

Soft Magnetic Cobalt-Iron Alloys

VACOFLUX 48 • VACOFLUX 50
VACODUR 49 • VACODUR 50 • VACODUR S Plus
VACOFLUX 17 • VACOFLUX 18 HR • VACOFLUX 9 CR



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INTRODUCTION

VACUUMSCHMELZE is one of the world's leading manufacturers of special alloys with a particular focus on magnetic and specific physical properties. In addition to soft magnetic alloys, VAC's full product range comprises permanent magnets, inductive components and other materials with special physical properties.

With our strong materials expertise and experience, especially in the area of magnetism, we are able to offer our customers innovative solutions to meet their visions and design ideas. Our aim is to work with our partners to develop products which can generate a market advantage through the introduction of new technology.

Our range of soft magnetic materials comprises pure iron, nickel-iron, silicon-iron and cobalt-iron alloys, as well as amorphous and nanocrystalline alloys.

Thanks to their high magnetic saturation of up to 2.35 T, the cobalt-iron (CoFe) alloys VACOFLUX® and VACODUR® are generally suitable for all applications where high flux density and minimum weight are required.

Table 1: Composition and material standards

Material	Composition in % by weight	IEC 60404-8-6¹⁾	ASTM A801-09
VACOFLUX 48	49 % Fe, 49 % Co, 2 % V	F11	Alloy Type 1
VACOFLUX 50	49 % Fe, 49 % Co, 2 % V	F11	-
VACODUR 49	49 % Fe, 49 % Co, 2 % V + Nb	F11	Alloy Type 1
VACODUR 50	49 % Fe, 49 % Co, 2 % V + Nb	F1	-
VACODUR S Plus	49 % Fe, 49 % Co, 2 % V + Ta, Zr	F1	-
VACOFLUX 17	Residual Fe, 17 % Co, 2 % Cr	-	-
VACOFLUX 18 HR	Residual Fe, 18 % Co, 2.5 % Cr, 2 % V, 1.5 % Mn	-	-
VACOFLUX 9 CR	Residual Fe, 9 % Co, 10 % Cr, 2 % Mo, 1 % Al	-	-

1) equivalent to DIN EN 60404-8-6 and BS EN 60404-8-6

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The CoFe alloys of VACUUMSCHMELZE can be divided into three groups.

VACOFLUX 48 / 50

VACOFLUX 48 exhibits the lowest coercive field strength and the highest permeability due to the high level of alloy purity. Particularly with the normal form of supply in thin strip thicknesses, VACOFLUX 48 is considered to be the fully optimised solution for low-loss lamination stacks made from cobalt-iron.

VACOFLUX 50 is an alloy similar to VACOFLUX 48 with a very high saturation, low coercive field strength and low specific core losses. It is available in various strip dimensions and also as solid material.

VACODUR 49 / 50 / S Plus

The family of VACODUR alloys has been developed for more demanding requirements with respect to high strength combined with high saturation. The yield strength can be set to a wide range of different levels by varying the heat treatment temperature.

VACODUR 49 The yield strength can be set over a wide range from 250 to 400 MPa. This makes the material especially suitable for applications in electric motors: Stators and rotors can be stamped from the same material and then undergo different heat treatments in order to attain a magnetically optimised stator and a rotor with defined yield strength.

VACODUR 50 can be heat treated to achieve a significantly higher yield strength, covering the range from 390 to 450 MPa.

VACODUR S Plus can achieve yield strengths of up to 800 MPa and is therefore ideally suited for high speed rotors. Even at such a high yield strength, the material still has comparatively low losses.

VACOFLUX 17 / 18 HR / 9 CR

The alloys of VACOFLUX 17, 18 HR and 9 CR with reduced cobalt content have been developed for use in high speed actuator systems:

VACOFLUX 17 exhibits a very high saturation of 2.22 T and is used in the area of diesel injection. The alloy can be cold formed.

VACOFLUX 18 HR is a further development that has a high saturation of 2.09 T and an increased electrical resistivity of 0.65 $\mu\Omega\text{m}$. The increased resistivity enables faster switching times and additions to the alloy composition have improved the machinability.

VACOFLUX 9 CR has a significantly improved corrosion resistance accompanied by a much higher electrical resistance. The high saturation of 1.8 T compared to iron-chromium steels is due to the optimisation of the chromium, molybdenum and cobalt content of the alloy.

