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Technical Sheet on Magnet Wire and Role in Motors

Magnet Wire

Magnet wire is a product, which has principally two tasks: it has to be conductive in longitudinal direction and, at the same time, insulating in transversal direction. According to Ampere´s Law, when an electric current passes through a conductor, an annular magnetic field is created around the conductor. If the conductor is wound in the shape of a coil, the magnetic field generated in each subsequent turn of the wire passes through the centre of the coil and is superimposed to form a stronger field. The adjacent turns of wire, however, must be insulated from each other in order to avoid a short circuit and as a result, a malfunction of the electric equipment.

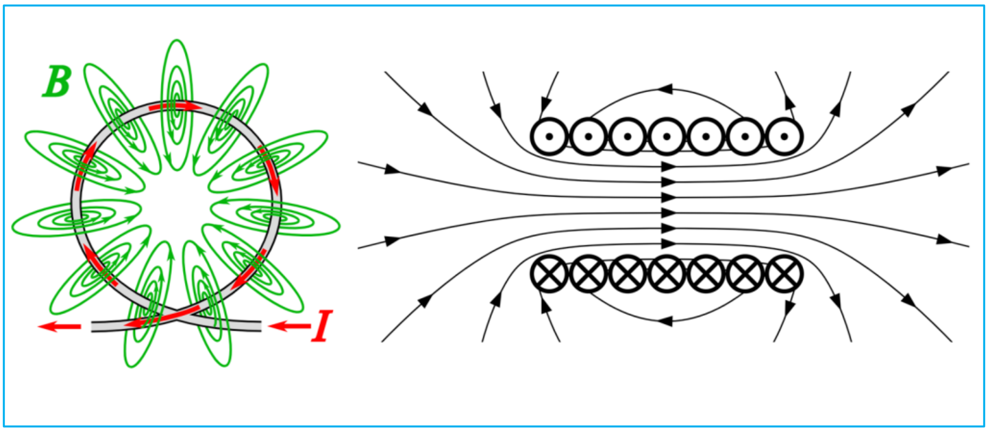

Figure 1 Left: Magnetic field B induced by current I passing through a curved conductor. Right: Superposition of a magnetic field induced in a coil with 7 windings [Source: Wikipedia.com].

Electromagnetic coils and windings are used in devices such as electric motors and generators, transformers, electromagnets, sensors coils or inductors. A very good example for the application of magnet wires is a typical car. In a modern electric or hybrid vehicle, the electric motor (which is simultaneously a generator) is a core of the powertrain. However, even in a traditional combustion engine, one can find dozens or even hundreds of coils, e.g., cooling, fuel or air pumps, cooling fans or blowers, power of windows, mirrors or seat positioners and all the electromagnetic valves, actuators and detectors. In addition to the automotive, coils and windings are used in energy production, transformation and distribution, household appliances, industrial motors, hand tools, electronics and much more.

Conductor material

In the vast majority of magnet wire applications, only two materials are deployed. Either copper or aluminium. Copper is the most widely used electrical conductor material mainly because of its superior conductivity, reaching as high as 58 - 59 MS/s. These values are only a bit lower than the conductivity of Silver, the most conductive (at room temperature) commercially available conductive material. On the other hand, the density of as much as 8,96 g/cm^3 and relatively high price (around 10,300 $/to 2022/04/20) are making the copper applications relatively heavy and expensive.

Aluminium, on the other hand, is less expensive and lighter material, compare to copper. However, due to its significantly lower conductivity, the used conductor cross-sections are higher. In order to compensate poorer electrical properties, the volume of electrical components increases. First of all, the increase in volume is intolerable in many fields. Second, the overall material price may be higher than in case of copper due to the bigger housings and laminated cores necessary.

Table 1 LME Prices to the April of 20th 2022.

