results

Property		UTS			S_y			e_{tot}		
Angle (°)		0	90	45	0	90	45	0	90	45
Material variation	BH340-HA	0.447	0.408	0.002	0.620	0.994	0.155	0.120	0.854	0.173
	BH340-HB	1.000	0.997	0.174	0.074	0.028	0.618	0.797	0.792	0.561

data sets are. From Table 2, it is observed that 89% of the 3MA-measured properties of the new blanks randomly selected from the coil were similar to the tensile testing data (p-values > 0.05). The $UTS_{45°}$ for BH340-HA and $S_{y\_90°}$ for BH340-HB showed a small mismatch (p-values ≤ 0.05) between the new 3MA measurements and tensile data. Figure 6 shows the box plots for these two cases. The box plot describes groups data based on a five-number summary: minimum, maximum, median, and standard deviation above and below the data mean. Outliers are excluded in the analysis and are represented with a star (*). From the plots, it is observed that the 3MA-measured values for the $UTS_{45°}$ of BH340-HA are slightly higher than the tensile testing results; however, they are within the maximum and minimum values. For $S_{y\_90°}$ for BH340-HB, the 3MA-measured values are also within the tensile test data range; however, the 3MA data mean value is lower than the tensile test data mean value. Therefore, the calibration was considered reasonably accurate and robust.

A further analysis used a new calibration model with only 26 random tensile samples from the original 50 samples. The correlation of the calibration (R^2 values) improved over 90% for all the properties. The same blanks were measured again using the new calibration model; however, for this case, the ANOVA test results showed that only 17% of the 3MA-measured data of the new blanks were similar

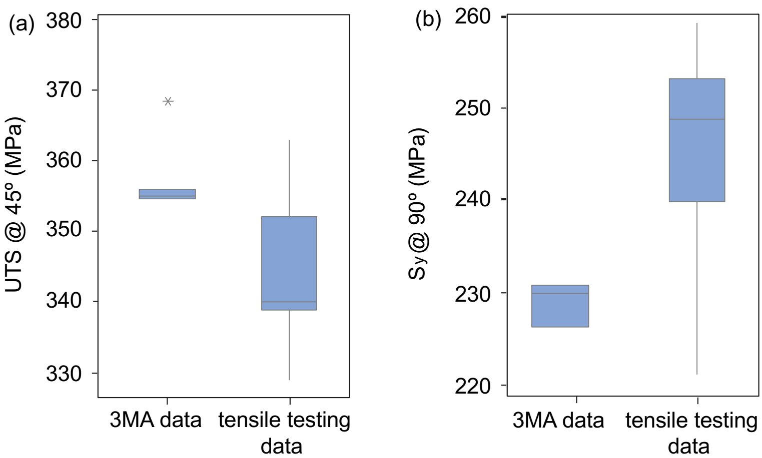

Fig. 6 Box plots for: **a** UTS at 45° for BH340-HA and **b** at 90° for BH340-HB. (Color figure online)

to the tensile testing data. The robustness of 3MA measurements improves significantly with increasing the number of tensile tests; therefore, proper and representative sample size is critical for reliable calibration.

Also, a similar ANOVA test was performed to access the consistency of the 3MA measurement; most measurement variations were made by manually holding the 3MA equipment and then holding it with the flexible robot. An ANOVA test was performed, and the results showed negligible differences of the measured data between both methods.

4 Discussion

In this study, both 3MA data and tensile test data showed a significant variation of the BH340 mechanical properties. Important variations on the material properties (ultimate tensile and yield strength, and elongation) were found even for the same coil. In addition, the automated 3MA-robot system provided accurate, consistent, and repeatable measurements for BH340 steel. Therefore, after a reliable calibration process, automated NDE tools can be practically used in tracking the incoming coil material variations by taking real-time measurements in production to reduce the uncertainties of the process and potentially improve part qualities and reduce costs by adjusting the forming process parameters or machine control.

One of the limitations of 3MA equipment is that different grade or different gauge materials require new calibrations. Different calibration functions need to be used for different coil thickness, or thickness needs to be incorporated as a variable of the calibration function. It is recognized that calibration can be expensive; however, the well-calibrated 3MA tool has great potential for cost-saving by inspecting the incoming coil properties and adjusting forming process in production. Additionally, this study leads to develop generalized material calibration databases and use advanced simulations and machine learning to minimize calibration efforts [4].

The calibration procedures for 3MA recommended by the manufacturer do not fully guarantee a robust calibration. Therefore, from this study, the following calibration procedure for ultimate tensile and yield strength, and elongation is recommended for steel strip coils:

1. Choose at least 24 randomly selected blanks from different parts of the coil for each material variation.
2. Draw two sets of tensile test specimens for each direction (0°, 45°, and 90° with respect to the rolling direction) as shown in Fig. 3a.
3. Record 40 3MA measurements at four random points (10 per each point) for each specimen (Fig. 3b).
4. Conduct tensile testing of the drawn specimens from step 2.
5. Store the 40 3MA measurements and the tensile testing data in the same database and find the calibration functions using regression analysis. The correlation

coefficient of the calibration model should be: R^2 (adjusted) > 0.7 and %RMSE < 10%. If $0.6 < R^2$ (adjusted) < 0.7, then %RMSE < 3%.

6. Choose ten randomly selected blanks from different parts of the coil for each material variation and take nine 3MA measurements (three for each direction) for each material as shown in Fig. 4.
7. Run a one-way ANOVA test (significant level = 0.05) for each mechanical property independently, comparing the tensile testing data with respect to the 3MA measurements of step 6. If more than or equal to 75% of the p-values are higher than 0.05 (no significant differences), the calibration is successful. If less than 75% of the p-values are higher than 0.05, the calibration is not successful and more tensile testing data should be included in the ANOVA test.

The 3MA NDE tool is sensitive to the operating conditions and the proper cautions are needed to avoid significant measurement errors. The precautions that need to be considered while taking measurements were discussed in Sect. 2.1.

It was observed that the robustness of the 3MA calibration is significantly improved by increasing the number of tensile testing samples. New advanced high-strength steels typically have a large variation of the material properties because they have multiphase microstructures, which makes them more challenging to obtain consistent mechanical properties [3, 4]; therefore, calibration specimens should be chosen carefully to include the entire range of material properties. Since a coil strip can be kilometers long, it is crucial to select multiple blanks across different parts. Moreover, the 3MA-measured tensile properties are found by computing the calibration functions, which are based on empirical data; therefore, extrapolation outside of the calibration range can lead to significant fault data. For this reason, a wide range of value needs to be used for the calibration to minimize calibration errors.

5 Conclusion

The following conclusions can be made based on this study:

- A significant variation on the incoming mechanical properties was observed for the same batch coil of BH340 steel.
- The automated 3MA equipment integrated with the flexible robot measurements consistently obtains the repeatable results.
- A BH340 steel calibration model for yield and ultimate tensile strength, and total elongation was obtained and validated successfully.
- A new robust calibration procedure was established for industrial applications.
- NDE tools can effectively detect mechanical property variation of the incoming material.
- NDE automated tools used as an input to adjust forming process parameters have a great potential in reducing costs and time for sheet metal forming production environment.

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