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Industrialization of metal powder bed fusion through machine shop networking

Vegard Brøtan[a,*], Johan Fahlström[b], Knut Sørby[a]

[a]*Department of Production and Quality Engineering, NTNU Norwegian University of Science and Technology, NO-7491 Trondheim, Norway*
[b]*SINTEF Raufoss Manufacturing AS, NO-7034 Trondheim, Norway*

[*] **Corresponding author**. Tel.: +47-9300-2677; *E-mail address:* vegard.brotan@ntnu.no

Abstract

Even though journalists write about the 4th industrial revolution, the metal additive manufacturing (AM) machines are still "that awkward machine in the corner". However, the research community and the European Commission have seen that hybrid solutions are necessary to improve the competitive factor of additive machines, making them an integrated supplementary part of the production plant, as other manufacturing processes are today. Hence, a discussion is raised on changing the way additive machines are operated. The paper discusses new planning systems and support systems for reliable operation of AM processes.

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1. Introduction

The metal additive manufacturing (AM) technology can produce geometries that is impossible to create using traditional production technologies[1–3], while at the same time achieving good material properties with high performance metals [4,5]. However, for massive parts AM is a slow manufacturing process that usually have a roughness exceeding a *Ra* value of 10 μm. The geometrical accuracy is poorer than many traditional methods, since inherent stress will cause the part to deform during production and heat treatment. Therefore, an additive manufactured part is often machined, grinded and/or polished to get the part within its tolerances. Hence, machining allowance is added to the near net shape additive part. A company producing additive parts in metal, therefore, needs to have subtractive production machines for finishing operations. This is not in line with the common journalistic view of the simple one-operation AM machine, rather the AM machines are supplementary to the rest of the workshop, as the AM machines are not the solution to all production needs.

1.1. The supplementary additive process

The idea of hybrid systems are not new, as there are several hybrid solutions available. Already in late 2011 the company Matsuura displayed a CNC milling and laser powder bed fusion hybrid machine. Such a process was also presented in 2014 by the American machine builder Sodick. These machines deliver a hybrid manufacturing solution in a single machine unit, where the perimeter of one to four AM applied layers are milled before the application of the next layer, producing a smooth part with high dimensional accuracy. However, this solution still needs to start with a machined build platform, i.e. platform that provides the surface upon which the build is started and supported during the build process. This leads to another machining operation, as the platform has to be removed after the build. The layerwise milling is an additional operation which furthermore slows down the AM process sequence, and the restriction to 3-axis milling limits the possibilities to use the milling operation in the most efficient way. Chips blended into the powder bulk and magnetism are other major concerns regarding this process, as well as the deformation seen from the inherent internal stress that is added to the component during the build.

Deposition based hybrid manufacturing machines have been developed for many years [6,7]. In 2013 Hybrid Manufacturing Technologies displayed their AMBIT^{TM} deposition head, which is a deposition head that could be retrofitted into virtually any CNC machine. Shortly thereafter DMG Mori Seiki showed a large deposition and milling hybrid machine. This type of hybrid machines became popular in 2014, when Mazak, Hurco and Hermle announced their plans for additive-milling mixed machines [8]. However, all these solutions are based

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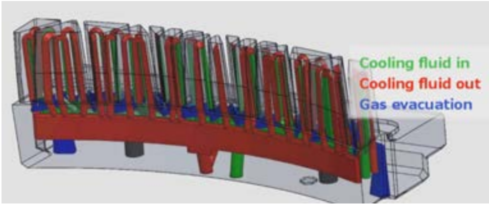

Fig. 1. A hybrid produced case study from the EU-project IC2

on the relatively coarse deposition method, often called Laser Cladding. In these hybrid machines milling and AM can not be done simultaneously, so there is always one process waiting for the other. Furthermore, between AM and milling there is also a cooling phase where the machine is waiting for the component to cool down. Hence, having separate machines instead of the 2-in-1 solution would be beneficial for the availability of each process.

