Magnetic properties of stainless steels: applications, opportunities and new developments

Presenter:
Dr. Denis Fofanov  
Deutsche Edelstahlwerke GmbH  
2001 Master degree in St. Petersburg State Polytechnical University, Russia, „Physic of metals and alloys”  
2006 PhD in materials science, University of Hamburg  
2006 "Research and Development of stainless steels", Deutsche Edelstahlwerke GmbH

Co-author:
Dr.-Ing. Sascha Riedner  
Deutsche Edelstahlwerke GmbH  
2004 Engineer degree in mechanical engineering of Ruhr-Universität Bochum  
2009 "Research and Development of stainless steels", Deutsche Edelstahlwerke GmbH  
2010 PhD in materials technology of Ruhr-Universität Bochum
1. ABSTRACT

The most rapid area of growth in the modern technique is the development of electromagnetic systems. In many cases stainless steels are irreplaceable in the production of such systems due to their corrosion resistance and mechanical stability. In some instances the electronic components are placed in a corrosion resistant housing produced from stainless steel sheet or machined bar, whilst in others, the stainless steel forms an integral part of the electrical system, e.g. solenoids.

As a result, many questions being raised about the magnetic properties of these steel grades. In some applications, for example, it has been noted that the magnetic properties of the stainless steel housings adversely affect the functioning of the electronic equipment. The other systems, like electromagnetic valves, on the other hand, can work only if their working part is ferromagnetic.

This prompted a study to determine the magnetic responses of the various grades of steel within the branches of the stainless steel family (austenitic, martensitic, ferritic and ferritic-austenitic steels). In addition to the determination of the magnetic properties of these grades in the as-delivered condition, supplementary testing has been performed to show the effect of chemical composition, cold deformation and thermal processing on their magnetic properties.

For investigated steels, their mechanical properties, corrosion resistance, measured magnetic properties together with the factors which affect them as well as actual and possible electromagnetic applications are presented. Primarily graphical illustration allows easy understanding and serves as a quick reference tool to developers by allowing them to obtain an estimate of the magnetic properties, even after some processing and production steps.

Summarized:

Austenitic stainless steels (1.4301, 1.4305, 1.4307, 1.4404 and 1.4435) are nonmagnetic. They have to be applied, when any magnetic interaction between a steel component and a system must be eliminated. The small magnetization can be caused by the presence of deformation martensite or ferrite. The possibilities to estimate and eliminate the magnetization were investigated.

Ferritic stainless steels (1.4003, 1.4511 and 1.4105) are soft-magnetic (high permeability and polarisation and low coercivity). They can be used for induction or shielding devices. Their ferromagnetic properties can be optimized through a changing of the chemical compositions and/or thermal processing.

Martensitic stainless steels (1.4005, 1.4104, 1.4021, 1.4034, 1.4057 and 1.4044) are hard-magnetic (lower permeability and polarisation and much higher coercivity than that of ferritic steels). They can be used for semi-magnet applications or when their high mechanical strength and hardness are important. Their magnetic properties can be optimized through a changing of chemical compositions and/or thermal treatment either in the hard- or in soft-magnetic direction.

Duplex stainless steels (1.4362 and 1.4462) have the worst ferromagnetic properties, somewhere between austenitic and ferritic steels but the best corrosion resistance, higher toughness than ferritic or martensitic steels and higher strength
than austenitic ones. They can be used when their high corrosion resistance or mechanical properties are relevant.

2. INTRODUCTION

Recently our everyday life becomes more and more “electrified” by the use of electronic gadgets. Computers, notebooks, cell phones and subnotebooks are well known and since years extensively applied whereas smart phones, navigation systems, parking sensors, big flat screen TV’s and induction hobs are only a few examples of electrical items just becoming widely spread.

Comparatively hidden to the average consumer electromagnetic devices are also being developed and spread very fast. They are intended to replace components of or complete mechanical, pneumatic or hydraulic systems in mechanical engineering and soon in the automotive industry as well. To the latter electromagnetic valves, gears or fuel injectors are popular examples. Here the material has to possess magnetically soft characteristics, whereas for permanent magnetic applications magnetically hard characteristics are needed. Other applications do not allow a magnetic interaction between the electromagnetic device and the material used. Examples are roller bearings in a magnetic resonance tomography, retaining rings on generator shafts or drill collars for oil and gas exploration. The carriers for the electromagnetics of electron synchrotron accelerators like in Hamburg, Berlin, Karlsruhe or the most famous CERN in Geneva as well as these of experimental nuclear fusion power plants which are under construction in Greifswald and Cadarache are more exotic applications for so called “nonmagnetic” steels.

