The Synergies of Hybridizing CNC and Additive Manufacturing

Jason B. Jones, PhD

Hybrid Manufacturing Technologies, Plano, Texas, USA & Coventry, Warwickshire, UK

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ABSTRACT

Since its inception, Additive Manufacturing (AM) has been dominated by stand-alone system architectures. This has fostered implementation of AM independent from other manufacturing technologies. With mirrored myopia, the CNC world has largely been an idle spectator to the advancements in AM of metals during the last decade.

The compatible and complementary nature of CNC and AM means that they need not and should not be mutually exclusive. To fully leverage the potential synergies of additive and subtractive technologies, hybrid machine tools, equipped for CNC and AM, enable the use of both technologies in optimal proportions as needed. This paper demonstrates hybrid CNC machines equipped with laser cladding capabilities. This combination provides an ideal platform for high-value part repair, refurbishment and modification. It enables in-process finishing of metal AM parts, typically achieving an order of magnitude improvement in accuracy and surface finish straight out of the machine (including elimination of stair-stepping effects inherent in layered manufacturing). Furthermore, interleaving material deposition and milling enables the creation of unique hybrid parts which are not achievable using either technology independently. The author asserts that as AM surges forward with end-use part production, the sun is setting on the era of its use in isolation.

1 Introduction

The combination of AM with CNC has been widely practiced in academic and research circles and even in isolated industrial applications for many years. Despite the widely acknowledged benefits [1-6] of this combination, its implementation has been limited primarily for reasons of practicality [7]. This paper reports progress to implement additive functions (especially directed energy deposition) into CNC machine tools so that changeover from adding material to subtracting (milling) it is as easy as a conventional tool change. This paper reports interim progress of an ongoing case study of this new hybrid approach following on from a report ~two years ago [8].

1.1 The productivity dilemma

Despite many improvements to AM in the last decade, its productivity is typically an order of magnitude lower than CNC. In fact, one study recently asserted that CNC technology (rather than AM) is the primary driver and facilitator of the maker and customization trends in the market [9]. This fact incentivizes AM to improve its productivity which leads to the following dilemma:

Inherent in all planar layer-based AM methods is the tension between the desire to improve surface finish without sacrificing productivity and vice versa (Figure 1). This issue has been a strong and recurring theme for more than two decades according to Bourell [10] and features prominently in virtually every roadmap the author is aware of [for example see 11, 12]. Perhaps this dilemma is most tactfully phrased on Objet machines when the user must choose between “high speed” (high productivity) or “high quality” (improved surface finish), *but cannot have both.*

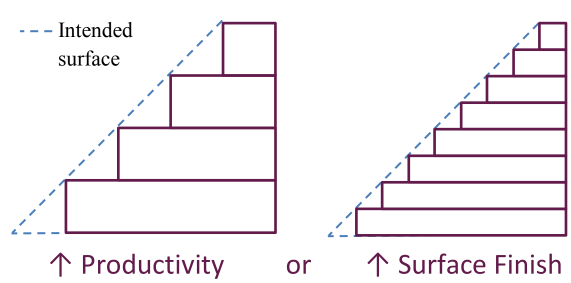


Figure 1: Cross-section showing the productivity dilemma of AM – is it better to have increased productivity or improved surface finish?

2 Why Hybridize?

One approach to solving this dilemma is to combine additive deposition with subsequent machining, thus independently controlling surface finish and productivity (which is largely governed by layer thickness).

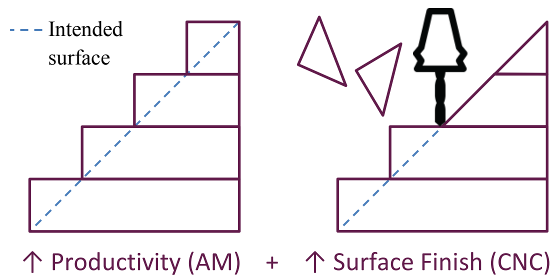


Figure 2: Cross-sectional view showing higher productivity AM deposition, then overbuilt outer surface CNC machined

Using AM in tandem with machining is currently standard practice for the vast majority of metallic parts produced by AM which require machining in order to have a suitable surface finish to mate surfaces, avoid stress risers, improve cosmetics, etc. While this practice provides one answer to the dilemma (and is entirely appropriate for some cases), it requires a substantial investment in multiple machines, operators, etc. A more synergistic approach to integrating these complimentary techniques has been the subject of substantial research since the 1990's when metal AM research began [13-15].

