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RESEARCH ARTICLE

Manufacturing Techniques for Electric Motor Coils With Round Copper Wires

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ABSTRACT To design and manufacture electric machines that are competitive in terms of cost, performance, and efficiency, various parameters must be considered. Winding type selection and manufacturing are among these aspects. The winding needs to be designed optimally according to the electric machine type and application. Choosing the suitable magnet wire is one of the essential steps in winding design and manufacturing. For this purpose, several parameters need to be considered, including the diameter, thermal class, conductor type, and insulation material of the magnet wire. Also, the type and material of the bobbin should be selected properly. The tension applied to the wire during the winding process is an important parameter to achieve perfect layering and a high fill factor. Automatic winding techniques can be chosen according to the winding process requirements and the manufacturing volume. Different steps in the manufacturing process of electric machine coils are investigated in this paper, including the factors that should be taken into account to have a high-quality product. For design-for-manufacturing considerations, the approaches for selecting the proper magnet wire, insulation, bobbin, and layering technique are presented. Finally, different winding techniques are introduced, and their specifications and capabilities are discussed and compared.

INDEX TERMS Automated winding machines, design for manufacturing, electric motor coil, orthocyclic layering, winding techniques.

I. INTRODUCTION

The global electric motor market size was \$106.45 billion in 2019. It declined by −9.6% in 2020 due to the global impact of the covid pandemic. However, the market is anticipated to grow at a compound annual growth rate (CAGR) of 7.0%, from \$113.14 billion in 2021 to \$181.89 billion by 2028. The market demand and growth are expected to return to pre-pandemic levels, which fuels a rapid increase in CAGR [1]. Electric motors are heavily used in industrial, agricultural, and automotive applications. Technological advances and urbanization in the last few decades have also increased the demand for motors across the residential and commercial sectors. The heating, ventilation, and air conditioning (HVAC) sector has experienced the fastest rate of motor deployment [1], [2], [3]. Due to this growing demand, electric motors have become a major consumer of electrical energy. Hence, the manufacturers are trying to build more efficient motors with better packaging. Copper losses account for a significant part of the power losses in an electric machine. The design and manufacturing process of the windings play a critical role in achieving lower copper loss, higher performance, and smaller packaging, as they can reduce the total winding resistance and improve the power density.

In order to achieve high electromagnetic and thermal performance, it is important to select the right conducting material. Copper has high electrical and thermal conductivity, and it is the most commonly used conductor in electric motor applications. Aluminum is an alternative conductor that can be considered for electric motor coils. The electrical conductivity of aluminum is 61% that of copper. Therefore, to achieve the same ohmic DC loss, the cross-sectional

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area of an aluminum conductor should be 1.6 times larger than a copper conductor for the same conductor length. However, on volumetric bases, copper is more expensive than aluminum. In May 2021, the price of copper was USD \$93,450/m^3 and the price for aluminum was USD \$6,6883/m^3 [4]. Therefore, on a volumetric basis, copper is 13.6 times more expensive than aluminum. For the same ohmic DC loss, a copper conductor would be 8.5 times as expensive as an aluminum conductor. However, the thermal conductivity of aluminum is 55% of that of copper. This might require an even larger cross-sectional area to maintain a similar temperature rise with an aluminum conductor and it might lead to a smaller difference between the cost of a copper and aluminum conductor for the same ohmic loss and operating temperature. Aluminum can be considered for weight-restricted applications because its mass density is 3.29 times smaller than copper [5]. There are also new conducting materials like carbon nanotubes (CNTs), graphene, and high-temperature superconducting (HTS) materials that are investigated for electric motor windings for high-performance applications [6], [7], [8], [9].

In general, electric motor windings are constructed using round wires or rectangular bar conductors. In bar windings, preformed bars made of enameled rectangular conductors are used. These bars, formed in a hairpin shape, are inserted into the slots, and then their free ends are connected through a welding process. Typically, bar winding provides a higher fill factor and better thermal performance compared to winding with round wires. But the motors with bar windings usually have higher AC resistance. As rectangular conductors have a larger surface area, the skin and proximity effects are more significant. This results in higher copper losses, especially at high-speed operations [10], [11], [12], [13], [14], [15].

In electric machines, coils with round wires are usually applied in concentrated and distributed windings [16], [17]. In a distributed winding, the current inflow and outflow sides of a coil are located at slots that are in the neighborhood of different stator teeth. It is used in the armatures of synchronous, induction, and DC machines. In a concentrated winding, the coils are wound concentrically around one stator tooth. This means that the current inflow and outflow sides of a coil are located on each side of a certain stator tooth. Depending on the motor type, the concentric coils around different stator teeth are connected to create the phase windings. Concentrated coils are used in the field windings of salient pole synchronous motors and DC motors, and the stator windings of brushless DC motors and switched reluctance motors. Concentrated winding can achieve a higher slot fill factor and shorter end-winding length as compared to distributed winding. Hence, it can provide a lower-cost solution in terms of manufacturing. However, depending on the motor design, an electric motor with a concentrated winding can have a larger distortion in the air gap flux density as compared to distributed winding, which might impact the motor performance [18], [19], [20], [21], [22].

There have been a variety of studies conducted on the design and manufacturing of electric motor coils. Reference [23] analyzes the thermal behavior of a novel compact winding process in which wires are pressed together to achieve a higher fill factor. In order to approximate the thermal behavior with good accuracy, various analytical approaches were compared. Additionally, several test samples were produced and compared with conventional random and hairpin windings. The application of additive manufacturing (AM) in production various parts of electrical machines, including windings, is presented in [24]. The study investigates additive manufacturing of windings with various materials and winding types. In [25] and [26], several winding technologies were assessed for traction applications, considering their effects on winding design parameters and machine performance. The latest winding technologies for transportation electrification were reviewed in [27], along with a review of the multi-physics aspects of electrical machine winding design.

