Hybrid Additive and Subtractive Machine Tools- Research and Industrial Developments

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Abstract

By synergistically combining additive and subtractive processes within a single workstation, the relative merits of each process may be harnessed. This facilitates the manufacture of internal, overhanging and high aspect ratio features with desirable geometric accuracy and surface characteristics. The ability to work, measure and then rework material enables the reincarnation and repair of damaged, high-value components. These techniques present significant opportunities to improve material utilisation, part complexity and quality management in functional parts.

The number of single platform workstations for hybrid additive and subtractive processes (WHASPs) is increasing. Many of these integrate additive directed energy deposition (DED) with subtractive CNC machining within a highly mobile multi-axis machine tool. Advanced numerical control (NC), and computer aided design (CAD), manufacture (CAM) and inspection (CAI) software capabilities help to govern the process.

This research reviews and critically discusses salient published literature relating to the development of Workstations for Hybrid Additive and Subtractive Processing (WHASPs), and identifies future avenues for research and development. It reports on state-of-the-art WHASP systems, identifying key traits and research gaps. Finally, a future vision for WHASPs and other hybrid machine tools is presented based upon emerging trends and future opportunities within this research area

Keywords: Hybrid manufacturing processes; Machine tool design; Additive manufacturing; Subtractive manufacturing

1. Introduction

The use of additively manufactured metal components in tight-tolerance and critical applications is limited by the attainable accuracy, uniformity of materials properties, and surface quality. Prevailing quality issues in additive manufacture relate to part resolution due to the smallest built-element, part density, partially bonded particulate and residual stresses. Until such a time as a step-change in build-material or energy delivery methods is made, it will not be possible to improve part tolerances without a significant increase in cost-to-build-rate ratio. This means that obtaining the resolution required to achieve conforming part in tight tolerance applications is currently not feasible. As such, additively manufactured metal parts almost always require post-processing to improve part quality characteristics and relieve residual stresses.

One possible solution to overcome these limitations is to `hybridise' two, or more, processes to create a heightened capability. At the present time, workstations for hybrid additive and subtractive processing (termed 'WHASPS' by the authors) are emerging on the machine tool market. These machines combine an additive manufacturing process, with a conventional subtractive process, such as CNC machining. WHASPs are creating significant opportunities in the design and manufacture of finished parts, and also in the reincarnation and remanufacture of high-value components [1]. The ability to both add and subtract material helps to address geometrical challenges, such as internal and overhanging features, and parts with a high 'buy-to-fly' ratio [2]. These advantages help to reduce material wastage, and excessive consumption of tooling.

There are already review papers in the field of hybrid additive and subtractive manufacturing. Wang et al. [3] discuss the repair of parts via laser-based additive manufacturing processes. This deals predominantly with welding-based processes and gives a general discussion on the necessary components for an integrated system. Similarly, reviews have been undertaken relating to hybrid manufacturing processes [4], [5]; however, these do not go into detail about specific configurations, themes and challenges in HASPs. Lorenz et al. [6] have recently published a review of hybrid manufacturing processes and machine tools that incorporate directed energy deposition (DED) processes. This review is highly focused and does offer coverage of alternative additive manufacturing processes. In terms of process planning and manufacturing strategies, Simhambhatla and Karunakaran [7] introduce strategies to manufacture undercut and internal geometries using HASPs, and Kulkarni et al. [8] have reviewed process planning in layered manufacturing. In recent history this area has drawn significant attention in academia and industry, including several commercialised systems. As such, this review aims to update and extend previous works, covering manufacturing process exploitation, machine configuration and design principles. Finally, future challenges and opportunities in WHASPs are identified, concluding with a future vision of this area.

2. Additive manufacturing of metal components and its limitations

The current additive manufacturing process landscape comprises eight process families, as defined by the "Standard Terminology for Additive Manufacturing Technologies," which is part of the ASTM F2792-12A standard series [9] (see Figure 1). In addition to those detailed in this standard, `cold spraying' has been added, which refers to an additive process that propels powdered material at a substrate at a sufficiently high velocity to cause adhesion and material build-up [10]. In metal additive manufacturing (MAM), material extrusion, sheet lamination, powder-bed fusion, directed energy deposition and cold spraying are used [10]; however, industry has predominantly focused on powder bed fusion and directed energy deposition [11]. In both of these processes, high-localised temperatures are used to either fuse powder within a bed, or create a melt pool into which powdered metal is deposited on the build surface. By their very nature, these high-localised temperatures cause many issues in MAM parts.

2.1. Limitations of additively manufactured metal parts

Considering directed energy deposition (DED) and powder bed fusion (PBF) processes, limiting factors include: part resolution or accuracy due to smallest built element, unsatisfactory surface quality, poor uniformity in material properties, and mechanical properties e.g. residual stresses. These issues necessitate post-processing to achieve the desired part properties.

Part resolution is largely defined by the smallest built-element. In both PBF [13]–[16] and DED [17]–[19] processes, the resolution is determined by the melt-pool geometry, which is affected by laser power, scanning velocity, hatch spacing and layer thickness. In DED, feedstock delivery also defines the process resolution, as material feedrate and the spatial distribution of the deposited particulate change the shape the deposited track [20], [21] e.g. width, height and dilution. In both PBF and DED processes, the thermal history of the build can affect the melt pool geometry, as previously heated material can be re-melted by adjacent scans [22]–[26]. Also, errors that compound over the course of

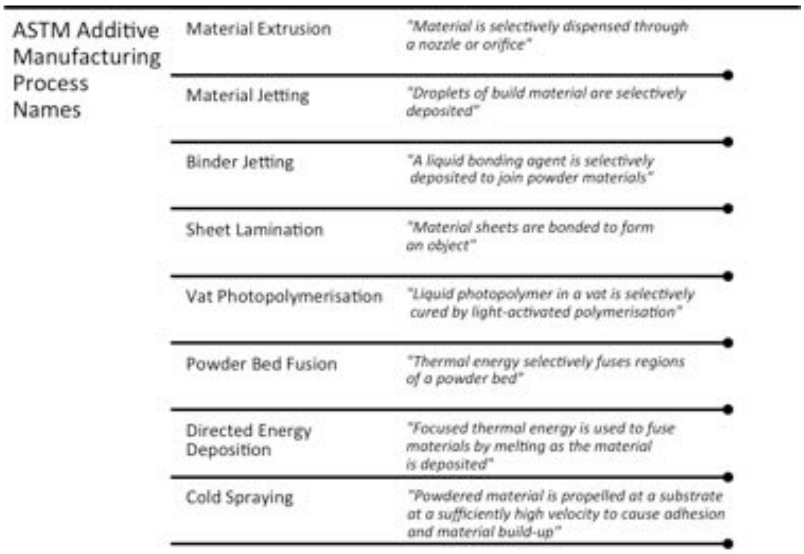


Figure 1: ASTM F2792-12A [9] **standard terminology for additive manufacturing processes, with description quoted from the Wohlers Report 2014**[12]**. Cold spraying has been added using the description of** [10]

the build lead to a change in standoff distance between feedstock outlet and substrate [18]. This, too, can lead to a change in melt-pool geometry.

Temperature gradients and the geometry of the melt pool can each have detrimental effects on MAM processes. Temperature gradients and associated surface tension can cause rapid hydrodynamic motions known as Marangoni flow, resulting in the `dishing' or `humping' of the solidified element [27]. Also, long thin melt pools can result the 'balling' of material, which degrades surface roughness and part density [28]–[30]. Other process phenomenon degrade the surface quality (roughness) of MAM components, which are discussed in [31]–[34]. One of the most fundamental of these is the 'staircase effect,' which is a result of the layer-wise approximation (zeroth order) of part geometries, affecting both PBF and DED. Further to this, the partial bonding of particulate is a common cause of surface quality degradation. In PBF, this occurs as a result of conduction to surrounding powder. In DED processes, propelled particulate may pass through the heat source, adhering to any (hot) surfaces [21].

The material properties of MAM components are related to the density of the built material and the formation of an appropriate microstructure during and after DED [19], [35]–[38] and PBF [16], [39]–[46] processes. For some PBF processes (Selective Laser Melting - SLM), it has been found that the microstructure is dependent on laser power, scanning velocity, hatch spacing and layer thickness [16]. This is largely due to their effects on the rapid solidification of the molten material. Scanning speed affects grain coarseness, grain alignment and material density, whereas hatch spacing affects part density and grain orientation [16]. Another layer of complexity exists due the dependence of microstructure on the material used and part geometry [23].

Residual stress in MAM parts is one of the greatest concerns in both PBF [47] and DED processes [22], [48]. Localised heating and phase transformations in materials induce stresses within the part, which can exceed the yield strength of the material and cause part distortion or even fracture. Research has begun relating residual stress to thermal gradients, subsequently reducing induced stresses via changes in processing parameters, such as laser power, scanning velocity and preheating of the part [24], [25]. It is somewhat unanimously agreed within the literature that post-processing to alleviate residual stresses is an essential part of any MAM process.

2.2. Mechanical finishing of additively manufactured metal parts

The finishing of additively manufactured metal components may be categorised into three mechanisms, namely: (i) machining and mechanical conversion e.g. machining, shot-peening and grinding; (ii) thermal processes including laser and electron beam melting; (iii) chemical and electrochemical processes, such as etching and electropolishing. Machining and other mechanical subtractive processes have been widely used in near-net shaping processes, such as moulding, casting and die-casting. This has now been extended to additive manufacturing, allowing feature geometries to be realised with greater accuracy and surface quality via subtractive processing. To give context to surface quality expectations, aerospace applications have reportedly specified surface roughness 0.8 µm < Ra < 1.6 µm.

Spierings et al. [49] used CNC turning to finish AM parts built in AISI 316 and 15-5HP steels, resulting in a surface roughness Ra of 0.4 µm. It was also noted that finishing of AM parts had limited affect on the fatigue stress at 10^6 cycles, but significant effect at 10^7 cycles. Taminger et al. [50] utilised high-speed milling (HSM) to finish aluminium AM parts. HSM was found to produce highly favourable surface roughness (8-56 µin RMS) and waviness (400 µin RMS); however, compared with other subtractive processes, HSS introduced large residual stresses in the finished surface.

Grinding has also been used to finish MAM parts. With AISI 316L steel, Löber et al. [51] were able to reduce the as-built surface roughness (15µm) to 0.34µm. Rossi et al. [52] reported that on horizontal surfaces, the surface roughness (Ra) was reduced from 12 µm to 4 µm, and on vertical surfaces from 15 µm to 13 µm in Nickel-Iron-Copper parts. This clearly illustrates the importance of orientation and build-direction. Complex and intricate geometries pose a challenge for conventional grinding. In an attempt to alleviate this, Beauchamp et al. [53] used shape-adaptive grinding to finish Ti6Al4V MAM parts. With this process, a surface roughness (Ra) of ~10nm was achieved by using three different diamond abrasive pellets.

3. An introduction to WHASPs

This research gives an insight into the technological and process developments that have furthered field of WHASPs. Most, if not all, WHASPs exhibit key modules, arranged into suitable configurations. The general architecture of a WHASP is described in Figure 2. As will be seen throughout this review, the definition of a new WHASP almost always begins with a target motion platform e.g. an existing machine tool. This platform is typically optimised in its layout for either additive or subtractive processing. The secondary process is then introduced via some form of integration, which might be the physical mounting of an additive deposition head, or the introduction of a separate industrial robot to deliver the secondary process. To be able to interchange between processes, some form of controller logic or physical reconfiguration of the machine must be present. The controller of the machine is responsible for motion and the auxiliary commands that facilitate additive, subtractive and, in many cases, metrology processes during manufacture. This controller receives instructions from the software layer, which encapsulates the representation of the part geometry, process sequences (process plan) and any inspection requirements. The presence of in-process sensing and metrology permits a bidirectional exchange between the software and controller layers, resulting in an adaptive or reactive process plan. Each layer of this architecture is given a dedicated section in this review. The `Hardware' layer is discussed for academic research and industrial developments in Sections 4.1 and 5.1, respectively. Similarly, the `Controller' layer is discussed in Section 4.2 and 5.2 and `Software' layers are discussed in Sections 4.3 and 5.2.

The remaining sections of this paper correspond to the layers of the architecture proposed in Figure 2. These layers are explored for both research and industrial developments, which are later compared and contrasted to identify emerging trends in WHASP development.

3.1. The generalised the hybrid additive and subtractive process

In general, Figure 3 describes the process interactions in a hybrid additive and subtractive manufacturing process. Any given process may exhibit some or all of these interactions as a WHASP creates a new part, or operates on an existing part. The manufacture of new parts necessarily starts with the addition of new material via additive processing. Conversely, part repair or reincarnation typically starts with a measurement or characterisation stage to identify the position and orientation of the part, or the nature of a defect in relation to the machine's coordinate frame of reference.

Hybrid additive and subtractive processing may be undertaken in an open or closed-loop fashion. To continue to process additively or subtractively, without conducting some form of verification on the recent process outcomes, is to conduct an open-loop process. Conversely, to characterise the recent

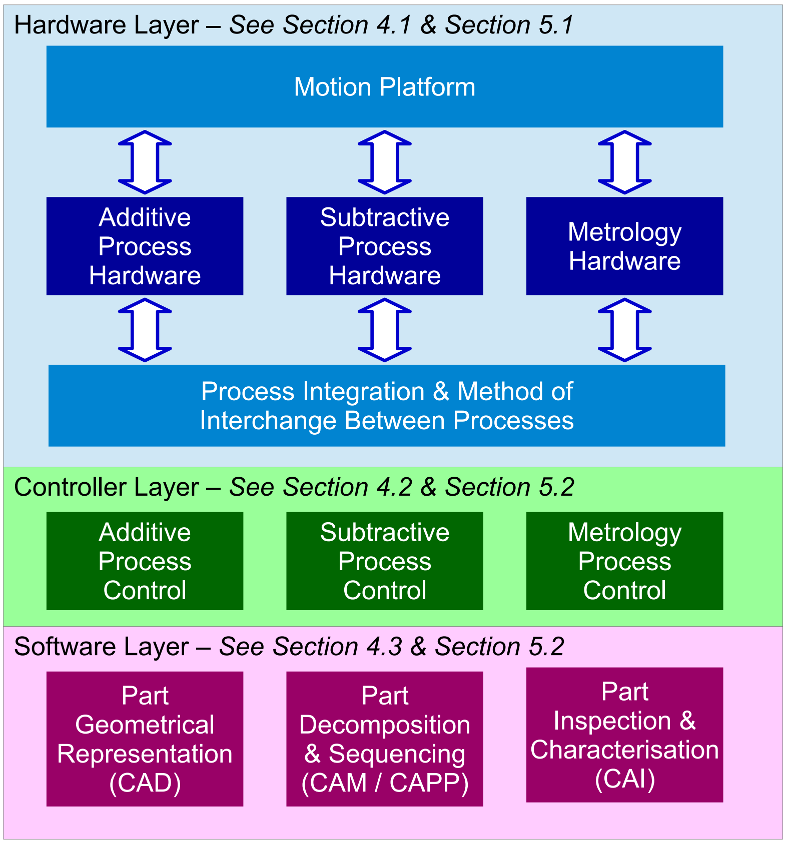


Figure 2: A general architecture for WHASPs, covering aspects from hardware, controller and software capabilities

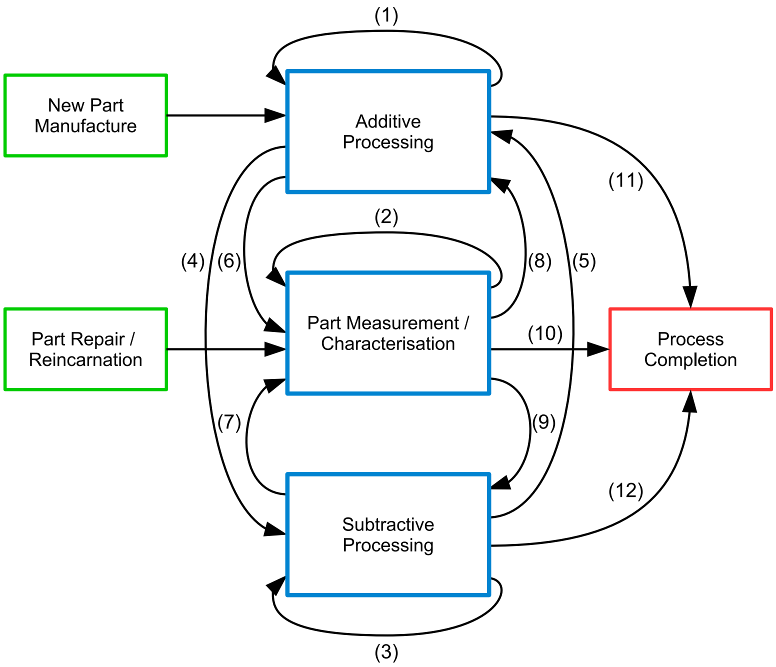


Figure 3: Process interactions within a hybrid additive and subtractive process, showing open and closed-loop operations

process outcomes using metrology and sensing capabilities, before committing to further additive or subtractive processing, is to undertake a closed-loop operation. Likewise, process completion is open or closed-loop depending on which of the three types of operation is final.