Table 2: Application examples of CoFe alloys

<i>Material</i>	<i>Application example</i>
VACOFLUX 48	Motors and generators with high power density and lowest losses, transformers with low losses at very high flux densities
VACOFLUX 50	Motors and generators with the highest torques, actuators with the highest forces, yoke parts, pole shoes for very high flux densities, magnetic lenses, dot matrix printers, relay parts
VACODUR 49	Motors and generators with high speeds, both stator and rotor applications
VACODUR 50	Motors and generators with high speeds Application mainly for rotor laminations for high centrifugal forces
VACODUR S Plus	Motors and generators with highest speeds Application specifically for rotor laminations for very high centrifugal forces
VACOFLUX 17	Components and actuators for the automotive industry operating at high pressures, e.g. diesel injection
VACOFLUX 18 HR	Components and actuators for the automotive industry with high switching speeds; generally fast switching actuators and solenoid valves
VACOFLUX 9 CR	Components and actuators for the automotive industry with special requirements for corrosion resistance, e.g. petrol injection or injection of biofuels; solenoid valves working at fast switching times and high pressures for corrosive media

MAGNETIC PROPERTIES

Before delivery to the customer, every semi-finished product is tested with respect to its magnetic properties. These tests are based on ring, strip or rod samples. The sample undergoes a heat treatment for optimising the magnetic properties. The measurement is based on the standards IEC 60404-4, IEC 60404-6 and IEC 60404-7. An air flux correction of the measured induction at high field strengths is carried out for the ballistic measuring method on rings.

Depending on agreed customer specifications, the measured values can also be taken directly from the product to be supplied.

In this case, however, the individual details with respect to the measured object, test method and the relevant measuring points should be agreed with corresponding limiting values.

Table 3: General magnetic properties after magnetic final annealing
Typical values

Material	Curie temperature	Saturation magnetostriction	Saturation polarization	Saturation magnetization
	T_C °C	λ_s ppm	J_s T	B_s T
VACOFLUX 48	950	+70	2.30	2.35
VACOFLUX 50	950	+70	2.30	2.35
VACODUR 49	950	+70	2.30	2.35
VACODUR 50	950	+70	2.28	2.33
VACODUR S Plus	950	+70	2.25	2.30
VACOFLUX 17	920	+25	2.22	2.27
VACOFLUX 18 HR	920	+25	2.09	2.14
VACOFLUX 9 CR	800	+30	1.80	1.85

DC magnetic properties of strip material

Table 4: DC magnetic properties after magnetic final annealing (strip thickness 0.35 mm)
Typical values

<i>Material</i>	<i>H_c</i> <i>max.</i> <i>A/m</i>	<i>H_c</i> <i>typ.</i> <i>A/m</i>	<i>μ_{max}</i>	<i>B</i> at <i>300</i> <i>A/m</i> <i>T</i>	<i>B</i> at <i>800</i> <i>A/m</i> <i>T</i>	<i>B</i> at <i>1600</i> <i>A/m</i> <i>T</i>	<i>B</i> at <i>4000</i> <i>A/m</i> <i>T</i>	<i>B</i> at <i>8000</i> <i>A/m</i> <i>T</i>	<i>B</i> at <i>16000</i> <i>A/m</i> <i>T</i>
VACOFLUX 48	≤40	35	18000	2.05	2.18	2.24	2.275	2.29	2.30
VACOFLUX 50	≤80	50	15000	1.90	2.10	2.20	2.255	2.28	2.30
VACODUR 49 ¹⁾	≤80	50	15000	1.90	2.10	2.20	2.255	2.28	2.30
VACODUR 49 ²⁾	≤160	110	7000	1.80	2.05	2.15	2.25	2.27	2.30
VACODUR 50 ¹⁾	≤160	120	9000	1.80	2.05	2.15	2.22	2.26	2.28
VACODUR 50 ²⁾	≤200	160	5000	1.70	2.00	2.11	2.19	2.23	2.26
VACODUR S Plus ¹⁾	≤140	120	6000	1.60	1.92	2.07	2.15	2.19	2.21
VACODUR S Plus ²⁾	≤700	600	1100	-	1.20	1.80	2.03	2.11	2.15
VACOFLUX 17	≤200	140	3500	1.2	1.5	1.6	1.75	1.9	2.05

H_c = coercive field strength, μ_{max} = relative maximum permeability, B = induction