In the literature, only a few papers have investigated the manufacturing aspect of electric motor coils in detail. Therefore, this paper comprehensively discusses the manufacturing techniques for electric motor coils, which need to be considered for design-for-manufacturing. The essential steps and parameters that should be considered in coil design and manufacturing are investigated. In the manufacturing process, the first step is selecting the proper magnet wire, insulation, and bobbin based on the stator type and operating conditions. A higher fill factor can be achieved by inserting more copper into the stator slots either as strands or turns. This leads to higher current density and magnetomotive force and, hence, higher power and torque density. This is where the proper wire tension shows its importance. Wire tension should be applied properly during the winding process, and methods such as perfect layering should be utilized to achieve a higher fill factor. Different components of the winding machines have a key role to reach the desired tension and retain it in the winding process. Hence, the winding machines and their main components are discussed to develop a better understanding of the winding process. Finally, different winding techniques including linear winding, flyer winding, needle winding, and shed winding are investigated, and their specifications and capabilities are discussed.

II. COIL DESIGN PARAMETERS

A. MAGNET WIRE & INSULATION

The insulated wire used in electric motor coils is generally called magnet wire. In order to satisfy electrical and thermal requirements, individual conductors or strands are coated with an insulating layer [28]. The winding insulation prevents contact between the conductors of different turns or between the conductors and the core. National Electrical Manufacturers Association (NEMA) Magnet Wire (MW) 1000 standard provides the insulation materials, the dimensions, and testing details for magnet wires. Table 1 summarizes some of the most commonly utilized magnet wire standards, their

TABLE 1. Insulation characteristics and thermal class for magnet wires [29], [30], [31], [32], [33], [34].

Insulation Characteristics	NEMA Standard	Thermal Class	Application
Polyvinyl Acetal (Formvar) • Excellent mechanical properties such as abrasion resistance and flexibility. • The film can withstand excessive elongation without rupture. • Formvar can be removed mechanically or chemically during terminal preparation.	MW 15-C	105	• Solderable films such as Class 155 MW 80-C replaced MW 15-C in many applications. • Commonly used in oil-filled transformers.
	MW 19-C		• Same underlying coating as MW 15-C; overcoated with self-bonding resins • Self-bonding overcoat can be activated by heat (oven or applied current) or solvent • Electrical, chemical, physical, and thermal properties of self-bonding wire are equivalent to those of base insulation, except for the melting point or solvent resistance of the bondcoat
Polyurethane • Polyurethane insulation allows soldering without prior removal of the film • Low temperature solderability at 390°C	MW 79-C (Solderable)	155	• Small motors, relays, ignition coils, solenoids, low voltage transformers • MW 131-C has the same coating with self-bonding overcoat for the same thermal class
	MW 82-C (Solderable)	180	• Suitable for applications that require high thermal resistance and low soldering temperatures • Automotive relays, ignition coils, transformers, and solenoids
Underlying coat: Polyurethane **Superimposed coat: Polyamide** • Similar to MW 79-C and MW 82-C with additional Polyamide (nylon) overcoat • Polyamide improves abrasion resistance and heat shock characteristics • Solderability at 430°C for low AWG, 390°C for high AWG	MW 28-C (Solderable)	130	• Appliance motors, relays, timer and clock coils, encapsulated coils • Suitable for automated winding machines; not recommended for severe overload conditions
	MW 80-C (Solderable)	155	• Single build MW 80-C is a commonly stocked magnet wire in most sizes • MW 136-C has the same coating with self-bonding overcoat for the same thermal class
	MW 83-C (Solderable)	180	• Small motors, armature windings, automotive coils, toroidal coils, encapsulated coils, speciality power transformers • MW 137-C has the same coating with self-bonding overcoat for the same thermal class
Polyester-imide • Insulated with a modified polyester resin (polyester-imide) • High thermal endurance, solvent resistance	MW 30-C	180	• Low coefficient of friction to improve windability • Non-solderable, requires mechanical or chemical stripping
	MW 77-C (Solderable)		• Solder strippable at 470°C • Not recommended for applications subject to high winding stresses
	MW 74-C	200	• Normally produced in high AWG sizes • Motors, small coils, transformers
Underlying coat: Polyester-imide **Superimposed coat: Polyamide** • Modified polyester basecoat and a Polyamide (nylon) topcoat • Combines high thermal properties of polyester and mechanical properties of nylon	MW 76-C	180	• Fractional & integral HP motors, coils & relays, control & dry-type transformers, DC field coils • Not suitable in refrigerant or high moisture environments
	MW 78-C (Solderable)		• Solders at 455°C • Shaded-pole motor coils, special encapsulated coils, relays, yoke coils
Glass Fiber Covered, Silicone Treated • Glass fiber covering, produced in the form of a yarn, wrapped firmly around the wire (continuous filament glass yarn) • Silicon varnish can be applied for a tough outer finish	MW 44-C (Glass)	200	• High overload resistance • Motors, dry transformers
	MW 47-C (Dacron® Glass)		• Dacron glass is a combination of polyester and glass fibers • Physical protection to severe winding application, high abrasion resistance, increased flexibility
Underlying coat: Polyester-imide **Superimposed coat: Polyamide-imide** • Provides physical toughness, high dielectric properties, and better chemical resistance to common solvent and refrigerants • Improved thermoplastic flow, heat shock resistance	MW 35-C	200	• Suitable for inverter applications which can have higher voltage spikes • Good windability performance; commonly used in rotating machines and for motor repair
	MW 73-C (Hermetic)	220	• High moisture resistance • Suitable for open motor and high moisture applications • Not softened by refrigerants
Aromatic Polyamide Paper Covered • Physical toughness, moisture resistance, high temperature dielectric breakdown	MW 61-C (Nomex® Paper)	220	• Insulation properties will be retained after continuous operation at high temperature • Dry-type or oil-filled transformers, form wound coils
Aromatic Polyimide • Thermoplastic flow (temperature at which the coating softens) of over 400°C • Insulation can withstand excessive overloads	MW 16-C (Hermetic)	240	• The insulation can operate in excess of 240°C for intermittent duty • High resistance to chemical solvents • Fractional & integral HP motors, hermetic and sealed units

thermal classes, and their insulation characteristics [29], [30], [31], [32], [33], [34]. For most thermal classes, different insulation materials are available, as shown in Table 1. There are many factors that influence the choice of insulation materials, including thermal stability, heat shock resistance, self-bonding capability, abrasion resistance, flexibility, windability, solderability, dielectric breakdown, and solvent, refrigerant, and moisture resistance.