Concept Laser, one of the major metal powder bed machine builders, have presented the idea of a bigger automated hybrid system. The company plan to release their first factory system at the end of 2016 [9]. The system will mainly focus on additive production with separate powder handling and removal stations. Furthermore, it will have a post-processing section, where the parts are machined, heat treated and cut off from its build plate. The focus is therefore on complete additive builds, with simplified post-processing steps.

1.2. Cell structures

The focus on automated cell structures are still not much discussed by the machine builders. However, a different approach to hybrid manufacturing started in 2009 at the Norwegian University of Science and Technology and SINTEF in Trondheim, Norway [10]. With this approach a powder bed AM machine for metallic materials is integrated with a 5-axis milling center into a hybrid manufacturing cell. Physical integration is done by a pallet system, while the machines are connected to a local network for information exchange, e.g. part position coordinates and part name. The intention of this approach was to achieve coordinated functionality while the integrity of each process was maintained to the highest degree possible [11].

This development was a part of the European project FP7 IC2. A case study on an injection molding tool insert revealed more than 50% decrease in mold cooling time, and much less wear on the mold. This extreme decrease in wear was seen from the change of material, better venting and much better cooling. The vents where built additive and the cooling channels where comprised of many parallel conformal cooling channels, as seen in Figure 1.

A recent contribution to the development of hybrid manufacturing is the MetalFAB1^{TM}, shown by Additive Industries at the FormNext exhibition in 2015. It is a modular machine that is supposed to integrate many different process steps, like powder bed fusion, heat treatment, powder removal, storage and probably some subtractive modules. These are all connected by a supervising control system and a linear robotic unit. A pallet system is used to achieve consistent part positioning in the machines. This modular system has the potential to be a major success, if implemented correctly. However, from the information available at this time, it seems that the system will focus on building a part completely in the additive machine, just like the Concept Laser factory system.

As stated, AM is slow and rough, which is why it is usually not the preferred method when compared to subtractive processes. On the other hand, the unique possibility to produce geometrical complexity is important for some products. Hence, there is a need for AM, but there is also a cost-driven need to reduce the use of AM. This is why hybrid systems has been developed, integrating very different production machines together, to improve the speed and performance [12].

2. The hybrid modular manufacturing system

The idea of the hybrid modular system is to link together several production machines in a workshop, while maintaining the integrity of each individual machine. There has to be a network-based connection, as the machines need to exchange information, e.g. part location, deviations, identification and production files. As a result, a single setup of the crude base section on a pallet system will reduce the setup time, and the accuracy of the setup will be reflected by the accuracy of the pallet system. 3D-scanning or coordinate measuring machines (CMMs) will inspect the parts between the process steps to identify problems and to learn about the different failure modes. Figure 2 displays an example of a communication flow in an automated system, where part positions, deviations, identification, machine codes and other relevant information is communicated through a common system router. Some of the feedback is also sent to a learning database, which is used for learning the process deviations and failure modes.

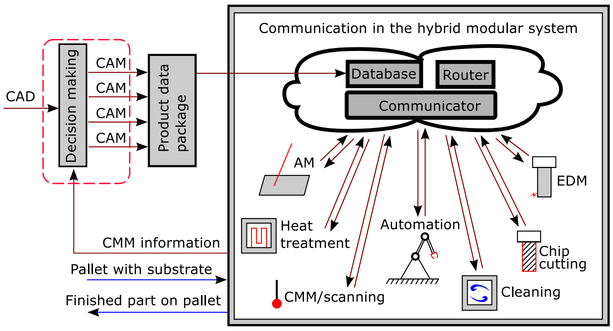

Fig. 2. The hybrid modular manufacturing system

The hybrid process starts when a CAD-model is loaded into a hybrid manufacturing toolbox. This toolbox analyzes the geometry and gives feedback to the engineer on which production method that is recommended in different sections of the part. The feedback could give indications of design modifications that could make the manufacturing process less resource demanding. The feedback is based on knowledge of each production process and a knowledge database which is developed over time. The option at this point is to redesign the part, or to section the part as the toolbox recommends. Each section is then presented in a CAM-software for each of the process steps, where the tool paths are programmed. The toolbox then produces a product data package that will hold the production files and identification. This package is updated with positioning through a 3D-scan, or for more accuracy, a CMM.

