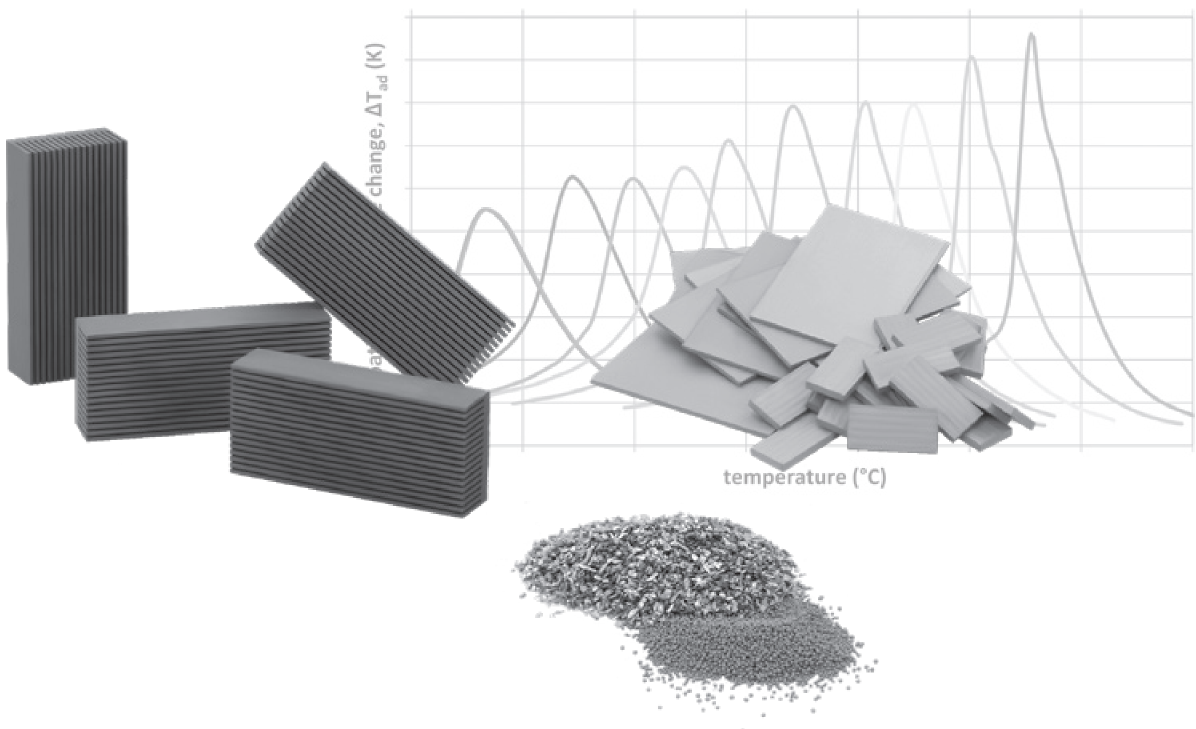
MAGNETOCALORIC MATERIALS

CALORIVAC



ADVANCED MATERIALS – THE KEY TO PROGRESS

VAC®
VACUUMSCHMELZE

THE COMPANY
VACUUMSCHMELZE

VACUUMSCHMELZE GmbH & Co. KG (VAC) is one of the world's leading producers of special metallic materials with particular physical properties and products produced from them. With approximately 4,100 employees worldwide, the company is represented in 50 countries and currently achieves a turnover of approximately EUR 400 million. The headquarters and registered office of the company is in Hanau, Germany, with additional production plants in Slovakia, Finland, Malaysia and China.

Contents

® = registered trademark of VACUUMSCHMELZE GmbH & Co. KG

1. INTRODUCTION

Cut blocks of CALORIVAC C

DELIVERING EXCELLENCE FOR OVER 90 YEARS

VACUUMSCHMELZE is one of the leading global manufacturers of advanced magnetic materials and related products. Our company is represented globally in over 50 countries with over 4,000 employees. The headquarters and operational centre of VACUUMSCHMELZE is in Hanau, Germany, and the company also has facilities in Finland, Slovakia, China and Malaysia.

The company's success story started in 1923 with the melting of alloys under vacuum in a small factory in Hanau. With over 90 years of experience, and in combination with our exceptional process-related know-how, we are able to offer you high-quality materials with special magnetic and physical properties. We have always manufactured our alloys in Hanau in accordance with industry required quality standards (certified according to ISO/TS 16949:2009). Cost-effective production equipment, the latest testing techniques and the responsible protection of resources are as natural for our company as is active environmental protection (certified according to DIN EN 14001) and continuous improvement training of our staff.

OUR PRODUCT RANGE – THE KEY TO YOUR PROGRESS

From large volume production in the automotive industry to small series production in the aerospace industry, or even one-off high-tech components for top level scientific research, our products and assemblies have a proven track record for their high quality and reliability, in practically every sector and branch of industry.

The VACUUMSCHMELZE product range spans:

- Rare-earth (RE) permanent magnets
- Magnetically soft semi-finished products and parts
- Toroidal cores
- Inductive components
- Magnetic shielding
- Materials with special physical properties
- Complete components and assemblies to customers' specifications

We assist our customers with the development process, implement their requirements and produce custom-built products. Therefore our services extend from consulting at the initial planning stage to the design engineering and the actual production of the components or assemblies.

Granules of CALORIVAC H

MAGNETOCALORIC ALLOYS – OUR LATEST DEVELOPMENT

Since 2013, a new alloy has been added to our product range: CALORIVAC is a material with excellent magnetocaloric properties that can be used in several new technologies.

