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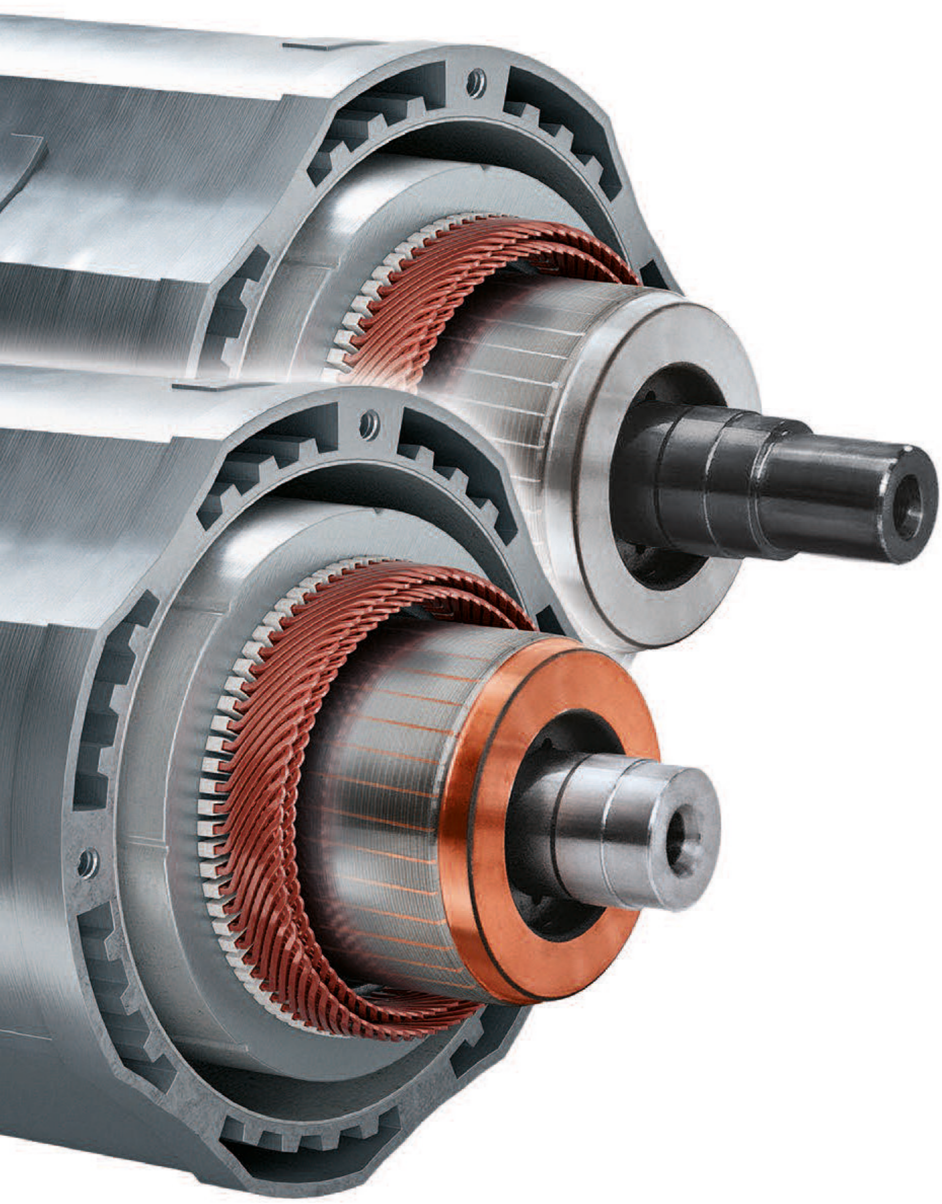
Efficiency gains for asynchronous motors: Zero Porosity Rotor – ZPR®



ZPR®
Zero Porosity Rotor

Efficiency gains for asynchronous motors: Zero Porosity Rotor – ZPR®

Casting of new types of rotors from aluminium and copper for highest efficiency electric motors free of rare earths.

1. Introduction

The following losses occur with electric motors:

a) Current losses in the stator (stationary part) and rotor (rotating part)
b) Iron losses in the rotor and stator
c) Friction losses (air- and bearing losses)

The rotors in asynchronous machines consist of a package of stamped electrical sheets which are encased in aluminum or copper during a casting process. The resulting cast cage consisting of conductor material has a strong influence on the electromagnetic performance of the machine. The losses in the rotor account for about one third of the total losses of the electric motor. These losses are mainly dependent on the electrical resistance in the rotor and thus on the electrical conductivity of the cast cage.With the Zero Porosity Rotor – ZPR it is possible for the first time to produce a cast squirrel-cage free of defects, thus introducing a new era of enhanc-ing the efficiency of asynchronous electric machines.

This improved asynchronous machine is thus becoming a significant alternative to the synchronous machine. Especially with the crucial advantage that the asynchronous machine, in contrast to the permanently excited synchronous machine, is free of rare earths and thus has a better ecological footprint.
Furthermore, this type of machine offers greater security of procurement and supply.