2.1. FUNDAMENTAL TERMS OF MAGNETIC PROPERTIES

SEW 390 (Stahl Eisen Werkstoffblatt) names the relative magnetic permeability $\mu_{\text{rel}} \leq 1.01$ to define a non-magnetisable steel. The relative magnetic permeability is a dimensionless number with a value of 1 in vacuum as it is the magnetic permeability related to the magnetic permeability in vacuum $\mu_0$ ($\mu_0 = 4 \pi \cdot 10^{-7} \text{[Vs/Am]}$).

\[
\mu_{\text{rel}} = \frac{\mu}{\mu_0} \quad \text{(eq. 1)}
\]

The magnetic permeability $\mu$ is the ratio of the magnetic induction $B$ [T] and the magnetic field strength $H$ [A/m] taken from the magnetic hysteresis curve (Fig. 1).

\[
\mu = \frac{B}{H} \quad \text{(eq. 2)}
\]

Further synonyms for $H$ are “magnetic field intensity”, “magnetic field” and “magnetizing field”. For $B$ “magnetic field” and “magnetic flux density” are used as well. Often instead of the induction $B$ the magnetisation $I$ [T] is measured. These values are connected by:

\[
B = H + 4 \pi \cdot I \quad \text{.} \quad \text{(eq. 3)}
\]

The magnetisation $I$ is proportional to the magnetic field strength, where $\chi$ is the magnetic susceptibility of the volume. Its value is 0 in vacuum.

\[
I = \chi \cdot H \quad \text{(eq. 4)}
\]
Connecting the equations 2 to 4, results in an expression relating $\mu$ and $\chi$ to each other.

$$\mu = 1 + 4 \pi \cdot \chi \quad \text{(eq. 5)}$$

The magnetic susceptibility is connected to the relative permeability by the following equation.

$$\mu_{\text{rel}} = 1 + \chi \quad \text{(eq. 6)}$$

Usually the relative permeability $\mu_{\text{rel}}$ is measured with a magnetic field strength of about 100 A/cm. But the dependence of permeability from field strength is only small in this area. Experiments show that it is usually unimportant if the measurement is made with 50 or 500 A/cm [1].

Commonly magnetic properties of a ferromagnetic material are described by the hysteresis loop, where the measured induction $B$ is entered above the given magnetic field strength $H$. Several values are taken from this curve (Fig. 1). Initially it starts in the zero point of the scales where the material is not magnetized. An increasing magnetic field strength applies non-linearly a magnetic induction to the material up to a point of saturation, where a further increased magnetic field strength does not raise the magnetic induction anymore. The electromagnetic saturation induction $B_s$ depends on structure and temperature. Following the virgin curve, which forms with the very first magnetisation process, reversible small shifts of Bloch walls appear (1). After that, irreversible big movements of Bloch walls and reversible switch processes of magnetic dipoles occur (2). Further rising of field strength leads to irreversible dipole switch processes (3) and initiates saturation (4) (Fig. 1). The slope of the tangent of the initial curve subtending the zero point of the scales was defined to mark the maximum permeability $\mu_{\text{max}}$ of the material. When the magnetic field strength is reduced again the induction does not follow the virgin curve but creates the hysteresis. Is the magnetic field strength lowered to zero again there is still induction left in the material, which means that it remains magnetic or rather is magnetized. This induction is called magnetic remanence $B_r$. A negative magnetic field strength is necessary to remove the induction. When the magnetic induction is zero again the applied magnetic strength marks the coercive field strength $H_c$. Further lowering of the magnetic field strength to the negative saturation point and increasing it again to the positive saturation point closes the hysteresis loop (Fig. 1).

The magnetic induction can be seen as the magnitude of the magnetic force which is applied to other ferromagnetic materials within the magnetic field. Simplified the
higher the magnetic induction at a given field strength is, the bigger is the weight which can be lifted by an electromagnetic crane, working with this material for example. Thus the higher the magnetic saturation is, the higher is the force that can be applied by a defined magnetic field strength. Similarly the higher the remanence is, the more powerful is the material as a permanent magnet. If the coercive field strength is small, only a low magnetic field strength is necessary to induce and remove the magnetic induction whereas a high coercitivity goes along with a high field strength needed to remove the remanence. This is for example important for magnetic data saving, like tapes or credit cards. Information on material with low coercitivity can be erased easily with weak solenoids whereas strong solenoids are necessary to erase data from the high coercitivity materials.