For further automation the hybrid cell could be automated with robotic manipulators and advanced powder handling systems. In metal powder bed fusion no automated powder removal exists at the marked at the present time. However, EOS presented a concept at Euromold 2013 where a clean-up program comprising rotation and vibration was suppose to clean all excess powder.

2.1. Failure modes

It is clearly useful for any AM producer to decrease the amount of production defects. Production cost and loss of production time due to AM build failure hinders the development of AM as a commonly used manufacturing method. Data collection of build deviations should be a part of the hybrid system. Moreover, automatic optimal selection of manufacturing method would increase the productivity. The implementation of such a system is therefore important for a wider industrial usage of metal AM. Simulations on the build process would help avoid the failure modes that can occur in additive production. With mitigation made on results from simulation, a higher production rate as a result of higher rate of successful builds would make AM a stronger and more cost effective candidate as a supplementary production method.

2.1.1. Large factories

In larger factories the hybrid cell could be one of several ways to make the utilization of the machines higher, as the integrity of each machine is kept. This means that there is no waiting time, as there is in the combined machines. Hence, machines could use extra capacity to manufacture traditional parts as well. This cell would not have an automated handling system, as it would require operators to move inside and around the machines. Another way to build the cell, would be to connect it with robots. Robots that would move the pallets between the machines, making use of an automated powder removal system and cleaning machines for removal of fluids and attached powder. Such a system would require a part magazine for storage of parts on pallets awaiting next process, as the speed and time consumed in the different processes would be different. The manual work hours in such a system would be minimal and the throughput would be very high.

2.1.2. Connecting expert factories

Small factories may not have all the machines needed for high end production. SMEs can utilize other workshops to get the right processes and machine availability without making the investment themselves. Using a common pallet system with a unique coordinate system and identification, together with online part data, companies with different expertise and geographical location can be involved in the different process steps. As a result, companies with a limited machine park could cooperatively add value to a product through their specialty or machine access. Small and medium sized enterprises could therefore expand their marked potential with this cell structure, while still being able to run their machines without the complete system. This would strengthen the SMEs' competitiveness and maintain a high utilization of machines in the companies that join the common hybrid solution.

2.2. The pallet system

A pallet system consists of chucks or pallet holders that clamps the pallets into a specific orientation with high accuracy. The clamping must be strong to enable vibration-free machining and fixed positioning during the process. The pallet system is the holder of an identity in form of a bar code, QR code or similar. This identification is used to send and receive the correct data from the database, through the translating communicator. The communicator is needed to interpret the information received from the different systems. The pallets should be resistant to high temperatures as they may need to go through the post heat treatment together with the parts.

The focus on larger connected factories is a recent development from the machine builders. There is often an option to install pallet systems in new machines, which is a key enabling technology for a hybrid cell structure. However, these pallet systems does not come with any software or further implementation toward hybrid manufacturing. There might be a good reason for that, as the pallet systems delivered today does not cope well with powder. The self-locking ball lock mechanisms will get stuck under the influence of powder. Furthermore, such systems are quite difficult and time consuming to clean, which shows that they are in fact far from suitable for powder additive manufacturing. Therefore, more technically suiting pallet systems should be developed.

