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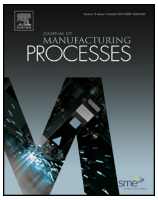

Inertia welding for assembly of copper squirrel cages for electric motors

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ABSTRACT

The automotive industry is developing designs and manufacturing processes for new generations of electric motors intended for use in hybrid and electric vehicles. There is interest in replacing the aluminum traditionally used in induction motor rotors with copper to improve motor capability. This paper focuses on solid-state welding to join copper end rings to copper spokes in the fabrication of copper rotors. Inertia friction welding was explored to examine weldability of these copper components. A better understanding of inertia welding characteristics will help the advancements in its application for induction rotors. The limitations of this application are discussed.

1. Introduction

Large efforts have been devoted in developing energy-efficient and environmentally friendly technologies for hybrid vehicles. Vehicle electrification efforts demand efficient motors with increased power and minimal losses. Two of the motor configurations used in current automotive applications are internal permanent magnet motors (IPM) and induction motors (IM). IMs are simpler and lower cost than IPM motors and, therefore, IMs are becoming very important to the automotive industry to reduce dependency on high performance magnets [1–3].

Induction traction motors have used aluminum in the rotor to conduct electricity due to its relatively low manufacturing costs and good electrical properties (Fig. 1). Since the resistive losses are a direct function of the resistivity of the rotor spokes (conductor bars) and end rings (the so-called squirrel cage structure) of the rotor, materials selection plays a key role. Use of a copper rotor improves power density and efficiency. Copper, which has over 60% higher electrical conductivity than aluminum, is also much more difficult (i.e. costly) to process, given its significantly higher melting point (1080 vs. 660 °C), thermal conductivity, density, and price-per-unit (the latter two by a factor of nearly 3.5). A motor efficiency increase of 2–4% was obtained with copper rotors while using improved magnetic steels for the lamination stack [1,4–7].

Squirrel cages for induction motors are currently manufactured by aluminum die casting. This process includes direct casting of the aluminum into a steel lamination stack. Such aluminum die casting processes result in relatively poor mechanical and electric performance of the material (compared to wrought products) [1–6]. As a replacement material, copper may necessitate larger slot sections in the squirrel cage design. Die casting of copper is more challenging than aluminum due to higher melting temperature and thermal conductivity of copper and higher filling difficulties of the slots especially for long rotors. An alternative is to produce the squirrel cage through an assembly of the bars and end rings which are joined together by a welding process. This would include inserting extruded wrought copper conductor bars through the lamination stack, and welding them to wrought copper end rings.

The high thermal conductivity of copper is considered good for the rotor performance. However, this property hinders the welding process because it diffuses rapidly most of the heat (in the lamination stack and welding fixture) required for local softening at the weld sections. Fusion welding of copper may require special fixture and high temperature preheating of the copper end rinds. On the other hand, friction welding (solid state welding process) is a good candidate [8,9] because: (1) the rotor presents rotational symmetry, (2) a smaller quantity of heat is required for joining, (3) the weld cycle time is extremely short, (4) the process is suitable for high volume mass production applications, and (5) the internal structures of the material are not affected by the heat and oxygen and, hence the weld interface generally remains free from cracks and blow holes.

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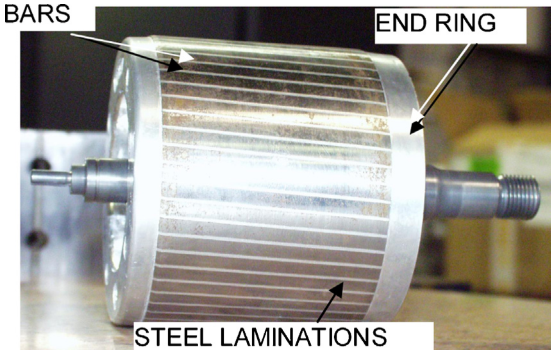

Fig. 1. Induction rotor core with aluminum as the conducting material.

The aim of this paper is to investigate the performance of inertia friction welding for the assembly of copper squirrel cages for induction electric motors (Fig. 1). High-integrity joints between copper end rings and spokes rotor components should be obtainable using inertia friction welding as supported by Refs. [10–15]. Process analysis was used to estimate the characteristic parameters and relate them to those for copper inertia welding provided in the ASM Handbook to better understand the mechanical loads acting on the part. The combination of tests and analysis allows a better description of the inertia welding process. This work helps define the process characteristics and limitations to assist improvement in copper rotor manufacturing.

