Institution: Liverpool John Moores University

Unit of Assessment: 15

Title of case study: Improving Fluid Delivery in Abrasive Machining

1. Summary of the impact

Work and tool temperature are major issues in abrasive machining. Cooling fluids, usually oil based, are used to control these temperatures. This research aimed to achieve much more effective use of coolant. The established industrial practice was to use very high volumes of oil, under very high pressures. This is an expensive and environmentally unfriendly approach. This research improved coolant flow quality by improving nozzle design and established the underlying physics to improve penetration of coolant into the cutting zone. It then went on to show that it was not only possible, but sometimes it may actually be beneficial, to dramatically reduce coolant flow volume by a factor of up to 20,000. Before industry would adopt these ideas it was necessary to have firm scientific evidence of their validity. This research by the General Engineering Research Institute (GERI) provided that foundation and has led to successful adoption by industry, which has in turn led to both economic and environmental impact. This case study will evidence industrial take-up via specific examples and shows that GERI's research in this area has had a global impact on the training of industrial engineers employing the grinding process.

2. Underpinning research

The work is originally founded on an understanding of the mechanisms of heat generation within abrasive machining [1]; only by understanding these mechanisms can we determine the true role required of the coolant. Knowing the location, strength and dynamic behaviour of thermal sources means that we can better assess exactly where the coolant needs to penetrate and how much of it needs to be there at any given time. By developing new thermal models for grinding we were able to effectively study the mechanisms of heat transfer that are present; not just simple heat transfer to the fluid, but convective transfer to the air boundary layer and conductive/convective transfer into the wheel itself via the fluid [2]. This in turn led to the ability to predict workpiece and tool temperatures. All of this modelling was validated with extensive experimentation on industrial scale machine tools running at speeds typically encountered in manufacturing and even beyond those machining rates in the case of High Efficiency Deep Grinding (HEDG).

Once the generation and transfer of heat is better understood it is possible to begin to define the parameter space within which efficient and effective grinding can take place [3]. More pro-actively it is also then possible to investigate bringing about cooling fluid conditions in the cutting zone that can better control temperatures. To do this it was necessary to explore the underlying physics involved in the process of getting cooling fluid into the critical areas which had been identified. These considerations had to include the efficient and effective delivery of fluid via the nozzle, as well as the role the fluid undertakes in cooling, lubricating and cleaning the cutting interface.

An important step forward in helping industry to achieve this aim was secured within the EPSRC-Industry project: Grant GR/S82350/01. This work delivered the new knowledge and understanding required to determine the conditions which would achieve maximum fluid efficacy and just as importantly, it provided the necessary evidence base for authoritative guidance on methods by which fluid delivery systems used in grinding could be optimised [4].

Using sophisticated flow measurement techniques and boundary layer profiling methods, such as Laser Doppler Anemometry, we have been able to probe the flow very close to the cutting interface and so determine the cooling fluid delivery conditions required to overcome the periphery boundary layer flows that inhibit coolant penetration into the cutting zone.

From this it was clear that one factor that is influential in getting the cooling fluid to precisely where it was needed was the coherence of the fluid jet from the nozzle. This is largely determined by the flow parameters and the detailed design of the nozzle geometry. This aspect was investigated via FE simulations of nozzle interior flows and a new solution was devised for jet coherence. These simulations enable a ready and accurate visualisation and assessment of nozzle efficiency and performance without the need for extensive experimental testing.

Related research we were undertaking in the emerging process of High Efficiency Deep Grinding (HEDG) identified that the cooling effect following the transition to HEDG is not as important as in other grinding processes [1]. This understanding led to a further innovative programme of research exploring the possibilities of **dramatically** reducing coolant flow rate. This regime is known as "Minimum Quantity Lubrication" (MQL). Our work in MQL was the first to demonstrate conclusively that a regime exists in shallow cut grinding where MQL (MQL ~50ml/hr, i.e. a spoonful per minute) offers cost and performance advantages compared with conventional fluid delivery methods (~20 l/min, i.e. bucketsful per minute) and our research here has provided the strong scientific evidence needed to promote industrial acceptance [5]. These findings obviously have enormous implications both economically and environmentally. Cooling fluid purchase costs are high; delivering it at large flow-rates and pressures requires capital equipment and environmentally acceptable disposal is expensive. MQL radically reduces the volumes of such coolant required.

