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HYBRID MANUFACTURING; INTEGRATION OF ADDITIVE TECHNOLOGIES FOR COMPETITIVE PRODUCTION OF COMPLEX TOOLS AND PRODUCTS

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ABSTRACT

During the last decade, the development in metallic material additive manufacturing (formerly also known as Rapid Manufacturing, RM or Rapid Tooling, RT) has brought this technology from niche applications and short run tooling to be a competitive method capable of producing complex geometries in industrial grade materials, such as for example injection moulding tool inserts with integrated conformal cooling system. However, while the geometric complexity has little, or no, affection the price or production time in additive manufacturing, this is neither a cheap or particularly "rapid" manufacturing technology. CNC milling is by comparison cheaper and more rapid for basic geometries, but the production time and cost of manufacturing increases with geometric complexity and the amount of material removed. On the other hand, there are strong limitations on the geometric complexity that is possible to produce by CNC milling. This paper presents an approach to exploit the combined benefits of each, additive and subtractive, manufacturing technology and integrate these into a hybrid manufacturing solution. This will be demonstrated by the development of a hybrid manufacturing cell which is a combination of a powder bed additive manufacturing metal system and a 5 axis milling machine with the primary objective of producing injection moulding tooling inserts, however the principle should be applicable for a variety of different types of products.

Keywords: Hybrid manufacturing, Metal powder bed additive manufacturing, Machining

1. INTRODUCTION AND BACKGROUND

1.1. Additive-, Subtractive-, and Hybrid Manufacturing

The introduction of additive manufacturing (AM) technology for metallic materials during the 1990s and early 2000s, have enabled the production of metal parts with geometries that previously have not been possible with traditional manufacturing technologies. In the early years of introduction, the practical use of this technology was limited to niche applications, such as functional prototypes and small series injection moulding tools, but major break-troughs in material- and process development during the last decade have made this side of AM capable of producing net-shape, and near-net shape, metal parts with properties well comparable to part made by conventional procedures. However since additive manufacturing forms product by successive addition of material, this is an entirely different manufacturing principle compared to, for example, conventional CNC machining, which shapes the products by successive removal of material (i.e. a subtractive manufacturing process), and both principles have their respective merits and limitations. For instance; the basic principle of AM is successive addition of material, because of this will the price of a product made by AM increase with building time and the amount of material added, however the price will not be significantly affected by the part's geometric complexity. Meanwhile, for corresponding reasons, will the price of a conventionally CNC machined product increase with the amount of material removed (subtracted), and because of the limitations in the reach of cutters, it is not possible to produce the most complex geometries, see Figure 1. On the other hand, CNC milling is capable of producing parts with a surface quality and precision that still is beyond what most AM processes can achieve AM, besides geometric complexity, offers the possibility to manipulate the materials' microstructure and integrate functionally graded material properties.

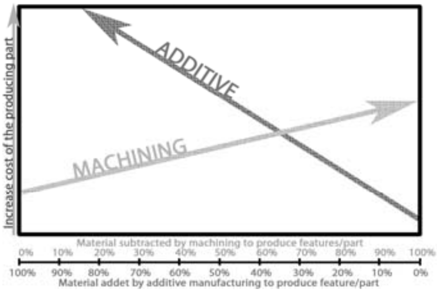

***Figure 1**: Schematic illustration of the development of the cost of production for a machined part respective one produced by AM depending on the amount of material subtracted or added to produce the final geometry.*

This situation is well known, and in order to bring the benefits of each manufacturing principle together several hybrid manufacturing solutions have been proposed, [2, 3, 4, and 7]. Since one of the most significant limitations of early metallic AM systems was the apparent stair-stepping on the products' surface, it was an obvious solution to remove this and generally improve the precision on critical surfaces by finishing machining [1], [2], and while the stair-stepping effect is much less significant in today's technology, this finishing machining is still a desired feature of any hybrid manufacturing solution. Other solutions have been dividing the CAD model of the intended product in different modules depending on the most suitable manufacturing method, and then assembled the manufactured modules in a subsequent process step [3]. The more recent development in AM technology have allowed some companies to offer a hybrid manufacturing solution, based on a powder bed metal AM system, where the AM part is built directly on top of a CNC machined part [4]. However this solution is still based on the principle of two different modules which are designed and produced separately, with significant manual operations such as heat treatment as well as part fixation and positioning required between the subsequent parts of the manufacturing process. It is the object of this paper, to present an even more integrated solution to hybrid manufacturing with a streamlined workflow and minimized intermediate operations.

1.2. Primary intended product: tooling inserts with conformal cooling

Until the present times, cooling channels for injection moulding tooling have mostly been straight drilled holes with limited ability to direct the cooling effect to where it is most needed. However, the introduction of AM technologies has made it possible to build a cooling channel system which conforms to the contours of the tooling insert or cavity, a so called conformal cooling system. With conformal cooling it is possible to achieve significantly better dimensional accuracy in the part and dependent of part dimensions a reduction of injection moulding cycle times up to 20 – 50 % [4, 5, 6] Because of these benefits, and since conformal cooling must be produced by AM, while the larger part of injection moulding inserts are made of massive material and thereby suitable for subtractive CNC milling, the hybrid cell is primarily intended for manufacturing injection moulding tool inserts with conformal cooling system.

