Expert-System - Electromagnetic Intrinsic Properties and Microstructure of Steels

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1. Introduction

Magnetic and electromagnetic testing methods are often used to check structure and mechanical properties as well as chemical composition of construction materials. These non-destructive methods are well suited to this task due to the strong relationship between electric and magnetic properties and structure (Fig. 1).

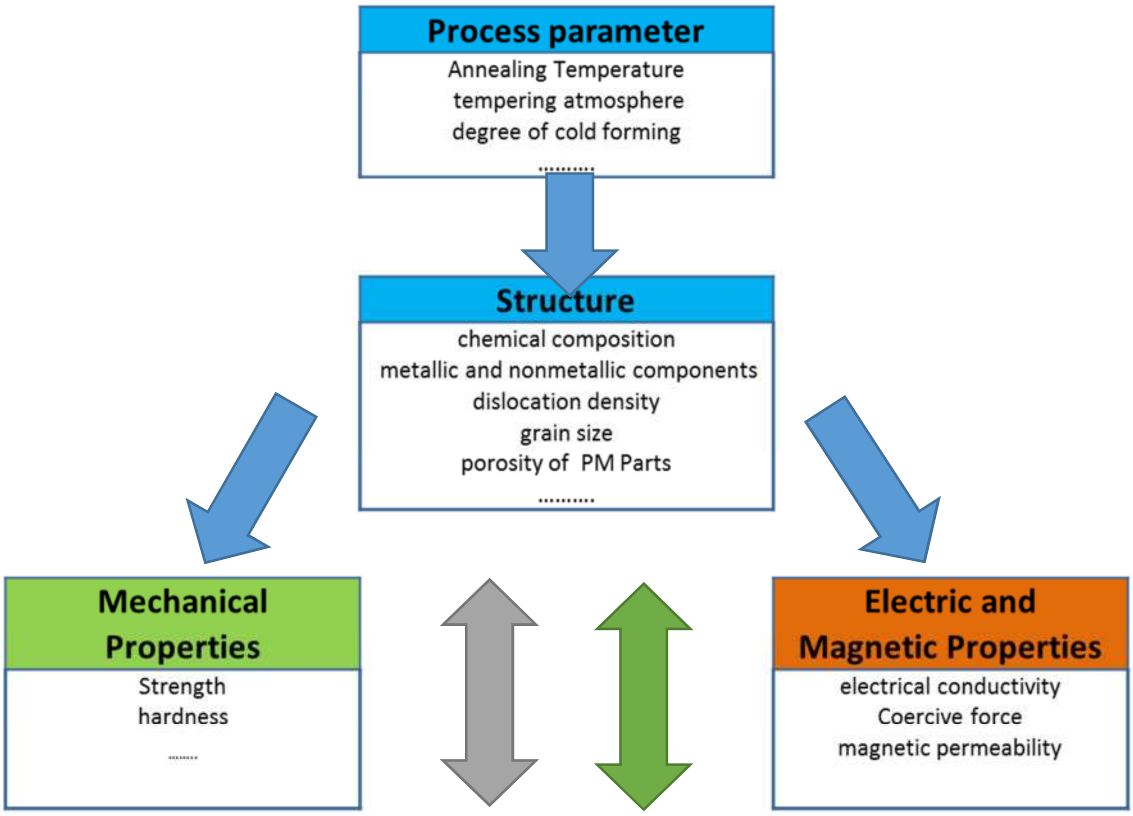


Fig.1 Scheme of Structure- property relationships

The analysis of structure-properties relationships allows drawing conclusions for the applicability of these NDT methods for specific testing tasks. Fig. 2 shows 3 different types of structure-property relationships.

