A REVIEW OF HYBRID MANUFACTURING

K. A. Lorenz*†, J.B. Jones§, D. I Wimpenny* and M.R. Jackson†

*The Manufacturing Technology Centre, Ansty Business Park, Coventry, CV79JU, UK
†EPSRC Centre for Innovative Manufacturing for Intelligent Automation, Loughborough University, Hollywell Way, LE11 3UZ, UK
§ Hybrid Manufacturing Technologies, 2000 North Central Expressway, Ste. 200, Plano, Dallas, Texas, USA

Abstract

In recent years the combination of laser-based Additive Manufacturing and Computer Numerical Controlled (CNC) machining has become increasingly popular, with several machine tool manufacturers exhibiting products based on different machine tool configurations. This technology, widely known as Hybrid Manufacturing, generally exploits Directed Energy Deposition processes using powder feedstock that is fed into a melt pool created by a laser. Although Directed Energy Deposition processes predate powder bed fusion Additive Manufacturing (at least in terms of coating and repair applications), commercialization of Hybrid Manufacturing systems is still very much in its infancy. However, they do offer clear advantages, combining a high deposition rate together with the accuracy and surface finish associated with machining. This paper presents the history of the development of Hybrid Manufacturing Systems (HMS), dating back from work undertaken in the mid 1990s through to the present day. The relative merits of different material deposition approaches are compared and some of the key technical challenges which remain are highlighted and discussed.

Introduction

Global manufacturing pressures place a significant demand on processes to provide flexibility and efficiency whilst maintaining part quality. For complex parts the production sequence may involve numerous process steps, involving multiple setups in different production cells. Transfer and set up of parts can be inefficient, time consuming and introduces the risk of errors, as well as lowering the overall process accuracy. Moreover, using multiple processing cells consumes valuable shop floor space. Significant advantages can be achieved by combining multiple processes in the same machine. These commercial benefits are key drivers in the development of machine tools which allow several machining operations to be conducted in a single cell, such as Mazak's Integrex machines. This range of Computer Numerical Control (CNC) machine tools combines milling and turning in one process cell to offer a done-in-one™ solution, a process referred to as multi-tasking. It has been reported that a multi-tasking machine that has one operator and one program can replace up to five machines with three operators and five programs significantly reducing part costs and processing times [1, 2].

Additive Manufacturing (AM) of metals is now transitioning from production of prototypes to manufacture of end-use parts, especially in the aerospace sector [3]. Although AM offers geometric flexibility, high percentage of material utilization (significantly reducing the buy-to-fly ratio) it suffers from poor surface finish, long cycle time and poor accuracy. Conversely, these disadvantages are all benefits of CNC machining, especially when using the multi-tasking approach.

Combining AM and CNC machining into a hybrid additive and subtractive machine would seem to be a logical step for multi-tasking technology. This paper will focus on the combination of blown powder laser Directed Energy Deposition (DED) into a Computer Numerical Controlled (CNC) machine tool by presenting a timeline of research and commercial machine release. This will include a comparison of different machine tool platforms and present some of the challenges currently faced in the hybrid approach. However, first it is important to introduce the different types of DED and the relative merits of each kind of feedstock and heat source.

Directed Energy Deposition (DED)

Directed Energy Deposition (DED) is an AM process whereby a focused heat source is used to melt feedstock which is deposited as a bead in a '3D welding' approach [4], resulting in a metallurgical bond between layers. DED has been highlighted as one of the AM technologies that will have a significant impact on the aerospace industry [5]. The source used to generate the heat in DED can vary, but is most commonly either a laser, electron beam or plasma arc; the merits of each will be discussed later. DED process are different to powder bed fusion methods as the material is fed into the weld pool as a controlled stream of powder or a wire filament.

The size of the feed stock, powder or wire, has a direct bearing on the surface finish of the part created. For small to medium sized parts, that require little or no post-processing, the feedstock for DED tends to be powder, as it is available in much smaller sizes than standard gauge wire. Generally, this powder is gas atomized [6-8] and for DED often has a range anywhere between 15 – 180 microns. There are advantages of using different particle size distributions within this range. These advantages are best described in the work undertaken by Nestler, Sharma [9] as indicated in the graph shown in Figure 1.