3 Review of Hybrid Approaches

Hybridizing between additive and subtractive technologies has a substantial history [2, 5, 6, 16-20]. A few of these systems are reviewed here for context.

Many AM practices and techniques have grown out of the CNC industry. Some such as FDM/extrusion have selectively incorporated some CNC features, but did not match the form or construction rigidity of CNC. Others such as tape lamination by ultrasonic consolidation have always been undertaken in some variation of a machine tool in order to provide the high accuracy and surface finish needed for the target application.

Dr. Rado Kovacevic led research based at SMU in Dallas to create a tandem system which combined a robot welder with a CNC machine to finish the deposited material [21]. More recently several laser cladding heads have been mounted into a CNC machine most notably work by Steven Nowotny [22].

AeroMet Corp. (Eden Prarie, MN) was one of the early systems which offered laser cladding/deposition on a milling machine and focused on production of aerospace alloys/parts and produced parts flying on the F-15 [23]. Unfortunately, technical problems with the CO_2 lasers, among other difficulties, compromised the viability of the company which has ceased trading.

Work undertaken recently in the EU used a common part fixturing system in a selective laser melting machine and a CNC machine in order to facilitate part transfer between the two [6, 20].

Research at the University of Texas El Paso under the direction of Dr. Ryan Wicker has made a variety of systems which use a CNC machine, primarily for its flexibility as a platform rather than for productivity reasons, to combine different variations of FDM deposition and other technologies [24, 25]. An image of their system is shown in Figure 3.

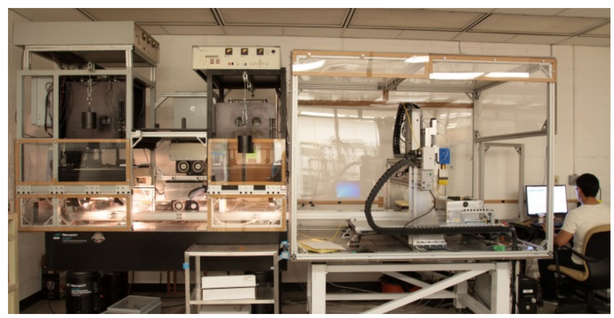


Figure 3: Multi-material, multi-technology FDM which shuttles the part platform back and forth to achieve the combined use of multiple technologies (and multiple materials) in a single build (Image courtesy of Ryan Wicker, University of Texas at El Paso and described in [25])

4 Practicality

Each of the aforementioned endeavors has made a valuable contribution technically and also helped promote understanding of the benefits that make hybrid systems desirable; however to date, none of them has experienced widespread adoption. Apart from ultrasonic consolidation and discontinued historic systems, the only commercial offering of integrated hybrid systems is a combined SLM and CNC machine (Lumex Advance-25, Matsuura, Japan) which has been piloted only in Japan and Asia, with a 2014 North America release announced.

This absence of commercial hybrid offerings, supports the observations of Zue et al. that in combining multiple stand-alone technologies inevitably involves some compromise and a tremendous amount of learning [7]. Furthermore, Nau et al. expressed that one of the challenges for hybrid technologies is "how to launch these technologies into an existing shop-floor" help them realize the "intended productivity" [5].

Given the consensus of potential benefits for hybridizing AM and CNC, yet lack of widespread adoption, it appears self-evident that *practicality has been the primary impediment to its adoption*. The following subsections are dedicated to identifying the development innovations and conditions which the author submits have resulted in the most practical and scalable approach realized to date.

