CARPENTER ELECTRIFICATION®

WHITE PAPER

THE EVOLUTION OF THE ELECTRIC VEHICLE MARKET

Materials solutions for advanced powertrain design

SUMMARY

High-performance electric vehicles (EV) are growing in popularity. Models with more than 500 horsepower peak power are forecast to account for 13% of total EV sales by 2030. At least 14 new EV models with more than 700 horsepower are planned. Automotive manufacturers will adopt improved power- and torque-dense, efficient, compact powertrain technology to meet the new requirements for these high-performance EVs.

Electric motors serve as one of the key components of the EV powertrain. There are several design options to improve the power and torque density of an efficient motor. One potential approach uses thin, high-induction iron cobalt (FeCo) soft magnetic alloys with low loss. Hiperco® 50 FeCo stators and rotors can notably improve motor and vehicle performance, as compared to the thicker non-grain oriented electrical steel (NOES) commonly used in current EVs. EV motor simulation results indicate that for a Hiperco motor with 0.15 mm lamination, the peak torque would increase in the range of 15–18%, while the continuous power can improve by 25–60%, as compared against NOES motors with 0.25 and 0.35 mm thick laminations. Further, the Hiperco solution can enable the designer to make the motor 15% smaller and still maintain significant benefit in continuous power. These motor performance enhancements can help improve the vehicle acceleration, estimated up to 10%. Moreover, in an EV drive cycle simulation study, the Hiperco motor consumes 8–11% less motor power, which would improve EV range and/or operating costs.

Incorporating a higher power inverter in combination with motor design and power supply optimizations enables better utilization of the superior induction and permeability of Hiperco. The continuous power profile is dictated by thermal constraints, and Hiperco motors are able to take more current than the NOES motors. In this case, the Hiperco motor can have 32% higher maximum torque, or can be 25% smaller with similar torque while still offering up to 35% higher continuous power than the bigger NOES motors. Given the combination of the benefits of higher saturation induction, lower loss, and additional supplied current, a Hiperco 50 motor is able to achieve nearly 30% more peak power as compared to the same size electrical steel motor.

The evolution of the EV market

When the battery electric vehicle market was first established, the initial focus was on small economy cars that were good for the environment. Today, Tesla is the poster child for the industry, having reinvented the EV as a performance and luxury category. The watershed year for high performance EVs was 2017, when the number of Tesla Model X and Model S cars produced with more than 700 horsepower (hp) more than doubled from the prior year to more than 40,000 cars. During the same year, Tesla produced a similar number of Model X and Model S cars with 524 hp.

High-performance EV is now a dynamic sector with start-ups and traditional vehicle manufacturers entering the space. During 2020, cars with more than 500 hp accounted for 4.1% of the total EVs sold. By 2028, more than 13% of all EVs are expected to meet this performance level—2.7+ million vehicles.

During that same period, 700+ hp EVs are expected to see similarly increased activity. As of the end of 2021, there were nine companies planning to produce 24 different models of EVs at this performance level by 2028 (see Table 1 below). Based on announced plans, 700+ hp EVs will grow to more than 150,000 produced per year from approximately 26,500 units in 2021. Given recent market news and activity, the actual number is likely to be greater.

TABLE 1 — NUMBER OF BEV MODELS PRODUCED WITH 700+ HP AND NUMBER OF COMPANIES PRODUCING THEM.

	2016	2021	2028
Number of models	2	10	24
Number of companies	1	4	9

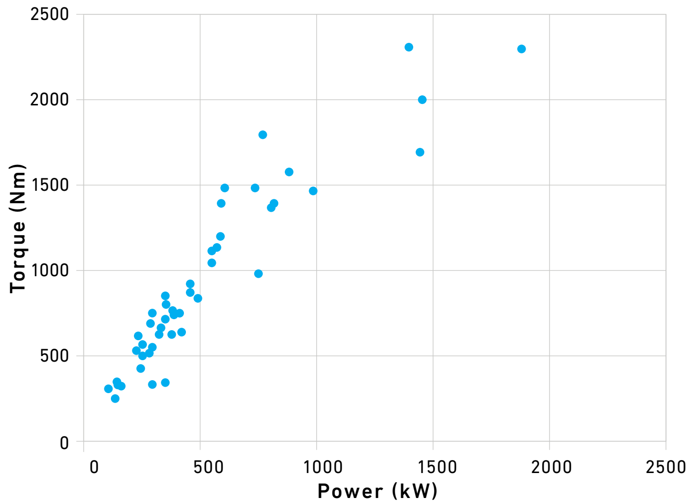
There are plans for additional supercars not included in the numbers above that will feature full electric or hybrid powertrains. Hybrid supercars typically have more than 700 hp of electric motor power to complement the gas engine. The highest performing EV supercar will feature more than 2000 hp.

Advanced technology for increased performance requirements

Vehicle engineers have many design options at their disposal for improving performance, across nearly every zone of the car. The powertrain is particularly important. Within the powertrain, batteries have received the majority of technology investment and headlines over the last decade as EVs established a foothold in the global passenger car market. Improvements in battery energy density and cost per kilowatt hour have been significant and were necessary for the viability of EVs. With the coming generation of high-performance EVs, vehicle OEMs are focusing more of their development resources on other areas of the powertrain: power electronics and electric motors.