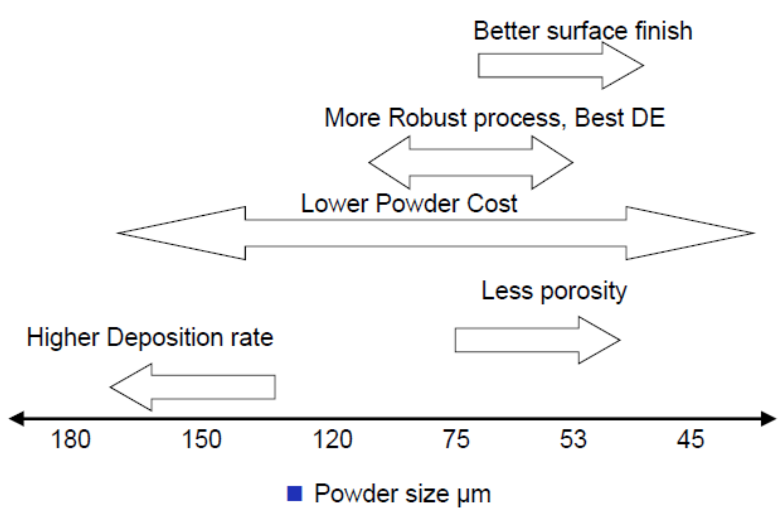


Figure 1 A graph detailing the merits of different particles size distributions of powder in blown powder DED [9].

In blown powder DED metal powder is supplied to the melt pool using a gravitational powder feeder and inert carrier gas via a processing head. The processing head channels the powder either coaxially or off axis, an example of this is as sketched in Figure 2. Unfortunately, the catchment efficiency (ratio of powder supplied to that consolidated) of blown powder DED is never 100% and can be less than 50% for some part configurations. The unfused (over spray) powder represents an economic and environmental problem, pushing up the cost of the process and contaminating the processing cell. Consequently, there is demand to increase efficiency of blown powder DED by reducing overspray and capturing excess powder.

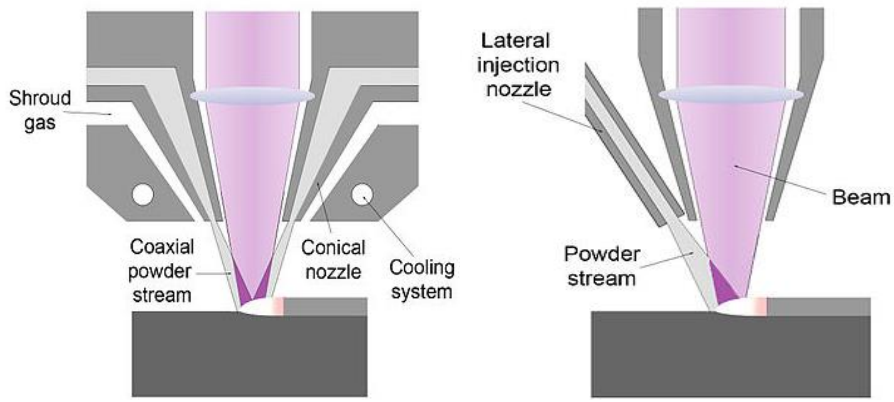


Figure 2 Left is a cross-section sketch of a coaxial blown powder processing head. Right is a cross-section sketch of an off-axis blown powder processing head [5]

Unfortunately, there are significant challenges, including investment in equipment, with capturing and classifying the excess powder and moreover ensuring it is still suitable for use (not contaminated or degraded). Furthermore, capturing and classifying highly reactive powders such as titanium or aluminum alloys present a potential fire risk, even with specialized and costly ATEX rated equipment. Therefore, depositing large quantities of material for long periods using blown powder DED may not be the most cost effective solution due to the poor powder capture efficiency and difficulty in reusing any waste powder. However, this disadvantage has to be measured against the merits of using powder feed stock including better surface finish and material availability.

Metal wire is an alternative feedstock used in DED processes. The capture efficiency of the process approaches 100 % and it avoids many of the challenges associated with processing metal powders. Although metallic wire is readily available (commonly used in welding) it is only available in a limited size range and not all materials are suitable. Metal wire can be fed into the melt pool either off axis or coaxially, much like the powder processing heads, as shown in Figure 2.