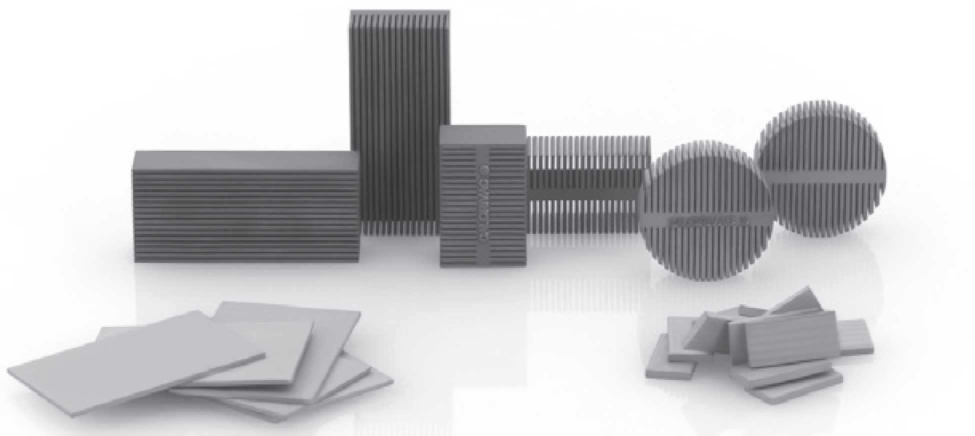
The magnetocaloric effect (MCE) dates back to 1881 when it was discovered by the German physicist Emil G. Warburg. In 1949 William F. Giauque, and later on in 1997, Percharsky and Gschneidner set milestones in the further development of magnetocaloric materials and their applications.

Magnetocaloric Materials (MCM) exhibit a unique effect around their phase transition temperature (Curie temperature). MCM heat up when they are put inside a magnetic field and cool down when they are moved out of the magnetic field.

The high degree of innovation at VACUUMSCHMELZE led to the development of magnetocaloric alloys as a new product family for green technologies. The main application areas for MCM are magnetic cooling and heating devices such as commercial cooling, electronics cabinet cooling, heat pumps, air conditioning, household appliances, sensors and actuators, gas liquefaction or energy conversion from waste heat.

Besides the magnetocaloric material, VAC also provides suitable permanent magnets and magnet assemblies for producing strong magnetic fields as needed for the operation of MCM-devices.

2. PRODUCT RANGE AND FORMS OF SUPPLY



Plates and cut blocks

CALORIVAC ALLOYS

Our product range of magnetocaloric alloys comprises two alloy families. Both families are based on the ternary rare earth intermetallic compound $LaFe_{13-x}Si_x$. Firstly, VACUUMSCHMELZE offers CALORIVAC C in which cobalt is used as the main alloying element to adjust the magnetic properties. In the second family – CALORIVAC H – manganese and hydrogen are used to adjust the magnetic characteristics of the material. Both material families differ in their magnetocaloric properties, as well as in possible forms of supply.

2.1 CALORIVAC C

CALORIVAC C alloys are available with Curie temperatures over a wide temperature range. The alloy can be shaped into various geometries which makes it the ideal material for complex regenerator designs for magnetocaloric refrigerators and heat pumps. Fig. 1 shows the typical adiabatic temperature change of a series of CALORIVAC C alloys for an external magnetic induction change of 1.5 T. For a more comprehensive overview of magnetic properties, please refer to the appendix.

Possible shapes of CALORIVAC C include individual plates which can be arranged by the customer. With plates, it is easy to vary the fluid channel thickness through which the heat exchange fluid is pumped. Other geometries are, for example, blocks with fluid channels cut into them. Design constraints can be found in the next table. Due to the limited mechanical stability which is intrinsic to intermetallic alloys, it is recommended to have two or more smaller parts instead of one large part. Please contact us if you require any other shape that is not listed here. Our contact data is on the rear cover of the brochure.

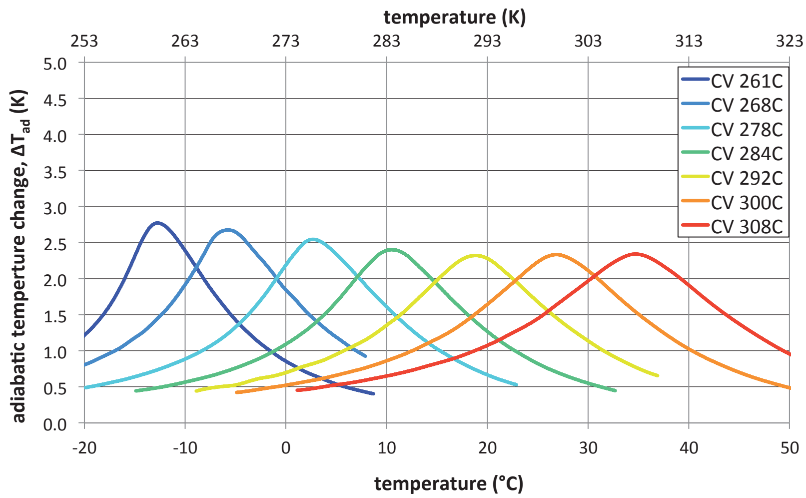
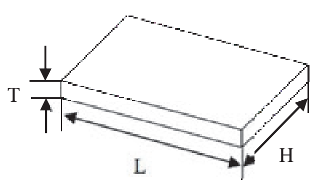
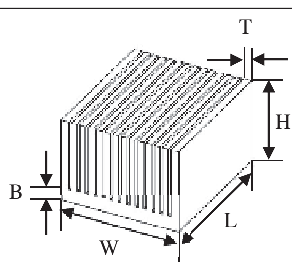


Fig. 1: Typical adiabatic temperature change of CALORIVAC C alloys for a magnetic induction change of 1.5 T

Shape	Sketch	Outer Dimensions	Plate Thickness	Remarks
Plate		H < 30 mm L < 40 mm	T > 0.5 mm	Fluid channel width adjustable by customer
Comb		W < 20 mm L < 30 mm H < 15 mm	T > 0.4 mm B > 1.5 mm	Fluid channel width is fixed at 0.2 mm

DIMENSIONAL TOLERANCES

Machining of parts is usually performed by grinding or electric discharge machining (EDM). The tolerances are ±0.05 or ±0.1 mm for grinding and EDM, respectively. General tolerances as per DIN EN 2768 mK in connection with tolerance levels as per DIN ISO 8015 can be met. For shaped parts with more complex geometry we usually offer a surface profile tolerance. On request, even tighter tolerances can be met. If no tolerances are specified, we supply according to DIN ISO 2768 mK.

Irregular particles and granules

2.2 CALORIVAC H

The second product with special magnetocaloric properties is CALORIVAC H. The introduction of hydrogen into the material leads to limitations with regard to possible shapes. Currently CALORIVAC H can be supplied as irregular granules sieved to customer requirements (see table 1 for details). These granules have good mechanical stability and long term stability with regard to magnetocaloric properties.

