Direct Rapid Manufacturing of Metallic Parts
A UK Industry overview - February 2008

What is Rapid Manufacturing?

Rapid Manufacturing (RM) is the name given to the production of 'series' or 'end-use' component parts made using 'Additive Layer Manufacturing' (ALM) processes. Traditionally, ALM processes were used to manufacture prototypes and casting patterns. However, recent advances in ALM technologies and materials, now allow us to manufacture parts in polymers, ceramics and metals for a variety of production applications.

How Does Additive Layer Manufacturing Work?

The principle of additive layer manufacturing is relatively simple. As opposed to machining, where material is removed from a solid block, or casting where material is melted and forced into a cavity, additive processes work by 'building-up' the required geometry particle-by-particle, layer-by-layer, from the bottom-up.

Figure 1 – Laser sintering of Cobalt Chrome powder during the build process within an MCP Realizer 100 machine

There are many different mechanisms for both generating a single layer and also for bonding layers together. In some simple systems, layers are cut from sheet material and bonded using adhesives or ultrasonic welding type processes. In other systems, layers are generated by melting fine powder using a laser or electron beam, and consolidating the new layer onto the previous layer by remelting. *(See Figure 1)* In all, there are over 30 different ALM processes marketed by over 40 different companies around the world. The majority of these systems are however focused on polymeric materials and not yet metallic's.

Why is RM becoming so important to the UK Economy?

RM is seen by some as one of the most important emerging technologies that will drive the future manufacturing economy. One of the most notable advantages of RM is the potential elimination of tooling. Without the constraints of casting or moulding tools, or machining jigs and fixtures, RM provides manufacturers the ability to produce cost effective batch sizes of 'one', or the ability to manufacture parts at multiple locations or with multiple product design iterations at no additional cost.

Why is RM different to traditional manufacturing?

Because RM uses layer-wise manufacturing, many of the traditional Design for Manufacture (DFM) principles no longer need apply, as parts are not made in tool cavities or held within fixtures. Therefore, RM components can be manufactured with no split lines, or with complex internal and re-entrant features. RM therefore allows for significant part consolidation, reducing manufacturing, assembly and inspection costs. *(See Figure 2)*

Figure 2 – Complex single piece geometry manufactured on a powder bed laser system. The part is an optical lens holder.

RM also allows for the manufacture of topologically optimized components, producing parts that are 'manufactured-for-design' as opposed to 'designed-for-manufacture'. This can eliminate many secondary manufacturing steps such as internal machining operations or secondary fabrication. *(See Figure 3)*

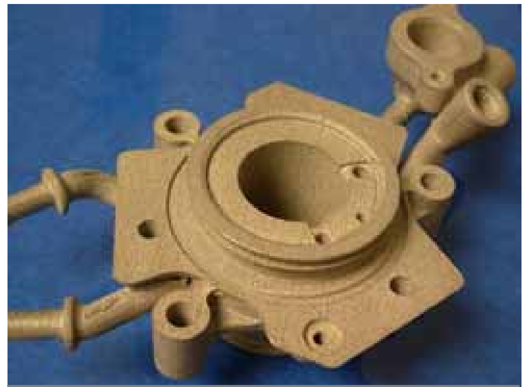

Figure 3 – Topologically optimised diesel pump housing manufactured using MCP Selective Laser Melting This part weights 60% less than the original casting

How will RM affect the traditional supply chain?
In principle, RM can reduce or eliminate many stages of the traditional supply chain, which reduces lead times, inventory and supply chain transaction and logistics costs.

Moreover, because RM parts are made using additive manufacturing technologies, as opposed to subtractive or formative processes, little if any waste material is generated. This is particularly true of the newer metallic processing technologies, which we will discuss later. Additive manufacturing processes are therefore lean, yet agile, allowing the manufacture of low volume batches of component parts, with little manual intervention.

So who is using RM today?
In recent years, there has been an almost exponential increase in the number of companies using RM across a broad range of industrial sectors. Examples of RM applications include aerospace and automotive components *(See Figure 4)*, packaging, medical implants *(See Figure 5)*, hearing aid shells and surgical guides, and consumer products as diverse as light shades, furniture and even football boots.

