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A Review of Hybrid Manufacturing Processes – state of the art and future perspectives

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Abstract

Today, hybrid manufacturing technology has drawn significant interests from both academia and industry due to the capability to make products in a more efficient and productive way. Although there is no specific consensus on the definition of the term ‘hybrid processes’, researchers have explored a number of approaches to combine different manufacturing processes with the similar objectives of improving surface integrity, increasing material removal rate, reducing tool wear, reducing production time and extending application areas. Thus, hybrid processes open up new opportunities and applications for manufacturing various components which are not able to be produced economically by processes on their own. This review paper starts with the classification of current manufacturing processes based on processes being defined as additive, subtractive, transformative, joining and dividing. Definitions of hybrid processes from other researchers in the literature are then introduced. The major part of this paper reviews existing hybrid processes reported over the past two decades. Finally, this paper attempts to propose possible definitions of hybrid processes along with the authors’ classification, followed by discussion of their developments, limitations and future research needs.

Keywords: CNC, process integration, process capability, hybrid manufacturing processes, transformative processes

1. Introduction

In today's manufacturing industry, various manufacturing operations have been widely used for producing products for many industrial sectors. These processes are generally recognised as CNC machining, additive manufacturing, transformative processes such as forming, joining and dividing operations, for example welding and sawing (Kalpakjian and Schmid, 2010).

However, these manufacturing processes have their inherent drawbacks which cannot be eliminated. In other words, due to their technological constraints, they are not always feasible for the production of various components in terms of geometry, dimension and strength etc. (Tawakoli and Azarhoushang, 2008; Kolleck et al., 2011). CNC machining can have the difficulties in machining complex shapes due to tool accessibility. High temperature and tool wear are other considerations while machining hard materials (Dandekar et al., 2010). Rapid prototyping is still restricted because of long production time and low accuracy, as compared to CNC machining (Suryakumar et al., 2011). Limited materials' formability and springback effect confines the development of forming processes (Duflou et al., 2007). In addition, dimensional accuracy is difficult to fully control in welding processes.

Based on the problems mentioned above, hybrid manufacturing, which can be considered as the combination of two or more manufacturing processes, is becoming more and more topical for manufacturing researchers. The purpose of developing these hybrid processes is to enhance their advantages whilst at the same time minimise their disadvantages (Karunakaran et al., 2010). The combination of CNC machining and additive processes may provide a new substantial solution to the limitations of additive processes (Liang et al., 2002) due to the high accuracy and machining speed that machining processes offer. Moreover, the combination of laser heating and forming reduces springback behaviour (Duflou et al., 2007). The integration of ultrasonic vibration and drilling can reduce the cutting force and tool wear rate (Heisel et al., 2008). The involvement of laser drilling and ECM significantly removes the recast layer and heat affect zone (Zhang et al., 2009a).

The above indicates that hybrid manufacturing has huge potential for growth in terms of producing more complex parts with more flexibility and maintaining high accuracy in a relatively short production time. Hybrid processes open new avenues of research for enhancing processes capabilities, minimising their weaknesses and extending application areas.

The aim of this paper is to classify current manufacturing processes into technologies; clarify different techniques and terms used by researchers; define, identify and classify hybrid manufacturing processes. The major part of the paper provides a review on the various research conducted in the past two decades involving the combination of different processes in additive, subtractive, joining and transformative technologies, attempting to understand the state of the art of hybrid processes. The final part of the paper discusses these relevant topics and the prospective of hybrid processes research.

2. Existing manufacturing processes classifications

This section initially illustrates the classifications of manufacturing processes based on previous researchers' definitions and then provides the basis for the authors' categorisation, forming the foundations of the review, definition and classification of hybrid manufacturing processes in Sections 4 and 5.1.

2.1 Existing manufacturing processes classifications

A number of researchers have previously classified manufacturing processes, from which, two major classifications are widely adopted. The first by Swift and Booker (2003) classifies processes into casting, cutting, forming and fabrication. The second by Kalpakjian and Schmid (2010) is more comprehensive, they classify processes into six subsections with casting, machining and finishing processes similar to Swift and Booker (2003), but they have four further classes of joining, sheet metal, polymer processing and bulk deformation processes.

2.2 Classification of manufacturing processes into technologies

As the traditional classifications introduced in the previous sections have some difficulties in the identification of newly developed manufacturing technologies, Nassehi et al. (2011) proposed a technology based classification method consisting of five categories, namely joining, dividing, subtractive, transformative and additive technologies.

(i) *Joining technology*: consists of processes by which two or more workpieces are joined to form a new workpiece. Typical examples are welding and assembly.

(ii) *Dividing technology*: dividing processes are the opposite of joining processes, for example, sawing and disassembly.

(iii) *Subtractive technology*: subtractive/negative operations are material removal processes, by which material is removed from a single workpiece resulting in a new workpiece, such as machining operations (milling, water-jet cutting and EDM etc.).

(iv) *Transformative technology*: a single workpiece is used to create another workpiece and the mass does not change. Forming, heat treatment and also cryogenic cooling are the examples of transformative processes.

(v) *Additive technology*: material is added to an existing workpiece to build a new workpiece where the mass of the finished workpiece is greater than before. Rapid prototyping processes, die casting and injection moulding are the most widely used additive manufacturing processes.

3. Definitions of hybrid processes in the literature

This section briefly introduces the definitions of hybrid processes as well as other related 'hybrid' terms from other researchers in order to provide the basic fundamentals of hybrid processes.

It is recognised that hybrid manufacturing/processes is a vague term. Many researchers call the combination of different manufacturing processes as hybrid manufacturing or hybrid processes without a precise definition.