Classically steels are divided into soft magnetic, hard magnetic and nonmagnetic (Fig. 2). If steels are called “nonmagnetic” it is only true in technical terms, which means that a strong permanent solenoid does not noticeably gravitate to the steel. In physical terms these steels are not non magnetisable, nonmagnetic or even paramagnetic like aluminium or titanium. They are ferromagnetic even though very weak [2]. Their hysteresis is very flat with negligible permeability and remanence, whereas the coercitivity can reach as high as usually for permanent magnets [1].

Soft magnetic steels are easy to magnetize. Usually they are supposed to amplify and transmit magnetic flux with minimized losses. A high permeability, high magnetic saturation and small coercitivity are required for soft magnetic applications like electromagnetic valves or d.c. relays. A low remanence hinders bonding after releasing, on the other hand a high remanence means a big breakaway torque because of the implemented steep hysteresis loop. The hysteresis losses are kept small in soft magnetic materials. Their coercitivity $H_c$ is below ca. 400 A/m (the criterion to distinguish them to hard magnetic materials is usually 1000 A/m).

Hard magnetic materials are supposed to keep a state of magnetization as high and long as possible. They are identified by high coercitivity with lowest values of about 3000 - 5000 A/m and high remanence. Both make them feasible for such applications as permanent magnets. Important as well is the dense of energy $\mathbf{BH}$, which is magnetic energy related to the volume of the solenoid.

Among stainless steels in general, austenites are referred to as nonmagnetic, ferrites are named soft magnetic and martensites are described as hard magnetic. This article presents the results of the magnetic properties investigation of selected typical stainless steels taken from running production. Included are austenitic, ferritic, martensitic, maraging and duplex stainless steels.
3. EXPERIMENTAL

Investigated were the magnetic properties of conventional stainless steels. The samples were taken from the core of standard production material. The initial diameters of the investigated long product stainless steel were between 20 and 80 mm. The investigated grades are listed in Table 1.

<table>
<thead>
<tr>
<th>Grade</th>
<th>DIN-Name</th>
<th>Structure</th>
<th>Main alloying elements in Mass.-%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>C</td>
</tr>
<tr>
<td>1.4301</td>
<td>X5CrNi 18-10</td>
<td>austenitic</td>
<td>&lt;0.07</td>
</tr>
<tr>
<td>1.4307</td>
<td>X2CrNi 18-9</td>
<td>austenitic</td>
<td>&lt;0.03</td>
</tr>
<tr>
<td>1.4305</td>
<td>X8CrNiS 18-9</td>
<td>austenitic</td>
<td>&lt;0.10</td>
</tr>
<tr>
<td>1.4404</td>
<td>X2CrNiMo 17-12-2</td>
<td>austenitic</td>
<td>&lt;0.03</td>
</tr>
<tr>
<td>1.4435</td>
<td>X2CrNiMo 18-14-3</td>
<td>austenitic</td>
<td>&lt;0.03</td>
</tr>
<tr>
<td>1.4003</td>
<td>X2CrNi12</td>
<td>ferritic</td>
<td>&lt;0.03</td>
</tr>
<tr>
<td>1.4511</td>
<td>X3CrNb17</td>
<td>ferritic</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>1.4105</td>
<td>X6CrMoS17</td>
<td>ferritic</td>
<td>&lt;0.08</td>
</tr>
<tr>
<td>1.4005</td>
<td>X12CrS13</td>
<td>martensit.</td>
<td>0.08-0.15</td>
</tr>
<tr>
<td>1.4006</td>
<td>X12Cr13</td>
<td>martensit.</td>
<td>0.08-0.15</td>
</tr>
<tr>
<td>1.4104</td>
<td>X14CrMoS17</td>
<td>martensit.</td>
<td>0.10-0.17</td>
</tr>
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<td>martensit.</td>
<td>0.16-0.25</td>
</tr>
<tr>
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<td>X46Cr13</td>
<td>martensit.</td>
<td>0.43-0.50</td>
</tr>
<tr>
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<td>X17CrNi16-2</td>
<td>martensit.</td>
<td>0.12-0.22</td>
</tr>
<tr>
<td>1.4044</td>
<td>X22CrNi17-2</td>
<td>martensit.</td>
<td>0.12-0.22</td>
</tr>
<tr>
<td>1.4418</td>
<td>X4CrNiMo16-5-1</td>
<td>(Ni-) mart.</td>
<td>&lt;0.06</td>
</tr>
<tr>
<td>1.4542</td>
<td>X5CrNiCuNb16-4</td>
<td>maraging (mart.)</td>
<td>&lt;0.07</td>
</tr>
<tr>
<td>1.4362</td>
<td>X2CrNiN23-4</td>
<td>duplex</td>
<td>&lt;0.03</td>
</tr>
<tr>
<td>1.4462</td>
<td>X2CrNiMoN22-5-3</td>
<td>duplex</td>
<td>&lt;0.03</td>
</tr>
</tbody>
</table>