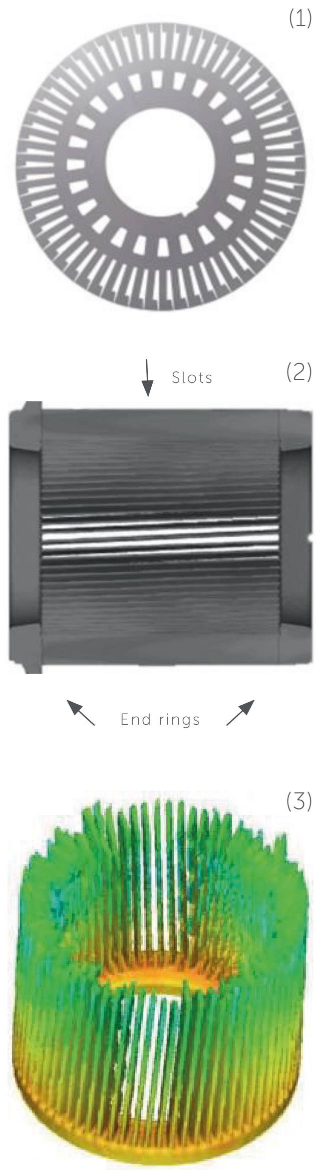
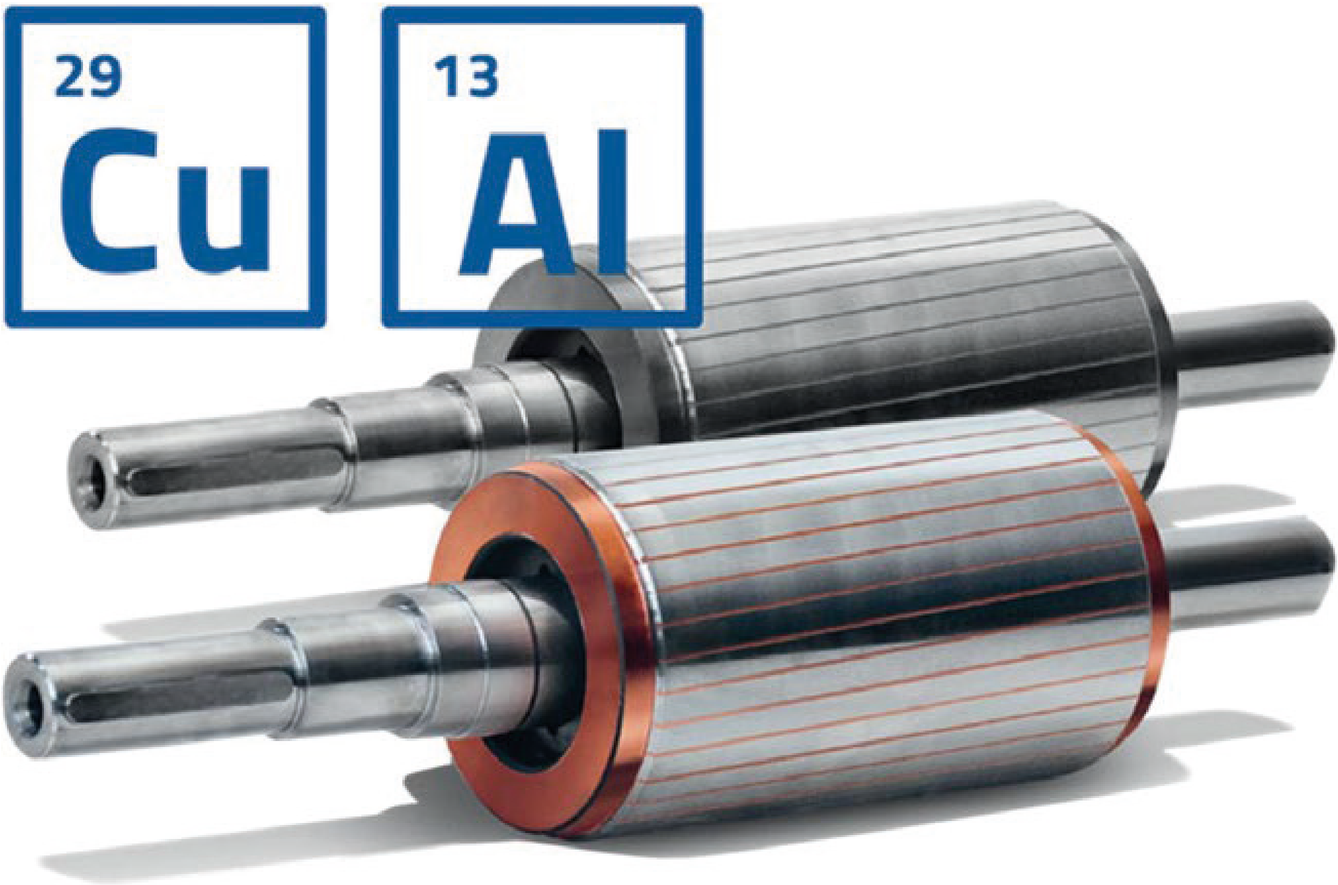


Fig. 1:
Electrical steel sheet, cast squirrel-cage (consisting of the first and second end ring, connected by conductor rods); manufactured via casting process, shown here: Laminar Squeeze Casting.



The efficiency is directly increased through the higher conductivity and the lower resistance – while the conductor cross-section and the outer dimensions of the rotor remain the same. Indirectly, this results in lower heat development or rotor temperature, improved rotational speed stability, better balance quality and more narrow tolerance fields during production.
In addition, this new casting process allows for the realization of geometric dimensions in the area of the short-circuit bars, which was previously not possible.
The entire drive train can thus be consequently designed up to the performance limit.

This development is of importance for all application fields with requirements for electric motors of highest efficiency. Due to various simultaneously occurring problems and trends (scarcity of rare earth elements, climate change, autonomous driving, digitalization, etc.) the demand from the electromobility industry for the ZPR is enormous. However, the potential of the ZPR can also be greatly exploited in other market segments. These trends are also largely based on technical solutions to counteract climate change without economic losses. Applications are conceivable in the following industries:

- Automotive industry: In accordance with the United Nations Framework Convention on Climate Change (UNFCCC), emissions from automobiles must be reduced urgently. Therefore, the drive system is being converted from combustion engines to electric motors. The robust and field-proven asynchronous machine is very well suited for the market ramp-up of electromobility.
- Rail vehicle industry: The sector covers the civic needs of the urbanization megatrend. The high-speed train can also be an alternative to short-distance air travel.
- Industry: New global standards for the energy efficiency of electric motors have been developed and inefficient motors are banned by law.
- Aeronautics: The hydraulic system is replaced by many decentralized electric motors („fly-by-wire“), resulting in enormous weight savings.

Alongside the efficiency advantages, the laminar filling of the ZPR offers greater safety in air traffic compared with standard cast rotors, as motor failures due to rod interruptions can be ruled out due to the production process.

2. Rotor production

The rotor consists of (1) a stack of many individually stamped electrical sheets and (2) a surrounding cage, which is usually manufactured in a high-pressure die casting process (3) (Fig. 1). The cage is cast in one piece and is defined by the technically relevant areas of end rings and conductor bars (slots).
The high-pressure die casting process is the most economical and therefore most common manufacturing process for rotors in asynchronous machines. It can be highly automated and allows cycle times of 1 to 2 minutes. Casting also offers those calculating and designing electrical machines greater freedom in the electromagnetic design of the rotor (slot and end ring geometry) than alternative manufacturing processes, such as machining, soldering or welding of the short-circuit cage.

From the casting technology point of view however, rotors are very complex composite castings. The stack of laminations is inserted into the casting tool, then a so-called casting chamber is filled with melt, and a piston forces the melt into the casting tool at high speed.

The five biggest tasks in casting squirrel cage rotors are:

I) Mould filling: to completely fill the entire cage, especially the narrow slots, without the melt solidifying prematurely
II) Shrinkage porosity: to compensate for the shrinkage during the transition from the liquid to the solid state of aggregation through sufficient residual liquid melt
III) Gas porosity: to remove the air and process gases from the cavity during filling
IV) Residual stresses: to control the thermally induced mechanical stresses of the composite casting.
V) Thermal management: to ensure that the electrical laminations and their coatings are not damaged by the high temperatures of the casting process.