Rajurkar et al. (1999) described ‘hybrid machining’ as a combination of two or more machining processes to remove material. This definition is still seen to be vague. Kozak and Rajurkar (2000) highlighted that ‘the performance characteristics of hybrid machining processes must be considerably different from those that are characteristic for the component processes when performed separately’. In detail, Aspinwall et al. (2001) stated that the combination of machining operations can be considered either in terms of a hybrid machining method, by which two or more machining processes are applied independently on a single machine, or in terms of an assisted machining approach, by which two or more processes are utilised simultaneously. Similarly, Menzies and Koshy (2008) used ‘hybrid machining process’ to represent the combination of two or more machining processes with ‘distinct mechanisms of material removal’. Furthermore, Curtis et al. (2009) provided a limited definition, stating that only a method, where two or more material removal processes work simultaneously can be termed ‘hybrid’.

Alternatively, Rivette et al. (2007) adopted a prototype oriented definition to describe hybrid manufacturing as, ‘the prototype is manufactured by different processes, usually the rapid prototype process and conventional process’. In terms of energy consumption, Klocke et al. (2010) and Nau et al. (2011) view hybrid processes as an approach where ‘different forms of energy or forms of energy caused in different ways respectively are used at the same time at the same zone of impact’. Lauwers et al. (2010) stated that ‘hybrid’ could mean ‘a combination of processes having a large influence on the process characteristics’, which means hybrid processes combine active principles. Typical examples are laser assisted turning/milling (Dandekar et al., 2010) and laser assisted water-jet cutting (Molian et al., 2008). Moreover, Lauwers et al. (2010) and Klocke et al. (2011) also define it as ‘the combination of effects that are conventionally caused by separated processes in one single process at the same time’. In addition, Lauwers et al. (2010) extend the definition, presenting that ‘processes should be created resulting in one or more significant process effects such as large force reductions’. Based on that, cutting through the use of high pressure coolants is also identified as a hybrid process due to a change in the chip formation (Lauwers et al., 2010).

CIRP, namely the International Academy for Production Engineering (CIRP, 2011), suggested three definitions to define hybrid processes, which are:

- i) Integrated application or combination of different physical active principles e.g. laser assisted machining (Dandekar et al., 2010);
- ii) Integrated combination of usually separated performed process steps e.g. stretch forming and incremental sheet metal forming (Araghi et al., 2009);
- iii) Integrated machines, so called hybrid machines, that can perform different processes at one place e.g. mechanical milling and turning (She and Hung, 2008).

In 2010, CIRP refined these definitions and proposed an open definition and a narrow definition (CIRP, 2011):

- i) Open definition: a hybrid manufacturing process combines two or more established manufacturing processes into a new combined set-up whereby the advantages of each discrete process can be exploited synergistically;
- ii) Narrow definition: Hybrid processes comprise a simultaneous acting of different (chemical, physical, controlled) processing principles on the same processing zone.

In addition, products that have a hybrid structure or hybrid function (e.g. metal plastic composite components) are seen as hybrid products (Roderburg et al., 2011) or hybrid components (Holtkamp et al., 2010).

4. Major research areas of hybrid manufacturing processes

The authors have classified and defined the research of hybrid manufacturing processes into seven investigation areas. Each of these research areas deals with different combinations of manufacturing operations in five manufacturing categories presented in 2.2. The first three headings relate to the processes only combined in their own categories with the aim of enhancing process capabilities, such as material removal, tool wear and surface quality. The four subsequent headings focus on the processes that are incorporated between different manufacturing categories in order to extend application areas in terms of materials and part geometry.

4.1 Hybrid subtractive manufacturing processes

A significant number of papers have reported the development of hybrid processes for integrating different machining methods as described below. These hybrid processes typically aim to achieve higher performance, in terms of material removal rate (MRR), surface integrity and tool wear,

4.1.1 Mechanical machining and ECM

A few studies have been reported on applying electrochemical and mechanical machining (finishing processes) at the same time, in which case material is removed mainly by chemical dissolve dissolution. Komanduri et al. (1997) reviewed chemical mechanical polishing processes and showed its effectiveness for polishing of semiconductors. Lee and Jeong (2009) conducted experiments for polishing workpieces made from copper, in which the copper ion is dissolved electrochemically in an electrolyte and followed by mechanical polishing on a single machine. However, the electrolyte contamination was unavoidable. Zhu et al. (2011) investigated the mechanical-electrochemical machining of small holes by ECM and grinding. Electrochemical machining is also used in the in-process machining of grinding wheels. Lim et al. (2002a) studied the mechanisms of dressing and grinding operations. The retrofitted grinding machine they developed consisted of a metal-bonded grinding wheel and a dressing unit which utilises the effects of electrical discharge and electrochemical processes for the in-process dressing of the wheel (Fathima et al., 2007).

4.1.2 Mechanical machining and Electric Discharge Machining (EDM)

The application of mechanical and EDM has enabled the exploration of machining micro features in hard and brittle materials. Aspinwall et al. (2001) combined EDM and high speed milling (HSM) by mounting a graphite electrode on the spindle of the HSM centre to machine nickel-based alloys. An attempt has been made by Lim et al. (2002b) to machine components with microstructures by turning and micro-EDM, where turning was used for fast preparation of the thin tool electrode on-machine. Kozak et al. (2003) replaced graphite and brass grinder with a metal-bonded grinding wheel in the electro discharge grinding process for rough machining, where the synergistic interactive effect of the combination of conventional and electro discharge grinding realised a higher material removal rate (Kozak and Oczos, 2001). Similarly,

Menzies and Koshy (2008), modified a wire-EDM process in which the original wire was replaced by a fixed wire with a number of electrically non-conductive abrasives. Therefore, the workpiece was machined by spark erosion and moreover the abrasives abraded the workpiece.

4.1.3 Mechanical machining and laser cutting

As laser cutting provides high precision and zero tool wear, the resulting combination of mechanical machining and laser cutting dramatically reduces tool wear, leading to increased accuracy.

