Institution: University of Hertfordshire		
Unit of Assessment: 12 – Engineering		
Title of case study: Exploiting novel brazing technologies to benefit the UK economy and the global machine tools industry – and reduce exposure to an at-risk metal		
Period when the underpinning research was undertaken: 2002 – 2020		
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:**
Andreas Chrysanthou	Professor in Materials Engineering	1996 – present
Yong Chen	Professor in Applied Mechanics	1998 – present
James O'Sullivan	Principal Lecturer in Engineering & Technology	1997 – 2005
Period when the claimed impact occurred: 1 August 2013 – 31 December 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

Research at UH has translated novel metal-ceramic bonding technologies into specialist cutting tools that deliver improved performance and durability within the £3.4bn 'linear edge' market of the global machine tools industry. Through its collaboration with UH for the duration of the impact period, Cambridgeshire-based company C4 Carbides secured £600,000 in Innovate UK funding, more than doubled its annual turnover from £6.7m to £13.75m, posted cumulative gross profits directly relating to UH's research contribution of £11.5m, and created or supported 32-37 jobs. This success turned C4 Carbides from a niche SME into a global leader in specialist diamond cutting tools and enabled it to plan strategically for an annual turnover of £70m by 2027. The products created through the research have generated at least £50m in retail sales globally, benefitting multinationals including Milwaukee, Stanley Black & Decker, Bosch and AEG, and DIY and hardware stores around the world. The tools are sufficiently affordable for contractors, tradespeople and DIYers, cutting labour time and improving efficiency and performance. They have also contributed to a reduction in the industry's reliance on tungsten, an 'at risk' metal.

2. Underpinning research (indicative maximum 500 words)

Industrial tool manufacturers have traditionally relied upon tungsten carbide for their cutting blades; the compound's hard, durable properties and high temperature resistance set it apart from steel. However, tungsten is geochemically scarce. It is in the top ten of the British Geological Survey's most at-risk elements and is on the European Commission's Critical Raw Materials list.

The need to find alternative materials and optimise performance for industrial applications, such as wear-resistant metal-ceramic composites, underpinned novel research in the 2000s by UH's Materials and Structures Research Group into the synthesis and strengthening of such materials. Titanium was the initial focus of studies led by Chrysanthou. The Group aimed to develop titanium-matrix composites – where titanium carbide (TiC) was used as the ceramic reinforcement – that would demonstrate improved durability and heat resistance. It was noted that to achieve this, a chemically stable and strong bond was necessary between the reinforcement and the matrix. Experimental work tested the viability of various TiC composites that were prepared by combustion synthesis using elemental powders; the combustion products were sintered to near-net-shape products at 1160°C [**3.1**]. The key observation was that each TiC particle that had formed exhibited two distinct compositions, making it possible to create a compositionally-graded carbide at the interfacial bond with improved compatibility and lower residual stresses.

In 2004, Chrysanthou began a five-year, EU-funded collaboration with Politecnico di Torino (Italy) [**G1**, **G2**] to develop novel metal-ceramic composites with superior strength and hardness. Building on the TiC research, studies [**3.2**] led by Chrysanthou investigated whether the addition of vanadium to form titanium-vanadium carbide could improve wetting between the metal (in this case, iron) and the carbide reinforcement. Chrysanthou showed that the reinforcement particles were rich in vanadium carbide within the outer regions and formed under conditions of high carbon activity. In the central regions the particles were rich in TiC and formed under lower carbon activity. The development of the microstructure of the carbides was explained through an understanding of the chemical thermodynamic relations of the titanium-vanadium-carbon system. The approach improved the bond between the metal and the carbide and increased the hardness.

Further research explored methods to strengthen bonding within ceramic-matrix composites, specifically based on TiC and titanium diboride, which were exhibiting properties that were ideal for cutting tools: high degree of hardness, good wear resistance and high fracture toughness. The use of additives like borax and techniques such as self-propagating high-temperature synthesis (SHS) were shown to improve material performance [**3.3**]. The SHS technique was adapted by injecting mixed titanium and carbon-pressed powders into molten metals like copper. Additions of aluminium to the copper matrix led to further improvement in hardness [**3.4**].