	Conductivity [MS/m]	Conductivity [% IACS]	Density [g/cm^2]	Price [€/to]*
Silver	63	105	8,96	813,400
Copper	58	100	10,50	10,240
Gold	41	70	19,30	63,000,000
Aluminium	38	61	2,60	3,230

Shapes

Magnet wires are commercially available in various cross-sections and sizes. Each application and winding process have different demands on the magnet wire. The most typical cross-section is a round wire. The thinnest round wires have a diameter of few micrometres, the heaviest rectangular magnet wires are surpassing 100 mm2 cross-section. For special applications like High Frequency parts or too massive cross-sections, where single conductor have only very limited flexibility, litz wires made of many small conductors are used. Another special case are hollow conductors for the applications, where inner cooling of the conductor is required.

Figure 2 Left: Round and flat wires on a plastic spool, right: spread or wrapped litz for special applications [Source: ©SYNFLEX-Group].

Manufacturing

The state of the art of magnet wire manufacturing process is the application of liquid enamel (varnish) on a drawn conductive material. First of all, the wire is drawn to the required conductor dimension. After the drawing, the wire is annealed in order to restore mechanical properties for further processing. The enamelling process consists of enamel application, curing and cooling. First of all, the bare annealed conductor passes through a bath with liquid enamel. Due to its high viscosity, a thick film forms on the wire. After that, the wire passes through an enamelling die with specified cross-section. The gap between the conductor and the die delivers the enamel increase per one pass. Subsequently, the wire passes through the curing oven, where at a temperature of approx. 600 °C the organic solvents evaporate from the liquid enamel, creating a compact, solid insulating layer. After the cooling of the wire, the process is repeated over and over again until the required insulation thickness is reached. Before the coated wire is wound onto a spool, the wire passes through an inline measurement device, where every inch of produced wire is tested for surface imperfections and discontinuity of insulation.