In industry, the most wide-spread application of this technology is the use of mechanical machining centres integrated with laser processing units (DMG, 2011). In the academic literature, more variations of this technology have been identified and are recognised below. A high speed milling machine equipped with an Nd: YAG laser source has been developed by Quintana et al (2009), which is capable of producing micro metallic components. Li et al. (2005a) reported a 100% increase in MRR compared to pure laser milling, while simultaneously applying an abrasive jet to the laser melted pool for removing the molten material in-situ.

Instead of using a laser simultaneously, Okasha et al. (2010) used a sequential laser and mechanical drill for the micro-drilling of Inconel[®] 718. Similarly, Biermann and Heilmann (2011) used a laser to pre-drill a pilot hole, followed by single-lip deep hole mechanical drilling on non-planar surfaces.

4.1.4 Laser cutting and EDM

Laser cutting and EDM research concentrates on micro-machining applications for reducing production time and eliminating the recast and heat affected zone caused by laser ablation. Li et al. (2006) used a sequential laser and EDM for the micro-drilling of a fuel injection nozzle with a diameter of 137-140 μm . Kim et al. (2010) applied laser cutting for rough machining of grooves and subsequently, micro EDM was employed to finish machine the parts, therefore significantly reducing the tool wear of the electrode.

4.1.5 Laser cutting and ECM

This is a method that uses laser drilling with an electrochemical dissolution, which has been investigated to improve the quality of drilled holes in terms of recast layer, spatter and heat affected zones (Li and Achara, 2004). A jet electrolyte was aligned coaxially with the laser beam, where the material was removed mainly by the laser with the recast layer and spatter being dramatically reduced by the effect of ECM jet simultaneously (Zhang et al., 2009a).

4.1.6 EDM and ECM

The electro chemical discharge machining (ECDM) process, which combines ECM and EDM on a single platform, has been studied since the 1970s (Cook et al., 1973; Tsuchiya et al., 1985; Chikamori, 1991). Electrical discharges between the cathodic

electrode and the anodic workpiece occurs, whilst the electrochemical dissolves the workpiece (Chak and Rao, 2007). Bhattacharyya et al. (1999) and Schopf et al. (2001) successfully used an ECDM process in trueing and dressing of metal bonded diamond grinding wheels/tools.

4.1.7 Turn-mill, mill-grind

Turn-mill machine tools incorporate both a spindle for milling operations and a spindle for turning operations, and have been on the market for a considerable number of years (She and Hung, 2008). These types of machines have led to other combinations, namely mill-grind, turn-grind and turn-hone machining centres (MAG, 2010; Mazak, 2011).

4.1.8 Ultrasonic assisted mechanical machining

Ultrasonic assisted mechanical machining is not a new hybrid process and has been known for over 50 years (Colwell, 1956). It is the simultaneous application of mechanical machining by spindle rotation, and ultrasonic vibration by a high frequency axial ultrasonic oscillation of the cutting tool or the workpiece (Markov and Neppiras, 1966).

4.1.8.1 Ultrasonic assisted grinding

A large proportion of ultrasonic assisted mechanical machining research lies in ultrasonic assisted grinding aimed at achieving better surface integrity of ground surfaces. Uhlmann and Hübner (2007) applied the superposition method to combine a grinding operation with a secondary oscillation, by which the oscillation of the grinding tool was excited by piezoelectric oscillators. Whereas, in the experiments by Yanyan et al. (2009), the ultrasonic vibration actuator was adhered to the workpiece instead of the diamond grinding tool, which led to the oscillations of the workpiece. With vibration assistance, tool wear can be reduced and Lauwers et al. (2008) further developed an algorithm of tool path generation for machining of ceramic component, obtaining better surface quality. Brecher et al. (2010b) suggested a new way to design vibrating components which aims to increase MRR. From the aspect of rotary grinding, Ya et al. (2002) built a model for analysing MRR in ultrasonic assisted rotary grinding. Li et al. (2005b) designed a series of experiments to drill holes on ceramic matrix composite (CMC) panels.

4.1.8.2 Ultrasonic assisted turning

In the turning of hardened steel, Klocke et al. (2009) used a monocrystalline diamond tool with superimposed ultrasonic linear vibration to machine moulds for optical replication. Zhong and Lin (2006) mounted an ultrasonic vibration rig onto a CNC machine tool for the turning of aluminium based metal matrix composite (MMC) workpieces.

4.1.8.3 Ultrasonic assisted drilling

The shortcomings of conventional mechanical drilling gradually emerge in the drilling of deep and micro holes in hard materials, in particular in the aerospace industry. By

continuous frequency vibration of cutting tools during drilling operations, the quality of the deep micro-holes can be significantly improved. Azarhoushang and Akbari (2007) developed a drilling tool with high frequency and low amplitude ultrasonic oscillation for the drilling of Inconel[®] 738-LC, which showed a noticeable improvement in terms of average surface roughness and circularity, but, Liao et al. (2007) argued that the vibration amplitude of more than 12 μm is likely to result in negative effects, such as reducing tool life. Heisel et al. (2008) and Potthast et al. (2008) designed a piezoelectric actuator and a piezoelectric transducer, which was used for deep hole drilling of electrolytic copper. This indicated a decrease in feed force and drilling torque when compared to gun drilling. Although ultrasonic assistance provides superiority, there are a number of drawbacks. For instance, due to the higher tool tip temperature and variations in ultrasonic assisted drilling, Pujana et al. (2009) argued that the heat generation mechanism needed further study.

4.1.9 Ultrasonic assisted EDM

The combination of USM and EDM has the potential to reduce tool wear and electrode deflection in EDM of micro-holes and grooves. In the paper by Jia et al. (1997), the mechanical signal was generated and transmitted to the tool-electrode, which was applied to remove material. On the other hand, Jahan et al. (2010) attempted to drill micro-holes, where the tungsten carbide workpiece was being vibrated while the EDM process was carried out. Other studies employing similar configurations have been reported by Yeo and Tan (1999), Zhao et al. (2002), Huang et al. (2003), Sundaram et al. (2008) and Yu et al. (2009) for producing high aspect ratio of micro-holes on steel, stainless steel, titanium alloy and nitinol workpieces, respectively.