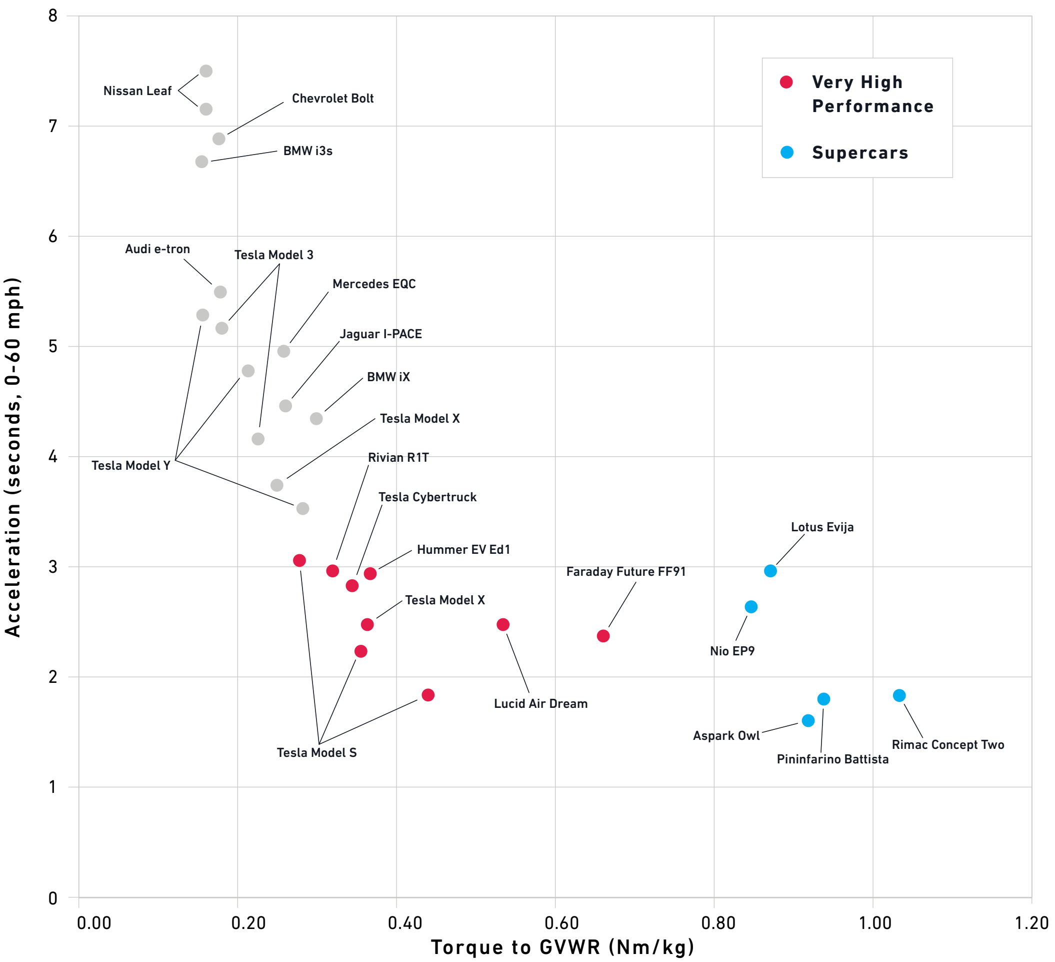
The specified power of a vehicle provides a good indication of vehicle performance. Higher power cars tend to have better acceleration. Motor torque is an even more direct measure of acceleration. It has been observed that "the engines in high-performance cars are tuned so that the horsepower and torque ratings complement each other and provide a well-balanced driving experience."[1] The same is true for electric motors and BEVs. A plot of torque and power for current and planned EV models highlights the correlation between the two in Figure 1.

FIGURE 1—TORQUE VERSUS HORSEPOWER FOR EVS ACROSS VEHICLE CLASS.



Vehicle weight is another important factor. Thus, comparing acceleration versus torque to gross vehicle weight rating (GVWR) provides a good guide on the level of technology required. Figure 2 depicts this performance for various existing and announced BEV models.[2] The high-performance EVs and supercar EVs require high torque but with an energy-dense and power-dense, lightweight, and compact powertrain design. The technology powering many of these vehicles will derive from Formula E, where teams have advanced the performance of their batteries, power electronics, and motors over recent racing seasons.

FIGURE 2—ACCELERATION VERSUS TORQUE/GVWR FOR ANNOUNCED EV MODELS.



The electric motor is a critical component of the powertrain and EV performance. Energy-efficient, powerful motors can offer higher acceleration and torque responses in combination with more range per kWh of energy. Producers are evaluating and incorporating a variety of electric motor technologies to maximize the torque and power density. Focus areas include topology, cooling, windings, permanent magnets, rotor sleeves, stator-rotor air gap, and stator and rotor iron.

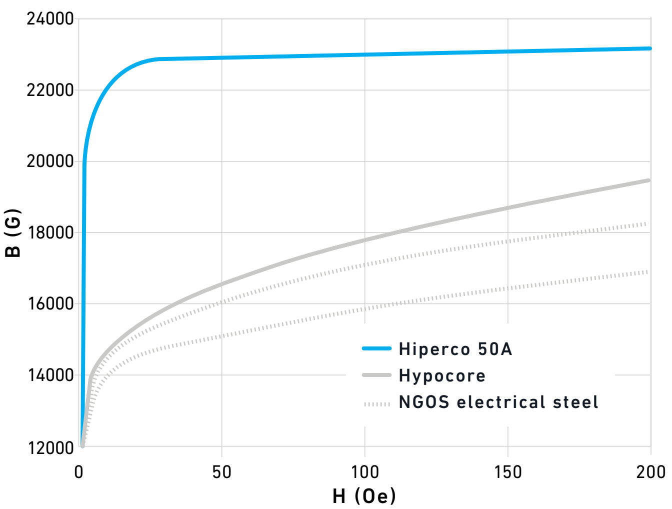
Improved performance with iron cobalt alloys

The soft magnetic stator and rotor iron play an important role in motor performance. Presently, nearly 3% silicon-containing soft magnetic non-grain oriented steel (NGOS electrical steel) of about 0.25–0.35 mm lamination thickness is most commonly used. Iron cobalt (FeCo) alloys demonstrate higher induction and enhanced permeability as compared to NGOS. As shown in Figure 3, the Hiperco® 50 family of alloys, such as Hiperco® 50A, provide the highest magnetic saturation of all soft magnetic alloys available in the market today. Hiperco 50A also offers higher permeability and nearly 20–30% lower iron losses than the NGOS material of similar thickness, while another material, Hypocore, works as a gap material with about 5% higher saturation induction and 10% lower iron losses.

