EVS30 Symposium
Stuttgart, Germany, October 9 - 11, 2017

Investigation on the Mechanical and Electromagnetical Performance of a special fabricated Squirrel Cage Copper Rotor for Induction Machines

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Executive Summary

— In this paper a new rotor design which allows for radially welding is presented comprising end rings which are made up of several thin copper discs. The radial welding process permits very short processing times which are important for series production. Furthermore, due to the focused heat impact on the material, the copper disc design allows high circumferential speeds above 150 m/s with pure copper material which may even be increased by using different material combinations. It is shown by means of measurements that the mechanical as well as the electrical performance requirements both are achieved by the induction machine with radially laser welded end ring connections.

Keywords — AC motor, asynchronous (induction) motor

1. INTRODUCTION

Electric and hybrid electric vehicles will gain increasing relevance for future motor traffic because they are (possibly) independent of fossil fuels as well as free from local emissions. Besides the popular permanent magnet synchronous machine which is used regularly inside electric vehicle drive trains, the squirrel cage induction machine has recently become more and more interesting for this application [1] [2]. The main advantages of squirrel cage induction machines are their high robustness, their insensitivity against an overheating of the rotor, the small drag losses and the absence of rare earth materials. Additionally, they offer an inherent safety in case of failure (only small induced voltages, small braking torque).

The squirrel cages of induction machines in the range up to several 100 kW of rated power are normally made of die-casted aluminum. However, driven by the increasingly stricter efficiency standards for industrial induction machines [3], rotor cage materials with higher electrical conductivity are required leading to smaller rotor losses. For electric traction motors, the rotor current losses shall be minimized due to the limited energy storage capacity of the battery and the difficult heat dissipation of the rotor, too. One possible solution is the usage of copper bars in the rotor cage which are connected by a copper end ring on each side [4] [5]. The contact between the bars and the end ring is crucial because both electrical (low contact resistance) and mechanical (structural strength with respect to numerous thermal cycles) requirements have to be taken into account [6] [7]. For connecting the bars with the end ring, several joining processes have been investigated by the manufacturers. Hard-soldering of the contact area may reduce the yield strength of the material. Especially for automotive applications with high rotor circumferential speeds up to 100 m/s, this may lead to a widening of the copper end ring which would damage the motor. Die casting of the copper rotor cage requires a very mature casting process and is quite energy-intensive due to the higher melting point with regard to aluminum. Next to the quality requirements, the joining technology has to allow a fast processing time which is necessary for cost-efficient series production.

In this paper, a new method of joining the rotor bars and the end rings of a squirrel cage induction machine with copper rotor cage is discussed. The process is characterized by a special construction of the end rings and a welding process for the connection between the end rings and the bars. The difference to other fabricated copper rotors is that the end ring is divided into several copper discs with a thickness of 2 mm to 4 mm. With this end ring design it is possible to join the discs and the bars with a radial welding process. This enables a very simple and economic rotor construction, also for higher production volumes. The components can be produced with well-known and mature serial processes, like a conform extrusion process of the copper bars or a stamping process of the copper discs. In comparison to the traditional extrusion process, with a conform process very tight tolerances and also very small grain sizes can be realized. The radial welding process of the several discs enables a targeted and really quick joining process. The heat input of the welding process is limited to the short circuit rings. Therefore, any damage to the coating(s) of the lamination stack can be avoided.

The electrical performance of the laser-welded rotor is studied on several customers test benches for electric vehicle drives. The machine is driven in current-controlled mode to obtain the torque-slip-characteristic (i.e. the shaft torque at varying slip frequency at imposed stator current with constant amplitude). The torque-slip-characteristic allows the calculation of the end ring resistance if all other electrical parameters (especially the equivalent circuit parameters) of the machine are known. The results of the radially welded rotor are compared to those of a rotor with axially laser-welded end ring connections.

2. Laser Welding Process for Joining the Bars and End Rings of a Copper Squirrel Cage Induction Machine

2.1 Laser Welding of Copper Material

The industrial demand on complex components made of copper is increasing. Copper components are necessary for electric drives in the automotive industry as well as for energy transportation systems in the field of regenerative energy sources. Modern battery technology also uses copper components for interconnection and current transport. In order to produce such components and assemblies, an adequate joining technique is required. For automotive industry production the joining technique must be fully automatable, highly reproducible and reliable. It should also be fast and flexible without changing the properties of the welded parts.

In comparison to joining of steel, which in numerous cases is done by laser remote welding, welding of copper is associated with additional challenges. Three major facts have to be considered:

1. Low absorptivity of infrared laser radiation on the copper surface at room temperature,
2. Low viscosity of the copper melt,
3. High thermal conductivity of copper.