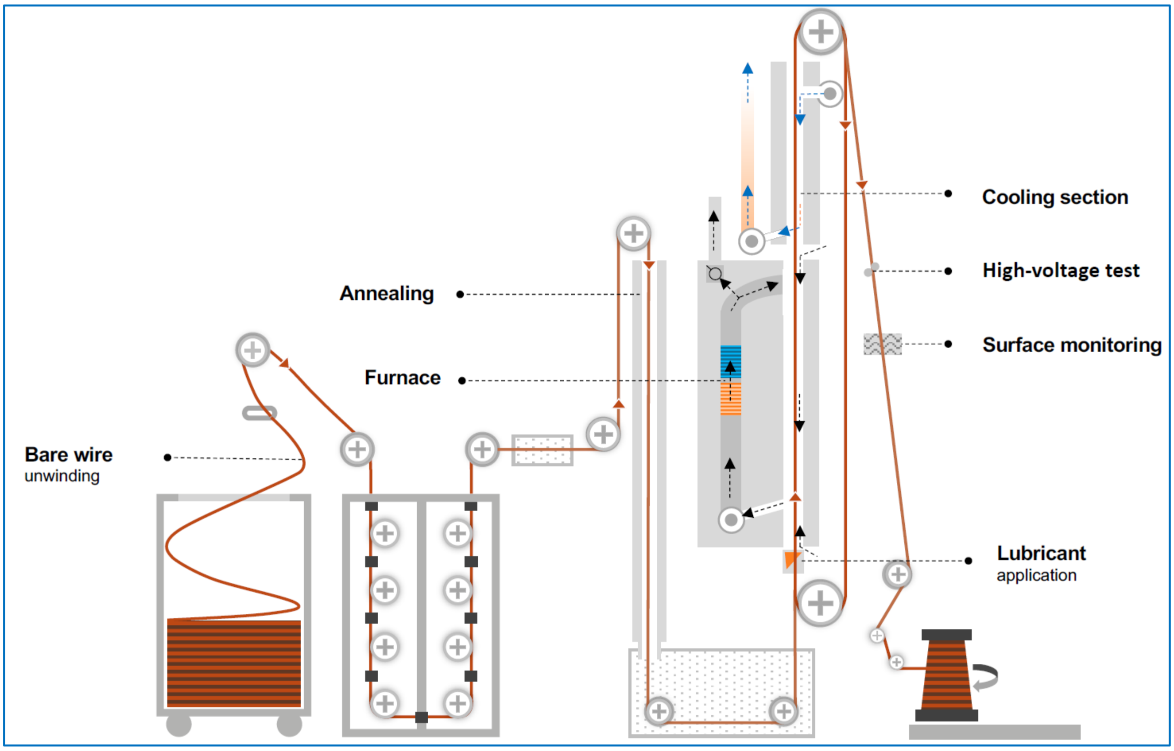

Figure 3 The process of magnet wire production [Source: ©SH-Wire].

Depending on the material type, diameter, cross-section of enamel thickness, vertical (built in towers approx. 30m high) and horizontal lines are in use. Despite the fact that the basic principal of a cyclic application of liquid enamel with subsequent curing hasn't changed since decades, the modern machines work much more efficiently, productively, are significantly more environmentally friendly and they are fully integrated into the industrial infrastructure of the 21st century.

The first industrially available alternative to the enamelled copper wire seems to be an extruded PEEK magnet wire. Here the conductor is covered with one single layer of a high performance polymer (in this case PEEK – Polyetheretherketon). Although these wires are not standardized yet and they are on the market only since a couple of years, they are being utilized in some rare high performance applications. They are popular due to their outstanding chemical and mechanical resistance, which is, together with high applicable thicknesses and surface nearly free of any imperfection a good premise for high performance applications. On the other hand, optimized enamel wires are already comparable with extruded wires. Last but not least, for relatively small performance step forward, significantly higher price must be paid (price factor of approx. 3 – 5 times over magnet wires).

Requirements

Depending on the requirements for the manufacturing process and operating conditions of the product, magnet wires can be clustered into these basic categories:

Thermally resistant wires: Product class, which requires a very good permanent thermal and overload resistance. Moreover, the wires must withstand severe mechanical stresses during processing as well as the operation at high temperature conditions with strong exposure to various chemical substances. The service life of a magnet wire as well as the additional insulation system is designed for an operation at thermal class temperature for 20,000 hours.

Table 2 The different thermal classes of insulation systems defined by NEMA, [1] Underwriters Laboratories (UL), [2] and IEC standards.

Thermal Class	90	105	120	130	155	180	200	220	240
Old designation	Y	A	E	B	F	H	N	R	-

Solderable wires: These wires provide the possibility of being contacted through a direct contact with a tin bath, without prior removal of the insulation film.

Self-bonding wires: As a top layer, a special self-bonding layer is applied. This provides the possibility of being bonded, when required shape of the coil is achieved.

Wrapped wires: A group of wires, in which an insulating paper, a glass or polyester fibre, polyimide tape or a combination thereof is applied to bare wire or already enamelled wire. These layers provide additional mechanical protection and an additional layer of insulation. There are some more special wire classes, e.g., wires with optimized gliding properties, hollow conductor wires and others.

The specific magnet wire classes are standardized and defined in the standards IEC 60317 and NEMA MW 1000 for European and US market, respectively.

Properties of magnet wires

In order to ensure that the magnet wire withstands winding, assembly and impregnation, as well as the service life of the electrical system including overload conditions or the exposure to coolants, oils or other aggressive substances, its integrity and resistance is being demonstrated by a series of different tests. These tests are defined in the Standard IEC 60851, where the tests are divided into the following groups:

- Electric properties (e.g., partial discharge resistance, breakdown voltage, continuity of insulation)
- Mechanical Properties (e.g. elongation, springiness, flexibility and adherence, resistance to abrasion)
- Chemical Properties (e.g. solderability test, resistance to solvents, refrigerants or transformer oils)
- Thermal properties (e.g., heat shock, cut-through, temperature index).