1) annealed for optimum magnetic properties

2) annealed for optimum mechanical properties

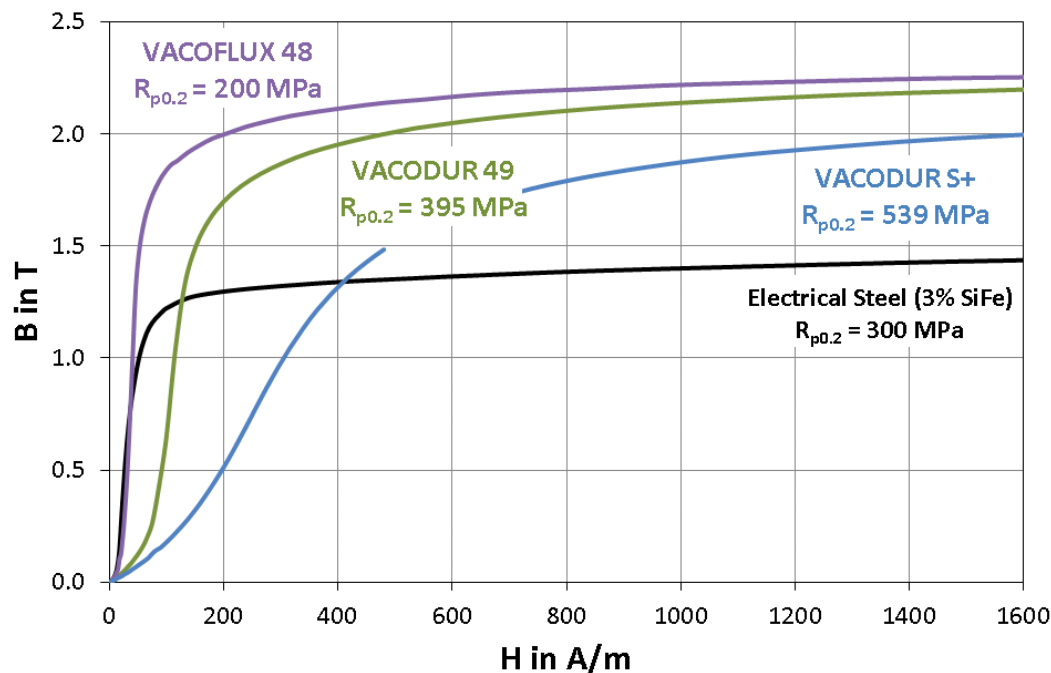


Figure 1: Normal DC magnetization curves of some 50 % CoFe alloys and a reference material (3 % SiFe) with corresponding yield strengths R_{p0.2}.

DC magnetic properties of solid material

Table 5: DC magnetic properties after magnetic final annealing (solid material)
Typical values

<i>Material</i>	<i>H_c</i> <i>max.</i> <i>A/m</i>	<i>H_c</i> <i>typ.</i> <i>A/m</i>	<i>μ_{max}</i>	<i>J at</i> <i>10 kA/m</i> <i>T</i>	<i>J at</i> <i>16 kA/m</i> <i>T</i>	<i>J at</i> <i>20 kA/m</i> <i>T</i>	<i>J at</i> <i>40 kA/m</i> <i>T</i>
VACOFLUX 50 ¹⁾	≤ 240	100	7000	2.27	2.28	2.28	2.29
VACODUR 49 ^{1) 3)}	≤ 240	100	7000	2.27	2.28	2.28	2.29
VACOFLUX 17 ²⁾	≤ 200	140	3200	1.94	2.04	2.09	2.19
VACOFLUX 18 HR ²⁾	≤ 350	170	2500	1.87	1.96	2.00	2.06
VACOFLUX 9 CR ¹⁾	≤ 200	130	3000	1.70	1.76	1.78	1.80

H_c = coercive field strength, μ_{max} = relative maximum permeability, J = polarization

1) hot-rolled, 2) cold drawn, 3) only magnetically optimised state

Specific core losses of strip material

Table 6: Specific core losses of strip material after magnetic final annealing (strip thickness 0.35 mm)
Typical values

<i>Material</i>	<i>p_{Fe}</i> <i>1.5 T 50 Hz</i> <i>W/kg</i>	<i>p_{Fe}</i> <i>1.5 T 400 Hz</i> <i>W/kg</i>	<i>p_{Fe}</i> <i>2 T 50 Hz</i> <i>W/kg</i>	<i>p_{Fe}</i> <i>2 T 400 Hz</i> <i>W/kg</i>
VACOFLUX 48	1.5	30	2.2	58
VACOFLUX 50	1.6	31	2.5	60
VACODUR 49 ¹⁾	1.6	31	2.5	60
VACODUR 49 ²⁾	2.9	43	5.0	78
VACODUR 50 ¹⁾	3.0	44	5.0	80
VACODUR 50 ²⁾	4.5	53	7.7	93
VACODUR S Plus ¹⁾	3.0	41	5.0	74
VACODUR S Plus ²⁾	17	154	32	290
VACOFLUX 17	4.5	57	7.0	88

p_{Fe} = specific core losses

1) annealed for optimum magnetic properties

2) annealed for optimum mechanical properties

MECHANICAL PROPERTIES

The typical mechanical properties of strip and solid material after final annealing are summarized in the tables below. The data is only to be regarded as a guide because the final state depends considerably on the heat treatment and cold forming. Depending on the as-delivered state of the material, a minor directional dependency of the characteristic values is possible.