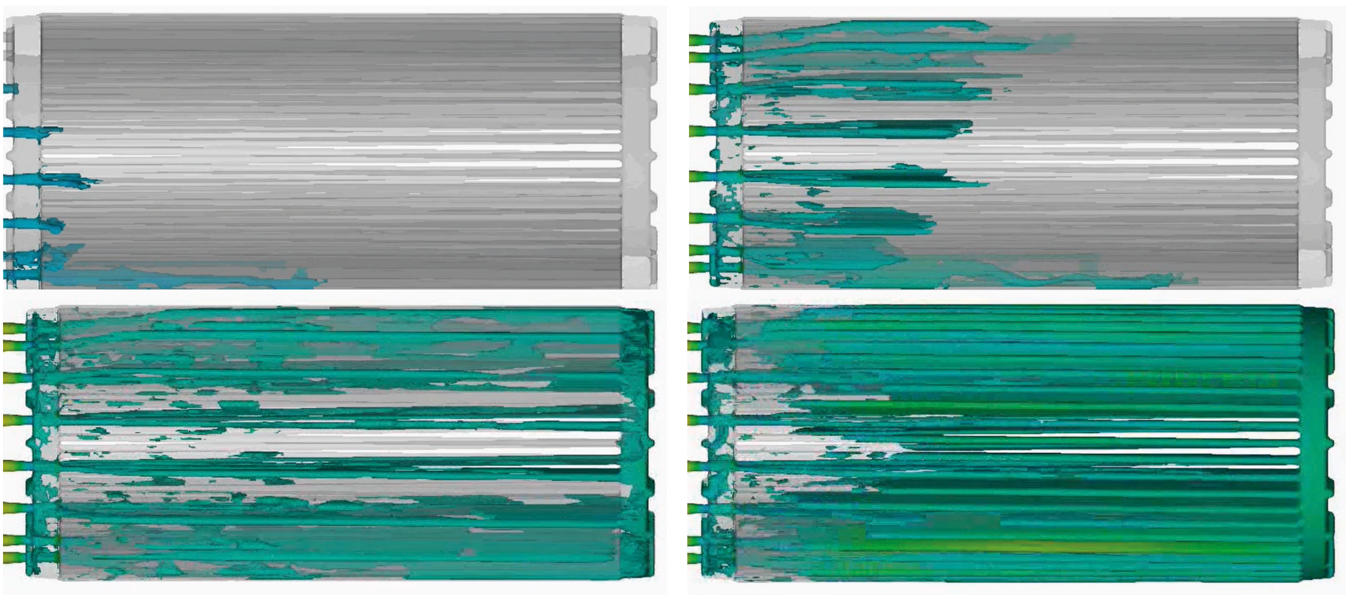


Fig. 2:
Four sequences of the casting process in the conventional casting process [3,4].

3. Issues of the conventional casting process

The aluminum or copper melt solidifies rapidly in the mould when the lamination stack is filled, which is why the current state of industrial technology recommends very short mould filling times of less than 100 ms and high flow rates of more than 50 m/s (Fig. 2). To achieve a flow velocity of 50 m/s at a piston velocity of 5 m/s, the gate must be smaller than the piston area by a factor of 10. In application, therefore, thin point gates are typically selected, through which the melt is accelerated sufficiently strongly. The main disadvantage of these point gates, however, is that not all of the slots in the stack are filled at the same time. As a result, the melt first flows through the slots located directly at the gate, then flows into the opposite short-circuit ring, and only then are the remaining slots filled from the rear side. Consequently, trapped air, process gases and melt fronts contaminated by oil and oxides can no longer escape. This results in lower conductivity and, in the worst case, entire rod discontinuities.

As soon as the mould (cavity), including all slots, is completely filled, the melt solidifies extremely quickly. During the transition from the liquid to the solid state, there is a decrease in volume, the so-called solidification shrinkage. To compensate for this shrinkage, the casting piston continues to press, even after the mould has been filled to its full capacity, in order to re-feed the liquid melt. The re-feeding can only be carried out during the time when the casting material in the channel to the cavity is still liquid. As soon as this gate has solidified, the short rings solidify without post-pressure, resulting in massive shrinkage cavities. The thin point gates from application experience increase the flow velocity, but lead to air inclusions and are also so thin that they solidify only a few hundred milliseconds after filling. This means that re-feeding for a duration of several seconds is not possible. The combination of gas and shrinkage porosity results in a high total porosity, far above the usually required 5 % according to the porosity determination based on BDGP202. [1,2] Typical porosity values for current rotors are around 10 % (Fig. 3 & 4).

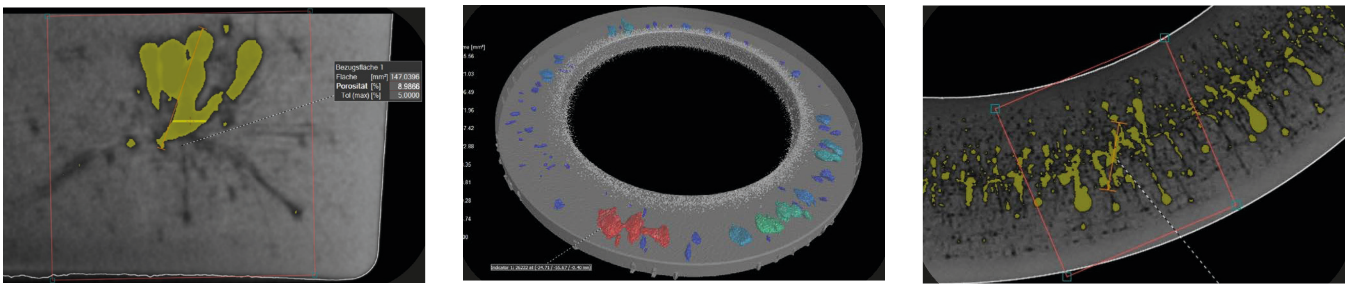


Fig. 3:
Xray image of the rotor end ring [3,4].

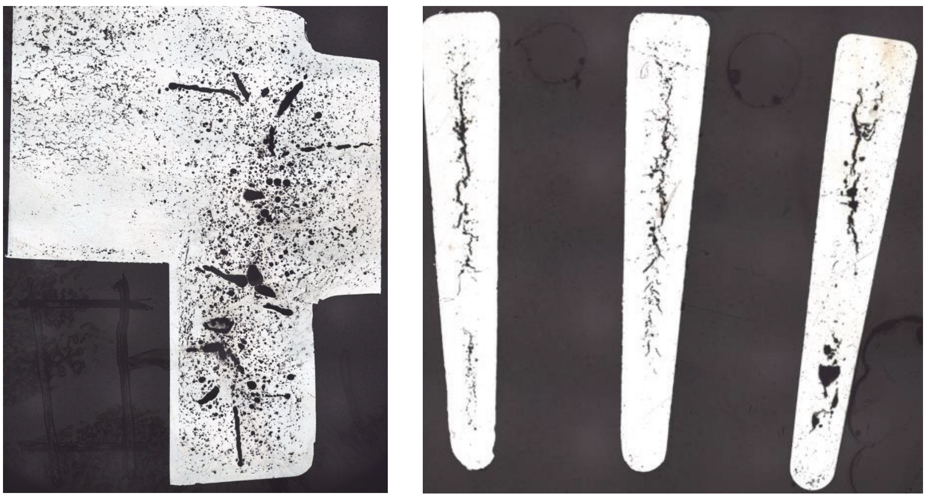


Fig. 4:
Micrographs of the slots and end rings of the rotor in the conventional casting process [3,4].

These pores reduce the conductive cross-section, cause imbalance and compromise the mechanical properties. In addition, they occur in random shapes, sizes and areas. Each rotor is therefore a coincidental product. In the best case, the pores are centered in the short-circuit ring and evenly distributed on the axis of rotation. However, they can also occur at the transition from the slot to the shortcircuit ring. High current densities and the greatest mechanical stresses due to shrinkage processes and centrifugal forces can be expected there. Due to the manufacturing problems described above, many foundries limit the geometrical freedom for the electromagnetic design, for example by limiting the number, length and width of slots. Similar manufacturing limitations exist for alternative manufacturing processes, such as the machining, soldering and welding of rotors. The potential of asynchronous motor technology is thus not fully exploited.

