Institution: Liverpool John Moores University

Unit of Assessment: Sub-panel 12: Aeronautical, Mechanical, Chemical and Manufacturing Engineering

Title of case study (0065/12/2): Realising innovative and adaptive product design and optimisation through an integrated materials and modelling system

1. Summary of the impact

The investigators of this impact case study have utilised their expertise in materials engineering, theoretical/numerical modelling and product development to achieve significant economic, social and environmental impacts in a range of fields through developing a systematic methodology for innovative product design and optimisation. Through several industrial projects and collaborations, significant impacts have been witnessed including new products creating several million pounds in revenue annually for businesses in different sectors and green manufacturing technologies in repair and reclamation of components. All the described impacts were results of investigation in the Mechanical Engineering and Materials Research Centre (MEMARC) over the assessment period.

2. Underpinning research

The research work in MEMARC has been conducted by effectively integrating materials engineering, theoretical/ numerical modelling and product development through intensive collaboration with industrial partners from different sectors. The main research activities included the development of a novel material characterisation methodology and the modelling of materials at different scales such as atomic level, crystal nucleation and microstructure. Most of the research has been developed with a clear application focus or involvement of industrial partners either in the UK or internationally.

The methods for characterising localised material properties by combining experimental tests and numerical modelling have directly led to applications in characterisation of sports materials [research output 1] and human foot tissues *in vivo*. The research work in materials engineering and numerical modelling has been successfully applied to improve the understanding of biological systems and associated product development, in particular in medical engineering and sports technologies. One joint project with Clatterbridge Centre for Oncology [research project 1 in Section 3] has led to the modelling of the human bladder and the effects of water filling level on the accuracy of radiotherapy treatment of prostate cancer, which has benefited from the research work in materials characterisation and modelling. Another area of application oriented research [research outputs 2 & 3] is the investigation of biomechanics of the human foot under abnormal loading conditions, which is crucial for sports injury prevention. One major research theme at MEMARC has been studies of the effect of landing angle on the deformation and fracture of human metatarsal bones. A new concept arising from the research of partitioning the soles with different materials under the metatarsal bones to balance comfortableness and protection has been adapted by an industrial partner in its product developments.

Another continuing research area [research outputs 4-6] has been on materials design, modelling (thermal dynamics, phase transformation and heterogeneous nucleation with rare-earth oxides), structural integrities (residual stresses) and machining of welded hardfacings, which are essential for promoting the application of welded hardfacing as a green manufacturing technique. One major outcome has been the development of new rare earth enhanced welded hardfacings that could effectively eliminate or reduce the use of preheating workpiece materials of poor weldability (e.g. high carbon/alloy steels). This has made the reclamation and production of duplex components more material and energy effective, delivering significant cost reductions. The work has found applications in a range of industrial sectors, in particular the Far East where new green technologies are urgently needed to be incorporated into the regional fast industrial developments.

All of this research was either conducted at MEMARC and led and principally performed by X. Ren or in collaboration with international researchers. All other authors in the key papers were either PhD students/PDRAs (e.g. Li (2006-2010) and Gu (2007-2011)) or collaborators/joint LJMU PhD supervisors (e.g. Yang from Yanshan University, Jenkinson and Lake (Sport Science)).

3. References to the research

Six key research outputs are given as follows:

1. Li B., Gu Y.D., English R., Rothwell G., Ren X.J. (2009), "Characterisation of nonlinear material parameters of foams based on indentation tests", *Materials & Design*, Vol.30, No.7, 2708–2714 (doi: 10.1016/j.matdes.2008.09.040).
2. Gu Y.D., Li J.S., Ren X.J., Lake M.J., Zeng Y.J. (2010), "Heel skin stiffness effect on the hind foot biomechanics during heel strike", *Skin Research and Technology*, Vol.16, No.3, 291-296 (doi: 10.1111/j.1600-0846.2010.00425).
3. **Gu Y.D., Ren X.J., Li J.S., Lake M.J., Zhang Q.Y., Zeng Y.J. (2010), "Computer simulation of stress distribution in the metatarsals at different inversion angles using the finite element method",** ***International Orthopaedic*****, Vol.34, No.5, 669-676 (doi: 10.1007/s00264-009-0856-4).**
4. **Yang Q.X., Ren X.J., Liao B., Yao M., Wan X. (1998), "Effect of RE oxide on cracking resistance of hardfacing metal",** ***Journal of Rare Earths*****, Vol.16, No.4, 295-299. (Can be supplied by the HEI on request)**
5. Ren X.J., Yang Q.X., James R.D., Wang L. (2004), "Cutting temperatures in hard turning chromium hardfacings with PCBN tooling", *Journal of Materials Processing Technologies*, Vol.147, No.1, 38-44 (doi: 10.1016/j/jmatprotec.2003.10.013).
6. **Li D., Liao B., Liu L.G., Zhao C.M., Zhao X.Q., Ren X.J., Yang Q.X. (2008), "Process stress simulation of medium-high carbon steel after hard-face-welding during martensite transformation",** ***Computational Materials Science*****, Vol.44, No.2, 280–285 (doi: 10.1016/j.commatsci.2008.03.034).**

