ONLINE ACQUISITION OF MECHANICAL MATERIAL PROPERTIES OF SHEET METAL FOR THE PREDICTION OF PRODUCT QUALITY BY EDDY CURRENT

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1. Introduction

In industrial sheet metal forming processes several factors influence the quality of the produced parts. These are the human factor, method - especially the tooling, equipment like the press and its settings, raw material and environment (Figure 1). [1] The variations of these parameters, although they are inside the specified tolerances can cause defects in the manufactured part or product. In this work, the focus is on the variations of the mechanical material properties like yield strength or uniform elongation. The mechanical properties can change fast and become evident only when defects in the finished parts are detected.

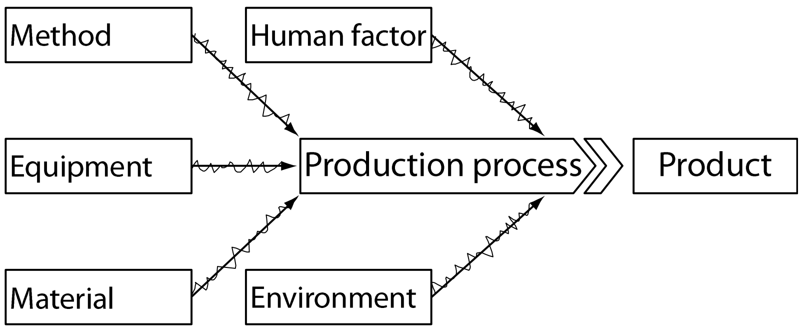

Figure 1: Influences on the production process

Especially in the automotive industry the press shops face several challenges: Because of the increasing unification of technical standards and the wide model range customers differentiate the products by their outer shape rather than their technical specifications. For this reason, the body shell parts of the cars are increasingly complex and the material is utilized to its limits. [2] Nevertheless, these parts must be manufactured with high accuracy and no rejections at low cost. Therefore systems to eliminate or compensate the scattering material properties are required in production. There are two ways to achieve this, either by sorting out inapplicable material or by adjusting the parameters of the forming process to the material properties. For both of these options inline measurement systems for the non-destructive acquisition of material properties are necessary. As it is shown in Figure 2 the microstructure of a material determines the mechanical as well as the electromagnetic material properties. The correlation between these properties can be reproduced by appropriate mathematical models. [3] [4]

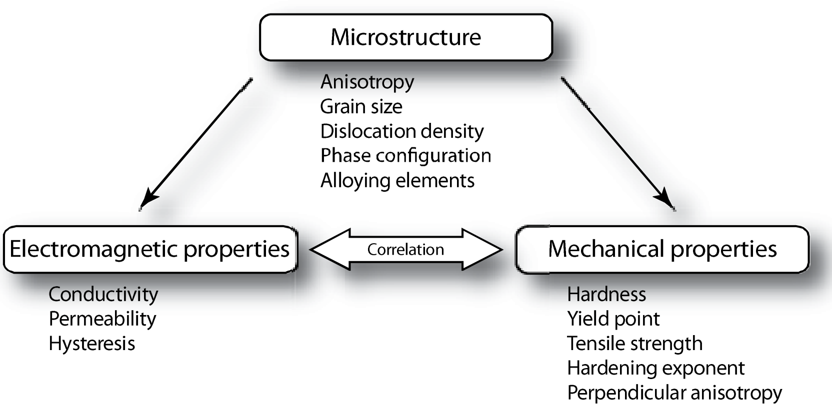

Figure 2: Correlation between electromagnetic and mechanical properties

Eddy current measurement systems are well known in quality assurance and commonly used to detect defects in materials. [5] In this work, an eddy current system for the quantitative acquisition of material data is presented. In using a multifrequency eddy current system, a fingerprint of the inspected sample can be obtained. [6] Combining the eddy current values with modern data mining algorithms allows measuring the mechanical properties of conductive materials like steel or aluminum. The examined material is DC06 a cold rolled mild steel, with a thickness of 0.8mm and a zinc coating on both sides. According to the specifications, the mechanical properties of this material can vary in a wide range: $Rp_{0,2}$ = 120 to 180MPa, Rm = 270 to 330MPa, A_{80} > 41%.
The measurement system was developed to acquire the material properties of sheet metal inline in production. The accuracy of the system is high enough so that the measured data can be used to adjust the press settings and to generate a database for future sensitivity analysis.