4.1.10 Wire-EDM and etching

A novel approach, combining wire electric discharge machining (WEDM) and anodic etching into a single process for slicing/cutting of silicon ingots into wafers has been developed by Wang et al (Wang et al., 2009; Wang et al., 2011).

4.2 Hybrid transformative manufacturing processes

This section is concerned with the processes combined within the transformative manufacturing operations category such as sheet metal forming (Emmens et al., 2010) and laser heat treatment (Zhang et al., 2009b).

4.2.1 Sheet metal forming processes

Each sheet metal forming process has its specific application in terms of the features formed (Micari et al., 2007). The combination of different forming processes enables a part to be produced with various features. Araghi et al. (2009) and Galdos et al. (2010) first employed the stretch forming process for pre-forming the rough shape and then an asymmetric incremental sheet forming (AISF) process was carried out to produce the final parts.

4.2.2 Laser heat treatment and sheet metal forming

The heat energy provided by a laser beam has been found to be effective for changing the microstructure and mechanical properties of the irradiated workpieces, facilitating the following metal forming process. Duflou et al. (2007) utilised a laser to heat the underside of the sheet for increasing formability in the single point incremental forming process (Duflou et al., 2008). Alternatively, Biermann et al. (2009) used a laser beam to heat the workpiece in front of the forming tool to assist the forming process. In addition, Shen et al. (2006) developed a model to predict the bending angle in laser assisted incremental forming. A deep drawing process with laser assistance has been investigated by Schuocker et al. (1999) and Kratky et al. (2004). Before the drawing operation takes place, laser energy is used to selectively heat the material near the drawing edge, which is able to reduce the drawing force (Schuocker, 2001), reduce forming steps and produce deeper features than that of conventional deep drawing (Geiger et al., 2004).

4.3 Hybrid Additive manufacturing processes

The majority of additive manufacturing processes (Bingham et al., 2007) can also be considered as layered manufacturing (Levy et al., 2003) and in recent years laser cladding (Onwubolu et al., 2007) and arc welding deposition (Jandric et al., 2004) have received significant attention especially for hybrid process research.

4.3.1 Melting deposited material

In general, there are two methods for material deposition i.e. deposit material (usually powders) and then melt them, or directly deposit melted material. In this type of hybrid additive processes, powders are pre-placed on workpiece surfaces waiting to be melted and bonded. Two different additive processes – one as a major heat contributor and another one as an additional heat energy – are applied to build the part (Qian et al., 2006), improving the corrosion, wear resistance as well as tensile strength of the workpiece. Ono et al. (2002) used a Nd:YAG laser beam as the major contributor to the welding process and an arc welding electrode was located behind the laser radiation point to increase the temperature, whereas, Zhang et al. (2006) used a laser beam to act as a assistant tool rather than the plasma arc. Moreover, there are another two hybrid laser-arc welding processes with similar configurations and functions, which are (i) hybrid CO₂ laser – GMAW (MIG) process (Campana et al., 2007; Casalino, 2007; Bang et al., 2010) and (ii) hybrid Nd: YAG laser – GTAW (TIG) process (Liu et al., 2004; Song et al., 2006).

4.3.2 Deposition of melted material

This type of hybrid additive processes is a synergic process able to build a part consisting of multi-materials by depositing a binder/powder mixture (i.e. one extrusion head), or by means of the depositing different materials alternatively (i.e. multiple extrusion heads).

4.3.2.1 Mixed Material Deposition

Fessler et al. (1997) fabricated an injection moulding tool comprised of functional

gradient materials, namely nickel iron alloy, stainless steel and copper, showing that the mixed material provides material properties intermediate to those of the constituent feed powders.

4.3.2.2 Multi-material deposition

Allahverdi et al. (2001) installed two additive heads on a single machine, where two materials were extruded for the deposition of ceramic microstructures (Gasdaska et al., 1998). Jafari et al. (2000) and Safari et al. (2001) further investigated this process enabling up to four different materials to be deposited in a single deposition step with arbitrary geometry. A freeform fabrication method developed by Malone et al. (2004) and Malone and Lipson (2006) uses two separate deposition tools for fabrication of 3D functional assemblies with embedded conductive wiring, power sources and actuators. Other examples of simultaneously using multiple deposition tools are: Hayes et al. (1998) investigated a micro-jet printing process for polymer and solder deposition for chip-scale packaging (CSP) in microelectronics manufacturing; Fuller et al. (2002) employed multiple ink-jet deposition heads mounted on a computer-controlled 3-axis gantry to continuously squeeze nano-particles to additively build micro electromechanical systems and electrical circuitry.

4.4 Hybrid additive and subtractive manufacturing processes

Generally, hybrid additive and subtractive manufacturing processes methods use an additive process to build a near-net shape which will be subsequently machined to its final shape with desired accuracy by a subtractive process.

4.4.1 Laser cladding and mechanical machining

Some research activities were carried out to retrofit traditional milling machines with a laser cladding unit, which aimed to utilise the flexibility of laser cladding operations and higher surface finishes provided by milling operations, and further reduce set-up time. Jeng and Lin (2001) fabricated metal and alloy injection moulds by conducting laser cladding and milling operations in series. Choi et al. (2001) claimed that a reliable mechanical connection between layers was formed. Liou et al. (2001) and Zhang and Liou (2004) incorporated a five-axis laser cladding unit with a five-axis milling machine, where any deposition feature can be built in the horizontal direction by rotating the workstation. Thus, the need for supporting material during the deposition is eliminated, further reducing build time (Ruan et al., 2005; Liou et al., 2007). Hur et al. (2002) used a five-axis CNC machine performing drilling, milling and grinding to machine laser clad parts. Nowotny et al. (2010) further claimed that this technology has the potential to produce components for gas turbines due to high hardness and accuracy.