Magnet wires have standardized dimensions, which are given in the American Wire Gauge (AWG), and they have an insulation layer (called *build* for film-insulated wires and *type* for self-bonding wires). A larger gauge number indicates a smaller wire diameter. The wire dimensions for the AWG number vary for film-insulated, self-bonding, and fibrous-covered wires. But, for each insulation category and the same AWG number, the wire size should be the same even though the insulation material is different (e.g., for MW 35-C and MW 76-C standards, 20 AWG heavy-build wire will have the same diameter within the given tolerances). For thicker wires, the elongation at break increases, which is a measure of the maximum wire deformation. However, the spring-back angle decreases as the wire thickness increases. Spring-back occurs when the wire tries to return to its original shape after bending. This means that thicker wires (lower AWG values) require higher bending forces, but they can be strained more since they can have a lower spring-back angle [35].

Usually, another layer of insulation is needed for the electric motor winding to improve the electrical, thermal, and mechanical properties of the motor. This insulation layer is generally applied by impregnating the body of the windings with a polymer material, such as an epoxy resin or varnish. Electric winding impregnation improves the insulation, the winding's resistance to stress, and its heat transfer capability [36]. The volumetric ratio of air to the impregnation body determines the quality of the impregnation. Air has a lower thermal conductivity than that of the impregnation material; therefore, impregnation can help improve the heat transfer. Varnish has been used in electric motor manufacturing for a long time, as it can be easily applied to the winding with a dip and bake process, and it has good electrical, chemical, and mechanical properties. As an alternative to varnish, epoxy resins offer higher thermal conductivity, but lower resistivity and dielectric strength. Polymer nanocomposites have recently gained attention as an impregnation material in electrical machines. In order to improve heat transfer inside the stator slots and end windings, there is an increasing need for materials with higher thermal conductivity [37].

Due to the friction properties of the insulation, lubrication is usually applied to the film-coated magnet wire [29]. The lubrication enables an easier de-reeling of the wire out of the spool and maintains a compact winding [35]. Oily lubricants can absorb dust and drain out of the spool; therefore, solid agents such as paraffin and waves are used on the magnet wire to create a solid dry sliding surface [38]. An insulation topcoat with better lubrication properties can also be used to eliminate the additional lubricants.

B. FILL FACTOR

The slot fill factor is defined as the ratio between the total wire area and the slot area, and it is an important parameter in electric machine design. For round wires, the slot fill factor will always be smaller than one. This is because, even with orthocyclic layering (ideal placement of the upper layer wires onto the valleys of the lower layer wires), there will be some gap between the wires. The typical slot fill factor for electric motors is usually around 60-70% in practice. This fill factor can usually be achieved with proper slot and coil design, and by utilizing winding machines. In order to achieve a high fill factor, many design parameters should be carefully considered including the size and insulation material of the magnet wire, the number of turns and strands, slot shape, bobbin design, axial length of the stator core, placement of wires in the slot, slot opening, and the winding manufacturing process [38].

A higher slot fill factor means that more wires can be inserted into the slot and these wires make the turns and strands. A higher number of turns increases the magneto-motive force, which can help improve the torque density of the motor. A higher number of strands increases the effective surface area the current flows through. This reduces the phase resistance and current density, which can help reduce copper losses and achieve lower temperature rise. The forming and layout of the wire are critical in achieving a high fill factor, and the bobbin and the tension have a significant impact on it. A bobbin is used to form the coil and carry the winding. In order to make sure the wire is properly placed on the bobbin, tension is applied.

C. BOBBIN

A bobbin holds the coil within the boundaries of the slot, and it provides electrical insulation between the coil and the stator core. Fig. 1 shows three bobbin types that are commonly applied in electric motors. In a full lamination stack bobbin, the winding is wound continuously, which is generally referred to as closed-stator winding. In the segmented stator bobbin and single-tooth bobbin, the area around the bobbin is more easily accessible. Hence, these bobbins can provide a higher fill factor compared to the full lamination stack bobbin. A single-tooth bobbin is usually wound separately outside of the stator and then inserted into the stator teeth.

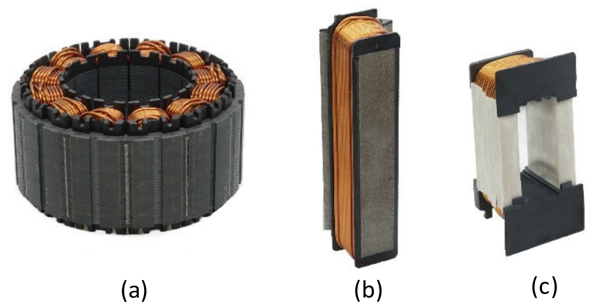

FIGURE 1. **Different bobbin types used in electric machines: (a) full lamination stack bobbin, (b) segmented stator bobbin, (c) single-tooth bobbin.**

Synthetic materials are widely used for bobbins. The processing methods for these materials are continuously improved and that has provided new options for winding technologies. The improvements in the processing of bobbins have led to the production of materials with higher strength and operating temperature [34]. Table 2 shows a list of different synthetic materials used in bobbins.

Several parameters should be considered when selecting the bobbin material, such as mechanical strength, electrical insulation, and thermal resistance. In a winding process, high enough force should be applied to develop the necessary tension to achieve a higher fill factor. This tension can deform the bobbin. The mechanical strength of the bobbin is related to its wall thickness. The wall thickness of the bobbin should be sufficient to prevent deformation during the winding process. If the mechanical strength of a bobbin material is low, the bobbin might need a thicker wall. However, that might reduce the fill factor. Electrical insulation should be considered especially in high voltage applications. The tendency of the material to absorb water can have a significant impact on its electrical insulation. The absorption of water from high humidity conditions can reduce the dielectric strength of the bobbin material. Improving the power density of electrical machines has led to higher operating temperatures. Hence, the bobbin material should be chosen properly to prevent any deformation or meltdown [41].

