Test of electromagnetic, non-destructive method for determining material properties in steel

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This study, in the area of non-destructive testing and measuring technology, shows that it is possible to inspect and determine the mechanical properties and micro structure of a material using electro-magnetic technique. The goal has been to on-line determine material properties like residual stress distributions, variations in tensile strength and fatigue strength in a material. In the project the latest in materials inspection using electro-magnetic methods combined with statistic modelling is used. The project has shown that these new methods can non-destructively determine the mechanical properties of a material or a machine detail. It is believed that this measuring technique has a clear place in industry.

Keywords: Steel - Non-destructive testing - Mechanical properties - Electro-magnetic technique

Swerea MEFOS has tested at a combination instrument for measuring electromagnetic properties of a ferromagnetic material for investigating if such a device can "measure" material properties such as internal residual stresses, tensile strength and variations in fatigue strength on gears due to shot blasting. The instrument tested is The MikroMach made by Q-Net, a daughter company to Fraunhofer Institute. MikroMach is a smaller version of the *Micro-Magnetic Multi parameter Micro structure and Stress Analyzer*, 3MA [1], designed by Fraunhofer IZFP in Saarbrücken Germany. The advantage of these instruments is that they utilises four different measuring techniques for detecting the electromagnetic properties of the material. The system creates a multivariat model based on calibration measurements using the parameters that reflect the variation you want to measure.
The four different measuring techniques are:

1) Harmonic analysis of the magnetic tangential field strength
2) Barkhausen Noise signal analysis
3) Incremental Permeability analysis
4) Multi-frequency Eddy Current analysis.

All the different measuring techniques measures and stores a number of parameters for the tested material. The signals are filtered in to be able to determine different magnetic parameters in the material. By choosing the parameters that strongest correlates to the parameter calibrated against and making a regression analysis it is possible to make a model with the strongest parameters. It is possible to choose parameters manually from looking at the different responses or you can let the system decide automatically.
In this work two tasks have been analysed; residual stress in a hot rolled and a heat treated steel strip and an analysis for mapping the variation in yield stress that occur near the strip ends.

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Calibration of the MikroMach.

The first test with the equipment was to study the possibility to measure residual stresses in a 8 mm thick EHS-steel plate. The first task was to quantify the residual inner stresses on a "as rolled", coarsely levelled steel sheet. We should then try to take away all the residual stresses by stress-relief annealing the plate. We started with a careful calibration. To be able to do this we made a setup in a testing device where we were able to apply both tension and compression under controlled conditions.
To be able to calibrate the equipment we had a test sample with same properties, i.e. analysis, thickness, surface properties etc. as the plate that we were going to measure on. In this case we took a piece of the test plate we had and attached it to a tensile testing machine that could apply loads corresponding to loads up to +/-250MPa.
In Figures 1 and 2 we see the MikroMach measuring head on the side of the calibration test piece. This is a part of tensile testing machine so the loads could be applied with great accuracy.

Fig. 1 - Measuring jig for applying tensile stress during calibration

Fig. 1 – Apparecchiatura di misura della sollecitazione per trazione durante la calibratura

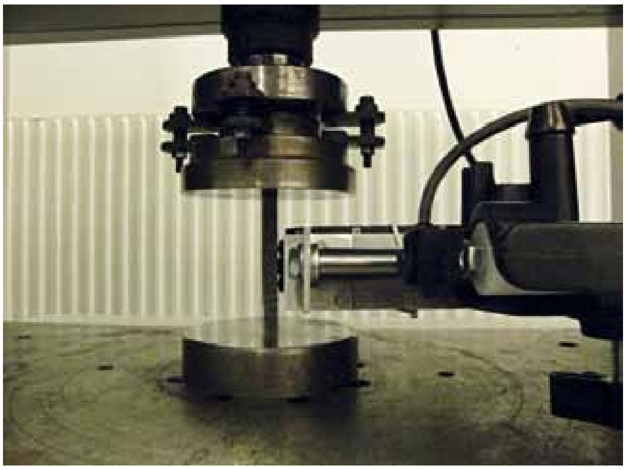

Fig. 2 - Measuring jig for applying compression. Since the test piece had a tendency to buckle the test piece was shortened to 100 mm length

