4.4.1 Alnico Magnets

Alnico alloys contain 7 – 13% Al, 12 – 18% Ni, up to 40% Co and up to 6% Cu as well as possibly small amounts of Ti, Si, S and Nb. Alnico 5 (or Alnico V) is often mentioned in connection with guitars. This numbering system (Alnico 1 -12), typical for the USA, should classify the increasing BH_{max} value (volume-specific energy), however, a precise specification of the magnetic characteristics and composition is not possible. Particularly, one has to take into account that Alnico 2 is stronger than Alnico 3. Alnico 2, Alnico 3 and Alnico 5 are used most often in pickups.

	B_r / T	H_c / kA/m	BH_{max} / kJ/m^3	Al	Ni	Co	Cu	Ti
Alnico 3	0.65 - 0.75	32 - 45	10 - 11	12	24-26	0	0-3	–
Alnico 2	0.7 - 0.85	34 - 52	12 - 14	10	17-19	12-15	3-6	0.5
Alnico 5	1.1 - 1.3	50 - 62	30 - 50	8	12-15	23-25	0-4	0-0.5

Table: Magnetic characteristics and composition percents of Alnico-magnets; remainder = Fe.

Alnico magnets are differentiated in casted and sintered ones, which can be isotropic or anisotropic, depending on their production method. The production of **cast** magnets consists of melting the metallic constituents and casting the melt in the mold where it solidifies, e.g. sand casting, chill casting, and vacuum precision casting. Untreated casted magnets have a dark greyish-brown color. During **sintering**, the fine-milled constituents are baked under high pressure and high temperature. Sintered magnets are shiny metallic, similar to nickel. Contrary to the cast magnets, sinter magnets have improved mechanical but slightly worse magnetic characteristics. In particular, their remanence is slightly smaller than that of cast magnets. The coercive field strengths are similar. Sinter magnets can only be produced economically with small dimensions and in large quantities. They exhibit fewer pores, shrink holes and cracks than cast magnets and better retain their required composition. Alnico magnets can only be ground due to their very high mechanical **hardness** (Rockwell hardness 45 – 60 HRC). The ground surfaces are shiny metallic.

Isotropic material characteristics are independent of direction. In contrast, anisotropy means that a spatially predominant direction exists in which a certain characteristic, in this case magnetic, is more pronounced (*oriented material*). Cast as well as sintered magnets without special treatment are isotropic.

Magnetic alloys with Al, Ni and Co constituents were, and still are, produced world-wide under different brands. As the first commercially successful pickups were developed and wound in the USA, the American abbreviation Alnico became accepted. **Seth Lover**, the developer of the Gibson “Patent Applied For” humbucker, answered the question whether he *always* used Alnico V magnets with “We also used Alnico II and III, because Alnico V was not always available. The only difference was that Alnico V did not lose its magnetization as easily [13].”

There is something to add from a physical point of view and, obviously, also from a commercial point of view: in 2002 Gibson communicated on their homepage: *"BurstBucker pickups now give guitarists a choice of three replica sounds from Gibson's original "Patent Applied For" pickups – the pickups that give the '59 Les Paul Standard it's legendary sound. ... with unpolished* ***Alnico II*** *magnets and no wax potting of the coils, just like the originals"*. However, one should keep in mind that Alnico II as well as Alinco V were produced in different variations before wondering about the fact that today's replica pickups are produced out of a material that once was a stopgap. C. Heck [21] maintains four different Alnico II and 8 different Alnico V versions:

	B_r / T	H_c / kA/m	BH_{max} / kJ/m^3	Al	Ni	Co	Cu
Alnico II	0.73	46	12.8	10	17	12.5	6
Alnico II A	0.70	52	13.6	10	18	13	6
Alnico II B	0.75	46	13.6	10	19	13	3
Alnico II H	0.84	48	16.8	10	19	14.5	3

	B_r / T	H_c / kA/m	BH_{max} / kJ/m^3	Al	Ni	Co	Cu
Alnico V A	1.20	58	40	8	15	24	3
Alnico V AB	1.25	55	44	8	14.5	24	3
Alnico VABDG	1.31	56	52	8	14.5	24	3
Alnico VB (V)	1.27	52	44	8	14	24	3
Alnico VBDG	1.33	55	52	8	14	24	3
Alnico V C	1.32	46	44	8	13	24	3
Alnico V E	1.10	56	36	8	14.5	24	3
Alnico V-7	1.28	62	56	8	14	23	3

Table: Magnetic characteristics and percent compositions of Alnico magnets; remainder = Fe.

Obviously, a "typical" Alnico 5 material does not exist. The remanence values given in this table vary by ±10% and the coercive field strength by ±11%. The variation of the respective hysteresis curves is shown by **Fig. 4.7**. The units correspond to the CGSA-system common in the USA: 1Oe = 80 A/m, 10 kG = 1T, 1 MGOe = 8 kJ/m³. When considering whether Alnico 5 "sounds" better than Alnico 2, one also has to investigate which special Alnico variation is applicable. In addition, it is especially problematic that the magnetic characteristics of a material not only derive from its chemical composition but also from the physical parameters of its production process. In particular, the temperature treatments and external magnetic fields can have lasting (permanent) impact.