4.1 AM as a (Retrofittable) Machine Tool Accessory

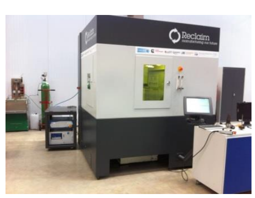
The first step toward improved practicality was to set the scope of development to be an AM system which could be added to virtually *any* CNC machine without fundamentally modifying it. This trajectory was set in part due to uncertainties in the early research project nicknamed RECLAIM [8]. Prior to the commencement of the project in 2008, no machine tool builder could be persuaded to join the research, but with optimism that would be addressed in due course, preliminary work on head development began as soon as the funding was granted. The acquisition of a suitable CNC machine was pursed for two years before resorting to the use of a "nearly end-of-life" CNC machine used by the author for teaching on the MSc course at De Montfort University (which was loaned to the project only after much persuasion). During the initial two years without a machine, progress fell behind schedule and some criticism was raised due to the uncertainty about which machine tool platform would be used as several candidate machines were sought, but not acquired.

In consequence of the lack of a machine tool during the first half of the project, efforts and expectations evolved to focus on development of a laser cladding system which could be *retrofit to virtually any CNC machine* (new or old), regardless of its controller. Although the uncertainty was frustrating at the time, it was a critical constraint which led to adoption of a more practical approach to implement this technology on the shop floor. The last few years has demonstrated the compatibility of the system with a variety of CNC machine formats (including vertical and near horizontal spindles) as shown in Table 1.

4.2 Retrofit: An Untapped Sales Channel for AM

The technical decision to package this cladding system as a machine tool accessory naturally led to the possibility of offering AM as a retrofit onto new, used or end-of-life CNC machines. Although this practice is not entirely unknown [26], augmenting existing machines represents a virtually untapped sales channel in the AM field. The original RECLAIM system (labelled as A in Table 1) was a double retrofit to a) upgrade an end-of-life CNC machine [8] and b) to add the new laser cladding module to it. This approach allowed substantial savings compared to the purchase of a new CNC or alternative motion platform. In connection with the lower cost-of-entry into laser cladding, retrofitting existing CNC machines provides for a way to derive additional value out of end-of-life machines, defer additional capital expenditure and become familiar with the process capabilities with less commercial risk. The benefits of retrofitting to used equipment were confirmed with the order for another system (not shown in Table 1) even before the original hybrid system was fully complete.

Table 1 – Hybrid CNC machines which have been retrofit with tool changeable laser cladding

Machine tool platform	A) Bostomatic BD18	B) Hamuel HSTM 1000	C) GF HPM 450U
No. Axes	4	5	5
Machine type	Vertical milling machine horizontal rotary A-axis	5 axis mill-turn machine with synchronized horizontal rotary axes	Compact 5 axis, vertical milling with tilt-rotary table
Size of machine (XYZ mm)	450x300x300	1450x400x570	600x450x450
Laser power (W)	200	400	1,200
Spindle speed (rpm)	10,000	16,000	12,000
Powder hoppers	1	2	4
Application(s)	Impellers/Parameter dev.	Complex blade repair	New part manufacture
Image of the hybrid systems			

4.3 Open & Transparent Control

The integration of this system into multiple CNC machines necessitated use of conventional G&M code programming for motion (deposition tool paths) and the deposition parameters. This approach makes the system inherently open and "backwards compatible" with existing CNC programming. Thus machinists are able to understand, run and even edit part programs for hybrid processing in the same way they do for subtractive tool paths. In the case of the first Bostomatic machine, the spindle on-off M-code was even hijacked (only while the laser cladding head was in the spindle) in order to turn the laser on and off, thus demonstrating that it is possible to integrate the system without using custom M-codes if absolutely necessary. In subsequent systems user definable M-codes have been used (individually and multiplexed) to augment process control options.

4.4 Deposition on Spindle Centerline

Many researchers have approached the combination of these technologies by mounting welding equipment on the side of the spindle or spindle column [4]. Indeed the early prototypes and developments of this system included bench top and telescopic mounting on the side of the spindle as shown in Figure 4.