Once processing begins, there are a total of 12 interactions within and between processes: (1) consecutive, open-loop addition of material, (2) consecutive acquisition of measurement data, (3) consecutive, open-loop subtraction of material, (4) interchange from additive to subtractive processing, without verification of additive outcomes, (5) interchange from subtractive to additive processing, without verification of subtractive outcomes, (6) verification of additive processing outcomes, (7) verification of subtractive processing outcomes, (8) additive processing with additional insight from prior measurement and characterisation, (9) subtractive processing with additional insight prior measurement and characterisation, (10) verified process completion, based on measurement or characterisation of the final part, (11) unverified (open-loop) process completion, ending with additive processing, and (12) unverified (open-loop) process completion, ending with subtractive processing. Where required, the remaining sections of this review shall refer back to this interaction diagram to help describe the process interactions and strategies employed in each implementation.

3.2. Motivations for hybridisation of additive & subtractive technologies

MAM parts require further post-processing to refine geometrical accuracy, improve surface quality and relieve residual stresses. Conventional mechanical mechanisms for finishing of metal parts may be advantageous in finishing MAM components, due to ease of hardware integration, and the ability to selectively process material, producing the required surface characteristics imposed by some critical applications (e.g. aerospace and medical). As many of the existing mechanical finishing techniques require `line-of-sight’ to access overhanging or internal features, it is advantageous to be able to select the interval at which finishing occurs i.e. build material, finish this material and then subsequently add more material.

The ability to fluently add and subtract material from a workpiece creates significant opportunities in the manufacture of new parts and the remanufacture of worn or damaged parts [3]. Remanufacture is regarded as a cost and energy efficient way to extend the useful life of parts and products, receiving attention form civilian and military arenas [54]. WHASPs provide the opportunity for raw materials to be transformed into finished parts using only one visit to a single machine tool, increasing process capability [55].

The ability to work, inspect and then rework material until the part conforms to tolerances and specifications may provide a step-change in quality management. The realisation of these concepts leads to reductions in costs incurred owing to floor space requirements, generation of scrap and swarf, and potentially improved processing times. Moreover, highly complex parts with external and internal features or high geometrical precision and surface quality can be produced [7],[56]. As such, WHASPs may overcome existing manufacturing challenges, thereby satisfying the objective of “1+1=3” for hybrid manufacturing as defined by Lauwers et al. [5]. For these reasons, research into the development of workstations for hybrid additive and subtractive processing will be of significant importance to high value manufacturing of the future.

4. Hybrid additive and subtractive manufacturing processes – research

Based on the architecture detailed in Figure 2, academic research relating to WHASPs may be broken down into the constituent layers, namely: the hardware, controller and software layers. The proceeding sections report on the literature from the perspective of each of these layers.

4.1. The hardware layer

Figure 4 gives a cross-section of how academic research has addressed the `Hardware’ layer of WHAPSs. The diagram should be read from top to bottom, first selecting a subtractive process, then an additive process, thirdly a motion platform configuration is chosen and finally a method of process interchange or reconfiguration. The number of references in each box of is indicative of the abundance of research concerning a given configuration.

Figure 4 shows that subtractive processing is almost exclusively limited to CNC machining, with a single example of Selective Laser Erosion (SLE). Similarly, Directed Energy Deposition (DED) dominates the additive processing tier, with a small number of cases considering powder bed fusion (PBF) and material extrusion. As a final introductory observation, WHASPs are largely built upon existing commercial machine tools, with adaptations in the form of additive process integration. Typically, the only variants on this theme include the addition of extra robotic manipulators, or the development of low-cost in-house machine tools, which closely resemble commercial systems. Each configuration will now be examined in detail, with a critical assessment of its capability and suitability in an industrial setting.

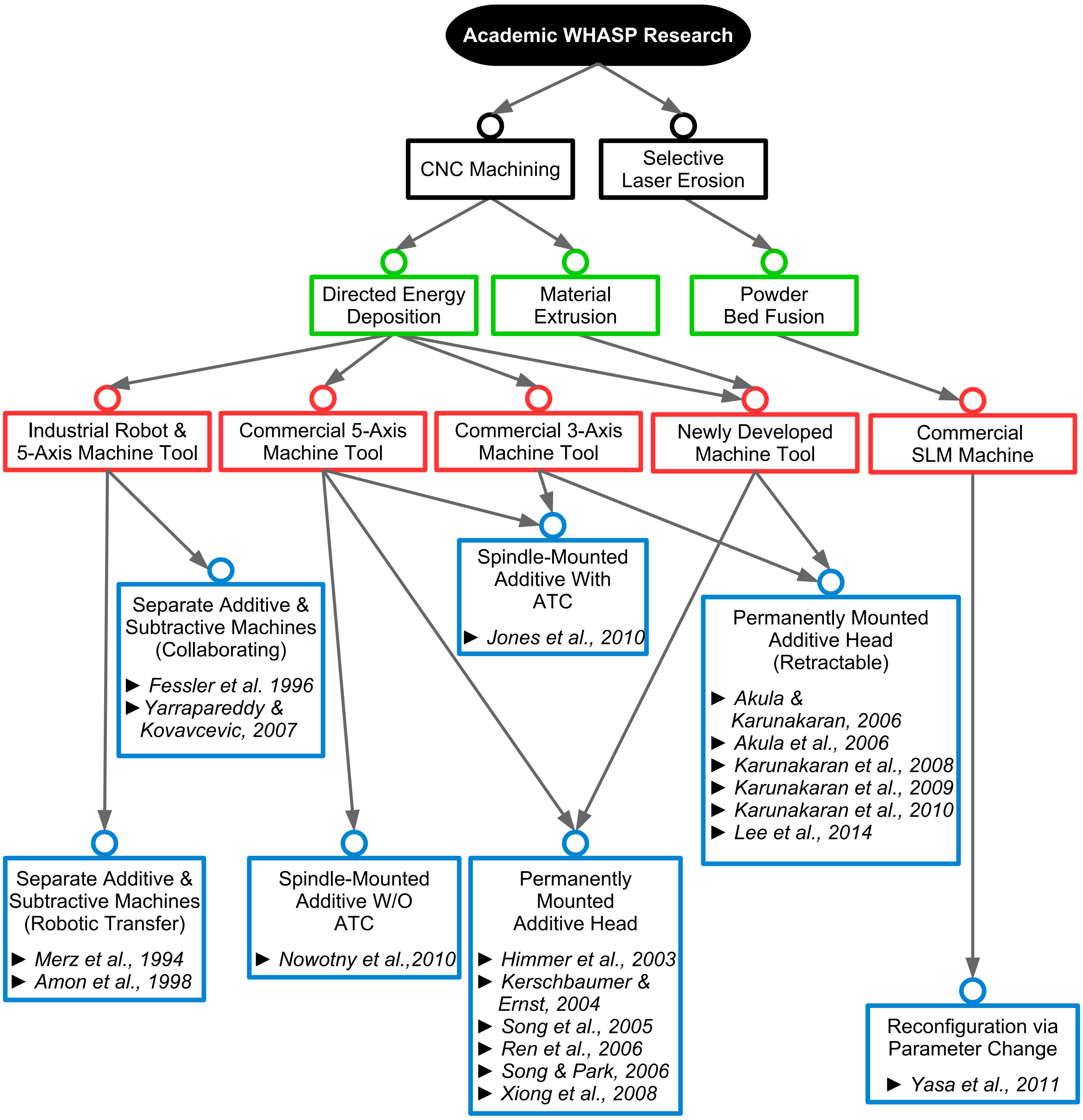


Figure 4: A breakdown of the hardware configurations developed in academic research, grouped according to process inclusion, the type of motion platform used and the method of machine reconfiguration and interchange between additive and subtractive processes.

4.1.1. CNC machining with arc-based directed energy deposition

The hybridisation of CNC machining and directed-energy deposition is the most abundant combination in academic research. One form of this is arc-based directed energy deposition, where an electrical power supply is used to establish an arc between an anode and cathode. The heat from this arc creates a melt-pool into which wire-fed or powdered material is deposited.

The use of arc-based directed energy deposition has been realised through the mounting of an additive head (welding torch) within a machine tool, or on an industrial robotic manipulator. Merz et al. [57] developed 'Shape Deposition Manufacturing' (SDM), which hybridised a newly defined additive process, 'Microcasting,' and CNC machining. In Microcasting an arc is initiated within the welding head between the electrode and the feedstock wire. The wire is melted in the arc, depositing a stream of relatively large droplets onto the substrate. Mechanical testing showed that Microcasting surpassed the specified tensile strength of 308 weldments.

In this research a test-bed facility was developed, which included four distinct processing stations, namely: 5-axis CNC machining, a robotic deposition station, part cleaning and shot peening stations. A further robot performed transfers of the part between stations. The deposition station had the ability to deposit primary material (stainless steel) or support material (copper) onto the substrate to assist with overhanging features. The presence of cleaning and shot-peening stations facilitates the removal of cutting fluid residue and relief of residual stresses from the additive process, respectively.

Later in 1997-1998, Amon et al. [58], [59] extended the work of [57] by modelling a 'Microcasting' droplet impacting on an ambient substrate. As a result of this modelling, torch power, droplet deposition rate, droplet size and free-fall distance were optimised to reduce the likelihood of interlayer de-bonding and excessive thermal stress build-up in single and dual-material parts. Amon et al. [19] also theorised about the integration of multiple manufacturing processes into a single machine tool. More specifically, Amon et al. [58], [59] describe the mounting of an additive head to the Z-axis of a CNC milling machine; a configuration that would later become popular in research-led WHASP implementations. See Figure 7 and Figure 12 for examples of this configuration.

In 2005, Song et al. [60] also sought to integrate an additive process within single, commercial 3-axis machine tool. In this research Gas Metal Arc Welding (GMAW) was utilised in a similar manner to that proposed by Merz et al. [57] and Amon et al. [58], [59]. This research integrated two GMAW welding heads by mounting them adjacent to the spindle of a commercial 3-axis machine tool. This facilitated the deposition of different materials or deposition widths i.e. coarse and fine. The principle aim of this investigation was to analyse the effects of different welding parameters on the built material, such as welding voltage, current and speed. It was found that by depositing a layer of metal, followed by planar milling and then depositing the next layer resulted in high density parts (>90%), with final surface roughness 2 μm (Ra) after milling and tensile strength that is comparable to wire mild steel. This research was supplemented in 2006 by Song and Park [61] who demonstrated the manufacture of multi-material components using the same set-up. In a cubic specimen, a mild steel core was enshrouded within a stainless steel layer using two additive heads. Two distinct materials were clearly evident on the micrograph; however, the authors expressed concerns over the induced stress in materials with dissimilar thermal expansion coefficients.

Figure 5: Complex features, including a triangular helical duct (left) and a hollow torus (right), manufactures using 3-axis hybrid additive and subtractive manufacturing processes [7]

Akula et al. [62], [63] developed an in-house machine tool to accommodate both CNC milling and GMAW (MIG / MAG) welding. By developing a machine tool and associated PLC-based control internally, the authors retained the ability to redesign both hardware and software modules. The final hybrid process adopted the notion of depositing layer, planar milling this layer, and then depositing the next layer. Once a near-net shape was achieved, profile milling was undertaken to complete the part. The research undertaken by Akula et al. [62], [63] focused on optimising the process parameters for additive/subtractive processes. The authors claimed that by using this method, the cycle time for manufacturing moulds and dies could be significantly reduced. Furthermore, integrating their system into an existing commercial CNC centre could reduce capital investment. Investigations indicated that the desired material properties for moulds and dies could not be entirely achieved by arc-based directed energy deposition methods. Akula et al. [62] concluded that parts manufactured by this method are mechanically inferior to their counterparts manufactured conventionally; however, after CNC milling, similar geometrical accuracy is achieved. The overall part accuracy is process and workpiece dependent; however figures stated in [64] describe part accuracies of ±0.030 mm for a combined DED and CNC machining processes. In another study, Akula et al. [63] analysed the effect of deposition parameters in additive/subtractive manufacturing and highlighted variations within material microstructure and in part/build plate distortion due to uneven heating and cooling during the welding process.

Karunakaran et al. [65]–[67] reported on the integration of the GMAW (MIG / MAG) additive welding process (as described by Akula et al. [62], [63]) into commercial 3-axis machine tools. They emphasised that the integration should not interfere with the existing capabilities of a CNC machine tool. Therefore, a pneumatic actuator configuration was used to raise and lower the additive head between manufacturing processes to avoid collisions. The welding power source was also housed within the machine tool's protective panels [67]. In this research, the authors commented on the possible use of automatic tool changing to reconfigure any 3 or 5-axis machine tool; however, they disregarded this notion due to the need to establish electrical, gas and wire feedstock connections [65], [66]. In a case study [65], the authors found that this WHASP can significantly reduce the costs and the time required for manufacturing any metal tool or die as compared to other individual techniques. Furthermore, they identified near net-shape building and finish machining on a singular platform as the most significant feature of WHASPs. Example mould parts manufactured by the proposed method are displayed in Figure 6. Karunakaran et al. [67] highlighted that heat management during this process is essential to prevent unwanted distortion and residual thermal and mechanical stresses in finished parts. Furthermore, the possibility of thermal spikes during the material deposition (welding) process should be considered to prevent undesirable damage to the machine tools' controller.

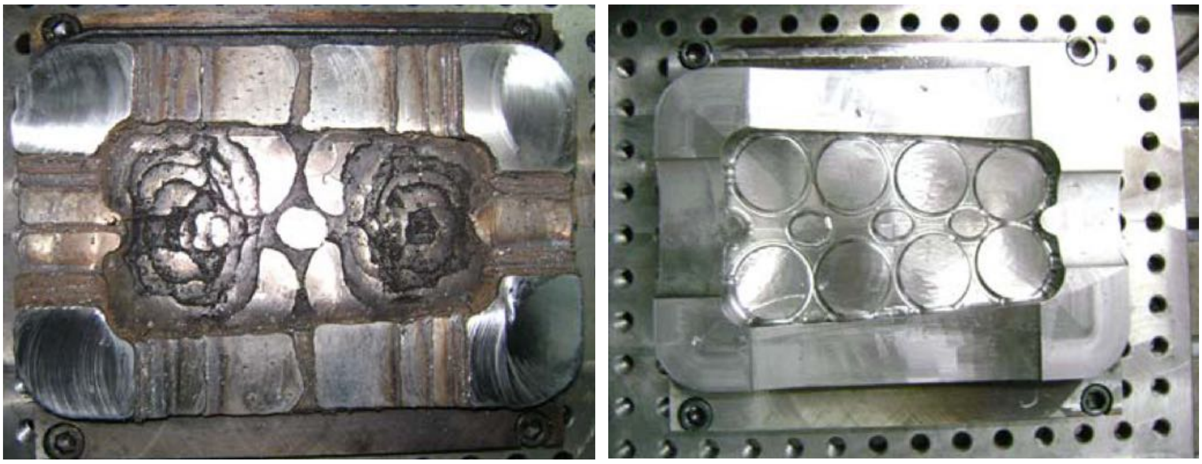


Figure 6: Example manufacture of a mould core using retro-fitted additive (GMAW) and subtractive (CNC machining) [66]

The Southern Methodist University in Texas have developed their own WHASP capability in the form of the MULTIFAB system [68], [69]. The MULTIFAB system comprises a multi-axis robot for material deposition and welding which is synergistically integrated into a 5-axis machine tool [70]. This system can accommodate both arc and laser-based directed energy deposition processes, using a 6-axis robotic manipulator to execute either laser (1kW / 2.5 kW Nd:YAG) or micro-plasma welding facilities. This robotic system was able to process material that is fixtured within a 5-axis machine tool. The MULTIFAB capability has primarily focused on the repair of high-value metal components, which in turn necessitates integrated machine tool metrology to characterise and existing component's geometry. Scanning technologies are used to achieve this, by enabling reverse engineering and in-process inspection of component geometries.

The following points summarise the developments made in arc-based directed energy deposition and CNC machining WHASPs. Motion platforms take the form of commercial three-axis machine tools, with retrofitted welding facilities to deposit material. In some cases, the welding head is retractable to avoid interference with the CNC machining operations. Alternatively, industrial robots have been used to work collaboratively with commercial 5-axis machine tools. Process sequencing generally alternates between layer deposition and planar milling. There has been no particular focus on the use profile milling between deposited layers, which could potentially make finishing of overhanging and internal features difficult. There are differing opinions on the mechanical and microstructural properties of the manufactured parts, with some researchers claiming comparable performance, and other stipulating the need for heat treatment and careful avoidance of thermal build-up to minimise residual stresses.