Table 1: Table of available sieves with mesh size in µm

250	315	400	500	630	800	1000	1250

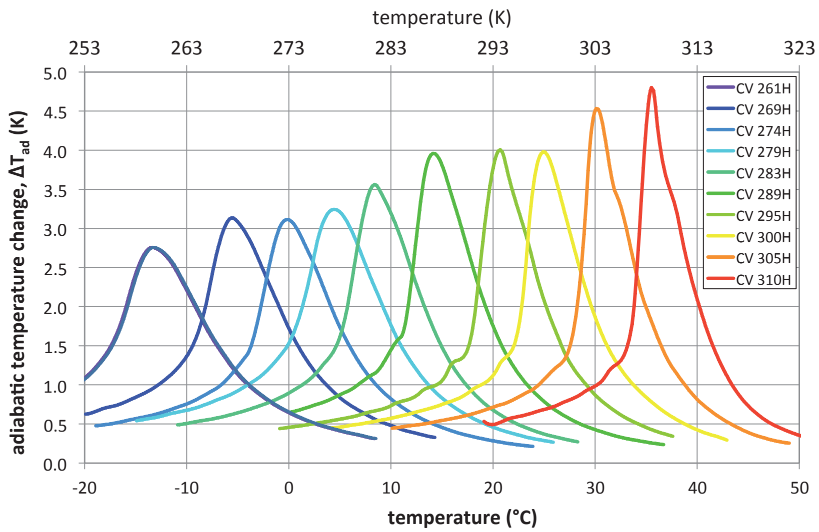


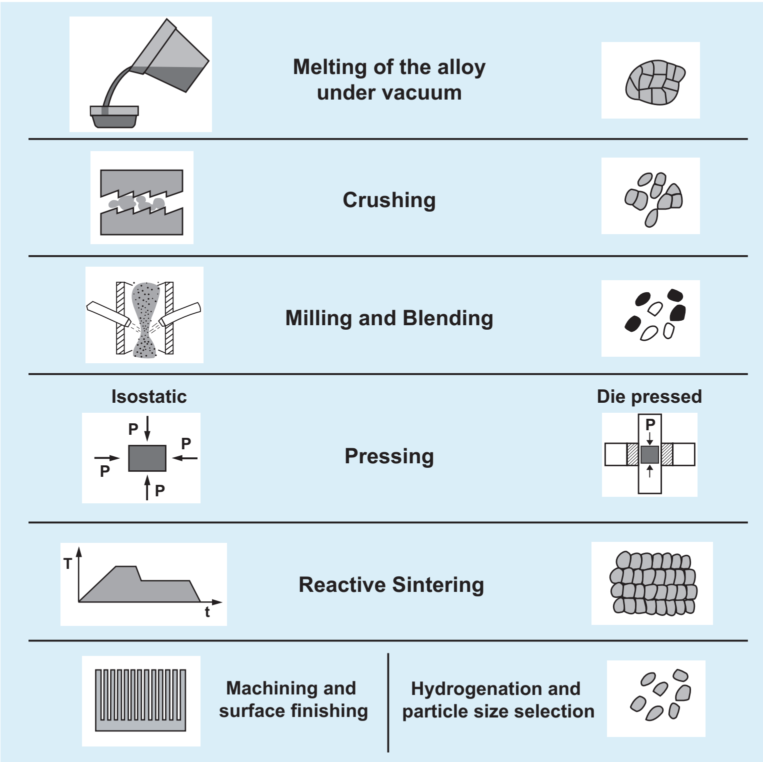
Fig. 2: Typical adiabatic temperature change of CALORIVAC H for an external magnetic induction change of 1.5 T

CALORIVAC H alloys show superior magnetocaloric properties around room temperature with effects up to two times larger than CALORIVAC C. Fig. 2 shows the typical adiabatic temperature change for a series of CALORIVAC H alloys for an external magnetic induction change of 1.5 T.

The crossover temperature at which the magnetocaloric performance of CALORIVAC C is comparable to that of CALORIVAC H is between -20 °C and -10 °C. For higher temperatures CALORIVAC H has the better properties, for lower temperatures CALORIVAC C is superior.

2.3 PRODUCTION STEPS

VACUUMSCHMELZE has over 40 years of experience in the handling and production of rare earth transition metal alloys. CALORIVAC belongs to this group of materials and is produced by power metallurgy methods. Starting from vacuum induction melting and casting of the master alloys, a fine powder is produced by several milling steps. These fine powders are compacted by either die pressing of near net shape parts or cold isostatic pressing of semi-finished blocks. In a secondary machining step the final shape of the product is generated.



3. MATERIAL PROPERTIES

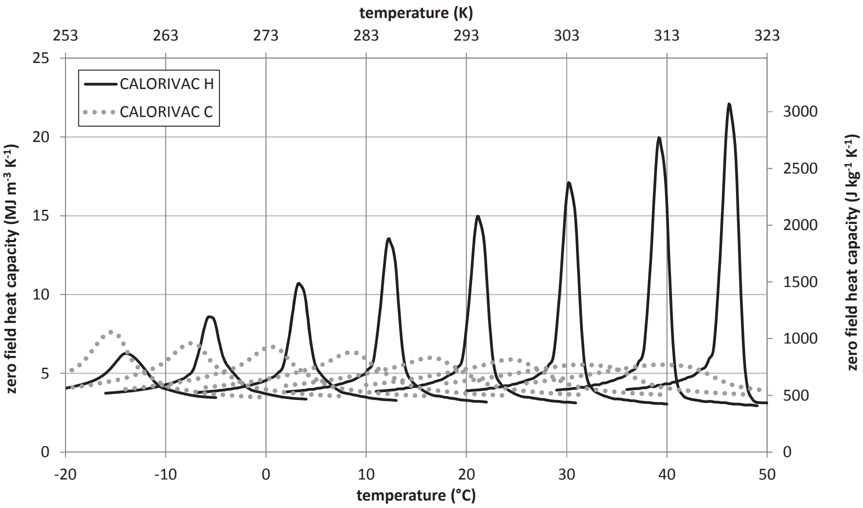


Fig. 3: Zero magnetic field heat capacity of CALORIVAC C (dotted lines) and CALORIVAC H (full lines)

TYPICAL MATERIAL PROPERTIES IN DETAIL

In principle, the magnetocaloric properties of CALORIVAC alloys could be determined from the relationship of heat capacity as a function of the applied magnetic field. The typical heat capacity in zero applied magnetic field of CALORIVAC C and H alloys when measured by differential scanning calorimetry is shown in fig. 3. However, as no measurement apparatus for determining heat capacity as a function of an applied magnetic field is commercially available, we therefore describe our CALORIVAC alloys by the most characteristic magnetic properties, the temperature dependence of polarization, the isothermal entropy change and the adiabatic temperature change which are shown in the following. Please refer to the appendix for a detailed description of measurement techniques. In addition, table 2 summarizes some further properties of CALORIVAC alloys.