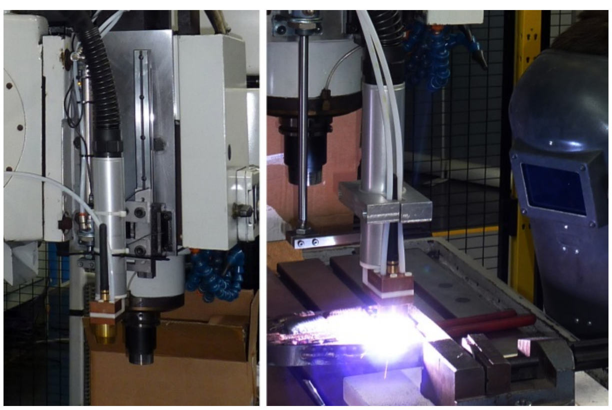


Figure 4: Welding equipment attached to the side of the spindle using a telescopic mount which can be lowered for deposition (right) and then retracted out of the way during other operations (left).

Although mounting on the spindle column provides the desired additive functionality it encroaches on the working area of the CNC machine (because the offset from the spindle centerline effectively reduces the machine travel). This encroachment may be considered only a minor nuisance for large 3-axis machines, however as axes of rotation are added the reduction is compounded dramatically reducing the effective working volume. Furthermore, directed energy deposition typically undertaken with minimal support structures and therefore relies on manipulation of the part with linear and rotary axes. In order to avoid both compromises, it was determined that the laser cladding system would be developed for use on the spindle centerline. The obvious mechanism for mounting a cladding head on the spindle was to use a tool holder.

4.5 Heat Source: Laser

The heat source for directed energy deposition is typically an arc, laser, or electron beam. The development of a system using a laser was prioritized because of the relatively minor changes needed to adapt the machine tool for its use (including beam delivery and fully enclosed/interlocked guarding to make it laser safe). Although an alternative arc-based welding approach was undertaken and is ongoing, the best method for electrically grounding the work piece in four and five axis CNC machines (and avoiding the catastrophic consequences of grounding the high arc voltage through the CNC machine itself) continues to be the subject of research. Furthermore the need for a vacuum environment for effective use of an electron beam discouraged its use where retrofittability is a priority.

4.6 Cable Management for Automated Changeover

Several prior endeavors to combine directed energy deposition into machine tools have used tool holders as the mounting method [22], however as far as the author is aware, in every instance these heads were supplied by an umbilical cable (which was not easily disconnected) which imposes cable management requirements on machine tools during use and storage of the additive head. This created significant compromise, therefore it was determined that to fully capitalize on the benefits of hybrid additive and subtractive systems, convenient disconnecting of the supply lines would be required.

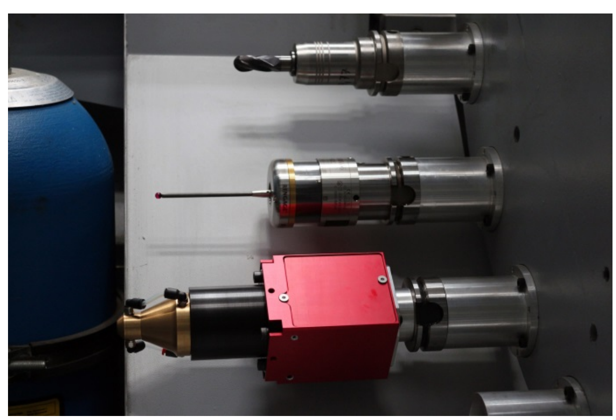


Figure 5: Image showing a developmental cladding head, touch probe, and end mill all co-existing in the tool changer (and disconnected from any supply lines)

The proposed solution was to develop a manifold which would dock with the cladding head when it was loaded into the spindle and then undock after deposition operations. In this way cable management would become much simpler during use of the head and equally importantly, it would facilitate storage of the head outside of the working volume of the CNC machine. Having the head on a tool holder would make the natural place to store it in the tool changer (as shown in Figure 5).