The characteristics of a deposition can be characterized by several geometrical, mechanical and material properties. Although mechanical and some material properties may vary between different materials the geometrical features of a deposition remain the same; these are best described by the sketch in Figure 3, where W, h and θ are the width, height and wetted angle of the deposition, and b is the clad depth. An important property of a deposited track is the dilution, geometrically this is a percentage that defines the area that has melted into the base material and can be calculated by $b/(h+b)$ [10]. Although dilution can be simply presented as a percentage it is in fact a result of a complex function of the focused heat source, process feed and material deposition rate [11]. Almost all manufacturing processes surfer from inherent defects, this is the same with DED. Some of the typical defects that occur are lack of fusion, interun porosity, porosity, ‘hot cracking’ and dilution.

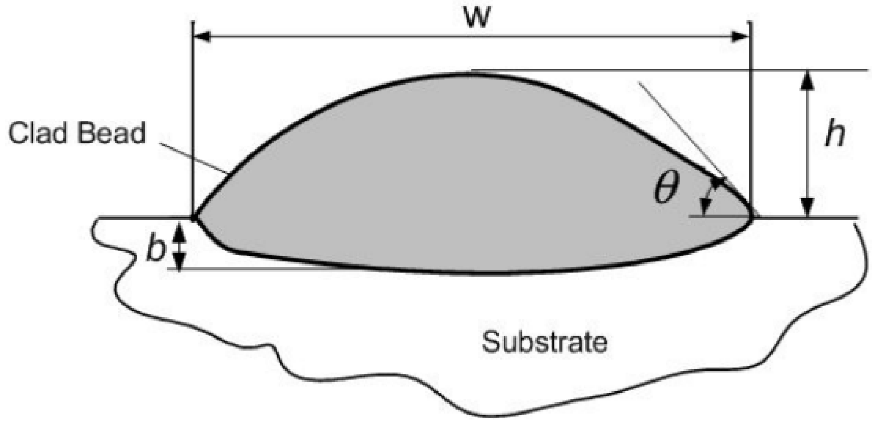


Figure 3 A sketch of a cross section of a typical deposition [10]

As mentioned earlier there are different methods used to generate the heat source for DED, these include laser, electron beam and Plasma Transfer Arc (PTA). A true comparison of the advantages and disadvantages of each heat source and their interaction with the different feed stocks is out of scope of this paper, however, Table 1 briefly summarizes some of the benefits associated with each heat source.

Table 1 A comparison of the different heat sources available for DED.

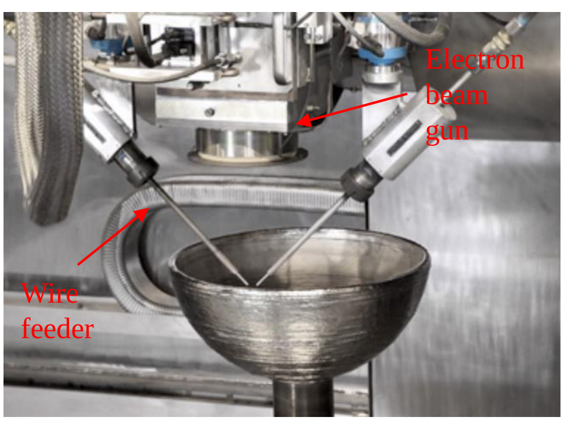
	Laser	*Electron Beam*	*Plasma Transfer Arc*
Advantages	Good control over dilution. Low heating of work piece Fiber delivered laser allows for integration into a wide range of platforms	Ability to manipulate the electron beam into multiple beams Cleanliness of a low pressure atmosphere	Lower capital costs, particularly for high power systems
Disadvantages	Lowest efficiency (wall-to-plug) as well as coupling efficiency % Cost of laser significantly increases with power	Requires a low pressure atmosphere which may contribute to high capital cost and long processing time required for evacuation of chamber	Medium to high heating of work piece Difficult to control dilution below 10%

Commercially Available DED

Conventionally, blown powder laser DED has been used for coating surfaces and repair [12-14], and is most commonly referred to as laser cladding. Wilson, Piya [15] demonstrate the successful repair of defective voids in turbine airfoils with 316L, which includes generating tool paths based on a 'worn' component using blown powder laser DED. More recently DED has been used for the application of new part manufacture for the aerospace and defense sector for various materials such as Titanium Ti-6V-4Al, nickel alloys and Stainless Steels [6-12]. There are a wide variety of commercial DED systems which use different heat sources and feedstock; Table 2 is a list of some available systems.

Table 2 A list of different commercially available DED solutions and services.

