Institution: Newcastle University

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

Title of case study: Development of National and International Gear Standards

1. Summary of the impact

Reliable engineering standards for the manufacture of gears are critical to industry as they ensure the development of products that will operate safely and reliably and are often mandatory within supply contracts. It is essential that standards evolve with time in order to provide continual improvement of performance and to take advantage of technological developments. Newcastle University gear research in the fields of geometry measurement and calibration, non-destructive testing and gear fatigue mechanisms has directly contributed to the development and revision of BS (British Standards), ISO (International Standard Organisation) and Def Stan (Defence Standards) publications. These affect nearly every mechanical power transmission application worldwide in an industry where the gear supply component market is estimated to be worth in excess of £200M annually to the UK economy and over $5B globally.

2. Underpinning research

Through the Design Unit - Gear Technology Centre (commonly known as "Design Unit"), Newcastle University has played a leading role in gearing and power transmission research since its formation in 1970. Two specific areas of research which have been actively pursued since 1987 are gear geometry measurement and calibration, and gear performance testing for improved understanding of micro-pitting and gear surface engineering.

2.1 Gear Geometry Measurement and Calibration

The Design Unit operates the UK National Gear Metrology Laboratory (NGML) which, since 1987, has been part of the UK National Measurement System (NMS) and is a Designated Institute (DI) for gear measurement. The NGML is part funded by the NMS to support and maintain the UKs national gear standards.

In 1993 Frazer surveyed UK industrial measurement capability and found that poor measurement practice caused significant errors in many organisations. The lack of reliable reference calibration data for this survey prompted the NGML to extend the survey to include other national laboratories (funded by G1 as listed in section 3). The results from this suggested that there were also significant differences between National Laboratories. The first international comparison of gear measurement capability was organised by Frazer at the NGML in 1998-1999 (G2) with the results published in 2004 (publication P1 as listed in section 3). The work evaluated profile, helix and pitch errors and showed that excessive differences with gear profile measurement were linked to different data sampling strategies. When these issues were corrected, the differences in measurements became acceptable.

2.2 Micro-pitting and Gear Surface Engineering

The extensive gear performance and characterisation test facilities at Design Unit are used to define reliable permissible stresses and to understand gear failure modes. Physical testing of gears allows the effects of material, processing, heat treatment, design, lubrication and running conditions on gear performance to be understood. Research in this area has been led by Shaw, and has specifically addressed:

- The development of residual stresses through shot peening and the associated benefits to fatigue strength (G3 and G4), which included developing a model of the shot peening process which was the first to realistically model the particle dynamics of shot peening, including particle generation in the nozzle and the interaction between incoming and rebound shot (P2).
- The use of magnetic Barkhausen noise to evaluate the quality of ground gears (G3 and G5),

including the first detailed studies to demonstrate that the magnetic Barkhausen emission technique could be used to non-destructively estimate the average residual stress in the near-surface and subsurface regions of hardened steel components (P3 and P4).

- Understanding gear fatigue strength and failure modes related to micro-pitting (fatigue failure of the surface of a material; G3, G6 and G7), and in particular the first study to show that the initiation and propagation of cracks leading to the formation of micro-pits are related to a material phase transformation known as martensitic decay (P5).

The key researchers across this research have been:

- Frazer: Research Associate, 1988 – 2001; Senior Research Associate, 2001 to date.
- Shaw: Senior Research Associate, 1993 – 2006; Director Design Unit, 2006 to date.

3. References to the research

Outputs:

P1. RC Frazer, R Bicker, B Cox, H Harary and F Haertig. An international comparison of involute gear profile and helix measurement, Metrologia, 2004, **41**, 12-16.
Key output: *Highlighted errors associated with gear measurement practice and the importance of data sampling strategies.*

P2. Hong T, Ooi J Y, Shaw BA. Numerical simulation to relate the shot peening parameters to the induced residual stresses. *Engineering Failure Analysis,* 2008, **15**(8), 1097-1110.

P3. Moorthy V, Shaw BA, Day S. Evaluation of applied and residual stresses in case-carburised En36 steel subjected to bending using the magnetic Barkhausen emission technique, *Acta Materialia,* 2004, **52**(7), 1927-1936.
Key output: *The first detailed study showing how Barkhausen emission can be used to non-destructively characterise stresses in carburised gear steels.*

P4. Blaow M, Evans JT, Shaw BA. The effect of microstructure and applied stress on magnetic Barkhausen emission in induction hardened steel. *Journal of Materials Science*, 2007, **42**(12), 4364-4371.

P5. Oila A, Shaw BA, Aylott CJ, Bull SJ. Martensite decay in micropitted gears, *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology,* 2005, **219**(2), 77-83.
Key output: *Presented new information on an observed martensitic decay mechanism in gear steels that was linked with the development of micropitting damage.*

Key Research Grants:

G1. Hofmann and Frazer, DTI Programme for Length, 'Research into Gear Metrology', Contract Ref: MPU 8/29.3, April 1993 - March 1996, £155k.

G2. Hofmann and Frazer, DTI Programme for Length, 'Research into Gear Metrology', Contract Ref: MPU 8/44.5, April 1996 – March 1999, £231k.

G3. Evans and Hofmann, EPSRC, 'Microstructural and Metallurgical Aspects of the Fatigue Strength of Gear Materials', GR/J08324/01, July 1993 - October 1996, £219861.

G4. Shaw and Evans, EPSRC, 'Improving shot peening for greater structural integrity of metallic components', GR/R28188/01, September 2001 - March 2005, £369605.

G5. Shaw, MoD, 'Barkhausen Emission Research', contract MPS CBc/64697, March 2002 - March 2006, £194116.