4. New casting process: Laminar Squeeze Casting

The Laminar Squeeze Casting (LSC) process developed by Wieland eTraction Systems GmbH, on the other hand, was specifically developed for casting rotors without porosity (Fig. 5). The casting tool and the innovation in the machine environment allow completely new geometric freedom. The patented gating system guarantees parallel and simultaneous filling of all slots of any type and shape. In contrast to conventional turbulent filling, the filling process is ascending and laminar. The work effort required differs only slightly from the conventional casting process, so that economical, cost-effective production can be maintained (Tab. 1).

The laminar squeeze casting process allows significantly lower flow rates, which means that the cast material in the gate remains liquid for a longer time for refeeding. Active thermal management allows controlled solidification starting from the laminar core to non-critical areas, such as the casting run and overflow. As a result, the short-circuit rings solidify with sufficient residual melt and solidification cavities are thus avoided.

The same is achieved for the conductor rods (slots). The result is the Zero Porosity Rotor, or ZPR for short, the world's first rotor without any casting porosity (Fig. 6 & 7). It is the outcome of several development cycles for casting tools and casting machines, specifically for these rotors types.

Fig. 5:
Four sequences of the laminar squeeze casting process [4].

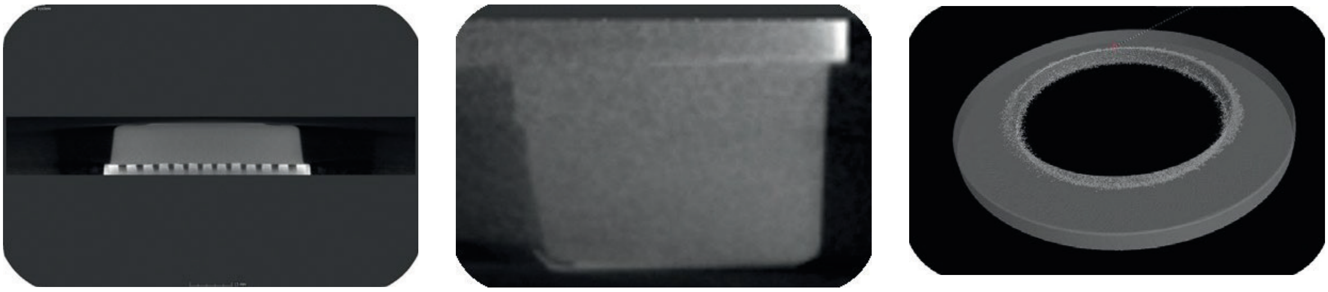


Fig. 6:
X-ray image of the rotor end ring [4].

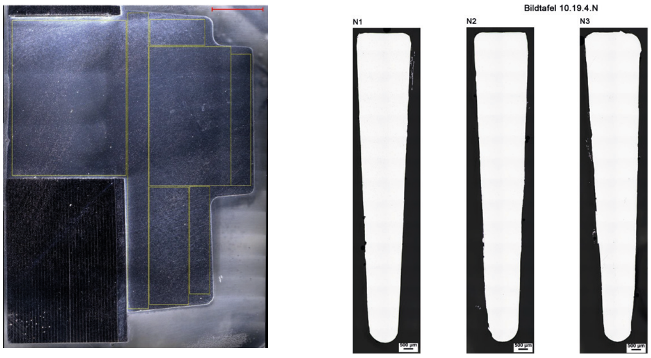


Fig. 7:
Micrographs of the slots and end rings of the rotor in the laminar squeeze casting process [4].

4.1 Advantages of the new casting process

The new defect-free casting process (Laminar Squeeze Casting) brings fundamental technical advantages. The Zero Porosity Rotor – ZPR produced in this way provides a development leap for many design parameters for the optimization of asynchronous machines.

	Conventional casting process	Laminar Squeeze Casting
Porosity (shrinkage + gas)	~ 10 %	~ 0 %
Filling behaviour	turbulent	laminar
Flow paths	long (back-filling)	short (no back-filling)
Filling time	< 100 ms	< 1.000 ms
Shrinkage densification	no	yes
Casting chamber filling level	30 – 50 %	100 %
Casting direction/gravity flow	Usually horizontal (some vertical)	vertical
Conductivity of the cast cage > less heat development	–	~ 3 – 5 % increased
Rotor speed stability	–	~ 12,5 % increased
Evacuation of the mould	no	yes
Residual stress state	undefinded due to random filling	definded by always same filling

Table 1:
Comparison of conventional casting process and laminar squeeze casting.

4.1.1 Electrical conductivity

Since all the slots are filled at the same time in the laminar squeeze casting process, the contaminated melt front can be optimally directed into the overflow via the second short-circuit ring. The melt remaining in the rotor is thus very clean. This is reflected in a typically 3 % – 5 % higher electrical conductivity. As a result, losses are lower and heat generation is reduced. In addition, the simultaneous filling of all rotor slots results in a lower dispersion with respect to the conductivities of the individual slots (Fig. 8). This noticeably reduces common torque fluctuations and also minimizes noise emissions.

4.1.2 High-speed resistance

In cooperation with the Institute of Metal Forming Aachen GmbH of RWTH Aachen University, different pore morphologies were taken from CT scans and the mechanical behavior was simulated (Fig. 9). On the basis of these calculations, it was determined that a speed increase of approximately 12.5 % is technically possible with a porosity-free rotor. This behavior was confirmed in actual bursting tests (Fig. 10).