Recordable outputs have included 5 PhD completions, over 20 journal papers, more than 20 conference papers and the findings are extensively described in three recent text books on the subject.

GERI research staff contributing to these outputs include: Dr Michael Morgan, who led this work from 2002 and is submitted in this UoA, Prof W Brian Rowe, a founder of GERI and retired in 2001, Dr Andre Batako originally a researcher on the EPSRC HEDG project, now a member of staff and submitted here, Dr Vadim Baines-Jones a PhD student supervised by Dr Morgan, now Research and Development Manager with Cinetic-Landis Ltd.

3. References to the research

1. W Brian Rowe, Tan Jin, "Temperatures in High Efficiency Deep Grinding (HEDG)", 2001, Annals of CIRP, 50 , 1, 205-208. ISBN 3-905 277-35-2. http://dx.doi.org/10.1016/S0007-8506(07)62105-2 [Cited 66 times]
2. Rowe, W.B., Black, S.E., Mills, B., Qi, H.S., Morgan, M.N., 'Grinding Temperatures and Energy Partitioning', 1996, Proceedings Royal Society, London, A 453, pp1083-1104, DOI:10.1098/rspa.1997.0061 [Cited 36 times]*
3. W B Rowe, M N Morgan, S Ebbrell, 'Process Requirements for Cost-Effective Precision Grinding', 2004, Annals of the CIRP, v 53/1, pp 255-258 Online ISSN 1726-0604, http://dx.doi.org/10.1016/S0007-8506(07)60692-1 [Cited 11 times]
4. Morgan, M N., Jackson, A R., Baines-Jones, V., Batako, A., Wu, H., Rowe, W.B., 2008, 'Fluid Delivery In Grinding', Annals of the CIRP, Vol 57/1 pp 363-366, DOI: 10.1016/j.cirp.2008.03.090 [Cited 37 times]*
5. Barczak, L.M., Batako, A.D.L. and Morgan, M.N., 'A Study of Plane Surface Grinding under Minimum Quantity Lubrication (MQL) Conditions', 2010, Int. Journal of Machine Tools and Manufacture, v50, pp 977-985, DOI: 10.1016/j.ijmachtools.2010.07.005 [Cited 18 times]*

* - indicates main publications.

4. Details of the impact

It is estimated that grinding makes up 25% of all machining processes used in manufacturing world-wide [E1]. During these grinding operations cooling fluid is required, but the provision of this involves major costs including: purchase, filtration, refrigeration, storage and environmental disposal. In many cases, machining fluid may consume up to 20% of the total production cost of a component. There is therefore a strong motivation on industry to reduce the quantity of fluid used, whilst retaining performance, reliability and quality. But it is potentially a high-risk strategy to reduce coolant, as the added value of a part is typically already considerable when it reaches a grinding station and component scrappage at this point would be expensive. To be industrially adopted any reduction in coolant volumes, no matter how potentially economically or environmentally attractive, must be firmly underwritten with clear scientific evidence.

We will now itemise some examples of the way our research into the delivery of fluids has been taken up by industry and how it is influential in shaping modern grinding practice.

Cinetic-Landis Ltd. is a subsidiary of Fives, who have their corporate headquarters in Paris. Fives are an industrial engineering group of international scope with total revenues approaching €1.5 Billion [E2]. The company designs and manufacturers capital equipment, such as machining lines, mainly for the automotive, aluminium, steel and cement industries. Cinetic recruited a GERI PhD graduate to a lead position in Research and Development. This has enabled a rapid transfer of knowledge and experience to the company and has also resulted in the implementation of our nozzle positioning systems and fluid optimisation methodologies within the company's products. The Engineering Director of Cinetic-Landis UK Ltd states:

> *"The work completed at LJMU has been invaluable for the improved control and management of our machining coolant. In particular, the nozzle studies and delivery guidance work has helped us extract enhanced and more reliable cooling and lubrication from our coolant systems. Our implementation of GERI's work in the area of cooling fluid delivery leads to significant recurrent annual savings for our customers; for our larger customers we estimate that such cost savings are easily in the region of £100k/annum. But these direct cash savings mask a possibly even greater benefit; for example by being able to reduce fluid use by the employment of these methods one automotive customer avoided having to significantly expand his crankshaft grinding line which represents a very substantial one-off capital cost saving".* [Corroborative witness ID=1]