Table 1: Rough alloying ranges of investigated stainless steel grades

A Magnetoscop 1068 from Institut Dr. Förster was used to measure the relative permeability of the austenitic stainless steels. The selected austenitic grades are 1.4301, 1.4305, 1.4307, 1.4404 and 1.4435. The inspected surface of austenitic samples was in the bar core, rectangular to the hot rolling direction, polished, cleaned and dried. A minimum of three measurements each on three specimens per batch were used to determine the average relative permeability.

The magnetisation curves of ferritic, martensitic, maraging and duplex stainless steels were measured with a Remagraph C500 from Dr. Steingroever GmbH. The instrument with fixed exploring inductors measures the magnetic polarisation \(J\) [T] depending on the magnetic field strength \(H\) [A/m]. The magnetic polarisation is connected to the magnetic induction by equation 7.

\[
J = B \cdot \mu_0 \cdot H \quad \text{(eq. 7)}
\]

The specimens (\(\varnothing\) 10 mm, \(L = 100\) mm) were taken from the core of standard production long product stainless steel with diameters from 20 to 80 mm. After an evaluation of the stability and reproducibility of the results, for the determination of the hysteresis loop of the magnetisable steels (ferrite, martensite, maraging, duplex) two samples per batch were measured once each. The investigated ferritic stainless steels were 1.4003, 1.4511 and 1.4105. The martensitic stainless steel grades
1.4005, 1.4006, 1.4104, 1.4021, 1.4034, 1.4044 and 1.4057 were supplemented by the soft martensitic grade 1.4418 and the maraging grade 1.4542. Two duplex stainless steels, 1.4362 and 1.4462, were also chosen for investigations.

4. RESULTS AND DISCUSSION

The structure dependence of the magnetic properties of steels makes it feasible to classify the results by the microstructure of the stainless steels investigated. Beginning with austenitic stainless steels the following ferritic, martensitic and duplex stainless steels will be presented. Stainless maraging as well as Ni-martensitic steels are sub items of martensitic stainless steel.

4.1 AUSTENITIC STAINLESS STEELS (ASS)

The austenitic face-centred cubic lattice (fcc) of steel is, in technical terms, nonmagnetisable. The value to measure the magnetization of ASS is $\mu_{\text{rel}}$ which should be below 1.01 for nonmagnetisable materials. Sometimes in fact some magnetization can be observed. Two reasons are known for that. One reason is $\delta$-ferrite remaining after solidification, the other is strain induced $\alpha$-martensite. Both are phases with ferromagnetic character.

For many ASS the chemical composition is balanced in such a way, that they embody some $\delta$-ferrite at higher temperatures. Weldability as well as castability for curved type continuous casting is improved by small amounts of $\delta$-ferrite. Main elements to control the content of $\delta$-ferrite in ASS are Cr, Mo, Ni and N or (C+N) respectively. The first two elements increase the susceptibility to $\delta$-ferrite whereas the others mentioned suppress it. Even if the temperature range of the $\delta$-ferrite phase field is high, for example ca. 1300-1400°C derived by ThermoCalc for 1.4404, caused by segregation or fast cooling, small amounts of it remain in the ASS down to room temperature. Because of that $\mu_{\text{rel}} \leq 1.1$ is a common value that can be achieved after solution annealing (Fig. 3, Tab. 2). A ferrite number (FN) can be used to rank the sensitivity for retaining $\delta$-ferrite of ASS by their chemical analysis in mass.-% (eq. 8).