Figure 4 – Replacement classic motor cycle water pump impeller manufactured using EOS Direct Metal Laser Sintering (diameter 50mm)

Figure 5 – Replacement mandible for maxiofacial reconstructive surgery. Manufactured in Cobalt Chrome on an MCP Realizer 100

How did we get to where we are today?
The technologies behind RM have been in existence since the mid to late 1980's, when processes with names like Stereolithography (SLA), Fused Deposition Modelled (FDM) and Selective Laser Sintering (SLS) were introduced as solutions to manufacture prototype parts directly from 3D CAD data *(See Figure 6)*. Hence, the term Rapid Prototyping or RP was coined. However, in these early days, the processes produced exclusively polymeric or paper parts. As the accuracy and repeatability of these early systems improved, parts were then used as patterns for down stream casting processes, such as investment (lost wax) casting *(See Figure 7)*, sand casting or vacuum casting of low melting alloys into silicon tools. Hence, Rapid Casting or RC was born.

Figure 6 – Traditional polymeric rapid prototyping model manufactured using Selective Laser Sintering of Nylon

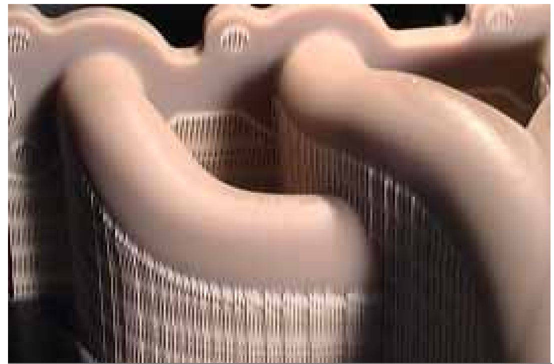

Figure 7 – Rapid Casting pattern 3D Printed in investment casting wax using a 3D Systems Thermojet modelling system

During the mid 1990's, developments in both ALM systems and materials allowed us to manufacture 'quasi-metallic' parts, directly from 3D-CAD data without the need for intermediate Rapid Casting. There processes produced 'green-state' parts made of metallic powders held together with either binders *(See Figure 8)* or polymers mixed with the metal powder. These 'green-state' parts were then fired and infiltrated to achieve there ultimate strength. The main limitation with this 'in-direct' approach, was that the final part, although resembling a production part had none of the mechanical or metallurgical characteristics of the desired component. Hence, these parts were very seldom used as end use production items. However, some technologies were used to manufacture Rapid Tool (RT) cavities for injection moulding and die casting

Figure 8 – Pro-Metal RX1 in-direct metal 3D Printing machine using powder and binder

Figure 9 – Direct Medical implant manufactured using ARCAM Electron Beam Melting

In the late 1990's advances in both laser power and electron beam control technology, allowed companies to develop ALM systems capable of manufacturing parts in 'real' engineering metals. With the advent of higher powered solid state lasers, such as yttrium fiber lasers in the early years of this millennium, 'Direct' additive manufacturing in engineering grade metals has now become a reality. (See Figure 9)

The polymeric to metallic RM divide?

Although RM has now become a relatively main steam (albeit little exploited) production process for polymeric parts, the process remains in its infancy for metallic parts. This is largely due to a lack of understanding of the technologies available but also the relative immaturity of the technologies on offer. Moreover, most metallic parts are subject to greater stresses, loading and environmental exposure than polymeric parts. Hence, process and materials validation of metallic RM is a far greater consideration to end users than for polymeric parts. Again, this has in many cases slowed the technology implementation. However, there is no doubt that true metallic RM will happen. For example, aerospace companies such as Airbus, Boeing, Rolls Royce, GE, and BAE Systems have all investing in either direct metal technology platforms or research collaborations to implement direct metallic RM into mainstream production.

So what are the processes available for 'direct' metallic RM?

Direct Metallic ALM processes fall into three camps, powder bed systems, powder feed systems and sheet consolidation systems. However, processes must also be considered as both net shaped and near net shaped. Net shaped parts are within the manufacturing tolerance to the original CAD representation, whereas near net parts will require some form of post process finishing or machining to achieve their ultimate geometric tolerance.

Sheet Consolidation RM

The concept of sheet consolidation or lamination is not new. For many years, tooling companies in the Far East have manufactured low pressure foam moulding tools by cutting out a tool cavity profile into hundreds of steel sheets, which are then assembled, clamped and bonded to make a laminate tool. More recently, this concept has been adopted by US based Solidica Inc. (www.solidica.com) and incorporated into their Ultrasonic Compaction (UC) Form-ation™ Machine tool. It should be noted that this process is not truly additive, as it also required a significant level of in-processes machining.

