3. Magnetics of the string

In order to be able to change the magnetic resistance in the magnetic circuit, the vibrating string needs to consist from ferromagnetic material. Ferromagnetics come in great variety – if they are to be suitable as basic material for guitar strings, one feature is a predominant requirement: they have to withstand the extremely high tensile stress. Just about every guitarist will have broken a string during play at least once; that clearly shows how close to the limit we are operating! Typical tensioning forces of strings fall into the range of between 50 N and 140 N. Given the rather small cross-sectional areas this implies **tensile stresses** of up to 2000 N/mm^2. Given to such high stress, only high-strength ferromagnetic **special steel** qualifies as material for strings. As a protection against corrosion, the surface of the string is usually coated with a thin layer of nickel or gold; this layer has no magnetic effect due to its small thickness. Wound strings behave differently: their core diameter is about 30 – 60% of the overall diameter, with the **winding** consequently giving a substantial contribution to the cross-sectional area (the latter growing with the square of the diameter). Testimony to this issue is the effect we get when trying to use – on an electric guitar – strings with steel core and bronze winding as manufactured for acoustic guitars. Compared to the solid treble strings, such wound strings are picked up with too little volume – because bronze is not magnetic. The three bass strings of the electric guitar (E-A-D) are therefore wound with a magnetically conductive material: usually with nickel, nickel-plated steel, or special non-corrosive steel. In the following paragraphs, the magnetic properties of typical steel strings are discussed. Subsequently, **Chapter 4** will contribute a detailed description of magnetic fields.

3.1 Steel, nickel, bronze

High tensile strength requires a smooth surface because cracks and pores would increase the risk of breakage. As a protection against corrosion, the string surface may be coated (TINNED MANDOLIN WIRE); there are also uncoated strings, though. "Tinned" does not compulsorily imply that the surface is coated with *tin*: in fact the coating of typical guitar strings is formed of nickel (NICKEL PLATED STEEL). The two highest treble strings (E_4, H_3) are always solid (PLAIN), and the three bass strings (E_2, A_2, D_3) always sport a winding (WOUND); the G-string is solid (plain) in light string sets, and wound in heavy ones. The winding does not absorb tensile forces but merely serves to increase the mass. Other than steel, less stress-resilient materials may be used for the winding, as well.

Without doubt, the material of the strings does influence the **sound** of the guitar. The reason for this is, however, not that self-evident. Obviously, we will think of the inner damping of the material. When bending steel, nickel, copper, or other metals, different amounts of energy are converted into heat (dissipated). The decay of vibration therefore is material-dependent. The differences between the customary metals are, however, not pronounced to the extent that an audible difference in sound will result in tones of short duration.

The main effect results from the string bouncing off the frets. Even with regular strength of plucking/picking, the string will hit and bounce off the frets many times (Chapter 7). In this process, the winding (or coating) acts as elastic and therefore sound-determining buffer between fret and core of the string. An exact description of the **string-bounce process** is only possibly with a very high effort: each individual string/fret contact is a non-linear occurrence that will rule out the otherwise so helpful principle of superposition. The great number of these non-linear contacts can only be described in a non-linear, stochastic model – which would include a frightful variety of parameters.

Every string/fret-contact implies a mechanical impact. Mechanics know two kinds of impacts: the elastic one, and the inelastic one. For the **elastic** impact, there is no generation of thermal energy during the contact phase – it is termed the **loss-free** condition. However, this does not mean that the string is not loosing any energy, but only indicates that the sum of the energy in both partners involved in the impact is constant! The vibration energy transferred to the fret is lost to the string at first: the string experiences a damping from the elastic impact. Also, we may not expect that the vibration energy stored in the fret is re-transferred to the string later – in fact, a substantial portion of the energy is lost in the fretboard and the neck of the guitar. Given an **inelastic** impact, energy is dissipated irreversibly already in the deformation of the material during the impact phase, i.e. it is irretrievably converted into caloric energy.

Each contact between string and fret is also a source of two fresh **secondary waves** running in opposite directions. The energy contained in these secondary waves is not introduced to the system from the outside but withdrawn from the original wave-energy. *After* each contact, the system is again a linear one, and all waves may be superimposed. The contact phase itself, however, is a non-linear, drive-level-dependent process that cannot be described via superposition. The multitude of contacts renders the system non-linear during the first 10^{ths} of a second; only the subsequent decay process is linear.

