



Contents lists available at ScienceDirect

CIRP Journal of Manufacturing Science and Technology

journal homepage: [www.elsevier.com/locate/cirpj](http://www.elsevier.com/locate/cirpj)



## A cyber-physical system for quality-oriented assembly of automotive electric motors

M. Colledani<sup>a,b,\*</sup>, D. Coupek<sup>c</sup>, A. Verl<sup>c</sup>, J. Aichele<sup>d</sup>, A. Yemane<sup>a</sup>

<sup>a</sup> Politecnico di Milano, Department of Mechanical Engineering, Via la Masa, 1, 20156 Milan, Italy

<sup>b</sup> ITIA-CNR, Institute of Industrial Technologies and Automation, Via Bassini 15, 20133 Milan, Italy

<sup>c</sup> Institute for Control Engineering of Machine Tools and Manufacturing Units (ISW), Seidenstraße 36, 70174 Stuttgart, Germany

<sup>d</sup> Corporate Research Robert Bosch GmbH, Postfach 300240, 70442 Stuttgart, Germany

### ARTICLE INFO

Article history:  
Available online xxx

**Keywords:**  
Assembly  
Quality  
Productivity  
Electric vehicle  
Electric motor  
Cyber-Physical Systems

### ABSTRACT

The production of motors for the electric vehicles requires innovative and systematic quality control approaches to boost efficiency while moving from low volume towards mass production. In this context, end-of-line quality testing methods are usually applied to assess the product functionality at the end of the process chain. However, this approach does not allow process monitoring and the in-line prevention and correction of defects, leading to significant scrap rates and value losses.

This paper presents a new system-level strategy for the in-line quality-oriented assembly of rotors in the production of automotive electric drives. The new strategy is based on a new cyber-physical system that optimizes the assembly strategy depending on the quality of magnetized stacks, monitored with data gathered by in-line inspection. For each batch, the magnetic stacks to be assembled and their orientation is selected according to an optimization algorithm, aiming at minimizing the deviation from the target total integral magnetic flux and maximizing the field uniformity in the magnetized rotor. The impact of the proposed strategy on the quality and productivity related performance measures are predicted by analytical methods. Experimental results based on an industrial case study are reported, showing that the application of the proposed strategy yields a significant increase in the production rate of conforming engines. The proposed approach paves the way to innovative zero-defect manufacturing strategies at system level in emerging, high-tech, manufacturing sectors.

© 2017 CIRP.

### Introduction

Sustainable mobility is one of the most important challenges towards a low carbon economy and a more sustainable society. According to the 'European Roadmap for Moving to a Competitive Low-Carbon Economy in 2050', transportation is one of the most relevant sectors for reducing emissions [1]. This sector accounted for 16% of the total global emissions in 2015 [2]. In order to reduce emissions of the current car fleet, the trend is going towards zero-emission vehicles using electric motors [3]. Recent studies show the huge potential of electric motors in replacing combustion engines (petrol and diesel), in particular for medium-sized cars [4]. Following these trends, a requirement to move from small series to mass production of electric motors is observed in the automotive sector, for hybrid and purely electric vehicles. Governmental

regulations and targets for increasing the amount of electric vehicles accelerate this development [5,6]. In this favourable context, the market growth of electric vehicles is, however, strongly constrained by the availability of advanced manufacturing technologies and methods able to support their production at affordable prices. Therefore, efficient production and quality control strategies play a significant role to boost an economically and environmentally sustainable transition to mass production of electric vehicles.

In the current production scenario, end-of-line quality testing strategies are usually applied to assess the product functionality before delivering the electric drive to the market [7,8]. At the end of the process-chain, the functionality of the assembled motor is tested, in terms of power, torque, and absence of cogging, yielding to a classification into conforming and non-conforming parts. Non-conforming parts are either disassembled and reworked, or scrapped. Both actions entail a significant operational cost due to material losses and non-value-adding processes. To avoid these problems, manufacturers usually apply wide tolerance limit

\* Corresponding author at: Politecnico di Milano, Department of Mechanical Engineering, Via la Masa, 1, 20156, Milan, Italy.  
E-mail address: [marcello.colledani@polimi.it](mailto:marcello.colledani@polimi.it) (M. Colledani).

widths and a conservative motor design [8]. In other words, large variability in the product performance is accepted and the target requirements are met by oversizing the product by design. An alternative cost-effective strategy would be to smooth the product performance variability by implementing process monitoring and in-line prevention of defects, before the product reaches the final stage of the process-chain. To this aim, innovative quality control methods and strategies for avoiding the generation and propagation of defects along the stages of the production line need to be introduced, with the objective to move towards the zero-defect manufacturing paradigm in this strategic industrial sector.