2.3. Simulation and analysis of the AM processes

The analysis of the physical process when metal powder is transformed into a solid part is a complicated task. However, it is not impossible, and many researchers are working on accurate AM simulations, as for example Hodge et al.[13] and Kamath[14]. The status of this development is in many ways similar to the development of simulation tools for injection molding processes. 20 years ago injection molding did not have any simulation software, so a working production was heavily reliant on experienced engineers. These engineers had insight into failure modes and how to fix them, but without any good simulation tool the molds often needed to go through several iterations before it was working fine. Today the use of injection molding simulation tools are standard procedure during a design phase, just as simulations of AM builds will be standard solution to avoid failure modes in the future.

Figure 3 shows an etched material test of hybrid manufactured maraging steel, with the microstructure clearly visible. The part is laying on its side, so the layers where added from the left to the right. In this microstructure, downwards penetrating melt pools are clearly visible. The penetration of the melt pool is between three and four layers, depending on geometry. This means that most of the melted metal will actually be melted up to four times. The difficulties with large complex multi-physics simulations of the additive processes are the large number of parameters that affect the build quality. This complexity leads to high computational costs [15]. With a high number of variables, both testing and analysis of the process parameters require large amounts of experiments. Computational costs have a tendency to decline with time as CPU calculation power rise, however, with more advanced simulations so will the amount of calculations. Yadroitsev[16] estimated that the number of parameters that affect the build process was at least 130 for the SLM powder bed process. Hence, verification work becomes expensive and time consuming, as testing relays on many additive manufactured parts. The simulation model will be AM technology dependent, where deep understanding of powder melting is needed. Furthermore, to ensure that the simulation model corresponds to the real world experience, a database of builds with related build errors is needed. This database serves as a governing guide to how real life builds and the simulation corresponds, where simulations are analyzed and compared to the result to ensure confident results. The failure modes for AM are many, and some can be simulated while others must be solved through better control of the machines. The AM build process will in the near future still be dependent on craftsmanship of the machine users and engineers, but software will give better results as simulation accuracy improves along with better processes and process understanding.

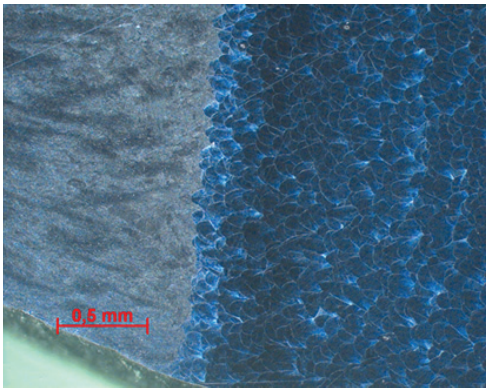

Fig. 3. A hybrid part, where the base material is to the left and the additive section is to the right. The material is Marlok-C1650

3. Learning

The decision of when to use which manufacturing method relays on production engineers which need to have knowledge of each available machine. However, AM is new to many engineers and it is therefore difficult to understand the process characteristic. The decision to use AM as manufacturing method on a chosen part needs to come from experience and deep process understanding. Furthermore, there can be many equally optimal routes to produce a part, which would make it difficult for a software or an algorithm to give a specific solution. Since AM suffers from many failure modes, rough finish and coarse tolerances, an analysis is needed to reduce cost and uncertainty in the final result.

3.0.1. Choosing the correct manufacturing method

Additive manufacturing can in some design cases be the only manufacturing option, for example on components with the use of internal geometry like conformal cooling channels or lattice structures. To understand when and in which sections AM is beneficial, one needs to understand the technology limitations and strengths. By calculating the time and cost of each option, a list of possible solutions can be presented. Today's CAM software for subtractive methods have the possibility to analyze certain processes. AM can be integrated and be analyzed in the same way. Commercial products like "NX CAM Hybrid Additive Manufacturing" from SIEMENS can simulate the use of both additive and subtractive technologies in one software tool. Typical variables like size, batch size, geometry, material etc. are parameters the software use to simulate and create the tool paths of hybrid machines based on milling and deposition. Consequently, the part can be divided into sections by a post processor that knows the available methods, and the most efficient production sequence can be found. For finer surface roughness tolerances, machining might be required. A software could through design rules and learning make this analysis more efficient and thereby support both the designer and manufacturer in the choice of manufacturing process sequence. It can also give input to needed design changes to allow for a more efficient production.