The mechanical properties are measured in accordance with DIN EN ISO 6892-1 (tensile testing of metallic properties) and DIN EN ISO 6507 (hardness test as per Vickers). The tensile yield strength is denoted by the term $R_{p0.2}$.

In the case of stamped parts from the VACODUR range of alloys, a higher strength can be achieved by annealing at lower temperatures (“annealed for optimum mechanical properties”). Alternatively, an optimized magnetic part can be attained by annealing at high temperatures (“annealed for optimum magnetic properties”). It is only possible to set defined yield strengths in the case of strip material.

Figure 2 provides an overview of the adjustable yield strength ranges of the available VACODUR alloys and the associated magnetic properties. Maximum yield strengths of up to 800 MPa can be attained with VACODUR S Plus.

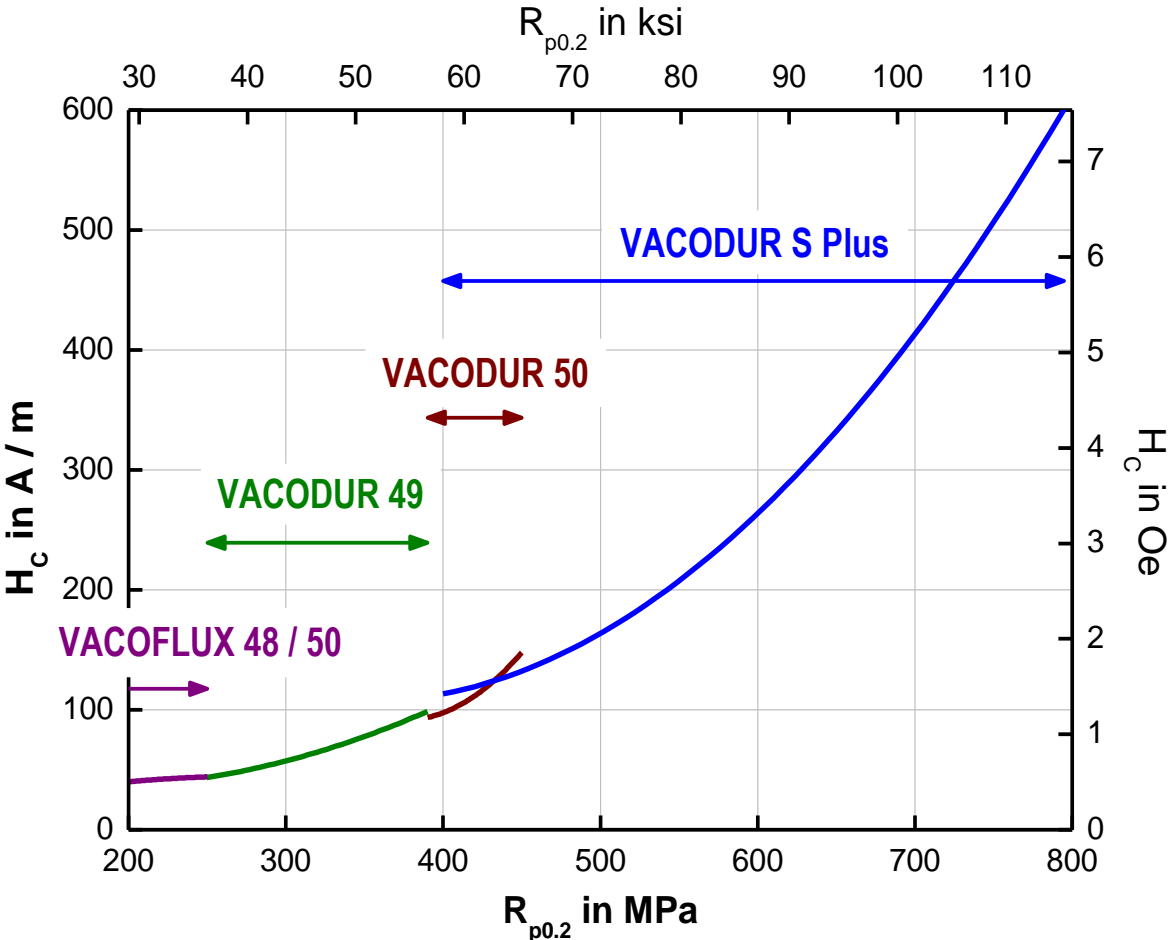


Figure 2: Bandwidth of the ranges adjustable by final annealing for the yield strength $R_{p0.2}$ and coercive field strength H_c for VACOFLUX and VACODUR (strip material 0.35 mm).