Fig. 2 - Apparecchatura per la misurazione della compressione. Poichè il provino aveva una tendenza a deformarsi per compressione è stato accorciato alla lunghezza di 100 mm

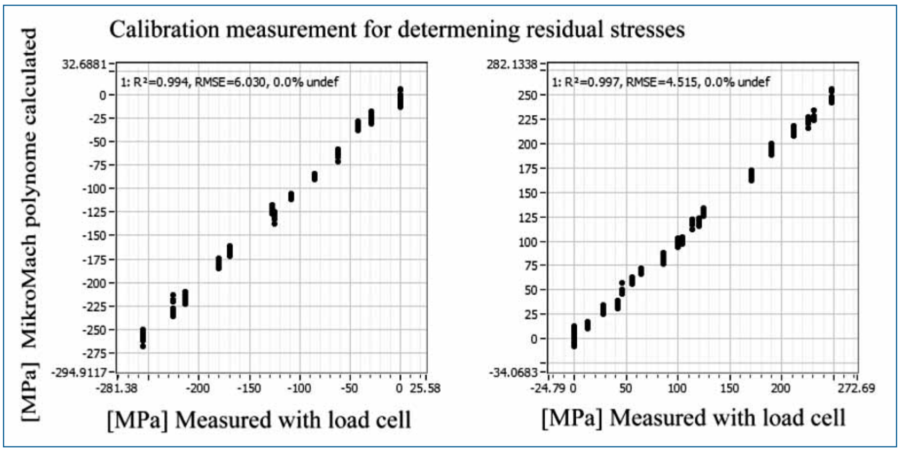

Fig. 3 - Calibration result for both tension and compression on a 8 mm thick EHS-steel plate.

Fig. 3 – Risultati della calibratura per trazione e compressione su una lastra in acciaio EHS dello spessore di 8 mm.

The calibration was performed on untreated cut test pieces from the test plate. The test pieces were 50 mm wide. The test piece for applying pressure had to be cut shorter since it had a tendency to buckle under the load (fig. 2).

The measurements were made both under increased compression/tension and when decreasing compression/tension, this to get as many reference points as possible. Since the set-up had to be changed when going from compression to tension the calibration measurements had to be done in two separate parts that had to be added together to one calibration afterwards.

By using the MikroMach system regression analysis a polynomial was created that gave a fit to the state of tension in the material. This polynomial was then used to “determine” the internal residual stresses in the 8 mm EHS-steel plate. The calibration evaluation is done in fig. 3.

The polynomial fit that was obtained by the MikroMach system was based on values, direct or indirect, from Barkhausen Noise and “Harmonic distortion”. These parameters have a direct connection in the physics of tension and compression in the atomic lattice in steel. There is also a connection in the EC-part of the measurements.

Measuring residual stresses in a hot rolled steel plate

A coarsely levelled hot rolled EHS-steel plate, Figure 4, with the length of 1200 mm, width 1600mm and a thickness of 8 mm was obtained. When measuring a grid was drawn on the plate and we avoided placing measuring points too close to the edges. Tests had shown, and also advice from the manufacturer, that the magnetic field is influenced by the edges of the material. You should try to avoid measuring closer than 25 mms from the edge. Measurements were made both in the rolling direction and 90° to the rolling direction, on both top and bottom sides of the plate.

When we evaluated the measurements of the unannealed,

Fig. 4 - 8 mm EHS-Steel plate unannealed with the probe for the MikroMach

Fig. 4 – Lastra in acciaio EHS di 8 mm di spessore non sottoposto a ricottura con la sonda per la prova MikroMach

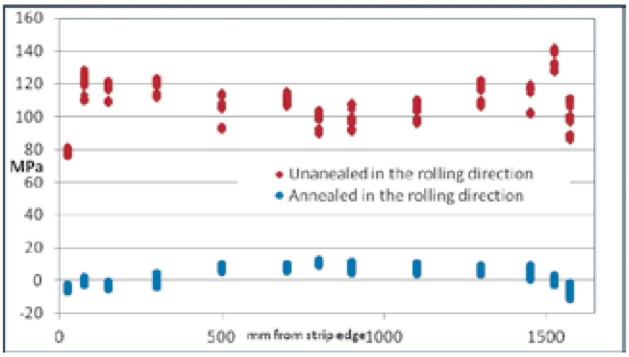

Fig. 5- Measured distribution of residual stresses top side before and after annealing