However, after two years of pursuing a docking system without success, (due to a variety of complications concerning reliable connecting and disconnecting fittings for powder, coolant, shielding gas, and laser optics in a compact format), a motion was made to abandon the docking approach and instead settle for mounting the cladding head to the side of the spindle (similar to the approach in Figure 4). After a passionate discussion, the motion did not carry and a working docking solution was developed which indeed enabled automated change over from milling to cladding. An image of the pre-production dock supplying a pre-production head during cladding for a dimensional restoration application is shown in Figure 6.

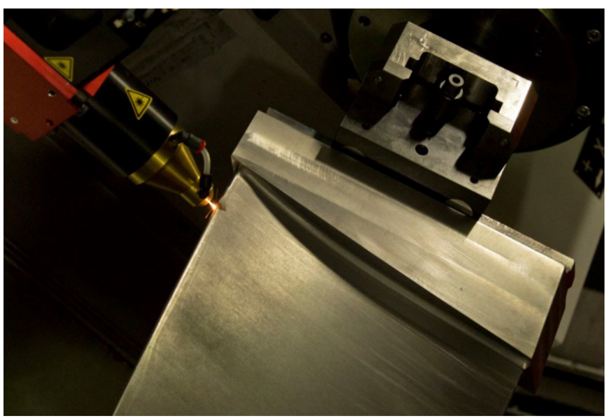


Figure 6: Cladding of a steam turbine blade with the pre-production cladding head and dock as demonstrated at EMO 2013

4.7 Cladding Head Robustness

With an operating docking system came the ability to store the head in the tool changer; however this imposed high acceleration forces on the head which needs precise alignment to function. This requirement was compounded with the need to survive the harsh conditions inside the working volume of a machine tool including high cutting forces, heat, chips, coolant, and a high probability that ultimately it will get crashed into the work piece or its fixturing. A review of all known cladding heads indicated that they were *too fragile* to survive routine use in this environment, and that the nature of some of the optical components would be difficult to make more robust.

In order to achieve robustness, a range of laser cladding heads has been re-designed and re-built from scratch. More delicate optical components were relocated into the docking manifold (which is controlled with more gentle acceleration and deceleration that most tool changers). This enabled a reduction in the number of components (and selection of only robust components) in the heads. Thereby head survival dramatically increases after a drop or CNC crash (all of these are inevitable in a CNC environment and have been tested, sometimes inadvertently, throughout the course of this research and development). Also, in the case of head failure, replacement cost decreases. The ability to readily replace only a portion of the head after an accident, together with the optional redundancy of having additional/spare heads in the tool changer exposes the user to lower financial and downtime risks. This effort has resulted in the first commercially available tool changeable laser cladding head as shown in Figure 7.

Figure 7: The world's first commercially available tool changeable laser cladding head

Another increased measure of system robustness was achieved by storing the head outside the working volume of the machine. Most importantly, the CNC is not restricted from cutting with coolant, as is/has been the case in some alternative approaches. Storage of processing heads in the tool changer helps avoid contamination by chips, coolant, etc. Normally no modification to the tool changer is required; however in certain changers, storage orientations make modifications to the tool pockets or head covers/flaps desirable to provide added protection.

5 The Impact so Far

Although this research began as an academic endeavor (and will doubtless continue to be an ideal platform for research), the underlying aim was to encourage the full engagement of the CNC community with AM.

In late 2012, a number of machine tool builders saw the first working prototype hybrid system (see Table 1).

Hamuel GmbH (Meeder, Germany), a specialist CNC builder for turbine blades, asked it if would be possible to collaborate and show this technology at the EMO 2013 Exhibition in Hannover, Germany (the largest CNC show in Europe). Hybrid Manufacturing Technologies agreed and provided a pre-production cladding system which was collaboratively integrated into an HSTM 1000 machine. The work including demonstration of adaptive repair (Figure 6) and was undertaken in collaboration with Delcam plc (Birmingham, UK) and the Manufacturing Technology Centre (Coventry, UK). The hybrid solution was awarded first place for product innovation (multi-functional machine category) by industry magazine MM Maschinenmarkt. The award and attention it received inspired subsequent activity including a quick reaction by DMG (which created a hybrid system demonstration for Euromold 2013) and subsequently an America Makes award to Optomec to develop a machine tool mountable "LENS engine" derived from their line of dedicated machine solutions, which was announced at the beginning of 2014.