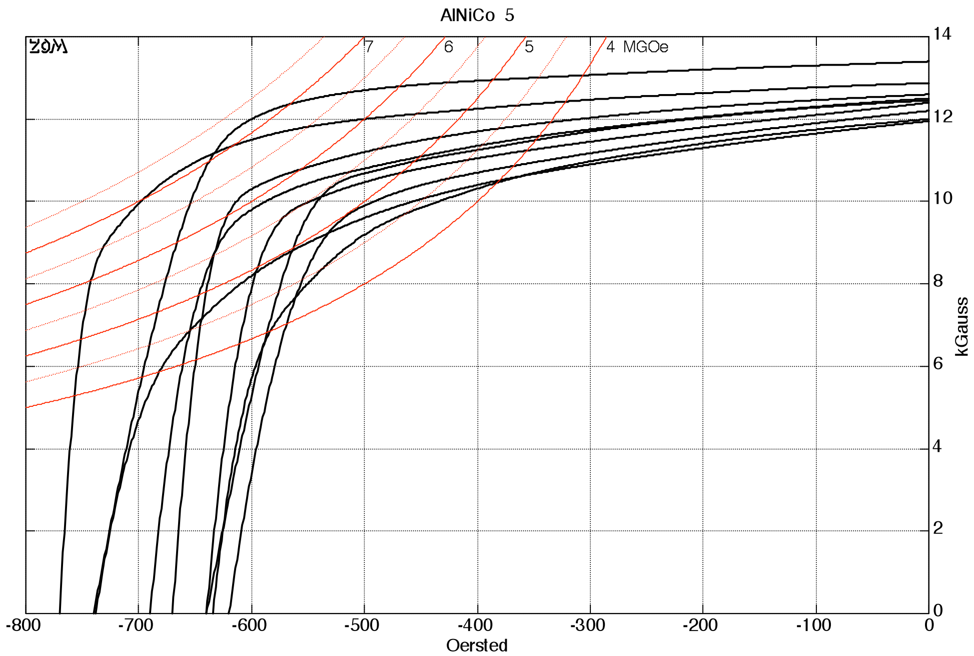


Fig. 4.7: *B/H*-characteristics of various Alnico-5-magnets [22, 23]. 1Oe = 80A/m, 10kG = 1T, 1MGOe = 8kJ/m^3.

The basics of material science are helpful in understanding of the characteristics of Alnico: In solid metals the atoms arrange themselves in a regular periodic lattice. However, this **crystal lattice** is not constructed perfectly, but also contains crystal defects which have a significant influence on the material properties. The supply of energy (heating) results in a rearrangement of the atoms in looser structure and the metal becomes liquid. During the subsequent **cool-down** (solidification), crystallization begins at many different sites (the so-called **nucleation centers**). The growth of these internally regular crystals, also called grains or **crystallites**, persist until they hit a neighboring crystallite. At room temperature the metal has a **polycrystalline structure**. Polycrystalline means that the entire metal volume is made up of many single crystallites that butt up at their grain boundaries. Inside, every crystallite is **monocrystalline**, i.e. all atoms are essentially arranged in a periodic lattice. However, the orientation of each crystallite, which is only several micrometers in size, points into a different direction.

The properties of a crystal lattice result from its constituents, the bonding conditions and the lattice geometry. It is well known, that diamond as well as graphite consist of pure carbon. Both materials, which in fact do not belong to the metals, have completely different characteristics because their carbon atoms are arranged in different crystal configurations (cubic or hexagonal). Likewise, some metals occur in different (polymorphic) crystalline structures: iron, cobalt, manganese, titanium, tin and zirconium. At a certain temperature their lattice system changes and so do their material properties. The change of material characteristics is especially pronounced for alloys, i.e. metal mixtures. For instance, for an iron-carbon alloy **steel** the physical properties can be changed by hardening and annealing, although the chemical composition is not changed substantially. Also non-iron metals like copper can change their stiffness by bending (strain hardening) although their chemical composition remains unchanged. The root cause again is a change in the lattice structure (lattice defects).

The magnetic material properties also depend on the crystal structure. In the iron atom the electrons *orbiting* around the nucleus produce individual magnetic fields that are externally completely compensated. On the other hand, the magnetic fields originating from the electron *spin* are not completely compensated. Thus, every atom displays an **elementary magnetic dipole**. Inter-atomic forces try to orient the dipoles parallel to each other as well as parallel to the edges of the iron crystal lattice. In a cubic lattice there are six sign-dependent orthogonal edge directions in which the elementary dipoles of a non-magnetized iron crystal are oriented. Accordingly, regions of neighboring atoms with the same magnetization directions are formed. PIERRE WEISS was the first to postulate these regions of equal magnetization direction which were, hereafter, called WEISS domains, elemental domains or simply **domains**. All domains are magnetically saturated; all domain atoms point in the same magnetic direction. In general, a crystallite incorporates many domains. Their individual orientation is statistically uniform with respect to the six lattice orientations. The entire piece of iron is initially macroscopically non-magnetic as a result of this uniform orientation.

Initially the domain walls will move reversibly with application of a very weak external magnetic field. These domain walls are called **Bloch walls**, named after FELIX BLOCH. As a result, the domains that are parallel to the external field will grow. At higher external magnetic field strengths the movement becomes irreversible, i.e. the Bloch walls will no longer return to their initial position after removal of the external magnetic field, but will remain in the nearest energetically favorable level. The movement of the Bloch walls may even lead to a degradation (annihilation) of smaller domains in favor of the larger ones. Even higher magnetic field strengths may lead to the reversible and/or irreversible orientation of the elementary dipoles from the crystal axis direction to the direction of the external field. Once irreversible changes have occurred, the magnetic orientations of the (newly formed) domains are no longer equally distributed and a persistent (permanent) magnetization (**remanence**) will be remain after the external field has been removed.

Permanent magnets are characterized by their excellent resistance of the domain magnetization to external fields. One possibility to achieve this is to reduce the magnetic particles to a size where no Bloch walls may be included and every magnetic crystallite may contain only one domain. In this configuration only the more difficult, less accessible, reorientation processes may occur without the easier movement of Bloch walls. Small magnetic particles may be produced by milling (powder magnets) or by cooling down fused alloys. Alnico magnets belong to the class of **precipitation alloys**, in which magnetic particles can be grown to the right size by an appropriate temperature treatment (annealing).

Alloys are mixtures of materials with metallic properties. For Alnico, the main constituent (the base metal) is iron with additional alloy elements (Al, Ni, Co, Cu). After heating (e.g. up to 1670°C), all of the components are mixed up in a melt which solidifies during cooling. The solidified alloy is single phase (phase = crystal class) at temperatures above 1100°C, which means that it is made up of only one single cubic face-centered crystal class (α). Although the alloy is already solidified, the miscibility of the components is described as the *solubility* which, in this case, means a solid solution. There is, however, a maximum solubility of the alloy components which is temperature-dependent: The maximum solubility becomes lower with decreasing temperature.