$$FN = 3.34 \cdot (1.5\text{Si} + \text{Cr} + \text{Mo} + 2\text{Ti} + 0.5\text{Nb}) - 2.46 \cdot \{30 \cdot (\text{C+N}) + 0.5 \cdot (\text{Mn} + \text{Cu} + \text{Co}) + \text{Ni}\} - 28.6$$

(eq. 8)

An increasing FN is connected to higher amounts of $\delta$-ferrite which causes higher permeability (Fig. 3, Tab. 2). Solution annealing (SA, 1050°C / 2 h / H2O) can lower the content of magnetizing phases but often $\delta$-ferrite is not removed completely. In Fig. 3 the difference between 1.4301 and 1.4307 for example results from a higher Ni content of the investigated 1.4301 melts. Another heat treatment to remove the magnetisation induced by $\delta$-ferrite is an annealing between 700 and 800°C. At this temperature $\delta$-ferrite is transmuted to the
nonmagnetic σ-phase. As the presence of σ-phase causes embrittlement and reduced corrosion resistance this treatment should be avoided. Additional to the "natural" δ-ferrite, a wrong heat treatment can induce α-ferrite to an ASS. Annealing at 500-600° C can cause this transformation in some ASS if the holding time exceeds 30-60 min.

The pitting resistant equivalent number (PREN, eq. 9) gives a hint to the alloys resistance against pitting corrosion. The PREN-numbers vary within the specifications depending on customers requirements. As can be seen comparing 1.4301 and 1.4435 the PREN is not markedly connected to the relative permeability of ASS (Tab. 2).

\[
\text{PREN} = \text{Cr} + 3.3\cdot\text{Mo} + 16\cdot\text{N} \quad \text{(eq. 9)}
\]

The second magnetisable phase, strain induced α-martensite, appears after cold deformation, usually below 100° C. Nohara [3] developed a formula using the chemical composition in mass.-% to estimate the temperature \(M_{d30}\) [°C], where 50 vol.-% strain induced martensite occur after 30 % true deformation \((\varphi = 0.3)\) (eq. 9). The smaller \(M_{d30}\) is, the more stable is the austenite against the formation of strain induced martensite and the lower is the relative permeability of a cold deformed ASS (Tab. 3).

\[
M_{d30} = 551 - 462\cdot(C + N) - 9.2\cdot\text{Si} - 8.1\cdot\text{Mn} - 13.7\cdot\text{Cr} - 29\cdot(\text{Ni} + \text{Cu}) - 18.5\cdot\text{Mo} - 68\cdot\text{Nb} \quad \text{(eq. 10)}
\]

Some ASS are especially designed for nonmagnetic properties and high strength. These grades, for example 1.3816, 1.3964, Magnadur 501 or Magnadur 601, are highly alloyed to suppress any strain induced martensite and designed to avoid δ-ferrite for \(\mu_{rel} \leq 1.01\) even after cold deformation. Cr and Mo serve up sufficient corrosion resistance.

### 4.2 FERRITIC STAINLESS STEELS (FSS)

Ferritic stainless steels have a body-centred cubic lattice (bcc). They usually own soft magnetic properties like low coercitivity, high permeability and high saturation induction.

As a rule FSS have the lowest amount of alloying elements among stainless steels which influences \(B_s\). From stainless steels they are the closest to pure iron,
accompanied by magnetic properties close to iron. The saturation induction $B_s$ of technically pure iron (99.8 mass.-% Fe) is 2.15 T [5]. For low alloyed steels like 1.0577 with 97.87 mass.-% Fe $B_s$ is about 2.03 T. With increasing amounts of alloying elements the possible $B_s$ is lowered (Fig. 4). For stainless steels Cr is the main responsible element for that. According to DIN EN 10020 stainless steels contain at least 10.5 mass.-% Cr and max. 1.2 mass.-% C. By that $B_s$ of ca. 1.9 T can not be exceeded.

The coercitivity can be influenced by alloying Si or Al [6, 7]. This is shown in Fig. 5 for Si in ferritic 17 mass.-% Cr-steels. Si and Al lower the coercitivity by stabilising the ferritic phase and suppressing the formation of retained austenite and martensite [7].

