Institution: Oxford Brookes University

Unit of Assessment: 12, Engineering

Title of case study: Influencing the development of YASA high performance electric motors for sustainable mass production of next-generation vehicles

Period when the underpinning research was undertaken: 2007 – present

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Professor James Broughton Professor Allan Hutchinson Dr Stephen Samuel	Head of JTRC Head of SVEC Reader	[text removed for publication]

Period when the claimed impact occurred: 1 August 2013 – present

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact

The Joining Technology Research Centre (JTRC) has provided substantial and critical knowledge transfer to YASA Limited (Oxford, UK), centred on the introduction of engineered polymer materials (EPMs) for reducing the weight of high-powered lightweight electric motors, designed and manufactured by YASA. Key achievements over two successful knowledge transfer partnerships (KPTs) included:

- Improvement of the motor that enabled YASA to radically shorten production times, save material used and reduce defect rate, leading to significant cost reductions in motor production, and preparing the company for mass production.
- Increased high-profile client base, through data driven assurance of motor performance, creation of assembly protocols, improved build robustness and reliability, and increased power demand potential of the motor.
- Development of new joining processes (patented technology) to accommodate the introduction of EPMs. This led to investigations for alternative novel cooling mechanisms that drove key strategic decisions for future motor design.
- Generation of predicative numerical tools to determine noise and vibration reductions for future motor development and diversification of motor applications, as a direct result of employing EPMs.

This all represented a huge step change for the company, leading to the successful mass production of subsequent YASA motor models, their take up in high-profile companies [text removed for publication] and signing multiple long-term development and supply agreements with automotive Original Equipment Manufacturer (OEM) customers, paving the way towards its inclusion in lower cost electric-driven production vehicles.

2. Underpinning research

The collaborative research and knowledge exchange between the Joining Technology Research Centre (JTRC) at Oxford Brookes University and YASA Motors involved three key technical strands: (1) adhesive development for dissimilar material joining; (2) novel heat exchange concepts; and (3) predictive dynamic modelling.

YASA, the Oxford based manufacturer of electric motors and motor controllers for use in automotive and industrial applications, was founded in 2009 by the CTO, Dr Tim Woolmer, to commercialise a permanent-magnet axial-flux electric motor (YASA stands for Yokeless and Segmented Armature). Having magnetic poles aligned axially enabled for a much narrower compact design that was also, and uniquely, liquid cooled. YASA electric motors typically are half the size and a third of the weight of conventional radial motors, including simpler manufacturing and integration processes. However, the construction of early prototypes was hand-built, slow and expensive to produce, with a high fail rate, which led to considerable inefficiencies. A critical aspect to the novel motor design and significant contributor to these reported issues was the fact that almost the entire assembly of the motor relied upon adhesive bonding.

Professor James Broughton's (Head of JTRC) underpinning work on adhesive joint design **[3.1]**, fatigue endurance **[3.2]** and durability test-rig development **[3.3]** were all directly applicable to tackling the above issues. YASA approached JTRC in 2011, due to their knowledge and expertise, and access to specific equipment for solving joining issues related to lightweight composite materials. Specifically, JTRC were contacted to help develop YASA's in-house knowledge and capabilities related to adhesive technology, which led to the first KTP, entitled 'Development of sustainable joining technologies for the mass manufacture of high reliability, high torque, low mass electric motors' (KTP008367, 2011–2013, GBP106,890), funded by Technology Strategy Board (TSB, now Innovate UK).

Under the Principal Lead of Professor Allan Hutchinson, Head of Sustainable Vehicle Engineering Centre (SVEC), and supervision of Professor (then Dr) James Broughton, Head of JTRC, the partnership achieved several key objectives. These included: (i) new manufacturing process rules to reduce assembly errors; (ii) an improved bonding process that led to a reduction in potential defects (motor robustness); and (iii) a reduction in motor production times by implementing detailed design modifications that eliminated time-consuming and expensive rework. In turn, this contributed to a significant reduction in the cost of the motor **[3.4]**. For future high-volume production models, utilising lightweight 'injection moulded' engineered polymer materials (EPM) will lead to more sustainable motor designs with greater potential for recycling at end-of-life. Work was undertaken to investigate co-bonding of EPMs using laser and heat welding technologies, and their effects on bond performance and durability; many of these materials exhibit low surface energies, which can translate to poor adhesion if not treated. This work developed solutions involving co-bonding and over-moulding technique innovations and led to the filing of three patents. The outcomes of this work received significant national recognition as the award-winning KTP for Engineering Excellence and runner-up finalist in the Best of the Best Award, Innovate UK, 2014.