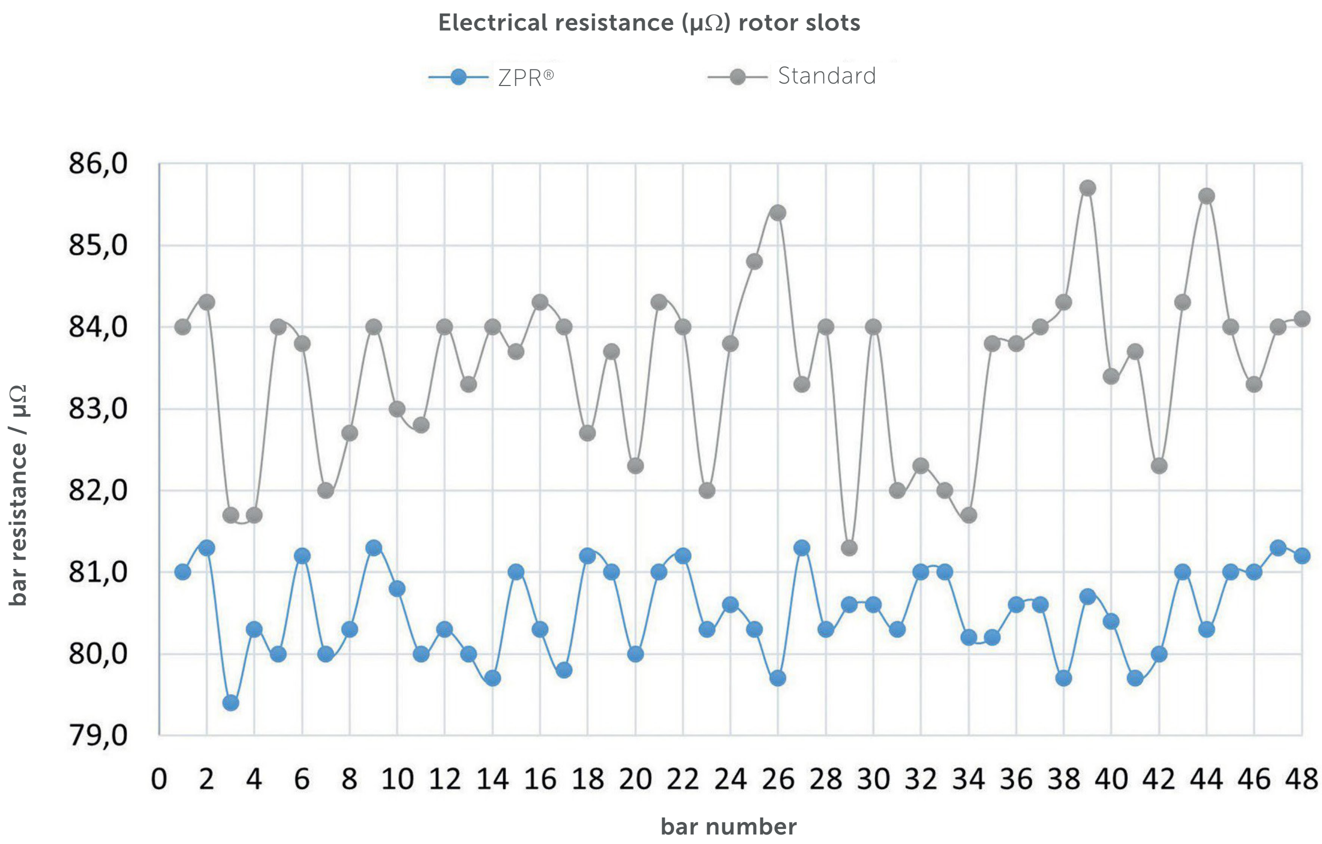


Fig. 8:
Electrical resistance measured in the rotor slots [5]*; the electrical resistance in laminar squeeze casting is typically reduced by 3 % – 5 %, and the electrical conductivity of rotors produced with laminar squeeze casting is correspondingly higher.*

4.1.3 Geometrical freedom

In addition to the pores, the slot geometry has a significant influence on the strength behavior of the rotor. The laminar squeeze casting process is also advantageous here in that it permits complex slot geometries. Slot geometries with radial undercuts, which increase the bond with the laminated core have already been successfully cast. In this context, mechanically high-strength electrical steel laminations are used, which are optimally suited for the centrifugal forces of the copper slots (Fig. 11).

At circumferential speeds above 80 m/s, it is also common practice to apply reinforcements such as carbon fiber bandages or bronze caps to the short circuit ring in an additional process step to enable these high speeds. With laminar squeeze casting, this process step can be integrated directly into the casting process due to the even and consistent filling.

A suitable material for the cast-in reinforcement is CuBe2 (copper-beryllium) since it has the same thermal expansion as copper and thus no thermal stresses occur during the manufacturing process and when operating at changing temperatures (Fig. 13). Due to the high yield strength of more than 1,000 MPa, even narrow rings or sleeves allow a considerable increase in the strength of the entire rotor without significantly reducing the cross-section of the shortcircuit ring (Fig. 12).

In addition to new and complex geometries, thin, slim slots and high numbers of slots can be produced in the laminar squeeze casting process. This leads to lower noise emissions and torque ripple. Furthermore, both degrees of freedom (new/complex – thin/slim) can be combined to further increase overall efficiency, which was previously not possible in the conventional high-pressure die casting process.

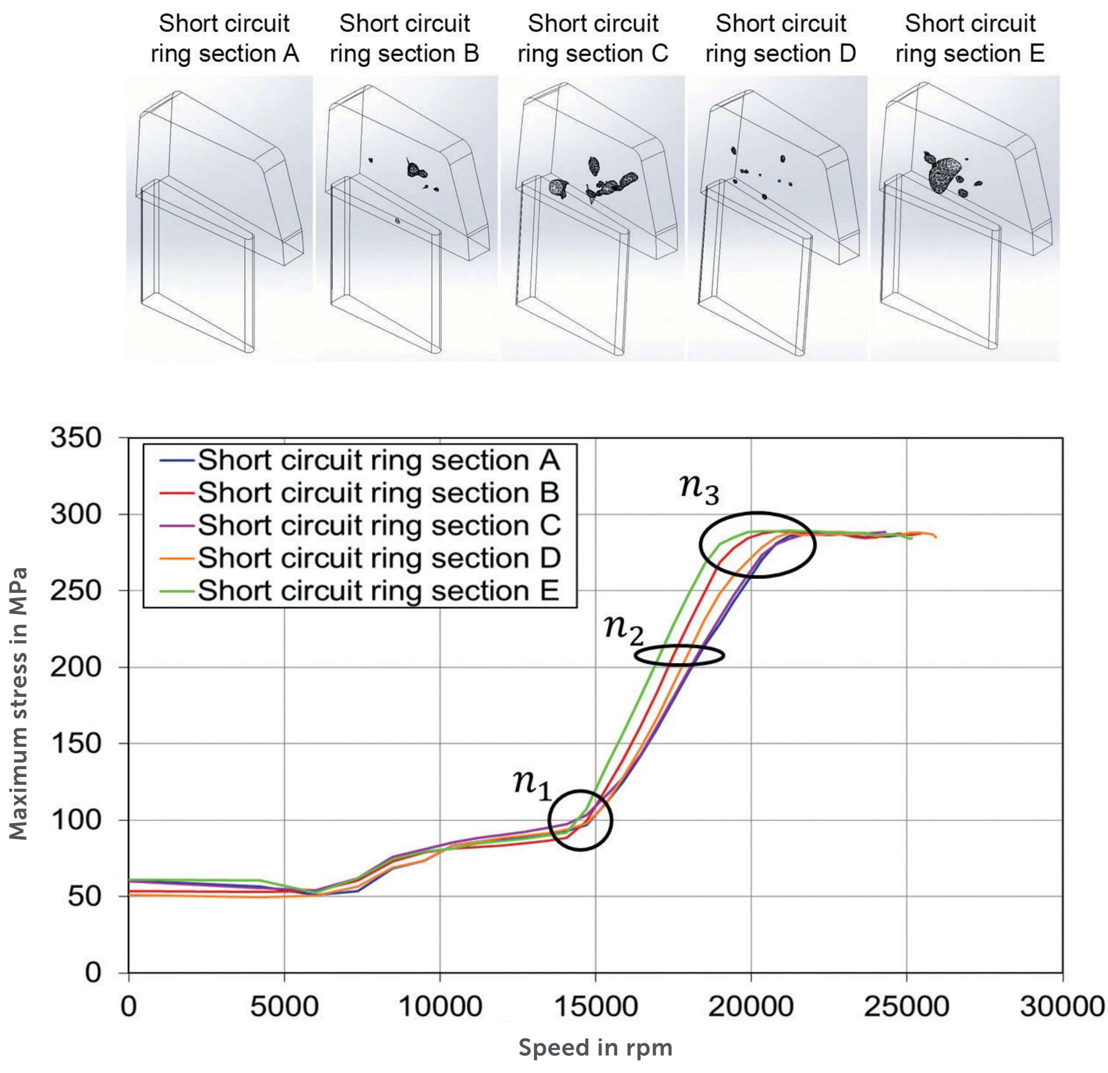


Fig. 9:
top: CAD pore models; bottom: maximum mechanical stresses in MPa versus rotor speed [6,7].