The homogenous one-phase mixed crystals that exist at high temperatures dissociate into two new phases which are also cubic space-centered: into the Fe-Ni-Al **matrix** (α_2, basic substance) and into an internally finely distributed Fe-Co phase (α_1). The matrix is only weakly magnetic. However, the ball- or rod-like Fe-Co particles are heavily ferromagnetic. The change of texture from the mono-phase into the double-phase configuration which will evolve during the cool down from 850°C to 750°C is called **spinodal decomposition** (spinodal dissociation) [24]. Electron microscopic investigations have shown that the developing ('precipitated') α_1-particles are located along the cubic edges of the matrix. Once the particles can be magnetized during their development, they can be influenced by an external magnetic field so that they orient in a **preferred direction**. To achieve this, the Curie-temperature has to be decreased by a suitable addition of Co so that it is lowered below the spinodal temperature, because ferromagnetics can be magnetized only above the Curie-temperature. Magnetic materials which have been cooled down in this way in an external magnetic field will show a spatial anisotropy, i.e. their magnetic characteristics are direction dependent. The size of the α_1-particles developed during spinodal decomposition can be changed to a large extent by a several hours long annealing (**tempering**) at 600°C – with substantial influence on the maximum coercive field strength. Most effective are elongated particles with lengths several times their diameter but with sizes well below the onset of Bloch wall generation.

Cubic matrix crystallites with arbitrary orientation are formed during segregation; their edges are pointing in uniformly distributed directions. (For one single crystallite the orientations of the edges are, of course, orthogonal). During cool down in a magnetic field the α_1-particles are arranging predominantly next to the nearest edge orientation, but as the crystallites are still directed in different orientations, the best result is not yet realized. To achieve this, all crystallites in the matrix have to be oriented parallel to each other, which means they have to be grown parallel to the lattice directions. Applying special treatments (unidirectional cooling, homogeneous temperature gradient, quenching plate) it is possible to come close to the ideal situation. Magnets produced in this manor are called *grain oriented, crystal oriented, preference oriented or columnar oriented*. However, they can reach their optimum properties only if the oriented crystal growth (**crystal anisotropy** of the matrix) is combined with a proper magnetic field treatment (**form anisotropy** of the α_1-particles).

In this short excursion into material sciences it should be pointed out that it is not sufficient to simply characterize pickup magnets by their chemical composition. The description of "Alnico V by 8% Al, 14% Ni, 24% Co, 3% Cu" does not provide information on the remanence, coercivity or permeability. Moskowitz [23] summarizes this complex of problems: *There are 16 factors that determine the actual performance of a specific basic magnet in a particular circuit. The magnetic and physical properties of the material are directly dependent on the following factors in the manufacturing process: chemical composition, crystal or particle size, crystal or particle shape, forming and/or fabrication method, and heat treatment. Permeability, coercive force, and hysteresis loop are specifically affected by gross composition, impurities, strain, temperature, crystal structure and orientation. The effects of each of these factors are metallurgically complex and beyond the scope of this book.* After all, "this Book" is called PERMANENT MAGNET DESIGN AND APPLICATION HANDBOOK. This book has most probably not been read by the author of the 2001 published book "E-Gitarren" who wrote: *"The production of a magnet is quite simple. The basic materials will only be exposed to a high electrical voltage ... The field strength of a magnet produced in such a way might be measured in Gauss."* ?? ☹ !!

Magnets with defined magnetic properties *cannot* be produced easily. Contrary to the constant current resistance, magnetic parameters are not easily measured. The resistance variations of ±5% are discussed in depth in pickup literature and the sound difference between Alnico-5 and Alnico-2 is addressed in epic scope. However, the variation of magnetic parameters is usually not mentioned.

Very pure components are necessary for the production of Alnico magnets. McCaig [26] claims iron with a maximum carbon concentration of 0,02%, whereas Cedighian [25] recommends aluminum with a purity grade of at least 99,6%. Moskowitz [23] claims *very close metallurgical controls* and tolerances of, for example, ±0.05% for titanium and ±0.06% for silicon. These tolerances must not only be realized during weighing but also for the melt. Moskowitz [23] demands that Alnico-3 has to be homogenized at 1290°C ±5°C and McCaig writes that a temperature deviation of only 10°C can lead to *extremely poor results*. Did all magnet suppliers apply such a high precision, particularly in the forties and fifties of the last century when the famous vintage pickups were produced? The scientists that were involved in magnet production tried to gain insight into the crystal structures with the microscopes available at that time. However, the optical microscopes could not resolve particles as small as approximately 40nm x 8nm x 8nm. Electron microscopes as well as X-ray equipment were already available, but not in large numbers. McCaig [26] notes: *We at the Central Research Laboratory of the Permanent Magnet Association became interested in the angular distribution of crystal axes in the late 1950s. At this time we did not possess our own X-ray equipment ... Each crystal required an exposure of several hours, so the experiment was not carried out on many samples.* This statement was made in the late fifties. McCaig writes further: *Unfortunately the details of manufacturing processes are rarely sufficient to enable you to produce magnets successfully yourself. Even when a process for making permanent magnets is fully and honestly described, it may take several months for someone skilled in the art to reproduce it successfully in a different environment.* This was at the end of the seventies - and is still valid.

In the early years (decades?) pickups not only had different numbers of turns but also different magnets. **Seth Lover**, developer of the Gibson “Patent Applied For” humbuckers answered to the question whether he permanently used **Alnico-V**-magnets: “We have also used Alnico II and III because Alnico V was not always available. We have purchased whatever was currently available, because they were all good magnets. The only difference was that Alnico V did not lose its magnetization as fast [13]”. In contrast to this Gibson’s advertisement claims: "*BurstBucker pickups now give guitarists a choice of three replica sounds from Gibson's original "Patent Applied For" pickups – the pickups that give the '59 Les Paul Standard it's legendary sound. ... with unpolished* ***Alnico II*** *magnets and no wax potting of the coils, just like the originals*". Right you are, if you think you are ...

“We have purchased whatever was currently available.” Obviously, the only important thing was that it was marked “Alnico.” However, this name only means that an Iron-Aluminum-Nickel-Cobalt alloy was used. The magnetic properties only develop during heat and, where necessary, magnetic treatments and are manufacturer secrets. One would have to determine the B/H hysteresis to reveal the characteristics of a certain magnet. However, to achieve this, one would have to to demagnetize and remagnetize several times and what owner of a 1952-Les Paul would like to perform such a treatment? Vintage pickups will therefore always be surrounded by a mystical aura.