4.1.2. CNC machining with laser-based directed energy deposition

The limitations of GTAW, such as poor accuracy and reliability, part deformation, poor bonding and restricted material choices, has resulted in an increased interests in using laser-based material deposition methods [54]. Laser-based directed energy deposition is similar to its arc-based counterpart; however, in these processes, a laser is used to create a localised melt-pool on the substrate to which material is then deposited. Another widely adopted term for these processes is 'laser cladding.'

In 1996, Fessler et al. [71] described the installation of a laser-cladding head on a 4-axis robotic manipulator. CNC machining was used achieve desirable geometrical accuracy and surface quality in additively manufactured near-net parts. In this research, the authors utilised a 2.4 kW CW Nd:YAG laser (spot size of 2.5mm) in the DED process. Additive and subtractive processing were alternated on a layer-wise basis, using separate deposition heads to deposit copper support structure and stainless steel part features. The support material was later removed by acid etching. A comparison of the mechanical properties of the deposited material and wrought 316L stainless steel showed comparable performance, with heightened yield strength. These properties were also found to be comparable for different build-directions.

The authors highlighted that residual stresses resulting from thermal gradients can lead to warping and a loss of strength. To circumvent this issue, experiments with alternative build strategies, in which towers were built and then the gaps were latterly filled in to promote relaxation throughout the build. Additionally, the notion of thermally stable (INVAR) support structures was considered. A possible solution was proposed whereby support material is protected by a buffer layer that is sacrificial. This research also alluded to the future use of multi-material deposition to produce functional material gradients (i.e. multi-material deposition) by experimentally depositing INVAR, stainless steel, copper and bronze on a single part. Apart from the thermal issues associated with laser deposition of materials with various thermal properties, the authors identified building upon an existing part may adversely affect existing features, surface quality or material microstructure [71].

In 2003, Himmer et al. [72], described the process of laser build-up welding. In this research, a laser-cladding unit was integrated within a commercial 3-axis machine tool by mounting it adjacent to the machining spindle. In this way, the machine could add material to support laminated mould dies by building a near-net representation of the final geometry, which was latterly refined using subtractive CNC machining. The authors hypothesised about the future use of five-axis machine tools to facilitate finish machining of more complex geometries.

Kerschbaumer and Ernst [73] published research on the development of a hybrid laser-cladding and CNC machining system. The authors integrated a Nd:YAG laser cladding nozzle and powder feeding system into a commercial Röders 5-axis CNC machine tool (Figure 7). In this implementation, 5-axis material deposition permitted multiple build directions, avoiding molten material flow along an inclined build surface, whilst significantly reducing the requirements for support structures. The heightened dexterity also led to increased tool accessibility during material removal. In their process, the authors machined the additively built component after every few layers to allow machining access with small tools into the complex internal geometries of the part, potentially reducing the need for die sinking EDM. This study identified that alternating laser cladding and machining operations prohibits the use of cutting fluids during machining. Furthermore, they noted that since complete heat treatment of the workpiece after machining is not possible, only very tough high strength alloys should be used. This has highlighted the material costs for this process and the requirement for specialised milling processes, which can withstand machining of advanced alloys at high temperatures.

Figure 7: (Left) WHASP presented in [73]**, with additive head permanently mounted adjacent to the machining spindle, (Right – Top) Example of multi-axis deposition capability of WHASP** [73]**, (Right – Bottom) Component after finish-machining** [73]

The Laser-Assisted Manufacturing Process laboratory of the University of Missouri, Rolla, has developed the Laser-Aided Manufacturing Process (LAMP). Eiamsa-ard et al. [54] described a hybrid system with laser cladding and machining capabilities. The authors used this system in the repair of metal parts by first removing (machining) material surrounding the damaged zone, depositing new material and then finish-machining the deposited material to refine the geometry and surface characteristics. This notion of repair by material addition and subtraction sits naturally within sectors that produce low-volume, high-complexity parts that are subject to wear and damage e.g. aerospace, military, medical and mould and die industries. Ren et al. [74] described the integration of additive laser cladding capabilities on a FADAL 5-axis CNC machine tool and extended Eiamsa-ard et al.'s research for multi-axis surface patching of damaged and worn die tools. The authors proposed a 3-D patching method where the material is deposited on an existing feature and follows its surface contour as opposed to 2-D material deposition as shown in Figure 11. The integration of laser cladding into a 5-axis CNC machine tool meant that material deposition and finishing could be achieved with a single setup. This facilitated higher geometrical accuracy whilst minimising the time required for repair, reducing associated costs.

The Fraunhofer IPT institute developed a WHASP through the integration of a wire-fed laser deposition head on a 3-axis high speed milling centre [64]. This research was initially aimed at the repair and modification of steel moulds. The layer-by-layer material deposition and milling capability of the system allows machining to be carried out in-between building processes. Therefore, precision features could be manufactured using standard milling cutters, reducing the need for post EDM machining. Synergistically utilising layered additive manufacturing techniques with conventional milling permitted the manufacture of engineering features with high aspect ratios; however, this is perhaps more applicable to internal features, as external features, such as pins (bosses), would be susceptible to damage during machining.

The 'RECLAIM' project [75] sought to develop hybrid manufacturing technologies via multi-purpose machine tools [76]. This research focused on the combination of additive, subtractive and inspection processes to facilitate the remanufacture of high-value parts [77]. A more detailed description of this process cycle is illustrated in Figure 8. The initial focus of this research was to repair turbine blades made of Ti-6Al-4V alloy with tip damage and wear. In a preliminary case study [76], time and cost saving could be achieved using this system. As shown in Figure 9, no significant microstructural abnormalities were detected in the repaired turbine blades, whilst good fusion to base materials and low weld porosity were found. However, Figure 9 does show a clear boundary between the base and cladded materials. The authors stated that further investigation on optimising the cladding head design and process parameters were necessary to guarantee part quality [76]. Many commercial WHASPs now adopt an identical or similar approach to this implementation, which is discussed in more detail in Section 5.

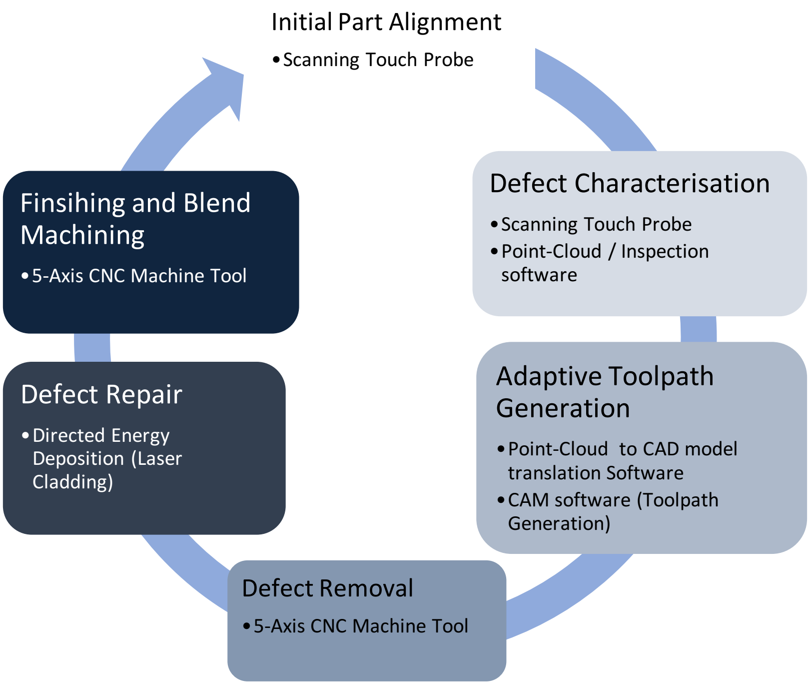


Figure 8: Description of the RECLAIM remanufacturing process [76]

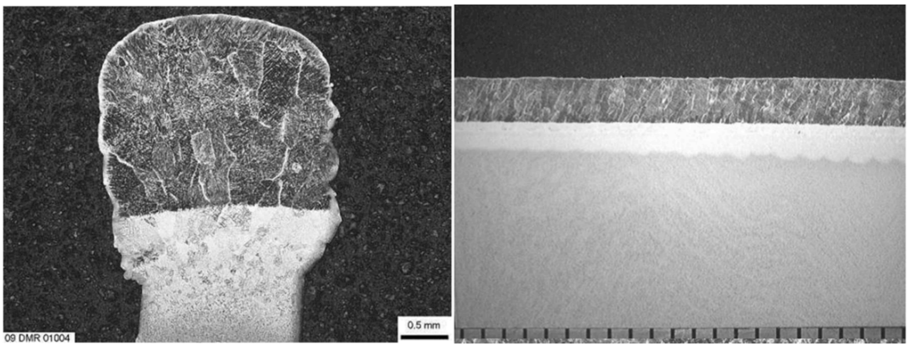


Figure 9: Transverse and longitudinal section micrographs of Ti-6Al-4V laser cladded turbine blade tip [76]

4.1.3. Combined selective laser melting and selective laser erosion

Producing fine (micro) features on metal additive parts is a significant challenge. External features are too delicate to withstand the impact from the next layer of powder, applied using the wiper. Internal features become partially obscured by trapped or partially bonded particulate. Traditional mechanical subtractive processes also struggle to deal with this type of feature, especially if the feature has a high aspect ratio.

To address these issues, Yasa et al. [78] adopted a different approach to hybrid additive and subtractive processing. By taking a commercial Selective Laser Melting (SLM) machine and operating the Nd:YAG laser in two different ways, two distinct manufacturing processes could be executed. The first of these is an additive SLM process, which requires the laser to be used in continuous mode. The second process, Selective Laser Erosion (SLE), utilises a pulsed laser mode to evaporate material from the workpiece during or after SLM coalescence. Due to the non-contact nature of the process, cylindrical pins with diameters between 50μm and 350μm we produced using this process. Internal features were also produced using SLE to drill holes of 126 and 120 μm diameters. It was noted that the laser was commanded to follow the perimeter contour of the circle, rather than a stationary processing point.

Using the same machine, the authors were also able to improve surface roughness and reduce residual porosity using laser re-melting. For planes normal to the build direction, the average surface roughness (Ra) was reduced from an average of Ra 12μm to 1.5μm, which is within the range that is appropriate for critical applications e.g. aerospace [79]. This process could be undertaken layer-wise, but also on side-profiles by raising the build part out of the powder bed and blowing excess powder away. For inclined planes with inclinations of 10 and 30 degrees, a 50% and 75% reduction in surface roughness Ra could be achieved. Using a relative metric derived from image processing, the porosity of the laser re-melted specimen had a material-pore ratio of 0.036%, whereas the as-built specimen was 0.77%, showing an improved density. This research represents the only example of machine reconfiguration via parameter change i.e. no hardware changes; offering a reminder that HASP processes are not always manifested via the physical connection of separate hardware modules.

4.2. The controller layer

Literature reporting on the development of dedicated controller capabilities for WHASPs and HASPs is sparse. This is in contrast to research addressing additive manufacturing as a discrete process. In metal additive manufacture (MAM), control is broken out into two tranches: parameter optimisation (open-loop), and closed-loop control. Closed-loop control is challenging due to complex correlations between parameters and the need to use penetrative measurement techniques to gather information about the build within a powder bed.

There are numerous examples of research into closed-loop control of metal additive manufacturing processes. Various imaging techniques have been used to measure the shape and temperature of the melt-pool in metal additive processes. The melt pool geometry and temperature have been measured with thermal imaging [40], [80], and using a combination of a high-speed cameras and thermal imaging [22], [81]. Other systems use a high-speed camera and photodiode to measure melt pool geometry [82]–[84]. Information regarding the shape and temperature of the melt pool can be used to facilitate feedback control of process parameters, such as laser power. Research has also addressed closed-loop control of feedstock material flow-rate in the DED process using a laser diode to measure material throughput [80], [81]. Open loop control has also commanded the attention of several research efforts. In additive processing, this may be undertaken by optimising processing parameters. One example of this is given in [85], where the authors experiment with different laser power profiles to control heating of the powdered material. Another form of control adjusts spatial aspects of the build, compensating for shrinkage effects in final part geometry by adjusting the commanded melt pool location [86]–[88].

Despite this body of research, most of the literature on WHASPs and HASPs opts for open-loop control strategies, freezing parameters after initial optimisation [62], [63]. Jeng et al. [89] identified limitations of open-loop control of DED parameters, such as excessive material build-up in corner profiles due to the acceleration and deceleration phases whilst traversing the corner profile. Powder build-up resulting from unsuitable powder flow-rates and a mismatch between melt pool and powder stream diameters were also investigated. Finally, the inability to deposit powder effectively once the profile of previous deposition tracks had become pointed was discussed. Research in this area often exploits the presence of a subtractive process to correct errors geometrical errors and poor surface quality arising from the additive process [89].

Merz et al. [57] identified the need for closed-loop control of HASP parameters in 1994. Karunakaran et al. [65] has also explicitly stated the need for control over several welding parameters in order to affect a change in a single process output, such as additive layer thickness. Kerschbaumer and Ernst [73] devise an extended CNC control to accommodate the additive process in a commercial 5-axis machine tool. This research addressed the need to accurately control machine feedrates and feed-stock volumetric flow-rates. The laser power was related to the feedrate of the machine via third order polynomial relationship creating a form of closed loop control. Choi et al. [90] investigated individual wire-fed welding parameters such as track and layer dimensions. Intuitively, an increased feedrate for a constant material feedrate resulted in a reduction track width in the deposition. Likewise, increasing the material feedrate, with a constant laser power and table feedrate, resulted in an increased track width. The work of Jones et al. [91] uses fixed additive parameters in an open-loop sense, but has provision for inspection (tactile probing) of the workpiece to characterise the outcomes of both additive and subtractive processing. This makes it possible to operate closed-loop processing in accordance with the interactions described in Figure 3. This research makes use of commercial CNC controllers and CAD, CAM and CAI software to deliver this facility.

Research has also focussed on controlling the interchange from the additive to the subtractive process and vice versa. The use of available machine controller tool preparatory commands (G and M-codes) has been discusses [62], [63], [66], [67]; particularly when a process is either in an 'on' or 'off' state (open-loop).

4.3. The software layer

The software layer of the WHASP architecture is largely concerned with three tasks, namely (i) Identifying a suitable build-direction (part orientation), (ii) decomposing a part geometry into a layer-wise representation, and (iii) Defining a process sequence to facilitate the layer-wise manufacture of a part. In each case, identifying a preferable part orientation and build-direction is key to maximising the eventual part quality.

4.3.1. Identifying a suitable build orientation

Identifying a suitable build orientation is highly dependent on the manufacturing processes, part geometry and hybrid manufacturing strategy employed. For example, DED processes require support structures for features that overhang significantly, or that have no contact with existing structures. The use of high degree-of-freedom motion platforms permits a change in build direction during manufacture. The sequence of material deposition and removal also changes the build orientation requirements. For example, planar milling of a deposited face will generally always be available; however, profile milling of a deposited feature can pose tool-accessibility issues.

Kulkarni and Dutta [62] identified the build orientation as an 'essential' part of the hybrid process chain. They identified considerations when choosing the build direction as part height in the build direction, the implications on surface roughness due to the staircase effect, the area of the part that is mounted to the build-plate, the effects on mechanical properties, part distortion and volume of necessary support material. Kulkarni and Dutta [62] suggested that optimisation of build orientation may be undertaken for each of these metrics in isolation, or as part of a multi-objective optimisation problem

Other research efforts have identified build-directions via optimisation, with Hu et al. [92] identifying candidate build directions that are assessed based on cutting tool accessibility, deposition time, machining time, number of bridged structures and the number of support structures. The authors use a weighted cost function to allow users to specify their individual requirements. Zhang and Liou [56] also search for the optimum build-direction by setting an optimisation problem. In this research, build-directions minimising the total area of overhanging surfaces or inaccessible features are the target for the optimisation algorithm.

4.3.2. Part decomposition

As additive processes build parts layer-by-layer, research focuses on part decomposition. For hybrid additive and subtractive processes, this is generally divided into two categories, namely: planar slicing algorithms and feature recognition methods. Planar slice thicknesses are either equally spaced or adaptively changed to suit the part geometry.

The work of Kulkarni and Dutta [62] uses equally spaced planar slices of the part's STL file to identify layer-by-layer process plans and tool-paths. This method is often described as a 'zeroth-order' edge approximation. To reduce the staircase effect, coarse planar slices are further decomposed into fine slices to represent the part geometry to a suitable degree of accuracy. Akula and Karanakuran [63] also used zeroth-order edge approximation to calculate the slice thickness and layering of the part design. In each layer, material was built using either direction-parallel (zigzag) or contour-parallel (spiral) area filling. Each deposited layer was face-milled to unify the height of the deposited layer and remove surface defects.