D. TENSION

In order to achieve a high fill factor, it is essential to form the wire to the determined winding structure. Hence, wire stresses and subsequent forming characteristics are important. The relative movements between the bobbin and the wire cause stress during the winding process. The other sources of wire tension are wire mass and the friction between the wire and the guiding elements of the winding machine. These tensions are not enough and would result in undefined wire placement on the bobbin. In order to ensure that the wire is positioned properly on the bobbin, more tension is required. On the other hand, the wire tension should not be above the copper wire's yield strength because it can taper the wire diameter irreversibly and increase the resistance of the winding. In addition, the wire will tear if the stresses that

TABLE 2. Characteristics of the synthetic materials used for bobbins [39], [40].

Material	Dielectric strength (kV/mm)	Max Continuous Temperature (°C)
Polyethylene (PE)	19.7	100-130
Polypropylene (PP)	30-70	90-130
Polystyrene (PS)	15-28	65-122
Polyacetal (POM)	13.8-20	80-105
Polyvinylchloride (PVC)	10-40	50-80
Polyethylene terephthalate (PET)	16.8-60	80-140
Polyamide (PA)	10-55	80-160
Polycarbonate (PC)	16-38	60-193

occur during the winding process exceed the tensile strength of the copper wire [34], [42].

Constant and defined wire stress will maintain a consistent winding cross-section, which positively affects the winding properties. Other than the wire diameter tapering, variations in stresses in the winding process can cause strain hardening. Strain hardening is the strengthening of the material (e.g., copper) due to deformation. It happens as a result of the dislocation movements and dislocation generation within the structure of the copper [43]. Strain hardening increases the hardness of the wire and also decreases its elongation at break.

Elongation at break is the ratio between the change in the length of the material after breakage and its initial length [34]. Hence, the diameter and hardness of a wire are the parameters that can be influenced by the resulting wire tension. The wire properties like electrical resistance and mechanical strength are dependent on the remaining elongation after the winding process and the elongation at the break of the wire.

Fig. 2 illustrates the effects of proper and also unacceptable wire tension control. The bobbin flange bending or divergence from the intended coil geometry may be another indication of excessive wire tension as shown in Fig. 2 (c). This tension can lead to wire tearing in extreme cases. On the other hand, uncontrolled residual wire stress may result in loose winding or errors in layer structure as a result of low wire tension. Also, this may lead to gaps between the coil and the bobbin as shown in Fig. 2 (b). Another problem with low wire tension is poor thermal conduction from the coil to the bobbin as well as a higher electrical resistance due to the higher wire length.

During the early days of winding technology, the tension on the wire was achieved by clamping the wire between two parts. However, excessive pressuring can occur when the wire is clamped and that can damage the wire insulation. Therefore, the clamping method is less commonly used these days [44]. Today's latest winding technology uses a programmable and closed-loop tension device as shown in Fig 3. A closed-loop tension device is used to vary and maintain proper tension control throughout the various acceleration/

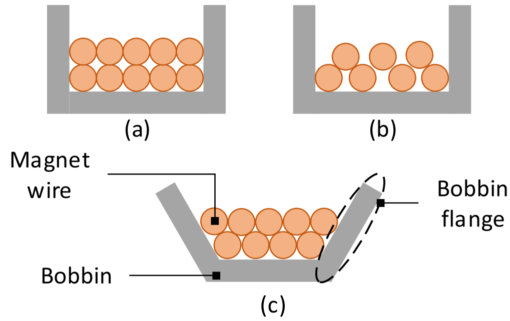

FIGURE 2. Wire tension control levels and their consequences (a) proper wire tension (b) low wire tension (c) excessive wire tension [34].

deceleration, wire placement, and termination operations in the winding process. Key components of the tension device ensure proper wire path and wire retention to fulfill the varying and rigorous tensioning requirements in the winding process.

III. LAYERING FOR MAXIMIZING THE FILL FACTOR

The winding scheme is primarily determined by the product requirements and its functionality. For example, a high-power-density motor would require an orderly-layered winding structure. However, in some applications, a lower-cost option might be preferred with random layering, which would potentially result in a lower fill factor.

Random layering is the simplest type of layering in the winding process of electric motor coils. In a random layering, the wires are wound around the bobbin randomly. But a high fill factor might not be usually achieved with random layering. The maximum fill factor for the winding with random layering is approximately 65% to 75% when using round wires [45]. Fig. 4 (a) illustrates the structure of a winding with random layering. In a random layering, the overall length of the wire varies widely, and this results in a relatively high coil resistance. Despite these disadvantages, random layering is the most commonly used and the lowest-cost layering method. It is generally well-suited for mass production, because, with random layering, the speed of manufacturing is usually high both from a winding machine and winding operator perspective. Random layering can be used for high-turn-count applications with rather thin wire diameters up to 0.5 mm [45].

Orthocyclic layering depicted in Fig. 4 (b) can provide a perfect layering and high fill factor. But it can be more challenging to apply in manufacturing as compared to random layering. In orthocyclic layering, the conductors are placed mostly parallel to the bobbin flange, and the conductors from the upper layer are laid onto the valleys of the conductors from the lower layer, as shown in Fig. 4 (b).