The author asserts that reason for the large scale impact of hybrid approaches in a short time is because a) of the large asymmetry in the respective market sizes of AM and CNC; b) it potentially makes AM relevant to almost anyone who has access to a CNC machine; and c) it taps a mostly latent but intense desire of many machinists to do AM in some form (and perhaps receive a proportion of the attention given to AM of late).

6 The Tool Changer as an Automation Solution

This innovation not only bridges between the AM and CNC worlds, but it opens up the possibility of a new wave of innovation based on the same methodology. The foundational innovation enabling practical use of directed energy deposition AM is the combination of cable management with re-packaging of deposition technology so that it can be transported and deployed easily (in this case mounted onto the highly accurate, yet relatively inexpensive standard tool holders). The combination of these to relatively simple innovations comprises the *new hybrid methodology* which is to use the tool changer (without modification) as an automation system. This eliminates the cost and complication normally associated with part transfer between technologies done up until now by human operators, robots, or other automation solutions. There is no inherent limitation to the types of technologies which can now be mixed and deployed including multiple additive, subtractive and inspection technologies.

For example consider the expanded capability of the current laser-based hybrid system currently in development as illustrated in Figure 8.

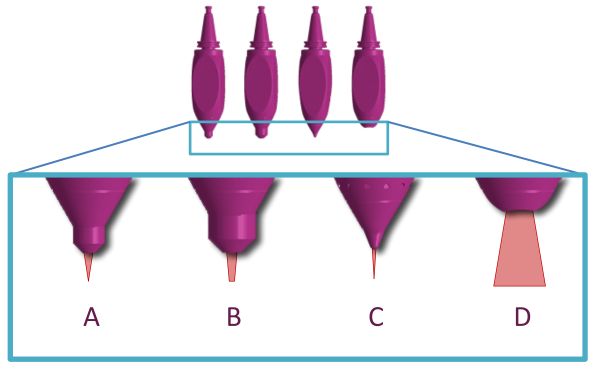


Figure 8: Four different laser-based processing heads are shown each with a different laser profile optimized for A) fine cladding B) high rate cladding C) laser hole drilling and D) divergent focus for area pre-heating, annealing, or heat treatment

The use of a tool changer allows convenient changeover of a variety of laser processing heads – each with optimized optics, powder focus, and shielding gas for a specific task. Using a selection of different heads opens up a wider range of effective operations than is typically achieved using a single processing head (even of the most modern sophistication). Figure 8 shows some examples of the range of heads including: A) a conventional co-axial laser cladding head; B) laser cladding head with optics for top-hat power distribution and focus for a high power multi-mode laser; C) A laser cutting head with optimized profile and high pressure/velocity inert assist gas; D) A parallel or divergent focus head used for cleaning (including for removal of coolant residue), preheating, annealing, heat treatment, etc. Using this set of heads, it is easy to see the dimension restoration of a turbine blade at the fastest possible repair rate where any holes covered over during cladding can be re-opened by laser drilling in the same setup.

This is an example of how hybridizing increases the flexibility of current tools. Combining laser processing with in-machine inspection then builds another layer of in-process quality assurance in a system which can actually correct problems arising (by detection, removal and re-addition of material) before parts simply become very expensive scrap.

7 The Near-Future: Dissimilar Multi-material Parts Through Multiple Technologies

Significant and continued advances in processing speed (productivity) achieved through materials engineering/process optimization will progressively reduce the dilemma discussed in 1.1 which leads to discussion of the next frontier for AM.

For many, the "holy grail" of AM is to be able to combine *dissimilar materials* into multi-material parts with **fully optimized topology and composition** [27].