The introduction of EPMs, however, had negative consequences, including increased noise, vibration and poor heat extraction. A follow-on KTP project was formed, entitled 'Development of a prototype axial flux motor using novel cooling technologies with the aim of providing a step change (30%) in power output' (KTP009387, 2013–2015, GBP94,587), funded by TSB and under the joint supervision of Professor Broughton and Dr Stephen Samuel. Analytical models developed by Dr Samuel on heat transfer of IC engines **[3.5]** formed the basis for specialised models for optimising cooling and heat flow dynamics. One of the options explored was heat pipe technology (HPT) because of its simplicity and compactness. Experimentation evaluated various wick types and cooling fluid types to validate the models. The research delivered 12 technical reports on experimental, theoretical and numerical investigations into flow rates, coolant systems and fluids, wetting of wicks for heat pipes, and dynamics of heat flow **[3.6]**. Although the overall outcome established that HPT was not currently a viable option, the findings informed company strategy and diverted significant R&D resource to other areas. Preliminary frequency analyses also demonstrated limitations with the current aluminium cover of the YASA P400, leading to a sponsored PhD on the dynamics of certain motor components. This work immediately identified issues with the dynamic response of some motors and further issues that could arise with the introduction of EPMs for light-weighting purposes. This work continues to guide YASA's implementation of EPMs and re-design of the motor to reduce noise levels and improve dynamic response.

3. References to the research

3.1 Fessel, G., Broughton, J., Fellows, N, Durodola, J., Hutchinson, A. (2007). Evaluation of different lap-shear joint geometries for automotive applications. *International Journal of Adhesion and Adhesives, 27*(7), 574-583. https://doi.org/10.1016/j.ijadhadh.2006.09.016

3.2 Hooper, M., Hutchinson, A., Broughton, J., Taylor, M. (2012). Development of a novel test rig for the evaluation of aircraft fuel tank sealant. *Journal of Testing and Evaluation, 40*(1), 177-183. https://doi.org/10.1520/JTE103420

3.3 Fessel, G., Broughton, J., Fellows, N., Durodola, F, Hutchinson, (2009). Fatigue performance of metallic reverse-bent joints. *Fatigue and Fracture of Engineering Materials and Structures, 32*(9), 704-12. https://doi.org/10.1111/j.1460-2695.2009.01378.x

3.4 *KTP008367 Partners final report (KTP1)

3.5 Otero, V.T. and Samuel, S. (2018). Numerical Simulation of a 2018 F1 Car Cooling System for Silverstone Circuit. *SAE Technical Paper* 2018-01-0169 https://doi.org/10.4271/2018-01-0169

3.6 *Samuel, S. and Goh, S. (2015). Cooling System for Electrical Motors and Generator, YASA Engineering Report, Documents 674, 695, 735, 817, 936, 943, 950, 959, 960, 1011, 1012, & 1052

*can be supplied on request by Oxford Brookes University's Research, Business & Development Office

4. Details of the impact

The Joining Technology Research Centre at Oxford Brookes University has been the source of invaluable expertise for YASA Motors. Two successful KTPs led to a significant increase in the technical and commercial capabilities of YASA and further contribution towards a lower carbon economy.

Currently, most of YASAs production of motors and controllers resides in the automotive sector, enabling automotive manufacturers to meet increasingly stringent emissions targets whilst delivering exciting driving experiences. In addition to automotive applications, YASA motors are used in defence, marine and aerospace sectors where high power density and torque density are critical. All these markets demand highly reliable, lightweight and robust motors, given the extreme environments these types of vehicles operate within. In 2018, YASA officially opened its 100,000 unit motor production facility. The Business Secretary, Greg Clark MP, who delivered the opening address said, "*YASA is a brilliant example of what can be achieved when government, academia and industry come together to turn the best ideas from the best minds into scale-up companies*" **[5.1]**. YASA is now well-placed to capture significant market share within these sectors too and a significant aspect of this is down to the robust bonding technologies and company knowledge gained through the unique, on-going, relationship fostered between Oxford Brookes University and YASA.