UC works by taking sheet material in the form of foil, which is then placed on a build platform. A rotating ultrasonic sonoatrode connected to a transducer is then passed over the foil causing localised bonding of the foil to the platform. A CNC milling head then subtractively machines the profile of the first layer into the foil. The platform is then lowered by one layer thickness and a second layer of foil is positioned over the first. The ultrasonic consolidation processes and machining are then repeated. This cycle is continued until the geometry is complete.

UC has some advantages compared to other metallic ALM processes, as it can be used to bond dissimilar materials, manufacture metal matrix composites and to build parts with embedded optical fibres'. UC is also a net shaped process, which is governed by the accuracy of the machining head within the process cell. However, part complexity is seriously restricted, as the system is incapable of easily processing overhanging or re-entrant features. Moreover, the process is also highly wasteful, as expensive ultrasonic welded metallic foil is machined away as waste.

Powder Feed RM

Research into metallic feed systems started in the late 1980's using MIG welding torches fitted to multi-axis robots, as a way of building up material onto expensive damaged parts, such as turbine blades or mould tools. In the 1990's welding wire was replaced with blown powder, which although much slower, enabled far better melt-pool control and subsequent part accuracy. *(See Figure 10)*

Figure 10 – The direct powder deposition process using a TRUMPF DMD machine cell

The principle of a powder feed system is to take a jet of metallic powder and literarily fire this into the path of a laser beam. At the point of convergence, the powder is melted. By moving the laser beam and powder feed nozzle over a substrate, using either a 3 or 5-axis CNC machine or robot, layers of material can be deposited onto the substrate at the point of convergence.

Powder feed technology is available either as complete machine tool *systems* or as modular *solutions*.

Powder feed – Systems

Powder feed systems, intended in some cases exclusively as repair technology, include the LENS 850-R and 750 systems from Optomec Inc. (www.optomec.com), the Huffman Corporation HP115 and HC-205 systems (www.huffmancorp.com) and the Trumpf DMD 505 System (www.trumpf.de). In each case these technologies produce, near net shaped parts that will require some post process finishing of critical surfaces.

More recently, machine tool company Hermle Innovaris (www.innovaris.de) have launched the Alchemy C40 high material deposition system. Unlike other powder systems, the C40 does not use a laser to melt the powder, but relies on supersonic jetting of the powder onto the substrate causing localised super-plastic deformation and bonding. This supersonic jetting is achieved through the expansion of super-heated steam. The main benefit of the C40 is the very high deposition rate achieved by the process when compared to laser systems. The system also incorporates a multi-axis CNC milling centre, which is used to datum the top of the layer following deposition, but also, like the Solidica process, to cut out the exact profile of each layer, resulting in a net shaped part.

Figure 11 – Internal configuration of a TRUMPF Direct Metal Deposition Powder Feed solution using modular robot & laser

Powder feed - Solutions

In addition to commercial powder feed systems, a number of companies have taken the approach of selling modular powder feed solutions. Leading German machine tool manufacture Trump (www.trumpf.de) sells a number of modular solutions where a laser head can be integrated with an industrial robot and powder feed systems, to deliver a high flexible and tailored solution. Like the Trumpf DMD system, the Trumpf bespoke solutions also produce near net shaped parts. *(See Figure 11)*

Canadian based Accufusion (www.accufusion.com), a spin out company from the Canadian National Research Council also market and sell a modular powder feed laser process called Laser Consolidation. Unlike other power feed systems, Laser Consolidation works by pulsing both the laser beam and powder into an accurately controlled melt pool. The results is a net shaped part that requires little (if any) post process finishing. *(See Figure 12)*

Figures 12 – Motorsport exhaust port manufactured using ACCUFUSION Laser Consolidation process (diameter 40mm)

Overview of powder feed technologies

Like all technologies, powder feed technologies have their advantages and disadvantages. When compared to powder bed systems, powder feed systems are relatively fast in depositing material. They also have larger build enveloped and most significantly they allow the deposition of material onto a substrate, which could be an existing part. Powder deposition systems are therefore often used to add detailed features onto much larger fabricated structures.