2. The measurement system

To obtain the best accuracy, the eddy current probe has to be placed directly on the inspected material without a gap between probe and material. This way the highest sensitivity and reproducibility is achieved. Therefore the measurements have to be done when the sheet metal does not move, at the same time as the cutting process. Thus, the measurement system had four main functions: moving the eddy current probe up and down, measure the eddy current values for each blank, mark each blank for correct identification after cutting and calculate the mechanical material properties. The setup of the system is shown in Figure 3. The probe is moved up and down by a linear drive, which is mounted on a crossbeam in front of the feeder unit and the subsequent cutting process. At this place the sheet movement is discontinued. Figure 4 shows the mounted measurement head in the press. An inkjet printer was used to mark the sheet metal with a number to identify the blanks when taken from the pack at the end of the cutting press.

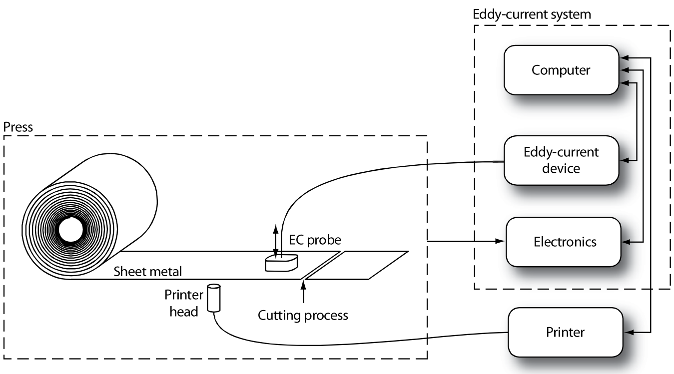

Figure 3: The eddy current system

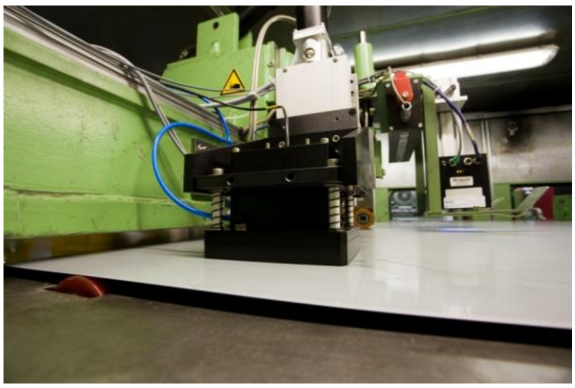

Figure 4: Probe mounted in the press

As soon as the sheet metal stops, the probe is moved down and pressed on the sheet. Then the eddy current measurement is done. The measurements are triggered through a signal from the cutting press to assure the sheet metal has stopped. The eddy current device used is a Magnatest D device from Institut Dr. Förster. It is a multifrequency device working in serial mode which also allows the evaluation of the signal harmonics. The settings of the eddy current device like amplification and attenuation are adjusted automatically, using one sample of the material. Seven frequencies 1024Hz, 512Hz, 256Hz, 128Hz, 64Hz, 32Hz and 16Hz are used including the 3^{rd}, 5^{th} and for the lower frequencies also the 7^{th} harmonic, resulting in 48 scalar values representing one eddy current measurement.

3. Model generation

Because an explicit formulation of the relationship between the electromagnetic and the mechanical material properties shown in Figure 2 is not feasible, a different representation has to be found. Using modern multidimensional regression algorithms it is possible to reproduce this correlation and calculate the mechanical properties. These models must be trained in advance with a sufficient large set of data. For each target value, i.e. yield strength $Rp_{0.2}$, tensile strength Rm, uniform elongation A_{gl} and breaking elongation (l_0= 80mm) A_{80}, a separate model must be generated. The minimal amount of data to achieve a good accuracy is ten samples from at least ten different batches taken from normal production. These samples must be measured with the eddy current system, afterwards the conventional measurment of the sample, in this case the tensile test, has to be done.