Table 2: Typical material properties of CALORIVAC alloys

Thermal conductivity	6 - 8 $Wm^{-1}K^{-1}$
Density	7.0 - 7.2 g/cm^3
Relative permeability	800 - 1200
Flexural strength	150 - 200 N/mm^2

3.1 CALORIVAC C

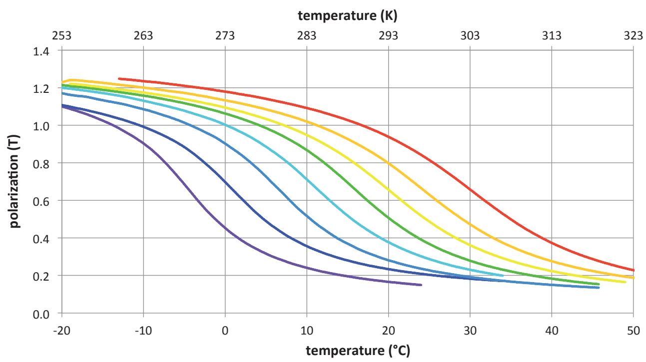


Fig. 4: Polarization as a function of temperature for a series of CALORIVAC C alloys in an external magnetic field of 1273 kA/m (16 kOe)

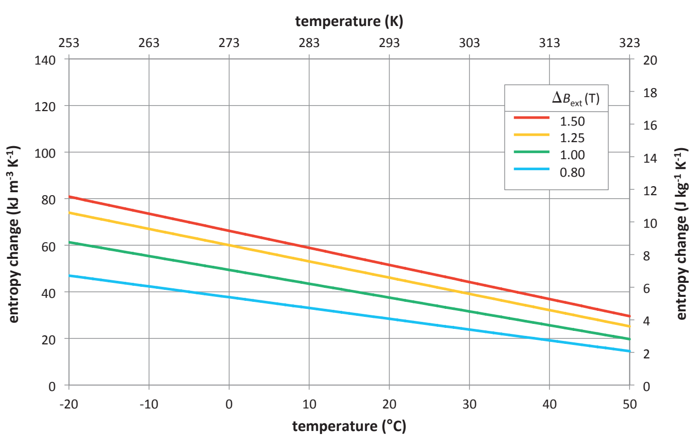


Fig. 5: Typical isothermal entropy change for CALORIVAC C alloys for different levels of magnetic induction change

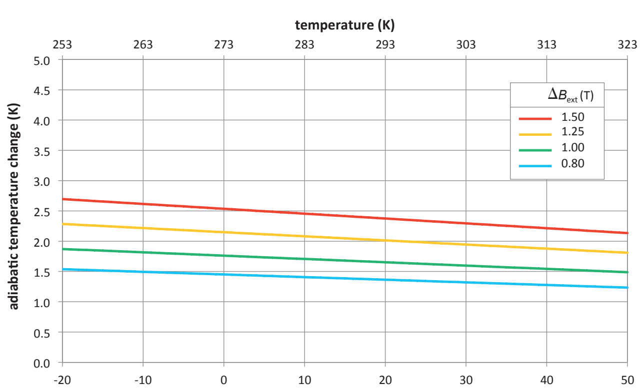


Fig. 6: Typical adiabatic temperature change for CALORIVAC C alloys for different levels of magnetic induction change

3.2 CALORIVAC H

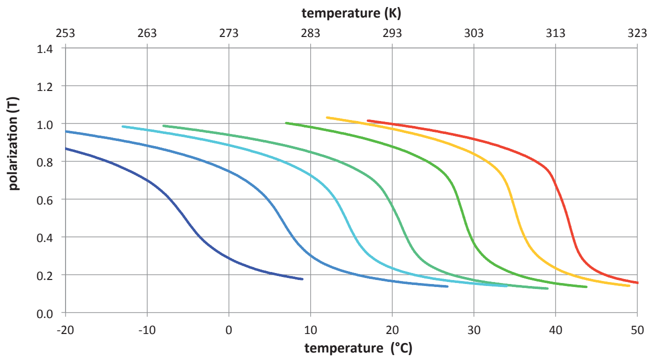


Fig. 7: Polarization as a function of temperature for a series of CALORIVAC H alloys in an external magnetic field of 1273 kA/m (16 kOe)

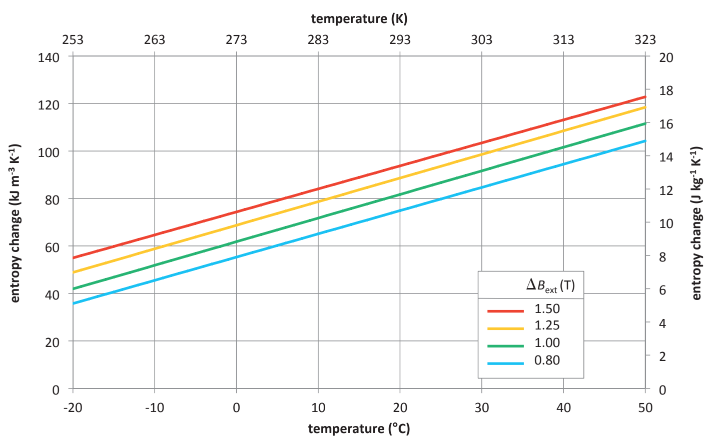


Fig. 8: Typical isothermal entropy change for CALORIVAC H alloys for different levels of magnetic induction change