Fig. 5 - Distribuzione delle tensioni residue misurate sulla parte superiore prima e dopo ricottura

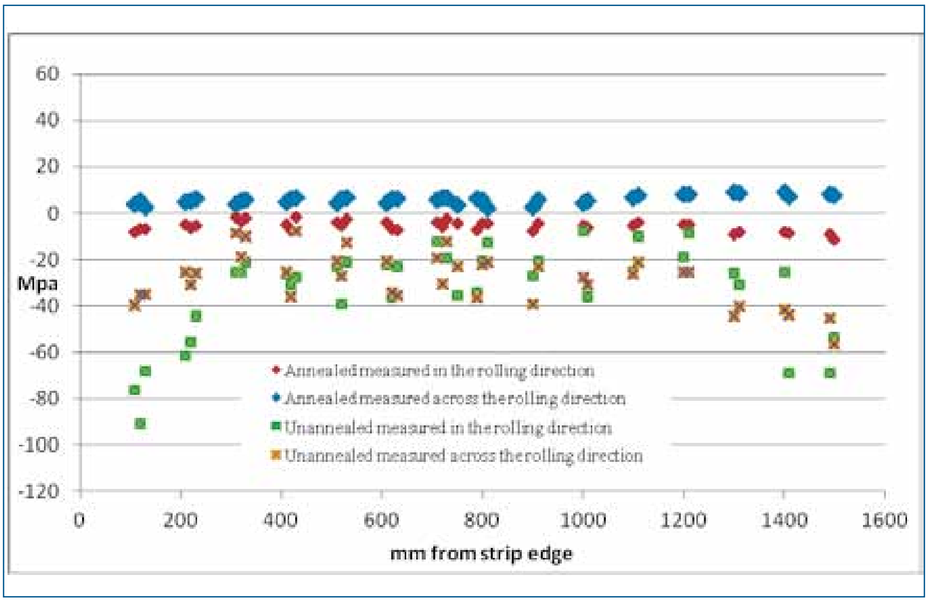

Fig. 6 - Measured distribution of residual stresses bottom side before and after annealing

Fig. 6 - Distribuzione delle tensioni residue misurate sulla parte inferiore prima e dopo ricottura

coarsely levelled plate, we found, not unexpected, that there were big residual stresses in the plate in the rolling direction. One side had big compressive stresses and the other had tension. This is naturally what you could expect to find on a plate that is taken off a coil and just levelled coarsely. See Figures 5 and 6.

After annealing the residual stresses were almost totally gone and this is also no surprise since this is what was expected. The equipment had no problems detecting the difference since it is quite big. The predicted, calculated residual stresses were all within the calibration limit that is very important when “measuring” with the MikroMach and the annealed plate had as expected residual stresses close to 0 MPa.

The unannealed plate shows big differences in residual stresses across the width both on the top side and the bottom side, with clear tension on one side and compression on the other. This can be correlated to the fact that the plate has been coiled and a part of it was uncoiled and coarsely levelled, hence the differences in residual stresses between the sides, before annealing.

SUMMARY

The measurement showed a realistic level of internal stresses inside the hot rolled steel plate. There were tensile stresses on one side that were balanced by compressive stresses on the other side. After annealing the stresses were very small as expected.