Moreover, some efforts have been made on process optimisation. Mognol et al. (2006) conducted topologic and dimensional analysis, suggesting suitable features that can be produced by laser cladding and high speed milling. Another method used to estimate manufacturing complexity has been presented by Kerbrat et al (2010).

4.4.2 Arc welding and mechanical machining

The principle of this type of hybrid process is similar to laser cladding & mechanical machining, but replaces laser cladding with arc welding. An example by Song and Park (2006) utilised two gas metal arc welding (GMAW) guns for deposition of different materials, and CNC milling to fabricate injection mould inserts. Karunakaran et al. (2004), and Suryakumar et al. (2011) used face milling to machine each slice built by metal inert gas (MIG) and metal active gas (MAG) welding. However, Karunakaran et al. (2008) argued that face milling of each layer is the major barrier for reducing production time. Furthermore, Karunakaran et al. (2009) pointed out that the tools fabricated by this hybrid process might be inferior to their conventional counterparts in composition and tool life. Xiong et al. (2009) studied the mechanism of plasma arc deposition and integrated the plasma torch on a milling machine.

4.4.3 Shape Deposition Manufacturing (SDM) and mechanical machining

SDM has been synonymous with Stanford University from the first development introduced by Merz et al. (1994) and their continuous work (Pinilla and Prinz, 2003; Dollar and Howe, 2006). SDM deposits melted material from a container and the material solidifies as soon as it is deposited. Cooper et al. (1999) applied SDM to drop wax beads for building the rough shape of the parts, then curing them and finally shaping to the final dimensions by milling. Lanzetta and Cutkosky (2008) utilised the combination of SDM and milling to build smooth and sculpted 3D contours of dry adhesives which could be used to aid human and robotic climbing.

4.4.4 Electroforming and polishing

Electroforming is a variation of the electroplating process, but with moderate surface quality due to the presence of pinholes and nodules on the coating surfaces. In order to eliminate this drawback, Zhu et al. (2006) employed abrasive polishing operations for removing pinholes and nodules by the movement of the spherical ceramic particles filling in the space between the cathode mandrel and the anode.

4.4.5 Injection moulding and milling

Kelkar et al. (2005) developed a re-configurable moulding process where a part surface is approximated using an array of discrete and movable pins so as to generate the part mould cavity. By re-positioning the pins, a new mould cavity can be generated according to the change of product design. Kelkar and Koc (2008) incorporated re-configurable mould tooling and multi-axis machining. After a part is moulded, multi-axis machining was conducted to improve the surface accuracy of the part.

4.5 Hybrid joining and subtractive manufacturing processes

This section reports on the platforms capable of performing joining and milling operations in series. Taylor et al. (2001) developed a method which combines CNC milling and solvent welding technology, by which a number of the solvent weldable thermoplastic sheets were welded and machined in sequence. By contrast, Kuo et al. (2002) developed a single platform, which combines a micro-EDM mechanism for the

micromachining of the metallic parts and Nd:YAG laser welding performing the micro-assembly of parts machined. However, Kuo et al. (2003) revealed that the cumulative errors were likely to increase during the entire hybrid process.

4.6 Hybrid additive and transformative manufacturing processes

A small amount of research focuses on the investigation of effectively applying additive and transformative processes together. Lucchetta and Baesso (2007) tested the feasibility of performing injection moulding and sheet metal forming processes. A sheet metal was inserted between the open halves of a mould, and was bent to form the desired shape while closing the mould cavity. The molten polymer material was subsequently injected into the remaining cavity with adhesion taking place between the metal and the polymer (Bariani et al., 2007; Baesso and Lucchetta, 2007). Yasa et al. (2011) used selective laser melting (SLM) to build 2D layers and after building each layer, the same laser source was applied to heat the solidified layer as a laser erosion process, showing significant improvement in surface quality in comparison to individual SLM.

4.7 Hybrid subtractive and transformative manufacturing processes

In this category, most of the transformative processes e.g. laser heating are used as an assistant tool to provide better machining conditions for mechanical machining. The subsections below summarise the studies into each kind of combinations and their applications.

4.7.1 Thermally enhanced mechanical machining

Thermally enhanced mechanical machining applies external heat sources to heat the workpiece locally in front of the cutting tool. With the effect of heating, the workpiece is softened along with a change in the microstructure, facilitating the conventional machining process in terms of hardness reduction, cutting forces and tool wear (Ding and Shin, 2010). The external heat sources that are most frequently used are plasma (Novak et al., 1997) and laser beam (Pfefferkorn et al., 2004; Anderson et al., 2006).

4.7.1.1 Laser assisted mechanical machining

Laser assisted mechanical machining (LAMM) has been developed and investigated for over twenty years (Rozzi et al., 2000; Lei et al., 2001). Recently, LAMM has been considered as an alternative process for machining of high-strength materials, such as ceramics, metal matrix composites, high-temperature alloys (Rebro et al., 2002; Tian et al., 2008; Bejjani et al., 2011).