Company	*Location*	*Heat source*	*Feedstock type*	*Supported materials*	*Maximum working area (LxWxH) mm*	
Sciaky	Chicago, Illinois, USA	Electron beam	Wire	Titanium Inconel, Tantalum, Tungsten, Stainless Steels and more	5800 x 1200 x 1200	[16]
Norsk Titanium	Hønefoss, Norway	Plasma arc	Wire	Titanium	2150 x 1200 x 1800	[17]
RPM Innovations	Rapid City, South Dakota, USA	Laser	Powder	Wide variety of metal powders	1500 x 1500 x 2100	[18]



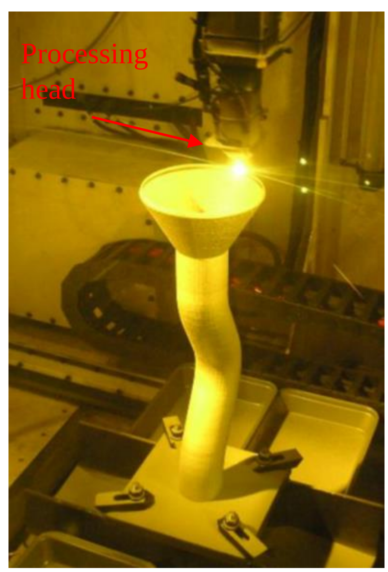


Figure 4 Left a picture of a fuel cell being built on the Sciaky EBAM machine. Right a picture of a complex automotive component being manufactured on the RPM Solutions machine [18, 19].

Figure 4 left is a picture of a near net shape billet manufactured using the Sciaky Electron Beam Additive Manufacturing (EBAM) cell. The Sciaky EBAM cell uses an electron beam to generate a melt pool which is supplied by either single or dual wire enabling a functionally graded component or higher deposition rates with the same material. The working envelope of the machine makes it ideal for wide variety of large parts up to 5.8 m in length, far beyond the working envelope of current powder bed fusion machines. However, the coarse beads of material produce undulations and pronounced stair stepping on inclined surfaces [20]. For this reason it is usual to machine the surface of a DED AM part to achieve a suitable surface finish or accuracy [21]. Using AM and CNC machining in tandem can be best explained by the sketch shown in Figure 5 where the intended surface can be achieved by overbuilding parts with a post processing step, by milling, turning, grinding etc.

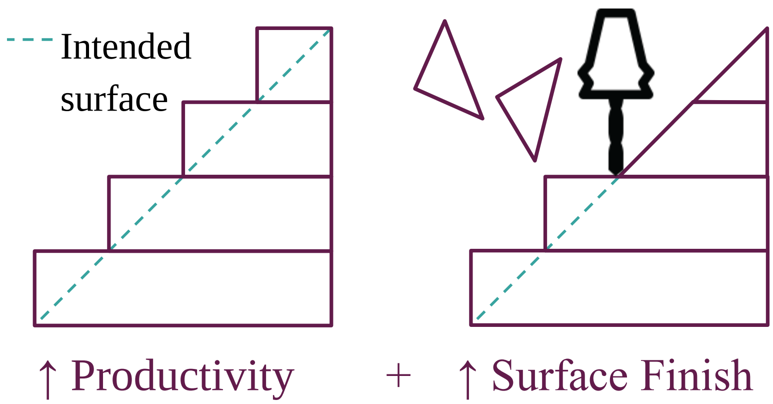


Figure 5 Cross-sectional view showing how an overbuilt part can be machined using the combination of AM and CNC machining [21].

Hybrid Systems and Research

The approach of having more than one cell to first deposit either an oversize near net shape billet or build a final part and then finish it is costly and consumes valuable shop floor space. Moreover, each cell entails separate programming and operations, all of which can contribute to long lead times. Therefore, there is an argument to combine AM with high productivity machining into one cell overcoming the drawbacks and exploiting the advantages synergistically. The most popular approach has been to integrate blown powder laser DED into a horizontal or vertical machining center [22-29] with research first taking place in the mid to late 1990s by Klocke and Wirtz [22]. Table 3 is a timeline in chronological order from inception to the release of commercial systems of the combination of blown powder laser DED and subtractive machining. The date used to arrange the table is that when the research or system was disseminated to the public, in journals, online articles or exhibitions. Consequently, it is very difficult to explicitly state when the institute or company first started research in the area of hybrid manufacturing.