An advancement of the fixed-thickness part slicing strategy is the 'adaptive' slicing strategy. Zhang and Liou [56] were able to change the orientation of the slicing plane to alleviate the dependency on support structures for overhanging geometries. This algorithm first searches for the optimum slicing direction and then tool-accessibility is checked to avoid collision and to ensure that successive layers are within the limits of acceptable overhang. Ruan et al. [93] furthered this work by introducing non-uniform layer building, where the thickness of the layer varies from point to point. Ruan et al. separated the build process into two stages, as shown in Figure 10. Firstly, a uniform layer with

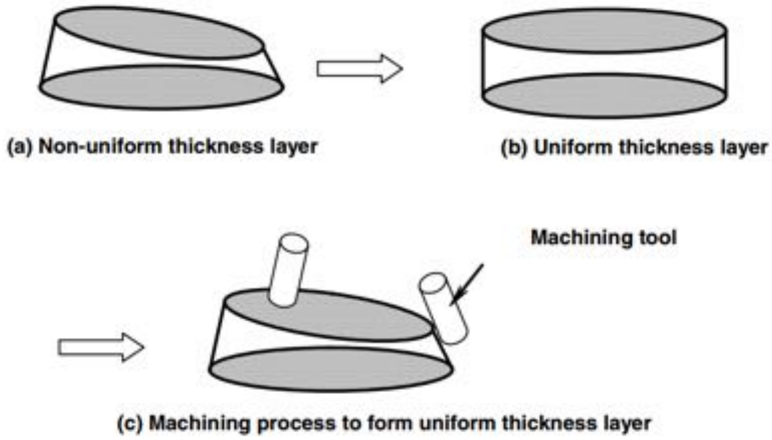


Figure 10: Part slicing using non-uniform layer thickness for use with additive and subtractive processes [93]

constant thickness is deposited and then the machining capability is used to subtract the excess material and form a non-uniform layer with a top-face that is normal to the preferred build direction of the following layer.

Chang et al. [94] decompose parts by identifying undercut, non-undercut and non-monotonic surfaces in an additive build. Graph theory is then employed to identify a minimal build sequence, inclusive of manufacturing precedents (e.g. surface B cannot be built before surface A). Furthermore, consideration towards avoiding interference between the cutting tool and existing part structures is given.

Other related works include Hu and Lee [95] and Hur et al. [96]. Both of these publications present part decomposition algorithms for parts that are made via gluing fixed-thickness sheets together, with interim machining of the assembled structure. Although it could be argued that this is a hybrid joining and subtractive process, the part decomposition theory remains relevant, as the layer thickness could simply be adjusted to reflect the thickness of an additive layer. The algorithm employed in these publications divides a part into slices, identifying the sign of the Z-component of the surface normal unit vector for each surface. Positive (+) Z-components and negative (-) Z-components are separated and their build direction chosen accordingly.

4.3.3. Process planning

In HASPs, process planning refers to the identification of a sequence of operations that will lead to the manufacture of the desired part, along with any necessary support structure. At the highest level, this may be broken down into sequences of additive, subtractive and metrology-based processes. At a lower level, individual toolpaths and process parameters are defined. An important difference between process planning for HASPs and process planning of a conventional manufacturing process is the fact that they can be bi-directional. Material may be added and subtracted, ad infinitum, until a desirable outcome has been achieved. This notion can greatly increase the complexity of the process-planning task.

For repairing/remanufacturing processes, Eiamsa-ard et al. [54] and Ren et al [74] identified 4 major steps for process planning, namely: (i) defining the worn/damaged feature, (ii) generating machining tool paths for removing the damaged/worn feature, (iii) generating the deposition tool path for re-building the worn/damaged feature and (iv) post-processing the tool paths into machining codes. In [54], toolpaths were defined by using Minkowski operations of dilation and erosion to offset the tool-centre point from the desired feature contour. Later, [74] proposed a 3-D patching method where the material is deposited on an existing feature and follows its surface contour as opposed to 2-D material deposition as shown in . The integration of laser cladding into a 5-axis CNC machine tool meant that material deposition and finishing could be achieved with a single setup. This facilitated higher geometrical accuracy whilst minimising the time required for repair, reducing associated costs.

Kerbrat et al. [97] adopt a novel process assessment and planning approach, which is driven by the relative complexity of manufacturing a feature either additively or subtractively. Complexity in this case is related to well understood process limitations, such as geometrical feasibility, diminishing stiffness in structures and tools with high aspect ratios, and tool accessibility. Although not explicitly applied to the field of hybrid processes, identifying when it is advantageous to manufacture a feature using a particular process could provide a valuable insight when process planning for WHASPs.

The works of Zhu et al. [98]–[100] focus on process planning for hybrid additive and subtractive manufacturing, including the use of inspection. The authors decompose parts into 'manufacturable' sub-parts, each with their own build direction. Attention is given to the ability 'promptly' inspect features as they are produced. In this way, out of tolerance features may be reworked whilst they are still accessible, which avoids unnecessary material wastage and is essential for internal or overhanging features. As such, the process plan starts with a static set of operations, but quickly becomes dynamic as features are created, measured and reworked.

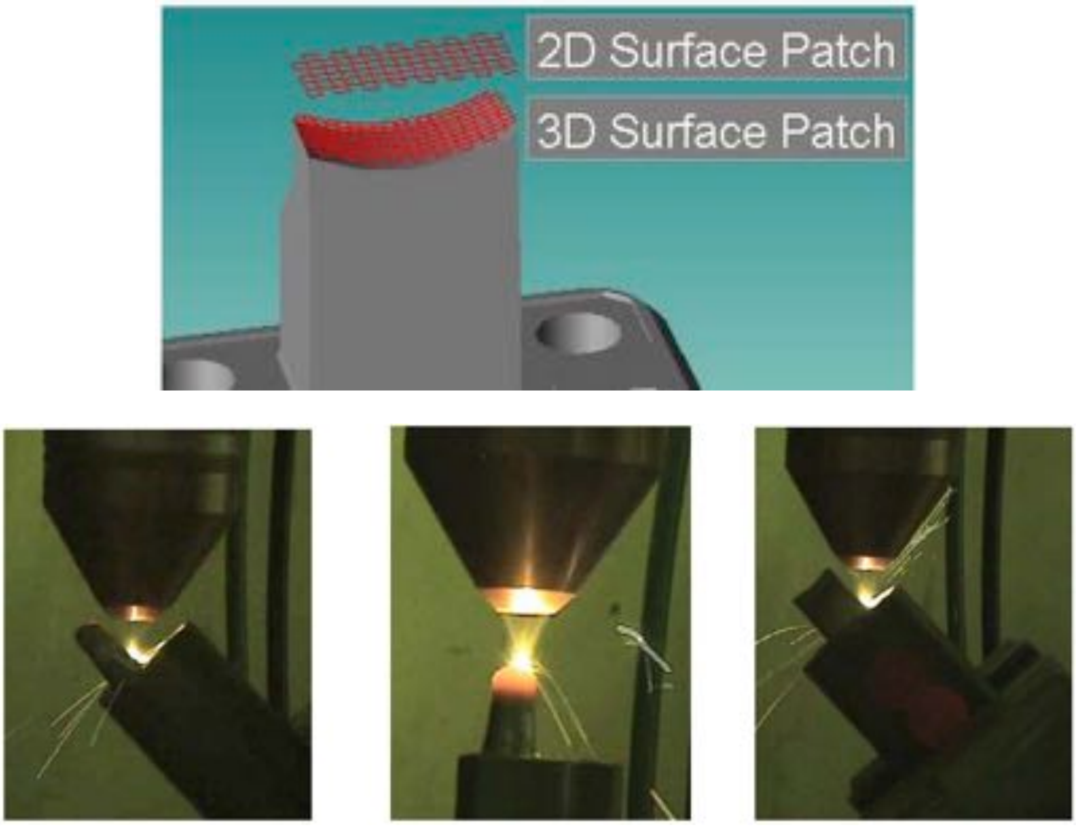


Figure 11: Patching of a 2D zigzag onto curved surface (top) and part repair using multi-axis additive manufacturing [74]

5. Hybrid additive and subtractive manufacturing processes – industrial perspective

Since 2003, additively manufactured part production has increased from 3.9% to 34.7% of all product and service revenues [12]. With specific reference to metal AM processes the future market size and growth rate are expected to exceed polymeric-based AM [101]. Furthermore, focus lies in customised and reconfigurable manufacturing, the application of layered and other freeform manufacturing techniques to fabricate intermediate and end-use products, and near-net shaping that reduces the need for excessive surface finishing [102]. Despite having been a fertile research topic since the mid-late 1990s, the commercialisation of hybrid manufacturing processes has been gradual. At the present time, the pace of development for commercial hybrid manufacturing machine tools is accelerating.

Trends suggest that the future manufacturing economy will rely heavily on reconfiguration and responsiveness, with a migration away from production lines and towards highly capable single machines that are able to transform raw material into a finished part in a single machine visit. This notion is particularly well aligned with the WHASP vision. The proceeding subsections give a summary of commercially available and commercially announced WHASPs.

5.1. The Hardware Layer

Table 1 gives a summary of the commercially available products and publically announced developmental work being undertaken in industry with regards to WHASPs. DMG Mori Seiki possess two hybrid additive and subtractive machine tool capabilities, each at different stages of development. The most developed of these is the LASERTEC 65 3D, integrating laser cladding and 5-axis CNC machining [106]. DMG Mori Seiki has also announced the development of the NT 4300 3D hybrid machine tool [107], which utilises a turn-mill machine. In terms of material readiness, DMG Mori Seiki list stainless steel, Nickel-based alloys (Inconel 625,718), tungsten carbide matrix materials, bronze and brass alloys, chrome-cobalt-molybdenum alloys, stellite and weldable tool-steels as being 'tried and tested' [118]. Obvious omissions from this list include titanium alloys and aluminium alloys, which appear to still pose considerable commercial issues in DED additive processes.

In 2013, Hamuel Reichenbacher announced the development of the HYBRID HSTM 1000 machine tool [119], [120], focusing largely on the repair of high-value parts. Using an existing Hamuel turn-mill machine, this offering combines high speed milling, directed energy deposition via laser cladding, inspection, deburring / polishing and laser marking. Particular focus is given to the integration of inspection processes to close the loop between the additive and subtractive processes, and the damaged part. Mazak Corporation has announced a hybrid multi-tasking machine, namely the INTEGREX i-400AM. This machine utilises two Ambit laser cladding heads [108], coarse and fine, for high speed and high accuracy deposition, respectively. This WHASP is based on a multi-tasking machining centre as a foundation, permitting the end-user to mill, turn and laser-mark additively manufactured parts using 5-axis motion.

Table 1: Announced or commercially available machine tools with hybrid manufacturing process capabilities. Information has been populated from the publicly available references. (*ATC = Automatic Tool Change, (†) = Terminology defined in ASTM F2792 standard [9]**)**

Additive Process	Product, Company	Subtractive Process	Additional Capabilities	Motion Platform	Reconfig. Mode	Ref.
Sheet lamination (†)	Formation, Fabrisonic	✓3-Axis CNC Machining		Dedicated machine tool development	ATC*	[103]
Directed Energy Deposition (†)	Ambit Laser Cladding Head, Hybrid Manufacturing Techonologies	-	-	-	ATC*	[104]
	HYBRID HSTM 1000, Hamuel Reichenbacher Ltd.	✓5-axis CNC Machining	✓ 3D scanning, ✓ Inspection, ✓ Deburring / Polishing ✓ Laser marking	Hamuel Reichebacher Mill-Turn	ATC*	[105]
	LASERTEC 65 3D, DMG Mori Seiki	✓5-axis CNC Machining	-	DMU 65 Monoblock 5-axis Machining Centre	ATC*	[106]
	NT 4300 3D, DMG Mori Seiki	✓5-axis CNC Machining ✓Turning	-	NT 4300SZ M Turn-Mill	ATC*	[107]
	INTEGREX i-400AM, Mazak Corporation	✓5 – Axis CNC Machining, ✓Turning	✓ Laser Marking ✓ Fine & Coarse Additive Nozzles	Mazak INTEGREX i400 Mill-Turn Machine	ATC*	[108]
	Replicator, Cybaman Technologies, traki-iski Ltd.	✓6 – Axis CNC Machining ✓Grinding	✓ Robot welding ✓ 3D scanning ✓ Laser Processing	Dedicated machine tool development	Automated and manual	[109], [110]
	WFL Millturn Technologies	✓5 – Axis CNC Machining, ✓Turning	✓ Laser-based hardening ✓ Laser Welding ✓ Laser Cladding	WFL Millturn Technologies M80 Turn-Mill	Unknown	[111]
	ZVH 45/L1600 ADD+PROCESS, Ibarmia	✓5-axis CNC Machining	-	Ibarmia 5-axis machining centre	ATC*	[112]
Cold Spraying	MPA 40, Hermle AG	✓5 – axis CNC Machining	✓ Multi-metal deposition	Hermle 5-axis machining centre	Unknown	[113], [114]
Powder Bed Fusion (†)	Lumex Avance – 25, Matsuura Machinery Corp.	✓3 – axis CNC Machining	✓ Vision-based monitoring	Dedicated machine tool development	Automated	[115]
	OPM250E, Sodick	✓3-Axis Machining	-	Dedicated Machine Tool Development	Automated	[116]
Material Jetting (†)	Solidscape Product lines, Solidscape Inc. (Stratasys)	✓Planar milling	-	Dedicated machine	Automated	[117]

Cybaman Technologies offer a comparatively compact solution [110], [121] built upon a 6-axis machine tool, which may be reconfigured to deliver CNC milling, grinding, welding, laser processing, directed energy deposition (additive) and 3D digitising. These technologies may be combined to suit end-user requirements, often utilising automation for ease of reconfiguration.

The year 2015 has also seen announcements from a consortium led by Optomec and backed by TechSolve, Lockheed Martin, MachMotion and U.S. Army Benét Labs regarding the development of a legacy CNC machine tool upgrade (retrofit) to include additive manufacturing via the LENS™ [122] DED process [123]. This research, undertaken in conjunction with America Makes, aims to make hybrid manufacturing more accessible to machine tool owners by focussing on existing machine upgrades. This takes the form of a modular, permanently mounted additive head, adjacent to the machine tool spindle. This is intended to be a more 'cost effective' means by which to bridge the gap between conventional and hybrid processing. This development is one of the first explorations of the adjacent mounting configuration in a commercial setting, having been popularised in the research (See Section 4.1 and Figure 12).

5.1.1. CNC machining with additive cold spraying processes

In this context, Cold Spraying refers to an additive process that propels powdered material at a substrate at a sufficiently high velocity to cause adhesion and material build-up [10]. The use of the word 'cold' refers to material adhesion at a temperature significantly lower than the material's melting point; although, upon collision, localised temperatures are high as a result of kinetic energy transfer [10]. This method contrasts with other additive processes considered for use in WHASPs, as it operates at a comparatively low temperature. The only reference available for integration of cold spraying processes with a subtractive process to form a WHASP is by Hermle [124]–[126].

In 2015, Hermle released information pertaining to their hybrid additive and subtractive machine tool [113], [114], [126]. Through varying the composition of the propelled material, functional material gradients may be additively constructed. By integrating Hermle's 'Metal Powder Application' within a five-axis machining centre, multi-metal deposition may be combined with 5-axis finish machining to create parts that are both geometrically and compositionally complex (constituent materials).

5.1.2. CNC machining with powder bed fusion

Matsuura's Lumex Avance – 25 [115] offers combined laser sintering and CNC milling within a single machine tool. The technology is used to simplify mould manufacture by removing mould-splitting processes and including complex internal mould features such as conformal cooling channels. In contrast to some of the other commercially available technologies, only three-axis machining is utilised. To avoid tool-accessibility issues, the machining process is sequentially interlaced with layered additive manufacturing to machine internal features whilst they are still exposed.

A similar product has been released by Sodick via their OPM250E machine [116]. Primarily targeting the moulding market, this machine combines high-speed three-axis milling with powder-bed fusion in what is termed 'a fully automatic' fashion. The additive process is delivered by a 500W Yb fiber laser. Sodick describe their process, whereby ten layers are additively manufactured, before a single machining pass is made. This sequence is then repeated until the build is complete.

5.1.3. CNC machining with material jetting

Solidscape offer a variety of 3D-printing solutions [117], all of which utilise material jetting (ink-jetting) to additively manufacture part geometries. A variety of wax-blends and wax-like organic compounds are melted to allow high frequency deposition of droplets onto a substrate [127]. Between the layers, the part may be 'planar milled' to provide a flat build surface, at a known height, for the next layer to be built upon.

5.2. The controller and software layers

With a WHASP, material may be added, removed and also measured. As such, it is possible that there will be no well-defined sequence of operations as a HASP process may be adaptive and reactive [99]. Therefore, process planning becomes significantly more complex as there are potentially an infinite number of feasible process sequences to manufacture a part. Therefore, the need to update information relating to the current part geometry and develop new process plans during manufacture is of great importance.

The fact that sacrificial or support material may be added to a finished part may necessitate more insightful metrics such as: build time, material usage, accuracy of features, cost etc. In addition to this, less obvious metrics may also play an important role in the process planning stage. A hypothetical example of this might be the maximisation of tool-tip (or deposition head) access to a part's engineering features throughout the manufacturing process; thereby maximising the opportunity to rework these features to meet manufacturing requirements. This type of metric may become critical in 'right-first-time' or 'zero-defect-manufacture' of high-value parts.