(i) Laser assisted turning

Laser assisted turning is considered to be the most favourable laser integration process. This is because the cutting tool keeps stationary during the machining operation. As a result, it is relatively easy to incorporate the laser beam within the conventional turning machine (Sun et al., 2010). Sun et al. (2010) provided a comprehensive review, summarising various laser assisted machining processes and identified the available materials and surface integrity in these processes. For further increases in the

capability of LAMM and reductions in tool wear, the researchers came up with two improvement strategies: (1) Dumitrescu et al. (2006) attempted to use a high power diode laser instead of a conventionally employed CO₂ or Nd:YAG laser, suggesting that higher machining efficiency and better metal absorption can be expected. (2) Anderson and Shin (2006) proposed a new configuration in which two laser beams were simultaneously applied to irradiate the machined chamfer and unmachined surface next to the machined chamfer, respectively. Researchers also realised that a better understanding of heat energy generation during the operations is able to provide optimisation methods for the hybrid process mechanisms. Therefore, Pfefferkorn et al. (2005) modelled the heat distribution in laser assisted turning, illustrating that the temperature is mainly affected by laser power and feedrate. Tian and Shin (2006) also built a transient thermal model for predicting heat transfer during laser assisted turning of silicon nitride workpieces.

(ii) Laser assisted milling

Laser assisted milling normally has two configurations, where a laser beam is located next to a milling tool or integrated on a tool spindle (Sun et al., 2010). Recently, the trend has been towards micro-machining, where Melkote et al. (2009) investigated the micro-milling process and a laser for grooving a hardened A2 tool steel. Brecher et al. (2010a) employed a similar configuration for the dry machining of Ti- and Ni-based-alloys. Singh and Melkote (2007) applied an ytterbium fibre laser to assist micro-scale grooving of H-13 mould steel and reported the accuracy improvement of the groove depth.

(iii) Laser assisted grinding

Kumar et al. (2011) used a laser to scan the surface of the silicon nitride ceramic workpiece followed by a grinding tool to remove the laser affected area. The experimental results indicated that the grinding forces were reduced and the tool life was increased as compared to the individual grinding process.

4.7.1.2 Plasma enhanced mechanical machining

An approach called plasma enhanced machining e.g. turning and milling has been developed in which the plasma jet is primarily used for heating and softening the workpiece locally to make turning or milling easier than traditional turning or milling (Leshock et al., 2001). Wang et al. (2003) introduced the application of plasma heating in the turning of Inconel[®] 718 material. De Lacalle et al. (2004) used plasma gas and an electrode to generate a plasma beam in the front of a milling cutter to machine superalloys.

4.7.2 Laser assisted water-jet cutting

A laser beam, again, acts as an assistant tool to pre-heat the workpiece followed by a water jet functioning as a material removal process. Molian et al. (2008) and Kalyanasundaram et al. (2008) conducted an experiment, where a CO₂ laser heated a small zone on the ceramic workpiece for creating a temperature gradient. Then the

pure water-jet trailed the path of the laser beam on the workpiece leading to thermal shock fracture in this zone. Barnes et al. (2007) explained that the increase of cutting efficiency was due to the kinetic energy of the water jet that removes the material and washes debris away. Based on the previous research, Kalyanasundaram et al. (2010) established and then validated a model which was used for the determination of transient temperature and stress distribution.

4.7.3 Laser assisted ECM

Unlike laser drilling with chemical dissolution by Zhang et al. (2009a), the use of a laser beam in laser assisted ECM, is just for heating the material, which helps and accelerates electrochemical reaction. In the experiment by Pajak et al. (2006) and De Silva et al. (2011), a laser beam was coaxially aligned with an electrolyte jet creating a non-contact tool-electrode, in which case the dissolution in the localised zone was intensified (Kozak and Oczos, 2001). Consequently, the material removal rate increased and furthermore, the localisation enhanced machining accuracy by reducing stray machining action (De Silva et al., 2004).

4.7.4 Laser assisted shearing

Laser assisted shearing has been developed by Brecher and Emonts (2010), where the laser beam was applied to the underside of the shearing zone on the sheet metal plate before the cutting stamp punched the top side of the metal plate. A significant reduction in cutting forces and edge warping were achieved and punch-sheared edges with continuous clear-cut surfaces were observed.

4.7.5 Cryogenic machining

Cryogenic machining methods apply a cryogen, primarily liquid nitrogen rather than oil coolant, to cool either a cutting tool or a workpiece to a very low temperature e.g. -197°C (Yildiz and Nalbant, 2008). The majority of cryogenic machining research can be split into two areas i.e. cooling of cutting tools and cooling of workpieces.

4.7.5.1 Cryogenic machining of hard metal materials

Traditionally, machining of hard materials especially ceramics and superalloys is considered to be difficult due to high tool wear rate, partially resulting from the extreme high temperatures in the shear zone (Krain et al., 2007; Zhang et al., 2010). Most of the papers focus on the development of a spray jet system which sprays liquid nitrogen (LN_2) directly to the cutting zone to decrease the tool temperature, which in turn reduces the temperature dependent tool wear and increases the tool life in successive cuts (Wang et al., 1996).

(i) Turning

Hong and Ding (2001) introduced an economical cryogenic cooling system where the liquid nitrogen is directly jetted at the tip of the cutting tool. By the cooling effect of LN_2 , the crater and flank wear are reduced along with the temperate reduction of the tip of the cutter (Hong et al., 2001). Wang and Rajurkar (2000) experimentally validated that the surface finish of the machined titanium and Inconel[®] alloy parts

with cryogenic cooling was much superior than that of conventional machining. In addition, Venugopal et al. (2003) developed two liquid nitrogen jets in one system for cooling the rake surface and principal flank, tool nose and auxiliary flank, respectively.

(ii) Milling

Rahman et al. (2003) employed two nozzles constantly supplying chilled air of -30°C to the workpiece and the cutting tool on a CNC milling machine, separately. Goujon et al. (2001) also conducted a series of experiments on cryogenic milling of Al alloy / AlN powders at -196°C produced by LN_2 , suggesting that some chemical reactions e.g. oxidation and nitridation need to be studied.

(iii) Grinding

There are quite a few research papers reporting on cryogenic grinding (Dhokia, 2009). This may be partly because, originally, coolant is not often used in conventional grinding. In the research by Ben Fredj et al. (2006), it was demonstrated that cryogenic cooling was able to improve surface integrity. Nguyen et al. (2007) installed a nozzle on the wheel guard providing steady LN_2 jet to the grinding point.