In literature, only few approaches try to overcome the drawbacks of the current end-of-line quality control solution in the production of electric drives for the e-mobility sector. The majority of the approaches focus on the critical process stage of rotor magnetization and rely on the inspection of single magnets. For example, in [8] the authors propose the inspection of single permanent magnets after magnetization, by storing them in an automated warehouse system next to the assembly station. The advantage of this approach is that the actual magnetization of the permanent magnets is individually measured and compared to the set-point. However, this approach is usually too conservative and results in high scrap rates, since the opportunity to obtain conforming rotors by a proper combination of magnets with highly deviating magnetization levels is neglected. In addition, there are several drawbacks while handling magnetized materials, e.g. restrictions in transportation, contamination of the magnets and operators' safety [9]. For these reasons, permanent magnets are mostly magnetized after assembly. Inspection of permanent magnets before magnetization and assembly are described in several papers [10–13]. However, this strategy introduces an additional handling and inspection station into the production line, increasing costs and line complexity and shifting the quality problem to the magnet suppliers, thus increasing their costs.

Emerging Key Enabling Technologies (KETs), such as in-line data gathering solutions, data storage and communication standards, data analytics tools and digital manufacturing technologies offer new opportunities for zero-defect manufacturing, in complex production environments. These technologies are increasingly becoming integral part of modern production systems [14]. If these technologies are properly integrated with a cross-KETs approach, new Cyber-Physical Systems (CPSs) can be designed and implemented at shop floor level, to support systemic zero-defect manufacturing solutions [15].

CPSs are usually defined as systems integrating computation and physical actuation capabilities [16]. In CPSs, embedded computers and networks monitor and control physical processes, usually with feedback loops, where physical processes affect computations and vice versa [17]. Innovative applications of CPSs for improving manufacturing efficiency and responding to emerging industrial problems is attracting the interest of both industries and researchers [18]. This trend is transforming the manufacturing industry to the next generation, namely the fourth industrial revolution "Industry 4.0" [16]. It envisions the promise to couple the world of production and network connectivity into an "Internet of Things" to realize "Smart production" as the new norm in a world where intelligent ICT-based machines, systems and networks are capable of independently exchanging and responding to information to manage industrial production processes [19]. This potential in connectivity and computational power in manufacturing can also be exploited to support the implementation of efficient in-line quality-oriented production solutions [20].

This paper proposes a new quality-oriented strategy for the assembly of electric motors in the e-mobility industry. The solution

is based on a CPS that optimizes the assembly strategy depending on the quality of magnetized stacks, monitored with data gathered by in-line inspection. For each batch, the magnetic stacks to be assembled and their orientation is selected according to an optimization algorithm, aiming at maximizing the field uniformity in the magnetized rotor. An analytical method for the analysis of percentage of conforming rotors, total production rate and work in progress of the system operating under this new assembly strategy is developed. The proposed solution is validated with real data obtained from Robert Bosch GmbH, as one of the Use Cases of the *MuProD* project, funded by the European Union [21,22]. The experimental results show that the application of the proposed strategy yields a significant increase in the production rate of conforming engines.

The paper is organized as follows: Section **Description of the production system** describes the process chain of the Bosch electrical motor assembly line. Section **Design of the CPSs solution** introduces the design of the CPS solution and the techniques for the measurement and estimation of two key quality characteristics of the rotor. Section **In-line quality optimization methods** describes the proposed methods for enabling a quality-oriented rotor assembly by considering the two key quality characteristics. Section **System level performance** presents an evaluation method for estimating the output performance measures of the system operating under the new assembly strategies. Section **Implementation architecture and demonstration** describes the implementation architecture and discusses the demonstration of the proposed solution in real industrial settings.

## Description of the production system

In this section, the Bosch electrical motor production line for permanent-magnet synchronous motors, that are widely spread in the automotive industry, is described [23,24]. The rotor of such an electrical motor consists of  $S_p$  stacks. Each stack contains  $M_p$  permanent magnets radially embedded in a circular steel ring. By piling several stacks together, rotors of different torque can be produced with the same cross-section. The production line is composed of three main branches, namely rotor assembly, stator and housing production (Fig. 1). In the figure, light blue squares represent processing stages, red squares represent inspection stages and circles represent buffers for temporarily storing in-process inventory. In this paper, the analysis is focused on the rotor line that is composed of seven main stages, described in the following:

- $M_1$ : loading of the stacks on the pallet.
- $M_{2,1} \dots M_{2,x}$ : assembly of the embedded permanent magnets on the stacks.
- $M_3$ : stack magnetization process and inspection.
- $M_4$ : heating station for glue drying.
- $M_5$ : rotor assembly machine.
- $M_6$ : rotor balancing station.
- $M_7$ : rotor marking station.

After the motor is assembled in  $M_g$ , it undergoes a final quality control at the end of line (EOL) inspection station,  $M_k$  [7]. Two key quality characteristics are inspected. First, the overall magnetic moment of the motor should be within a tolerance limit of 4% from the target value. Secondly, the motor should be free from significant cogging and vibration. The main drawback of the current inspection is that it is performed at the final stage of the manufacturing line, where defects cannot be corrected [23,25]. Consequently, a defective motor can only be recycled, by disassembly, or scrapped, with significant value losses [26].

Download English Version:

<https://daneshyari.com/en/article/8038877>

Download Persian Version:

<https://daneshyari.com/article/8038877>

[Daneshyari.com](https://daneshyari.com)