Evidence of the quality of selected research outputs (3, 4 and 6 as highlighted in bold):

Research outputs 3 is a key representative outcome of biomechanics related research. The work combines *in vivo /in situ* material testing of biological tissues and inverse modelling to provide important data for new biomechanics led footwear designs. The investigation of stresses within the human metatarsals under landing at an inversion angle is the first of this nature and provides a new methodology capable of integrating biomechanics, materials modelling and FE modelling to improve the protection function of sports shoes in competitive games (e.g. basketball, tennis and football). The findings in research outputs 3 have contributed to a major product development project with a leading sports footwear company, ANTA (China) [research project 6].

Research outputs 4 and 6 are key outcomes of continuous joint research on the development of new welded hardfacing materials and their applications with the Chinese Key National Laboratory of Metastable Materials Science and Technology, Yanshan University, China. Research output 4 presents original findings produced with the financial support from the Excellent Talents Foundation of the Ministry of Machinery Industries [research project 7]. This is a key original paper leading to the use of rare earth oxides in welded hardfacing materials. Research output 6 was sponsored by the Science and Technology Program of Hebei Province, China [research project 8]. The work provides a practical method for characterising and modelling stresses in the welded hardfacings incorporating key structure and phase transformation. This research work and other collaborative works have directly contributed to the award of a China National Natural Science grant (Yang at Yanshan University, China, £60K, 2012-2016). X. Ren has been directly involved in the original pioneering research on welded hardfacings and has jointly led the project with Yang. The original research on the use of rare earth oxides in crack resistant hardfacings, machining of welded hardfacings, and structural integrities of hardfaced components has produced a critical breakthrough in broadening industrial applications of the products over the assessment period.

Research projects/grants highly relevant to this case study:

1. Ren X.J., “Image registration and FE modelling for cancer treatment planning”, *EPSRC/ Clatterbridge Centre for Oncology*, £80k, 2006-2010.
2. Ren X.J., “Process simulation of the micro discharge welding process and development of novel micro mineral insulated thermocouples”, *EPSRC CASE*, £60k, 2010-2013.
3. Darlington R., Jenkinson I.D., Ren X.J., “Development of water resistance access chambers”, Northstone/Cubis Industries, *KTP Programme*, No. 8079, £70k, 2010-2013.
4. Ren X.J., Gu Y.D, “Development of a novel feature based materials selection system”, *Xia Men Tong An Jie Qiang Municipal Engineering Ltd (China)*, Industrial Research Project, £60k, 2009-2014.
5. Ren X.J., “Development of gasket plate heat exchangers and design optimisation”, *Bei Fang She Bei Gong Chen Ltd (China)*, Industrial funding, £38k, 2012-2015.
6. Ren X.J., Gu Y.D., “Development of natural structure basketball/tennis shoes”, Industrial Enterprise Project, *ANTA International Ltd (Hong Kong)*, £41k, 2008-2010.
7. Yang Q.X, “The hot cracking mechanism of hardfacing on high carbon steels and new materials design”, *Excellent Talents Foundation of the Ministry of Machinery Industries, China*, PN95250505, £5k, 1995-1998.
8. Yang Q. X. “Experimental and Numerical investigation on the residual stresses of welded hardfacing for medium/high carbon steels”, *Science and Technology Program of Hebei Province, China*, PN04212201D, £30k, 2005-2007.