4.7.5.2 Cryogenic machining of soft materials

Shih et al. (2004) used solid carbon dioxide as a cryogen to cool the elastomer workpiece during the machining operation. The elastomer was cooled to approximately -78.6°C at which it transformed to a brittle phase. Dhokia et al. (2010a) developed a novel cryogenic CNC machining method, which sprays LN_2 onto the workpiece (i.e. soft elastomer) for rapidly reducing the material to its glass transition temperature (Crabtree et al., 2009). This increases of the stiffness of the workpiece and makes it possible to be machined by conventional CNC machining methods.

4.7.6 Thermally and cryogenically machining

4.7.6.1 Laser assisted and cryogenic machining

Dandekar et al. (2010) utilized a CO_2 laser to alter workpiece material properties and CNC turning tools to machine titanium alloys combined with liquid nitrogen to cool the cutting tools at the same time.

4.7.6.2 Plasma enhanced and cryogenic machining

Based on plasma enhanced machining, Wang et al. (2003) designed a cooling chamber which supplied liquid nitrogen for cooling the cutter during the plasma enhanced turning of Inconel[®] 718.

4.7.7 High pressure cooling assisted mechanical machining

High pressure cooling (HPC) has been recently found to be an effective way to improve machining conditions in terms of cutting force, chip formation and tool life. The coolant of 11Mpa was applied in the drilling and turning of Ti6Al4V and Inconel[®] 718 by de Lacalle et al. (2000). Sanz et al. (2007) and Kramar et al. (2010) compared the experimental results of turning titanium alloys with and without HPC, claiming that HPC could provide longer tool life, lower cutting forces and increased

chip breakability. In addition, Nandy et al. (2009) argued that using water-soluble oil coolant, instead of neat oil coolant, is beneficial in terms of improving cutting tool life. On the other hand, Ezugwu et al. (2005) studied the effects of using different cooling pressure and suggested that higher cooling pressure does not always lead to higher tool life. Sorby and Tonnessen (2006) revealed that high pressure rake face cooling is likely to result in adverse effects for other parts of the workpiece surface.

4.7.8 Grinding and hardening

Brinksmeier and Brockhoff (1996) proposed a concept of the grind-hardening process, where the grinding wheel acts as a movable and moving heat source, by which the temperature of the workpiece surface was raised above that of austenitisation. Along with the following self-quenching by heat dissipation and/or using coolant, martensitic phase transformation takes place (Salonitis and Chryssolouris, 2007). Salonitis et al. (2008) further claimed that grind-hardened cylindrical parts have high hardness.

4.7.9 Milling and forming

In deformation machining, as identified by Smith et al. (2007), thin features are machined to the desired accuracy by milling. Forming operations are then carried out to create deformations of the thin sections by bending or stretching the features to finally form the designed shapes.

4.7.10 Turning and rolling

Hybrid machines which are able to perform turning and cold rolling operations have been reported (Axinte and Gindy, 2004; MAG, 2010). A cold rolling unit is integrated on a turning machine, enabling the gears to be turned and rolled in series, indicating the potential to reduce production cost and time.

5. Discussion and future hybrid processes research directions

The authors have classified a range of hybrid processes referred in this paper, into seven major areas. In addition the authors have developed their own classification, which is used in the following subsections to define the term ‘hybrid processes’, and to discuss the various research and suggest possible future research trends.

5.1 Definition of hybrid processes

The authors’ classification of hybrid processes is shown in Figure 1. This consists of four hybrid and three sub-hybrid types. From the authors’ viewpoint, the term ‘hybrid processes’ is defined as an approach that combines two or more manufacturing operations, each of which is from different manufacturing technologies, as mentioned in section 2.2, and has interactions and influences to each other. This can be achieved from the processes being carried out simultaneously or in a serial manner on a single platform.

In order to clarify confusion, the following statements are made:

- (i) As hybrid manufacturing is mainly concerned with the combinations of different manufacturing technologies, if all of the constituent processes are

from the same manufacturing technology, this type of combination is defined as sub-hybrid process.

- (ii) Constituent processes should have interactions or influences between each other. Examples are: in laser assisted turning (Sun et al., 2010), the laser beam softens the material, which generates the influence that makes the turning easier and faster. In laser cladding and milling (Zhang and Liou, 2004), the milling machine removes material from the near-net shape produced by laser cladding; on the other hand, the new layers are deposited on the smooth surface machined by the milling operations, which reduces the stair effects in the laser cladding process. This indicates that the laser cladding operations have the influence on the following milling operations. The dimensions of the milled part also affect the next step of the laser cladding process.
- (iii) Constituent processes should directly act on the workpiece being manufactured.

Based on the above description, magnetic field assisted finishing (Riveros et al., 2009; Yamaguchi et al., 2010) is not considered as a hybrid process. This method uses the alternating magnetic field to drive the magnetic fluid which contains abrasive slurry, to flush mirror chips in the micro-pore x-ray mirror fabrication process (Yamaguchi et al., 2011). However, the magnetic field actually drives the fluid but the field does not directly work on the workpiece. Similarly, using robot(s) to hold milling cutter(s) in the machining operations (Chen and Song, 2001; Yang et al., 2002) is not considered as a hybrid process. In addition, water-jet guided laser cutting (Li et al., 2003; Kray et al., 2007), where the water-jet guides the laser beam before the beam reaches the workpiece surface, is not categorised as a hybrid process, as the jet itself does not change the microstructure of the workpiece or remove the material.