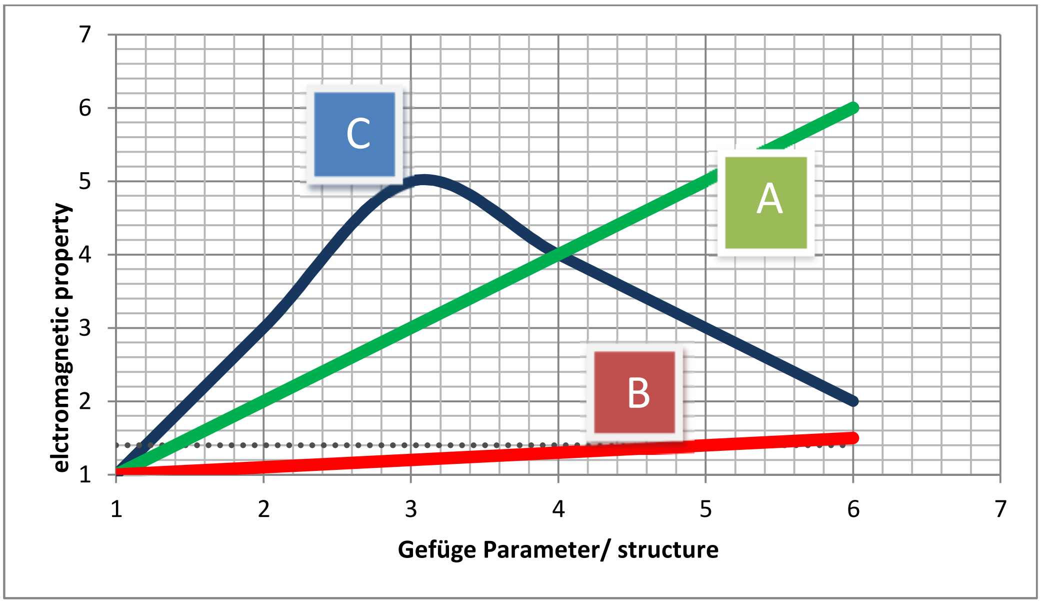


Fig. 2 Types of relationships between structure and electromagnetic properties

The linear function A shows the ideal case for NDT. In contrast, the function B represents a weak dependence vanishing into the signal noise. Curve C shows a maximum. This means that you can find a definite relation between signal and structure only in a limited range of values below or beyond the maximum.

Unfortunately in case of construction materials these structure-property-relationships are not known in a sufficient way or known only in a qualitative manner. There are some detailed results for special materials but there is a lack of overviews on this topic. Thus it is difficult for engineers who are not specialist in material science or in solid state physics to decide whether it is possible to check the structure or related properties by using an electromagnetic NDT method. The expert-system allows the calculation of electrical and magnetic intrinsic properties of annealed steels versus structure by using reliably proved approximations.

2. Structure –Property Relationships

The relationships between specific electric resistance ϱ, coercive force H_c, initial and maximum magnetic permeability μ_i or μ_m and structure parameters, respectively used in the expert system are mainly related from works of M.Seidel /1/, /2/, /3/, I. Altpeter /4/ , B.G. Livshitz /5/ and Kneller /6 /. Furthermore single values of electromagnetic properties of steels measured by other authors are used, too. In the user documentation users will find more detailed information on bibliography.

The structure parameters considered in the expert system range from content of carbon (i.e. volume fraction of pearlite) and content of alloying elements, grain size, distances of lathes in pearlite to volume fraction of porosity. Fig.3 shows the different level of knowledge of the special relationships.

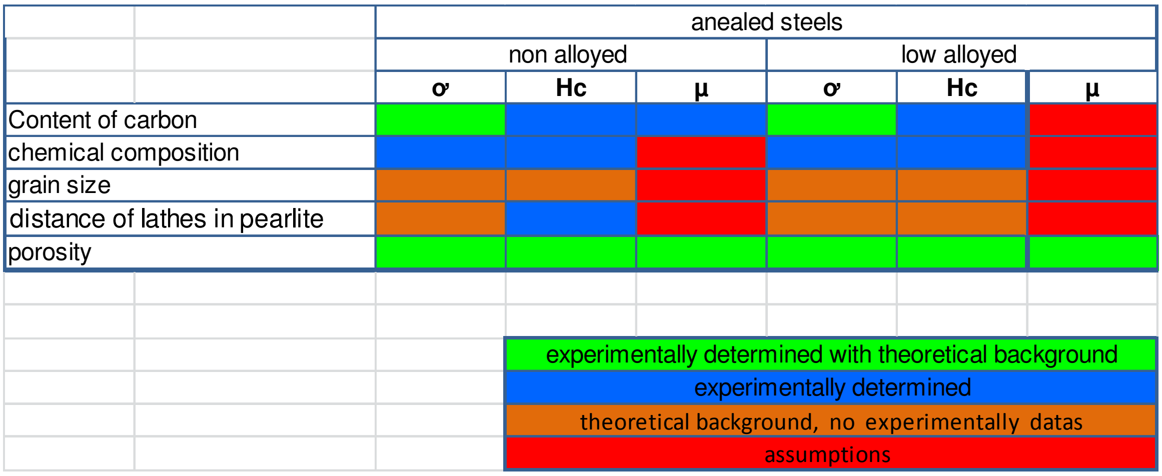


Fig.3 Different level of knowledge of the property-structure relationships used in the expert-system