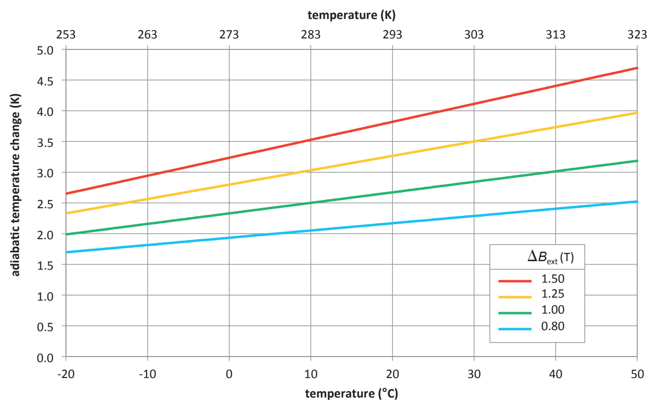


Fig. 9: Typical adiabatic temperature change for CALORIVAC H alloys for different levels of magnetic induction change

CALORIVAC C

TABLE 3: TYPICAL MAGNETIC ENTROPY CHANGE, ΔS_T AND ADIABATIC TEMPERATURE CHANGE, ΔT_S, FOR DIFFERENT EXTERNAL

	1.50 T				1.25 T			
	ΔS_T kJ/m³K	FWHM K	ΔT_{ad} K	FWHM K	ΔS_T kJ/m³K	FWHM K	ΔT_{ad} K	FWHM K
250 C	81	10	2.7	12	74	9	2.3	11
260 C	76	11	2.6	14	69	11	2.2	13
270 C	68	14	2.6	16	62	13	2.2	15
280 C	61	16	2.5	19	55	16	2.1	17
290 C	54	19	2.4	21	48	18	2.0	20
300 C	46	21	2.3	23	41	20	2.0	22
310 C	39	23	2.2	26	34	23	1.9	24
320 C	32	26	2.2	28	27	25	1.8	26

CALORIVAC H

TABLE 4: TYPICAL MAGNETIC ENTROPY CHANGE, ΔS_T AND ADIABATIC TEMPERATURE CHANGE, ΔT_S, FOR DIFFERENT EXTERNAL

	1.50 T				1.25 T			
	ΔS_T kJ/m³K	FWHM K	ΔT_{ad} K	FWHM K	ΔS_T kJ/m³K	FWHM K	ΔT_{ad} K	FWHM K
250 H	55	10	2.6	12	49	9	2.3	10
260 H	62	9	2.9	11	56	8	2.5	10
270 H	71	9	3.1	10	66	8	2.7	9
280 H	81	8	3.4	9	76	7	3.0	8
290 H	91	7	3.7	8	86	6	3.2	7
300 H	101	7	4.0	7	96	6	3.4	6
310 H	110	6	4.3	6	106	5	3.7	5
320 H	120	5	4.6	5	115	4	3.9	4

Irregular particles

MAGNETIC INDUCTION CHANGES. FWHM VALUES GIVES THE FULL WIDTH AT HALF MAXIMUM VALUE OF THE RESPECTIVE QUANTITY

	1.00 T				0.80 T			
	ΔS_T	FWHM	ΔT_{ad}	FWHM	ΔS_T	FWHM	ΔT_{ad}	FWHM
	kJ/m^3K	K	K	K	kJ/m^3K	K	K	K
	61	9	1.9	11	47	8	1.5	10
	57	10	1.8	12	44	9	1.5	11
	51	13	1.8	14	39	12	1.5	13
	45	15	1.7	16	35	14	1.4	15
	39	17	1.7	18	30	16	1.4	17
	33	19	1.6	20	25	18	1.3	19
	27	22	1.6	22	21	21	1.3	21
	22	24	1.5	24	16	23	1.2	23

MAGNETIC INDUCTION CHANGES. FWHM VALUES GIVES THE FULL WIDTH AT HALF MAXIMUM VALUE OF THE RESPECTIVE QUANTITY

	1.00 T				0.80 T			
	ΔS_T	FWHM	ΔT_{ad}	FWHM	ΔS_T	FWHM	ΔT_{ad}	FWHM
	kJ/m^3K	K	K	K	kJ/m^3K	K	K	K
	42	8	2.0	9	36	7	1.7	8
	49	7	2.1	9	43	6	1.8	8
	59	6	2.3	8	52	6	1.9	7
	69	6	2.5	7	62	5	2.0	7
	79	5	2.6	6	72	4	2.1	6
	89	4	2.8	6	82	4	2.3	5
	99	4	3.0	5	92	3	2.4	5
	109	3	3.1	4	101	2	2.5	4

4. CORROSION BEHAVIOUR OF CALORIVAC

Magnetocaloric materials based on lanthanum-iron-silicon (La-Fe-Si) contain iron up to 70 - 80 % by weight. This element dominates the corrosion behaviour of the alloy. In contact with humidity and air (oxygen), red rust formation occurs on La-Fe-Si, similar to pure iron parts. These loose rusty corrosion products consist mainly of hydrated Fe^{2+}, Fe^{3+}-oxides (red color) and of lanthanum hydroxide $La(OH)_3$.

CORROSION PROTECTION OF CALORIVAC PARTS

The best way to avoid corrosion is to store the parts under dry conditions (< 65 % rel. humidity) or under an oxygen free atmosphere. In addition, all temporary and passive corrosion protection measures for iron are also useful on La-Fe-Si.

Examples for temporary corrosion protection of La-Fe-Si are phosphate treatment, oil coverage or suitable organic rust inhibitors.

Passive long-term corrosion protection is generated by spray coatings. VAC approved organic spray coatings belonging to the VACCOAT® series are recommended. These coatings are successfully approved on other rare earth products like VACODYM® permanent magnets (neodymium-iron-boron alloys) and also represent a very effective corrosion protection of La-Fe-Si.

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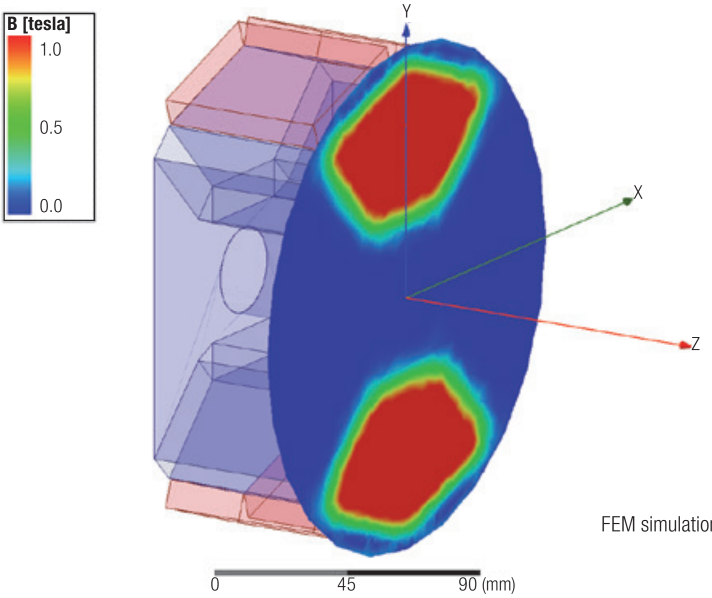
Cut blocks of CALORIVAC C