The drawback of powder feed technology is that it is often expensive to operate, as they have a large machine foot-print, require a significant volume of inert shielding gas and often produce only net shaped parts which require post-process CNC machining. However for certain applications in the tool making, defence and aerospace sectors, powder feed technologies will have a significant future impact.

<u>Powder Bed RM</u>

Powder bed ALM systems are enclosed machine tools very much on the scale of a small 3-axis CNC machine. They incorporate a build chamber into which powder material is deposited onto a build platform. The build platform is allowed to move down in the Z-axis in incremental steps equal to the desired layer thickness. An energy source such as a laser or electron beam is then directed into the build chamber. In the case of a laser beam, this is directed onto the surface of the build platform using scanning mirrors. In the case of an electron beam the beam is directed onto the build platform using magnetic fields.

The process starts by depositing a single layer of powder, typically 0.02mm – 0.2mm onto the build platform. Following pre-heating, the laser or electron beam is then scanned across the surface creating a moving melt pool'. This consolidates the powder material to the both the particles around it, but also the material below. By scanning both the profile and internal cross section of a slice, a layer can be consolidated that represents a slice taken from the original CAD file. After the layer is consolidated, the build platform moves down by a single layer thickness and another layer of loose powder is deposited. The melting process is then repeated using the scan data for the next layer, before the platform is indexed again and new powder is added. The process is repeated over and over again until the last layer is consolidated. With laser based direct metal systems the whole process takes place in an inert gas atmosphere. However, for the electron beam system the process takes place in a vacuum.

To-date a wide range of production engineering metals have been processed using powder bed ALM systems, these include, stainless Steel (17-4, 316L, Ph1), tools steel (20ES – 91RW) and Maraging steel (18 Mar 300), Cobalt Chromium, Inconel 625, Titanium (Ti pure, TIAl6V4, Ti Al6 Nb7) and Aluminium (Al Si 12 Mg, ALSi12). Research and development is also being conducted to commercialise Inconel 600 and 718, beryllium, copper and hastelloy. *(See Figures 13, 14, 15 & 16)*

Figure 13 – Polished cobalt chrome part made using EOS Direct Metal Laser Sintering

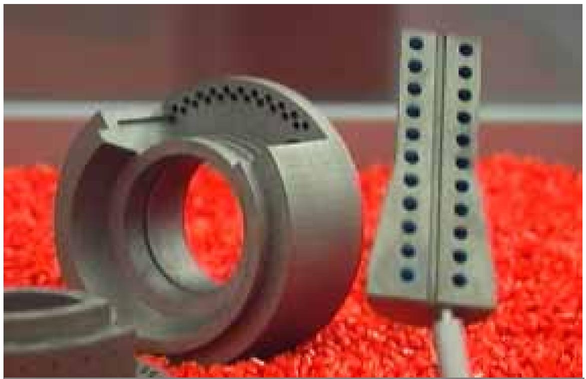

Figure 14 – Injection Mould tooling inserts made in Tool Steel using the Concept Laser Cusing System. Note – the parts have been sectioned to show the internal cooling flow channels

Powder bed direct metal systems are available from a number of companies, all of which are currently based within Europe. Direct Laser Technologies are available from MCP Tooling Technologies Ltd located is Stone Staffordshire (www.mcp-group.com), Electro Optical Systems (EOS) GmbH, based in Munich Germany (www.eos.info), Concept Laser, part of the Hoffman Tooling Group based in Lichtenfels Germany(www.concept-laser.com), and Phenix Systems of Clermont Ferrand in France (www.phenix-systems.com). In all cases laser based powder bed systems are marketed as net shaped production technologies.

In addition, ARCAM AB of Mölndal Sweden (www.arcam.com) manufacture and sell the Electron Beam Melting (EBM) process, which replaces the laser energy source with a high power electron beam. Although significantly faster than laser based systems, the EBM process works in thicker layer with a lower X-Y accuracy. Hence, it is more suited to near net shaped parts.

Figure 15 – Stainless Steel automotive component manufactured using the MCP Selective Laser Melting Process

Figure 16 – Accetabular cups used as replacement hip sockets. Medical grade Titanium parts manufactured directly on an ARCAM EBM machine

How do powder bed systems compare?