2. DESCRIPTION AND CHALLENGES OF THE INTEGRATED HYBRID CELL

The proposed hybrid cell combine the benefits and over bridge the limitations of the additive and subtractive manufacturing processes. This process will be more streamlined with minimized number of process steps and auxiliary operations. For the additive manufacturing, a "ConceptLaser M2 Cusing" machine has been selected. This is a powder bed laser melting process which has the capability to build parts in stainless- and tool steels as well as reactive materials such as titanium and aluminium, of virtually any geometric shape within the build envelope. For the production of massive

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sections and high precision surfaces will a Deckel-Maho 5-axis high-speed milling machine be used. This will enable a manufacturing process where the larger part of the product is milled, and the part with conformal cooling is built directly onto the milled part.

2.1. Workflow

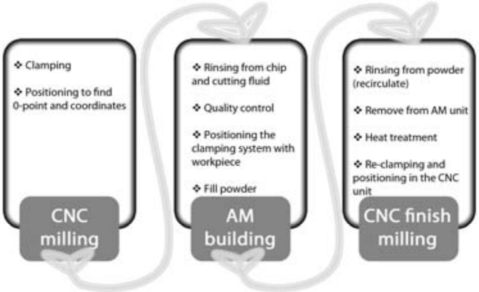

***Figure 2**: Schematic of workflow for the production of injection moulding tool inserts in the hybrid cell.*

Figure 2 shows the schematic workflow of the proposed hybrid cell for the objective of manufacturing injection moulding tool inserts. A work piece is firmly clamped to the pallet in the CNC milling machine, and the position; 0-point and coordinates, is determined by an integrated measuring device before the CNC milling begins. All chips and cutting fluids must be cleaned from the part after the milling is completed, since both of these would pollute the AM machine and seriously damage the building process. It would be desirable to keep this, and all additional intermediary operations, at a minimum, if possible omit the use of cutting fluids altogether. Dependent on the material, a hardening operation of the newly milled base part could be required between the milling and AM processes. The next step is positioning the base part in the AM machine, and provided satisfactory precision in the clamping system the base part should be in the correct position for building the remaining part of the insert by AM. On completion of this operation, the insert is rinsed from loose powder and removed from the building chamber. A careful cleaning of all remaining powder from channels and internal structures is required before the subsequent heat treatment to desired hardness. Finally the part is re-clamped and positioned in the CNC milling machine for finishing machining to final measures and surface quality. If required, the hybrid processing could be followed by grinding and polishing operations which for now will not be integrated in the hybrid cell.

2.2. Clamping, positioning and control system

To maintain correct and accurate positioning in the hybrid cell requires the use of a common clamping system in all machine units. In the present hybrid cell this need has been met by an EROWA chuck and pallet system [8] with a repeatability of 0.002 mm. This will enable quick and easy removal and repositioning of the work piece for each new machine operation, and in combination with a measuring probe installed in the CNC milling machine, also maintain control of the zero point and coordinate system for all process steps. A higher degree of integration of the hybrid cell operations requires the development of a common control system to link the individual machines together, and to provide the necessary in-data for each operation. Equally important is to develop a system for optimizing the manufacturing operational sequence based on defined product features (OMOS). This system will be computer software which will automatically recognise which part of product that should be produced by each respective process, and then split the model into separate parts accordingly. Dependent on the manufacturing process, each part would then be saved in a file format suiting to the intended production process; for AM the STL format, and for machining STEP or similar format, and used to create a manufacturing file for each part in their respective process. The different manufacturing files will be communicated to the respective machines by the common control system.

2.3. Material

Nowadays the tool steel materials, which are available for AM, have properties well comparable to conventional tool steel. However, since the AM building onto the milled part is joined by selective melting of new material to the surface, it is necessary that the milled part material can withstand the tensions of this “micro welding” without cracking or any significant loss of properties. The most

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natural choice of material for making tools with hybrid manufacturing would be to use similar steels for the AM building and for the milled base part. Most AM tool steels are basically variations of a maraging tool steal, DIN W.nr.1.2709, this has the advantage that it hardens by precipitation during heat treatment for a long time, which also means that the steel does not harden or turn brittle during the building process and for hybrid manufacturing the whole tool would only require one heat treatment. However, W.nr.12709 is a challenging material for machining, which would hamper the milling process and the workflow in the hybrid cell. As an alternative Orvar Supreme steel from Uddeholm has been evaluated with positive results for both milling and, -provided that the Orvar base part is in hardened condition, also for AM building. The requirement for a hardened base part would also require an intermediary hardening operation between the milling and AM building, including removal and remounting of the work piece to the pallet, and it’s therefore not a desirable option. Investigation of new maraging tool steel with milling properties superior to W.nr.1.2709 is therefore in progress, and the preliminary results are very promising.

3. DISCUSSION

The hybrid cell is still under development, but it clearly has the potential to offer several advantages for the manufacturing of injection moulding tool inserts with conformal cooling channels, and possibly for a number of other products. As described in this paper, for the hybrid cell to be a competitive alternative there are a number of requirements to be fulfilled. However, the development is well on the way; the hardware is being installed during the third quarter of 2011, and the first pieces are planned to be produced in a prototype set-up by the end of this year. Continued development of OMOS and the common control system is planned for the first three quarters of 2012, and beyond this there are still several issues to address in future work. Automatic handling of the part between the workstations is one thing, and the filling and rinsing of powder in the AM machine is another challenging issue that presently is one of the most time consuming operations. Furthermore there could be need for integration of more machine units to the hybrid system over time. One of the biggest challenges with AM technology is that it is not very well known or recognized as a real manufacturing process by the toolmakers and other parts of industry. Many toolmakers, as well as other people of the manufacturing industry, are conservative, and often for very good reasons are careful with bringing new technology into a well functioning manufacturing system. The integrated manufacturing cell is a way to make the benefits of AM more accessible and easier to accept for more widespread practical use in tool making and other parts of manufacturing industry.

4. ACKNOWLEDGEMENTS

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