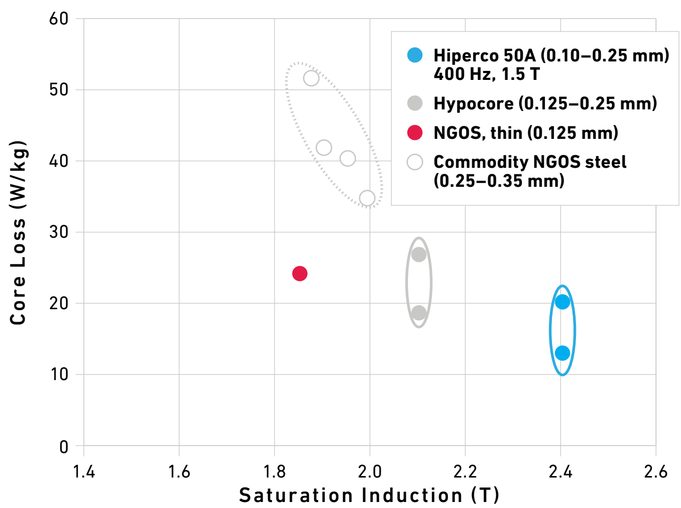
The mechanical properties of these FeCo alloys can be tailored to meet both stator and rotor design needs. These FeCo lamination materials can significantly improve motor and vehicle performance, especially when utilized in concert with the other technology focus areas mentioned above. The potential performance gains have been well documented in papers and presentations.[3,4,5]

FIGURE 3—MAGNETIC PROPERTIES OF IRON COBALT (FeCo) AND NGOS ELECTRICAL STEEL ALLOYS.

(A)



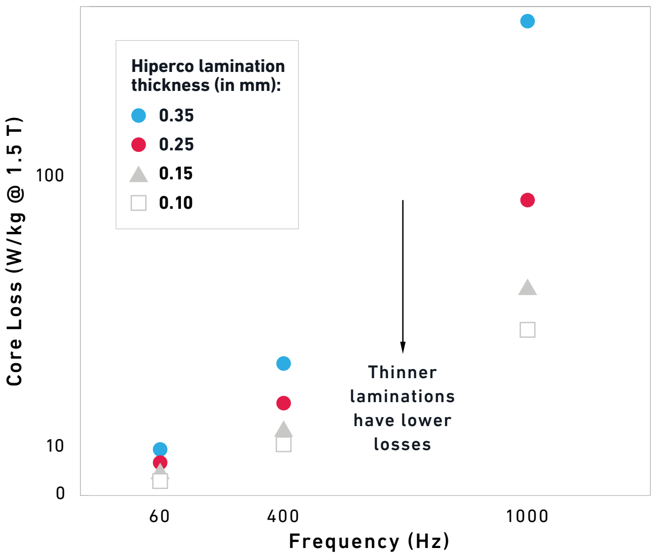
(B)



Reducing iron loss with thinner laminations

In an attempt to realize higher motor power density, there is a recent trend to increase motor speed and/or reduce motor size for high performance EVs. For example, electric motors designed for supercars may operate at higher frequencies and be much smaller than typical EVs. At these higher frequencies, stator and rotor iron lamination losses become the dominant factor limiting the motor responses at continuous operation. The impact of iron losses can be reduced significantly by moving towards thinner alloy laminations (see Figure 4). Supercar motor designers may be most interested in the 0.1–0.15 mm lamination thickness, while designers of high performance EVs may prefer 0.15–0.25 mm laminations to balance performance and cost.

FIGURE 4—CORE LOSS VERSUS OPERATIONAL FREQUENCY BY LAMINATION THICKNESS.



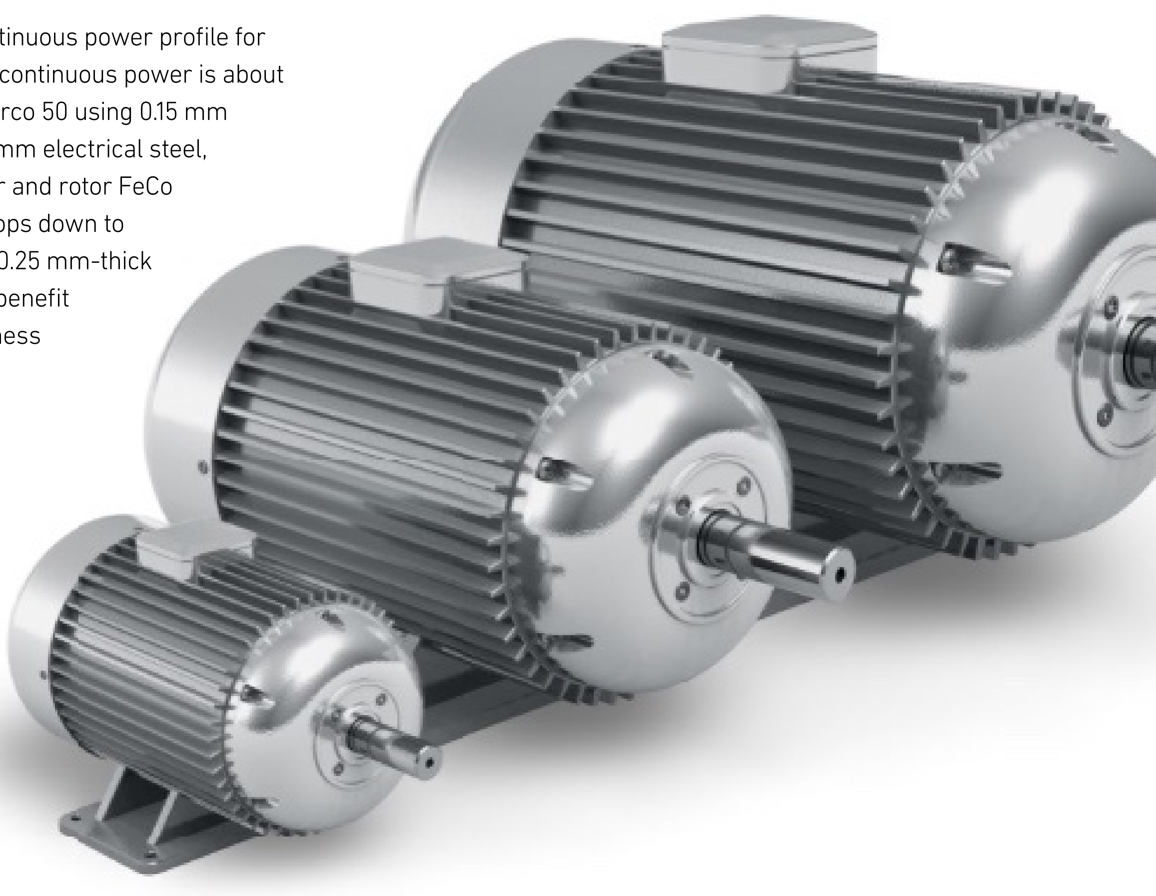
These laminations are stacked together by various methods, including adhesive bonding or interlocking to produce the stator or rotor stacks of desired design and form factor. Maximizing the magnetic responses by maintaining high stacking factors for the FeCo stacks is the key to realizing the enhanced motor responses with high torque and power density. Doing so requires specific materials and process knowledge. Carpenter Electrification is an expert in the alloy production and stack processing techniques required to maximize the performance of electric motors used in supercars and other electric vehicles.