The highest level got relationships which base on theoretically founded dependencies verified by measurements. In Fig.3 these ones are marked with green colour. The next level of knowledge concerns relationships based on experimentally found dependencies (marked blue). Another kind of relationships (marked orange) is drawn from theoretically found dependencies fitted to measured values of electromagnetic properties. This type of relationships is used in case of grain size and distance of lathes in pearlite. The lowest level of knowledge (marked dark read) bases on the simple assumption of reciprocal proportionality between coercive force and permeability $\mu = 1/H_c$.

3. Modular concept

The program is based on a modular concept. The current version consists of 7 modules (Tab. 1).

Nr.	Module	Field of application
1	Single steel	Calculation of ρ, H_c, μ_m and μ_i of a single steel.
2	Carbon content	Calculation of ρ, H_c, μ_m and μ_i of steels in relation to the carbon content of steels.
3	Grain size	Calculation of ρ, H_c, μ_m and μ_i of steels in relation to the grain size of steels.
4	Distance of lathes in Pearlite	Calculation of ρ, H_c, μ_m and μ_i of steels in relation to the distance of lathes in pearlite
5	Decarburization	Calculation ρ, H_c, μ_m and μ_i of steels of a cylindrical steel sample versus distance to sample surface.
6	Soft spotting	Calculation ρ, H_c, μ_m and μ_i on the surface of a steel sample along x-axis
7	Porosity	Calculation of ρ, H_c, μ_m and μ_i of steels in relation to the volume fraction of porosity.

Tab. 1 Modular concept of the expert-system (version 01/2014)

At each module electromagnetic properties of plain carbon steels and of low alloyed steels may be calculated in an approximate way. The carbon content has to be =< 1.5 Weight-%. The limiting values of alloying elements are consigned in the program. Users can choose between normalized or soft annealed steels and between conventional steels (i.e. produced by melting technologies) or PM steels.

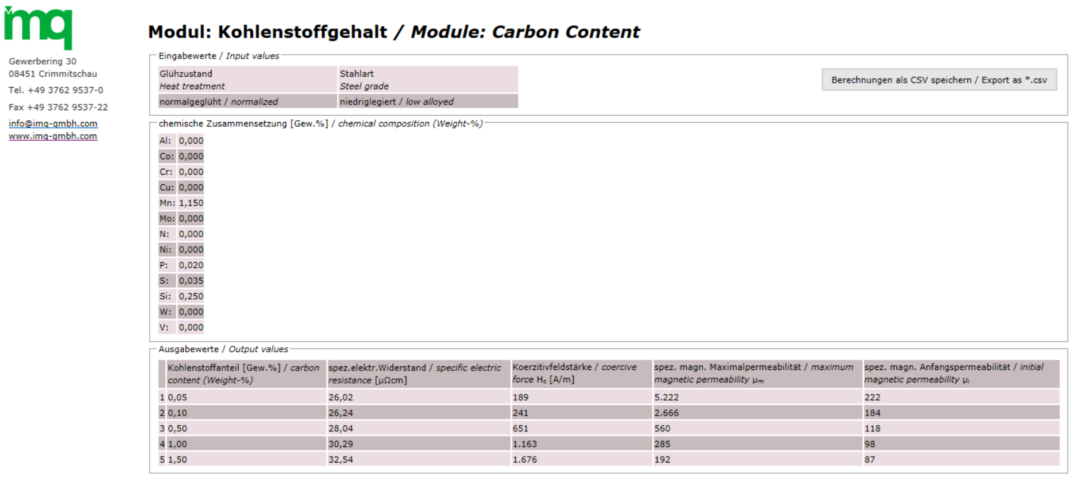
The calculated values of ρ, H_c, μ_m and μ_i are presented together with the input data in a table and as diagrams (only module 2 to 7). Furthermore the user may export the data in an xls-scheme to work with them.