5.2.1. Commercial solutions in the controller layer

Table 1 can be divided into those that utilise well-established controller-vendor products, and those that have developed their own controller capabilities. These controllers are used to exact control over the machine's motion, auxiliary functions and process parameters. In terms of commercial NC control implementations, the Siemens 840D [128] has been used with [129], [130] and Fanuc 31i [131] has been used with [129]. These capabilities have been utilised to control both additive, subtractive and inspection processes due to their multi-axis functionality, modularity and flexibility. In addition to the application of general purpose NC control, dedicated NC control has been developed for specific machines, such as with the Sodick OPM250E [116].

5.2.2. Commercial solutions in the software layer

Due to the complexity of manufacturing operations using WHASPs, there is often a need to include additional software to facilitate manipulation of the part geometry via CAD, process planning using CAM and potentially computer aided inspection (CAI) too. For each of the solutions in Table 1, there is an accompanying software capability. The availability, complexity and breadth of these software solutions can vary considerably. Traditionally, there is limited information available regarding the exact nature of proprietary process planning algorithms. Nevertheless, this subsection offers a description of existing capabilities based on available information. A survey of publically available information regarding the use of additional software products has been undertaken and the findings are list in Table 2.

A recent addition to the commercial software layer is a Hybrid Manufacturing Simulation software [136]. This software has been developed by MachineWorks Ltd. and offers a full-machine tool simulation, including DED and CNC machining capabilities. Although this is not a detailed process interaction simulation, it provides useful visual simulation of the part evolution as material is both added and subtracted. It also gives a clear indication of tool accessibility and collision risks. The developers say that this development has come in response to the 'increasing number of high-profile machine tool manufacturers that are bringing to market hybrid CNC multi-tasking machines [136].'

Table 2: Examples of CAD, CAM and CAI implementations in commercial WHASPs

CAD, CAM and CAI Software from Vendor			
WHASP	**Software**	**Description**	**Ref.**
HSTM 1000, Hamuel Reichenbacher	• Delcam powerINSPECT • Delcam powerSHAPE • Delcam powerMILL	Software to capture measurement data (powerInspect), translate this data into alignment and defect characterisation (powerSHAPE), and devise a process plan (powerMILL), including both additive and subtractive tool-paths [132]. It should be noted that the use of all three of these software products is not explicitly stated; however, these three products form Delcam's adaptive machining capability, which was used in the RECLAIM project, which – a precursor to the HSTM 1000 [75].	[132]
LaserTec 65 3D, DMG MoriSeiki	• Siemens NX	Parts and process plans are designed through the Siemens NX software suite.	[130], [133]
Replicator, Cybaman Technologies	• hyperMILL	A commercial CAM package for multi-axis toolpath generation for machining parts.	[134]
In-house CAD / CAM Software Development			
WHASP	**Controller**	**Description**	**Ref.**
Formation, Fabrisonic	• SonicCAM	SonicCAM imports a CAD model of the part and then automatically generates the tool-paths and part programs for the sheet lamination and CNC machining operations.	[121]
MPA 40,Hermle	• MPA-Studio	This software undertakes a layer-by-layer assessment of a part, resulting in the generation of process plans, including tool-path. Included within this software suite will be a simulation environment to allow checking of process sequences and quality assurance issues.	[126]
Solid-Scape Products	• 3Z Works • 3Z Analyser • 3Z Organiser	Software is divided into self-contained units, which take responsibility for CAD file processing, motion planning, design of necessary support structures, simulation of analysis of part manufacture, and batch processing of multiple jobs.	[135]
Sodick (OPM250E)	• MARKS-MILL • OPM-GenLaser • OPM-Optimizer • OPM-Verify	Sodick have developed a suite of softwares to facilitate hybrid manufacture via their combined high-speed milling and powder-bed fusion. MARKS-MILL is a CAM system, charged with the generation of generation of machining tool-paths. OPM-GenLaser assists in path planning (scanning strategy) for the powder-bed fusion process. OPM-Optimizer permits editing of the machining tool-paths generated in MARKS-MILL. Finally, OPM-Verify offers a simulation capability for both additive and subtractive processing, acting as a checking procedure.	

6. Observations, emerging trends and future perspectives

As a result of the literature survey undertaken in this research, a number of key observations have been made, emerging trends identified and future perspectives forecasted. These are grouped into subsections addressing machining platforms and their structural elements, control systems and process planning software, metrology and the further integration of additive and subtractive processes. A final subsection then outlines the future vision for this research area.

6.1. Machining platforms and structural elements

By surveying academic research pertaining to the development of WHASPs, some common traits have been identified. The overwhelming majority of research considers the integration of Directed Energy Deposition (DED) as an additive process and CNC machining as a subtractive process.

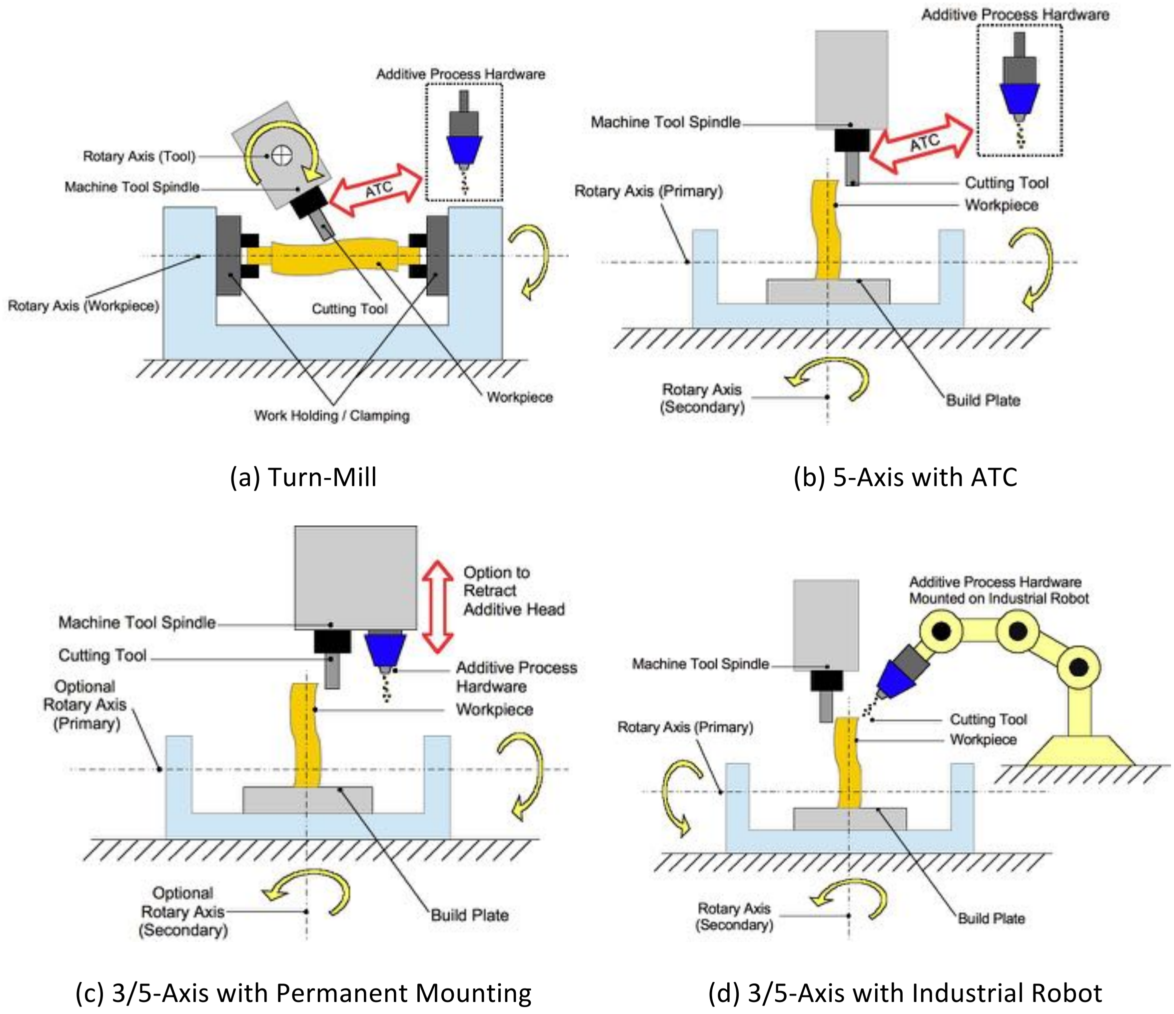
Motion platforms are either developed in-house to avoid the investment in unnecessary machine tool structure and functions, or an existing machine tool is used as a foundation. When the latter is employed, a popular configuration is to permanently mount an additive head adjacent to the milling spindle, which is controlled via the NC (M-codes). There are two more recent examples of machine tools that are reconfigured using automated tool-changes. This solution has now become attractive in the commercial arena. In addition, this more recent research has begun to place emphasis on the inclusion of in-process inspection to close the loop between the additive and subtractive processes.

6.1.1. Popular hardware configurations

As a result of this literature survey, emerging trends in WHASP hardware configurations have been identified. These configurations are illustrated in Figure 12. Figure 12a is a configuration that has gained traction in industry. It centres on the modification of a commercial mill-turn machine, where a workpiece is held in a spindle (rotary axis), which revolves to achieve different part orientations. The tool also has a rotary degree of freedom, to allow tool-access that is normal to the processed surface. This configuration is well suited to hybrid processing of existing workpieces (e.g. part repair or reincarnation), as the workpiece may be clamped at each end to reduce unwanted deflection.

Figure 12b represents the adaptation of a five-axis machining centre, in which the additive capability is interchangeable either manually or via automatic tool change (ATC). This configuration has been widely adopted in both academia and industry. Unlike the mill-turn configuration, these machines have the advantage of an easily accessible build-plate, which makes them well suited to the hybrid manufacture of new parts. Figure 12c is similar to Figure 12b; however, the additive capability is permanently mounted to the Z-axis of the machine tool. This significantly reduces the complexity of the integration, as the additive head is typically raised and lowered using available NC preparatory commands (G & M-codes). This configuration is widely utilised in academia but is yet to gain significant commercial uptake.

Finally, Figure 12d is a configuration in which the additive and subtractive manufacturing processes each have their own motion platform; typically an industrial robot and a machine tool. In this way, the machines work collaboratively (not simultaneously) to add and subtract material. Despite being highly dextrous, there is a significant requirement for additional investment in hardware, controller capability and integration. This configuration has yet to see industrial uptake. A possible advantage of this configuration is the ability to undertake differing simultaneous motions, making it possible to add



(a) Turn-Mill

(b) 5-Axis with ATC

(c) 3/5-Axis with Permanent Mounting

(d) 3/5-Axis with Industrial Robot

Figure 12: Machine tool configurations that are emerging as preferred methods of integration for CNC machining and DED processes

and subtract materials in unison. To the best of the authors' knowledge, this possibility is yet to be explored.

Although machine configurations for other manufacturing processes have been explored, both academic and industrial hardware developments have focused on the integration of DED processes. This is largely due to the ability to add material to new and existing workpieces, and the fact that transitioning from additive to subtractive processes is considerably more straightforward without a powder bed. Despite PBF processes being the most abundant in industrial additive manufacturing, their usage is limited in HASPs / WHASPs.

The review of the published literature suggests that there has been approximately equal use of WHASPs for new part manufacture, and existing part repair or modification. It is also highly foreseeable that HASPs will create differing, if not conflicting, design requirements for any eventual WHASP. As such, designers will have a choice: (i) Identify the limiting process requirements and design to meet these; (ii) Try to generate a design that meets both sets of requirements simultaneously.

The former of these approaches may be thought of as pessimistic and perhaps suboptimal. The second approach is considerably more complex and requires significant design effort; potentially at the

Table 3: A summary of the key characteristics of WHASPs developed in a research environment (left) and those developed in a commercial setting

	Academic Perspective	Industrial Perspective
Applications	• Equal focus on the manufacture of new parts and the repair / reincarnation of existing components e.g. mould dies and turbine blades	• Equal focus on the manufacture of new parts and the repair / reincarnation of existing components e.g. mould dies and turbine blades
Hardware Layer	• Significant trend towards the integration of DED and CNC machining processes • Generally built upon existing machine tool structures (3-axis & 5-axis) • Use of industrial robots for part transfer between processing stations • Process interchange via permanent mounting of additive head, adjacent to machining spindle	• Significant trend towards the integration of DED and CNC machining processes • Generally built upon adapted 5-axis and turn-mill machine tools • Examples of PBF integrated with CNC machining • Automatic reconfiguration / interchange between processes emerging as popular choice • Metrology through tactile probing and 3D scanning
Controller Layer	• Research focuses primarily on integrating additive functionality with existing controller syntax (G & M codes) • Control of additive process is predominantly open-loop, where parameters are optimise, then remain static • Some examples of closed loop processing facilitated by metrology	• Process control integrated within general purpose commercial NC control and also dedicated controller developments • Control of additive process is predominantly open-loop, where parameters are optimise, then remain static • Some examples of closed loop processing facilitated by metrology
Software Layer	• Software developments focus on part decomposition into layers (zeroth-order & adaptive slicing) • Limited examples of closed-loop additive-subtractive processing facilitated by CAD/CAM/CAI	• Usage of commercial CAD / CAM / CAI • More focus on closed-loop additive-subtractive processing facilitated by CAD/CAM/CAI • One example of machine and process simulation software

detriment of development cost. However, recent developments in the manufacturing community may provide a means by which to counteract conflicting machine requirements. Ultra-lightweight and highly stiff structural components may provide a means to meet the stiffness requirements of subtractive processes, whilst also meeting the dynamic motion requirements of additive and inspection processes. For instance, dematerialised machine tools and novel platforms.

6.2. Control systems and process planning software

The published research focuses predominantly software-based decisions regarding build-direction and planar slicing of parts into layers. Particular attention is given to undercut (overhanging) features and their implication on tool-accessibility. Some attention is given to other process planning considerations, such as the integration of part inspection to update the process plan, and the decision process behind whether to additively or subtractively create part geometries. Based on the findings of this paper, process planning is a major research theme for the future. In particular, it could be of great benefit to introduce advanced computation and mathematical tools, such as machine learning and decision science, to develop resource-efficient process planning techniques.

Much of the research relating to the control of hardware and associated process parameters is rigid in its implementation. Typically, experiments are undertaken to identify parameters that give desirable outcomes (e.g. laser cladding parameters), and then these are left unchanged during manufacture. Hence, future research opportunities exist in the design of adaptive process control that is governed by closed-loop feedback using in-situ measurements. An important factor in this development will be the availability of reliable process models and test data. Furthermore, the existing research is heavily based on optimising the process parameters for individual operations namely, additive and machining operations. A holistic view of WHASPs is required to optimise the process parameters where the additive and subtractive processes interact and are used interchangeably. For instance, the effect of machining on the material properties during the build process and the effects of build heat on the machining process are still unknown.

Commercial WHASPs have varying control and software implementations. Early developments saw the inclusion of both in-house and commercial NC control and software. However, recent machines that use existing 5-axis and turn-mill machines as a foundation are increasingly adopting high-level commercial NC control products. These are then used in conjunction with advanced CAD, CAM and CAI software packages to develop process plans that are based upon CAD model and inspection data. Future opportunities lie in enhanced integration and communication between NC control, and CAD, CAM and CAI software. If this is achieved, part inspection may be used to a greater extent to determine and adapt suitable process plan strategies. This may give more certainty in part quality and make more efficient use of machine and material resources.

The introduction of WHASPs that can alternately add material onto and subtract material from existing parts, make decision making for process planning a major challenge. The majority of existing process planning systems is for parts that are generally built by additive manufacturing on a build plate. Therefore, the machining process plans are either for finishing the additively manufactured parts or for in process finishing to improve the quality of the built surface. A holistic approach for decision-making and process planning is required to indicate the shape of the initial build block and where and when material should be added or removed. Subsequently, material, resources and power consumption, manufacturing carbon footprint, life cycle and costs analysis, and material properties are potential drivers for process planning.

6.3. Process monitoring and inspection

As part of this review of published research, observations have been made, trends identified and future perspectives derived for WHASP process monitoring and inspection. The dominant technologies in WHASP inspection are: tactile probing for characterisation of features and workpiece orientation, and scanning systems for reverse engineering of feature and part geometries.

There is a noticeable lack of research covering process monitoring in HASPs. Only one example of process monitoring and control has been identified [73], where material delivery and laser power are monitored and subsequently controlled via the WHASP's numerical control. There are still substantial opportunities for development of further WHASP process monitoring capabilities, which may be integrated within a closed-loop control system as a further development.

Figure 13: A roadmap for future research activities and holistic design considerations for WHASPs

7. Research challenges and future vision

This research scrutinises emerging trends and technologies and current research challenges to form what the authors believe to be the future of WHASP research. These trends and challenges have been categorised and structured to form a roadmap for future lines of enquiry regarding research and development. This roadmap is presented in Figure 13, and selected themes are expanded upon in the proceeding subsections.