During cooling ferritic grades run through an austenitic phase field which can expand down to the solution annealing temperature. By that martensite can occur after solidification, hot working or wrong heat treatment. If martensite occurs, the coercitivity and remanence are raised. Cold working increases the dislocation density and can reduce the grain size. That is why coercitivity increases and permeability decreases in FSS after cold deformation [6]. Cold deformation beyond a grade of typical critical deformation and subsequent annealing leads to grain growth and increased soft magnetical properties [6]. Even compared to the delivery state the soft magnetic properties can be improved by a subsequent annealing at 750-800° C. Martensite, retained austenite and cold work hardening are removed and the grain size is increased by this heat treatment. A bigger grain results in lower coercitivity [4, 6 and 7].

The magnetic properties of investigated ferritic stainless steel can be seen in Table 4.

### 4.3 MARTENSITIC STAINLESS STEELS (MSS)

#### 4.3.1 C-MARTENSITES

MSS are associated to hard magnetic properties like high coercitivity and high remanence. Similar to FSS the magnetic saturation induction of MSS is lowered with increasing amounts of alloying elements (Fig. 4). Again Cr is the element which is most responsible for this effect. $B_s > 1.9$ T seems to be unrealizable. C-atoms are important for the martensitic structure. In homogenous solution they distort the ferritic bcc-lattice and transform it into the tetragonal distorted martensitic lattice after rapid cooling. As C is responsible for the martensitic transformation and the martensitic lattice has hard magnetic properties, C influences (raises) the coercitivity and remanence. This can be seen up to C contents of 0.25 mass.-%, then saturation can occur. Because the combination of Cr and C leads to susceptibility to Cr-carbides, which harm the corrosion resistance and mechanical properties, usually MSS have...
low C contents up to 0.5 mass.-% C. Of course there exist exceptions like 1.4125. The combination of high Cr and low C leads to ferritic-martensitic grades like 1.4005 and 1.4104, where up 50 vol.-% of ferrite can be found in metallographic analysis. In 1.4021 and 1.4057 appear up to 5 vol.-% whereas in 1.4034 no ferrite is found [8]. Of course increasing ferrite content shifts the magnetic properties from hard to soft magnetic (Tab. 5).

Retained austenite can appear if the martensite start temperature \( M_s \), which is reduced the most by C and N (eq. 11), is too low. Then the magnetic properties are influenced by the austenitic phase which reduces the permeability and induction. Venable [9] created a formula based on the chemical composition in mass.-% to estimate the probability of retained austenite by calculating \( M_s \) (eq. 11).

\[
M_s = 1355 - 1655 \cdot (C+N) - 28 \cdot Si - 33 \cdot Mn - 42 \cdot Cr - 61 \cdot Ni
\]  
(eq. 11)

Retained austenite can be avoided by a cryogenic cooling after hardening or by strain induced martensite transformation. A third way is annealing to create a ferrite-pearlite structure, but this reduces the hardness and changes the magnetic properties significantly. Intense cold deformation has a similar effect to martensites as to ferrites. Coercitivity increases and permeability decreases after cold deformation [6]. Another similarity to FSS is the possibility to adjust the magnetic properties of MSS by heat treatment. The example of 1.4021 shows the influence of annealing from 550 to 1000° C, 2 hours, followed by quenching in water (Fig. 6, Tab. 6). With heightening the temperature up to 800° C coercitivity decreases and permeability increases slightly. At about 850° C the permeability abruptly decreases whereas the coercitivity growth in the same way. Both effects are connected to massive transformation into austenite at high temperature (Fig. 6). By that a heat treatment between 700 and 800° C was found to bring good soft magnetic properties to 1.4021 (\( H_e \downarrow, \mu \uparrow \)). The same was found for 1.4104 (Tab. 6).

The strength is reduced less than 10 % during that process. But the result depends on the initial state and the chemical analysis (grain size, content of retained austenite and ferrite, precipitations, C, Si etc.).

---

**Tab. 5:** Magnetic properties of selected martensitic stainless steels.

<table>
<thead>
<tr>
<th>Grade</th>
<th>( M_s ) [°C]</th>
<th>( H_e ) [kA/m]</th>
<th>( \mu_{max} )</th>
<th>( B_r ) [T]</th>
<th>( B_s ) [T]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4005</td>
<td>530</td>
<td>0.145</td>
<td>265</td>
<td>0.64</td>
<td>1.70</td>
</tr>
<tr>
<td>1.4006</td>
<td>504</td>
<td>1.170</td>
<td>350</td>
<td>0.93</td>
<td>1.65</td>
</tr>
<tr>
<td>1.4104</td>
<td>380</td>
<td>0.815</td>
<td>485</td>
<td>0.98</td>
<td>1.60</td>
</tr>
<tr>
<td>1.4021</td>
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<td>385</td>
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<td>405</td>
<td>0.85</td>
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<tr>
<td>1.4057</td>
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<td>0.135</td>
<td>350</td>
<td>0.83</td>
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<tr>
<td>1.4044</td>
<td>180</td>
<td>0.185</td>
<td>260</td>
<td>0.88</td>
<td>1.60</td>
</tr>
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</table>

