Institution:	**The University of Manchester**
Unit of Assessment:	**UoA 12b Mechanical, Aerospace and Manufacturing Engineering**
Title of case study:	**Reverse Tapered Hole Drilling for Automotive Fuel Injection Nozzle Manufacture**

1. Summary of the impact

The University of Manchester and Delphi Diesel Systems jointly developed a reverse tapered micro-hole drilling technique, which has resulted in wide commercial applications for the manufacture of fuel injection nozzles in diesel engines and is used by Volkswagen, Ford and Renault in passenger cars and trucks. The technique has resulted in 1.5% fuel saving, 35-40% reduction in particulate matter emission, 20% reduction in NOx emission, 3% reduction in CO_2 emission, and allows diesel engines to satisfy the new EU emission legislation Euro 5 in 2008/2009. Delphi's diesel engine component business increased by €0.8 billion/year as a result of the new fuel injection technology.

2. Underpinning research

The impact is based on research that took place at The University of Manchester from 2000-2004 with the first major publication in 2004."The key researchers were:

Professor Lin Li (2000-date), PI, academic principal supervisor.

Dr. John Atkinson (2000–date), Senior Lecturer.

Dr. Carl Diver (2000-2004), PhD student.

The aim of the research was to develop micro-drilling techniques for the next generation of fuel injection nozzle manufacture to meet the new EU emission legislations. We introduced the idea and pioneered the technology for drilling reverse tapered holes by a specific configuration of electro-discharge machining (EDM). The key findings from the research were:

1. We showed that by incorporating the electro-discharge machining (EDM) fuel injection drilling system with a specific rotational motion control, reverse tapered holes could be produced (with exit hole diameter greater than the entrance hole diameter where the tool enters) [1].

2. We showed that this new hole shape improved fuel efficiency and reduced environmental impacts and associated NOx production with an optimized degree of taper [1].

3. We showed that this new drilling technique met the productivity and repeatability requirements for diesel fuel injection nozzle production [1].

4. This research demonstrated a new drilling method, combining laser pilot hole drilling followed by electro-discharge machining (EDM), which has resulted in a 70% reduction in drilling time compared with standard EDM drilling, 42% reduction in cost, and 90% increase in capacity of existing fuel injection nozzle manufacturing equipment with similar hole quality [2].

5. In diesel fuel injection nozzle manufacture, EDM drilled holes typically have an undesirable keyhole that affects the fuel flow. This research identified the problem and provided a solution by hydro-erosive grinding (using a particle-embedded low-viscosity fluid) that has provided improved hole geometry and surface finish, resulting in better fluid flow. The two-phase fluid flow characteristics have been analysed [3].

3. References to the research

The outcomes of this research have been published in leading academic journals and international conferences.

Key Publications

[1] C.Diver, J.Atkinson, H.J.Helml and L.Li, "Micro-EDM drilling of tapered holes for industrial applications" Journal of Materials Processing Technology, Vol. 149, Issue 1-3, 10 June 2004, pp.296-343. DOI: 10.1016/j.jmatprotec.2003.10.064. (Citation: 22 times, Web of Science).

Other relevant publications

[2] L.Li, C.Diver, J.Atkinson, R. Giedl-Wagner and H.J.Helml, "Sequential laser and EDM micro-drilling for next generation fuel injection nozzle manufacture" *CIRP Annals – Manufacturing Technology*, Vol.55, Issue 1, 2006, pp. 179-182. DoI 10.1016/S0007-8506(07)60393-X (citation: 16 times, Web of Science).

[3] C.Diver, J.Atkinson, B. Befrui, H.J.Helml and L.Li, "Improving the geometry and quality of a micro-hole fuel injection nozzle by means of hydroerosive grinding" *Proceedings of Institution of Mechanical Engineers, Part B – Journal of Engineering Manufacture*, Vol.221, Issue 1, 2007, pp1-9. DOI: 10.1243/09544054JEM395 .