7.1. Further additive and subtractive technical challenges

So far, both research and industrial communities have focused heavily on the realisation of WHASPs through the amalgamation of Directed Energy Deposition and CNC machining processes. Although these developments are very encouraging for the manufacturing community, they only represent a small subset of the larger HASP and hybrid machine tool fields.

Regarding additive processes for metal parts, powder bed fusion and cold spraying processes have been under-explored compared to DED processes. There is scope for further consideration of these processes as candidates for WHASPs. As near-net shaping develops further, machining processes may be substituted by other subtractive, modification and transformative operations. Examples of these operations are cleaning, heat treatment, surface engineering, grinding and polishing. For this to be viable, near-net geometries must be a close representation of the final geometry, which necessitates continued improvement of the geometrical accuracy of additive processes; particularly with difficult to machine materials.

There are opportunities for further exploration of metal additive processes that have analogous counterparts in polymeric additive processes. When considering the use of metals, the absence of loose powder and the potential avoidance of support structures make wire-fed / droplet based processes viable candidates for enclosed geometries and also circumvent some material management issues. In terms of processing speed, current polymeric processes such as vat photopolymerisation are capable of producing parts of a high resolution with comparatively low processing times owing to the ability to cure an entire layer by projecting an image. Equivalent developments in metal additive processes would greatly increase the suitability of hybrid manufacturing processes to an industrial setting.

In order to realise complete integration of additive and subtractive processes, holistic consideration of the requirements of additive and subtractive processes is crucial. Swarf management systems are necessary to prevent mixing and provide a sustainable recycling/disposal of micro scale additive particles and machining chips. Additionally, the effects of materials management on machine longevity, and health and safety should be explored in detail. Furthermore, there is an opportunity to investigate the effect of surface quality of the build plate/existing parts on the quality of the finished parts. The heating capabilities of the laser head may be used to heat workpiece materials prior to machining, further hybridising transformative processes without the necessity to add another physical component to the system. On the other hand, the application of WHASPs is dominantly utilised for difficult-to-machine materials such as titanium, nickel and stainless steel alloys. Machining of these alloys is commonly undertaken using cutting fluids. Due to the contamination issues and the residuals left on the parts, the use of cutting fluids in WHASPS should be eliminated or minimised for the machining process. This necessitates the requirements for further research into development of advanced machining strategies and tooling to realise dry machining.

Finish machining of additive parts on a single platform eliminates the heat treatment stage for stress release after build process and prior to machining. It is known that heat treatments affect the material properties and geometry of materials [137]. There are significant research opportunities in studying the effects of (i) eliminating total heat treatment from the manufacturing process, (ii) heat treatment (post finish-machining) on residual stresses and part geometry, and (iii) partial heat treatment during the manufacturing process using WHASPs.

HASPs have the ability to create internal, otherwise inaccessible, and geometrically complex features. As such, inspection challenges relating to workpiece geometry, alone, are significant. The facts that as-built surfaces of many additive processes are equivalently complex due to partially adhered metal powder etc., further compounds this complexity. Finally, the introduction of high-temperature heat sources gives rise to numerous temperature control and material properties issues. Therefore, surface non-destructive inspection of geometry and surfaces and financially viable thermal measurement techniques will play a major role in future process monitoring and inspection in WHASPs. The National Institute of Standards and Technology (NIST) issued a report on the Measurement Science Roadmap for Metal-Based Additive Manufacturing [138]. This document is highly relevant in the forecasting of current and future process monitoring and inspection challenges that WHASPs will bring. Another significant publication in the field of metrology issues relating to additive manufacture is the proceedings from the 2014 American Society for Precision Engineering topical meeting: 'Dimensional Accuracy and Surface Finish in Additive Manufacturing' [139].

7.2. Future vision

As a result of this research, a future vision for the architecture of WHASPs and their associated controller and software capabilities has been defined. This is represented diagrammatically in Figure 14. The WHASP and its associated HASP are delivered through a machine tool that is inherently reconfigurable in accordance with the above definitions. Hardware and software are both modular in their architecture, with well defined interfaces for the addition of new modules. These modules each deliver a process or sensing (measurement) capability and new materials or production scales are achieved via integration of new modules.

It is proposed that all processing of the workpiece should form a closed loop. Each constituent process should be adaptive to tolerate a variety of material composition, processing conditions and part geometries. Measurements of cutting forces and melt-pool conditions would be an essential requirement for such a capability. On a different level, processing between differing manufacturing processes should also be closed-loop in accordance with Figure 3. This will necessarily require adequate metrology capabilities to inspect the workpiece before interchanging processes.

To generate an initial process plan and specific manufacturing instructions, an advanced and fully integrated software layer is required. The ideal part is represented in terms of its geometry and quality characteristics in CAD. These are then passed to a computer-aided process planning (CAPP) stage to decompose the part into a sequence of feasible sub-features that should result in successful part manufacture. In accordance with the quality requirements, computer-aided inspection (CAI) interlaces measurement routines within the process plan. Instructions regarding the specific process parameters and motion profiles required to execute a given manufacturing process are developed via a CAM capability. These instructions inform a prediction of manufacturing outcomes using virtual models of materials, processes, machine tool and controller behaviour. The outcomes of this stage undergo negotiations with overarching manufacturing objectives relating to cost, resource efficiency, productivity and quality etc. If the results of the virtual manufacturing phase satisfy the manufacturing objectives to within a predefined acceptance level, manufacture of the part may commence. Failure to meet the objectives results in an iteration of the process, thus far, to propose an alternative manufacturing strategy.

After negotiations, the instructions are passed to the controller layer. This controller is open in its architecture and can be reconfigured through the addition and omission of modules. The controller communicates with a machine tool hardware, which also has reconfigurable architecture to respond to changes in manufacturing requirements. During manufacture, data is fed back from the metrology domain to update virtual models of materials, processes, machine and controller behaviour, such that they mimic what is happening in-process. Further to this, measured part data is fed back to the CAD stage (via CAI) to update the perceived part geometry and to make a comparison with the the nominal CAD model and manufacturing objectives. Interventions are put in place to correct discrepancies through additional processing. In this sense, the process plan and manufacturing instructions are adaptive and and reactive. This loop of process-measure-reassess-process could be run ad-infinitum. However, a crucial role of the overarching objectives is to prevent excessive consumption of power, materials and tooling. To realise this vision, significant developments must be made in regarding supporting software, sensing and metrology capabilities, adaptive processing, and a generally reconfigurable architecture for both hardware and controller elements.

7.2.1. Design for machine tool and controller reconfiguration

It is the contention of this research that WHASPs are, by their very nature, reconfigurable. Reconfigurable Machine Tools (RMTs) have been a fertile research area since the late 1990s and throughout the 2000s. A cross section of this research may be gleaned from [140]–[142]. The underlying research in this area has matured into with well-defined characteristics, and design methodologies and tools [143]–[148]. Synonymous controller architectures exist in the form of Open-Architecture Control Systems (OACS) [149]. WHASPs are closely aligned with these paradigms, exhibiting aspects of portability, extendibility, interoperability and scalability [149]. According to [150], '*modularity'* requires that all major components are modular in design; '*convertability'* requires that the optimal operating mode is achieved through reconfiguration, which can be updated with a short conversion time; '*scalability'* stipulates that new scales of production are achievable through the addition and reconfiguration of modules; '*customisation'* provides permits flexibility within the desired part and feature range, which may later be changed through reconfiguration; '*integrability'* ensures modules are design with interfaces for ease of component integration; and '*diagnosability'* is achieve through the ability to rapidly identify the performance of the current configuration, and relate poor performance to a given module or interface within the system.

Almost all of the current WHASP implementations in both academia and industry have used an existing machine tool as a foundation. Although understandable from a financial standpoint, this notion risks contradicting RMT tool concepts, as the final WHASP solution should be equally sympathetic to additive and subtractive processing requirements, without incorporating redundant capability. It is suggested that future research should consider the design of a dedicated machine tool structure that is tailored to both processes, using well-defined interfaces to permit the inclusion of further modules.

Control systems development should follow a in a similar vein, taking on a modular and open architecture. It has become clear that bidirectional communication between the machine's NC controller and the CAD, CAM and CAI software needs to be detailed and frequent. This is largely due to the need to regularly acquire time-specific information relating to the workpiece and hardware interactions, which is then used this to update a digital representation of the manufacturing process. At present, it is only through the use of NC and advanced PC-based software that this can be achieved. It is, therefore, likely that there will be a convergence between the controller and PC workstation units, forming an integrated solution with significantly greater exchange of manufacturing data.

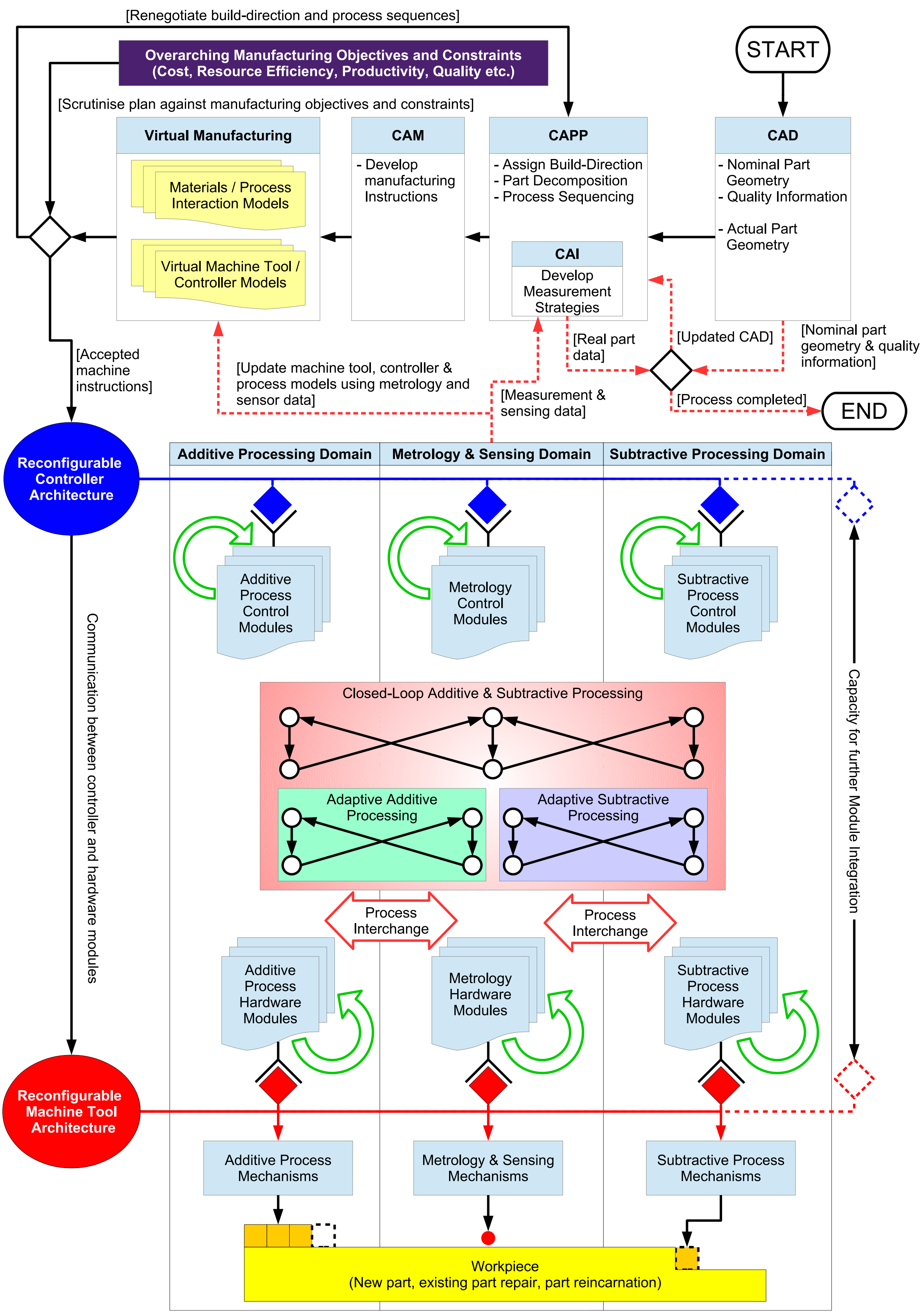


Figure 14: The future vision for WHASP architecture considering software, controller and hardware

7.2.2. Process monitoring and inspection

As a result of this literature review, the authors have identified metrology and process monitoring as an area of vast potential for future research. It is expected that future metrology for HASPs and WHASPs will be governed by a few central issues. There is a need to develop financially viable, non-destructive and penetrative measurement techniques (and technologies) to acquire data pertaining to geometry, surface characteristics and material properties. At present, technologies such as x-ray computed tomography are starting to address some of these issues.

It is envisaged that any metrology solution that is sufficient to permit quality management and process control would, by its very nature, produce large quantities of data. Therefore, data processing, transmission and storage are likely to become important issues in the realm of metrology for HASPs and WHASPs.

The presence of cross-manufacturing-process interaction in HASPs will necessitate the integration of metrology with process planning and process control. Issues such as thermal gradients, part deflection and changing workpiece geometries will require metrology solutions that can deliver salient metrology information, in a time and cost controlled manner. In particular, affordable thermal measurement systems and rapid part geometry scanning are burgeoning requirements.

Finally, HASPs and WHASPs open up new possibilities for metrology solutions, as new manufacturing metrics may become significant. The ability to measure material and part properties, in-process, may facilitate control over material microstructure, porosity, material interface characteristics and multi-material (functional material gradient) composition.

8. Conclusions

The design of hybrid additive and subtractive processes has been an active research theme since the late 1990s; however, the transition from research into the commercial arena has been gradual. Research has shown that HASPs may be used to manufacture geometrically and compositionally complex parts, which were previously considered too time consuming or even impossible. With the exception of some early-adopters, the number of commercial WHASPs has increased significantly since the late 2000s.

This research has surveyed literature from both academic and commercial sources, and identified current trends in the design of WHASPs. This predominantly includes the tendency to use directed energy deposition as a manufacturing process, combined with a highly mobile machine tool. There has been an equal application of WHASPs in both the manufacture of new parts and also the repair (remanufacture) of damaged components. The latter has clearly illustrated the need to unite advanced metrology, CAD, CAM and CAI capabilities to update an adaptive process plan based upon in-situ measurements. These requirements also translate into new part manufacture, as the ability to freely add or subtract material presents significant opportunities hybrid work, measure and re-work process planning strategies, which may facilitate a step change in quality management.

A major contribution of this research is the identification of research themes that are currently under-explored, or that could present significant opportunities and challenges in the future development of HASPs and WHASPs. This extends to the design of highly reconfigurable machine tool hardware and controllers to accommodate two, or more, manufacturing processes within the same machine. The need for multiple and varied inspection capabilities to provide closed-loop feedback between each constituent manufacturing process and the machine tool, as well as the acquisition of data for the development of predictive feed-forward process and machine models, is discussed. Finally, large opportunities in the development of novel process planning techniques are required, as manufacture moves away from well-defined sequences of operations into a more fluid 'crafting' of parts that meet manufacturing requirements.

The future vision of this research area is the emergence of highly capable hybrid machines that combine manufacturing processes from a number of process categories to transform numerous raw materials into finished parts and even assemblies. These machines will intelligently, fluently and automatically switch manufacturing processes to work, inspect and rework material until all necessary manufacturing requirements are met. This is envisioned to be a largely unsupervised process, as integrated sensors and comprehensive metrology solutions provide automatic updates to an ever-changing process plan, thereby demonstrating 'smart machine' characteristics. With the arrival of these technologies, manufacture, remanufacture and reincarnation of parts will become possible with a single workstation visit.

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References

[1] S. T. Newman, Z. Zhu, V. Dhokia, and A. Shokrani, "Process planning for additive and subtractive manufacturing technologies," *CIRP Ann. - Manuf. Technol.*, vol. 64, no. 1, pp. 467–470, 2015.

[2] F. G. Arcella and F. H. Froes, "Components from Powder Using Laser Forming," *Jom*, vol. 52, no. 5, pp. 28–30, 2000.

[3] J. Wang, S. Prakash, Y. Joshi, and F. Liou, "Laser aided part repair-a review."

[4] Z. Zhu, V. G. Dhokia, a. Nassehi, and S. T. Newman, "A review of hybrid manufacturing processes – state of the art and future perspectives," *Int. J. Comput. Integr. Manuf.*, vol. 26, no. 7, pp. 596–615, Jul. 2013.

[5] B. Lauwers, F. Klocke, A. Klink, a. E. Tekkaya, R. Neugebauer, and D. McIntosh, "Hybrid processes in manufacturing," *CIRP Ann. - Manuf. Technol.*, vol. 63, no. 2, pp. 561–583, 2014.