**Fig. 6:** Influence of the annealing temperature on the maximum permeability and the coercitivity (1.4021)

**Tab. 6:** Magnetic properties of 1.4021 and 1.4104 after annealing

<table>
<thead>
<tr>
<th>Grade</th>
<th>Heat treatment</th>
<th>( H_e ) [kA/m]</th>
<th>( \mu_{max} )</th>
</tr>
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<tr>
<td></td>
<td>bef.</td>
<td>aft.</td>
<td>bef.</td>
</tr>
<tr>
<td>1.4021</td>
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</tr>
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<td>1.4021</td>
<td>800°C 2h</td>
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<td>1.00</td>
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<tr>
<td>1.4104</td>
<td>740°C 1h</td>
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<td>0.97</td>
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<td>1.4104</td>
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<td>0.86</td>
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</table>
4.3.2 NI-MARTENSITES

The combination of Cr and C in steel makes it susceptible to Cr-carbide precipitation, mainly Cr$_2$3C$_6$. Only soluted Cr is able to hinder corrosion, thus Cr-carbides reduce corrosion resistance; additionally they impair the mechanical properties. A way to create a stainless martensitic grade without C is alloying with moderate amounts of Ni. Ni-martensitic steels are named “soft martensitic” as well, because they are not as hard as classical C-martensites. An example is 1.4418. The high Ni-content raises the coercivity and remanence but gives susceptibility to retained austenite which reduces the magnetic induction of a steel if it occurs. The same way C reduces the magnetizeability and increases coercivity by supporting retained austenite and Cr-carbides. This effect of C on remanence is contrary to its in C-martensites. Raising $M_s$ by alloying within the specification (eq. 11) can increase the permeability and reduces retained austenite and its effects. As in C-martensites ferrite content shifts the magnetic properties to the soft magnetic regime. In [10] is reported that Ni-martensites form fine dispersed austenite at temperatures about 600°C. This results in lower magnetizeability and higher coercivity. Starting from 560°C this effect can be seen in tempering investigations (Fig. 7, Tab. 7). The coercivity of 1.4418 shows hard magnetic characteristics (Tab. 7) with smaller $B_s$ compared to the investigated C-martensites (Tab. 7). Presently Ni-martensitic stainless steels are rarely used as magnetic material. It can change if their properties such as good weldability, high strength and toughness are also will be taken into account. Additionally they own a proper corrosion resistance.

4.3.3 MARAGING STEELS

Due to the fact that Ni-martensitic steels are not as hard as C-martensites, precipitation hardening is the only way to increase their hardness. On the basis of 1.4418 careful modifications and an addition of ca. 3-5 mass.-% Cu result in precipitation hardenable stainless steels, e.g. 1.4542 or 1.4545. After solution annealing and quenching these steels have 30-33 HRC and can be hardened by Cu-precipitations up to 42 HRC. Compared to 1.4418 the coercivity and permeability of 1.4542 is roughly the same (Fig. 7, 8), which is valid for the remanence and saturation induction as well.

![Fig. 7: Influence of the annealing temperature on the maximum permeability and the coercivity (1.4418)](image)

<table>
<thead>
<tr>
<th>Grade</th>
<th>annealing temp. [°C]</th>
<th>$H_C$ [kA/m]</th>
<th>$\mu_{\text{max}}$</th>
<th>$B_r$ [T]</th>
<th>$B_s$ [T]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4418</td>
<td>520</td>
<td>2.25</td>
<td>130</td>
<td>0.60</td>
<td>1.25</td>
</tr>
<tr>
<td>1.4418</td>
<td>580</td>
<td>2.28</td>
<td>125</td>
<td>0.55</td>
<td>1.20</td>
</tr>
<tr>
<td>1.4418</td>
<td>600</td>
<td>3.18</td>
<td>75</td>
<td>0.50</td>
<td>1.05</td>
</tr>
</tbody>
</table>

Tab. 7: Magnetic properties of 1.4418 after annealing

![Fig. 8: Influence of the annealing temperature on the maximum permeability $\mu_{\text{max}}$ and the coercitivity $H_C$ (1.4542)](image)
(Tab. 7, 8). To prove if the trends of $\mu_r$ and $H_c$ are similar for different annealing temperatures there are not enough values for 1.4542 (Fig. 8). But it can be suggested, that slightly shifted to higher temperatures it will be the same, as it is known, that austenite will form latest above 600° C in 1.4542 (Fig. 7, 8).