Power and torque increases using FeCo in motors with like designs

A study has been done to evaluate the impact of 0.15 mm Hiperco 50 on motor responses for a publicly available BMW i3-type EV interior permanent magnet motor design. This specific design (shown in Figure 5a) has 12 poles and 72 slots, with a stator outer diameter of 240.9 mm and an active length of 130 mm. Only the stator and/or rotor material has been changed. All other design parameters, such as motor dimensions, permanent magnet, and windings, along with the inverter remained the same.

Figure 5b shows the simulated torque versus speed profile for different materials as indicated. The peak torque for the Hiperco 50 motor is 15% higher for stator-only and about 18% higher for stator and rotor than the electrical steel motor due to higher FeCo induction. The lower loss from using thin gauge Hiperco 50 brings a benefit to the machine's thermal management, potentially allowing the machine to run with a higher amount of current.

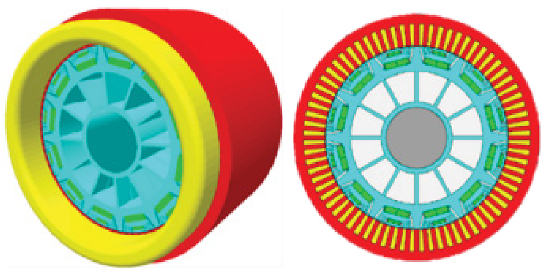
Figure 5c shows the simulated continuous power profile for different materials. The maximum continuous power is about 45% higher for the stator-only Hiperco 50 using 0.15 mm laminations in comparison to 0.35 mm electrical steel, and about 60% higher for the stator and rotor FeCo combination. The power benefit drops down to about 15–25% if compared against 0.25 mm-thick electrical steel, as a portion of the benefit achieved originates from the thickness difference of the materials.



The FeCo motors would run about 15–60°C cooler, which may increase the motor life. FeCo stack solutions in the 0.15 mm lamination thickness range are recommended to realize the optimal combination in terms of stacking factor, magnetic responses, and high volume production capabilities. And the motor performance benefits using FeCo alloys can be improved further through stator and rotor design optimizations without changing the overall motor form factor.

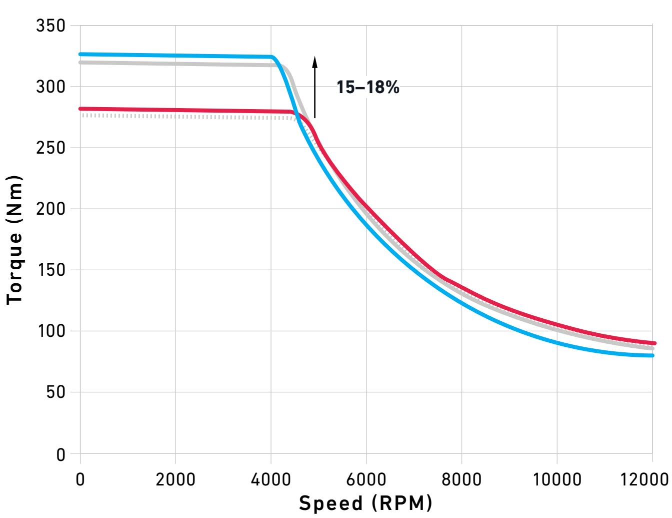
FIGURE 5—TORQUE AND POWER VERSUS SPEED FOR THE SAME MOTOR USING DIFFERENT STATOR/ROTOR IRON.

(A)

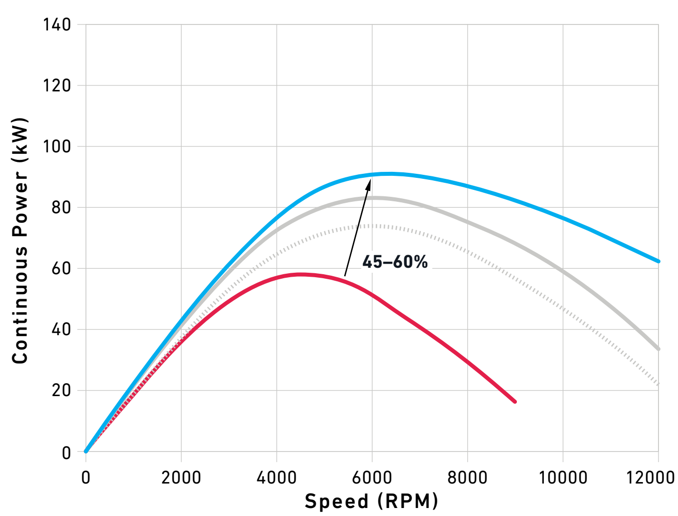


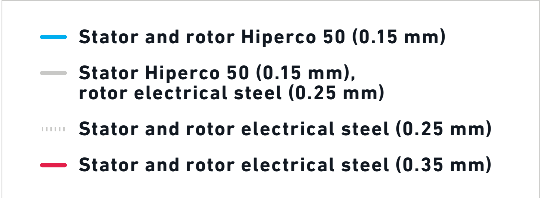
- 72 slot, 12 pole
- 0.5 mm air gap
- N38UH magnet
- Peak DC voltage: 360 V
- Peak current: 400 Arms

(B)



(C)