A string/fret contact (other than where the string is actually fretted) may only be avoided with very slight plucking of a (normally adjusted) string; in this case every analysis shows that the levels of the higher-frequency partials decay substantially faster than the low-frequency ones. The short impact of the string on the fret during the string-bounce represents a broad-band excitation that “refreshes” the treble, in a manner of speaking. Instead of being plucked one single time, countless “pickings” rain down on the string and make for a treble-rich, brilliant sound.

Auditory experiments with a E_2-string confirm this hypothesis: between a string wound with *nickel-plated steel* (Fender 250) and *pure-nickel-wound* string (Fender 150), there is a just-about significant, noticeable difference. However, raising the height of the bridge to the extent that any post-plucking string/fret-contact is avoided makes the two string-types sound the same. It needs to be emphasized here that the string/fret contacts are not generally perceived as string-buzz or clatter. Rather, these contacts merge, as auditory events, to a single homogenous plucking sound (ATTACK), as long as the contact noises do not dominate too strongly, or are audibly modulated by low-frequency components. Each string/fret contact transforms part of the low-frequency vibration energy into high-frequency vibration energy; therefore the attack of “bouncing” string sounds more trebly. Nickel – as a material that is the softer compared to steel – at the same time absorbs more of this add-on treble, and therefore nickel-wound strings have a sound not quite as brilliant as steel-wound strings.

On guitars having a piezo pickup mounted rather than a magnetic pickup, the magnetic conductance of the string winding does not play any role. Strings for these guitars therefore typically sport a winding made from brass or bronze. What again holds: harder, low-loss winding materials result in a more brilliant sound; softer winding materials also sound “softer”, i.e. not as brilliant.

The “**Zebra**”-strings made by DR with their double-start winding represent a peculiarity: they are manufactured with two different winding threads positioned next to each other. The bronze-wire is supposed to generate the sound typical for flattop steel-string guitars, the steel-wire is supposed to score with the magnetic pickup (see Chapter 3.2).

"Every other coil is nickel-plated steel, every other coil rare phosphor bronze, wound on hex cores", it says in the Internet ad. Only on the packaging we then read: "...by winding phosphor-bronze plated steel wire side-by-side with 8% nickel plated steel wire. Phosphor-bronze brings out the acoustic tones of your guitar. 8% nickel plated steel is designed to increase the response of a Piezo pickup in the bridge, or a magnetic pickup mounted in the soundhole, as well as the pickups in the archtop guitars." Nickel for the piezo? Be that as it may … However: a bronze wire, as it is customary for an acoustic guitar, turns into a bronze-coated steel wire. To meet the cosmetic expectations, the flimsiest of coating is sufficient … there’s that reddish gleam. It musn’t be much more, either, because bronze is a magnetic insulator! Just imagine that across the winding, an electric current would have to flow (along the string) … and then the guys wind around the core once bare copper wire, and alternately a combination of copper wire and enameled copper wire. This example speaks for itself. While bronze is not a perfect magnetic insulator, it still is less efficient than steel or nickel by several orders on magnitude. **Fig. 3.1** shows the approximate shape of the magnetic flux – strongly simplified in order to keep the calculation effort at bay. Finding: the magnetic resistance of the winding is determined predominantly by the surface touching the winding (Hertzian stress). In this range, the flux density is high, the material is magnetically saturated, and the exact calculation proves time-consuming.

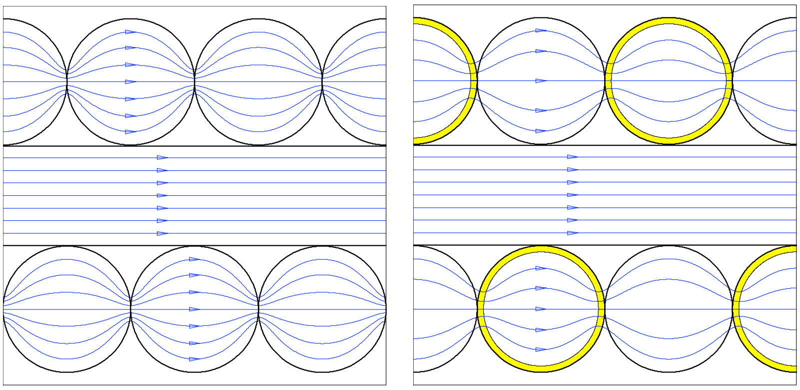

Fig. 3.1: Magnetic flux in a wound string. Single-layer winding (left), double layer winding with a bronze-coated winding wire (right). The lines of flux are not calculated precisely; in a real string, core and winding influence each other mutually.