Users find the access to the expert-system on the imq homepage following the link www.imq-gmbh.com.

4. Examples of application

4.1. Carbon content of low alloyed steels

Fig.4 shows results of the calculations carried out for a low alloyed steel with a chemical composition near to steel grade 16MnCr5 but with carbon content between 0.1 to 1.5 %.



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Modul: Kohlenstoffgehalt / *Module: Carbon Content*

Eingabewerte / *Input values*

Glühzustand *Heat treatment*	Stahlart *Steel grade*
normalgeglüht / *normalized*	niedriglegiert / *low alloyed*

Berechnungen als CSV speichern / Export as *.csv

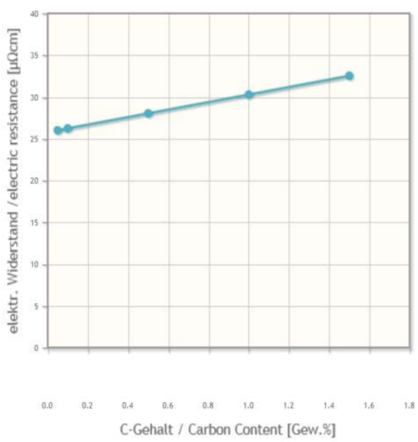
chemische Zusammensetzung [Gew.%] / *chemical composition (Weight-%)*

Al: 0,000
Co: 0,000
Cr: 0,000
Cu: 0,000
Mn: 1,150
Mo: 0,000
N: 0,000
Ni: 0,000
P: 0,020
S: 0,035
Si: 0,250
W: 0,000
V: 0,000

Ausgabewerte / *Output values*

	Kohlenstoffanteil [Gew.%] / *carbon content (Weight-%)*	spez.elektr.Widerstand / *specific electric resistance* [μΩcm]	Koerzitivfeldstärke / *coercive force* H_c [A/m]	spez. magn. Maximalpermeabilität / *maximum magnetic permeability* μ_m	spez. magn. Anfangspermeabilität / *initial magnetic permeability* μ_i
1	0,05	26,02	189	5.222	222
2	0,10	26,24	241	2.666	184
3	0,50	28,04	651	560	118
4	1,00	30,29	1.163	285	98
5	1,50	32,54	1.676	192	87

a)



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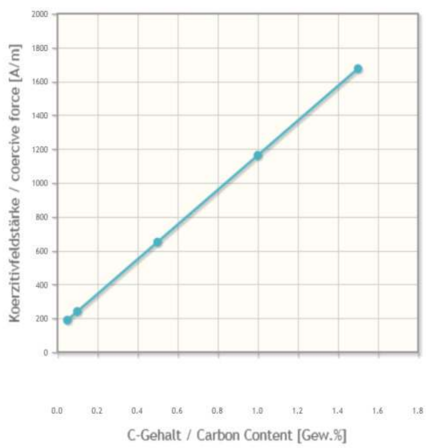

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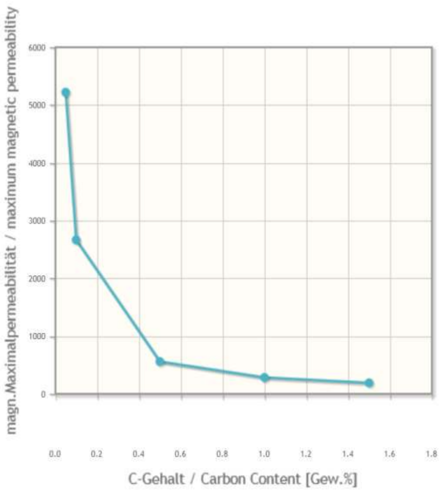

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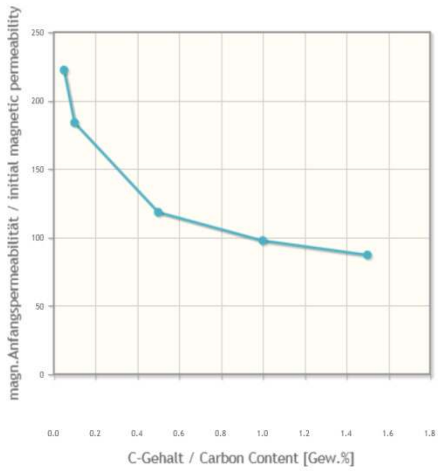

e)