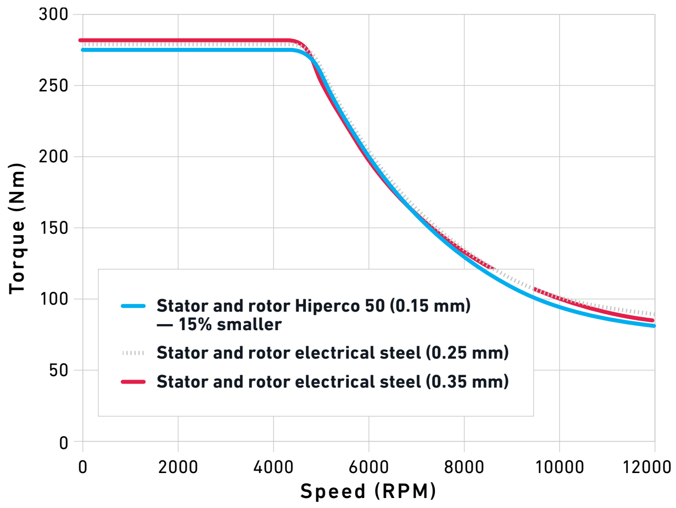


Motor size reduction of 15% with similar torque and higher continuous power using Hiperco 50

A second simulation study using the BMW i3-type design was performed to understand the size reduction opportunity using FeCo. Figure 6 shows the results for a Hiperco 50 stack with 15% stack volume reduction. As shown in Figure 6a, the peak torque versus speed profile remains similar for the smaller Hiperco motor in comparison to the bigger motors with electrical steel. However, the peak continuous power profile shows a nearly 45% increase versus the 0.35 mm electrical steel and nearly 15% higher than the 0.25 mm steel.

FIGURE 6—TORQUE AND POWER VERSUS SPEED FOR A 15% SMALLER FECO MOTOR AND NGOS MOTORS.

(A)



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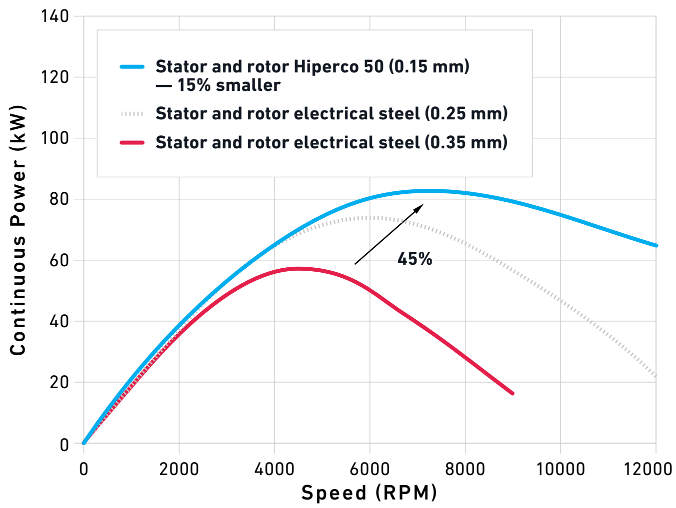
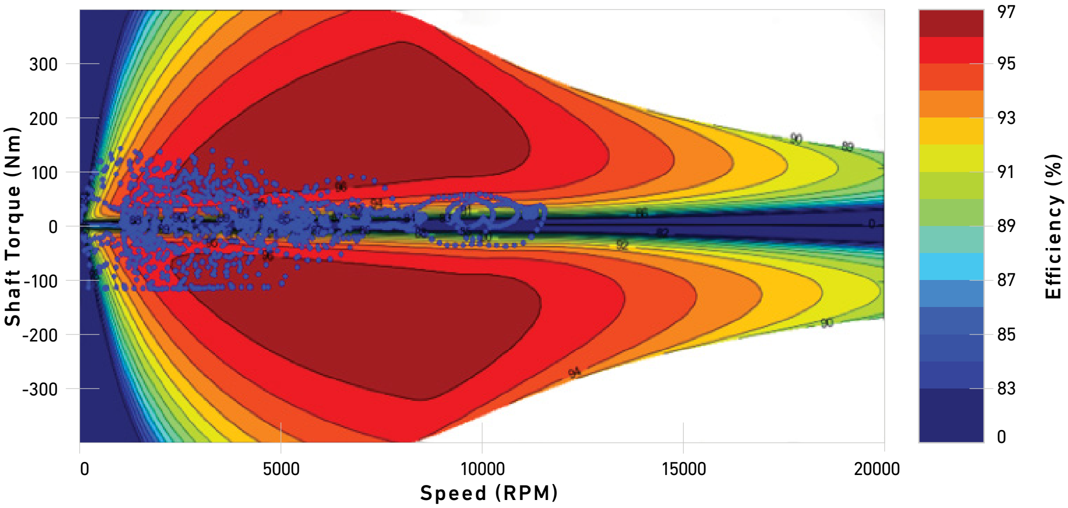


A UDDS drive cycle simulation study was also performed using the aforementioned Hiperco 50 and electrical steel motors. A Tesla Model S type EV model has been considered for the study. Figure 7 shows a representative torque versus speed versus efficiency profile for motoring and regeneration. The blue dots indicate motor response during vehicle operation at the different points in time during the drive cycle.

FIGURE 7 — TORQUE-SPEED PLOT FOR BEV BASED ON WLTP3 DRIVE CYCLE SIMULATION.



The drive cycle results are summarized in Table 2. As noted earlier, the Hiperco motor of similar size to the electrical steel motor would generate about 15–18% higher torque (as shown in Figure 5b), and the 15% smaller Hiperco design (as shown in Figure 6a) would generate similar torque to the electrical steel motor. The UDDS simulation indicates that the Hiperco 50 motor of similar size offers about 8% motor power saving, while the 15% smaller motor offers even more, nearly 11% power saving. These power savings originate from the combination of lower copper losses due to high induction and permeability along with lower iron losses for the FeCo alloys.

TABLE 2 — DRIVE CYCLE ENERGY CONSUMPTION, EFFICIENCY, AND MOTOR WEIGHT FOR FeCo AND ELECTRICAL STEEL MOTORS OF DIFFERENT SIZE.