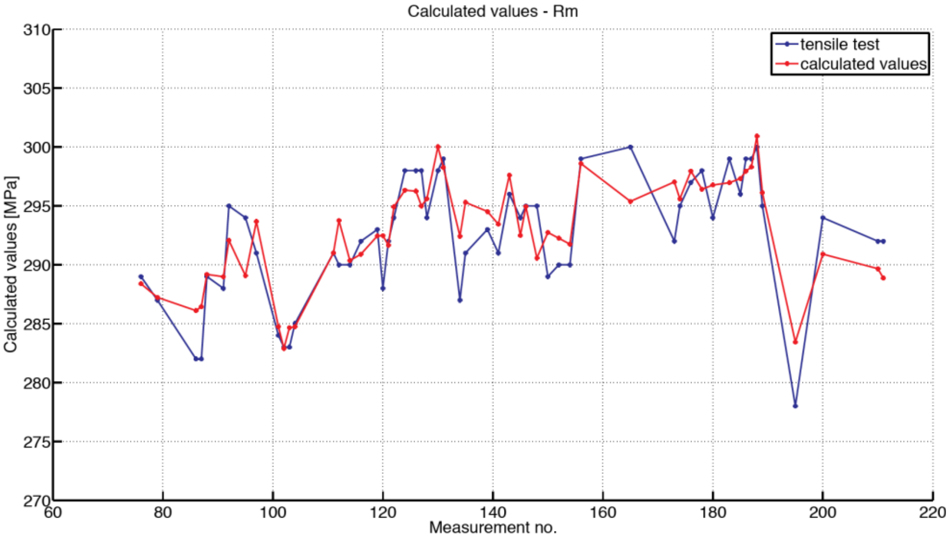

Figure 5: Test data for Rm

These data then are devided into two equally sized groups, the training data to generate the models and the test data to validate the accuracy of the models. It is often recommendet to use 20 – 30% of the samples for validation [7], but in this case more training data did not result in a better model and a larger group of validation data is more significant. In Figure 5 the course of the values calculated from the eddy current data and the measured values from the tensile test are shown. The quality measures used to validate the accuracy of the generated mathematical models and to compare the models to choose the best model. These measures were the mean absolute error (eqn. 1) and the root mean squared deviation (eqn. 2).

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|f_i - y_i| \quad \textbf{(1)}$$

$$RMSD = \sqrt{\frac{1}{n}\sum_{i=1}^{n}|f_i - y_i|^2} \quad \textbf{(2)}$$

For the used model the MAE is 2.04 and the RMSD is 2.57. The RMSD is only of interest to compare models and select the best one during training, whereas the MAE is the absolute mean error of the model. Figure 6 displays the accuracy of the test data. On the x-axis the tensile test data, on the y-axis the calculated values are plotted. The green lines are the +/-1% limit and the red lines the +/-2% limit respectively. All calculated mechanical values lie within the 2% error range, most of the samples (72% of them) even in the 1% range. The accuracies for the test data area are +/- 2.5% for $R_{p0,2}$, +/-2% for R_m +/-4.5% for A_{gl} and +/-4% for A_{80}.
To achieve a high accuracy the measurement of the training data has to be done under the same conditions as in the real measuring environment. The acquisition of the eddy current training data for these models took place in laboratory, because of logistic reasons. Although everything was done to assure identical conditions, the eddy current data showed a slight systematic error when comparative measurements were made in the production environment with three specimens that

were measured in the laboratory before. This error was compensated in the software to optimize accuracy.