Fig. 4 Calculated dependence of ρ, H_c, μ_m and μ_i. of a normalized low alloyed steel from carbon content

a) Input data and numerical results

b) to e) properties versus carbon content

It is obvious that the electrical resistance as well as the coercive force show a linear dependence. In contrast the magnetic permeability decreases exponentially with increasing carbon content. If the calculation was not done for a normalized steel but for a soft annealed steel you would get the same type of relationships but with a weaker sloop, since globular carbides in steel do not effect as strong on ρ, H_c, μ_m and μ_i. as the carbides in a pearlite structure do.

4.2. Grain size of plain carbon steels

Fig.5 shows results of the calculations carried out for plain carbon steel with low carbon content of 0.05%. The structure of this steel is mainly formed by ferrite grains. The grain size was chosen between 50 µm (i.e. coarse grain) over 10 µm (common grain size) down to extremely fine grain (0.1 µm).

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Modul: Korngröße / *Module: Grain size*

Eingabewerte / *Input values*

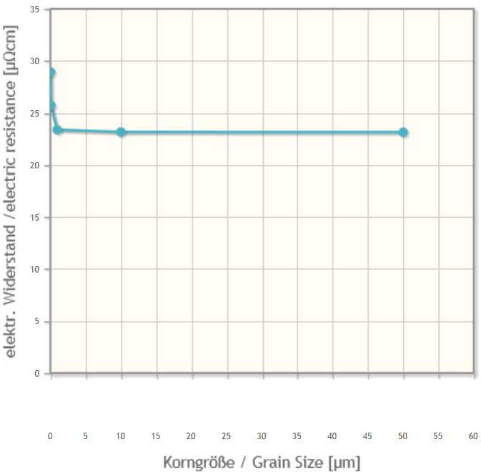
Kohlenstoffanteil [Gew.%] *Carbon Content (Weight-%)*	Glühzustand *Heat treatment*	Stahlart *Steel grade*
0,05	weichgeglüht / *soft annealed*	unlegiert / *plain carbon*

Berechnungen als CSV speichern / Export as *.csv

Ausgabewerte / *Output values*

Korngröße / *Grain Size* [µm]	spez.elektr.Widerstand / *specific electric resistance* [µΩcm]	Koerzitivfeldstärke / *coercive force* H_c [A/m]	spez. magn. Maximalpermeabilität / *maximum magnetic permeability* μ_m	spez. magn. Anfangspermeabilität / *initial magnetic permeability* μ_i
50	23,15	129	7.660	326
10	23,17	129	7.654	326
1	23,38	130	7.585	323
0.1	25,72	143	6.895	294
0.05	28,94	161	6.129	261

a)



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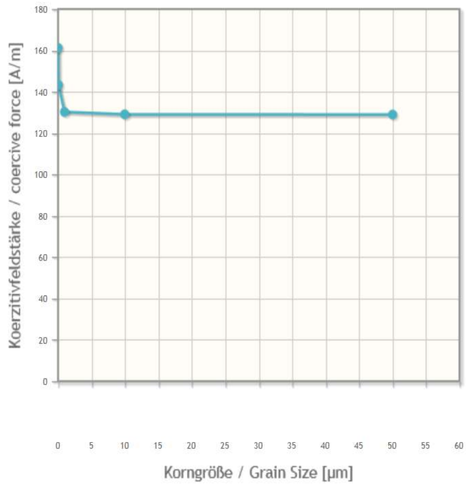

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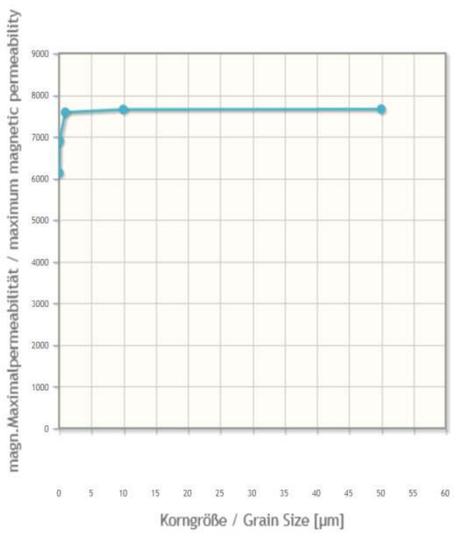