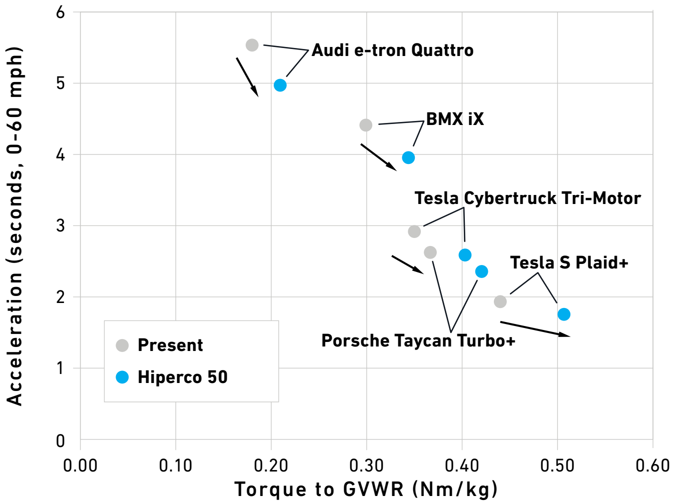
PARAMETER	BASE DESIGN			FeCo REDUCTION (15% SMALLER DESIGN)
	STATOR, ROTOR ELEC. STEEL 0.35 MM	STATOR: H50 0.15 MM ROTOR: ELEC. STEEL 0.25 MM	STATOR, ROTOR H50 015 MM	STATOR, ROTOR H50 0.15 MM
Net energy consumption (Wh)	978.10	902.90 (-8%)	900.80 (-8.2%)	876.80 (-10.8%)
Avg. efficiency (%)	82.29	92.65	92.96	92.88
Motor weight (kg)	31.57	31.85	32.53	27.65

Performance benefit for high performance EVs

Based on the motor performance enhancements mentioned above, a preliminary analysis was performed to depict the EV response improvement for the FeCo-based motors using publicly available information. Key assumptions were that present EV models use electrical steel motors, and that the 15% torque benefit from the FeCo motor corresponds to a 10% improvement in EV acceleration. Figure 8 shows representative data.

The torque to EV weight ratio and the acceleration improve for different EV models for Hiperco 50-based motor solutions when the Hiperco 50 electrical steel motor has a similar form factor and the same inverter and current profile is used. The performance benefits predicted here are for guidance only. Actual benefits may depend on motor topology, motor design optimizations, and the specific EV designs.

FIGURE 8 — POTENTIAL ACCELERATION AND TORQUE/WEIGHT IMPROVEMENTS USING SAME SIZE FeCo MOTORS.




EV

Additional performance from a combination of motor and inverter improvements

In order to understand the potential impact of FeCo alloys on high performance EVs, it is important to consider OEM model plans. In practice, each model is offered in a variety of trim options, each with a different level of performance. The publicly available data[6] for the Porsche Taycan (shown in Table 3) reveals six options. The Taycan was chosen as an example only, not to indicate that these models are presently using FeCo motors. The acceleration and peak power improve by 15–20% between the 4S and Turbo options, and another 10–12% from the Turbo to the Turbo S.

TABLE 3 — PUBLICLY AVAILABLE PERFORMANCE SPECIFICATIONS FOR THE PORSCHE TAYCAN.

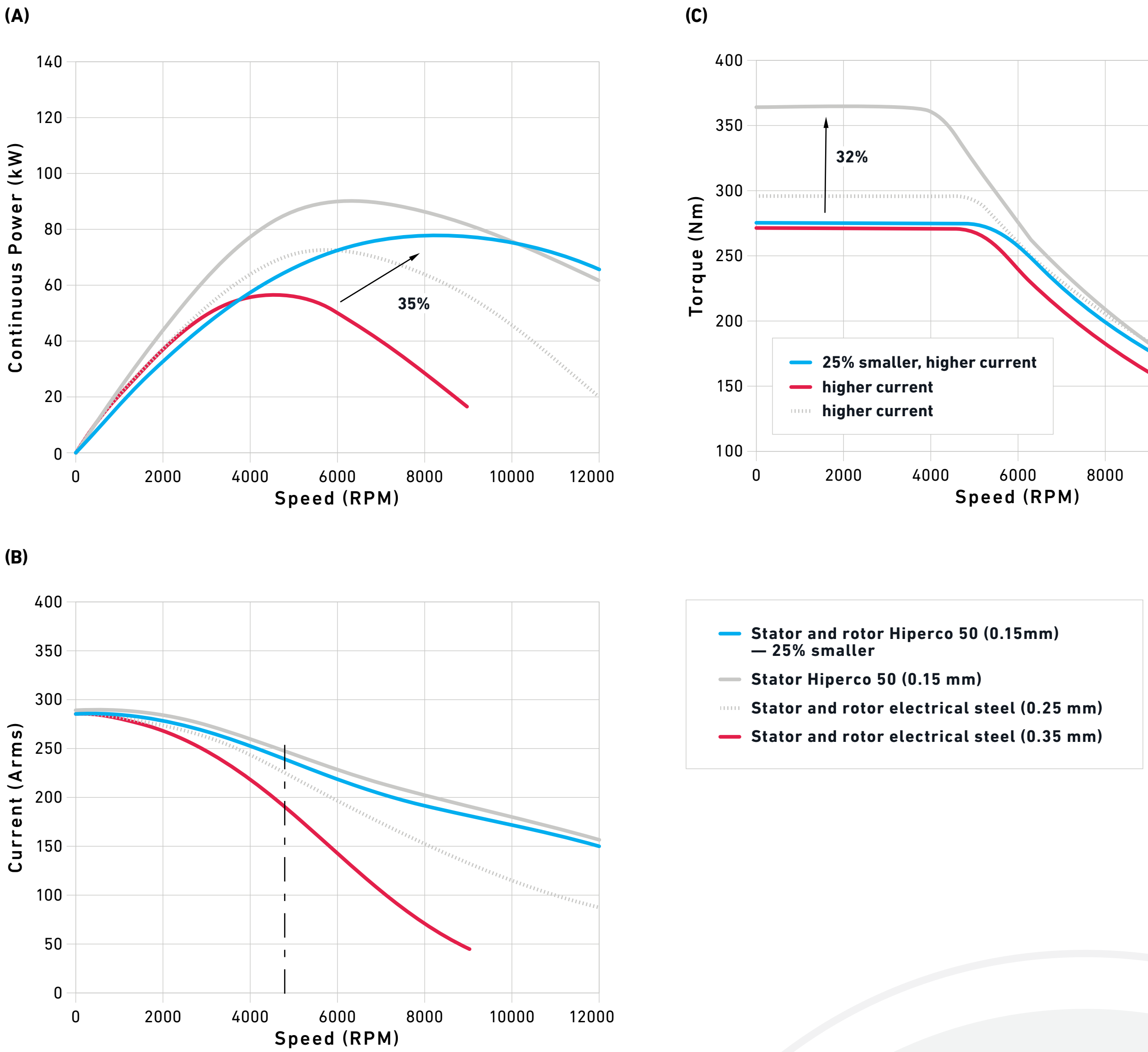
MODEL	ACCELERATION (0 – 60 MPH, S)	POWER (kW)	TORQUE (Nm)	RANGE (MILES)	BATTERY PACK (kWh)
Base	5.1	300	344	268	79
Base w/ PB+	—	350	357	301	93
4S	3.8	390	640	254	79
4S w/PB+	—	420	649	288	93
Turbo	3.2	500	849	281	93
Turbo S	2.8	560	1,049	258	93