4.4.1.1 Alnico-III and Alnico-I

Alnico-I was derived from Alnico-III by replacing 5% Ni by Co [21]. Both alloys do not differ significantly in their magnetic properties. Alnico-III is free of Co and, thus, is sometimes called **Alni**. In the USA, however, Alnico-III is assigned to the Alnico magnets, even without Co. **Alnico-I** is mainly used for larger magnets and is not important for pickups. **Alnico-III** was the material of choice for smaller and cheaper magnets – and this is the reason why it was used in the fifties by Leo Fender for the magnets of the Telecaster.

Most of the material science books quote the following composition for Alnico-III: 12% Al, 24-26% Ni, no Co, 0-3% Cu, remainder Fe. The maximum remanence which can be achieved is 0.6-0.75 T, the coercivity is 32-45 kA/m, the maximum energy density is 9-12 kJ/m³. The cool down procedure also has an influence on the magnetic properties, in addition to the chemical composition, and subgroups are designated by additional characters, e.g. Alnico-III-A. Alnico-III magnets are isotropic and are available as cast or sinter magnets.

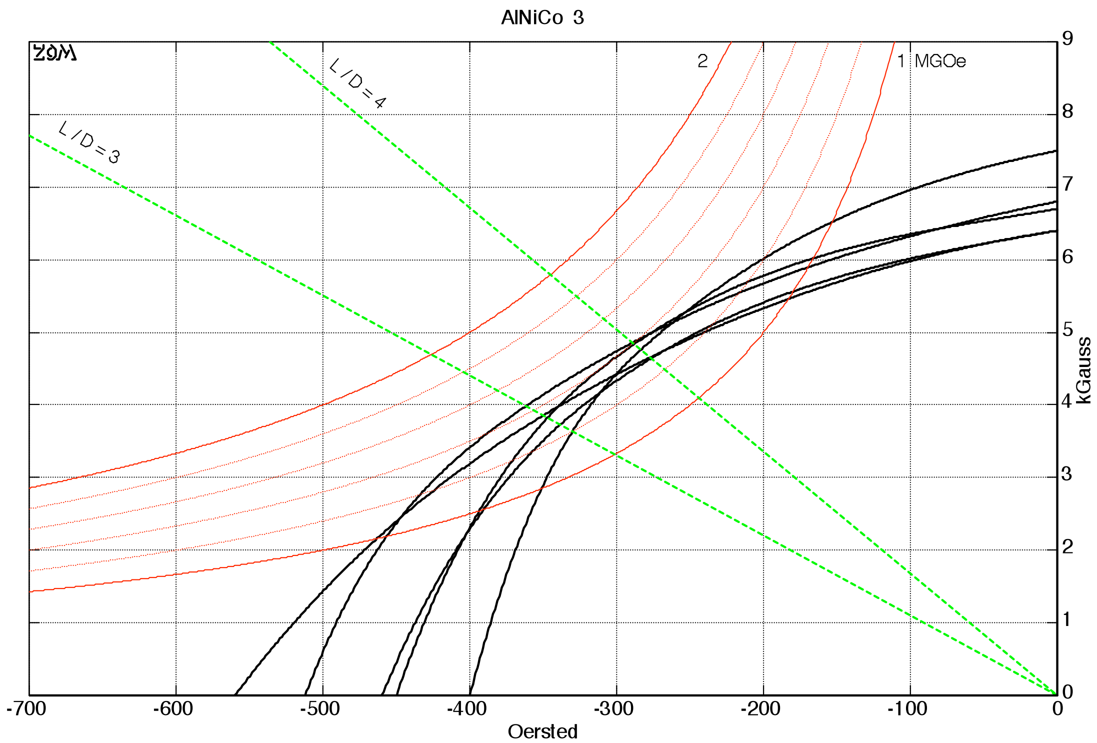


Fig. 4.8: *B/H*-characteristics of different Alnico-III-magnets [21 - 23]. 1Oe = 80A/m, 10kG = 1T, 1MGOe = 8kJ/m³. L / D = length / diameter (cf. Fig. 4.11).

Fig. 4.8 shows the *B/H*-curves of several Alnico-III magnets. Their points of intersection with the energy-hyperbolas are located close to 1.4 MGOe = 11,2 kJ/m³. The spread of coercivity values, which is depicted as on the abscissa, is considerable.

4.4.1.2 Alnico-II

Alnico-II contains more cobalt as well as copper, which leads to a slightly higher price compared to Alnico-I, -III and –IV magnets [21]. Alnico-II shows the highest BH_{max} value of all *isotropic* Alnicos.

Most material science books quote the following composition for Alnico-II: approx. 10% Al, 17-19% Ni, 12-15 Co, 3 - 6% Cu, sometimes some per mills Ti and S, remainder Fe. The achievable remanence is 0.7 - 0.85 T, the coercivity is 34 - 52 kA/m, and the maximum energy density is 11-16 kJ/m³. In addition to the chemical composition, the cool down procedure has an influence on the magnetic properties. Alnico-II is isotropic and available as cast or sinter magnet. Alnico-II can be treated with external magnetic fields but the gain in energy is only approximately 10% due to its relatively low cobalt content [21].