Mechanical properties of strip material

Table 7: Mechanical properties of strip material after final annealing (strip thickness 0.35 mm)
Typical values

Material	$R_{p0.2}$ MPa	R_m MPa	E GPa	A %	HV10
VACOFLUX 48	190	220	200	2	180
VACOFLUX 50	250	550	210	6	190
VACODUR 49 ¹⁾	210	400	200	4	185
VACODUR 49 ²⁾	390	720	250	8	220
VACODUR 50 ¹⁾	390	720	250	8	210
VACODUR 50 ²⁾	450	820	240	10	240
VACODUR S Plus ¹⁾	400	800	250	6	230
VACODUR S Plus ²⁾	800	1200	250	8	300
VACOFLUX 17	250	450	200	32	140

$R_{p0.2}$ = yield strength, R_m = tensile strength, E = modulus of elasticity, A = elongation at fracture, HV10 = Vickers hardness

Sampling parallel to the rolling direction

1) annealed for optimum magnetic properties

2) annealed for optimum mechanical properties

Mechanical properties of solid material

Table 8: Mechanical properties of solid material after final annealing
Typical values

Material	$R_{p0.2}$ MPa	R_m MPa	E GPa	A %	HV10
VACOFLUX 50	250	350	215	3	205
VACODUR 49 ¹⁾	220	350	205	3	205
VACOFLUX 17	250	450	200	32	140
VACOFLUX 18 HR	400	600	210	28	200
VACOFLUX 9 CR	330	490	180	35	170

$R_{p0.2}$ = yield strength, R_m = tensile strength, E = modulus of elasticity, A = elongation at fracture, HV10 = Vickers hardness

Sampling parallel to the rolling direction

1) annealed for optimum magnetic properties

With VACODUR 49, the yield strength can be set accurately by the annealing temperature. The resultant yield strength decreases linearly as the annealing temperature rises, cf. Figure 3. This is advantageous if a reliable setting of a defined strength is required under production conditions.

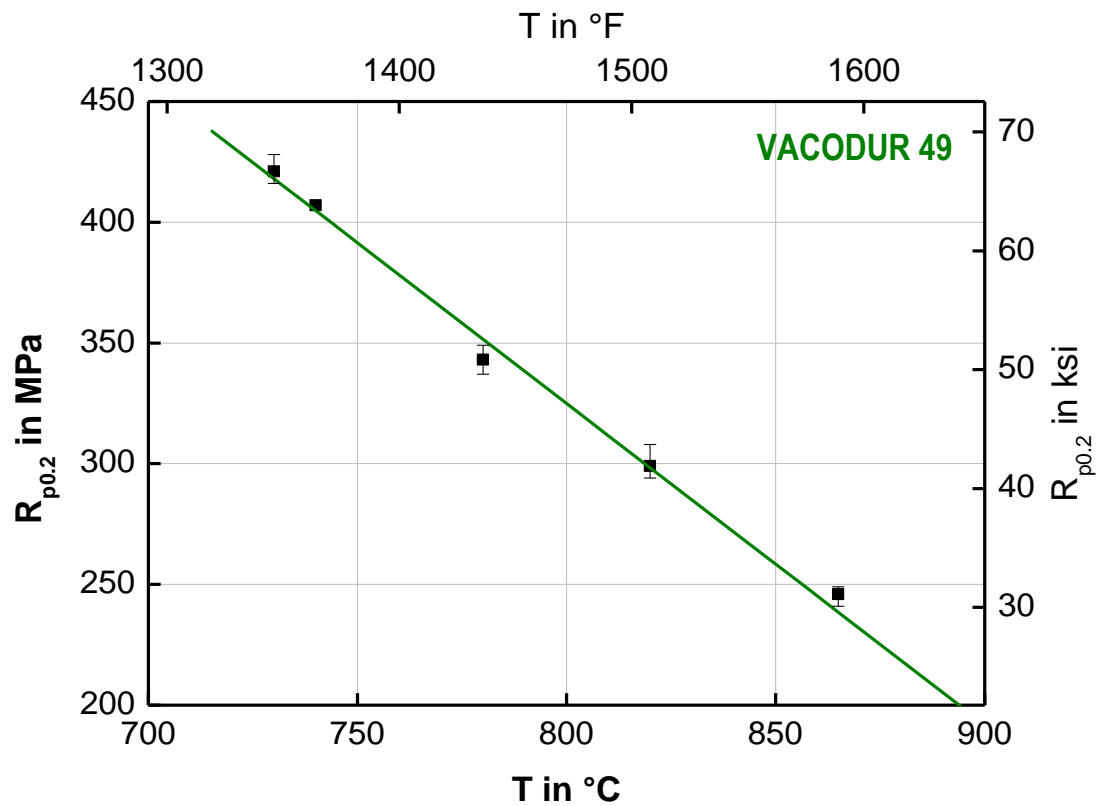


Figure 3: Variation of the yield strength $R_{p0.2}$ of VACODUR 49 strip material with respect to the annealing temperature T . Held at temperature T for 4 h (strip material 0.35 mm).