Through a Knowledge Transfer Partnership (KTP) project [**G3**], Chrysanthou applied his findings into how carbide systems could be optimised through reactions as predicted by chemical thermodynamics to address a quality issue affecting a key product manufactured by a Cambridgeshire SME. C4 Carbides, a manufacturer of cutting tools, was seeking to strengthen its diamond-brazed drill products. Through his novel methodology, Chrysanthou revealed that a thermal treatment introduced by one of the company's sub-contractors had led to weakness and failure of the bond between the titanium-tungsten-coated diamond and the braze, leading to premature failure. He proposed an alternative chromium-containing reactive braze, which enhanced the bond at the interface through the formation of chromium carbide at the diamond surface. This was achieved by diffusion of chromium through the titanium and tungsten coatings followed by reaction with diamond. By adopting the findings of his earlier work, he was able to predict the formation of a stable bond by reaction of chromium with diamond since chemical thermodynamic analysis suggested formation of chromium carbide at the high carbon activity side. He demonstrated improved tool performance through a graded titanium-tungsten-chromium carbide at the interface of the braze and diamond.

Chrysanthou proposed the implementation of new process controls on C4 Carbides' production line to improve product quality by reducing the degradation of the diamond grit. Two further Innovate UK grants developed novel bonding techniques for a new product that replaced tungsten carbide with cubic boron nitride [**G4**] and a new micro laser metal deposition process to improve the performance of cutting teeth on the company's diamond saw blades [**G5**]. Combined, this research resulted in the publication a patent in 2020 [**P1**].

3. References to the research (indicative maximum of six references)

3.1 A. Chrysanthou, Y.K. Chen, A. Vijayan and J.M. O'Sullivan, 'Combustion synthesis and subsequent sintering of titanium-matrix composites', *Journal of Materials Science* 38 (9), 2003, 2073-2077. https://doi.org/10.1023/A:1023562126927.

3.2 A. Chrysanthou, O.P. Modi, L. Han, N. Ramakrishnan and **J.M. O'Sullivan**, 'Formation and microstructure of (Ti,V)C-reinforced iron-matrix composites using self-propagating high-temperature synthesis', *International Journal of Materials Research* 99 (3), 2008, 281–6. https://doi.org/10.3139/146.101635.

3.3 D. Vallauri, I.C. Atias Adrian and **A. Chrysanthou**, 'TiC-TiB_2 composites: A review of phase relationships, processing and properties', *Journal of the European Ceramic Society* 28 (8), 2008, 1697-1713. https://doi.org/10.1016/j.jeurceramsoc.2007.11.011.

3.4 S. Rathod, O.P. Modi, B.K. Prasad, **A. Chrysanthou**, D. Vallauri, V.P. Deshmukh and A.K. Shah, 'Cast in-situ Cu-TiC composites; Synthesis by SHS route and characterisation'. *Materials Science and Engineering*: A 502 (1–2), 2009, 91–8. https://doi.org/10.1016/j.msea.2008.10.002

European grants

G1 EU FP6: Nanotechnologies and nanosciences, knowledge-based multifunctional materials and new production processes and devices. 'Knowledge-based Multi-component Materials for Durable and Safe Performance' (ID: 502243). 2004 – 2009. Overall budget: €8.1m; €250k to UH.
G2 EU FP6: Nanotechnologies and nanosciences, knowledge-based multifunctional materials and new production processes and devices. 'Processing of Nanostructured Materials through Metastable Transformations' (ID: 1470). 2004 – 2008. Overall budget: €2.01m; €62.5k to UH.

Innovate UK grants

G3 Innovate UK KTP, with C4 Carbides. 'Brazing of Diamond'. 2010 – 2014. £196,000.
G4 Innovate UK Circular Economy Call, with C4 Carbides. 'Linear Edge Superabrasives'. 2014 – 2015. £194,622.
G5 Innovate UK Collaborative R&D, with C4 Carbides. 'Zero radius laser forming of tungsten carbide/superabrasive cutting edges and teeth'. 2018 – 2020. £591,713.

Published patents

P1 "Carbide material for cutting devices and associated method of manufacture" European Patent EP3751019A1; UK Patent GB2584791A; US Patent US2020392607A1 (all published 2020). Inventors: Andreas Chrysanthou (UH), Choon Kong and Pavels Sevcenko (C4 Carbides).

4. Details of the impact (indicative maximum 750 words)

The research-driven collaboration between UH and C4 Carbides has placed the company at the forefront of brazing technology. The innovations made possible by the research have meant that C4 Carbides' portfolio of diamond and tungsten carbide power tool accessories, including hole saws, jig saw blades and industrial band saw blades, outperform those manufactured by their key competitors [**5.1**]. The availability of the products has benefitted groups across the global economy: multinational companies, SMEs, sole traders and contractors.