Table 3 A timeline of Hybrid Manufacturing research and commercially available systems.

Date	*Process name*	*Institute or Company*	*Machine tool type*	*Processing head mounting position*

1996	Combined Metal Build Up (CMB)	Fraunhofer Institute of Production Technology & Fraunhofer Institute of Laser Technology	3-axis vertical	Fixed to side of spindle	[22]
1990's	Laser Aided Manufacturing Process (LAMP)	University of Missouri	5-axis vertical	Fixed to side of spindle	[27]
2000	Selective Laser Cladding (SLC) and milling	National Taiwan University of Science and Technology	3-axis vertical	Fixed optics (separate station)	[30]
2004	Hybrid Manufacturing	Joanneum Research Forschungsgesellsc haft mbH, Austria	5-axis vertical	Fixed to side of spindle	[31]
2006	System and method for fabricating and repairing part	Southern Methodist University	Multi-axis	Attached to a robot	[32]
2008	Hybrid Manufacturing	De Montfort University & The Manufacturing Technology Centre	3-axis vertical	In spindle stored in tool magazine	[33]
September 2013	Hybrid Manufacturing	Hamuel & Hybrid Manufacturing Technologies	Retrofit to any machining platform	In spindle stored in tool magazine	[34]
December, 2013	Hybrid Manufacturing	DMG Mori	5-axis vertical	In spindle stored in own compartment	[35]
November, 2014	Hybrid Multi-Tasking	Mazak & Hybrid Manufacturing Technology	5-axis horizontal	In spindle stored in tool magazine	[36]
April, 2015	Additive Manufacturing	WFL Millturn Technologies	5-axis slantbed lath	Unknown	[37]
May, 2015	LENS®	Optomec	Retrofit to any machine platform	Fixed to side of spindle	[38]
June, 2015	Hybrid Manufacturing	ELB & Hybrid Manufacturing Technologies	millGrind Creep Feed 5 axis	Fixed to side of spindle	[39]

Note: the timeline omits further research from the same institute or company leading to gaps between the late 1990s to the first commercial release in 2013.

Ruan, Eiamsa-ard [28] developed a process to generate toolpaths for a non-uniform layer (in thickness) which is reported to increase efficiency of manufacturing hybrid parts. Liou, Slattery [26] successfully demonstrated the use of a Hybrid Manufacturing System (HMS) to manufacture metallic parts which included simulation of powder flow and powder-laser interaction. They also demonstrate building a small part with an overhanging feature that requires no support structure, pictured in Figure 6. This approach could further increase the catchment efficiency of the entire process as material is not wasted on support structure.

Figure 6 Picture of a part produced by a 5 axis Hybrid Manufacturing machine [26]

In 2012 Jones, McNutt [33] debuted a HMS that was able to store the deposition head in the tool magazine of a machine tool, allowing for seamless transition between milling, cladding and inspection [40]. To do this a novel method of coupling/uncoupling (docking) the cladding head to the laser, processing gas and powder feed was developed. The development work was undertaken in the RECLAIM project, supported by Innovate UK (formerly The Technology Strategy Board) in the United Kingdom. In late 2012, at the end of the project, a spin-out company Hybrid Manufacturing Technologies Ltd was formed to commercialize the "docking" processing tool approach which enables multiple processing heads to be used in a single manufacturing operation without the need for manual intervention. This ability of having multiple processing heads in one machine allows for a flexible approach to modern manufacturing and may eventually elevate many pressures of global manufacturing. Figure 7 is a picture of the world's first commercially available tool changeable blown powder laser DED processing head by Hybrid Manufacturing Technologies.

Figure 7 A picture of the world's first commercially available tool changeable blown powder DED processing head for a Hybrid machine [21]

Hybrid Manufacturing Technologies blown powder laser DED solution, commercially known as the Ambit™ system, can retrofit to almost any machine tool platform. Since the release of this technology, in 2012, Hybrid Manufacturing Technologies have contributed to the release of the worlds first Hybrid machine with multiple processing heads the INTEGREX i-400 AM made by Yamazaki Mazak Corporation at JIMTOF 14 in November of 2014; this is pictured in Figure 8.

Figure 8 A picture of the Yamazaki Mazak INTEGREX i-400 AM [36]

Challenges of Hybridization

To fully understand the impact of Hybrid Manufacturing it is important to mention some of the critical challenges faced for the hybrid approach. The critical challenges can be split into technical challenges and cultural/adoption challenges. Over the next few paragraphs a few of the technical and cultural challenges will be discussed.