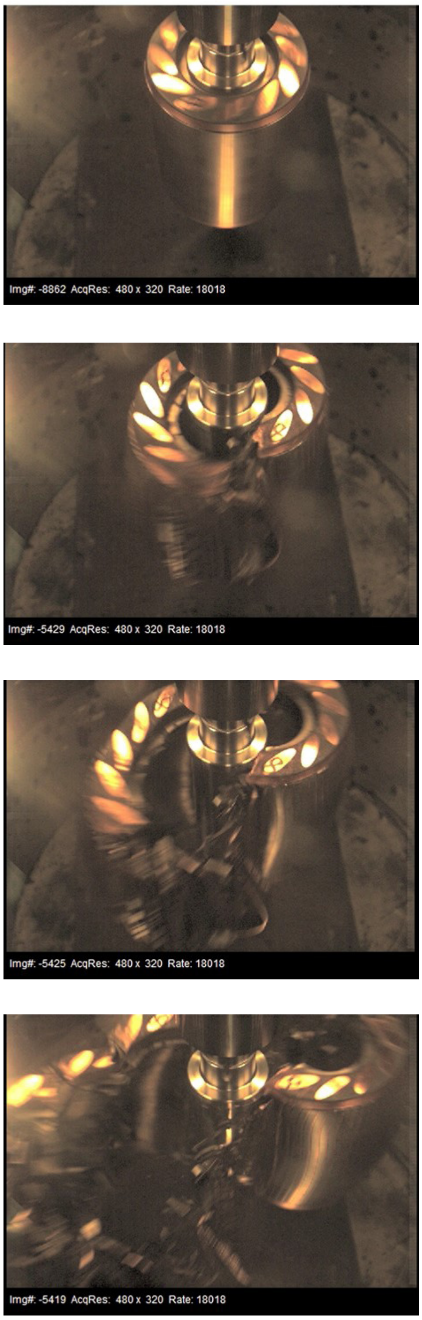


Fig. 10: burst test, ZPR® copper rotor, single frame video recording at 27,614 min^{-1} and a circumferential speed of 205.6 m/s.

4.2 External dimensions and cage mass

Laminar squeeze casting for the manufacturing of ZPR can look back on a development history of more than ten years. At present, production is possible with outer dimensions and cage masses of conductor material corresponding to machine generation 2 („Gen2"). A further increase in dimension and cage masses is already in the conceptual design phase in the form of „Gen3" (Tab. 2).

5. Choice of conductor material

In asynchronous machines, aluminum or copper are used as conductor materials (Tab. 3). Whilst pure copper has a very good electrical conductivity of 58 $m/\Omega mm^2$, that of pure aluminium is 37 $m/\Omega mm^2$. If these conductors in the rotor are manufactured through a casting process, the porosity also plays a major role. If there are air inclusions in the squirrel cage of the rotor, which consists of many short-circuit bars and two shortcircuit rings, the electrical resistance will increase. As a result, electrical losses increase as well. In asynchronous machines, therefore, there are two main factors that can increase the efficiency of cast rotors:

a) The use of copper instead of aluminum as conductor matieral
b) Minimization of porosity in copper or aluminum castings

High pressure die casting with copper is significantly more challenging than it is with aluminium. That is due to the necessary processing temperature being approximately 400 K higher. Even in the laminar squeeze casting process for the production of ZPR, copper casting remains more demanding than aluminium casting. Nevertheless, the laminar filling has a very positive effect on the casting quality and the tool life of the metallic casting mould. Geometric designs and shapes that were frequently pursued in the past in relation to copper casting can therefore be solved economically with the new process, even in high volume production.

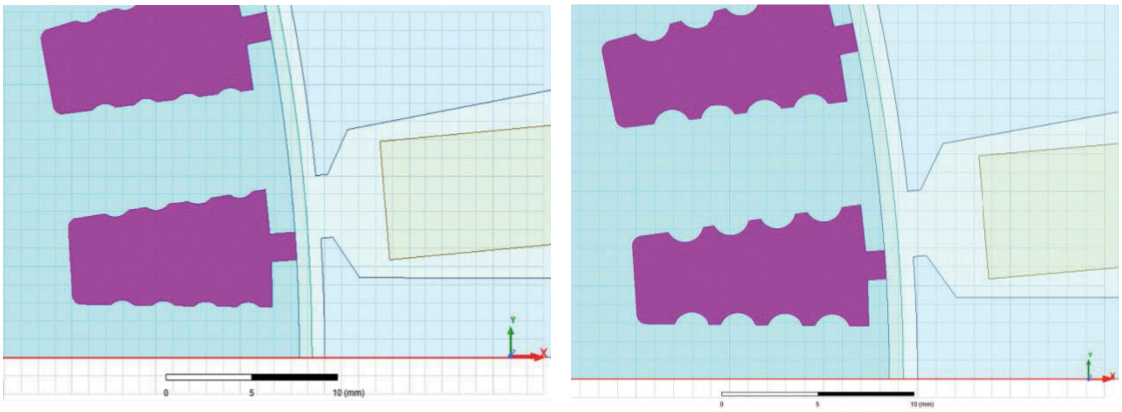


Fig. 11: Geometry of the pine tree slot as part of the mechanical R&D model.

5.1 Influence on the motor properties

The following technical effects occur when replacing the aluminum cage with a copper cage: [10]

- The resistance of the rotor is reduced by 40 %.
- The current heat losses in the rotor are reduced by 40 %.
- The current heat losses in the stator are slightly reduced due to lower heating of the rotor.
- Additional losses are also reduced by 20 % to 25 % due to smaller rotor cross currents.
- The rated slip and tip slip are reduced by about 40 %.
- The performance factor remains more or less constant.
- The maximum motor power (tilting power) is increased by about 20 %.
- The starting torque is slightly reduced and the starting current is slightly increased

This results in the following technical changes:

- Total losses are reduced by about 10 % to 15 %.
- The overall efficiency is increased by about 1 to 2 percentage points.
- Better behavior at the inverter, especially in the low speed range (stiffness) and at overload (higher tipping capacity) is achieved.
- However, slightly lower starting characteristics occur when supplied with a constant frequency (mains supply).

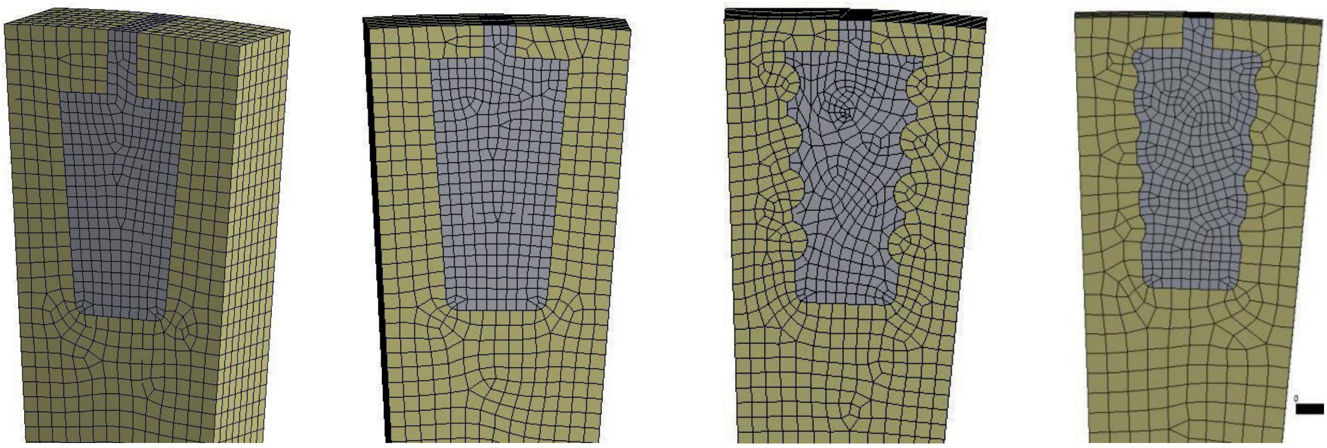


Fig. 12: Geometry of the pine tree slot as part of the mechanical R&D model.