Theoretically, around 90 percent fill factor can be achieved in a winding with orthocyclic layering of round wires. As shown in Fig. 5, the space between the wires in an orthocyclic layering can be calculated using the equilateral triangle formed between the wires. The fill factor is calculated as the

FIGURE 3. **Closed loop tension device and its components.**

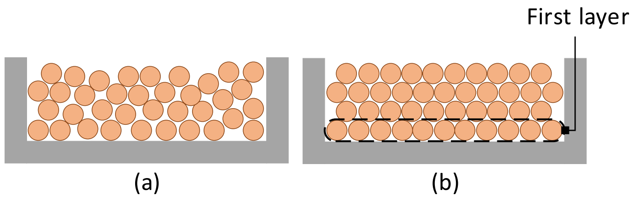

FIGURE 4. **Winding with (a) random layering (b) orthocyclic layering.**

ratio of the wire area inside the triangle and the total triangular area [45]. The best case is when a conductor from the upper layer is exactly laid onto the valley between the two lower conductors. The length of each side of the equilateral triangle equals the wire diameter, d. The area of the triangle is

$$A_t = \frac{1}{2} \times base \times height = \left(\frac{1}{2}d\right)\left(\frac{\sqrt{3}}{2}d\right). \tag{1}$$

The area of the conductor inside the triangle, which is comprised of three 60° sectors of all three wires, equals to

$$A_c = 3\left[\pi\left(\frac{d}{2}\right)^2 \frac{60^\circ}{360^\circ}\right]. \tag{2}$$

Hence, the fill factor is calculated as,

$$k = \frac{A_c}{A_t} \approx 0.91. \tag{3}$$

The bobbin can be designed with grooves to place the correct number of wires in the first layer and maintain their exact position. This helps achieve precise orthocyclic layering. Then, in the subsequent layers, it becomes easier to place the wires since the necessary grooves will be provided by the valleys of the conductors in the previous layers [46].

The location of the wire guide is another important aspect of orthocyclic layering. Fig. 6 illustrates the position of the wire guide with respect to the bobbin. As shown in Fig. 6, the wire guide is one of the components of the winding machine that feeds the wire onto the bobbin. In order to avoid a loose winding and spread between the turns in each layer, the position of the wire guide must not be in front of the wire

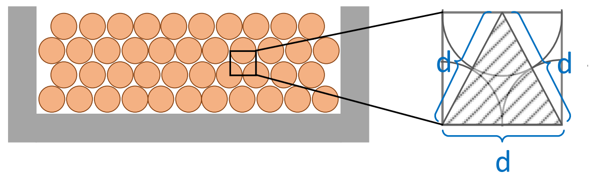

FIGURE 5. **Calculation of the maximum fill factor of orthocyclic layering.**

location (Fig. 6 (b)) in the direction of the winding. For a gap-free winding structure, the wire guide must be behind the wire location as shown in Fig. 6 (a). For this purpose, the caster angle is defined. As shown in Fig. 6, the caster angle corresponds to the angle between the segment AB, which is the distance between the winding axis and wire guide, and the segment AC, which is the distance between the wire location and wire guide. The caster angle is referred to as positive if the wire guide is behind the wire location in the winding direction [45].

The caster angle has a decisive influence on the structure of a winding. For a compact winding structure with closely spaced turns, it is advantageous to use a positive caster angle, so the wire guide trails behind the winding location by a few degrees. With a positive caster angle, the turns are tensioned against each other, and gaps between the turns are avoided. However, if the maximum positive caster angle is exceeded, the wire would run onto the turns that have already been wound and a perfect winding structure cannot be accomplished. The main influencing parameters for the determination of the caster angle are the wire diameter and the bobbin diameter. In order to quantify this relationship, systematic investigations with selected wire and bobbin diameters are carried out in [45]. Based on the measurement results obtained, a mathematical model is then derived for the calculation of the maximum positive caster angle as a function of the wire and the bobbin diameter. In the measurements, test bobbins are wound with the use of the wire guide standing next to the bobbin until the wire lifts off the bobbin surface and lands on the already wound layers. To ensure the transferability of the measurement results, the wires are processed with the corresponding permissible wire tensile force. Then curve fitting techniques are applied to the measured data to calculate the maximum caster angle. The maximum caster angle can be given by:

$$\alpha_{max} = 51.52\, d_b^{-0.41} + 11.31\, d_b^{-0.33} \ln(d_w). \tag{4}$$

where α_{max}, d_b and d_w are maximum caster angle, bobbin diameter, and wire diameter, respectively.

It must be taken into consideration that, even below the maximum positive caster angle, a spread in the winding structure can occur because of the tolerances in the wire tension and deviations in the wire and bobbin diameter. In order to avoid this situation, the maximum caster angle is limited by a safety factor. From practical experience, for winding with orthocyclic layering, a safety factor of 0.4 is usually selected [45].

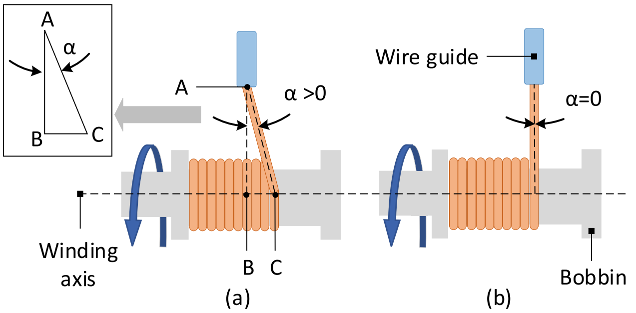

FIGURE 6. Illustration of the caster angle (a) positive caster angle (b) zero caster angle [45].

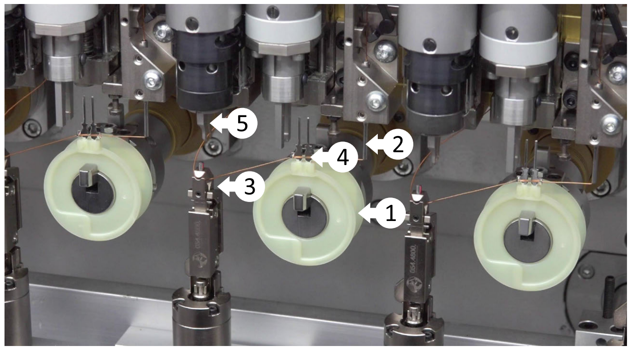

FIGURE 7. Components in a typical winding machine: (1) bobbin, (2) wire guide nozzle, (3) park pin, (4) contact post, (5) wire cutter.

IV. AUTOMATED WINDING PROCESS

There are various types of winding machines based on the requirements of the winding process. It is possible to find both manual and automatic winding machines. In most applications, automatic winding machines are preferred over manually operated ones because they have a lower failure rate, high-volume production capacity, and multitasking capability. Multi-tasking is possible by using multi-spindle winding machines. Compact installation space and higher production speed are the main advantages of multi-spindle machines.