Each of these technologies has its own unique benefits, including materials flexibility, cost of ownership, the speed of build cycle, cycle time between jobs, build envelope capacity, layer thickness, part accuracy and repeatability, surface finish and metallurgical properties. Some processes build within a heater chamber to reduce residual stresses, whilst other build parts onto strong base plates, which are post process heat treated to remove build stresses. In some processes the parts can literately be broken away from the build plate, whilst in other processes they require removal using wire erosion. Figure 17 shows a comparison between the build envelop, layer thickness and energy source of commercially available powder bed systems.

Manufacturer	Process	Model	Build Envelope (mm)	Layer Thickness (µm)	Energy source (Watts)
MCP	Selective Laser Melting	Realizer 100	125 dia. x 100	50	50W fibre laser
		Realizer 250	250 x 250 x 240	50	100W fibre laser
EOS	Direct Metal Laser Sintering	EOSINT M250X	250 x 150 x 185	20 - 100	250W Co_2 laser
		EOSINT M270	250 x 250 x 200	20 - 100	200W solid state laser
Concept Laser	Laser Cusing	M1 Cusing	120 x 120 x 120	20 – 80	100 W solid state laser
		M2 Cusing	250 x 250 x 280	20 – 50	200W fibre laser
		M3 Linear	300 x 350 x 300	20 – 80	200W fibre laser
Phenix Systems	Laser Sintering	PM100	100 dia. x 100	50 – 120	50 or 100W fibre laser
		PM100D	100 dia. x 30	20	50W fibre laser
		PM250	250 dia. x 300	20	100W fibre laser
Arcam	Electron Beam Melting	EMB12	250 x 250 x 180	50 – 200	3,500W electron beam
		A2	250 x 250 x 400	50 – 200	5,000W electron beam

Figure 17 – The build volume, layer thickness and energy source of powder bed additive layer manufacturing processes

Where are the current applications for direct metallic ALM technologies?
It would be misleading to suggest that all direct metallic ALM technologies are being used for volume direct part manufacture, as most of the parts produced are still being used as pre-production form, fit and function prototypes. This is very much the case in aerospace where the materials and production processes have yet to be fully validated. However, direct metallic RM has already been validated in the medial industry for the manufacture of Orthopaedic Implants *(as shown in Figure 16)*, maxiofacial reconstructive implants *(as shown in Figure 5)* and surgical cutting guides. Direct metallic RM has also been used in automotive and motorsport application *(as shown in Figure 15)* and in the manufacture of complex tooling cavities and inserts *(as shown in Figure 14)*

Economics and reality

Direct metallic ALM is expensive. Machine tools range from £200K to almost £1-million, added to material costs of £80 per Kg for 316L stainless steel up to £475 per Kg for titanium 6-4. Given the relatively slow deposition rate of some technologies, the resulting parts can seem disproportionately expensive when compared to cast or even machined parts. However for many users, the geometric complexity that is possible with RM, coupled with the economics and freedom of tool-less manufacture are compelling. It should be stressed however, that it is not possible to manufacture all geometries using these systems. Most notably machines are limited in size. *(As shown in Figure 17)* Moreover, certain geometries can cause problems such with residual stress during the build cycle, which can result in either delaminating or more likely fouling with the powder re-coating system. In truth, operator experience is the only current way of predicting whether a geometry will make a successful build.

Direct Metallic ALM within the UK

Given the nature and configuration of powder feed systems it is simply not possible to put an exact figure on the number of machines within the UK, as many machines have been self assembled using commercial robots and powder feed heads. To-date there is only one known UC system at Loughborough University which is used solely for applied research. However, within the UK, there are currently 26 installed powder bed direct metallic ALM systems. A further 2 MCP SLM systems have recently been sold to a leading research organisation with a global packaging company purchasing an EOSINT M270 (data correct as of Feb 08). Hence, the UK installed based for direct powder bed metallic ALM systems will be close to 30 machines by the end of Q1 2008.