Rotor properties	Unit	Gen2	Gen3*
Max. hight (iron length)	mm	350	400
Max. diameter	mm	250	500
Cage Al ca.	kg	7,5	11
Cage Cu ca.	kg	25	35

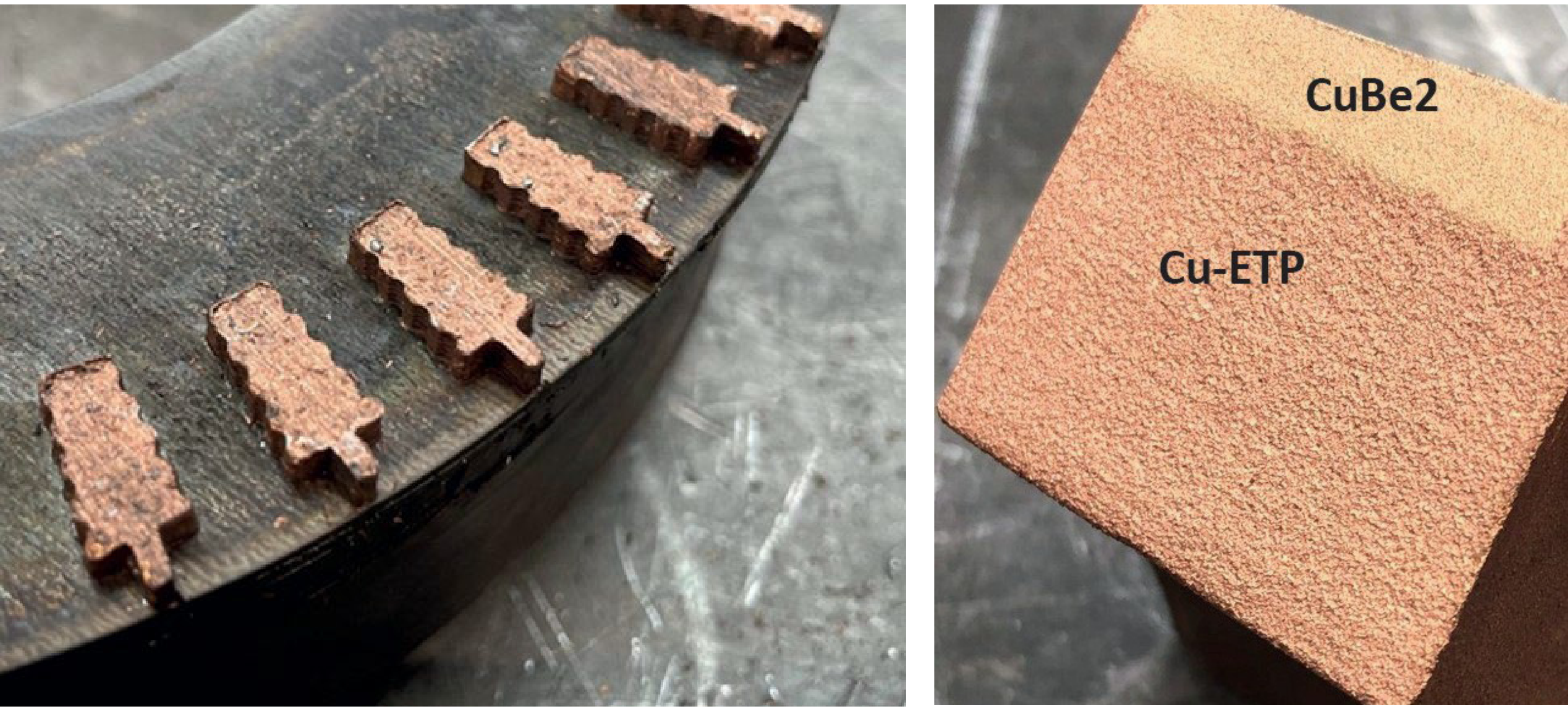
**System under conception/construction*
Table 2: outer dimensions and cage dimensions in laminar squeeze casting.

Thus, the following customer benefits occur with cast copper rotors: [10]

- Smaller construction volume compared to an aluminium motor with the same performance and efficiency at a comparable rotor moment of inertia.
- Stiffer rotational speed-torque ratio, resulting in significantly better load change behaviour, especially in inverter operation at low speeds.
- Higher speed at the tipping point, resulting in higher maximum engine power
- Higher efficiency over the entire power range saves energy even at partial load.
- Lower additional losses – this means that the fixed value specified by IEC 34-2 (EN 60034) (0.5 percentage points) is better achieved than with conventional motors.

Due to the higher conductivity of the rotor material (56 m/mm^2 instead of 35 m/mm^2), it is possible to dimensionalise the motor smaller with identical power and torque data. For a small electric drive for a parallel hybrid on the secondary axle, the volume reduction is 8.5 %. The iron length can be reduced from e.g. 150 mm to 130 mm. [11] This reduces the mass of the entire motor by 0.8 % despite the higher specific mass of the rotor material from 8.9 kg/dm^3 to 2.7 kg/dm^3.

Fig. 13: Photos from destructive testing (left: ZPR® and ring with CuBe2 reinforcing ring).



	Conductivity	Density	Melt temperature	Melt heat	Shrinkage from casting to room temperature	Heat capacity
	MS/m	350kg/dm³	°C	kJ/kg	%	kJ/kgK
Aluminium						
Aluminium pure	37	2,70	658	397	ca. 7	0,879
Aluminium casting Standard*	34	2,43	ca. 680	ca. 400	ca. 7	0,9
Aluminium casting ZPR®	35 – 36	2,70	ca. 680	ca. 400	ca. 7	0,9
Copper						
Copper Pure	58	8,9	1.084	172	ca. 4	0,394
Copper casting Standard*	55	8,01	ca. 1.100	ca. 170	ca. 4	ca. 0,4
Copper casting ZPR®	56 – 57	8,9	ca. 1.100	ca. 170	ca. 4	ca. 0,4
Iron						
Iron	8 – 10	7,8	1.530	210	ca. 4 – 8	0,490

**10 % porosity on average*
Table 3: physical properties in comparison.

This increases the power or moment density (Esson's number of cycles) by approx. 15 % (Tab. 4).

This is certainly interesting for the automotive sector, as the volume is of decisive importance with the mass. The max. rotor temperature is simultaneously reduced by 10 K – 15 K. [11] This has a positive effect on rotor losses and efficiency degree (Tab. 4) This reduction of the lamination and copper mass in the stator decisively reduces the additional cost of the motor. In the optimum case, the savings in mass in the stator and in the rotor laminations compensate for the additional costs of the copper casting, so that the manufacturing costs of the machine remain approximately the same with better performance.