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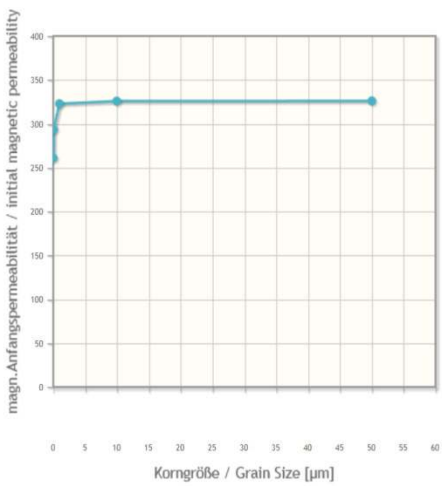

e)

Fig.5 Calculated dependence of ρ, H_c, μ_m and μ_i. of soft annealed steel (carbon content = 0.05%) from ferrite grain size b

a) Input data and numerical results

b) to e) properties versus grain size

One can see that grain size acts on electromagnetic properties only in case of an extremely fine state of grains. In case of resistance this is due to the fact that the mean free path of electrons ($l_e \approx$ 0.1 to 0.01 µm) is much smaller than grain size of annealed construction steels. Coercive force shows also a reciprocal relationship to grain size. If grains are very small, one ferrite grain consists of one magnetic domain. These materials show a rather high coercive force and low magnetic permeability respectively. In case of iron such behavior would be observed for very small grain sizes below 0.01 µm.

This means that changing ferrite grain size has only a weak influence on electromagnetic properties of annealed construction steels. On the other hand it means that it would not be possible to check the grain size using electromagnetic NDT methods.

4.3. Decarburization of a cylindrical work piece

Fig. 6 shows the calculated electromagnetic properties of a cylindrical steel sample with a decarburized surface layer versus distance to sample surface.

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Modul: Randentkohlung / *Module: Decarburization of sample surface*

Eingabewerte / *Input values*

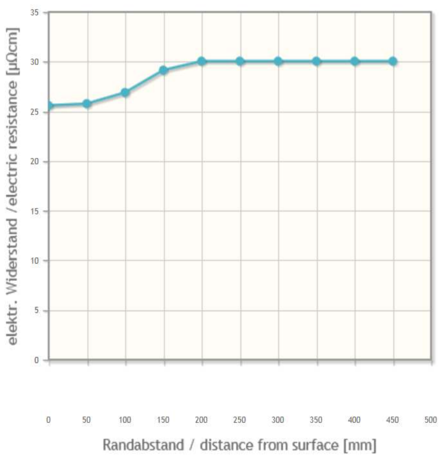
Volumenanteil Poren [Vol.%] *Volume Fraction of Porosity (Vol-%)*	Glühzustand *Heat treatment*	Stahlart *Steel grade*
10	normalgeglüht / *normalized*	unlegiert / *plain carbon*

Berechnungen als CSV speichern / Export as *.csv

Ausgabewerte / *Output values*

Randabstand [mm]	Kohlenstoffanteil [Gew.%] / *carbon content (Weight-%)*	spez.elektr.Widerstand / *specific electric resistance* [μΩcm]	Koerzitivfeldstärke / *coercive force* H_c [A/m]	spez. magn. Maximalpermeabilität / *maximum magnetic permeability* μ_m	spez. magn. Anfangspermeabilität / *initial magnetic permeability* μ_i
0	0,01%	25,60	119	28.206	392
0.5	0,05%	25,78	153	5.813	247
1	0,30%	26,91	368	1.002	149
1.5	0,80%	29,16	798	383	112
2	1,00%	30,06	970	307	105
2.5	1,00%	30,06	970	307	105
3	1,00%	30,06	970	307	105
3.5	1,00%	30,06	970	307	105
4	1,00%	30,06	970	307	105
4.5	1,00%	30,06	970	307	105

a)