Doubtless the advances in material engineering and processing will continue to widen the material-set amenable to each deposition technology, however in the short term, this goal has been achieved through the use of multiple deposition technologies, as highlighted by the title of a recent publication by Espalin, et al. [25].

Due to the technical barriers of material and process development, the author proposes that, hybrid systems will more quickly bridge between predominantly single-material (or at least similar material families) stand-alone AM systems toward dissimilar multi-material parts than any one deposition technology on its own. Although hybrid methodology has been demonstrated as a single machine solution it paves the way for related (but not mutually exclusive) methodologies including moving the part between technologies and machines such as has been published by Bovie et al. [6, 20] and others which the author extrapolates will ultimately result in some open/hybrid AM continuous production lines [28].

8 Significance & Conclusion

Hybrid solutions answer the productivity dilemma described in 1.1 and the approach presented opens up a myriad of opportunities to automate the use of multiple technologies to provide an optimized solution to the unique dilemma for making each individual part.

This endeavor has explicitly engaged CNC stake holders with AM. This will ultimately provide a more complete tool set to further empower machinists and AM practitioners alike. CNC and AM need no longer be considered independently, but are to be recast as extremes on the continuous spectrum of hybridized digital manufacturing technologies.

The recent market acceptance and reaction to hybrid approaches definitively marks the start of a new era for the use of AM fully integrated with other technologies.

9 Acknowledgements

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10 References

[1] K. Karunakaran, V. Pushpa, S. B. Akula, and S. Suryakumar, "Techno-economic analysis of hybrid layered manufacturing," *International journal of intelligent systems technologies and applications,* vol. 4, pp. 161-176, 2008.

[2] J. Hur, K. Lee, h. Zhu, and J. Kim, "Hybrid rapid prototyping system using machining and deposition," *Computer-Aided Design,* vol. 34, pp. 741-754, 2002.

[3] X. Xiong, Z. Haiou, and W. Guilan, "A new method of direct metal prototyping: hybrid plasma deposition and milling," *Rapid Prototyping Journal,* vol. 14, pp. 53-56, 2008.

[4] K. P. Karunakaran, S. Suryakumar, V. Pushpa, and S. Akula, "Low cost integration of additive and subtractive processes for hybrid layered manufacturing," *Robotics and Computer-Integrated Manufacturing,* vol. 26, pp. 490-499, 2010.

[5] B. Nau, A. Roderburg, and F. Klocke, "Ramp-up of hybrid manufacturing technologies," *CIRP Journal of Manufacturing Science and Technology,* vol. 4, pp. 313-316, 2011.

[6] K. Boivie, S. Dolinšek, and D. Homar, "Hybrid Manufacturing: Integration of Additive Technologies for Competitive Production of Complex Tools and Products," in *Proceedings of the International Research/Expert Conference:" Trends in the Development of Machinery and Associated Technology" TMT*, 2011.

[7] Z. Zhu, V. G. Dhokia, A. Nassehi, and S. T. Newman, "A review of hybrid manufacturing processes – state of the art and future perspectives," *International Journal of Computer Integrated Manufacturing,* vol. 26, pp. 596-615, 2013/07/01 2013.

[8] J. B. Jones, P. McNutt, R. Tosi, C. Perry, and D. I. Wimpenny, "Remanufacture of turbine blades by laser cladding, machining and in-process scanning in a single machine," in *23rd Annual International Solid Freeform Fabrication Symposium*, Austin, TX, USA, 2012, pp. 821-827.

[9] D. Browne, P. Spielvogel, and J. Rode. (2013). *The Make-for-Me Future. 41*. Available: http://fm.sap.com/data/UPLOAD/files/inquiry-the-make-for-me-future.pdf [Accessed 24 April 2014]

[10] D. L. Bourell, "A Roadmap for Additive Manufacturing – A United States Perspective (Presentation)," presented at the 22nd International Solid Freeform Fabrication Symposium, Austin, Texas, 2009.