Interestingly of the currently installed powder bed systems, only five are located ‘behind closed doors’ within leading aerospace, automotive, motor-racing and packaging companies. The remaining 21 machines are located in sub-contract service bureaus, research establishments or Universities, and as such are available in the most part to UK businesses. *(See Figure 18)*

Organisation	Location	Technology	No	Materials	Service provider	Research provider
Materials Solutions www.materialssolutions.co.uk	Birmingham	EOSINT M270	3	PH1 stainless 17-4 stainless Cobalt Chrome	YES	Some
3T RPD www.3trpd.co.uk	Newbury	EOSINT M270	3	PH1 stainless 17-4 stainless Cobalt Chrome Maraging Steel	YES	NO
CRDM www.crdm.co.uk	High Wycombe	EOSINT M270	1	17-4 stainless Cobalt Chrome Maraging Steel	YES	NO
		EOSINT M250	1	Direct Metal 20		
Wolverhampton University Innovative product development centre www.wlv.ac.uk	Telford	EOSINT M270	1	Titanium	YES	YES
		EOSINT M250	1	Maraging Steel		

Organisation	Location	Technology	No	Materials	Service provider	Research provider
Metropolitan Works Creative Industries Centre	London	EOSINT M270	1	17-4 stainless Cobalt Chrome	YES	Some
Sheffield University Innovative Materials Processing Centre www.impc.org.uk	Rotherham	EOSINT M270	1	17-4 stainless Cobalt Chrome	Some	YES
		ARCAM EBM12	1	Titanium 6-4 grade 5		
Liverpool University www.liv.ac.uk	Liverpool	MCP Realizer 100	1	Aluminium Stainless Titanium Cobalt Chrome	NO	YES
		MCP Realizer 250	2			
National Centre for Product Development & Design Research www.pdronline.co.uk	Cardiff	MCP Realizer 250	1	Stainless Cobalt Chrome	YES	YES
Exeter University www.exeter.ac.uk	Exeter	MCP Realizer 250	1	Stainless Cobalt Chrome	NO	YES
Loughborough University www.rm-consortium.com	Lboro	MCP Realizer 100	1	Stainless Titanium Cobalt Chrome	NO	YES
Warwick University www.warwick.ac.uk	Coventry	ARCAM EBM12	1	Titanium 6-4 grade 5	NO	YES
RapidForm RCA www.rca.ac.uk	London	ARCAM EBM12	1	Titanium 6-4 grade 5	YES	NO

Figure 18 – Powder bed metallic ALM systems within the public domain

The Future

Rapid Manufacturing has been described as *"an industrial revolution for the digital age"*. Given that over half of all direct metallic ALM systems in the UK were installed in the past 12-months, there is some evidence to suggest, that although not yet a full blown revolution, changes are afoot. The true scale of direct metallic ALM will only become clear as the processes are validated into new market sectors and demanded by corporate customers. However, it is not inconceivable to imagine hundreds, if not thousands of machines supporting industry in the future, if the economic balance.

ABOUT THE AUTHOR

Dr Phil Reeves *(PhD Engineering, BEng Hons manufacturing)* is the managing director of Econolyst Ltd, and an experienced Rapid Manufacturing Strategist. Phil has undertaken a number of projects, which focus on the implementation of Rapid Manufacturing systems into businesses, society and the global economy. Phil Reeves graduated from Brunel University with an honour's degree in Product Design & Manufacture Engineering and Nottingham University with a PhD in Advanced manufacturing focused on the Additive Manufacturing Stereolithography process. His career has centred within business to business consulting, strategic business planning and the business functions of new product & process innovation. Phil has now focused on stimulating and supporting the growth of the Rapid Manufacturing economy.

Econolyst Ltd is a UK based consultancy firm dedicated to providing technology strategies, project management, research and training in Additive Layer Manufacturing (ALM) technologies, and Rapid Manufacturing (RM) applications. Econolyst work with both private sector businesses looking to implement RM and public sector bodies responsible for assisting companies with technology change. Econolyst uses a six step 'RM implementation methodology' to assist companies around the world to fast track ALM processes into RM applications. we provide dedicated RM staff development through our ‘RM-Master Classes’, a series of interactive 1 or 2-day training programs for engineers, designer and business managers. Econolyst also provide support to Colleges, Universities and Research Technology Organisations across Europe looking to develop Rapid Manufacturing programs of education for both students and industrialists. Through our ‘RM-Media Service’, we can provide bespoke packages of video footage, process animations and interviews with leading ALM process and material vendors, and RM technology users. To maintain our unrivaled knowledge base, we are engaged in a number of National and European research projects and initiatives focused wholly on RM. We are always happy to assist clients from both the industrial and educational sectors with research funding applications and project bid writing.

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