FURTHER PHYSICAL PROPERTIES

Table 9: Physical properties after magnetic annealing
Typical values

Material	Electrical resistivity	Density	Coefficient of linear expansion (20..200 °C)
	ρ_{el} $\mu\Omega m$	ρ g/cm^3	α $10^{-6}/K$
VACOFLUX 48	0.40	8.12	9.80
VACOFLUX 50	0.40	8.12	9.65
VACODUR 49	0.40	8.12	9.15
VACODUR 50	0.40	8.12	9.20
VACODUR S Plus	0.40	8.12	9.15
VACOFLUX 17	0.40	7.94	10.8
VACOFLUX 18 HR	0.65	7.81	10.6
VACOFLUX 9 CR	0.79	7.75	11.0

CORROSION RESISTANCE (VACOFLUX 9 CR)

VACOFLUX 9 CR has been developed specially for applications in corrosive media. It has a good corrosion resistance in salt spray tests, comparable to 13 % chromium steel.

For an optimum corrosion resistance, as is also required for stainless steels, it is necessary that the surface does not contain any impurities e.g. foreign metal particles, salt impurities due to mechanical processing steps or oxidation layers due to annealing treatments.

From a technical viewpoint with respect to corrosion, a gentle mechanical processing with subsequent cleaning of the surface is recommended in order to attain an optimum surface condition. The extent to which an abrasive pickling process has to be carried out, together with a subsequent passivation, needs to be evaluated for each specific application.

Heat treated surfaces, or the oxide coatings resulting from such processes, must be removed by a mechanical processing with subsequent cleaning of the parts. An abrasive pickling of the heat treated surface with subsequent passivation leads to an optimum corrosion resistance (see the section on forms of supply, page 17).

Petrol-methanol water

A sample rod of VACOFLUX 9 CR was stored at 130 °C for a total of 150 hours in a petrol-methanol-water solution. The solution comprised 84.5 % fuel, 15 % methanol, 0.5 % corrosive water (16.5 mg sodium chloride/l, 13.5 mg sodium hydrogen carbonate/l, 14.8 mg formic acid/l). No signs of corrosion could be seen on the sample at 40x magnification.

Salt spray test

A sample rod of VACOFLUX 9 CR was subjected to a salt spray test as per DIN EN ISO 9227 for a total of 96 hours. The original sample was peeled finally annealed material and cleaned, thereby giving it a shiny surface. No signs of corrosion could be seen on the sample.

The recommendations and examinations outlined here can only serve as an initial overview, owing to the wide variety of possible requirements, media and processing methods.

FURTHER PROCESSING

Magnetic final annealing

A final heat treatment (“magnetic final annealing”) is mandatory for achieving the magnetic and mechanical properties. The necessary growth of the grains in the material, and hence the accompanying improvement in the characteristic magnetic values, only occurs during the final annealing. The values stated in the product data can only be attained after performing the final annealing.

The typical temperature profile of a possible heat treatment of VACOFLUX or VACODUR is shown in Figure 4.

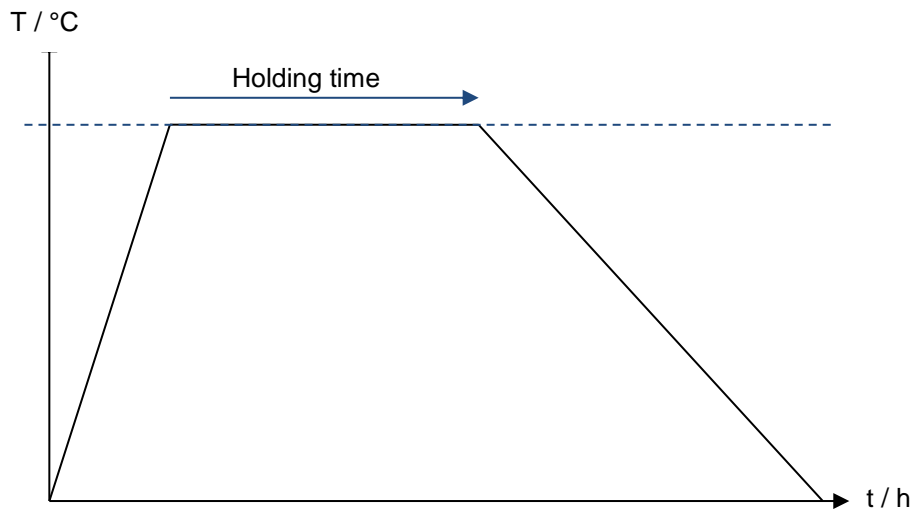


Figure 4: **Temperature profile of the final heat treatment of VACOFLUX or VACODUR alloys.**

Ideally, the annealing should be carried under pure dry hydrogen, taking into account the annealing temperatures and holding times listed in Table 10. The use of a vacuum or an inert gas atmosphere is possible, but the purity of the atmosphere does have a crucial influence on the magnetic quality.