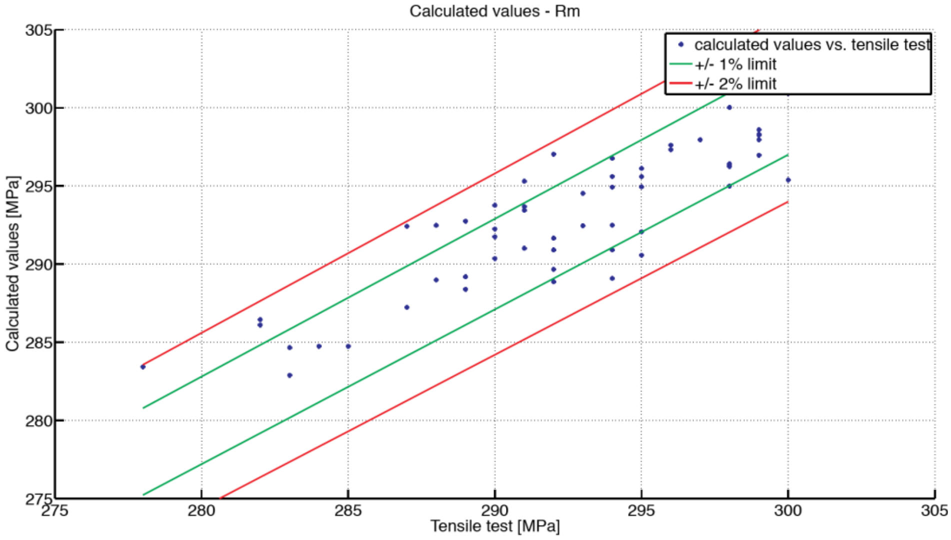

Figure 6: Calculated values vs. Tensile test - Rm

4. Measurements in production

The system was installed in the blank cutting press after the models were generated. Four complete coils were measured, one measurement representing one blank. One single eddy current measurement including calculation of the mechanical properties takes 0.58 seconds. A complete cycle including also the coil movement takes 0.76 seconds. If one measurment takes longer and the coil is not lifted off the sheet, the measurement is aborted and the probe moves upwards. This is necessary to avoid damage of the coil, because the cutting press and the feeder cannot be stopped immediately. During all measurments, approximatly 6300, this was never necessary. In Figure 7 and Figure 8 the behavior of yield strength $R_{p0.2}$ and R_m for two coils is shown.

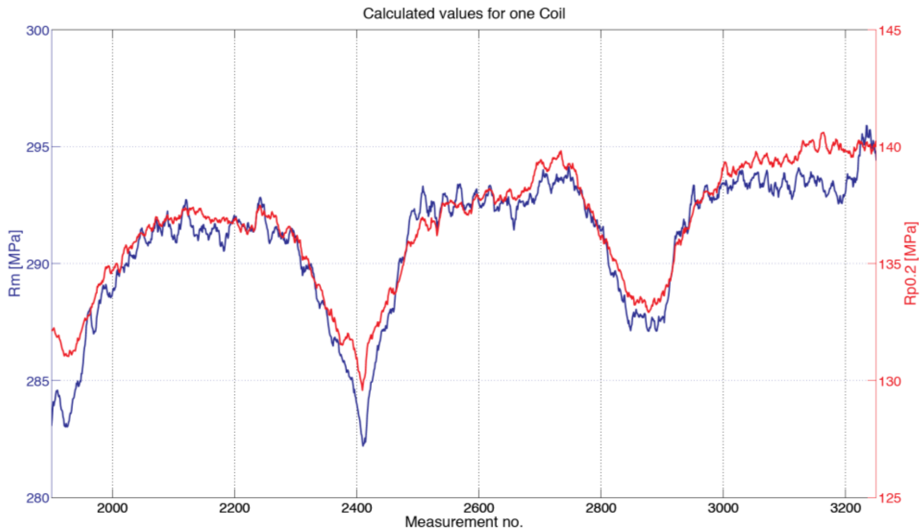

Figure 7: Calculated values coil 2

As it can be seen, the mechanical properties are not constant along one coil, and they also do not have a common behavior. During coil 2 $R_{p0.2}$ and R_m show the same behavior: when $R_{p0.2}$ falls R_m is falling too and vice versa. Coil 4 shows a different course: $R_{p0.2}$ is rising whereas R_m is slightly falling.