[11] R. Quarshie, S. MacLachlan, P. Reeves, D. Whittaker, and R. Blake, "Shaping our National Competency in Additive

Manufacturing," ed. UK: The Additive Manufacturing Special Interest Group for the Technology Strategy Board, 2012.

[12] D. L. Bourell, M. C. Leu, and D. W. Rosen. (2009, Roadmap for Additive Manufacturing - Identifying the Future of Freeform Processing. Available: http://wohlersassociates.com/roadmap2009.html

[13] J. Spencer, P. Dickens, and C. Wykes, "Rapid prototyping of metal parts by three-dimensional welding," *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,* vol. 212, pp. 175-182, 1998.

[14] L. Weiss, F. B. Prinz, and D. P. Siewiork, "A framework for thermal spray shape deposition: The MD* system," in *Solid Freeform Fabrication Symposium Proceedings*, 1991, pp. 178-186.

[15] M. Greul, T. Pintat, and M. Greulich, "Rapid prototyping of functional metallic parts," *Computers in Industry,* vol. 28, pp. 23-28, 1995.

[16] J. Y. Jeng and M. C. Lin, "Mold fabrication and modification using hybrid processes of selective laser cladding and milling," *Journal of Materials Processing Technology,* vol. 110, pp. 98-103, Mar 2001.

[17] Y.-A. Song, S. Park, D. Choi, and H. Jee, "3D welding and milling: Part I–a direct approach for freeform fabrication of metallic prototypes," *International Journal of Machine Tools and Manufacture,* vol. 45, pp. 1057-1062, 2005.

[18] X. Xiong, H. Zhang, and G. Wang, "Metal direct prototyping by using hybrid plasma deposition and milling," *Journal of Materials Processing Technology,* vol. 209, pp. 124-130, 2009.

[19] S. Suryakumar, K. P. Karunakaran, A. Bernard, U. Chandrasekhar, N. Raghavender, and D. Sharma, "Weld bead modeling and process optimization in Hybrid Layered Manufacturing," *Computer-Aided Design,* vol. 43, pp. 331-344, 2011.

[20] K. Boivie, K. Sørby, V. Brøtan, and P. Ystgaard, "Development of a Hybrid Manufacturing Cell; Integration of Additive Manufacturing with CNC Machining," in *Twenty- Second Annual International Solid Freeform Fabrication Symposium - An Additive Manufacturing Conference*, Austin, TX, USA, 2011, pp. 153-163.

[21] R. Kovacevic and M. E. Valant, "System and method for fabricating or repairing a part," ed: Google Patents, 2006.

[22] S. Nowotny, R. Muenster, S. Scharek, and E. Beyer, "Integrated laser cell for combined laser cladding and milling," *Assembly Automation,* vol. 30, pp. 36-38, 2010.

[23] T. Grimm, "Direct Metal on the Rise," *Manufacturing Engineering,* vol. 133, 2004.

[24] A. J. Lopes, E. MacDonald, and R. B. Wicker, "Integrating stereolithography and direct print technologies for 3D structural electronics fabrication," *Rapid Prototyping Journal,* vol. 18, pp. 129-143, 2012.

[25] D. Espalin, J. A. Ramirez, F. Medina, and R. Wicker, "Multi-material, multi-technology FDM: exploring build process variations," *Rapid Prototyping Journal,* vol. 20, pp. 8-8, 2014.

[26] K. Karunakaran, S. Suryakumar, V. Pushpa, and S. Akula, "Retrofitment of a CNC machine for hybrid layered manufacturing," *The International Journal of Advanced Manufacturing Technology,* vol. 45, pp. 690-703, 2009.

[27] J. B. Jones, D. E. Cooper, D. I. Wimpenny, and G. J. Gibbons, "SME Technical Paper TP12PUB36: Gateways Toward Dissimilar Multi-material Parts," presented at the RAPID 2012 and 3D Imaging Conferences & Exposition, Atlanta, GA, USA, 2012.

[28] M. Vaes and K. Polle, "Vision on mass production AM," presented at the RAPID 2012 and 3D Imaging Conferences & Exposition, Atlanta, GA, USA, 2012.