Hydrogen has the advantage that it is a powerful reducing atmosphere and therefore not only prevents oxidation but also removes impurities in the material. To ensure ultimate purity of the atmosphere, the content of water vapour and oxygen should be extremely low, meaning that a dew point $< -50^{\circ}\text{C}$ is required. If an alternative inert gas is used, then it should not contain any harmful impurities and have a low dew point.

The upper specified heat treatment temperature should not be exceeded, as otherwise a degradation of the magnetic properties could result because of the formation of a magnetically unfavourable phase in the material. Depending on the furnace geometry, loading conditions and the shape of the parts, it is possible to vary the holding times indicated. The cooling should always continue down to below 200°C in an inert gas atmosphere at a rate of 100 to 200 K/h.

VACOFLUX 9 CR typically exhibits a slight colouration after the final annealing.

For the VACODUR range of alloys, the annealing treatment can be varied in order to set a specific yield strength value. To achieve higher yield strengths, a lower annealing temperature and a shorter holding time are selected. In particular, at high yield strengths, compliance with an accurately controlled temperature and time specification must be ensured. The defined adjustability of the yield strength is only possible for cold-rolled strip material. A magnetically optimised final annealing is generally recommended for hot-rolled material.

To avoid thermal welding or stiction of laminations during annealing, the strip requires coating with a thin insulation layer, designated as DL1. After the final annealing, this coating is reduced to an insulating layer of magnesium oxide (MgO), with a typical layer thickness below 1 µm.

When increased demands for insulation are required, e.g. for laminated stator and rotor stacks, annealing in an oxidizing atmosphere is recommended in order to create a thin, additional insulating surface layer. Depending on the type of furnace and desired thickness of the oxide layer, such a heat treatment is performed for half an hour to three hours at 350 °C to 450 °C.

VACUUMSCHMELZE also provides the option of annealing and oxidizing parts or laminations of our VACODUR or VACOFLUX alloys which are produced by our customers.

Table 10: Recommended parameters for the final heat treatment

<i>Material</i>	<i>Temperature</i> °C	<i>Holding time</i> <i>strip</i> h	<i>Holding time</i> <i>solid material</i> h	<i>Cooling rate</i> K/h
VACOFLUX 48	880	10	-	~ 100
VACOFLUX 50	820	4	10	~ 100
VACODUR 49 ¹⁾	880	6	6	~ 100
VACODUR 49 ²⁾	750	3	-	~ 100
VACODUR 50 ¹⁾	820	2 – 5	10	~ 100
VACODUR 50 ²⁾	750	2 – 5	-	~ 100
VACODUR S Plus ¹⁾	840	4	-	~ 100
VACODUR S Plus ²⁾	720	1 – 2	-	~ 100
VACOFLUX 17	850	10	10	~ 100
VACOFLUX 18 HR	800	-	10	~ 100
VACOFLUX 9 CR	800	-	10	~ 100

1) annealed for optimum magnetic properties

2) annealed for optimum mechanical properties

General processing information

During the heat treatment of strip material of a CoFe alloy with around 50 % Co content (VACOFLUX 48, VACOFLUX 50, VACODUR 49, VACODUR 50 and VACODUR S Plus), a permanent, anisotropic length increase of up to 0.2 % occurs. Precision machined parts made from strip material should therefore only be processed to their final dimensions after the heat treatment.

It must be noted that the workability of the alloys with 50 % Co content is not improved by annealing, but actually becomes more difficult due to embrittlement.

Every processing of the finally-annealed material has an influence on the soft-magnetic properties. When manufacturing shaped parts with narrow tolerances, the last fine processing after the heat treatment should be performed as gently as possible.

The product brochure: "Machining Data of our Soft-magnetic Alloys" (AHT-001) is available as a download on the homepage of VACUUMSCHMELZE, or on request as a paper copy. This brochure provides an initial starting point for machining.

VAC can offer to produce complete laminated stacks according to a process specially adapted to CoFe alloys (VACSTACK® process). Optimizing the production method means that tight dimensional tolerances are achieved together with very low specific core losses.