Measuring variations in tensile strength in ends hot rolled coil

The goal with these measurements was to see if it is possible to use this equipment to determine where, how far in, the material properties of a hot rolled coil have even and approved tensile strength values. We also wanted

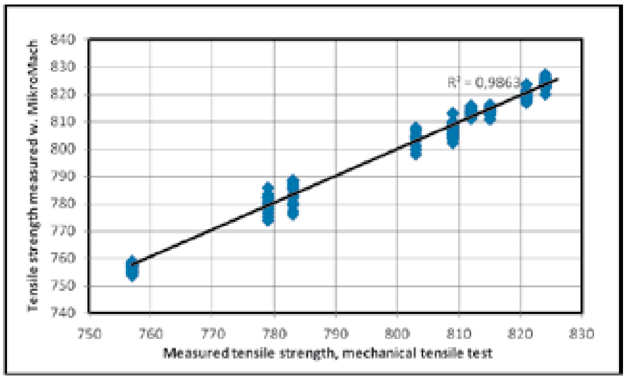

Fig. 7 - Repetition accuracy, tensile strength

Fig. 7 – Accuratezza della ripetizione, resistenza a trazione

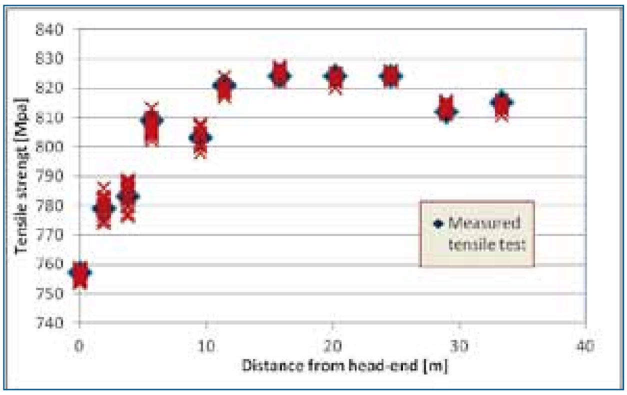

Fig. 8- Measured test samples head end EHS-steel strip

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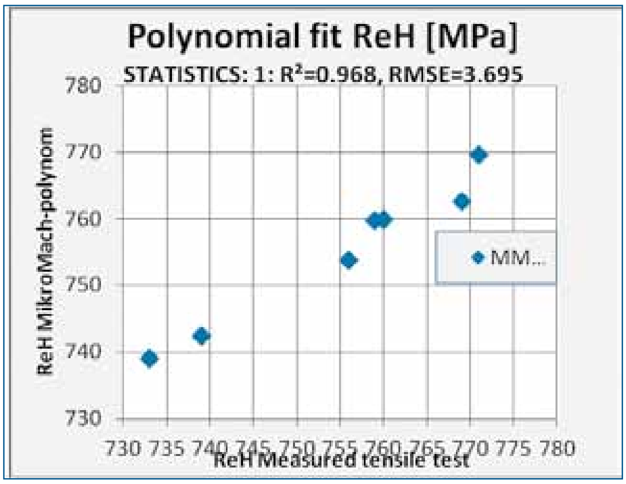

Fig. 9 - Polynomial fit, yield strength, ReH 3mm EHS-steel

Fig. 9 - Polynomial fit, resistenza allo snervamento, acciaio ReH 3mm EHS

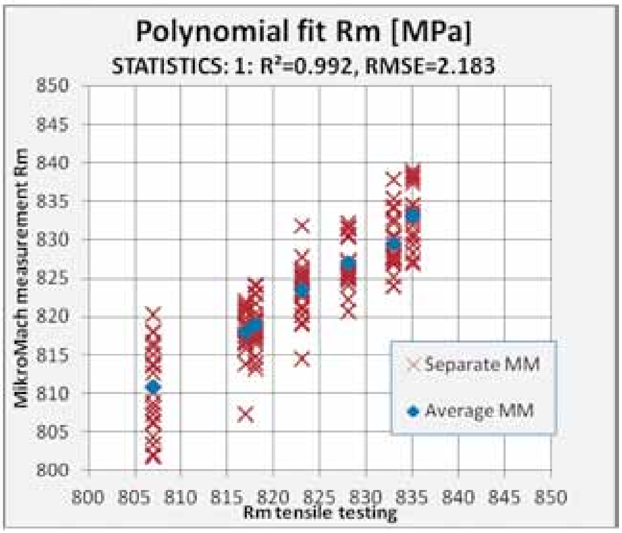

Fig. 10 - Polynomial fit tensile strength, Rm 3 mm EHS-steel

Fig. 10 - Polynomial fit, resistenza allo snervamento, acciaio ReH 3mm EHS

to see how big the variations would be in this type of measurement, this regarding other material variations that can influence these measurements e.g. residual stresses.
Calibration for yield strength and tensile strength
In this case we only had a few 10 mm test samples available which is not an ideal situation, fortunately the test samples were big, 100x200mms so it was possible to measure in different positions on the samples. The samples were measured with five measuring cycles on each. From these measurements a regression to tensile strength was made as calibration. We also had 3 mm test samples that were calibrated against bot tensile and yield strength.