4. Details of the impact

The research work has made direct significant economic impact/benefits in several key technical areas, in particular in combined uses of inverse Finite Element (FE) modelling and Computer Aided Engineering (CAE), biomechanics led sports footwear design and development, and application of hardfacing materials for green manufacturing over the assessment period.

1. The inverse FE modelling programs with research output 1 and other developments have been successfully used to test the constitutive parameters of different materials groups/systems where standard samples are not readily available. The framework has made it possible to integrate material testing with CAE in situations where rapid and realistic material property identification is crucial. Through several major enterprise projects [research projects 1-5], the developed inverse FE framework has been applied in different application environments over the assessment period. Typical cases include: continuous indentation tests of sports materials (foams and layered structures) for sports shoe design; *in situ* study of welded structures for car bodies and micro spot-welded joints of micro thermocouples; and indentation bending studies of latex rubbers/nano-composites for curing control and biological tissues (bladder tissues) for simulating human prostate movement and bladder filling. These applications have spread across several industrial sectors including sports engineering (basketball shoes), medical engineering (prostate cancer treatment) and energy sectors (heat exchanger gaskets). For example, the research has led to the evaluation of the feasibility of using indentation tests on extruded packaging materials (plastic properties of extruded cans and plastic bottles) for the Unilever (Port Sunlight Site) CAE team [source 5.1]. The efficiency of the top load simulation of three new packaging designs has been significantly improved; the estimated reduction of simulation time through confined property domain of Design of Experiment is over 20% [source 5.1]. The testing of biological tissues (e.g. human heel pad and human skin) using the research in inverse FE modelling has directly led to the development work of sports footwear, which is detailed in the next section.

2. Research outputs 2 & 3 have been used to establish a framework of combining materials, biomechanics and FE modelling for biomechanics led product development, enabling the industry to develop products through targeting key functional areas (e.g. protection of the 5th metatarsal bone). Over the assessment period, these two outputs and other associated publications have directly led to the development of sports footwear based on different functional regions of the foot with specific soft tissue properties and bone structures. As a result, an industrial patent has been granted to the industrial user (ANTA, CN102488352A,

27/12/2011-26/12/2031) to protect the intellectual property of their new products. The research has produced a new natural feature-based basketball shoe design. The market value for the products, directly benefitting from the research work, was over £2m worldwide in 2012 [source 5.2]. The research work in biomechanics has also generated significant social impact in raising the public awareness of science and technology. The work has been selected as a major news release by Inderscience Publisher [source 5.3] during the BBC's 2010 "Strictly Come Dancing", which has been widely reported by global science and technology media [source 5.3].

3. Research outputs 4-6 have advanced the development and application of crack resistant hardfacing materials. Welded hardfacing is a cost effective and environmentally friendly method in the repair/reclamation of key engineering components/tools (such as forging dies and hot work rollers) and production of duplex components. The main original research development on the use of rare earth oxides [research output 4] has extended welded hardfacing techniques to high value components made of steels with poor weldability (e.g. high alloys steels and tool steels) without an expensive full scale preheating process. With increasing public concern on green manufacturing and environmental issues, such technologies have been increasingly adapted by industries such as mining, iron and steels production and general machineries. The research work on the machining of hardfacings, cutting tool selection [research output 5] and structural integrity of the welded structure [research output 6] have further advanced the technologies, which is essential for the application of weld hardfacing technologies. Research outputs 4-6 have directly led to the production of a series of new hardfacing materials for different application conditions with two new application patents granted since 2008 (ZL 2008-1-007-9643.4, Yang *et al.*, 22/10/2008-21/10/2028; ZL 2010-1-0236826, Yang *et al.*, 23/07/2010-22/07/2030). A company implementing the findings from these research outputs has been set up in 2009, producing rare earth-based welding materials. The new products and hardfacing services directly benefiting from research outputs 4-6 have had an annual market worth over £5m in 2011 and 2012 [source 5.4].

5. Sources to corroborate the impact

Source 5.1: CAE Team leader, Unilever R & D (UK).

Source 5.2: Director (Human Movement and Product Development), ANTA.

Source 5.3: Press Officer, Inderscience Publishers (http://www.inderscience.com/).

Source 5.4: Managing Director, Qinhuangdao Weidi Special Welding Industry Ltd.