For the laser welding of copper squirrel cage rotors, a very important factor is the potential welding depth. The higher the depth, the better the connection area between the rotor bars and the end rings. This is dependent on the usage of the copper material as well as laser power source and parameters. The following chapter gives an insight into the different welding solutions for a fabricated copper rotor.

2.2 Axially Welded End Ring Connection

The fabricated copper rotor with a brazed end ring design is a common technology especially for bigger industrial induction motors. Together with several automotive customers, Wieland started to develop an alternative joining technology for the copper end rings in the year 2011. Our incentive to use the laser welding technology instead of the induction brazing technology was because of the various disadvantages of the brazing process. The high thermal stress on the laminations, shown in Fig. 1, as well as the long process time due to the cooling phase of the end rings in a serial mass production are the main challenges. Because of the brazing material we expect a higher resistance between the copper bars and end ring in comparison to a laser welding process, with no additional weld metal/material.

Fig. 1. Induction brazing process.

For the fabricated copper rotors, the copper bar profiles are manufactured with a common serial conform process. This is a special pressing and drawing process and today established for serial mass production. The massive copper end ring is manufactured for prototypes with a water jet cutting process. The copper bars subsequently get stuck into the laminations and end rings. An important topic in this process is the dimensioning of the tolerances between the copper bars and lamination gaps. Also, shifting between several lamination sheets makes the joining of the copper bars into the lamination stack very difficult.

After the mounting of the copper bars into the lamination, the whole component gets axially pressed to eliminate the air gaps between the copper bars and copper end rings. Then, with the laser welding process, every single copper bar gets axially welded on its circuit, as shown in Fig. 2 and Fig. 3.

Fig. 2. Axially laser welded copper rotor.

Fig. 3. Axially laser welded copper bars in end ring.

To verify the laser welding depth, some structure analyses have been done. Fig. 4 shows a cut through the laser weld seam of the copper bar and end ring disc. The copper end ring material is Wieland K14 (Cu-PHC) with a gritty structure. The rotor bar material is Wieland K10 (Cu-OFE) and is fine grained because of the pressing and drawing manufacturing process. The laser weld seam in the middle of picture 4, shows a cast structure with columnar crystals.

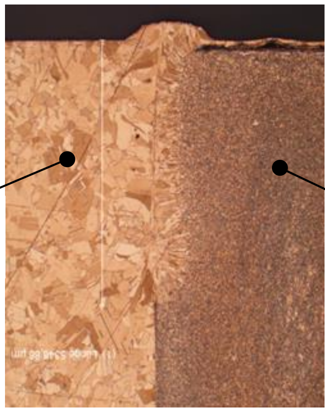

Fig. 4. Structure analysis of axial welded end ring..

To sum up, we can say that the axial laser welding process is useful for prototype copper rotors, but not for serial mass production. The challenges for a process with high volumes are the problems with the heat effect during the laser welding process. After welding one copper bar, the adjacent copper bar loses it square shape due to the heat effect and this forms a minimal air gap between the bar surface and the end ring. This effect makes a reproducible laser weld process very difficult. There is another challenge, namely the economic manufacturing of the copper end ring. Because of the end ring’s thickness of 22 mm it is not possible in a serial production to stamp the copper bar breaches in the end ring. So a new design for a better laser welding and manufacturing process of the end rings has to be developed. One solution is shown in the following paragraph.

2.3 Radially Welded End Ring Connection

To optimize the challenges of the axial laser welded copper rotor, a new design of the copper end rings was developed. Together with IAV, a similar copper rotor with analogous dimensions was designed. The only part which was changed was the design of the copper end rings. The massive 16 mm thick end ring was divided into 4 individual discs of 4 mm in thickness each. To realize the connection between the end ring discs and rotor bars, we weld on a radial position between every single disc. Depending on the laser depth, we can realize a connection between the rotor bars and the end rings.

Similar to the axially welded rotor, the rotor bars are produced with a serial conform process, and the different end ring discs with a water jet cutting process. Also the whole copper rotor gets axial pressed to eliminate any air gaps between the single parts. Only the position of the laser welding process is changed from an axial position to a radial position, shown in Fig. 5.

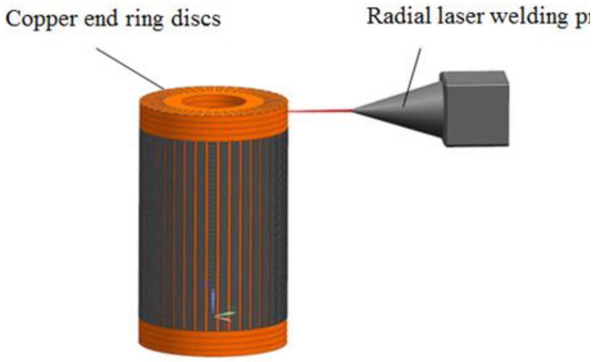

Fig. 5. Radial laser welding process.