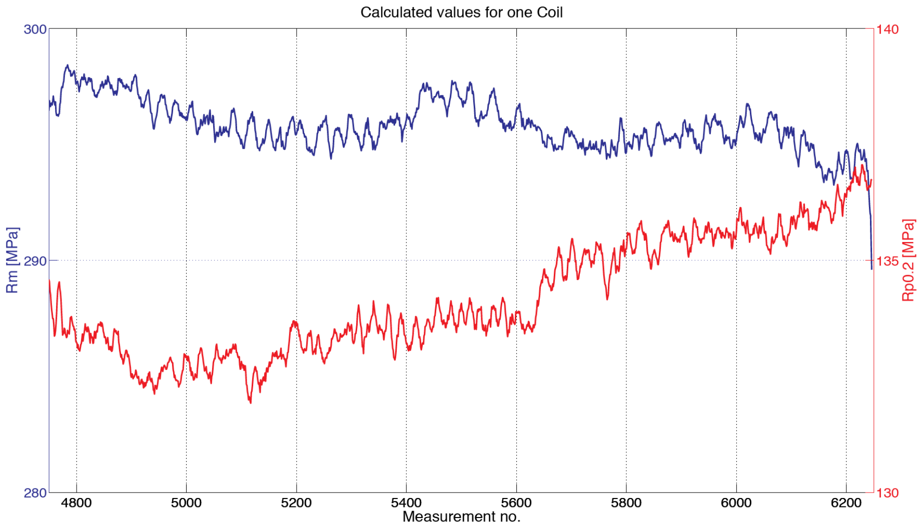

Figure 8: Calculated values coil 4

5. Results

Four complete coils were measured and a 100% monitoring was achieved. The validation of the mathematical model showed high accuracy, between 2 and 4.5%, depending on the mechanical property. During the measurements in the press shop at least 6 blanks per coil were collected for comparative measurements and very good agreement between the calculated values and the tensile test was found. See Figure 9 and Figure 10 for the results. The results for R_m are slightly better, which could be expected from experience with the training and test data.

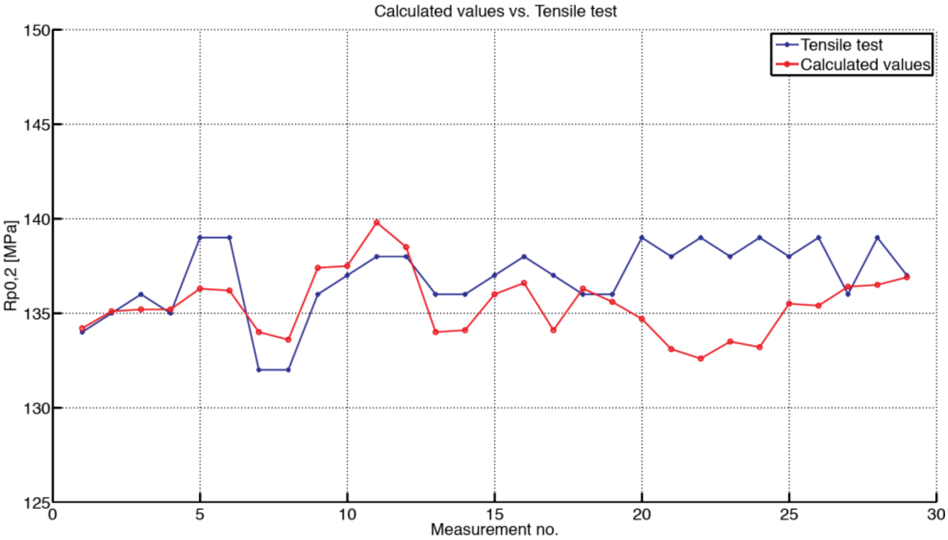

Figure 9: Calculated values and tensile test data for $R_{p0.2}$

The accuracy of the generated models strongly depends on accuracy of the training data. To improve the accuracy of the measurement system, the training data should also be acquired in the production line. This way errors caused by changes in the measurement conditions can be avoided.