[6] K. A. Lorenz, J. B. Jones, D. I. Wimpenny, and M. R. Jackson, "A Review of Hybrid Manufacturing," in *Solid Freeform Fabrication Conference Proceedings*, 2015, vol. 53.

[7] S. Simhambhatla and K. P. Karunakaran, "Build strategies for rapid manufacturing of components of varying complexity," *Rapid Prototyp. J.*, vol. 21, no. 3, pp. 340–350, 2015.

[8] P. Kulkarni, A. Marsan, and D. Dutta, “A review of process planning techniques in layered manufacturing,” *Rapid Prototyp. J.*, vol. 6, no. 1, pp. 18–35, 2000.

[9] “ASTM F2792-12A, Standard Terminology for Additive Manufacturing Technologies.” ASTM International, West Conshohocken, PA, 2012.

[10] V. K. Champagne, *The Cold Spray Materials Deposition Process: Fundamentals and Applications*. Elsevier Science, 2007.

[11] W. E. Frazier, “Metal additive manufacturing: A review,” *J. Mater. Eng. Perform.*, vol. 23, no. 6, pp. 1917–1928, 2014.

[12] T. T. Wohlers, *Wohlers Report 2014: 3D Printing and Additive Manufacturing State of the Industry Annual Worldwide Progress Report*. Wohlers Associates, 2014.

[13] S. Das, “Physical Aspects of Process Control in Selective Laser Sintering of Metals,” *Adv. Eng. Mater.*, vol. 5, no. 10, pp. 701–711, 2003.

[14] T. Childs, “Selective laser sintering (melting) of stainless and tool steel powders: experiments and modelling,” *Proc. …*, vol. 219, no. 4, pp. 339–357, 2005.

[15] J. P. Kruth, G. Levy, F. Klocke, and T. H. C. Childs, “Consolidation phenomena in laser and powder-bed based layered manufacturing,” *CIRP Ann. - Manuf. Technol.*, vol. 56, no. 2, pp. 730–759, 2007.

[16] L. Thijs, F. Verhaeghe, T. Craeghs, J. Van Humbeeck, and J. P. Kruth, “A study of the microstructural evolution during selective laser melting of Ti-6Al-4V,” *Acta Mater.*, vol. 58, no. 9, pp. 3303–3312, 2010.

[17] C. Doumanidis and Y.-M. Kwak, “Geometry Modeling and Control by Infrared and Laser Sensing in Thermal Manufacturing with Material Deposition,” *J. Manuf. Sci. Eng.*, vol. 123, no. 1, p. 45, 2001.

[18] J. Liu and L. Li, “In-time motion adjustment in laser cladding manufacturing process for improving dimensional accuracy and surface finish of the formed part,” *Opt. Laser Technol.*, vol. 36, no. 6, pp. 477–483, 2004.

[19] M. Gharbi, P. Peyre, C. Gorny, M. Carin, S. Morville, P. Le Masson, D. Carron, and R. Fabbro, “Influence of various process conditions on surface finishes induced by the direct metal deposition laser technique on a Ti-6Al-4V alloy,” *J. Mater. Process. Technol.*, vol. 213, no. 5, pp. 791–800, 2013.

[20] J. . Milewski, G. . Lewis, D. . Thoma, G. . Keel, R. . Nemec, and R. . Reinert, “Directed light fabrication of a solid metal hemisphere using 5-axis powder deposition,” *J. Mater. Process. Technol.*, vol. 75, no. 1–3, pp. 165–172, 1998.

[21] R. Vilar, “Laser cladding,” *J. Laser Appl.*, vol. 11, no. 2, p. 64, 1999.

[22] M. . Griffith, M. . Schlienger, L. . Harwell, M. . Oliver, M. . Baldwin, M. . Ensz, M. Essien, J. Brooks, C. . Robino, J. . Smugeresky, W. . Hofmeister, M. . Wert, and D. . Nelson, “Understanding thermal behavior in the LENS process,” *Mater. Des.*, vol. 20, no. 2–3, pp. 107–113, 1999.

[23] L. Costa, R. Vilar, T. Reti, and A. M. Deus, "Rapid tooling by laser powder deposition: Process simulation using finite element analysis," *Acta Mater.*, vol. 53, no. 14, pp. 3987–3999, 2005.

[24] P. Aggarangsi and J. Beuth, "Localized preheating approaches for reducing residual stress in additive manufacturing," *Proc. SFF Symp., Austin*, pp. 709–720, 2006.

[25] A. Vasinonta, J. L. Beuth, and M. Griffith, "Process Maps for Predicting Residual Stress and Melt Pool Size in the Laser-Based Fabrication of Thin-Walled Structures," *J. Manuf. Sci. Eng.*, vol. 129, no. 1, p. 101, 2007.

[26] B. Dillingh, G. Hayes, M. Hoppenbrouwers, V. Westerwoudt, and G. van Baars, "Control of Microstructural Evolution in Powder Bed Fusion Additive Manufacturing in Relation to Functional Properties of Metals," in *ASPE 2014 Spring Topical Meeting: Dimensional Accuracy and Surface Finish in Additive Manufacturing*, 2014, pp. 205–208.

[27] K. C. Mills, B. J. Keene, R. F. Brooks, and a. Shirali, "Marangoni effects in welding," *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.*, vol. 356, no. 1739, pp. 911–925, 1998.

[28] C. Hauser, T. H. C. Childs, K. W. Dalgarno, and R. B. Eane, "Atmospheric control during direct selective laser sintering of stainless steel 314S powder," *Proc. Solid …*, 1999.

[29] F. Abe, K. Osakada, M. Shiomi, K. Uematsu, and M. Matsumoto, "The manufacturing of hard tools from metallic powders by selective laser melting," *J. Mater. Process. Technol.*, vol. 111, no. 1–3, pp. 210–213, 2001.

[30] F. Klocke, C. Wagner, and F. Klocke, "Coalescence Behaviour of Two Metallic Particles as Base Mechanism of Selective Laser Sintering," *CIRP Ann. - Manuf. Technol.*, vol. 52, no. 1, pp. 177–180, 2003.

[31] J. Kruth, B. Vandenbroucke, J. Vaerenbergh, and P. Mercelis, "Benchmarking of different SLS/SLM processes as rapid manufacturing techniques," *Int. Conf. Polym. Mould. Innov. (PMI), Gent, Belgium, April 20-23, 2005*, pp. 1–7, 2005.

[32] K. Mumtaz and N. Hopkinson, "Top surface and side roughness of Inconel 625 parts processed using selective laser melting," *Rapid Prototyp. J.*, vol. 15, no. 2, pp. 96–103, 2009.

[33] G. Strano, L. Hao, R. M. Everson, and K. E. Evans, "Surface roughness analysis, modelling and prediction in selective laser melting," *J. Mater. Process. Technol.*, vol. 213, no. 4, pp. 589–597, 2013.

[34] J. Kranz, D. Herzog, and C. Emmelmann, "Design guidelines for laser additive manufacturing of lightweight structures in TiAl6V4," *J. Laser Appl.*, vol. 27, no. S1, p. S14001, 2015.

[35] J. Mazumder, a. Schifferer, and J. Choi, "Direct Materials Deposition: Designed Macro and Microstructure," *MRS Proc.*, vol. 542, pp. 118–131, 1998.

[36] A. Suárez, M. J. Tobar, A. Yáñez, I. Pérez, J. Sampedro, V. Amigó, and J. J. Candel, "Modeling of phase transformations of Ti6Al4V during laser metal deposition," *Phys. Procedia*, vol. 12, no. PART 1, pp. 666–673, 2011.

[37] G. Sun, S. Bhattacharya, G. P. Dinda, A. Dasgupta, and J. Mazumder, "Microstructure evolution during laser-aided direct metal deposition of alloy tool steel," *Scr. Mater.*, vol. 64, no. 5, pp. 454–457, 2011.

[38] J. Yu, M. Rombouts, G. Maes, and F. Motmans, "Material Properties of Ti6Al4V Parts Produced by Laser Metal Deposition," *Phys. Procedia*, vol. 39, pp. 416–424, 2012.

[39] P. A. Kobryn, E. H. Moore, and S. L. Semiatin, "Effect of laser power and traverse speed on microstructure, porosity, and build height in laser-deposited Ti-6Al-4V," *Scr. Mater.*, vol. 43, no. 4, pp. 299–305, 2000.

[40] W. Hofmeister and M. Griffith, "Solidification in direct metal deposition by LENS processing," *Jom*, vol. 53, no. 9, pp. 30–34, 2001.

[41] L. C. Zhang, D. Klemm, J. Eckert, Y. L. Hao, and T. B. Sercombe, "Manufacture by selective laser melting and mechanical behavior of a biomedical Ti-24Nb-4Zr-8Sn alloy," *Scr. Mater.*, vol. 65, no. 1, pp. 21–24, 2011.

[42] E. Brandl, U. Heckenberger, V. Holzinger, and D. Buchbinder, "Additive manufactured AlSi10Mg samples using Selective Laser Melting (SLM): Microstructure, high cycle fatigue, and fracture behavior," *Mater. Des.*, vol. 34, pp. 159–169, 2012.

[43] Z. Wang, K. Guan, M. Gao, X. Li, X. Chen, and X. Zeng, "The microstructure and mechanical properties of deposited-IN718 by selective laser melting," *J. Alloys Compd.*, vol. 513, pp. 518–523, 2012.

[44] I. Yadroitsev, P. Krakhmalev, I. Yadroitsava, S. Johansson, and I. Smurov, "Energy input effect on morphology and microstructure of selective laser melting single track from metallic powder," *J. Mater. Process. Technol.*, vol. 213, no. 4, pp. 606–613, 2013.

[45] Q. Jia and D. Gu, "Selective laser melting additive manufacturing of Inconel 718 superalloy parts: Densification, microstructure and properties," *J. Alloys Compd.*, vol. 585, pp. 713–721, 2014.

[46] I. Yadroitsev, P. Krakhmalev, and I. Yadroitsava, "Selective laser melting of Ti6Al4V alloy for biomedical applications: Temperature monitoring and microstructural evolution," *J. Alloys Compd.*, vol. 583, pp. 404–409, 2014.

[47] P. Mercelis and J.-P. Kruth, "Residual stresses in selective laser sintering and selective laser melting," *Rapid Prototyp. J.*, vol. 12, no. 5, pp. 254–265, 2006.

[48] S. Ghosh and J. Choi, "Modeling and Experimental Verification of Transient/Residual Stresses and Microstructure Formation in Multi-Layer Laser Aided DMD Process," *J. Heat Transfer*, vol. 128, no. 7, p. 662, 2006.

[49] A. B. Spierings, T. L. Starr, and K. Wegener, "Fatigue performance of additive manufactured metallic parts," *Rapid Prototyp. J.*, vol. 19, no. 2, pp. 88–94, 2013.

[50] K. M. B. Taminger, R. a Hafley, D. T. Fahringer, and R. E. Martin, "Effect of Surface Treatments on Electron Beam Freeform Fabricated Aluminum Structures Karen M. B. Taminger, Robert A. Hafley, David T. Fahringer, and Richard E. Martin NASA Langley Research Center, Hampton, VA."

[51] L. Löber, C. Flache, R. Petters, U. Kühn, and J. Eckert, “Comparison of different post processing technologies for SLM generated 316l steel parts,” *Rapid Prototyp. J.*, vol. 19, no. 3, pp. 173–179, 2013.

[52] S. Rossi, F. Deflorian, and F. Venturini, “Improvement of surface finishing and corrosion resistance of prototypes produced by direct metal laser sintering,” *J. Mater. Process. Technol.*, vol. 148, no. 3, pp. 301–309, 2004.

[53] A. T. Beaucamp, Y. Namba, P. Charlton, S. Jain, and A. a Graziano, “Finishing of additively manufactured titanium alloy by shape adaptive grinding (SAG),” *Surf. Topogr. Metrol. Prop.*, vol. 3, no. 2, p. 024001, 2015.

[54] K. Eiamsa-ard, H. J. Nair, L. Ren, J. Ruan, T. Sparks, and F. W. Liou, “Part Reapir using a Hybrid Manufacturing System,” in *16th Solid Freeform Fabrication Symposium SFF 2005*, 2005, pp. 425–433.

[55] J. M. Pinilla, J.-H. Kao, and F. B. Prinz, “Process planning and automation for additive-subtractive solid freeform fabrication,” in *Proceedings of the Solid Freeform Fabrication Symposium*, 1998, pp. 245–258.

[56] J. Zhang and F. Liou, “Adaptive Slicing for a Multi-Axis Laser Aided Manufacturing Process,” *J. Mech. Des.*, vol. 126, no. 2, p. 254, 2004.

[57] R. Merz, F. B. Prinz, K. Ramaswami, M. Terk, and L. Weiss, *Shape deposition manufacturing*. Engineering Design Research Center, Carnegie Mellon Univ., 1994.

[58] C. H. Amon, “Shape deposition manufacturing with microcasting,” 1997.

[59] C. H. Amon, J. L. Beuth, L. E. Weiss, R. Merz, and F. B. Prinz, “Shape Deposition Manufacturing With Microcasting: Processing, Thermal and Mechanical Issues,” *J. Manuf. Sci. Eng.*, vol. 120, no. 3, p. 656, 1998.

[60] 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,” *Int. J. Mach. Tools Manuf.*, vol. 45, no. 9, pp. 1057–1062, 2005.

[61] Y. A. Song and S. Park, “Experimental investigations into rapid prototyping of composites by novel hybrid deposition process,” *J. Mater. Process. Technol.*, vol. 171, no. 1, pp. 35–40, 2006.

[62] S. Akula and K. P. Karunakaran, “Hybrid adaptive layer manufacturing: An Intelligent art of direct metal rapid tooling process,” *Robot. Comput. Integr. Manuf.*, vol. 22, no. 2, pp. 113–123, 2006.

[63] S. Akula, K. P. Karunakaran, and C. Amarnath, “Statistical process design for hybrid adaptive layer manufacturing,” *Rapid Prototyp. J.*, vol. 11, no. 4, pp. 235–248, 2005.

[64] W. Meiners, C. Over, H. Pleteit, S. Stührmann, I. Wirth, T. Wirtz, and K. Wissenbach, “Research on layer manufacturing techniques at fraunhofer,” 2004.

[65] K. P. Karunakaran, V. Pushpa, and S. B. Akula, “Techno-Economic Analysis of Hybrid Layered Manufacturing,” *Int. J. Intell. Syst. Technol. Appl.*, vol. 4, no. 1, pp. 382–394, 2008.

[66] K. P. Karunakaran, S. Suryakumar, V. Pushpa, and S. Akula, "Retrofitment of a CNC machine for hybrid layered manufacturing," *Int. J. Adv. Manuf. Technol.*, vol. 45, no. 7–8, pp. 690–703, 2009.

[67] K. P. Karunakaran, S. Suryakumar, V. Pushpa, and S. Akula, "Low cost integration of additive and subtractive processes for hybrid layered manufacturing," *Robot. Comput. Integr. Manuf.*, vol. 26, no. 5, pp. 490–499, 2010.

[68] "MULTIFAB," *Southern Methodist University*, 2015. [Online]. Available: https://www.smu.edu/Lyle/Centers/RCAM/Labs/RapidManufacturing/MultiFab. [Accessed: 20-Apr-2015].

[69] E. Yarrapareddy and R. Kovacevic, "Numerical simulation and characterization of slurry erosion of laser cladded surfaces by using failure analysis approach," *J. Fail. Anal. Prev.*, vol. 7, no. 6, pp. 464–474, 2007.

[70] R. Kovacevic and M. E. Valant, "System and method for fabricating or repairing a part," US7020539 B1, 2003.

[71] J. R. Fessler, R. Merz, A. H. Nickel, F. B. Prinz, and L. E. Weiss, "Laser deposition of metals for shape deposition manufacturing," in *Proceedings of the Solid Freeform Fabrication Symposium*, 1996, pp. 117–124.

[72] T. Himmer, A. Techel, S. Nowotny, and E. Beyer, "Recent developments in metal laminated tooling by multiple laser processing," *Rapid Prototyp. J.*, vol. 9, no. 1, pp. 24–29, 2003.

[73] M. Kerschbaumer 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, vol. 97, pp. 1710–1720.

[74] L. Ren, A. P. Padathu, J. Ruan, T. Sparks, and F. W. Liou, "Three dimensional die repair using a hybrid manufacturing system," *17th Solid Free. Fabr. Symp. SFF 2006, August 14, 2006 - August 16, 2006*, pp. 51–59, 2006.

[75] "Leading a Remanufacturing Revolution," *CATAPULT High Value Manufacturing*, 2015. [Online]. Available: https://www.catapult.org.uk/-/leading-a-remanufacturing-revolution?inheritRedirect=true. [Accessed: 29-Apr-2015].

[76] 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 *International Solid Freeform Fabrication Symposium*, 2012, pp. 821–827.

[77] "Reclaim Project - Remanufacturing the Future," *CATAPULT High Value Manufacturing*, 2012. [Online]. Available: https://hvm.catapult.org.uk/-/reclaim-project-remanufacturing-the-future. [Accessed: 17-Aug-2015].