It has been reported by Nau, Roderburg [41] that the process of integrating technologies to create a hybrid cell is typically split into the following three activities: (1) process and parameter development; (2) integration into a commercial manufacturing environment; (3) evaluation and testing; knowledge and process management.

Process and parameter development: The parameters for the machining of well-established alloys are easily obtainable from many cutter tool suppliers, in easy-to-access platforms such as mobile apps or online applets [42, 43]. This is accompanied with, generally, a wealth of knowledge from machine tool operators on account of the maturity of the process. Parameters for blown powder laser DED are slightly more difficult to obtain, there are various research papers detailing the approach to optimize parameters for different materials [44, 45], however, the research explicitly states that before optimization initial parameters need to be determined based on prior knowledge in the field [45]. On account of the infancy of HMS it is unclear how the parameter dissemination will be handled which is critical to the uptake of the technology. Parameters for subtractive machining supplied by cutter tool suppliers are often an indication. Moreover, machining at the wrong parameters will often cause cutter tools to break but will rarely cause part(s) to be scrapped. However, the wrong parameters for blown powder laser DED may cause unwanted defects which may result in the final component being out of specification.

There are several approaches that could be implemented to tackle the issue of parameter development of HMS, some of which are known from the powder bed fusion market. Some of these concepts are: equipment suppliers provide parameters for specific cladding head/material combinations (this could include a cost of licensing the parameters); equipment suppliers provide training to enable operators to develop their own parameters or equipment suppliers declining to be involved in any parameter development. However, the latter could be detrimental to the growth of the hybrid approach.

Integration: Integrating blown powder laser DED into a machine tool forces some immediate technical challenges to be tackled, these are the use of coolant and maintaining the working envelope of the machine tool. The laser processing equipment found in a HMS normally consists of a laser and optics to generate and focus infrared light on the substrate. It is critical that the cleanliness of the optical chain is kept intact otherwise it could affect beam quality and more seriously permanently damage the laser unit through reflection phenomena. The early inceptions of HMS using blown powder laser DED, detailed in Table 3, have all had the processing heads attached off-spindle center line. This approach uses a fixed optical chain, however as the processing heads are in the machining envelope special attention needs to be paid to the coolant strategy when machining to ensure that the optics do not get contaminated. Additionally, the off-spindle centerline approach consumes valuable stroke of the machine limiting the additive stroke significantly. This has been overcome in recent years with the commercial release of various systems that tool change like the HMT Ambit™ and DMG MORI HMS. The HMT Ambit™ system uses a novel docking technology that allows for more than one processing tool, which can be stored in the machine tool magazine protecting the processing tools from contamination during machining. The DMG MORI HMS has a fixed umbilical cord which currently limits the processing tool to one, however, very much like the HMT Ambit™ system it stores the processing head in a compartment outside the envelope of the machine, also protecting the processing head from contamination. Given the recent release of several commercial systems it does appear that many of the integration issues of HMS have been resolved.

Knowledge and process management: The knowledge and process management of HMS is currently closely linked to the process and parameter integration. This is on account of finding suitable operators, capable of complex (often 5 axes) machining as well as taking on the responsibility for the material addition steps of the process.

Conclusion

In the past 4 years there has been a plethora of Hybrid Manufacturing Systems commercially announced with some now available either as a retrofit option onto an existing platform or a new combined machine from a machine tool manufacturer. As the technology is still in its infancy it is unclear where it lies in the Technology Readiness Level and its potential for high value manufacturing for highly demanding industries such as aerospace and defense. However, combining high productivity machining with material deposition is beginning to gain traction in the repair of blades, hard facing and other opportunities where it promises to reduce cost for repair applications.

A key challenge to overcome is not only the training off staff for complex Hybrid machines but also how parameters for material deposition are handled. It would be naïve of equipment suppliers to just rely on the knowledge of the operators like it is for machining with little or no support.

Acknowledgements

The authors of this paper are extremely appreciative for the funding provided by the Engineering and Physical Sciences Research Council (EPSRC) and The Manufacturing Technology Centre who are jointly sponsoring an Engineering Doctorate for Keith Lorenz.