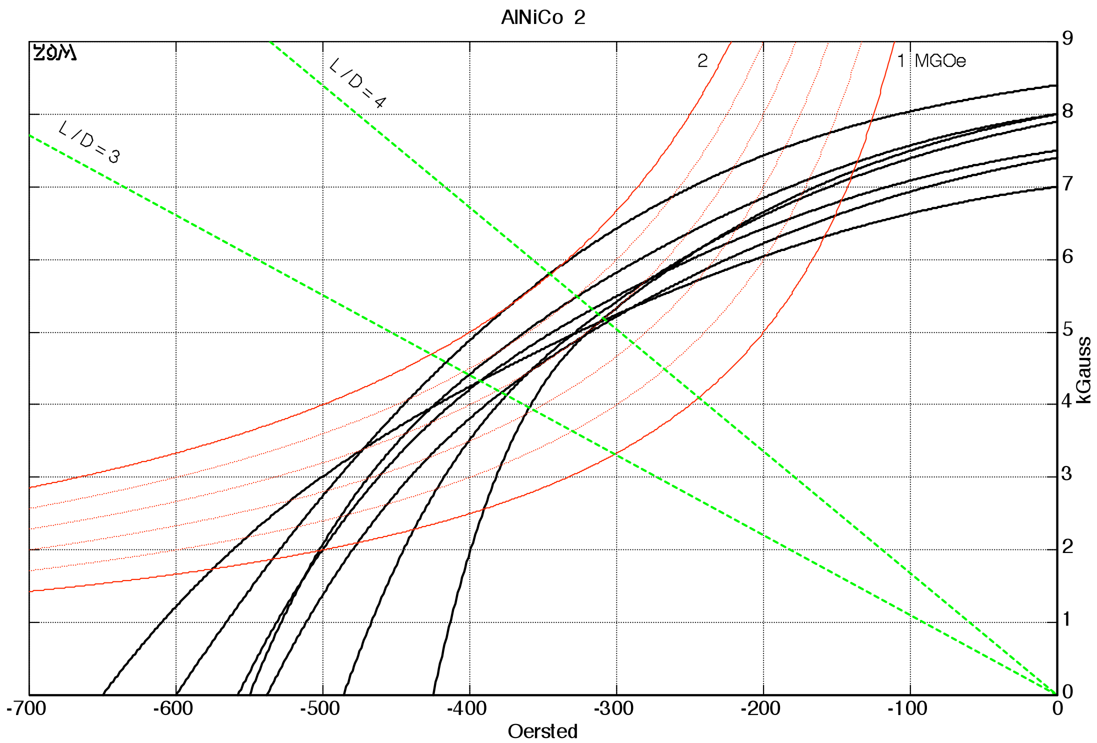


Fig. 4.9: *B/H*-characteristics of several Alnico-II-magnets [21 - 23]. 1Oe = 80A/m, 10kG = 1T, 1MGOe = 8kJ/m³. L / D = length / diameter (cf. Fig. 4.11).

Fig. 4.9 shows the *B/H*-curves of several Alnico-magnets. The maximum specific energy is located between 1.6 – 2 MGOe = 12.8 – 16 kJ/m³. The comparison with Alnico-III yields somewhat higher values for coercivity and remanence.

4.4.1.3 Alnico-V

Alnico-V is anisotropic and reaches the highest BH_{max}-values of all Alnico-alloys [21]. However, its price is higher due to its considerably higher cobalt content. Alnico-V is the material of choice for nearly all Fender pickups.

Most material science books state the following material composition for Alnico-V: approx. 8% Al, 12-15% Ni, 23-25% Co, 0-6% Cu, sometimes some per mills Ti, Si and S, and the remainder Fe. The maximum remanence is 1.1 – 1.3 T, the coercivity is 50-62 kA/m, and the maximum energy density is 30-60 kJ/m³. Besides the chemical composition, also the cool down procedure and the application of magnetic fields has a significant influence on the magnetic properties. Alnico-V is mostly anisotropic and is available as cast or sinter magnet. Alnico-V can be entirely (Alnico-V-7) and partially (Alnico-V-DG) grain-oriented. Many different brand names exist on the international market.

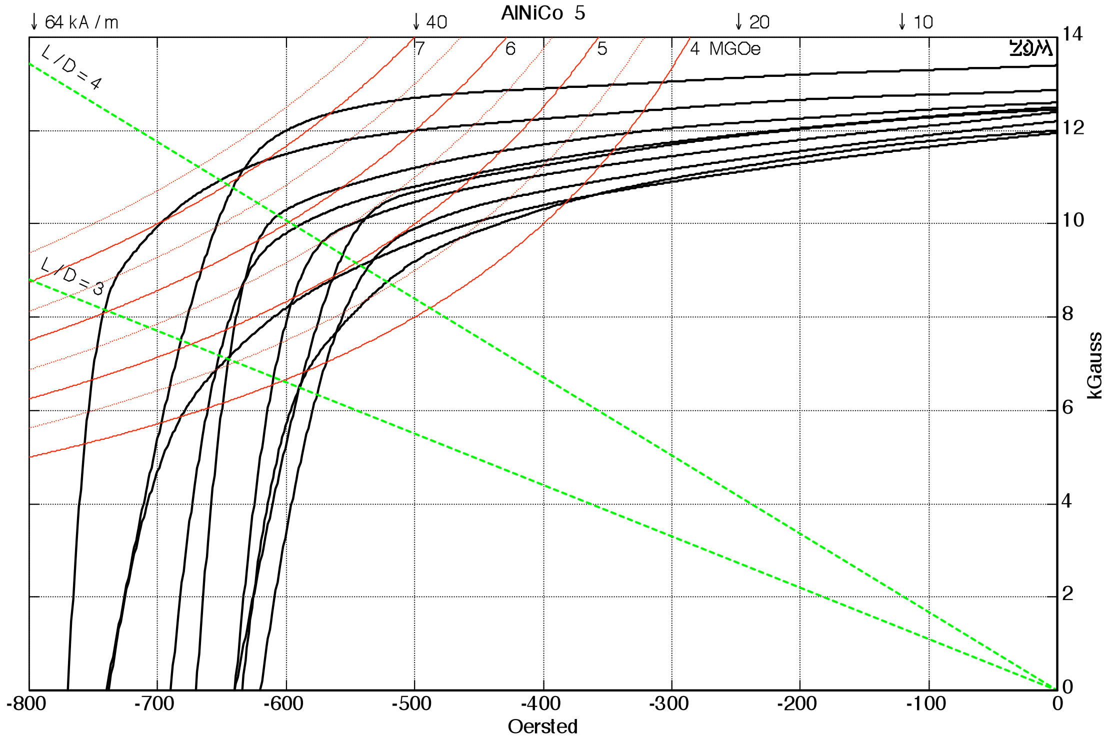


Fig. 4.10: *B/H*-characteristics of several Alnico-V-magnets [21 - 23]. 1Oe = 80A/m, 10kG = 1T, 1MGOe = 8kJ/m³. L / D = length / diameter (cf. Fig. 4.11).