CORROSION PROTECTION IN COOLING CIRCUITS

The most important factor to prevent failures in cooling circuits is to avoid electrochemical (galvanic) corrosion. The use of copper pipes in combination with La-Fe-Si parts is prohibited. A suitable cooling circuit is an air-tight sealed unit. Aqueous cooling media should contain water soluble corrosion inhibitors to prevent rust formation on La-Fe-Si parts. Approved substances are based on the chemistry of reaction products of N-acyl amino carbonic acids with alcohol amino compounds. Furthermore, it is very important to use the correct cooling water quality. We recommend deionized water (di-water) with a conductivity < 5 µS for new badges of cooling liquids. In general, the cooling water must be free of corrosive elements and ions like chlorine and other halogens or sulphur. The pH-value of the cooling liquid should be adjusted to mild alkaline conditions (typical pH 8-9). In any case, we recommend long-term or accelerated corrosion tests with La-Fe-Si parts under environmental conditions which are close to the designed application.

5. PERMANENT MAGNETS AND ASSEMBLIES



FEM simulation of a magnet assembly for magnetocaloric applications

DEDICATED TO MATERIALS

Our work with the magnetic properties and applications of such special metallic materials dates back more than 90 years. For the development and production of our magnet assemblies, we use our own high-quality rare-earth permanent magnet materials VACOMAX® and VACODYM. Our production of VACOMAX permanent magnets based on samarium and cobalt using powder metallurgical methods, started in 1973. Since 1986, we have produced VACODYM on an industrial scale. VACODYM magnets are based on neodymium-iron-boron alloys and exhibit the highest energy densities currently available. For support parts, we also have a wide range of soft magnetic materials, e.g. VACOFLUX® and VACOFER®. Our magnets have precisely defined magnetic properties and provide the ideal basis for a wide range of customer-specific functional requirements. Knowing the special properties of our materials enables us to adjust them throughout the whole manufacturing process.

We assist our customers with the development process, implement their requirements and produce custom-built magnet assemblies. Therefore our services extend from consulting at the initial planning stage to the design engineering and the actual production of the magnets, parts or assemblies.

Detailed information on these can be found in our brochures for Permanent Magnets (PD-002) and Magnet Assemblies (PD-004).

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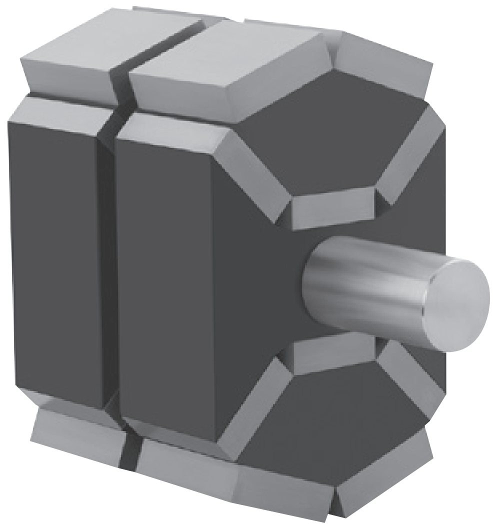


Magnet assembly for magnetocaloric applications

MAGNET ASSEMBLIES IN EVERY SIZE AND LEVEL OF COMPLEXITY

For you, we are not only a supplier of CALORIVAC but also your competent partner for the development and manufacture of advanced magnet assemblies, in every size and every required level of complexity. We apply our decades of experience using our own permanent magnets and soft magnetic materials to manufacture a large number of these magnet assemblies at our two production plants in Hanau and Horná Streda (Slovakia).

CUSTOMIZED INTELLIGENT SOLUTIONS

We manufacture our magnet assemblies strictly to customers' specifications. The solutions we develop together with our customers meet the optimum magnetic field profile for the magnetocaloric material CALORIVAC.

MANUAL ASSEMBLY

We manufacture small series, prototypes and test devices at our factory in Hanau, Germany. We have a team of highly specialized and experienced experts at our disposal, who look forward to every new challenge, especially complex ones. Whether it is for research and development, automotive or industrial applications – a wide diversity of what are often highly sophisticated one-off components and small series are produced in Hanau.

SUCCESSFUL PARTNERSHIPS – WHEN ARE WE STARTING OURS?

Magnet assemblies are always individual solutions. As leading experts in the manufacture of magnet assemblies on the basis of RE permanent magnets, we can assist you from the outset of the development stage to the manufacture of the components. Our range of products and services extends from particularly challenging one-off products and prototypes to cost-effective serial production running to millions. We will be pleased to assist you and look forward to receiving your enquiry.

6. INTEGRATED MANAGEMENT SYSTEM

Documentation of the quality, environmental and industrial safety management system was integrated into a joint management system (integrated management system) in 2003. It is currently based on the following set of standards in their respective up-to-date versions:

- ISO 9001
- ISO/TS 16949
- ISO 14001
- OHSAS 18001
- DIN EN ISO/IEC 17025

QUALITY MANAGEMENT

Quality is an essential aspect of our corporate policy. In order to reliably realize the high quality of our products and services based on a quality management system certified in accordance with ISO 9001 and ISO/TS 16949, we give priority to close cooperation of all operational divisions. Our Total Quality Management (TQM) process has undergone continuous improvement since its introduction in as early as 1994 and is based on business excellence models and our corporate goals.

The most important objective of our quality management measures is fulfilling all customer expectations and achieving high customer satisfaction, both externally as well as internally. To further optimize VAC-internal processes – with the primary objective of further cost reduction – the Six-Sigma analysis tool was introduced in 2002.