References

1. ANON. *Integrex i done-in-one*. 2015 [cited 2015 11/07]; Available from: http://www.mazak.eu/Multi-tasking-machines/Integrex-i-series.
2. Nagae, A., T. Muraku, and H. Yamamoto, *History and Current Situation of Multi-Tasking Machine Tools.* SME-Japan, 2012: p. 1-5.
3. ANON. *Rolls-Royce Breaks AM Record* Focus PM 2015 [cited 2015 11/07]; Available from: https://www.mpif.org/Newsroom/Focus_022.asp?linkid=133&week=070915#apm2_2.
4. International, A., *Standard Terminology for Additive Manufacturing Technologies*. 2015, ASTM International: United States.
5. Wimpenny, D.I., R.A. Trepleton, and J.B. Jones. *Additive Manufacturing in the Aerospace Industry*. in *16th International Machine Tool Engineers' Conference*. 2104. Tokyo, Japan: Japan Machine Tool Builders Association.
6. Ashgriz, N., *Handbook of Atomization and Sprays: Theory and Applications*. 2011: Springer.
7. Dunkley, J.J., *Which atomization route to high alloy steel powders*. 1990.
8. Yule, A.J. and J.J. Dunkley, *Atomization of melts for powder production and spray deposition*. 1994: Oxford University Press.
9. Nestler, M., S. Sharma, and T. Peters, *Powder development and manufacturing for laser cladding/LAM processes*, in *Laser Additive Manufacturing Workshop 2013*, S. Metco, Editor. 2013, s.n.: Houston, United States. p. 20.
10. Toyserkani, E., A. Khajepour, and S.F. Corbin, *Laser cladding*. 2004: CRC press.
11. Da Sun, S., et al. *Microstructure and mechanical properties of laser cladding repair of AISI 4340 steel*. in *28th International Congress of the Aeronautical Sciences*. 2012.
12. Boisselier, D. and S. Sankaré, *Influence of Powder Characteristics in Laser Direct Metal Deposition of SS316L for Metallic Parts Manufacturing.* Physics Procedia, 2012. **39**(0): p. 455-463.
13. Boisselier, D., S. Sankaré, and T. Engel, *Improvement of the Laser Direct Metal Deposition Process in 5-axis Configuration.* Physics Procedia, 2014. **56**(0): p. 239-249.
14. Calleja, A., et al., *Improvement of strategies and parameters for multi-axis laser cladding operations.* Optics and Lasers in Engineering, 2014. **56**(0): p. 113-120.
15. Wilson, J.M., et al., *Remanufacturing of turbine blades by laser direct deposition with its energy and environmental impact analysis.* Journal of Cleaner Production, 2014. **80**(0): p. 170-178.

16. ANON. *Electron Beam Additive Manufacturing (EBAM)*. 2015 [cited 2015 30/06]; Available from: http://www.sciaky.com/additive-manufacturing/electron-beam-additive-manufacturing-technology.
17. ANON. *Game changing technology for the production of complex Titanium components*. 2015 [cited 2015 30/6]; Available from: http://www.norsktitanium.no/en.aspx.
18. ANON. *Innovative Solutions for Industry*. 2015 [cited 2015 20/6]; Available from: http://www.rpm-innovations.com/.
19. ANON. *EBAM Drives Innovation for Many Applications and Industries*. 2015 [cited 2015 01/07]; Available from: http://www.sciaky.com/additive-manufacturing/applications-industries.
20. Rombouts, M., et al., *Surface Finish after Laser Metal Deposition.* Physics Procedia, 2013. **41**(0): p. 810-814.
21. Jones, J.B. *The Synergies of Hybridizing CNC and Additive Manufacturing*. in *Rapid*. 2014.
22. Klocke, F. and H. Wirtz, *Direct Manufacturing of Metal Prototypes and Prototype Tools*, A. Fraunhofer Institute of Laser Technology, FRG, Editor. 1996: United States. p. 140-148.
23. Amine, T., J.W. Newkirk, and F. Liou, *An investigation of the effect of direct metal deposition parameters on the characteristics of the deposited layers.* Case Studies in Thermal Engineering, 2014. **3**(0): p. 21-34.
24. Eiamsa-ard, K., et al. *Toward automatic process planning of a multi-axis hybrid laser aided manufacturing system: skeleton-based offset edge generation*. in *ASME 2003 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. 2003. American Society of Mechanical Engineers.
25. Eiamsa-ard, K., J. Zhang, and F.W. Liou. *Skeleton-based Geometric Reasoning for Adaptive Slicing in a Five-axis Laser Aided manufacturing Process System*. in *Solid Freeform Fabrication Conference, University of Texas-Austin*. 2001.
26. Liou, F., et al. *Applications of a hybrid manufacturing process for fabrication and repair of metallic structures*. in *Proceedings of the Seventeenth Solid Freeform Fabrication Symposium*. 2006.
27. Nagel, J.K.S. and F.W. Liou, *Hybrid Manufacturing System Design and Development*, in *Manufacturing System*, F.A. Aziz, Editor. 2012, InTech: United States. p. 223-224.
28. Ruan, J., K. Eiamsa-ard, and F.W. Liou, *Automatic Process Planning and Toolpath Generation of a Multiaxis Hybrid Manufacturing System.* Journal of Manufacturing Processes, 2005. **7**(1): p. 57-68.
29. Wang, Z., et al., *Stereo vision based hybrid manufacturing process for precision metal parts.* Precision Engineering, 2014(0).
30. Jeng, J.-Y. and M.-C. Lin, *Mold fabrication and modification using hybrid processes of selective laser cladding and milling.* Journal of Materials Processing Technology, 2001. **110**(1): p. 98-103.
31. Kerschbaumer, M. and G. Ernst. *Hybrid manufacturing process for rapid high performance tooling combining high speed milling and laser cladding*. in *Proceedings of the 23rd International Congress on Applications of Lasers and Electro-Optics (ICALEO), San Francisco, CA*. 2004.
32. Kovacevic, R. and M.E. Valant, *System and method for fabricating or repairing a part*. 2006, Google Patents.