Fig. 4.10 shows the B/H-curves of several Alnico-V magnets. When compared to Fig. 4.8 and 4.9, one recognizes the much more pronounced cubic form of the hysteresis; the maximum specific energy reaches values between 5 – 7 MGOe = 40 – 56 kJ/m³. It can be assumed, with all caution, that the Alnico-V-alloys used for guitar pickups exhibit the lower BH_{max}-values, for cost reasons.

4.4.1.4 Other Alnico-Materials [21]

Alnico-IV has, in comparison to Alnico-I to III, a relatively high coercivity which makes it suitable especially for magnets with a small length-to-diameter ratio.

Alnico-VI was derived from Alnico-V. The coercivity increases with higher Ti content (up to 5%) while, at the same time, the remanence decreases. A further increase of this trend is realized with Alnico-VII.

Alnico-VIII, -IX and -XII contain 35% Co. The expensive cobalt enables coercivities up to 130 kA/m, however production is difficult because the material is very brittle. The remanence and specific energy density are smaller than for Alnico-V.

Alnico-V and Alnico-II is used mostly for guitar pickups, occasionally also Alnico-III.

4.4.1.5 Comparison of selected Alnico-Materials

Most guitarists want to play the guitar without considering whether their pickup magnets are crystalline or form-anisotropic. This explains why pickup advertisement does not refer to the material parameters but rather to the sound. The advertizing message sounds more competent with the gleam of expert knowledge and the disclosure of proprietary information. This reads as:

Alnico-II:
"For a vintage-oriented, warm sound. Since the magnetic field is somewhat weaker than for an ordinary Strat-pickup, the string swings out more freely and naturally. The result is an improvement of the sustain behavior."
But also: *"For the rather weak Alnico-II the tone literally breaks down."*
Or: *"Pickups with Alnico-II-magnets are softer in their sound character, posses less treble, are more quiet, more rounded and somewhat less dynamic."*
But also: *"Due to its Alnico-II-magnet, the pickup does not loose treble."*
Or: *"Alnico-2 corresponds rather precisely to a mature Alnico-5-magnet."*

Alnico-V:
"Alnico-V = clear/powerful sound, more wiry twang, more powerful bass."
But also: *"Alnico-V = bluesy base character with pleasantly rounded tone."*
As well as: *"Alnico-V = fast attack and slightly undifferentiated reproduction."*
Or: *"Stronger magnets will deliver less treble."*
But also: *"The stronger Alnico-V-magnet sounds more brilliant."*

Alnico-VIII:
"The higher magnetic power of the Alnico-8-magnet results in a sustain loss."
But also: *"Louder pickups possess more sustain."*
As well as: *"Alnico-8: The pickup produces high output power with little compression also for hard plucking."*

Sources for chapter 4.4.1.7: Gitarre & Bass, Musik Produktiv; Rockinger; E-Gitarren (Day et al.).

Nearly no retailer who promotes pickups in his **advertizing material** makes an effort to investigate differences in sound produced by the exchange of magnets. They may compare two guitars, one of them sounding more trebly than the other, one of them with Alnico-V-magnets in the pickups, the other with Alnico-II-magnets. Then the root cause is clear at once and the advertizing text is ready. The rules of physics sometimes seem to be a real challenge for textbook authors as well:

'According to the information given by manufacturers of magnets, Alnico magnets are supposed not to weaken over the course of the years, but to retain their Gauss-values and thus their magnetic power over a long time. On the other hand, the pickup-industry claims that Fender-type pickups noticeably loose magnetic power already after 2 years, and that Gibson-type pickups do so after 3 years. However, this apparent discrepancy can be explained because the supposed loss in power evidently seems to be a decline in the „retentiveness" of the pickup-magnetism. This means that with the vibrating string disturbing the magnetic field, the particles of older magnets can be more easily thrown into disorder (and thus experience a short-term loss of magnetic force) – compared to brand-new magnets.' (E-Gitarren, Day et al. – German text retranslated into English). Of course, a magnet does have a force – it can draw an iron nail way from a table-top, for example. However this force is measured not in units of **Gauss** but in units of Newton. The unit Gauss relates to the magnetic flux density but this is not the definition applied by the above author-collective: „The field strength is measured in units of Gauss". Sorry, no agreement here – not with the scientific literature, anyway, which defines the **Oerstedt** (in the US) or the A/m (in Europe), respectively, as the unit for the field strength. Day et al. do have a quantity allocated to the unit Oerstedt, as well: "the resilience against demagnetization". That is not completely wrong if we think in terms of the coercive field strength that actually is measured using the unit of Oerstedt and A/m, respectively. However, the term "resilience" again opens the door to mix-ups. "Magnetic power", as well, is such a term that can be misunderstood easily, since power is measured in units of hp, or Watt, or Nm/s. Any author trying to explain difficult technical context with simple, musician-friendly terms runs the danger of being open to attack, and risks to be criticized in case of too rigorous simplification. It does not really help, however, to assign a new meaning to established terms just to achieve the simplification. Of course, a scientist will be criticized just as much if he remains lost in his non-linear differential equations in an effort to maintain exactness and full integrity. Accordingly, the journalist in the German magazine Gitarre & Bass (4/2006) opines: *'Caution, if – in the matter of guitar speakers – somebody brings **science** to the table. The man♣ will probably carry lots of misconceptions. It is in fact best to give such people a wide berth.'* Another statement: *'What's all that scientific nonsense, anyway?'* The same journalist does, however, also write: *'A myriad of these prejudices exist that seem to almost be set in concrete. Who actually decides on such bullshit? These theories are supported by numerous books on guitars written by famous (or infamous) luthiers who actually assume the right to stipulate how much a Telecaster may weigh, or how a Stratocaster pickup should be adjusted.'* And once more a passage from the book "E-Gitarren": *'If pickups remain close to AC-fields such as transformers or strong heat sources, their magnetic structure becomes totally jumbled and they age more quickly.'* O.k. – yes, above 500°C it will indeed start to be a critical situation – but it will not be only the magnetic structure that becomes jumbled, but the tone-generating guitarist's layout, as well: mighty quick aging! *(Paragraph translated by T. Zwicker)*

♣ this would be Dr. Bose, loudspeaker designer and lecturer at the M.I.T. "with dubious formulas"

Obviously, the magnet is involved in the generation of sound: without the magnet there would be no sound. It is also clear that the magnet itself does not have a sound. Alnico-II will not sound different compared to Alnico-V. There is, scientifically speaking, no tone at all if the string does not vibrate. However, one can moan less and talk less elaborately about the *"sound of the magnet"* if one means its effect on the transfer characteristics. So how does Alnico-V *sound*? Different from Alnico-II and, if yes, why?