G6. Shaw, EU FP6, 'X-GEAR - Development of Gear Drive Trains Based on New Materials and Novel Gear Systems', Proj Ref: 30433, September 2006 - August 2009, Euro 417416

G7. Shaw, British Gear Association, 'Understanding Micropitting', Proj Ref: P6 I&II, Sept 1998 - Sept 2007, £148004.

4. Details of the impact

Design Unit works closely with the British Gear Association (BGA), which provides expertise and support for maintaining and developing BS and ISO gear standards in the UK. The BSI committee *MCE/5 Gears* is the UK technical committee responsible for providing the UK input to *ISO/TC60 Gears,* which is the ISO technical committee concerned with the maintenance and development of gear related standards and between these, over 100 gear related standards are currently being maintained, reviewed and developed. Frazer is the current chair of MCE/5 Gears, and of MCE/5/-/2, the sub-committee concerned with gear accuracy. Shaw Chairs MCE/5/-/14, the gear materials sub-committee and is a member of MCE/5/-/15, the micropitting sub-committee. BGA Technical Executive (also Honorary Secretary to MCE/5) comments that (S1):

"Without the research contributions from the Design Unit, the UK would be unable to validate and contribute so effectively to the preparation of ISO/BS standards and supporting technical reports."

The research activities undertaken at Newcastle University has enabled staff to make significant contributions in gear geometry measurement and calibration, and micro-pitting and gear surface engineering. These contributions have underpinned the development of a range of standards for mechanical power transmissions which have either been in industrial use over the entire REF period, or have been established within the REF period.

4.1 Gear Geometry Measurement and Calibration

The research undertaken by Frazer to establish robust and consistent data sampling strategies for gear profile measurement have fed directly into:

- *ISO 18653: 2003 and 2009 Gears - evaluation of instruments for measuring individual gears* (contribution: methods for gear machine calibration).
- *ISO TR 10064-3: 1996/2006 Code of inspection practice - Part 3: Recommendations relative to gear blanks, shaft centre distance and parallelism of axes* (contribution: methods for measuring gear blanks and determining alignment tolerances).
- *ISO/TR 10064-5:2005/Cor 1:2006 Code of inspection practice - Part 5: Recommendations relative to evaluation of gear measuring instruments* (contribution: gear machine calibration methods and examples).
- *ISO/TR 10064-6:2009 Code of inspection practice - Part 6: Bevel gear measurement methods* (contribution: gear measurement method and examples).
- *ISO 21771:2007 Gears - Cylindrical involute gears and gear pairs -- Concepts and geometry* (contribution: geometry calculation procedure and logic for specifying gear geometry).
- *ISO 17485: 2003 Bevel gear accuracy* (contribution: gear measurement methods).

The key contributions of Frazer to these standards have been confirmed by the Honorary Secretary to MCE/5 (source S1 as listed in section 5), and the Chairman of ISO/TC 60 (S2). All of these standards have been active over the entire REF period, with the exception of ISO/TR 10064-6 which has been active since 2009.

4.2 Micro-pitting and Gear Surface Engineering

Research undertaken by Shaw on micro-pitting has directly informed *ISO TR 15144-1:2010 Calculation of micro-pitting load capacity of cylindrical spur and helical gears*. The Technical

Director of Allen Gears, also the Chairperson of ISO/TC60 SC1 sub-committee notes that (S3):

"It was only the physical testing and research conducted at Newcastle University that allowed certain elements of the standard to be developed. In particular, elements relating to key influencing features and testing techniques were developed resulting from specific Design Unit contributions. The BGA-DU micropitting test procedure developed by Newcastle University is now directly referenced in ISO TR 15144."

Design Unit also work closely with the MoD, and have supported the development of a key defence standard for ship gear systems: *MOD UK DEF STAN 02-381: Requirements for the Forging and Heat Treatment of Main Propulsion Gears, 2009*.

The Head of Gearing at Defence Equipment and Support, MoD (S4), notes that Design Unit were fully involved in the process of developing this standard and were able to include newly developed procedures within the standard, and specifically that this included *"grinding burn detection using Barkhausen noise when inspecting gears, and improvements to fatigue life of gears following shot peening of tooth roots"* and further notes that *"both of these procedures, although novel at the time are now standard practices"*.

4.3 Industrial Significance

These standards are clearly policy impacts which underpin an industry which within the UK has a value in excess of £200M annually to the UK economy (S1), with the annual worldwide market value estimated at over $5B (S6). The standards are widely used and are often mandatory within supply contracts. The Chief of Commodity Engineering, Drive Systems Structures and Transmissions Engineering at Rolls Royce (S5) notes that when designing new gearing systems for aerospace applications:

"the basis of our designs will still start with the fundamentals of gear standardisation, an area where Newcastle University, Design Unit research has been of critical importance in the development of the current range of gearing standards we utilise."

BGA Technical Executive, also Honorary Secretary to MCE/5 (S1), notes that:

"the research output from Design Unit has supported, and continues to support the development of a wide range of gear standards that are used in nearly every mechanical power transmission application worldwide."

5. Sources to corroborate the impact

S1. BSI Hon Sec to MCE-5 Committee, and British Gear Association Technical Executive.
S2. Chair of ISO TC60.
S3. Technical Director, Allen Gears and Chair of ISO TC60 SC1.
S4. Head of Gearing, Defence Equipment and Support, MoD.
S5. Chief of Commodity Engineering, Drive Systems Structures and Transmissions Engineering, Rolls Royce plc.
S6. British Gear Association Member Report, The World Market for Mechanical Power Transmission Products, BGA, Burton on Trent, UK.