A. MAIN COMPONENTS

As discussed earlier, wire tension control is an important part of the winding process. Depending on the winding task, various types of wire tension control devices and clamps can be employed as the wire tension control system.

Another important component of a winding machine is the wire guide nozzle which places the wire onto the coil. Fig. 7 illustrates the wire guide nozzle and some other components of a winding machine. Typically, a wire guide nozzle consists of a tube that has a diameter designed for the cross-section of the wire. Usually, tungsten carbide or high-strength tool steel alloys are used as the materials. Hence, it meets the requirements for high strength. In order to keep the friction at a minimum, the wire guide nozzle is polished on the inner side. All parts that are in direct contact with the wire must possess high surface properties to ensure long-term and low-friction operation [34]. The wire park pin, shown in Fig. 7, is the component that holds the wire, and it maintains tension on the wire when the wire is cut and separated from the bobbin. The contact post on the bobbin is used to fix the wire on the bobbin before and after winding the wire onto the bobbin. Therefore, the contact post prevents the winding from becoming loose after the winding process is completed. As a substitute for wire park pins, in some cases, a wire clamp can be used above the wire guide nozzle to clamp the wire, as shown in Fig. 8. This method prevents the waste of wire because the wire that is wound around the park pin is discarded after it is cut and separated from the bobbin.

B. WINDING PROCESS

The first step in automated coil manufacturing is to fix the wire on a wire park pin (component 3 in Fig. 7). Following that, the wire needs to be fixed to the contact post (component 4 in Fig. 7) on the bobbin (component 1 in Fig. 7). After that, the wire between the park pin and contact post should be cut by the wire cutter (component 5 in Fig. 7). To start the winding process, the wire park pin needs to be moved away. As the wire between the park pin and contact post is cut, some wires will remain on the park pin.

This is referred to as wire waste. When the wire park pin is relocated, the wire waste can also be disposed of at the same time, so the device will be free of wire in the next cycle. Then the winding process begins. Contact post and wire guide nozzle (component 2 in Fig. 7) locations determine the position of the first turn. When the winding process of the bobbin is completed, the same process at the beginning takes place in the reverse order. The wire is fixed on the bobbin contact post and then on the wire park pin. After that, the wire between these two points is separated, and the cycle is repeated. The coils wound on the bobbins are either automatically or manually removed from the machine, and then the machine is fed with a new bobbin or winding tool.

V. WINDING TECHNIQUES

A suitable winding technique is ultimately determined by the product type and the production cost. In this section, different winding techniques that are commonly used in electric motor manufacturing are introduced and explained.

A. LINEAR WINDING

Linear winding is the most common technique used for winding coils. Fig. 9 illustrates the wire guide and spindle axes in a linear winding machine [47]. In this winding method, the wire guide follows a linear path from one bobbin flange to the other, as the bobbin rotates on the spindle. Hence, the name originates from this wire placement characteristic.

In linear winding, a high winding speed can be achieved, especially when using thin wires. In order to be able to reach a high winding speed, the components of the spindle should be designed to achieve a high rotation speed.

Besides, vibrations must be dampened. For weight reduction in the machine components, materials like cast iron with lamellar graphite and aluminum cast alloy are used.

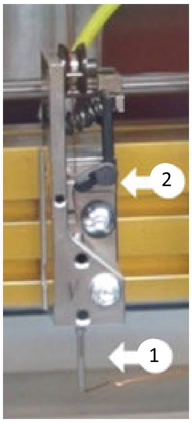

FIGURE 8. Wire clamping mechanism: (1) wire guide nozzle (2) wire clamp.

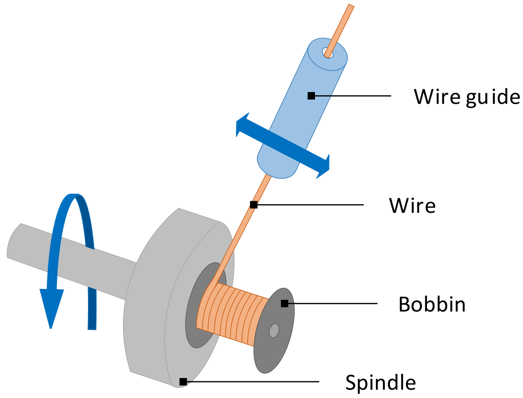

FIGURE 9. Illustration of the linear winding process [48].

For high winding dynamics, winding machines must be designed according to the product-specific process. Moreover, by designing the winding fixture and the guiding components in an interchangeable manner, it is possible to use the linear winding machine for winding different bobbins [34].

B. FLYER WINDING

The flyer winding technology gets its name from its motion sequence, or more specifically from the behavior of the wire during the winding process. Fig. 10 illustrates the functional elements of a typical flyer winding machine. In a flyer winding, the bobbin is fixed, and the wire makes a circular motion around it under the guidance of a flyer. The guiding element in Fig. 10 slides the wire into the winding space. The guiding element moves back and forth to position the wire on the bobbin after the flyer winds a turn by making a rotation.

For cylindrical and single-tooth bobbins rotational motion is easier to achieve without causing large vibrations. Hence, the linear winding technique is usually a good option for those cases. However, especially for full stack laminations, it can be a lot more challenging to spin a core on a spindle, as that might cause excessive vibration. Hence, the flyer winding technique is suitable to wind full stack laminations. For a high-quality winding, the rotating object (e.g., flyer) on which the wire is placed must operate smoothly.

The flyer winding method can apply higher stresses on the wire especially when a wound rotor or an interior stator the part requires a relatively low number of turns with thick wires. The linear in-slot winding method shown in Fig. 11 can be used for those cases instead of flyer winding. In the linear in-slot winding, the part to be wound and the jaw rotate. The tailstock makes a linear motion so that the jaw places the wire into the slot. The grid can expand and increase the size of the jaw so that the orthocyclic layering is maintained in multiple wire layers. The linear in-slot winding technique usually operates slower than linear winding applied to wind a bobbin, because the coil is wound inside the slot, and it works with thicker wires. For the wound-rotor case in Fig. 11, linear in-slot winding is a more feasible method as compared to needle winding, even though needle winding operates faster. This is because the wound-rotor part in Fig. 11 has a narrow slot opening for a needle to operate with thick wires.