Measurement on a 0,042"-**Zebra-string** showed that it is less sensitive by 2 dB compared to a steel-wire-wound 0,042"-Fender-string (Type 350). The core wires of both string have the same diameter and the same magnetic properties – the difference results from the winding exclusively. If one to the two winding wires were indeed made from solid bronze, the magnetic efficiency of the remaining other winding wire would practically disappear. Whether bronze-*coated* steel wire actually has a significant influence on the acoustic sound … that would be a topic for more extensive experiments. The issue was not looked into, though.

Unfortunately, not all manufacturers of strings give information regarding the actual build of their strings. Tom Wheeler uses the heading "Welcome to Fantasyland" for the chapter on strings in his reference oeuvre "Guitar Book". And he continues: “Advertisements for string often bristle with misleading information; one almost forgets that the only serious path to a good sound is paved with auditory experiments”. Indeed – it ain’t easy. Gerken at. al opine: “phosphor-bronze strings sound a little more mellow that 80/20 bronze or brass strings”; in Day et al., it conversely reads: “Phosphor-bronze sounds more brilliant than bronze”. Both books were issued (in Germany) by the same GC-Carstensens publishers within only 2 years.

Often, the declarations about materials used flounder on the marketing primacy: brass (which is a copper-zink-alloy), for example, turns into “bronze”. The reason might simply be that brass is also the term for horn instruments … as played in that other kind of “band” … the one in the football stadium. Do guitarists seek association with that scenario? Probably not, the contrary may actually be true. *(The translator recalls Pat Metheny’s “Forward March” here ...)* So: “bronze” rather than “brass”. This ab-use has even migrated in German guitar-“literature”. Now, how do you call the winding made of “real” bronze (a copper-tin-alloy), then? Right: name it “bronze”, as well! Or maybe “phosphor bronze”, to distinguish it from the (boring) other “bronze”. Come to think of: the mentioning of phosphor is not necessarily off, because bronze tends to become porous … indeed, phosphor is added: has a cleaning effect and reduces the porosity, and the high hardness of Cu_3P brings more brilliance to the sound. How much P the manufacturers add – that remains shrouded in the mystery that is string marketing.

Similar vagueness is found in “pure **nickel** strings”. Strings made from pure nickel could never, ever withstand the high tensile load – you have to use steel. Only the surface (nickel plated) or the winding (nickel wound) may consist of nickel. The winding may be made from pure nickel or form nickel-coated steel. The manufacturers are reluctant to hand out the specifics, though. Only the advertisement for most recent development is clear about which side one’s bread is buttered on: “special strings for lefties” …

3.2 The loudness of the strings

If you exchange on your guitar the 009-string-set for an 011 one, will it sound louder? Practical experience says: yes – theoretical considerations advise caution, though. First, we should look at a meaningful intermediate quantity rather than the loudness that is difficult to establish. Using the AC-component of the force at the bridge (acoustic guitar, pickup built into the bridge) come to mind, or the induced AC-voltage (magnetic pickup). Keeping the boundary conditions constant (!), there is no way around realizing that neither the bridge-force, nor the pickup voltage includes any dependency on the string diameter.

The **force at the bridge** first: the excitation force transferred to the string as it is plucked may be modeled as sum of two sub-components of equal value causing transversal waves running in opposite directions (Chapter 2). These two waves superimpose at the bridge with equal phase: the force at the bridge (only the AC component is of interest here) thus corresponds to the plucking force – that’s independent of the string diameter. Still, the diameter of the string has an effect on the sound because it affects the transverse stiffness (see appendix), and thus the displacement of the string The heavier the string, the larger the plucking force for a given displacement can be, and the louder the guitar will sound – if the guitarist takes advantage of this. With *equal* plucking force, heavier strings bounce less (Chapter 1.5.3) and sound fuller. We could have analyzed the dependency of internal damping mechanisms and radiation losses on string diameter – but that had less priority and was put on the backburner.