Initially, the partnership was sought to provide the capability to make high torque, low mass motors using injection moulding polymers with adhesive/composite bonds. Prior to the KTP project with JTRC, YASA lacked adhesive joining expertise, particularly relating to the design of interfaces and bonding of composite parts to proposed low surface energy polymers, as well as expertise in choosing or designing test methods suitable for testing such bonds against environmental and mechanical stresses, all needed for scaling to mass manufacture **[5.5]**.

With the first KTP focused primarily on production issues, there have been several significant impacts on the business. Dr Tim Woolmer, Founder and CTO, YASA Limited remarked, "*The combination of expertise and equipment had attracted us to the KTP – but everyone here has been blown away by the results*" **[5.2]**. These main technological impacts were first introduced in 2013, where the company at the time recorded a revenue of GBP1,600,000. Issues directly linked to the bonding process were resolved, which meant defect-rates had fallen by a factor of 100, saving almost GBP100,000 in avoidance of motor durability failures. The KTP Associate Jonny Biddulph conducted trials of new technology on injection moulded stator plates, where the outcome was a part-cost reduced from GBP177 to GBP7. With two of these parts included in every motor this represented a significant saving (GBP1,140,000 for 3,000 motors) and allowed the joining of neighbouring parts by laser welding, further increasing manufacturing speed. The manufacturing process time reduced from 7 days to 2 days, potentially saving GBP16,650,000 (reduced assembly time savings GBP18.50/hour production cost, based on predicted 90,000hours saved three years after completion of KTP) **[5.3]**. From Oxford Brookes University's first involvement with YASA in 2011, the company grew from 12 to ~150 employees in 2020, with a recorded revenue of GBP7,600,000 in 2018 **[5.4]**. This growth has been necessary to extend production rates from less than 50 motors per annum to a high volume capability of 100,000 units per annum **[5.1]**. This capability would not be possible without the key technology to deliver high-volume over-moulded bonded stator plates.

This KTP has subsequently proven instrumental to sustaining the growth of YASA Motors in the areas of materials and bonding technologies. On the back of demonstrating robust bonding procedures, the motors were adopted for the Jaguar C-X75 supercar, dubbed '*the most technologically advanced road car ever conceived*', and on the strength of this YASA were shortlisted for the Society of Motor Manufactures and Traders (SMMT) Award for Automotive Innovation **[5.6]**. Other high-end sports cars have since adopted the technology, proving its capabilities in demanding environments. For example, the [text removed for publication] uses three YASA motors and, according to [text removed for publication], delivers the fastest accelerating, most powerful production car ever. [text removed for publication] commented: "*YASA's motors are extremely power dense, making them the key-ingredient for the direct drive system. The torque capability of the YASA motors combined with our world-leading engineering expertise has given the* [text removed for publication] *an acceleration capability that is second to none*" **[5.7]**. [text removed for publication], like many other OEMs are now also heavily investing in hybrid and electric vehicles, and have integrated seven P400 motors in their new [text removed for publication] supercar **[5.8]**. YASA electric motors also power [text removed for publication] first hybrid series production sports car, the [text removed for publication]. YASA have been working closely with [text removed for publication], developing a custom version of its electric motor that meets [text removed for publication] demanding performance specifications. The [text removed for publication] was launched by [text removed for publication] on 29 May 2019, in [text removed for publication] **[5.9]**. Such projects are often the proving grounds for the adoption of new technologies into more mainstream vehicles.

As a direct result of the KTP and the strategy to develop high volume production motors, three key international patents were filed by YASA and the Oxford Brookes University KTP research assistant. Patent EP3044854: Stator Plate Over-moulding (2014) involved placing a resin membrane into a mould of an injection-moulding machine and injection moulding a set of reinforcing features onto the membrane using a bondable thermoplastic polymer **[5.10]**. Patent EP3044849: Pole Piece Bonding (2014) uses similar technology for bonding the pole pieces using a flexible resin membrane. The resin membrane, which may contain woven glass fibre reinforcement, may be an engineering polymer material (e.g. PPA, PEEK, PPS, ABS, PA) wherein reinforcement inhibits the stator bars from pushing through the membrane. An additional thermoplastic polymer resin is used for supplementary bonding injection moulded reinforcing features **[5.11]**. Due to the high rotational rotor speeds that generate large centripetal forces on the rotor stages, particularly on surface mounted magnets, any loss of magnet adhesion is a risk for this motor topology. In order to combat this issue a third Patent, EP2773023: Axial Flux Motor (2013), was filed. It introduced a composite rotor for the axial flux motor, wherein the rotor holds permanent magnets circumferentially spaced around the rotor. An over-winding of strands of reinforcement material are toroidally-wound over the rotor and magnets. The strands help strengthen the rotor and provide a lightweight and high performance product **[5.12]**. Together, the technology behind these patents helped deliver the third generation P400 motors.