4. Details of the impact

Context

Micro-EDM is the main process applied to producing micro-holes in diesel fuel injection nozzles in the automotive industry. In diesel fuel injection components, hole diameters can be less than 150 μm in diameter. Previous fuel injection nozzles had straight or parallel walled holes that generally had a neck at the end of the hole where the final drilling took place. This affected fuel flow and the fuel did not spread well for effective combustion. It is desirable to have reverse tapered hopes (i.e. fuel entrance hole is larger than the fuel exit) so that the fuel can spread out into a fan-shaped spray. However, there had been no practical solution for the manufacture of reverse tapered holes as drilling takes place from the outside of the nozzle. The hole size at the tool entry needs to be smaller than the hole size at the tool exit. The University of Manchester in collaboration with Delphi Diesel Systems (Germany) and GFH GmbH, pioneered the reverse tapered hole drilling technique which resulted in worldwide application of the technology in the automobile industry satisfying the new EU emission Euro 5, introduced in 2008-2009 [A-D].

Pathways to Impact

The work was done in collaboration with Delphi and GFH GmbH who provided PhD CASE funding and access to experimental facilities (e.g. EDM), fuel injection nozzle testing facilities, and materials. The research findings from the project were then commercialised as diesel fuel injection nozzle production systems [A-C].

Reach and Significance of the Impact

Automobile component manufacturers. The reverse tapered hole production technology was first introduced into diesel engineer fuel injection nozzle manufacture at full scale by Delphi, one of

the major car component manufacturers. The technology was patented by Delphi [D] and then certified by them to meet the new EU emission legislation Euro 5, in 2008-2009 [A-E]. The major differences between Euro 4 (introduced in 2005) and Euro 5 legislation (introduced in 2008/2009) are that for diesel engines, the NOx emission limit was reduced from 0.25 g/km (Euro 4) to 0.18 g/km (Euro 5), and particulate matter emission from 0.025 g/km (Euro 4) to 0.005 g/km (Euro 5) [E]. The key benefits of the new fuel injection nozzle manufacturing technology include improved fuel efficiency and reduced environmental impacts (1.5% fuel saving per nozzle, 35-40% reduction in particulate matter emission, 20% reduction in NOx emission, 3% reduction in CO_2 emission, and a reduction of 10°C in exhaust temperature) [F]. Delphi's diesel engine component business was €1.6bn in 2008. Because of satisfying Euro 5 conditions in 2008/9 due to the introduction of reverse tapered fuel injection nozzle holes [A,B], their business had grown to €2.4bn per year in the following years [G].

Passenger car and truck manufacturers. Reserve tapered hole diesel fuel injection nozzles are currently used by major passenger car and truck manufacturers such as Volkswagen, Ford, Isuzu, Volvo and Renault [A-C]. In Europe, around 50% of cars are diesel based. Worldwide vehicle sales are around 82 million per year [H], 20-30% of which are diesel based. Almost all the major diesel car manufacturers now use reverse tapered holes in fuel injection nozzles.

Benefits to consumers in fuel savings: Around 1.5% fuel saving per car due to the introduction of the reverse tapered hole technology for diesel cars [F].

Public Health: The world health organisation (WHO) survey shows at least 1 million people die each year due to urban outdoor air pollution [I]. The introduction of the reverse tapered hole fuel injection nozzles has resulted in a 35-40% reduction in particulate matter emissions and a 20% reduction in NOx, thus contributing to a cleaner environment as demonstrated by the compliance with Euro 5.[E].

5. Sources to corroborate the impact

[A] Letter received from Chief Engineer, Delphi Diesel Systems, confirming the use of the reverse tapered hole drilling technology in Delphi fuel injection nozzle manufacture, the production volume and major automobile costumers using the nozzles.

[B] Letter received from Managing Partner, GFH GmbH, confirming the reverse tapered hole drilling development background and its current use by the automobile industries.

[C] Letter received from Managing Director, CDAMC Ltd, confirming the research and impacts of the reverse tapered micro-hole drilling technology development and its applications.

[D] Apparatus for producing reverse tapered holes in EDM, patent number: DE10318403, 11th November 2004, by Delphi Technologies.

[E] http://europa.eu/legislation_summaries/environment/air_pollution/l28186_en.htm Confirming the higher standards imposed by the introduction of EURO 5.

[F] "Injection Nozzle" US patent: US2011/0215177 A1, 8 Sept 2011 by Delphi Technologies. Confirming the novelty and commercial importance of the technique developed.

[G] http://wardsauto.com/news-amp-analysis/euro5-accelerates-delphi-diesel-injector-business news article confirming the doubling of Delphi's business based on the new injector type.

[H] http://www.oica.net/category/sales-statistics/ demonstrating the size of the worldwide automotive vehicle market.

[I] http://www.who.int/mediacentre/factsheets/fs313/en/ WHO document confirming the impact of particulate matter and NOx emissions on public health.