Before the manufacturing of the copper rotors can be started, the parameters for the laser welding process have to be acquired. Test weldings on experimental parts, like shown in Fig. 6, have been done. The focus is to generate the final laser welding parameters, like focus position, welding speed and power. This testing has been evaluated with structure analysis, to check the depth and arising thereby the connection area as well as the porosity of the weld seam.

Fig. 6. Experimental part for test welding.

To reach the maximum contact area and therewith a small current density between the bars and discs, a high laser power source is needed. A laser weld depth in copper material between 6 mm and 10mm can be reached.

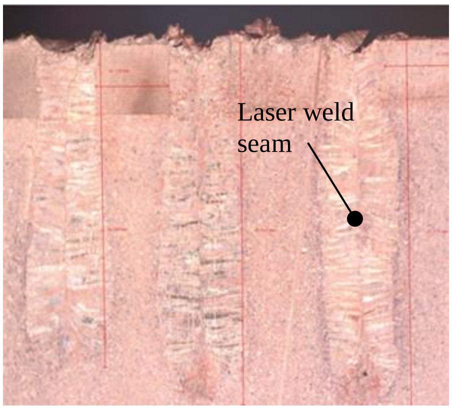

Fig. 7. Structure analysis of radially welded end ring.

Fig. 7 shows a structure analysis of 3 weld seams with no pores and blemishes inside. Also there is an almost consistent weld seam width of around 1,5 mm.

If this connection area is too small, that means that the contact resistance for the current flowing between the rotor bars and end ring is too high, it is possible to increase that area with thinner copper end ring discs by increasing the number of weld seams.

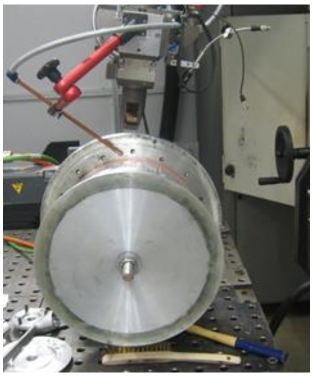

Fig. 8. Copper rotor construction in laser cabin.

After a successful pilot study and preparation of the laser parameters, the final copper rotors can be produced. In Fig. 8, the manufacturing of a rotor in the laser cabin is shown. The rotor is fixed in a horizontal position, and the laser source respectively the laser optics is placed above. The rotor spins in clockwise direction.

3. MEASUREMENT OF THE MECHANICAL PROPERTIES OF THE WELDED ROTOR

Wieland performed the balancing and also centrifuging tests (Fig. 99) at operating speed and overspeed of the customers application requirements. With this disc-shaped rotor dimension the maximum possible rotational speed was tested. The circumferential speed that could be reached before bursting was over 150 m/s with pure copper material in the end ring. Because of too high levels of tangential stress on the upper short circuit ring, the whole end ring was replaced on the test bench. This trial was done without any additional steel safety or containment ring.

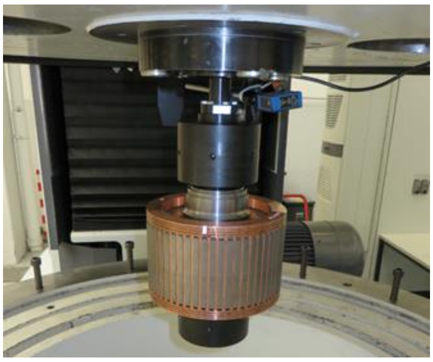

Fig. 9. Centrifuging test.

Finally, there are a few positive aspects which can be implemented with this rotor disc-shaped ring design. The laser welded, fabricated rotor design exhibits no pores and blemishes along the whole axial length, and it is also possible to realize circumferential speeds of over 150 m/s with pure copper material in the end rings. In comparison to the copper die-cast process, there is another advantage, if the rotor is spinning at higher speed. It is possible to use different material combinations, for example with Wieland K75 a high copper alloy (CuCrSiTi), in the end ring discs. So this material can achieve a higher mechanical strength without implementing any additional containment ring. Furthermore the softening behavior at high temperatures of this material is much better than of pure copper material. Over 300°C the mechanical strength of the material stay´s at it´s very high level. With this solution, circumferential speeds over 200 m/s may be reached. Furthermore, the possibility of an economic serial mass production is given with this design because of the simple manufacturing process of the sample parts and furthermore the assembling and welding process is very good automatable.

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