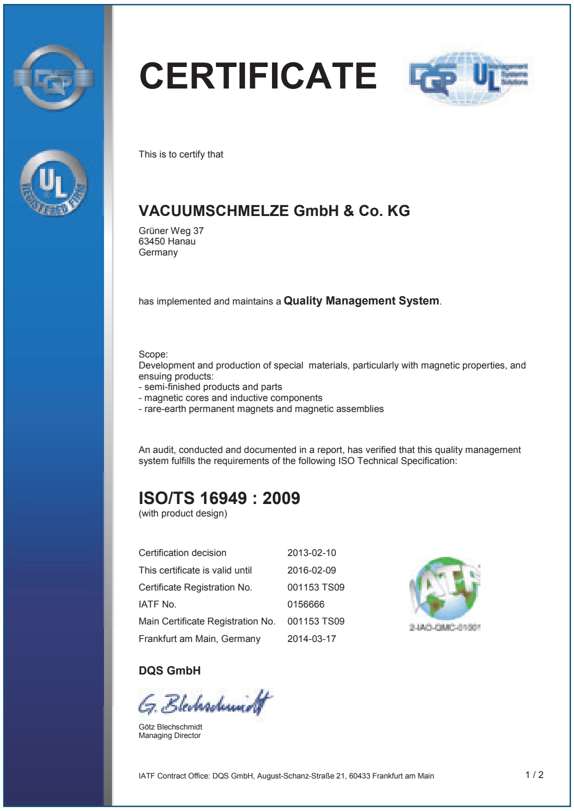
We achieve the product quality by defining and implementing QM measures in product and process planning, strictly controlling raw material procurement, and integrating test sequences into processes using a statistical process control system (SPC). Standard features of our quality management system include compliance with relevant process capabilities (cpk-values) and documentation of essential magnetocaloric and geometric properties. For complex tasks or very high requirements, we work with our clients to define a tailored quality assurance program. By providing qualified technical advice, we help to design and implement high-quality and cost-effective products and services; we also make quality assurance agreements (QAA) upon request. We see that our core competence lies in the production of materials with special, high-quality magnetocaloric properties.

TECHNICAL TERMS AND CONDITIONS OF SALE

Like most other permanent magnet materials, sintered magnetocaloric products made of RE intermetallic alloys are brittle. Regrettably, it is impossible to rule out fine hairline cracks or chipped edges. For serial production, the acceptance criteria for those defects shall be agreed jointly between the customer and VAC. For example, this can be accomplished by the exchange of limiting samples.

Under normal manufacturing conditions, slight amounts of magnetocaloric dust and material debris may adhere to the parts. If this is not acceptable, a special cleaning or packaging of the parts is to be provided.

The final inspection of our magnetocaloric parts is normally based on standardized sampling plans. Unless otherwise agreed upon with customers, the sampling scopes for the mechanical and magnetocaloric tests are conducted in accordance with DIN ISO 2859-1 with the acceptance criteria $c = 0$. By consistently employing the latest quality assurance techniques, we are often able to agree to even higher quality requirements upon request of the customer. For instance, products for the automotive industry require an additional process capability value of $cpk \geq 1.33$ for special characteristics.



CERTIFICATE

This is to certify that

VACUUMSCHMELZE GmbH & Co. KG
Grüner Weg 37
63450 Hanau
Germany

has implemented and maintains a **Quality Management System**.

Scope:
Development and production of special materials, particularly with magnetic properties, and ensuing products:
- semi-finished products and parts
- magnetic cores and inductive components
- rare-earth permanent magnets and magnetic assemblies

An audit, conducted and documented in a report, has verified that this quality management system fulfills the requirements of the following ISO Technical Specification:

ISO/TS 16949 : 2009
(with product design)

Certification decision	2013-02-10
This certificate is valid until	2016-02-09
Certificate Registration No.	001153 TS09
IATF No.	0156666
Main Certificate Registration No.	001153 TS09
Frankfurt am Main, Germany	2014-03-17

2-IAO-QMC-01001

DQS GmbH

Götz Blechschmidt
Managing Director

IATF Contract Office: DQS GmbH, August-Schanz-Straße 21, 60433 Frankfurt am Main

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ENVIRONMENTAL AND SAFETY MANAGEMENT

VAC is committed to the protection of the environment and using the available natural resources as economically as possible. This principle applies to our production processes as well as to our products. We evaluate potential damage to the environment right from the development stage of our products.

We aim at avoiding or minimizing any harmful environmental effects by implementing precautions that frequently exceed those stipulated by law. Our environmental management ensures that our environmental policy according to ISO 14001 is effectively put into practice. Technical and organizational means for this purpose are regularly audited and are subject to continuous improvement. A further goal in the design of our products, processes and workplaces is the health and safety protection of our staff and our partners based on OHSAS 18001. Here, the applicable laws, standards and regulations are taken into account together with assured expertise on occupational medicine and industrial science.

7. SAFETY GUIDELINES

Our CALORIVAC products do not pose any safety hazards in the supplied form. In case CALORIVAC material must be processed further, special safety precautions must be taken when handling the accumulating grinding debris. Legal regulations regarding the handling of cobalt-containing dust must be observed.

In the case of higher temperatures, as could happen with surrounding fire, the release of hydrogen has to be expected for CALORIVAC H.

Further important information for safe handling of CALORIVAC material can be found and downloaded on our alloy specific information sheets under following link:

http://www.vacuumschmelze.com/en/the-company/quality/information-sheets-msds.html

If you have any further questions please contact us. Our contact data is on the rear cover of the brochure.