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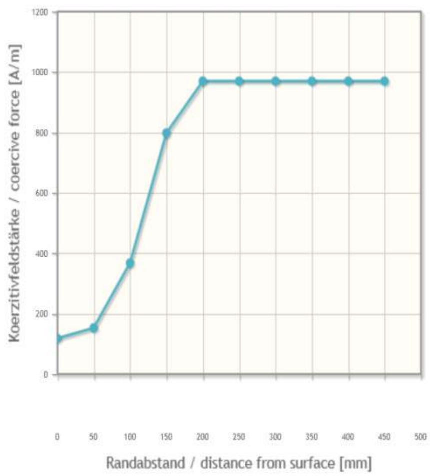

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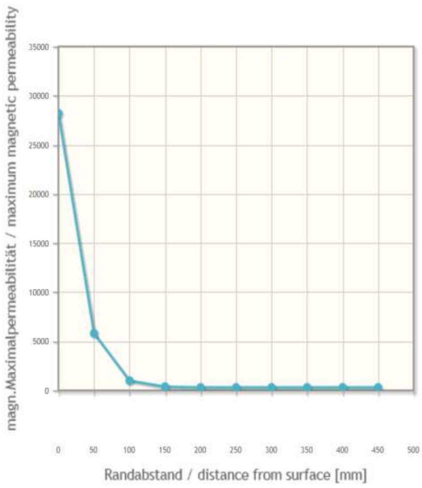

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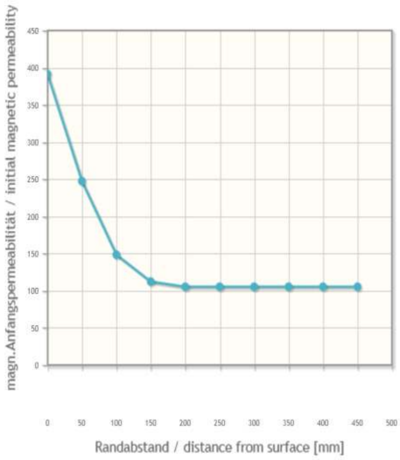

e)

Fig.6 Calculated dependence of ρ, H_c, μ_m and μ_i. of a normalized cylindrical work piece with a decarburized surface layer

a) Input data and numerical results

b) . e) propertiesversus diameter

It is obvious that decarburization acts on magnetic properties much stronger than on electrical resistance. For application of electromagnetic NDT methods for checking decarburization this fact should be taken into account: Lower testing frequencies are better suited than higher ones since they are stronger affected by magnetic permeability.

5. Summary

Magnetic and electromagnetic testing methods are well suited for structure testing of construction materials due to the strong relationship between electric and magnetic properties and structure. The analysis of structure–properties relationship allows drawing conclusions for the applicability of these NDT methods for specific testing tasks.

The presented expert-system allows in an approximate way the calculation of relationships between electrical resistance *ρ*, coercive force H_c and magnetic permeability μ_m *and* μ_i and structure of annealed construction steals.

Examples of relationships using the expert-system are presented. The calculated relationships between electromagnetic properties and carbon content show only a linear behaviour in case of ρ and H_c. In contrast, the magnetic permeability depends on carbon content in a nonlinear form. The effect of grain size of ferrite on electromagnetic properties is in practice negligible. The calculated electromagnetic properties of a normalized cylindrical work piece with a decarburized surface layer are presented, too. The dependencies versus work piece diameter show the expected behaviour but express that magnetic properties change stronger than electric resistance does.

The microstructure-properties relationships underlying the expert-system are based on current knowledge. Newer knowledge can lead to changes of the deposited structure-characteristics-relationships. The authors strive to consider the newly discovered results in the expert system. However, it cannot be guaranteed that this is always the case. The authors can therefore not provide any guarantee for calculated values and dependencies. Their plausibility is to be checked and judged by the users themselves.

All colleagues who carried out measurements of electromagnetic properties of construction steels are invited to share their results with the authors. These results are required to verify the calculated relationships or to fit them to newly measured values. Furthermore these results may be used to create new modules.

Currently a new module is in preparation: It concerns the dependence between degree of cold forming and electromagnetic properties. The authors also intend to realize a further expert system for hardened steels.

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