C. NEEDLE WINDING

As opposed to linear and flyer winding techniques, needle winding technology refers to the geometric structure of a winding nozzle rather than the approach of placing the wire on a bobbin or slot. In this technology, the wire guide nozzle is called a needle. Fig. 12 shows different parts of a typical needle winding machine and the direction of the movement of the wire guide. There are often special requirements for wire guides used in needle winding technology. As the needles are often handled deeply inside the slot, they are often designed longer. The inner side of a needle should be lubricated and has a high-precision surface finish. This has a significant impact on the winding quality. In needle winding, the wire guide directly moves around the bobbin or tooth to wind the coil. Rather than moving in a circular motion, the wire follows the winding geometry in a direct path. Products with thicker wires and fewer turns are typically wound with needle winding technology [49], [50], [51].

Needle winding is suitable for both external and internal stators, as shown in Fig. 13. Because of the type of the motion in the needle winding technique, the speed of the wire guide is usually lower as compared to linear and flyer winding techniques. This can limit the number of turns per minute that can be achieved.

A needle winder is also used in pole chain winding. The pole chains, as shown in Fig. 14, consist of multiple, linearly arranged single bobbins that are attached to a stator tooth. In a pole chain winding, bobbins for different phases are wound simultaneously using multiple needles. After the winding process is completed, the single bobbins are arranged into a circular stator shape by connecting them.

As compared to linear and flyer winding techniques, needle winding might lead to a slower, but more reliable winding process, and it can enable a higher fill factor with better utilization of the slot space. Linear and flyer winding techniques can provide higher manufacturing speed as compared

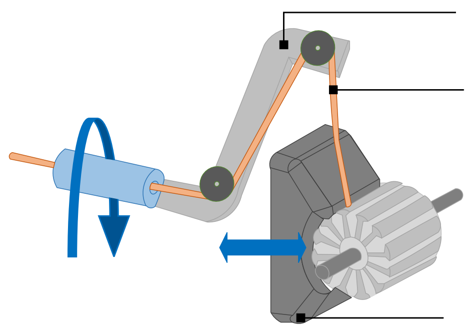

FIGURE 10. Illustration of the flyer winding process [48].

to needle winding. However, this higher speed may lead to a higher number of winding faults like a gap between the turns, loose wire, or overlaying the wires on top of each other. Moreover, in some stator configurations, such as switched reluctance machines, slots are shared by two coils. Considering adjacent coils, there is usually more space for the winding in the radially outer part of the stator (close to back iron) compared to the radially inner part of the stator (close to airgap). Using linear and flyer winding for these types of bobbins might end up with a lower fill factor. This is because, if the radially outer portion of a bobbin is filled with wire, it might not be possible to insert it into the slot, as it would need to be inserted through the smaller radially inner portion of the slot.

D. SHED WINDING

The shed winding technique is rather different from the linear, flyer, and needle winding techniques. In the previous methods, the coil is wound on the stator pole directly, or it is wound on individual bobbins and then inserted on the stator poles. However, in the shed winding process, the coils must first be manufactured as air coils by using a flyer winding machine.

In shed winding, the required number of turns is wound into an insertion tool by using a form, as shown in Fig. 15. Using a flyer winder (component 3 in Fig. 15), the coils are wound on a form (component 1 in Fig. 15) that is shaped for the motor being manufactured. As the coils are wound on the form, they are released into the insertion tool (component 2 in Fig. 15). Then, the coils are inserted into the stator slots with an insertion process. With the shed winding process, it is possible to wind and insert phases individually, or it is also possible to wind all phases on the insertion tool and insert them all at once [34].

Fig. 16 (a) illustrates the components of a typical insertion tool. The insertion tool is composed of three main elements: the outer needle, the inner needle, and the transmission tool. The needles guide the wire into the stator slots, and the transmission tool pushes the coils up inside the stator slots. The inserting process is conducted in three phases as shown in Fig. 16 (b). In Step A, the insertion tool moves into the stator. In Step B, the transmission tool moves up and pushes the coil into the slots. In order to avoid the winding entering the air gap, the transmission tool is extended into the slot in Step C, to a level where the coil is pushed into the bottom of the slot [34].

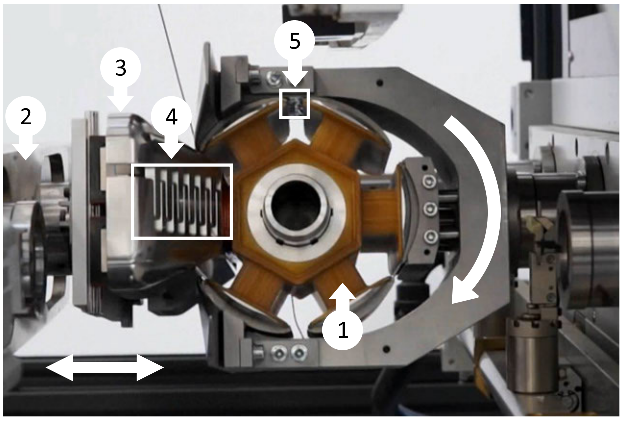

FIGURE 11. Main components of linear in-slot winding: (1) rotor to be wound (2) tailstock (3) jaw (4) grid (5) slot opening.

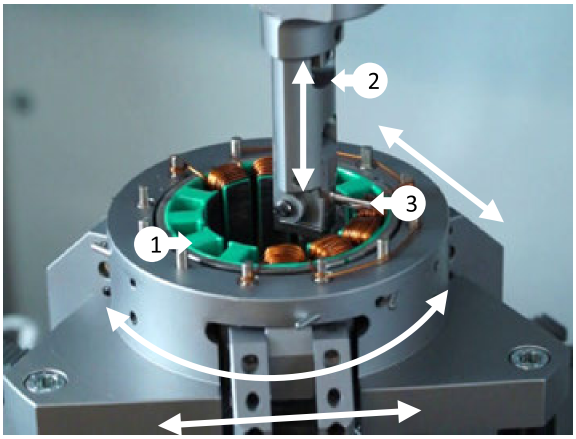

FIGURE 12. Functional elements of a typical needle winding process: (1) bobbin (2) wire guide (3) nozzle.