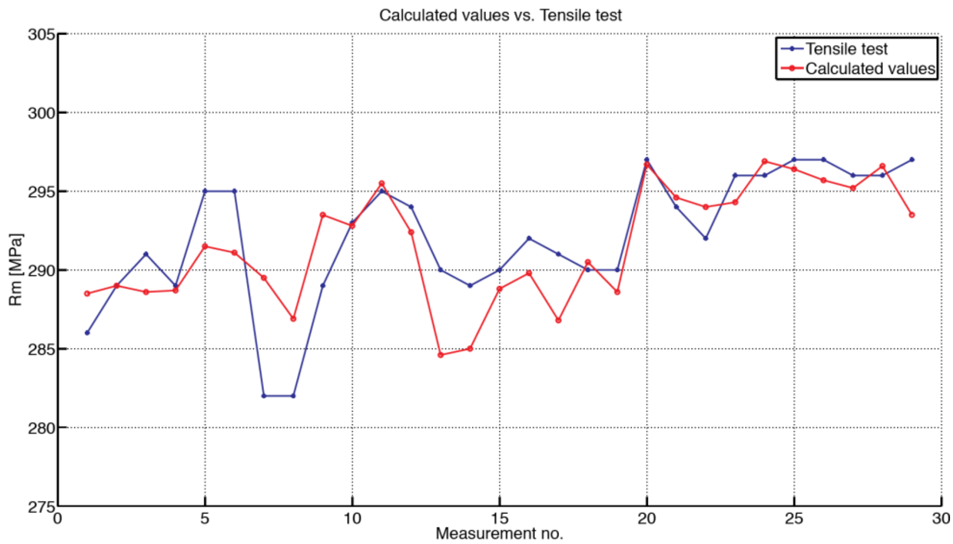

Figure 10: Calculated values and tensile test data for R_m

In Figure 11 the distribution of the yield strength is shown. All measurements lie at the lower end of the specifications. The same applies for the tensile strength. A normal distribution can be fit to the data, which can be used for stochastic simulations in software packages like AutoForm-Sigma® or LS-OPT® from LSTC. Stochastic simulations take a long time, because every input parameter is varied on the whole possible parameter range. By using the eddy current results as input, the parameter range is reduced to the effective range, which results in a significant reduction of simulation time.

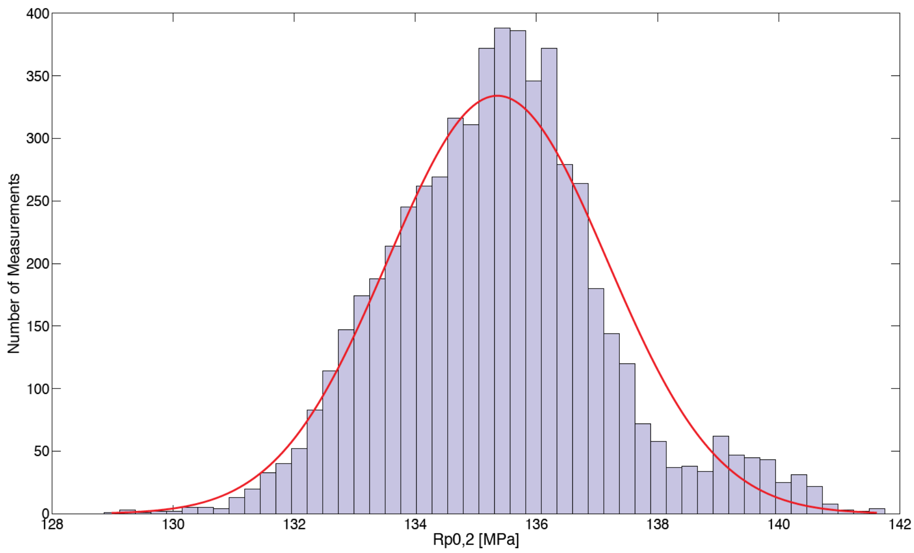

Figure 11: Distribution of $R_{p0.2}$ for all coils

6. Conclusions

The material properties are not constant along one coil. Although their variations lie within the specifications they can have a significant influence on the deep drawing process. The achieved accuracy of the measurement system is sufficient to use the acquired data to sort out inappropriate material or to adapt the press settings, e.g. die cushion pressure, blank holder force or lubrication. Scrap production can be reduced and the press operator will be unburdened.

When the system is installed in the press shop, it can also be used to generate a database for sensitivity analysis in the tool shop for draw die development and as input data for stochastic simulations to reduce simulation time.

Future work will be concentrated in two areas. The first one is the connection of the eddy current data to the yield curve and the forming limit curve. Both are more significant measures in sheet metal forming than the tensile test data are. The second area is to link the eddy current measurement system to the numerical simulations. The eddy current database can be used for sensitivity analysis; the results from sensitivity analysis will be used to specify the limits of the material properties.

Acknowledgements

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