As discussed earlier, there are several ways to increase the motor power and torque through different parameter optimizations, such as number of motors, motor design, size, and cooling. In some EVs, space is available, and several EV manufacturers have chosen to increase the number of motors[7] to boost the EV responses. However, such solutions may add to system-level tooling costs for those specific EV designs. In addition, it may take extra space, add to powertrain weight, and require additional motor design management.

Another potential solution would be to use FeCo stators and rotors to maintain the same number of motors and with a similar motor form factor. In this instance, the OEM's target specifications for their various EV models may require motor performance gains beyond those highlighted in previous sections. The previous designs utilized FeCo alloys for the motors but kept the other components in the powertrain fixed. This limited the potential design benefits from the higher induction and permeability of Hiperco 50. Modifying other parts of the powertrain in conjunction with the FeCo motor can deliver additonal performance.

Figure 9 shows the results for a model where a higher power inverter(s) can be used to drive the FeCo motors. Figure 9a shows the continuous power as a function of speed for the two electrical steels along with Hiperco 50 motors of the same size and 25% smaller size. This profile is dictated by the thermal constraints (in this case, the permanent magnet temperature was at 150°C, and the maximum winding temperature was at 180°C), where a 25% smaller Hiperco 50 motor still offers higher continuous power (up to 35% more) than the bigger electrical steel motors. Figure 9b shows current versus speed, and one can see that the Hiperco 50 motors are able to take more current than the electrical steel motors. Assuming the current increase ratio can be carried to calibrate the peak torque and power estimation (with the anticipation of the usage of a higher power inverter), an adjusted torque-speed curve for the machines under comparison is shown in Figure 9c. The Hiperco 50 motor with 25% smaller volume provides a similar torque profile as the electrical steel motor with 0.35 mm laminations, while the similarly sized Hiperco 50 motor offers nearly 32% higher peak torque. Given the combination of the benefits of higher saturation induction, lower loss, and additional supplied current, a Hiperco 50 motor is able to achieve nearly 30% more peak power as compared to the same size electrical steel motor.

FIGURE 9 — TORQUE AND POWER RESPONSES FOR MOTORS WITH DIFFERENT ELECTRICAL STEEL AND FeCo MATERIALS IN COMBINATION WITH INCREASED CURRENT AVAILABLE FROM INVERTER UPGRADE.



The future of electric vehicle design

There are many advanced technologies available for improving the powertrain for high-performance EVs. The electric motor is a critical sub-component of the powertrain. There are multiple design levers for improving motor performance; notable among those is the use of FeCo stator and rotor stacks as an alternative to NOES. There are several design options using FeCo, each with different levels of complexity and performance improvement.

- With a direct material swap of Hiperco 50 for 0.35 mm NOES, without any additional changes, motor torque is increased by 18%, maximum continuous motor power is 60% higher, the motor would run up to 60°C cooler, and the EV using this motor would use 8% less battery power throughout a typical UDDS drive cycle.

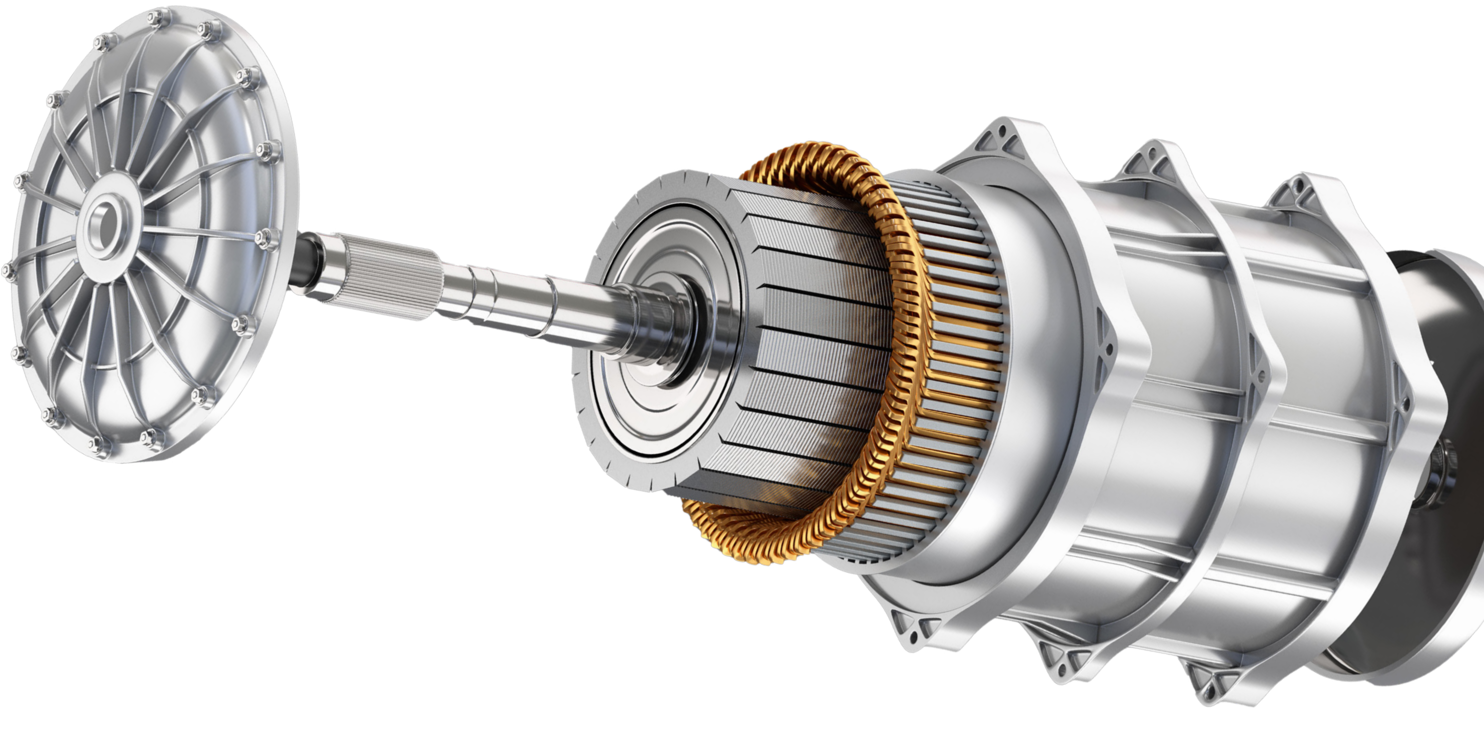
- The Hiperco 50 motor can be made 15% smaller and generate the same torque as the NOES motor with 45% higher maximum continuous power. The EV using this motor would use nearly 11% less battery power throughout the UDDS drive cycle.