Enamel Types

In order to achieve the required level of properties, suitable enamel types must be applied in appropriate manner. We differentiate between single, double, triple and multi coat enamel systems. Most of them are listed in relevant IEC and NEMA standards. The most commonly used enamels have the following polymer base:

- PUR Polyurethane
- PE Polyester
- PEI Polyesterimide
- PA Polyamide
- PAI Polyamideimide

The thermal stability of above polymers increases in the order as written. PUR has the lowest thermal stability. , it is preferred for solderable wires, because it evaporates after the contact with tin bath leaving tinned wires behind. PE or PEI are good candidates for base coat because of their good adhesion and flexibility. PAIs are good candidates for top-coats for their mechanical and chemical resistance. If special properties are required, e.g. self-bonding or low coefficient of friction, these properties typically results from the enamel applied as a very top layer. On the other hand, in order to improve the adhesion of the enamel on the conductor, a special primer is applied directly onto the conductor.

The liquid enamel consists not only of the polymer that determines the wire properties, but also of various solvents. These are necessary to keep polymers in an easily applicable liquid phase. During the curing process, these solvents evaporate from the wires´ surface and are catalytically burned.

Spool

Last but not least, the spool the wire is supplied on, is also an important feature of the wire in several respects. Naturally, it determines the length of the wire available for continuous processing without changing the spool. The wire must be able to be unwound without any problems and the wire quality must be guaranteed over the entire wire length.

Very thin round wires (20 µm – 0,2 mm) are usually delivered on conical spools from 5 to 20 kg, all the other round wires on oblong spools from 22 to 200 kg (optionally with protective cover), while rectangular wires are delivered on cylindrical reels with 20 to 400 kg on a reel. The spools are defined in the Standard IEC 60264.

Role in Motors

In the very beginning of this tech-sheet it is explained, that the role of magnet wire is to induce a magnetic field from electric current. The task of the electric motor is to convert electrical energy into mechanical energy. Electric motors use magnetic fields from electromagnetic coils in the stator winding to exert a force, which is caught in the rotor either by permanent magnets, an additional winding, or a specially shaped laminated core (reluctance) and transmitted into the rotational movement of the shaft.

Electric motors can be classified by power source type (DC, AC), number of phases (one-phase, two-phase, three-phase), cooling (air, liquid), direction of magnet flux with the axis of rotation (radial or axial), application, type of motion output, topology, construction and many more.

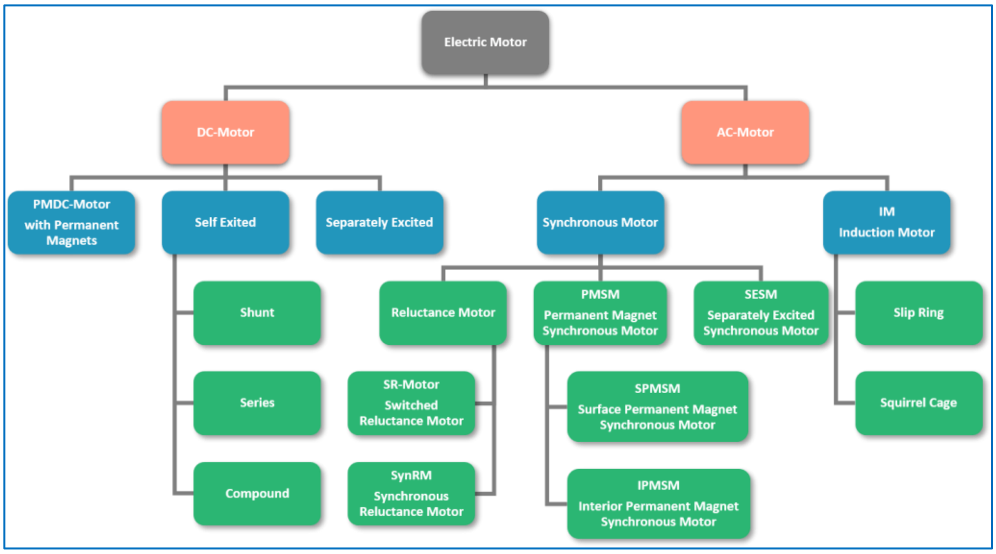

Figure 4 Classification of electric motors [Source: oswos.com].