PTG-Holroyd manufactures machine tools and equipment for a wide range of industrial sectors [E3]. The company have introduced a novel laser-based nozzle positioning technique on their products, based on a design by GERI, to improve process performance and reliability. They have also implemented the formal guidance on fluid management and optimisation which stemmed from our research. The General Manager of PTG-Holroyd states:

> *"The work carried out at GERI was significant in that it established the rules for coolant application which have been relied on by all our machine designers since then. Specifically, the guidelines on fluid velocity had big implications for pump capacity specified. Secondly, the effect of jet coherence on grinding behaviour was quantified, and the degree of jet divergence which can be tolerated is clear from the results. Both these studies have improved the performance of our machines by extending wheel life, reducing heat generation, and keeping grinding power and normal forces low. This confirms my view that UK machine tool research, although not concentrated in large organisations as in Germany, can be of both very high quality and impact, as was certainly the case here."* [Corroborative witness ID=2]

As a third example, to illustrate the breadth of our engagements and to show that our impact is on-going and at multiple levels of maturity, we cite Vibraglaz UK Ltd, a relatively new SME. Vibraglaz are innovators of a potentially disruptive technology, which is based entirely on thermally treated recycled glass. The global mass finishing abrasive market for this technology has an estimated value of £800m per annum [E4]. This process requires the controlled delivery of precise volumes of fluid to retain performance criteria. Our research provided the scientific underpinning needed by the company to design systems for optimal delivery of new fluid compositions. The company, at varying levels of maturity with its technology, has relied strongly on a research partnership with GERI to attain its present position. Whilst early impact is undoubtedly present in terms of economic and environmental benefits, it is envisaged that this advance, along with on-going research, marks a significant long-term development in vibratory mass finishing. The Technical Director of Vibraglaz (UK) Ltd states:

> *"The knowledge of GERI in fluid delivery and management has been critical in helping us achieve efficiency with our innovative new abrasive media product and has enabled us to service our first end-users. As a result of this successful foundation we are now engaged in actions to commence the build of a high volume manufacturing plant to meet anticipated early global demand."* [Corroborative witness ID=3]

Finally, we cite the further and wider impact achieved through professional dissemination and training. The research at GERI has resulted in the determination of what have become known in industry as '*Morgan's Rules'*, after Dr M. Morgan submitted in this UoA. These rules offer a straightforward way of determining optimal flow parameters under user defined conditions. The rules feature in training materials developed for the industry by a third-party American based company "TheGrindingDoc" [E5]. This company is a respected expert in the delivery of bespoke grinding training with a clientele in all areas of the industrialised world, providing training to more than 100 major industrial grinding users and practitioners in over 30 countries. Through this take-up of our research findings by "TheGrindingDoc", and the resulting dissemination via training, our work influences a world-wide user community. The three companies cited above are specific examples of our own dissemination and transfer. However, such training activies considerably enhance our outreach, resulting in many more companies employing guidelines drawn up directly from our research into fluid delivery in grinding. The Director of "The GindingDoc", states:

> *"The work done on cooling in several separate studies at GERI has established the velocities, pressures, flow rates and delivery methods needed for high-performance cooling. This technology is now being successfully transferred to the industrial setting in companies worldwide, resulting in shorter cycle times, better part quality, less scrap and, perhaps most importantly, much less coolant consumption and coolant-delivery-related power consumption, which minimizes the environmental impact."* [Corroborative witness ID=4]

5. Sources to corroborate the impact

E1. Malkin S, Guo C, "Grinding Technology: Theory and Application of Machining with Abrasives", 2nd Edition, Industrial Press Inc., New York, 2008, ISBN-10: 0831132477, p1. (Evidence of the size of the world grinding market)

E2. http://www.cinetic-landis.co.uk/index.php (Evidence of Cinetic-Landis as a major machine tool manufacturer; thus their wide adoption demonstrates the scope of the impact.)

E3. http://www.holroyd.com/index.php (Evidence of PTG-Holroyd as a major machine tool manufacturer; again their adoption, as a supplier, demonstrates scope and scale of impact).

E4. https://www.innovateuk.org/projects TSB Project – Thermally Treated Recycled Glass, (Evidence of significant industry financial support for the further growth of the technology and of its disruptive nature. Note – link leads to a search page – insert "Vibraglaz" in search box and click on the project title for details)

E5. www.thegrindingdoc.com (Evidence of the scale of training undertaken by this company which further disseminates our research findings to the international grinding community on a third-party basis).