The *change* of flux density is relevant for the induced voltage in the coil. A strong magnetic field will not induce anything as long it does not change. For a change of the flux density the string has to vibrate in a position-dependent, **inhomogeneous magnetic field**. If the magnetic field would be constant at every position, no voltage would be induced. The inhomogeneity of the magnetic field can be influenced by the magnet material as well as by the shape of the magnet. Replacing the magnet might also change the permeability and, consequently, the resonance of the pickup and/or the damping of resonances by eddy currents (resonance quality). Thus, the behavior is by no means mono-causal, where *one* cause produces *one* effect or rather that every effect can be attributed to *one* root cause. Rather, the relationships are complicated and multi-factorial.

The difficulties start already with the material specifications. Fig. 4.10 shows, that there exist several Alnico-V-alloys. In the pickup literature there are no indications on sub-groups, only "Alnico-V", "The holy grail" or "The originally PAF". Not even Seth Lover was able to tell which material was used during which time period, and how much turns were wound. Was Eric's favorite Paula equipped with Alnico-II or Alnico-V? Unfortunately she is no longer traceable (or rather she is hanging in Japan in 17 safes – and every one of them an original!). Does the transcendental sound of the Roy-B-guitar stem from the Alnico-III magnet or from the fact that vintage Telecaster pickups with resistances beyond 11 kOhm have been spotted? Or maybe it lies with the guitarist?

Fig 4.11 summarizes the **hysteresis-scattering**. In this graphical representation regions were defined based on the trends of the hysteresis curves of many Alnico-materials. One can recognize the scattering and the basic differences. Alnico-II is slightly stronger than Alnico-III but considerably weaker than Alnico-V. In **Fig. 4.11b** the attempt is made to extract a typical single curve from the many different possibilities, but without evidence that these curves are the authentic or the most suitable ones.

When comparing different magnetic materials one first has to define into which magnetic circuit the magnet will be integrated: single coil or humbucker (or special construction types). Single coil pickups with cylindrical magnets, like those that were originally designed for the Stratocaster, do not have ferromagnetic materials other than the magnet. The magnetic load is defined by the shape of the magnet, or rather, strictly speaking, by the shape of the surrounding air space. Frequently the length to diameter ratio is approx. 4 yielding a **working point** near the knee of the hysteresis. **Fig. 4.11** shows two straight load lines for $L/D = 3$ and $L/D = 4$. However, one has to take into consideration that literature values may differ [23, 25], and the slope of the lines is decreased by the neighboring magnets. Very roughly simplified, for pickups with cylindrical magnets Alnico-V will produce a magnetic field twice as strong as that of Alnico-II or Alnico-III. However, the flux density derived from the crossing of the curves corresponds to the center of the magnet (neutral plane, chapter 5.4.1), not to the location of the string.

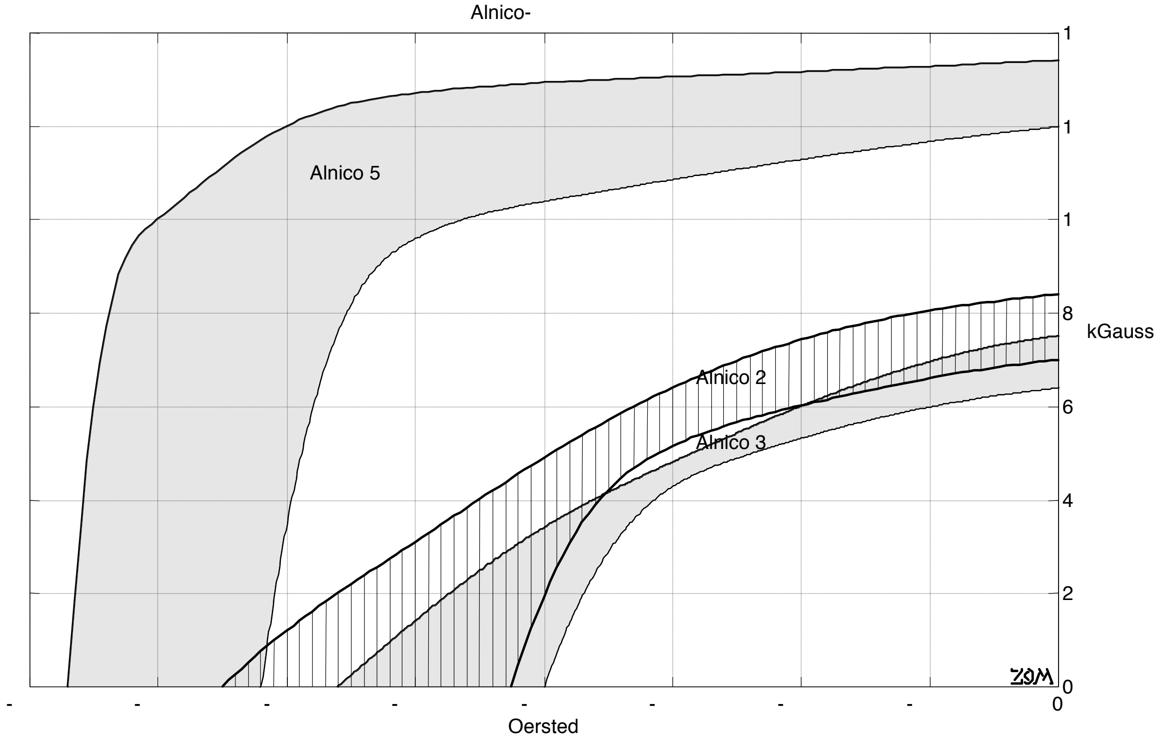
If the magnetic circuit were a linear system this would result in a simple relationship: the vibration of a string would change the magnetic resistance e.g. by 1% and consequently the magnetic flux by 1%. Doubling the static flux, e.g. by exchanging the magnets, would result in a doubling of the alternating flux and doubling of the induced voltage – the generated tone will become louder and possibly more distorted. However, as the magnetic circuit is nonlinear, doubling of the flux will result in an induced voltage slightly less than double. At the same time the magnetic aperture will be decreased (Chapter 5.4.4) and the aperture dependent treble drop becomes weakened, i.e. the pickup sounds slightly more brilliant. An additional brilliance gain with **cylindrical magnets** might evolve from the fact that stronger magnets possess a smaller reversible permeability – the inductance will become smaller, the resonance frequency will increase and the figure of merit will likewise increase slightly (chapter 5.9.3). On the other hand, a treble loss due to eddy currents will also be induced. The electrical conductivity of Alnico-V is approximately 40% higher than that of Alnico-II. It is hard to predict which effect will dominate; however, in most cases the stronger magnet yields a *gain* in brilliance.