3.0.2. Learning AM failure modes

Even with the newest machines on the marked, there is no feedback when it comes to geometrical errors and build failures in the additive machines. Hence, the operators need to become skilled in the art of building parts correctly. This skill develops through making many mistakes. Such mistakes costs a lot of money and delay production. Even the most skilled operators often do mistakes, and this is why quality control feedback is an important next step.

3D-scanning and/or coordinate measuring machine will be applied to compare the stock with the CAD model between each process step, assuring that there is a reason to continue production. Geometries with a larger risk of failure should be pointed out by the pre-process analysis to allocate which surfaces to measure. Furthermore, the in-process software is used to make a comparative analysis between the part and the data model where build and distortion errors can be identified and used to decide on mitigating action. The analysis data is then fed back to a knowledge database to improve the pre-process software. By creating such a feedback the simulation software can learn the actual machine limitations, obtaining experience that leads to additive build with few build errors.

3.1. Process planning software

It is quite clear that designers and engineers will not be happy with a software that changes the design for easier manufacturing. Hence, the software of the hybrid modular cell should not override the designs, but rather give feedback on production difficulties or suggestions of better production friendly designs. The feedback should be based on the analysis discuss in Chapter 2.3. Newman et al.[17] discuss a framework for process planning in a hybrid cell. This is a framework aimed at reusing and remanufacturing existing parts for reincarnation into new parts, by selecting manufacturing processes from four factors; process capabilities, process planning knowledge, geometry constraints and manufacturing knowledge. This framework might be simple, but it touches upon a subject where there is not much written material. However, many CAD/CAM-software companies are clearly working on such solutions. The ones seen on the marked now are all related to deposition and milling, as 2-in-1 machines are available. Ponche et al.[18] proposed a highly relevant 'design for additive manufacturing' concept based on a 'design for manufacturing' approach. This concept take into account both the physical phenomenons happening in the machine and studies based on geometrical analysis of the built parts. Here knowledge feedback is developed into three boxes; design rules, manufacturing sequence optimization and process development. A subtractive extension of such an approach would fit to the hybrid modular production cell.

3.2. Machine communication protocols

An obstacle for the hybrid modular cell is the software on existing powder bed machines, which are typically not open to any communication with the machine shop. As a result, without the producers involvement, it is not easy to make the hybrid cell structure discussed in this paper. However, since the machine controls are based on ordinary Windows operated computers, it is possible to gain back-door access for controlling some of the software, despite the fact that this solution is not as robust and smooth as the connection with a standard machining center. For further implementation in machine shops, this is a critical and relatively easy next development.

4. Conclusion

To industrialize the AM technology further, one needs to realize that the method is just as complementary as any other production method. The advantages of AM should therefore be applied in the part-sections where it is advantageous, and not where other production methods can perform better. By connecting the metal additive manufacturing machines to the rest of the machining shop a great potential for cost reduction is seen. Mostly this is because the AM-time spent on complex parts are severely reduced, as documented in the EU project IC2. Setting up the parts more times than normal is time consuming, but by using a pallet system, the time spent will be minimal. However, there need to be more investigation into pallet systems that can handle metal powder, as available ball lock systems will stick under influence of powder.

Another stopper to the hybrid modular cell is the lack of network communication protocols open for the user. And, without any good way to communicate with the AM machines, this system is difficult to implement. On the other hand, traditional machining centers will usually allow external communication and control.

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References

[1] Chu, C., Graf, G., Rosen, D.W.. Design for additive manufacturing of cellular structures. Computer-Aided Design and Applications 2008;5(5):686–696. doi:10.3722/cadaps.2008.686-696.