[78] E. Yasa, J. P. Kruth, and J. Deckers, "Manufacturing by combining Selective Laser Melting and Selective Laser Erosion/laser re-melting," *CIRP Ann. - Manuf. Technol.*, vol. 60, no. 1, pp. 263–266, 2011.

[79] M. Villeta, B. De Agustina, J. M. S. De Pipaón, and E. M. Rubio, "Efficient optimisation of machining processes based on technical specifications for surface roughness: Application to magnesium pieces in the aerospace industry," *Int. J. Adv. Manuf. Technol.*, vol. 60, no. 9–12, pp. 1237–1246, 2012.

[80] D. Hu and R. Kovacevic, "Sensing, modeling and control for laser-based additive manufacturing," *Int. J. Mach. Tools Manuf.*, vol. 43, no. 1, pp. 51–60, 2003.

[81] D. Hu, H. Mei, and R. Kovacevic, "Improving solid freeform fabrication by laser-based additive manufacturing," *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.*, vol. 216, no. 9, pp. 1253–1264, 2002.

[82] T. Craeghs, F. Bechmann, S. Berumen, and J. P. Kruth, "Feedback control of Layerwise Laser Melting using optical sensors," *Phys. Procedia*, vol. 5, no. PART 2, pp. 505–514, 2010.

[83] T. Craeghs, S. Clijsters, E. Yasa, and J.-P. Kruth, "Online quality control of selective laser melting," *Solid Free. Fabr. Proc.*, pp. 212–226, 2011.

[84] T. Craeghs, S. Clijsters, J.-P. Kruth, F. Bechmann, and M.-C. Ebert, "Detection of Process Failures in Layerwise Laser Melting with Optical Process Monitoring," *Phys. Procedia*, vol. 39, pp. 753–759, 2012.

[85] K. a. Mumtaz and N. Hopkinson, "Selective Laser Melting of thin wall parts using pulse shaping," *J. Mater. Process. Technol.*, vol. 210, no. 2, pp. 279–287, 2010.

[86] X. Wang, "Calibration of shrinkage and beam offset in SLS process," *Rapid Prototyp. J.*, vol. 5, no. 3, pp. 129–133, 1999.

[87] Y. Ning, Y. S. Wong, J. Y. H. Fuh, and H. T. Loh, "An approach to minimize build errors in direct metal laser sintering," *IEEE Trans. Autom. Sci. Eng.*, vol. 3, no. 1, pp. 73–80, 2006.

[88] M. Mahesh, Y. S. Wong, J. Y. H. Fuh, and H. T. Loh, "A Six-sigma approach for benchmarking of RP&M processes," *Int. J. Adv. Manuf. Technol.*, vol. 31, no. 3–4, pp. 374–387, 2006.

[89] J. Jeng and M. Lin, "Mold fabrication and modi ® cation using hybrid processes of selective laser cladding and milling," *J. Mater. Process. Technol.*, vol. 110, pp. 98–103, 2001.

[90] D.-S. Choi, S. . Lee, B. . Shin, K. . Whang, Y. . Song, S. . Park, and H. . Jee, "Development of a direct metal freeform fabrication technique using CO2 laser welding and milling technology," *J. Mater. Process. Technol.*, vol. 113, no. 1–3, pp. 273–279, Jun. 2001.

[91] 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, Texas, USA*, 2012, pp. 821–827.

[92] Z. Hu, K. Lee, and J. Hur, "Determination of optimal build orientation for hybrid rapid-prototyping," *J. Mater. Process. Technol.*, vol. 130–131, pp. 378–383, 2002.

[93] J. Ruan, K. Eiamsa-ard, and F. W. Liou, "Automatic Process Planning and Toolpath Generation of a Multiaxis Hybrid Manufacturing System," *J. Manuf. Process.*, vol. 7, no. 1, pp. 57–68, 2005.

[94] Y. Chang and J. Pinilla, "Automated layer decomposition for additive/subtractive solid freeform fabrication," in *Proceedings of the Solid Freeform Fabrication Symposium*, 1999, pp. 111–120.

[95] Z. Hu and K. Lee, "Concave edge-based part decomposition for hybrid rapid prototyping," *Int. J. Mach. Tools Manuf.*, vol. 45, no. 1, pp. 35–42, 2005.

[96] J. Hur, K. Lee, Zhu-Hu, and J. Kim, "Hybrid rapid prototyping system using machining and deposition," *CAD Comput. Aided Des.*, vol. 34, no. 10, pp. 741–754, 2002.

[97] O. Kerbrat, P. Mognol, and J. Y. Hascoet, "Manufacturing complexity evaluation at the design stage for both machining and layered manufacturing," *CIRP J. Manuf. Sci. Technol.*, vol. 2, no. 3, pp. 208–215, 2010.

[98] Z. Zhu, V. Dhokia, and S. T. Newman, "A novel process planning approach for hybrid manufacturing consisting of additive, subtractive and inspection processes," *IEEE Int. Conf. Ind. Eng. Eng. Manag.*, pp. 1617–1621, 2012.

[99] Z. Zhu, V. Dhokia, and S. T. Newman, "The development of a novel process planning algorithm for an unconstrained hybrid manufacturing process," *J. Manuf. Process.*, vol. 15, no. 4, pp. 404–413, Oct. 2013.

[100] Z. Zhu, V. Dhokia, S. T. Newman, and A. Nassehi, "Application of a hybrid process for high precision manufacture of difficult to machine prismatic parts," *Int. J. Adv. Manuf. Technol.*, vol. 74, no. 5–8, pp. 1115–1132, 2014.

[101] "Additive Manufacturing: Strategic Research Agenda." AM Sub-Platform, 2014.

[102] TSB, "High Value Manufacturing Strategy 2012-2015," 2012.

[103] "Fabrisonic Technology," *Fabrisonic*, 2015. [Online]. Available: http://fabrisonic.com/technology/. [Accessed: 26-Apr-2015].

[104] "Hybrid Manufacturing Technologies," *Hybrid Manufacturing Technologies Ltd.*, 2015. [Online]. Available: http://www.hybridmanutech.com/. [Accessed: 26-Apr-2015].

[105] "Hamuel Maschinenbau - Products - HSTM - Hybrid manufacturing," *Hamuel Reichenbacher*. [Online]. Available: http://www.hamuel.de/en/produkte/hstm/hybrid/index.php. [Accessed: 26-Apr-2015].

[106] "lasertec-65-3d," *DMG MORI SEIKI*, 2015. [Online]. Available: http://uk.dmgmori.com/products/lasertec/lasertec-additivemanufacturing/lasertec-65-3d. [Accessed: 26-Apr-2015].

[107] "NT 4300 Additive Manufacturing - New: Additive manufacturing in finished part quality," *DMG MORI SEIKI*. [Online]. Available: http://en.dmgmori.com/products/lathes/turn-mill-complete-machining-centres/nt/nt4300additivemanufacturing. [Accessed: 26-Apr-2015].

[108] "Mazak Introduces New HYBRID Multi-Tasking Technology," *Mazak*, 2015. [Online]. Available: https://www.mazakusa.com/news-events/press-releases/mazak-introduces-new-hybrid-multi-tasking-technology/. [Accessed: 26-Apr-2015].

[109] "Cybaman Replicator," *cybaman, Intelligent Robotic Manufacturing*, 2015. [Online]. Available: http://www.cybamantech.co.uk/. [Accessed: 26-Apr-2015].

[110] C. Connolly, "Innovations and applications of the Cybaman replicator from Traki-iski Ltd," *Assem. Autom.*, vol. 29, no. 3, pp. 209–213, 2009.

[111] A. Allcock, "WFL Millturn Technologies Open House underlines big developments," 2015. [Online]. Available: http://www.machinery.co.uk/machinery-features/wfl-millturn-technologies-kyal-machine-tools-additive-manufacturing/75353/. [Accessed: 03-Nov-2015].

[112] IBARMIA INNOVATEK, "IBARMIA, Additive Manufacturing and Multitasking Machining in the Same Machine," 2015. [Online]. Available: http://www.ibarmia.com/en/today/ibarmia-additive-manufacturing-multitasking. [Accessed: 03-Nov-2015].

[113] L. Griffiths, "Hermle introduces hybrid 5-axis additive manufacturing machine," *TCT Magazine*, 2015. [Online]. Available: http://www.tctmagazine.com/3D-printing-news/hermle-introduces-hybrid-5-axis-additive-manufacturing-machi/. [Accessed: 26-Apr-2015].

[114] T. Edwards, "Hermle Builds Hybrid 5-axis CNC Mill & 3D Printing Marvel," *3D Print*, 2015. [Online]. Available: http://3dprint.com/46227/hybrid-cnc-mill-and-additive-manufacturing-marvel/. [Accessed: 26-Apr-2015].

[115] "Unique one process solution: Laser sintering and milling," *Matsuura Corporation*, 2015. [Online]. Available: http://www.matsuura.co.jp/english/contents/products/lumex.html. [Accessed: 26-Apr-2015].

[116] Sodick Europe Ltd., "Sodick OPM250E(L)," 2015. [Online]. Available: http://www.sodick.jp/product/tool/metal_3d_printer/index.html. [Accessed: 03-Nov-2015].

[117] "3D Printing Solutions," *Solidscape, A Stratasys Company*, 2015. [Online]. Available: http://www.solid-scape.com/products/3d-wax-printers-rapid-prototyping-services-dimension-3d-printers. [Accessed: 26-Apr-2015].

[118] DMG Mori Seiki, "Additive Manufacturing in Milling Quality," 2015.

[119] "Hybrid Manufacturing," *Hamuel Reichenbacher*, 2015. [Online]. Available: http://www.hamuel.de/en/produkte/hstm/hybrid/index.php. [Accessed: 17-Apr-2015].

[120] "The World's First Hybrid Turbine Blade & Turbo Fan Remanufacturing Machine," *Hamuel Reichenbacher*, 2015. [Online]. Available: http://www.hamuel.de/documents/13-09-11_Korr_Prosp_HAMUEL_Laser_engl_LR.pdf. [Accessed: 17-Apr-2015].

[121] "Cybaman Replicator," *cybaman, Intelligent Robotic Manufacturing*, 2015. .

[122] Optomec, "LENS Systems," 2015. [Online]. Available: http://www.optomec.com/3d-printed-metals/lens-printers/. [Accessed: 21-Sep-2015].

[123] L. Griffiths, "America Makes unveils first hybrid CNC machine tool with Optomec 3D printing upgrade," *TCT Magazine*, 2015. [Online]. Available: http://www.tctmagazine.com/3D-printing-news/america-makes-legacy-cnc-tool-with-optomec-3d-printing-upgrade/. [Accessed: 21-Sep-2015].

[124] L. Griffiths, “Hermle introduces hybrid 5-axis additive manufacturing machine,” *TCT Magazine*, 2015. .

[125] T. Edwards, “Hermle Builds Hybrid 5-axis CNC Mill & 3D Printing Marvel,” *3D Print*, 2015. .

[126] Hermle, “HERMLE MPA Technology,” 2015. [Online]. Available: http://www.hermle-generativ-fertigen.de/cms/en/technology/. [Accessed: 30-Apr-2014].

[127] “3D Printing Materials,” *Solidscape, A Stratasys Company*. [Online]. Available: http://www.solid-scape.com/products/3d-printer-wax-materials-lost-wax-and-investment-casting. [Accessed: 30-Apr-2015].

[128] Siemens AG, “SINUMERIK 840D sl,” 2015. [Online]. Available: http://w3.siemens.com/mcms/mc-systems/en/automation-systems/cnc-sinumerik/sinumerik-controls/sinumerik-840/sinumerik-840d-sl/Pages/sinumerik-840d-sl.aspx. [Accessed: 14-Sep-2015].

[129] “HSC-TURN-MILLING CENTRE OF THE HSTM-SERIES,” *Hamuel Reichenbacher*, 2015. [Online]. Available: http://www.hamuel.de/en/produkte/hstm/index.php. [Accessed: 29-Apr-2015].

[130] “Additive Manufacturing in Milling quality ALL IN 1 : Laser Deposition Welding and Milling .,” *DMG MORI SEIKI*, 2015. [Online]. Available: http://en.dmgmori.com/blob/334060/ca4dd739aa0a0e367d40ead23f53c9f8/pl1uk14-lasertec-65-3d-pdf-data.pdf. [Accessed: 01-Jan-2015].

[131] Fanuc Europe Corporation, “Fanuc CNC Control Series,” 2015. [Online]. Available: http://www.fanuc.eu/uk/en/cnc/controls/cnc-control-series. [Accessed: 14-Sep-2015].

[132] “Delcam supports award-winning Hamuel hybrid repair machine,” *Delcam Ltd.*, 2013. [Online]. Available: http://www.delcam.co.uk/news/press_article.asp?releaseId=1664#.VUC8va1Viko. [Accessed: 29-Apr-2015].

[133] “About NX Software,” *Siemens PLM Software*, 2015. [Online]. Available: http://www.plm.automation.siemens.com/en_gb/products/nx/about-nx-software.shtml. [Accessed: 29-Apr-2015].

[134] OPEN MIND Technologies AG, “One CAM Software For Everything,” 2015. [Online]. Available: http://www.openmind-tech.com/en/products/hypermill-cam-software.html. [Accessed: 03-Nov-2015].

[135] “3D Printing Solutions,” *Solidscape, A Stratasys Company*, 2015. .

[136] C. Sesma, “MachineWorks Delivers Hybrid Manufacturing Simulation,” 2015. [Online]. Available: http://www.machineworks.com/machineworks-delivers-hybrid-manufacturing-simulation. [Accessed: 21-Sep-2015].

[137] M. Neslušan, I. Mrkvica, R. Čep, D. Kozak, and R. Konderla, “Deformations After Heat Treatment and Their Influence on Cutting Process,” *Teh. Vjesn.*, vol. 18, no. 4, pp. 601–608, 2012.

[138] National Institute of Standards and Technology (NIST), “Measurement Science Roadmap for Metal-Based Additive Manufacturing: Workshop Summary Report,” Columbia, Maryland, 2013.

[139] “Dimensional Accuracy and Surface Finish in Additive Manufacturing,” in *ASPE 2014 Spring Topical Meeting*, 2014.

[140] R. G. Landers, B.-K. Min, and Y. Koren, “Reconfigurable Machine Tools,” *Ann. CIRP*, vol. 50, no. 1, pp. 269–274, 2001.

[141] Y. Koren, U. Heisel, F. Jovane, T. Moriwaki, G. Pritschow, G. Ulsoy, and H. Van Brussel, “Reconfigurable Manufacturing Systems,” *Ann. CIRP*, vol. 48, no. 2, pp. 527–540, 1999.

[142] M. G. Mehrabi, A. G. Ulsoy, and Y. Koren, “Reconfigurable manufacturing systems and their enabling technologies,” *Int. J. Manuf. Technol. Manag.*, vol. 1, no. 1, p. 114, 2000.

[143] R. Pérez R, J. Aca S, A. Valverde T, H. Ahuett G, A. Molina G, and C. Riba R, “A Modularity Framework for Concurrent Design of Reconfigurable Machine Tools\nCooperative Design, Visualization, and Engineering,” vol. 3190, pp. 87–95, 2004.

[144] C. Riba, R. Pérez, H. Ahuett, a Sánchez, M. Domínguez, and a Molina, “Metrics for Evaluating Design of Reconfigurable Machine Tools,” *Coop. Des. Vis. Eng. Des.*, vol. 4101, pp. 234–241, 2006.

[145] T. Lorenzer, S. Weikert, S. Bossoni, and K. Wegener, “Modeling and evaluation tool for supporting decisions on the design of reconfigurable machine tools,” *J. Manuf. Syst.*, vol. 26, no. 3–4, pp. 167–177, 2007.

[146] M. Tolouei-rad, “Intelligent Design of Reconfigurable Machines,” vol. 3, no. 11, pp. 278–282, 2009.

[147] R. Pérez, A. Molina, and M. Ramírez-Cadena, “Development of an Integrated Approach to the Design of Reconfigurable Micro/Mesoscale CNC Machine Tools,” *J. Manuf. Sci. Eng.*, vol. 136, no. 3, p. 031003, 2014.

[148] H. Azulay, J. K. Mills, and B. Benhabib, “A Multi-Tier Design Methodology for Reconfigurable Milling Machines,” *J. Manuf. Sci. Eng.*, vol. 136, no. 4, p. 041007, 2014.

[149] G. Pritschow, Y. Altintas, F. Jovane, Y. Koren, M. Mitsuishi, S. Takata, H. Van Brussel, M. Weck, and K. Yamazaki, “Open Controller Architecture - Past , Present and Future,” *CIRP Ann. - Manuf. Technol.*, 2001.

[150] Y. Koren, U. Heisel, F. Jovane, T. Moriwaki, G. Pritschow, G. Ulsoy, and H. Van Brussel, “Reconfigurable Manufacturing Systems,” *Ann. CI*, vol. 48, no. 2, pp. 527–540, 1999.