10 MM EHS-STEEL

After calibration and regression/polynomial fitting of the magnetic properties to the measured yield strength we measured the samples to see how the distribution would be.

This is not the ideal situation, to verify the measurements on the same test pieces as the calibration has been made on. However, with rather big test pieces it was possible to measure on different positions. We wanted to see the spread of the measuring so new measurements were made. This meant that we made 15 new measurements on each of the 11 test pieces. Each measurement has ten measuring cycles that are averaged, and then the probe was lifted, replaced and next measurement with ten measuring cycles was made. This was repeated 15 times for each sample. The results from the "measured" tensile strength on the samples were then compared with the mechanical tensile tests. See Figure 7.
The tensile strength distribution of the MikroMach measuring is in the area of +/- 10MPa or less, this is to compare to the fact that tensile strength tests made in a testing machine show approximately the same distribution i.e. +/- 10 MPa. The result plotted against the tensile

testing results and the distance from the strip end gave the result in Figure 8.

3MM EHS-STEEL

The measurements made on the 3mm material tried to
As we can see we did not get the same good polynomial fit on the yield strength on 3 mm as we had on the tensile strength of 10 mm material, on the other hand, we all know that both yield and tensile strength testing has a certain distribution that usually is in the area of +/-10MPa.
When we continue to the result of the polynomial fit of the tensile strength of the 3mm EHS-steel Rm in Fig. 10 we can see that it gives a better fit. In total we can see that the measurements in all is lower or equal to +/- 10 MPa, in spite of the fact that we deliberately spread out the measuring points all over the test pieces. The stabile measurements are partly the result of introducing, as mentioned earlier, a better test jig.

Evaluation/summarising mechanical properties

These measurements and tests is not enough to be called a solid statistical base, but we still consider the measuring results as good. When studying results compared to measured tensile tests we can see that the distribution is less then +/- 10MPa that is close to the distribution of mechanical tensile testing results. Polynomial fit of the calibration curves for the 10 mm samples may be considered good also with R^2 = 0,968. The 3mm samples had a fit of R^2 = 0,992 that we think is as very good result. This is also for the averaged measurement that is the normal method of "measuring" with this instrument.
When we analyse what parameters we used in the polynomial fit we see that they are directly or indirectly coupled to Barkhausen Noise and Harmonic Analysis both parameters depending on the material strength/ hardness.

REFERENCES

[1] Bernd WOLTER, Gerd DOBMANN, Fraunhofer IZFP, Saarbrücken, Germany, Micromagnetic Testing for Rolled Steel, ECNDT 2006 – proceedings

Metodo di prova elettromagnetico non distruttivo per determinare le proprietà nell'acciaio

Parole chiave: Acciaio - Prove non distruttive - Proprietà meccaniche

Questo studio nel campo delle prove non distruttive e tecnologie di misurazione, dimostra che è possibile controllare e determinare le proprietà meccaniche e la microstruttura di un materiale utilizzando la tecnica elettromagnetica. L'obiettivo è quello di determinare in linea le proprietà del materiale quali la distribuzione delle sollecitazioni residue, le variazioni della resistenza alla trazione e della resistenza a fatica in un materiale.
In questo progetto si utilizzano le novità nel campo dell' ispezione dei materiali che prevedono la combinazione di metodi elettromagnetici con la modellazione statistica. Il progetto ha dimostrato che questi nuovi metodi non distruttivi sono in grado di determinare le proprietà meccaniche di un materiale o di un particolare della macchina. Si ritiene che questa tecnica di misurazione possa avere un ruolo chiaro nell'industria.