2. Experimental procedures

2.1. Materials

The final rotor assembly was made up of a loose silicon steel lamination stack (about 200 pieces) with copper spokes extending through slots in the outer periphery of the rotor. The stack was 70-mm tall as shown in Fig. 2. There were 56 narrow (open-to-the-OD) slots in the laminations. Two end rings were used to join the spoke ends on either end of the lamination stack to complete the electrical circuit of the rotor (see Fig. 1 as an illustration of the assembly).

Fifty-six copper spokes of C10100 material were required for each rotor assembly as illustrated in Fig. 2. A special contoured surface spoke was designed to fit the full-lamination slot space (Fig. 3). The end rings were made from C10100 tubing and machined to the shape in Fig. 3 with 101.6-mm OD, 70-mm ID, and 12.7-mm thick. Two versions of end ring were used: (1) Type A with rectangular cross-section and chamfered ends at the joint side with 93 mm OD and 76-mm ID; (2) Type B with a 0.5-mm deep groove as shown in Fig. 3. The Type A was used with a support ring at the ends of the lamination stack as illustrated in Fig. 2. The Type B end ring was used without a support ring while the spokes extended 1 mm above the laminations.

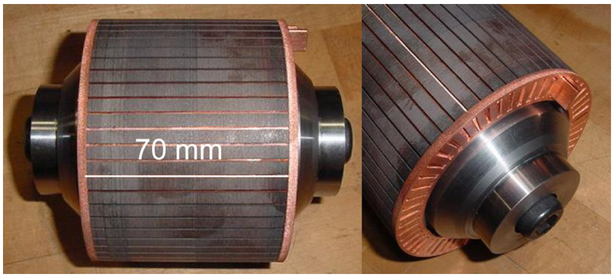

Fig. 2. Rotor assembly, lamination stack, spokes, and thin support end rings.

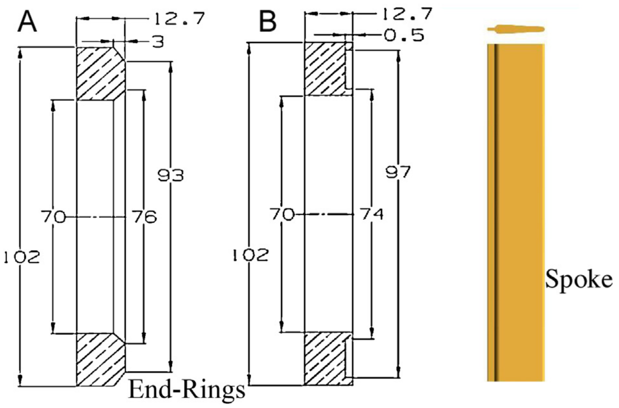

Fig. 3. Components of an assembled rotor.

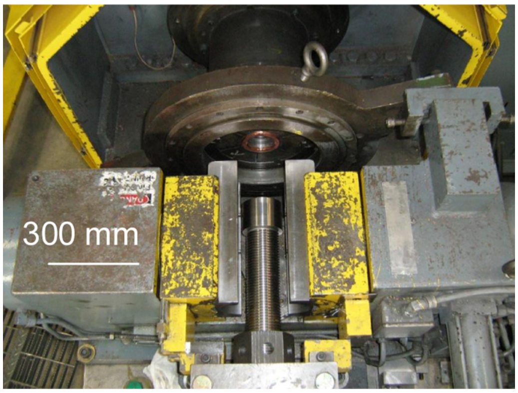

Fig. 4. Top view of Caterpillar 250 inertia welder spindle and tooling, end ring gripped in spindle collet.

The copper support rings (Fig. 2) were added to create a base for the weld with Type A end ring to be integrated with the spoke ends. The spokes were flush with the support ring that encompasses the ends of the spokes creating a nominally solid surface for welding. Two different support ring thicknesses were used in the trials: 3-mm and 12-mm.

2.2. Equipment

Friction welding was performed with a Caterpillar Model 250 A inertia welding machine (Figs. 4 and 5). The spindle holding the rotating end ring is attached to a flywheel. The lamination stack

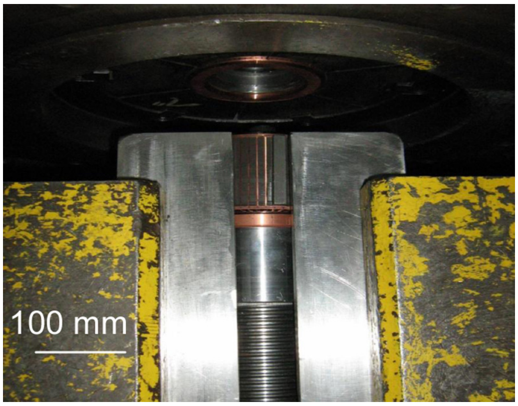

Fig. 5. Top view of welder tooling with rotor just before clamp closed, end ring gripped in spindle collet.