Facilitating the growth of a UK company from niche SME to global leader – and benefitting the wider UK economy

Over the course of the impact period, the annual turnover of C4 Carbides has grown from £6.7m to £13.75m [**5.1**, **5.2**]. Between the beginning of 2014 and the end of 2020, the company posted cumulative gross profits of £23m [**5.1**, **5.2**]. C4 Carbides' CEO Peter Nicolson reported that 50% of this total gross profit figure – £11.5m – is directly associated with UH's research contribution, which developed blades and hole saws coated in tungsten carbide and synthetic diamonds that cut through cast iron four times faster than standard blades [**5.1**]. This technology underpins C4 Carbides' key products: diamond mini hole saws, diamond band saw blades and diamond saw blades [**5.1**, **5.3**]. Chrysanthou's work has provided C4 Carbides with its key competitive advantage. *"It is our advanced metallurgical bonding technology that quite clearly differentiates us from our competitors. We have made a significant investment in state-of-the-art laboratory facilities and equipment, based on Andreas's guidance, which have ensured the integrity of our diamond-to-steel bond,"* Nicolson said [**5.1**]. As a high-tech digital manufacturing business, companies in this sector are often valued by annual turnover multiples of anywhere between 8 and 20, according to Nicolson, who attributes 90% of C4's total value to the diamond-steel bond developed by the Materials and Structures Research Group [**5.1**].

The UH-C4 Carbides collaboration has been responsible for '*fundamentally altering the profile of our business and shaping our strategic development plans for the next decade*', according to Nicolson. The publication *Business Weekly* reported in 2017: '*A key introduction was to the University of Hertfordshire, enabling Peter to inject academic rigour into his engineering team: "You're forced into making certain that your project really is new rather than something already invented 20 years ago in Germany." The result was a revolutionary hard metal blade, coated in diamonds, creating a cutting edge with unprecedented resilience* [**5.4**].'

The two Innovate UK projects between 2014 and 2020 [**G4**, **G5**], which delivered more than £600,000 in direct product development funding to C4 Carbides [**5.5**], resulted in two patented technologies [**P1**, **P2**], underpinned by innovative ceramic-to-steel bonding processes, to give C4 a greater share of the £3.4bn (source: Dedalus Consulting) global linear edge market [**5.1**]. The 2014-2016 Innovate UK project [**G4**] established new coating and brazing technologies in which cubic boron nitride is applied to the strip line for many ferrous cutting and drilling tasks (diamond is not suitable for ferrous materials). This created new market-leading products for the high-performance band saw sector [**5.1**]. The most recent Innovate UK project [**G5**] involved the application of laser-based additive manufacturing processes to develop new linear edge blades (again based on UH's bonding expertise), which can be manufactured 10 times faster than before [**5.1**]. These combined developments resulted in C4 Carbides moving from its Cambridge site to a significantly larger manufacturing facility in Newmarket in November 2019, with the company forecasting an annual turnover of £70m by 2027 [**5.1**].

The growth of C4 Carbides, driven by UH's research contribution, has benefitted the wider UK economy. Over the impact period, 12 skilled jobs (engineers and technologists) have been created at the company itself, with a further 20-25 jobs created through the local supply chain [**5.1**]. There is further unquantifiable employment abroad, associated with the painting, packaging and branding of products supplied by C4 Carbides' customers to the hardware sector.

Commercial benefits for companies in the global machine tool industry

C4 Carbides' customers include four multinational companies that develop, manufacture and market power tools for professional and DIY use: Milwaukee, headquartered in Wisconsin and owned by Hong Kong's Techtronic Industries (TTI); Massachusetts-based Lenox, which was bought by Stanley Black & Decker in 2017; AEG Power Tools, also owned by TTI; and Germany's Bosch. The former two account for 50% of the market share for diamond-bonded drills and saw blades. C4 Carbides supplies its manufactured blade and saw products directly to these companies; the products are distributed and marketed under these companies' own brands in thousands of hardware and DIY stores across the world [**5.1**]. At the end of 2019, 77% of C4 Carbides' annual turnover was associated with the United States market, 14% with the European market and 9% with the Rest of the World [**5.6**]. Based on its turnover, own commercial data and in-store retail prices, C4 Carbides can provide a confident estimate that the total retail value arising from global sales of its innovative blade and cutting products is £50m, with a ten-fold increase to £500m expected by 2030 [**5.1**].

As a representative example of the route to market of C4 Carbides' products underpinned by UH research, the wetDRY™ diamond mini hole saw manufactured by C4 Carbides [**5.3**] is marketed by Milwaukee as its Diamond Plus™ Wet/Dry diamond hole saw [**5.7**]. The technical specification highlights the advanced brazing technology made possible by UH research: '*To ensure long lifetime, we use high grade diamond for fast cutting and a superior brazed bond matrix to give best durability* [**5.7**].' A similar C4 Carbides product is marketed by Lenox as its Diamond™ hole saw; its technical specification highlights the product's '*brazed diamond edge for more holes in the hardest ceramic and stone materials*' [**5.7**].

In addition to the likes of Milwaukee, Lenox, AEG and Bosch, commercial beneficiaries include the hardware stores that sell C4 Carbides' products to building firms, contractors, tradespeople and DIYers around the world. The store locator function on the websites of Milwaukee and others shows that in the UK alone, these include Jewsons (600 branches), Selco Builders Warehouse (55 warehouses), Brewers Decorators Centres (178 stores), Euro Car Parts (200-plus branches), Speedy Asset Services (200-plus tool hire depots) and many smaller specialist stores. The products are sold across the United States, including through The Home Depot, the largest home improvement retailer in the US with over 90 distribution centres and 2,000 stores [**5.8**], and are widely distributed online via the likes of Amazon, Screwfix and Ebay.

Improving performance of specialist hand tools used by tradespeople, contractors and DIYers globally, and reducing labour time.

Internal testing by C4 Carbides has demonstrated, unequivocally, that the company's diamond brazed products outperform those of their competitors [**5.1**]. This represents a significant performance improvement since the beginning of the first UH-C4 Carbides KTP [**G3**]; in 2010, the C4 product performance was, on average, about 50% of the top-performing tools [**5.1**].

The efficacy of the C4 Carbides products is also borne out through online customer reviews. As a representative example, for the Milwaukee Diamond Plus™ Wet/Dry diamond hole saw [**5.7**], 41 reviews on Amazon gave an average rating of 4.5 out of 5 (73% were five star) and 1,458 reviews on The Home Depot gave an average rating of 4.4 out of 5 (70% were five star) [**5.9**]. Many of the reviews highlighted the product's strong performance in cutting holes in ceramics (e.g. tiles, planters), porcelain and granite.

Reducing demand for an at-risk metal

The products developed at C4 have succeeded in '*moving a proportion of the market away from tungsten towards using diamond for general purpose cutting*' [**5.1**]. The braze technology from **G4** removes the need for any tungsten. The linear edge tools developed through **G5** are up to 30% thinner (thus using less tungsten). Nicolson said: '*The price of industrial diamond has dropped considerably and because our bonding technology has ensured the diamond retains its excellent cutting properties at extreme temperatures, we have played a part in reducing the industry's reliance on tungsten, which is in scarce supply* [**5.1**].'

5. Sources to corroborate the impact (indicative maximum of 10 references)

5.1 Corroborating statement from the Chief Executive Officer of C4 Carbides.
5.2 C4 Carbides' accounts filed at Companies House.
https://beta.companieshouse.gov.uk/company/01902912/filing-history
5.3 C4 Carbides Product Range:
https://www.c4carbides.com/products
5.4 An article on the Business Weekly website: *Manufacturer bounces back from mid-life crisis to take on the globe*, 13 February 2017.
https://www.businessweekly.co.uk/export/europe/manufacturer-bounces-back-mid-life-crisis-take-globe
5.5 Two Innovate UK collaborative R&D grants demonstrating direct value to C4 Carbides.
https://gtr.ukri.org/projects?ref=101754 [**G4**]
https://gtr.ukri.org/projects?ref=104050 [**G5**]
5.6 C4 Carbides' strategic report for Year Ended December 31, 2019.
https://tinyurl.com/y2qgex8m
5.7 Diamond hole saw product pages on the Milwaukee and Lenox websites.
https://www.milwaukeetool.eu/en-eu/diamond-plus-8243;-wet-dry-drill-bits/
https://www.lenoxtools.com/Pages/Product_productId_DiamondHoleSaws.aspx
5.8 Example product order page for a Milwaukee hole saw on The Home Depot website (USA).
https://www.homedepot.com/p/Milwaukee-1-4-in-Diamond-Plus-Hole-Saw-W-Arbor-49-56-0505/204994400
5.9 Customer reviews of C4 Carbides-manufactured product on Amazon and The Home Depot.
https://www.amazon.co.uk/dp/B00L0CWGMM#customerReviews
https://www.homedepot.com/p/Milwaukee-1-4-in-Diamond-Plus-Hole-Saw-W-Arbor-49-56-0505/204994400