- The high magnetic saturation and permeability of Hiperco can be accessed through further design changes for even higher performance. Increasing the inverter power allows for more current to the FeCo motors to better access the advantages of the Hiperco stators and rotors.

- With a direct material swap of Hiperco 50 for 0.35 mm NOES and with a higher power inverter, the motor torque can be up to 32% higher. This allows for even faster EV acceleration upon demand (perhaps up to 20% faster times from 0–60 mph, though that is dependent upon a number of factors beyond the motor), while otherwise leaving the continuous power, motor temperature, and EV battery power draw unaffected for the typical UDDS drive cycle.

- Alternately, the Hiperco 50 motors can be 25% smaller and generate the same torque as the NOES motor with 35% higher maximum continuous power.

These examples highlight performance improvements using FeCo alloys within a limited set of design modifications. The expert designer will note that additional improvements in performance may be obtained using Hiperco 50 by making greater use of modifications in EV design rules and options.



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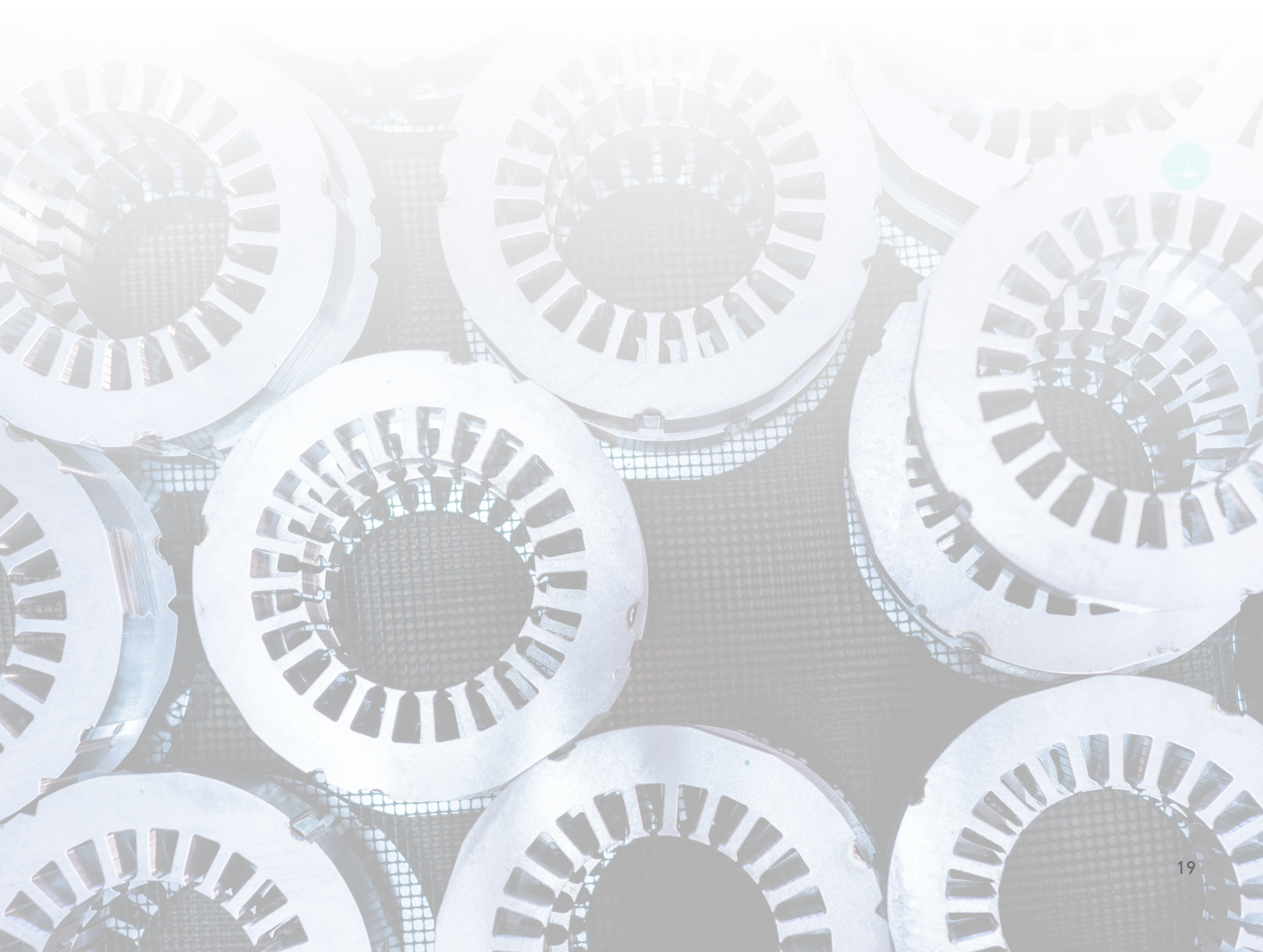

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