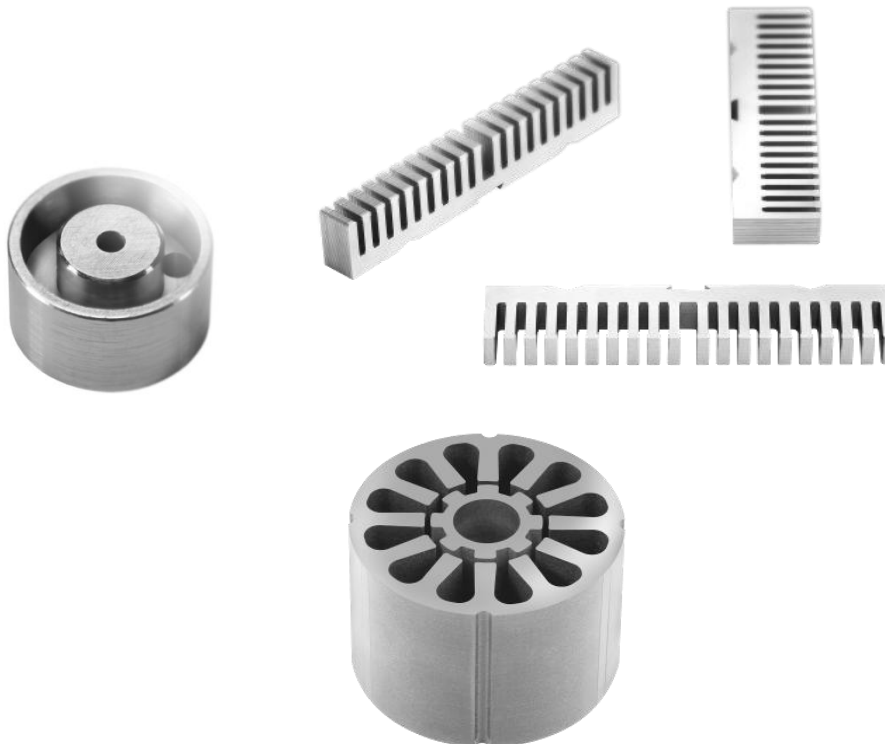


Figure 5: **Examples of parts made from cobalt-iron materials: Turned components for actuators, stamped lamination assemblies for motors and generators**

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FORMS OF SUPPLY

The soft magnetic CoFe materials are available in many shapes and dimensions. Besides supplying semi-finished products (strips, rods and wires), VAC also manufactures core laminations, stamped parts, shaped and solid parts as well as laminated assemblies. The manufacture of laminated stacks with optimised losses is offered especially for CoFe alloys under the trade name VACSTACK.

The following table provides an overview of the availability of our materials in the various forms of supply.

<i>Material</i>	<i>Semi-finished product</i>			<i>Finished parts</i>		
	<i>Strip</i>	<i>Rods</i>	<i>Wire</i>	<i>Core laminations, stamped parts</i>	<i>Laminated Assemblies VACSTACK</i>	<i>Shaped and solid parts</i>
VACOFLUX 48	●	-	-	●	●	-
VACOFLUX 50	●	●	-	●	●	●
VACODUR 49	●	●	-	●	●	●
VACODUR 50	●	●	-	●	●	●
VACODUR S Plus	●	-	-	●	●	-
VACOFLUX 17 ¹⁾	●	●	●	●	●	●
VACOFLUX 18 HR	-	●	-	-	-	●
VACOFLUX 9 CR ²⁾	-	●	●	-	-	●

● = available, - = not available or on request

1) delivery state "soft deep-drawable" possible for strip

2) delivery state "magnetically finally annealed" possible

The alloys with 50 % Co content (VACOFLUX 48, VACOFLUX 50, VACODUR 49, VACODUR 50 and VACODUR S Plus) are only available in hard or cold rolled condition. Soft delivery states are also possible for alloys with lower Co content (VACOFLUX 17, VACOFLUX 18 HR, VACOFLUX 9 CR). VACOFLUX 17 is also available in the delivery state "soft deep-drawable".

VACOFLUX 9 CR is offered in the state "magnetically finally annealed" as standard, i.e. the final annealing has already been performed on the semi-finished product. Depending on the geometry and application, an additional heat treatment of the parts can be omitted. A further advantage of this delivery state is the fact that parts that are machined from finally annealed rods have a bright, non-tarnished surface, resulting in an improved resistance in the salt spray test (see section on corrosion resistance, page 13).

For strip material in the thickness range 0.50 mm or thinner, an insulation coating based on Mg and designated as DL1 is recommended. Individual laminations have improved separation from one another due to the coating, thus reducing the risk of thermal welding of the laminations during the final annealing.