E. DISCUSSIONS

The selection of the winding technique and the winding machine depends on various factors such as the application, wire size, and the manufacturing process. The linear winding technique is usually used for the concentrated winding of single-tooth and segmented stator bobbins. It can provide a high winding speed and good layering of the conductors. But linear winding requires the coils formed outside of the stator. Hence, the motor manufacturing process needs to incorporate the insertion of the coils and bobbins into the stator slots, and the connection of the coils to create the phase windings. Needle winding has a broad application, and it can be used for most electric machine windings and both concentrated and distributed windings. An advantage of needle winding is that coils are wound into the slot, and this eliminates the post-manufacturing processes required when the linear winding is used. In needle winding, the coils of the same phase can be connected together during the winding process, as the needle

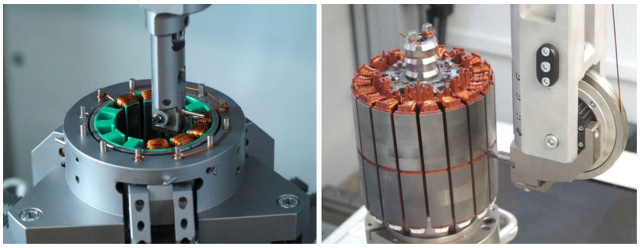

FIGURE 13. Needle winding technology applied for different stator configurations: (a) internal stator and (b) external stator.

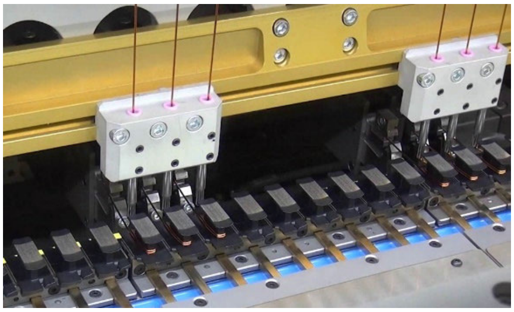

FIGURE 14. A needle winder applied to wind pole chains.

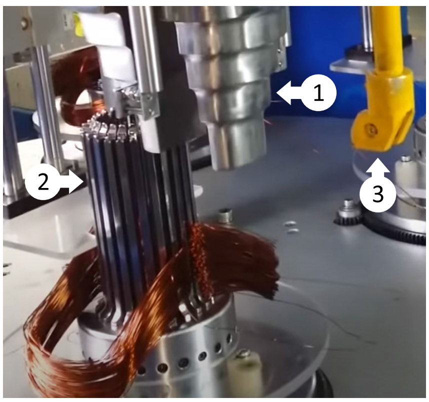

FIGURE 15. Main components in a typical shed winding process: (1) coil form, (2) insertion tool, (3) flyer [52].

can be programmed to route the wire between the coils. In needle winding, the stator is the rotating component, and the needle makes linear motion. In linear winding, the bobbin rotates, and the wire guide makes the linear motion. The mass of the stator is much larger than the bobbin; therefore, the motion control in a needle winding machine might require a tighter control and larger actuators. A linear winding machine with multiple spindles usually costs less and operates faster as compared to a needle winding machine with multiple needles with a similar center distance between the spindles or needles. When selecting a winding machine for a given application, these factors have to be considered to achieve the quality, cost, and volume targets.

The flyer winding is suitable usually for concentrated outer slot windings for inner stator motors and the rotor windings of synchronous motors. It can provide a relatively good layering if the winding machine is designed properly for the specified application. However, higher wire stresses can occur with

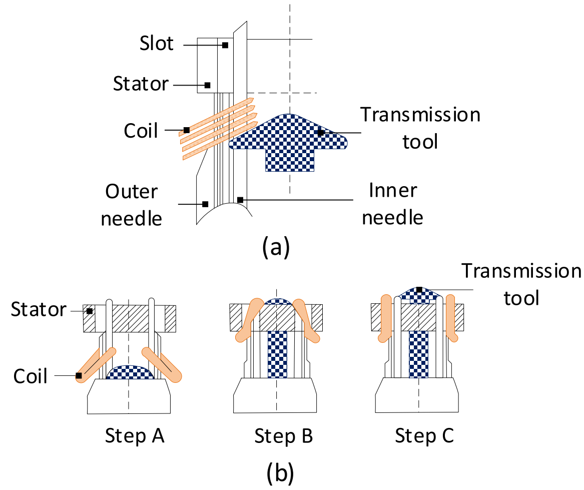

FIGURE 16. Illustration of the shed winding (a) components, (b) insertion process [34].

flyer winding, especially when a wound rotor or an interior stator has low number of turns with thick wires. Shed winding can provide a shorter cycle time compared to needle winding. It is mostly used in the distributed winding of stators in induction and synchronous machines. The shed winding technique creates random wire placement, which might result in a lower fill factor. Also, the overall length of the winding is higher due to the longer end turns.

VI. CONCLUSION

Important design-for-manufacturing considerations for electric machine coils are discussed in this paper. Selection of the proper magnet wire and bobbin is the first step. Conductor material, insulation characteristics and a thermal class of different magnet wires, and properties of the synthetic materials used in bobbins are provided. The fill factor is defined, and the importance of applying the proper amount of tension to the magnet wire and the orthocyclic layering technique is discussed to achieve a high fill factor. The automatic winding process is explained in detail, along with the typical components of winding machines. Finally, different winding techniques, including the linear, flyer, needle, and shed winding methods, are presented. Most of the components of linear, flyer, and needle winding machines are similar, but they have differences in the wire guide components. The comprehensive information provided in this paper serves as guidance for choosing the proper materials and manufacturing techniques of electric motor coils that are essential for design-for-manufacturing considerations. The main aspects of winding manufacturing are presented through discussions and examples on electric coil manufacturing and different winding techniques using exclusive illustrations of winding machines using cutting-edge technology.

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