In a sum, the magnetic properties of the investigated martensitic stainless steels are closer to soft magnetic behaviour than to hard magnetic. Only 1.4006, the Ni-martensitic 1.4418 and the maraging steel 1.4542 offer a coercitivity above 1 kA/m. The latter two exhibit $H_c$ of 2.1 kA/m but gain the lower remanence than investigated C-martensitic stainless steels (Tab. 5, 7 and 8). Thus most of the investigated MSS are an option for soft magnetic applications where high strength or wear resistance are important. The hard magnetic properties nowadays are often much better to achieve with magnetide-, FeAlNiCo-, SmCo- or NdFeB- solenoids (performance, weight / performance, etc.) or C-martensitic steels without corrosion resistance (price / performance).

### 4.4 DUPLEX STAINLESS STEELS (DSS)

Concerning their magnetic properties duplex stainless steels can be seen as ferritic steels with extremely high contents of retained austenite. To this point of view fits the typical primary ferritic solidification of DSS melts, followed by austenitic transformation. Consequences are strongly reduced permeability and induction compared to the investigated ferritic stainless steels (Tab. 4, 9). Comparing to austenitic stainless steels the nonmagnetism is significantly lost (Tab. 2, 9). The ferromagnetic behaviour, especially the permeability, of DSS is strongly connected to their ferrite content. Typically 50 vol.-% of ferrite are adjusted by heat treatment. The balance of ferrite and austenite is defined mainly by the solution annealing temperature. Chemically identical material from the same heat achieved $\mu_{\text{max}} = 160$ with a ferrite content of 50.9 vol.-% (single random sample, standard production) and $\mu_{\text{max}} = 81$ with 47.2 vol.-% ferrite (as before + 1040° C / 1-2 h / H₂O) (Tab. 9).

Similar to austenitic stainless steels cold deformation can also create strain induced martensite in the austenitic part. In this case the fraction of ferromagnetic phases is increased.

Thus, DSS are not very promising for the application in the areas there the magnetic properties are important. If superior corrosion resistance and good weldability comes to the focus DSS might be the choice.
5. SUMMARY

The results of a study on the magnetic properties of stainless steels are presented, covering typical austenitic, ferritic, ferritic-austenitic and martensitic stainless steels. In addition to the determination of the magnetic properties of the investigated grades in the as-delivered condition, supplementary testing has been performed to show the effect of chemical composition, cold deformation and thermal processing on their magnetic properties. The measured magnetic properties as well as their affecting factors are presented and connected to a rough classification by mechanical properties and corrosion resistance. Additionally actual and possible electromagnetic applications are mentioned.

Summarized, the austenitic stainless steels are nonmagnetic. They have to be applied, when any magnetic interaction between a steel component and a system must be eliminated (eddy currents, magnetic attraction). A small magnetization can be caused by the presence of ferrite or strain induced martensite. The ferritic stainless steels are soft magnetic (high permeability and polarisation and low coercivity). They can be used for induction or shielding devices. Their soft magnetic properties can be optimized by changing the chemical composition and/or thermal processing. Some martensitic stainless steels are hard magnetic (lower permeability and polarisation and much higher coercivity compared to ferritic steels). They can be used for semi-magnet applications or when their high mechanical strength and hardness are important. Their magnetic properties can be optimized by changing of the chemical composition and/or thermal treatments either into the hard- or into the soft magnetic direction. Most of the martensitic stainless steels offer a more soft magnetic behaviour, they can be used instead of ferrites when higher strength and wear resistance is needed. The ferromagnetic properties of duplex stainless steels are somewhere between austenitic and ferritic steels. Not very promising to the applications, which required good magnetic properties, they still can be used as they are nowadays, when their high corrosion resistance or good mechanical properties are relevant.

REFERENCES: