Institution: Sheffield Hallam University		
Unit of Assessment: UOA12 - Engineering		
Title of case study: High Power Impulse Magnetron Sputtering (HIPIMS)		
Period when the underpinning research was undertaken: 2000 - 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:**
Prof Arutiun P. Ehiasarian	Head of National HIPIMS Technology Centre – UK	2003 – present
Prof Papken Eh. Hovsepian	Head of Thin Films Research Centre	1997 - present
Period when the claimed impact occurred: 2014 - 2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

Research by the National HIPIMS Technology Centre at Sheffield Hallam University (SHU) has driven innovation and created value across the supply chain, achieving market-leading performance for applications in consumer electronics, manufacturing, and biomedical implants. New HIPIMS technologies have generated revenue in excess of GBP124,000,000 for coatings systems/equipment manufacturers and cutting tool businesses. The research has led to changes in manufacturing practice at Ionbond UK, the largest HIPIMS manufacturing facility in the UK, safeguarding 12 jobs, generating around GBP1,200,000 in new business and substantially increasing productivity. The application of HIPIMS technology has vastly improved performance and longevity for medical implants and the licencing of HIPIMS to Zimmer Biomet has created 8 new jobs in the UK and USA.

2. Underpinning research

Professors Ehiasarian and Hovsepian and their group at SHU have led the development of High-Power Impulse Magnetron Sputtering (HIPIMS), which has become an industrially important physical vapour deposition (PVD) method of applying coatings using high current plasma glow discharges which generate an ionised vapour that is free of macro-particles.

Surface pre-treatments and nano-scale coatings based on SHU's HIPIMS advances have fulfilled long-standing needs of industry for high-density and better adhesion and enabled end-users to improve coating performance, durability, and reliability of their products.

Since the original work at SHU which pioneered HIPIMS as a novel branch of PVD, the research has continued to make key contributions to the understanding and implementation of HIPIMS through an ongoing programme of collaborative experimental research. Sheffield Hallam has collaborated with industrial partners and more than 15 research groups across the world, including *Fraunhofer IST*, *Lawrence Berkeley National Laboratory*, *CERN*, *Rutherford Appleton Laboratory*, *Zimmer Biomet*, and *Gillette*.

A specific innovation that resulted from the research was a breakthrough for achieving "fully-dense" coatings [**R1,R2,R3,R4**] through application of $kWcm^{-2}$ power densities. This methodology proved capable of eliminating the intergranular pores and macro-defects which had previously led to coating failures associated with production by conventional PVD technologies. Research has focussed on three areas:

1. Investigation into the design of plasma generators to produce HIPIMS discharges

The first area relates to an investigation into how HIPIMS might be transformed into a commercial coating production process, which is dependable, controllable, and predictable. The research

established the principles of HIPIMS plasmas and applied them to the upscaling of the hardware and coating technology for industrial production. Ehiasarian's group collaborated with *Trumpf Hüttinger (TH)* to investigate the temporal development of the discharge and used it to co-develop the first industrial scale commercial grade HIPIMS generator with MW pulse capability [**R5**]. This led to the world's first large scale experimental HIPIMS tests at SHU in 2003. In 2007, the group's HIPIMS research facilities were upgraded to include an industrial production-grade automated deposition system, unique within the university sector.

This enabled the industrial applicability of HIPIMS innovations which proved to be critical in realising technology transfer to the manufacturing sector through collaborative research. Investigation of the electron-collision ionisation mechanisms [**R3**] and discovering plasma self-organisation led to research outputs underpinning a second-generation product with *TH* , the *HighPulse 4000 (G2*) in 2016, with precision-controlled power delivery. Research focussed on the stable deposition of materials for applications such as touch-screen displays, transparent thin film transistors, architectural glass, and semiconductor manufacturing.

2. Development of systems to apply the coatings

Ehiasarian and Hovsepian's research at Sheffield Hallam developed systems and technologies for HIPIMS deposition which was scalable beyond the research laboratory. An efficient plasma-etching and substrate pre-treatment method, patented in 2006 [**R1**], revealed local epitaxial coating growth on steel substrates and accounted for enhanced adhesion. Strong adhesion is a critical requirement for all coatings exposed to mechanical, thermal, and oxidative stress such as cutting tools, power generation, jet propulsion turbines, and automotive bearings/engine components. Ehiasarian's research into the confinement of the (ionised) deposition flux led to patenting a high deposition rate HIPIMS source (GB0608582A, applied 02.05.2006) and a substrate bias power supply (GB2437080B, granted 12.10.2011). This research delivered previously unobtainable coating coverage of through-silicon vias (aspect ratio 30:1) realised using appropriate ionisation conditions [**R4**]. Industrial research with *Evatec* (between 2008-2010) developed HIPIMS technology for through-silicon via (TSV) interconnects of next generation miniaturised 3D-Integrated microelectronics devices. Research via an Innovate UK project (132366) with *Ionbond* in 2017/2018 created the first digital twin of the HIPIMS process, and elevated Quality Assurance to high-value manufacturing standards.

3. Research into the formulation of nanolayer coatings for specific applications

The third aspect relates to Hovsepian's group's research into nanoscale multilayer coatings (nanolayers) produced by HIPIMS, where synergistic combinations of materials were tailored to withstand demanding environments. CrN/NbN combined wear and corrosion-resistant materials in a nanolayer stack to enable superhardening and were densified to achieve a material suitable for use in orthopaedic implants enhancing fatigue resistance and mitigating metal sensitivity. This work was applied through collaboration with *Zimmer Biomet* spanning 2005-2020, with the coating performance confirmed in independent testing in a total hip replacement ram model at the Institute of Orthopaedics and Musculoskeletal Science at University College London [**R6**].

TiAlCN/VCN and CrAlCN/CrBCN materials were investigated for use in cutting tools via a methodology that employed architecture gradation from nanolayer to nanocomposite where a carbon matrix reduced reactions with the workpiece. This research was undertaken in collaboration with *Sandvik* between 2015-2018 and a patent application was filed (EP3374537A1, 2016). Research into CrAlBYN/AlSiN nanolayers (2016-2018) employed dopants to investigate the enhancement of elasticity and potential to protect *Rolls-Royce plc* aero-engine turbine blades against hot corrosion, resulting in a patent application (EP3527688A1, 16.01.2019).

3. References to the research

R1. Main Patent granted on 20.09.2006 *EP1260603B1*
https://patents.google.com/patent/EP1260603B1

R2. Ehiasarian, A.P., Munz, W.D., Hultman, L., Helmersson, U. and Petrov, I., High power pulsed magnetron sputtered CrNx films, *Surf. Coat. Technol.* **163-164**, 267 (2003)
https://doi.org/10.1016/S0257-8972(02)00479-6

R3. Ehiasarian, A.P., Vetushka, A., Aranda Gonzalvo, A., Sáfrán, G.,Székely, L., and Barna, P. B., Influence of high power impulse magnetron sputtering plasma ionization on the microstructure of TiN thin films, *Journal of Applied Physics* **109**, 104314 (2011) https://doi.org/10.1063/1.3579443

R4. Weichart, J., Elghazzali, M., Kadlec, S., Ehiasarian, A.P., *PVD Processes in High Aspect Ratio Features by HIPIMS,* (*Proceedings of the 52nd Annual Technical Conference of the Society of Vacuum Coaters, United States, May 9–14, 2009 Santa Clara, CA*), 201 (2009) https://www.shu.ac.uk/~/media/home/research/meri/what-we-do/projects/pvd-processes-in-high-aspect-ratio-featres-by-hipims.pdf

R5. Ehiasarian, A.P., Bugyi, R., Industrial Size High Power Impulse Magnetron Sputtering, *Society of Vacuum Coaters 47th Annual Technical Conference; Dallas, TX; USA*; 24–29 April 2004. pp. 486–490 (2004) https://www.svc.org/DigitalLibrary/document.cfm/1288/Industrial-Size-High-Power-Impulse-Magnetron-Sputtering

R6. Blunn, GW, De Godoy, RF, Meswania, J, Briggs, TWR, Tyler, P, Hargunani, R, Wilson, H, Khan, I, Marriott, T, Coathup, MJ. 2019. A novel ceramic coating for reduced metal ion release in metal-on-metal hip surgery. *J Biomed Mater Res Part B*. 2019: 107B: 1760–1771. https://doi.org/10.1002/jbm.b.34268

Details of Key Research Grants

Grant Title	ID	Funder	Period	Total Award
InnovaTiAl	NMP3- CT 2005-515844	EU FP6	2005-2009	GBP10,000,000
Fundamentals of HIPIMS	EP/D049202/1	EPSRC	2008-2012	GBP360,000
Coatings for Orthopaedic Implants	Industrial Research	Zimmer Biomet	2012-2020	GBP 460,000
High Efficiency CuInSe2Photovoltaic Modules Deposited at Low Temperature by HIPIMS	EP/J011398/1	EPSRC	2012-2016	GBP329,149
HIPIMS Coatings for Propulsion	Industrial Research	Rolls Royce	2016-2018	GBP120,000
Real-time monitoring and control of magnetron sputter deposition	132366	Innovate UK	2017-2018	GBP93,506

The group's contributions to science and translation were recognized through the awards of Fellowships of the Institute of Physics in 2014 and 2015, and the Mentor Award of the Society of Vacuum Coaters in 2017 and 2012, to Ehiasarian and Hovsepian respectively. Ehiasarian received the 2019 Fellow of the American Vacuum Society and 2018 European Physical Society Plasma Physics Innovation Prize and was included in the World's Top 2% Scientists listing by Stanford University 2020.

4. Details of the impact

During the period 2014-2020 SHU collaborated with 23 companies across 8 diverse sectors applying HIPIMS research to develop the next generation of durable, high performance thin films, coatings and plasma enhanced diffusion treatments. SHU HIPIMS research has led to the following impacts:

1. Six New High-Performance Coating Deposition Technologies for Coatings Systems Manufacturers

SHU has licensed its patent on pre-treatment to *Hauzer TechnoCoating, CemeCon, and Systec SVS,* and has transferred knowhow on coating deposition to *Oerlikon Balzers*. SHU's know-how is also embedded in the Highly Ionised Sputter (HIS) sold by *Evatec* to target TSV wafer packaging applications.

Following the licencing/know-how transfer, the companies have created a market portfolio of HIPIMS deposition systems comprising the Flexicoat®, CC800® HiPIMS, NOVELC HIPIMS, INLENIA and the CLUSTERLINE® ranges, respectively.

According to Systec, the new HIPIMS sputtering technologies offered

> "*significant advantages over the more traditional arc technology … guarantee a droplet-free coating and thus offer a reduction in roughness and an improvement in corrosion resistance … [and] can avoid expensive and time-consuming re-polishing"*.[**E1**]

The CEO at Hauzer concurs:

> "*HIPIMS…performance increase in machining compared to conventional technologies is reaching 30-100% in life- time or in higher cutting speeds*" [**E1**]

Economic impact through sales (2014-2020) has been significant, with sales directly attributable to HIPIMS systems totalling **GBP16,200,000**, and with HIPIMS expanding markets for all the manufacturers [**E1**]. The Product Manager for Coating Equipment of CemeCon has stated that: "*HiPIMS coatings and HiPIMS equipment is a substantial part of our business"* [**CemeCon total reported revenues of GBP39,000,000 (2015-2020)**]*,* [**E1**] and:

> *"In our development efforts we have significantly been inspired by the research results in the field of HIPIMS published by Sheffield Hallam University in refereed journals and the interactions we have had at the International Conference on HIPIMS organised by Sheffield Hallam University and Fraunhofer IST."* [**E1**]

2. Improvements in products, production and profitability for tool manufacturers Paul Horn (HORN), Walter <text removed for publication>

The impact of SHU's research and knowledge transfer on HIPIMS extends to products that utilise the technology. Three leading tools manufacturers have developed new products with significantly improved tool life using HIPIMS coatings produced by equipment supplied by Hauzer and CemeCon which utilises SHU know-how as described in Section 1. *HORN's* Coating Engineer has noted that products with HIPIMS coatings were *"able to outperform the tool life of already existing arc and sputter coatings by a factor of 2 to 5*"." [**E2**]

For *Walter AG*, HIPIMS enabled the development of the M2131 90° ramping milling cutter which has increased metal removal rates and **extended tool life up to 200 percent**. [**E2**]

<text removed for publication> developed a suite of tools with HIPIMS coatings for one of the world's large manufacturers <text removed for publication>. The European Managing Director at <text removed for publication> stated that HIPIMS coated products had been central to the growth of sales to this customer, and that: "*we believe that based upon levels of activity in 2019, the customer would **save in excess of a seven-figure sum per annum**, that's just on the tooling costs"* [**E2**]

3. Established the first industrial scale Plasma Generators

HIPIMS products have **enabled additional hardware sales at a total value of GBP108,000,000** embedding SHU HIPIMS technology into >**20 new customers** and the **creation/safeguarding of 30 jobs.** [**E3**] In 2018, and in collaboration with SHU, *Trumpf Hüttinger, Poland* launched the *Highpulse 4000 (G2)* plasma generator, thus establishing the company as sole supplier of industrial scale generators. The superior rates and coating quality have reduced the cost of ownership in decorative, semiconductor, glazing and display industries.

HIPIMS research is further exploited via <text removed for publication> sales of >200 million iPhones per year (figures from 2018) to address the HIPIMS technology enabled durable, high-gloss gold version of the outer casing of the iPhone 12 Pro, launched in October 2020. The quality of the gold finish, which is not achievable by standard PVD technologies used for other colour options, formed a key element of the marketing surrounding the launch of the iPhone 12 Pro. *"…our new gold uses a **high-power magnetron coating process** that gives the stainless steel [underlying casing] a stunning bright gold finish." Greg Joswiak, SVP Worldwide Marketing, Apple* [**E4**]

4. Improvements to Manufacturing Practice and Productivity for Ionbond, UK

The partnership between SHU and global leaders in coating technologies, *Ionbond UK,* established the first industrial facility for HIPIMS in the UK. The CEO of Ionbond stated that:

> "*Our collaboration with SHU established the first industrial facility for HIPIMS in the UK. The industrial scale equipment armed with new HIPIMS technology and the technical support from SHU has given Ionbond the unique capability to develop the next generation of PVD coatings and to be a leader in industrial PVD coating development for many years to come ..."* [**E5**]

Since 2014, the company has collaborated with SHU to modernise its manufacturing practice by adding HIPIMS and its digital twin, **reducing the roughness of the coatings by a factor of 6, reducing scrap rate to <1%** and **eliminating the post-treatment step thus reducing production times by 20%,** boosting Quality Assurance and increasing productivity. New business enabled by these improvements is valued at **GBP1,200,000** resulting in **safeguarding 12 jobs** in the socially deprived area of Consett, County Durham. [**E5**]

Ehiasarian's work on this project earned him the IONBOND IHI Group Industrial accolade for his leadership in 2015 [**E5**].

5. Improved performance and longevity for biomedical implants

Zimmer Biomet (ZB), the world's largest manufacturer of orthopaedic implants, acquired a HIPIMS license from SHU for HIPIMS to develop a new durable coating for orthopaedics. The coating was fully validated and upscaled for manufacture (a multi-million-pound investment) **creating 8 jobs** in the UK and USA.

Zimmer Biomet's CTO, states:

> *"Zimmer Biomet is one of the world's largest manufacturer of orthopaedic implants. We acquired a HIPIMS license from SHU to develop a new durable coating for orthopaedic implants. Since 2014 the coating has undergone validation and upscaling for manufacture through a multi-million-pound research and development programme that has created or safeguarded 8 jobs at Zimmer Biomet in the UK and USA.*

These novel coatings provide significant bench-top improvements over contemporary coatings used in orthopaedics, promising superior implant performance and longevity clinically to enhance the lives of tens of thousands of patients around the world" [**E6**]

6. Driving growth and innovation across the sector through licencing

Other areas of industry where the SHU research has been licenced include: HIPIMS technology licenced to one of the largest automotive component manufacturer *Mahle* (Brazil) for tribological coatings to reduce fuel consumption; licencing, and in 2018, to <text removed for publication> for SHU's low temperature HIPIMS technology to develop the first <text removed for publication>. [**E7**]

5. Sources to corroborate the impact

E1. Statements and weblinks from system manufacturers statements including: Hauzer, CemeCon, Evatec, Systec, and Oerlikon.

E2. Statements and weblinks from cutting tool manufacturers including: Paul Horn, <text removed for publication>, Hauzer, CemeCon, and Walter Tools

E3. Statement from VP Engineering, Trumpf Hüettinger

E4. Weblinks to Apple launch event, sales article, and historical sales statistics

E5. Statement from Ionbond UK

E6. Statement from Zimmer Biomet

E7. Licence agreements from Sheffield Hallam University for HIPIMS technology