The magnetic field at the string location will be weaker for single coil-pickups with **bar magnets** instead of cylindrical magnets. The magnetic aperture tends to be larger and the aperture-dependent treble loss will be somewhat higher. The reversible permeability of the magnet nearly does not play a role because it will hardly be penetrated by an alternating flux. The frequency dependence of the impedance of the SDS-1, for example, will not measurably change if both bar magnets are removed. For the P-90 the magnets have a small influence. They increase the coil inductance by 10%.

The magnets have almost no influence on the pickup impedance for Gibson-type **humbuckers**. The alternating magnetic field passing through them is negligible and, hence, the reversible permeability and the eddy current damping play practically no role. As for the single coil, the magnetic aperture and absolute sensitivity do depend on the magnet strength. The working point of many Alnico equipped humbuckers is located below the hysteresis knee, in a rather inappropriate region. The table depicted in chapter 5.4.1 shows that the static magnetic flux densities of the investigated humbuckers are smaller than most of the single coils.

Mechanical Characteristics of Alnico-Magnets:

Density: approx. 7g/cm³
Hardness: 45 – 60 HRC, brittle, risk of fracture, moldable only by casting and/or sintering plus grinding
Specific resistance: 0.45 – 0.7 $\Omega mm^2/m$. Alnico-V has a slightly better conduction than Alnico-II. For comparison: nickel-silver = 0.3 $\Omega mm^2/m$, Cu = 0.018 $\Omega mm^2/m$, Fe = 0.1 $\Omega mm^2/m$. Ceramic magnets (ferrites) are, however, insulators.
Reversible relative permeability: approx. 4 – 6; usually lower for stronger magnets.
Alnico has a good corrosion resistance; however, it is not fully rust resistant.
Sinter magnets show a higher mechanical stiffness compared to cast magnets. Their magnetic values are, however, somewhat worse. The quality of cast magnets is also reduced when they have cavities.



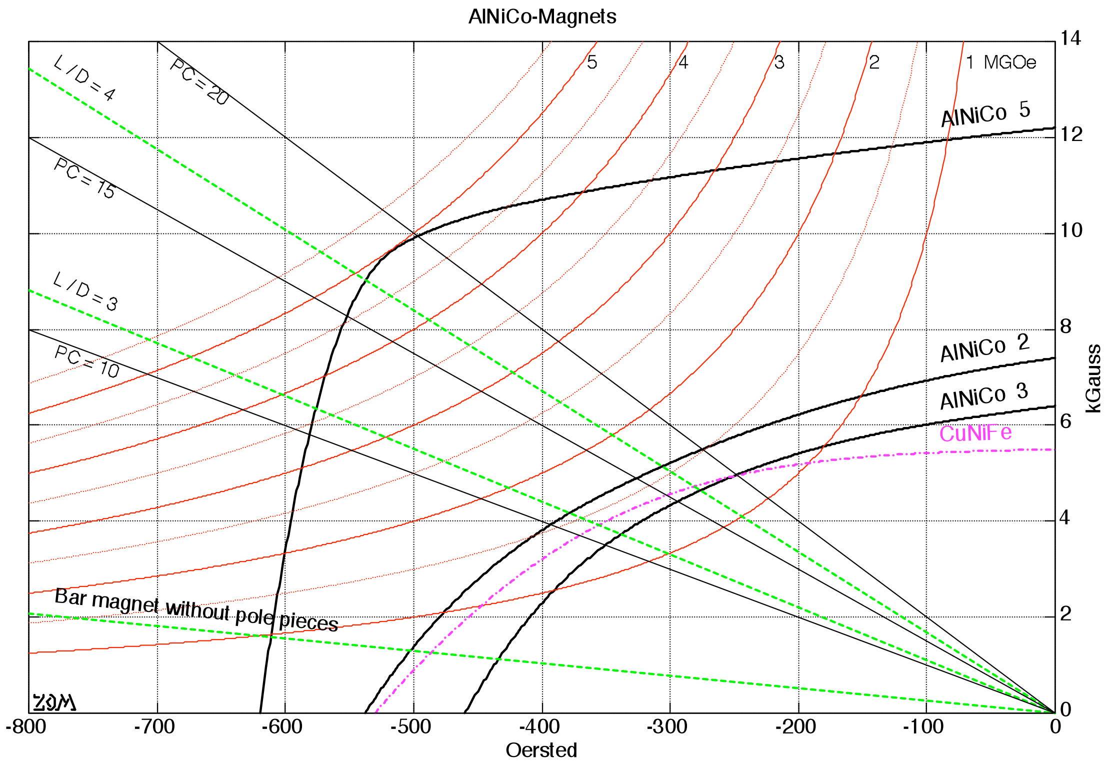


Fig. 4.11: *B/H*-regions of typical Alnico-magnets; the hysteresis curves are located in these regions (upper plot). Lower plot: *B/H*-curves of Alnico cast magnets, data from old specification sheets. 1Oe = 80A/m, 10kG = 1T. L / D = length / diameter. PC = Permeance Coefficient