The technical transition towards the launch of the P400 R from earlier models is consistent with the dramatic increase in demand for low carbon emission technologies, driven by legislation and motivated by climate change. The P400 R Series is now manufactured using advanced materials and proprietary construction techniques that enable high-volume production with significant customer cost benefits. An important innovation of the P400 R Series is the use of an engineering polymer housing for the motor stator, in place of the aluminium housing used in earlier models. The performance of engineered polymer material is strong, highly durable and lightweight, and is already in common use in volume automotive applications (not motors). Importantly, the materials used in the P400 R Series reduce both material cost and assembly time, the direct legacy of the first KTP. The low weight of the new polymer housing also helps to improve the overall motor performance **[5.13]**. Lightweighting also has secondary benefits that include reduced wear on components, reduced maintenance and an extension of service life.

Oxford Brookes University's contribution to the development of these electric motors for mass production puts UK industry at a significant advantage to deliver on Government targets for total electrification of transport by 2050. An example of the broader reach of this technology includes the application of electric motors in the [text removed for publication] hovercraft, as bow thrusters to provide reversible sideways thrust for craft manoeuvring at low speed. With minimal modification, two YASA P400 motors were incorporated into the design of the hovercraft. The principal benefit of using YASA electric motors was that two of the four diesel engines could be eliminated from the design. This reduced the noise levels from the engines significantly, without adversely affecting the reliability of the craft **[5.14]**. Likewise, [text removed for publication] has completed testing of the ground-breaking technology that will power the world's fastest all-electric plane. The plane is part of a [text removed for publication] initiative called ACCEL, short for 'Accelerating the Electrification of Flight'. The ACCEL project team includes YASA as key partners along with the aviation start-up Electroflight **[5.15]**.

The knowledge gained from the underpinning work with OBU to enable lightweight EPMs to be used effectively, has greatly assisted YASA to supply motors to production electric vehicles, owned by mainstream OEMs **[5.16]**. OEMs that have been associated with YASA products include [text removed for publication] **[5.1]**. Without robust assembly technologies and the ability to bond a multitude of different lightweight materials, the YASA motor could not supply a volume production unit of the highest quality demanded by OEMs. Indeed, without high quality bonding methods and procedures, the motor could not deliver on the performance required for today's transport requirements, let alone meet the future global transportation needs.

5. Sources to corroborate the impact

5.1 YASA (2018, February 1). *YASA opens new 100,000 unit Oxford production facility* [Press release]

5.2 Tim Woolmer (CTO YASA) – in conversation [available here, 1:08m to 1:36m]

5.3 Innovate UK TSB, *Best of the Best 2014*, Awards Brochure. YASA and Oxford Brookes University 'Best Partnership Award – Finalists' (page 4) and Engineering Excellence Award Winner (page 10) [available here]

5.4 Craft Financials & Metrics [available here]

5.5 Contact: Tim Woolmer, CTO and Founder, YASA Motors

5.6 SMMT (2013, November 13). *Auto industry gears up for innovation award* [News]

5.7 YASA (2015, March 6). *YASA powers record breaking hypercar* [Press release]

5.8 [text removed for publication]

5.9 [text removed for publication]

5.10 EP3044854: Stator Plate Over-moulding, 2014

5.11 EP3044849: Pole-Piece Bonding, 2014

5.12 EP2773023: Axial Flux Motor, 2013

5.13 YASA (2015, September 15). *YASA P400 Series Launch* [Press release]

5.14 YASA (2016, April 18). *First flight of new hovercraft* [Press release]

5.15 [text removed for publication]

5.16 YASA (2019, February 18). *YASA Signs Innovation Agreement with Global Automotive Manufacturer* [Press release]