33. Jones, J.B., et al., *Remanufacture of turbine blades by laser cladding, machining and in-process scanning in a single machine.* 2012.
34. Jones, J.B. *World's first commercially available hybrid CNC*. 2013 [cited 2015; Available from: http://www.hybridmanutech.com/news.html.
35. Woodcock, J. *Euromold roundup - bigger, bolder, busier* 2014 [cited 2015 27/7]; Available from: http://www.tctmagazine.com/blogs/jwblog/euromold-roundup-2013/.
36. Molitch-Hou, M. *Mazak Adds Hybrid Metal 3D Printer to Machine Tool Lineup*. 2014 [cited 2015 27/7]; Available from: http://3dprintingindustry.com/2014/11/04/mazak-hybrid-metal-3d-printer/.
37. Allcock, A. *WFL Millturn Technologies Open House underlines big developments*. 2105 [cited 2015 27/7]; Available from: http://www.machinery.co.uk/machinery-features/wfl-millturn-technologies-kyal-machine-tools-additive-manufacturing/75353/.
38. Koenig, B. *Optomec Unveils Hybrid Machine for 3D Printing, Traditional Manufacturing*. 2015 [cited 2015 27/7]; Available from: http://www.optomec.com/optomec-unveils-hybrid-machine-for-3d-printing-traditional-manufacturing/.
39. Jones, J.B. *Additive Reaches a New Level of Precision: World's First Grinding Machine with Additive*. 2015 [cited 2015 27/7]; Available from: http://www.hybridmanutech.com/news.html.
40. ANON. *RECLAIM Project - Remanufacturing the Future*. 2012 [cited 2015 27/7]; Available from: https://hvm.catapult.org.uk/-/reclaim-project-remanufacturing-the-future.
41. Nau, B., A. Roderburg, and F. Klocke, *Ramp-up of hybrid manufacturing technologies.* CIRP Journal of Manufacturing Science and Technology, 2011. **4**(3): p. 313-316.
42. Sandvik. *Machining Calculator*. 2015 [cited 2015; Available from: http://www.sandvik.coromant.com/en-gb/knowledge/calculators_and_software/apps_for_download/pages/machining-calculator-app.aspx.
43. Kennametal. *Engineering Calculators*. 2015 [cited 2015; Available from: http://www.kennametal.com/en/resources/engineering-calculators.html.
44. Sun, Y. and M. Hao, *Statistical analysis and optimization of process parameters in Ti6Al4V laser cladding using Nd:YAG laser.* Optics and Lasers in Engineering, 2012. **50**(7): p. 985-995.
45. Lin, C.-M., *Parameter optimization of laser cladding process and resulting microstructure for the repair of tenon on steam turbine blade.* Vacuum, 2015. **115**(0): p. 117-123.