If one says that there are many different electric motor types, constructions and designs, analogically, the variety of different coil or winding types is also extensive. Moreover, the technology of winding evolves as well. Nowadays, all possible techniques from hand winding towards fully automatized high speed winding of dozens of coils at once, often fully integrated into electric motor manufacturing process are utilized. Basic winding technologies definitely include:

Linear winding – winding the wire onto a rotating bobbin

Needle winding – a needle travels past the stator cores through the slot channel between the two neighbouring poles of the motor

Flyer winding – feeding the wire through a flyer that is rotating at a certain distance from the spool.

Figure 5 Variety of coil types [Source: Hagedorn *et al.* 2018, ©Springer].

The latest trends in the design of electric motor and magnet wires

Gliding optimized wire. A special class of magnet wires, where the top layer of enamel is functionalized regarding best gliding properties. The extremely low coefficient of friction ensures excellent winding properties, high filling factors, high process speeds and reduced filth formation during winding operation. The very good surface properties lead to less stress on the wire during processing. The most significant benefit for motor manufacturers is increased motor efficiency due to enhanced filling factor and thus more copper in winding and high manufacturing productivity as a result from high process speeds without the risk of breaking wires or other malfunction.

Another way, how to increase the motor efficiency through the increase of filling factor is to switch from round wire winding to hairpin technology. Since round wires always have some gap between each other and the requirement for some space for primary insulation (wire enamel) as well as for additional insulating material, the filling factor in the stators´ slots is far from ideal state (filling factor 40 ~ 50%). On the contrary, rectangular wires enable geometrically much better usage of slot space (filling factor up to 70 %). The increase of slot filling (active stator material) and simultaneously decrease of winding head height (material that only contributes to the losses, not to the output at all) results into favourable torque response and better efficiency compared to the insertion of conventional winding.

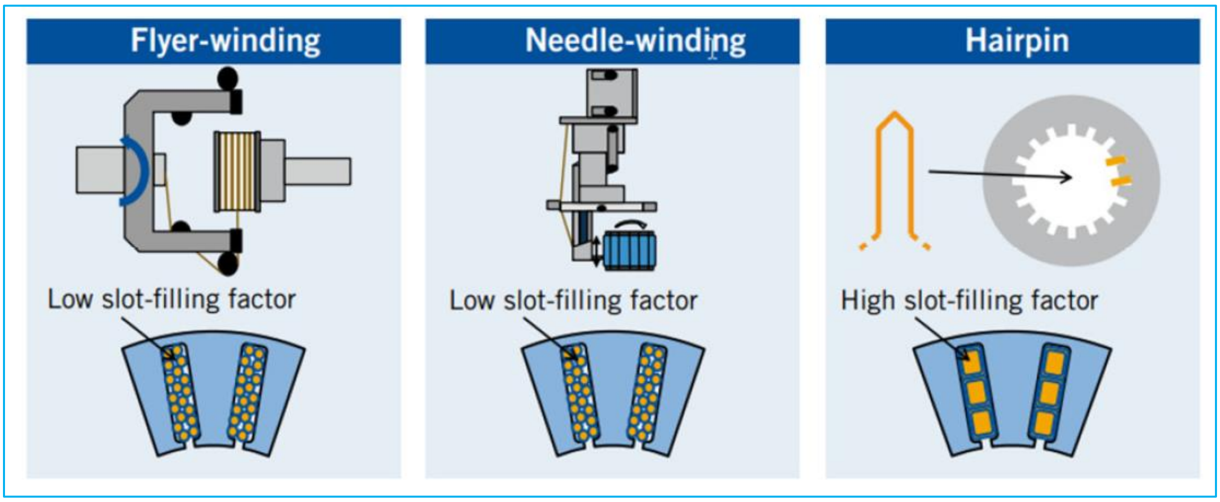

Figure 6 Comparison of winding technologies with hairpin technology [Source: Kampker *et al.* 2018, ©RWTH Aachen].

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