5.2 Potential energy and cost savings with copper

Table 5 shows the energy and cost savings of cast copper rotors compared to cast aluminium rotors in industrial applications.
The above comparative calculation (Tab. 5) shows that for a single-shift operation with an operating time of 2,000 hours per year, the savings of the copper rotor at the household rate (0.3 EUR/kWh) amount to 66.6 EUR and at the industrial rate (0.15 EUR/kWh) 33.3 EUR per year.
The price per kg of cast aluminium mass is approx. 9.9 EUR, for cast copper mass approx. 13.3 EUR (Tab. 6). [12] Since the specific mass of aluminium is 2.7 kg/dm³ and for copper 8.9 kg/dm³, the surcharge can be calculated as follows:
For the asynchronous machine with a power of 4 kW calculated in Table 5, this results in a surcharge of 91.40 EUR for the cast copper rotor compared to the aluminium rotor. For a single-shift operation with household rate, this additional investment would be amortised after approx. 1.5 years, for the industrial rate after approx. 3 years. For three-shift operation, these payback periods would be approx. ½ and 1 year respectively.

Cast aluminium rotors are rarely or never used in railway traction machines due to their lower efficiency

		ASM aluminium rotor	ASM copper rotor	Comparison related to aluminium rotor
Dimension	Unit			%
Outer stator diameter	mm	176,6	176,6	0
Iron length	mm	150	130	– 13,3
Total volume	dm^3	10,5	9,6	– 8,5
Total mass	kg	38,0	37,7	– 0,8
Active mass	kg	24,8	25,3	+ 2,0
Mass stator winding	kg	4,66	4,53	– 2,7
Mass rotor winding	kg	1,5	4,57	+ 204
Mass stator lamination stack	kg	11,73	10,17	– 13,4
Mass rotor lamination stack	kg	6,94	6,01	– 13,4
Torque S1, 2.800 min^{-1}	Nm	51	51	0
Esson's performance factor (S1-performance)	kW / min / m^3	2,85	3,28	+ 15
Degree of efficiency, 15 kW, 2.800 min^{-1}	%	88,5	88,3	– 0,2
Torque/total mass	Nm / kg	1,34	1,36	+ 1
Degree of efficiency, 15 kW, 12.500min^{-1}	%	87,3	88,5	+ 1,2
Max. performance at max. DC link current	Pab	42,4	44,0	+ 3,8

Table 4: Comparison of a secondary drive with asynchronous machine with aluminium rotor and copper rotor [11] *without ZPR efficiency increase (standard casting process).*

and higher temperature. For these applications, drawn short-circuit bars with soldered or welded copper short-circuit rings are used. At high circumferential speeds of over 80 m/s - 120 m/s, the centrifugal forces that occur are introduced into additional, highstrength bronze rings. These are thermally shrunk onto the two short rings. The production effort and also the costs could be significantly reduced by the presented new casting method. In this case, the high centrifugal forces described can be overcome with cast-in copper-beryllium rings.

Operation	Hours	Enegry Alu	Energy Copper	Difference Alu - Cu	Diff. OC* Alu - copper household rate	Difference OC* Alu - copper industrial rate
Shift	h	kWh/a	kWh/a	kWh/a	EUR/a	EUR/a
One	2.000	9.302	9.080	222	66,6	33,3
Two	4.000	18.604	18.160	444	133,2	66,6
Three	6.000	27.906	27.240	666	199,8	99,9

**OC: Operating costs (electrical energy or electricity costs)*
The following calculation parameters were used: Motor power P = 4 kW, efficiency of aluminium rotor: 86 %, efficiency of copper rotor: 88 %; costs per kWh: 0.3 EUR for household rate, 0.15 EUR for industrial rate.
Table 5: Operating cost calculation of an asynchronous machine with 4 kW with comparison of aluminium rotor and copper rotor.

6. Case study: Comparative rotor from the automotive sector

In order to demonstrate the essential advantages of the new casting process by means of a practical example, a comparison was made with a rotor from the automotive sector. For manufacturing reasons, the rodded rotor could only be designed with 40 slots. With the help of using the conventional casting process, the number of rotor slots was increased to 58. However, porosity values of the usual 10 % occurred. With the laminar squeeze casting process, it was possible to cast rotors with a slot count of 70 in copper or aluminium. Even a higher number of slots would have been possible in terms of production technology. No pores were detected either in the grooves or in the end rings in either destructive or nondestructive testing (Fig. 14).

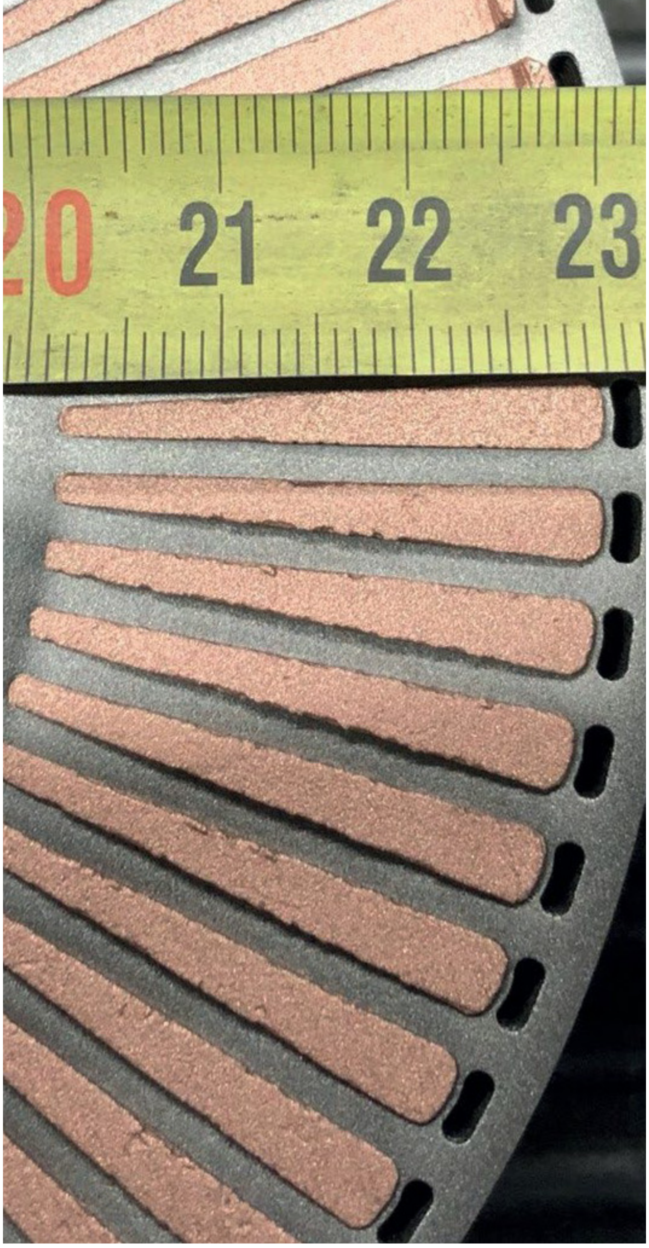


Fig. 14: Saw cut of a copper rotor produced by laminar squeeze casting.

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