8. APPENDIX – SPECIFYING CALORIVAC ALLOYS

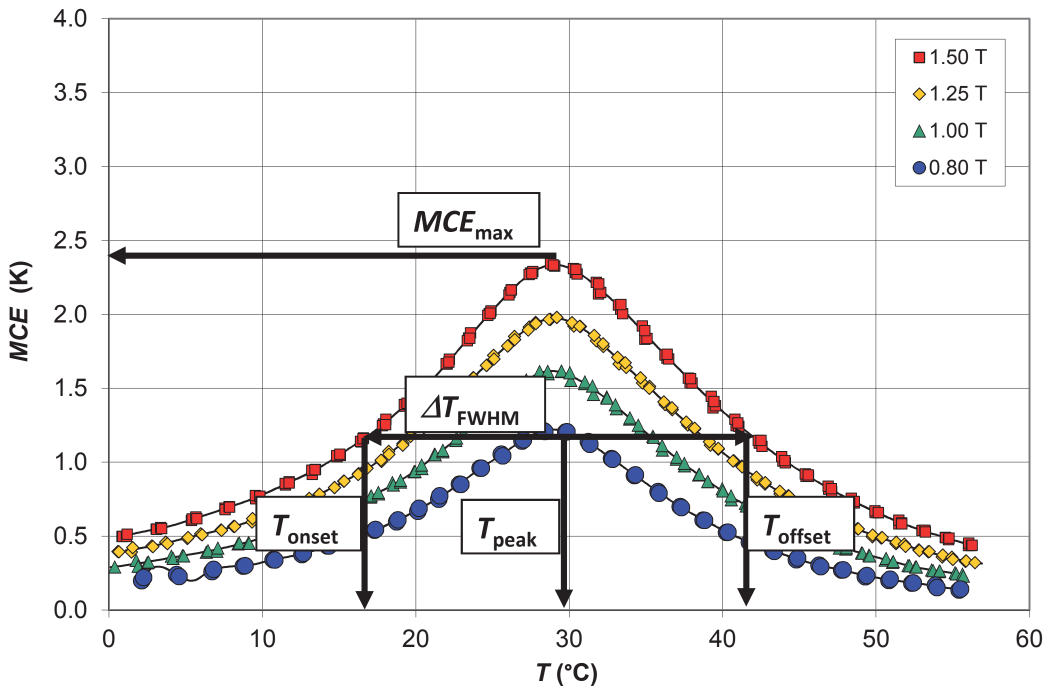


Fig. 10: Typical graph of adiabatic temperature change vs. temperature for different external magnetic induction changes

8.1 DEFINITION OF MAGNETOCALORIC PROPERTIES

By default, the magnetocaloric properties of CALORIVAC will be quality tested by measuring the adiabatic temperature change as described in Sec. 8.2.1. A typical graph of the adiabatic temperature change as a function of temperature for different external magnetic induction changes is shown in fig. 10.

The properties of the graph in fig. 10 are defined as follows

MCE_{max}	maximum adiabatic temperature change for a given change of magnetic induction
ΔT_{FWHM}	full width at half maximum, i.e. the width of the curve at half of MCE_{max}
T_{onset}	Upon increasing the temperature, T_{onset} is the temperature at which the adiabatic temperature change reaches half its maximum value
T_{peak}	Peak temperature, defined as $T_{onset} + \Delta T_{FWHM}/2$

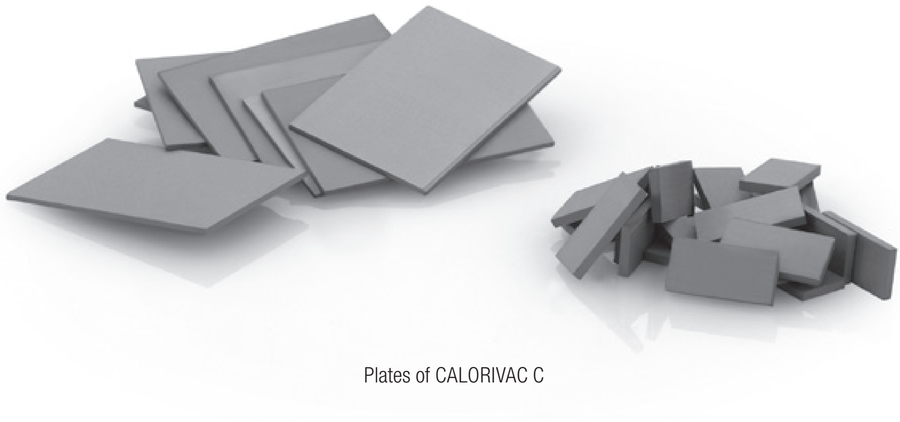
The peak temperature of the adiabatic temperature change curve is the most important property. It defines the name of the alloy which is a combination of brand name, peak temperature in units of Kelvin, and grade. For example CALORIVAC 300H refers to a CALORIVAC H alloy with a peak temperature of 300 K for a magnetic induction change of 1.5 T. All other properties defined in fig. 10 follow from the peak temperature and cannot be varied independently.

8.2 MEASUREMENT TECHNIQUES FOR MAGNETOCALORIC ALLOYS

The two physical properties defining the magnetocaloric effect – the isothermal entropy change, ΔS_T and the adiabatic temperature change ΔT_S – can be measured at VACUUMSCHMELZE. Since no international standards exist for the measurement of these properties, the equipment and procedures available at VACUUMSCHMELZE are explained here.

8.2.1 ADIABATIC TEMPERATURE CHANGE, ΔT_S

Since no commercial devices for such measurements exist, a bespoke apparatus has been designed and constructed at VACUUMSCHMELZE. The device consists of an aluminium capsule holding a powder sample of CALORIVAC and a permanent magnet assembly. The capsule has an integrated thermocouple ensuring good thermal contact to the sample. It is inserted into the air gap of the magnet assembly. The magnet assembly rotates stepwise around a fixed axis, therefore magnetizing and demagnetizing the sample in a periodic fashion. The difference in sample temperature between the magnetized and demagnetized state corresponds to the adiabatic temperature change. By changing the environmental temperature, the adiabatic temperature change can be measured as a function of temperature.



Plates of CALORIVAC C

8.2.2 ISOTHERMAL ENTROPY CHANGE, ΔS_T

We use a commercial vibrating sample magnetometer (VSM). It is equipped with an electromagnet capable of generating a magnetic field of up to 1350 kA/m between its poles. The variable temperature insert can be operated between about 100 and 500 K. The temperature of the sample is measured using a thermocouple in close proximity to the sample.

The magnetic moment of a sample is recorded as a function of decreasing temperature for four different magnetic fields. The temperature range is chosen to cover ± 50 K of the nominal Curie temperature of the sample. In order to calculate the isothermal entropy change, ΔS_T, the well-known Maxwell equation is used

$$\Delta S_T\,(T,H) = \int_0^H \left(\frac{\partial M}{\partial T}\right)_H dH$$

8.2.3 GENERAL REMARKS

All measurements are carried out within an air gap between the poles of the magnetic field sources and the sample. Therefore the sample is subject to a demagnetizing effect depending on the shape of the sample. This means that the magnetic field inside the sample is smaller than the externally applied magnetic field. Since sample shapes are in general irregular, the correction of demagnetizing effects is non-trivial. The typical demagnetizing factor, N of our samples is between 0.15 and 0.35. All magnetic properties are provided as a function of external magnetic field.

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