[2] Emmelmann, C., Sander, P., Kranz, J., Wycisk, E.. Laser additive manufacturing and bionics: Redefining lightweight design. Physics Procedia 2011;12(Part 1):364–368. doi:10.1016/j.phpro.2011.03.046.

[3] Xu, X., Sachs, E., Allen, S.. The design of conformal cooling channels in injection molding tooling. Polymer Engineering and Science 2001;41(7):1265–1279. doi:10.1002/pen.10827.

[4] Kempen, K., Yasa, E., Thijs, L., Kruth, J.P., Van Humbeeck, J.. Microstructure and mechanical properties of Selective Laser Melted 18Ni-300 steel. Physics Procedia 2011;12:255–263. doi:10.1016/j.phpro.2011.03.033.

[5] Sinirlioğlu, M.. Rapid Manufacturing of Dental and Medical Parts via LaserCUSING® Technology using Titanium and CoCr Powder Materials. RapidTech 2009 2009;1(718).

[6] Hur, J., Lee, K., Kim, J.. Hybrid rapid prototyping system using machining and deposition. Computer-Aided Design 2002;.

[7] Ren, L., Sparks, T., Ruan, J., Liou, F.. Integrated Process Planning for a Multiaxis Hybrid Manufacturing System. Journal of Manufacturing Science and Engineering 2010;132(2):021006. doi:10.1115/1.4001122.

[8] Wohlers, T.T.. Wohlers Report 2015: Additive Manufacturing and 3D Printing State of the Industry : Annual Worldwide Progress Report. Wohlers Associates; 2015.

[9] ConceptLaser, . "AM Factory of Tomorrow" opens up a great deal of potential with modular machine configurations. 2015. URL: http://www.concept-laser.de/en/news.html?det=114.

[10] Brotan, V.. Additive manufacturing for high value metal production in an optimized hybrid manufacturing cell. Ph.D. thesis; The Norwegian University of Science and Technology; 2014.

[11] Brøtan, V., Bovie, K.M.. The Hybrid Manufacturing Cell : Determining Key Parameters in the Integration of Powder Bed Fusion with High Speed Milling. In: The IEEE International Conference on Industrial Engineering and Engineering Management. ISBN 9781467329453; 2012, p. 583–587.

[12] Boivie, K., Ruusuvuori, K., Holl Christensen, B., Schönberg, T., Berg Åsebø, O., Lyngstad, O.V., et al. A practical case study for an intelligent tooling system. Rapid Product Development Association of South Africa (RAPDASA) conference 2013;.

[13] Hodge, N.E., Ferencz, R.M., Solberg, J.M.. Implementation of a thermomechanical model for the simulation of selective laser melting. Computational Mechanics 2014;54(1):33–51. doi:10.1007/s00466-014-1024-2.

[14] Kamath, C.. Data mining and statistical inference in selective laser melting. The International Journal of Advanced Manufacturing Technology 2016;doi:10.1007/s00170-015-8289-2.

[15] Khairallah, S.A., Anderson, A.. Journal of Materials Processing Technology Mesoscopic simulation model of selective laser melting of stainless steel powder. Journal of Materials Processing Tech 2014;214(11):2627–2636. doi:10.1016/j.jmatprotec.2014.06.001.

[16] Yadroitsev, I.. Selective laser melting: Direct manufacturing of 3D-objects by selective laser melting of metal powders. Lambert Academic Publishing; 2009.

[17] Newman, S.T., Zhu, Z., Dhokia, V., Shokrani, A.. Process planning for additive and subtractive manufacturing technologies. CIRP Annals - Manufacturing Technology 2015;64(1):467–470. doi:10.1016/j.cirp.2015.04.109.

[18] Ponche, R., Hascoet, J., Kerbrat, O., Mognol, P.. A new global approach to design for additive manufacturing. Virtual and Physical Prototyping 2012;7(2):93–105. doi:10.1080/17452759.2012.679499.