Figure 1 – classification of major hybrid processes research areas (corresponding section numbers are in brackets)

5.2 Hybrid subtractive manufacturing processes

Hybrid subtractive manufacturing processes normally involve thermal, chemical, electrochemical and mechanical interactions (Molian et al., 2008). As shown in Figure 2, the vast majority of research activities have focused on the combinations of subtractive processes, which have been gradually used to meet the challenges in the reduction of tool wear and production time and the increase of machining effectiveness with tight tolerances and high levels of surface finish. The implementation of ultrasonic assisted mechanical machining or EDM showed higher machining efficiency than that of the individual mechanical machining, USM and EDM. Similarly, the integration of laser cutting and EDM (Li et al., 2006) is able to drill micro-holes with lower tool wear and better surface quality. Those advantages are gained by the processes carried out simultaneously (e.g. laser cutting and ECM (Zhang et al., 2009a)) or in series (e.g. sequential laser drilling and mechanical

drilling (Biermann and Heilmann, 2011)). It is noted that hybrid subtractive processes are applied in not only the conventional machining scenarios, but also in other application areas e.g. micromachining (Lim et al., 2002b) and in the production of semiconductors in the photovoltaic industry (Wang et al., 2008).

Although encouraging results have been shown, some issues still need to be solved. In the ultrasonic assisted machining processes, high frequency and amplitude vibration mechanisms are likely to deteriorate the surface quality and the dimensional accuracy of the machined parts (Jahan et al., 2010), and the machining energy only decreased 10%. In addition, with its high precision, laser processing has the potential to be incorporated in wider application areas. Thus, more research effort will continue to be made in ultrasonic and laser related processes.

Figure 2 – Distribution of the collected hybrid research papers

5.3 Hybrid transformative, additive and transformative, subtractive and joining manufacturing processes

There is little research work reported on each of these three categories. As for hybrid transformative processes, two types of sheet metal forming processes were used in series, which improved the accuracy and decreased the forming steps. The layout with laser heat treatment and forming tools is another popular machine configuration as a laser beam is able to soften material, increasing formability of the material at higher temperature as well as reducing springback effects (Duflou et al., 2007). There is a possible research trend that integrates a laser unit inside a forming tool, which has the potential to effectively utilise the laser beam in the forming processes where the working spaces are enclosed e.g. deep drawing.

The development of hybrid additive and transformative process is still in an initial stage. Yasa and Kruth (2008) identified that, in the laser melting and erosion, longer processing times led to lower productivity, which restricts its further development. Lucchetta and Baesso (2007) used a mould to perform the sheet metal forming and injection moulding of sheet metal-polymer composites, providing a new method to produce multi-materials components. However, the feasibility of using the injection mould as a forming tool needs to be further validated.

With regards to hybrid subtractive and joining processes, the machining operations enhance the capability of the welding processes by providing a high level of surface finish. However the cumulative errors are likely to increase during the whole operation (Kuo et al., 2003).

5.4 Hybrid additive manufacturing processes

Researchers, who aim to fabricate functional parts comprised of multi-materials, apply a hybrid additive approach, which is able to deposit various materials alternatively by the mounted additive heads. Another building approach is the mix of different material powders by a user-defined ratio. As a result, the manufactured parts have new properties intermediate to their constituent materials. In addition, researchers also employed an additional heat source to provide higher energy in the laser cladding or the arc welding process, which accelerated the deposition speed,

reduced production time and more importantly increased welding stability (Ono et al., 2002). It was also noted that the change of additional energy input remarkably influenced the precision of the layer deposition (Qian et al., 2010). Hence, the investigation of appropriate energy input will receive research attention to some extent. Moreover, it is necessary to point out that hybrid additive processes, based on additive manufacturing techniques, also have inherited their drawbacks, which are slower production times in mass production, moderate surface finish and relatively high cost compared to CNC machined parts. Thus, these issues hinder a broader application of this technology. The improvement in surface roughness and the reduction of production cost will continue to be a major area of further development.

5.5 Hybrid additive and subtractive manufacturing processes

This review has identified that the research relating to hybrid processes combining an additive process and a subtractive process concentrates on the increase in manufacturing flexibility with no detrimental effect on surface finish (Choi et al., 2001). Two deposition methods are mainly utilised i.e. laser cladding and arc welding to build the near-net shapes directly from CAD models. Meanwhile, a machining process is implemented to ensure accuracy and eliminate the stair effects after certain layers have been deposited. Finally, the near-net shapes are finish machined to their desired surface finish.

On the other hand, this hybrid technology is currently only suitable for small batch production of customised products rather than for mass production. The review has revealed the main application is in the production of injection moulds and dies. Other applicable products are limited and it should be noted that the fabricated tools may be inferior to their counterparts produced by conventional machining in terms of tensile strength and tool life (Akula and Karunakaran, 2006). In addition, the limited range of materials that can be used for additive processes partly contributes to the limited hybrid additive & subtractive processes application areas. It is expected that future research will pay attention towards exploring broader application areas, possibly gradually moving towards metallic parts to other hard materials along side for the development in rapid prototyping technology.

5.6 Hybrid subtractive and transformative manufacturing processes (HSTMP)

Thermally enhanced machining and other laser assisted machining processes e.g. water-jet have generated significant research interest. In these processes, only one of the participating processes directly removes the material. The other one assists in the material removal operations by changing the machining conditions which is beneficial to the cutting process (Molian et al., 2008). The review has identified that the research in this category mainly focuses on the machining of hard-to-machine materials e.g. ceramics, composites and superalloys. The experiments by Pfefferkorn et al. (2004) and Dandekar et al. (2010) reported that the cutting tool life can be prolonged up to 3 times and the material removal rate can be effectively increased.

However, notwithstanding the tremendous advantages, HSTMP does not increase the flexibility of the original machining process. In other words, if a part cannot be machined by conventional CNC machining processes due to tool inaccessibility,

HSTMP is not able to manufacture it likewise. In addition, further efforts should be made for developing thermally enhanced machining with the capability of machining ductile materials (Sun et al., 2010). Some researchers have been working on the effects of a laser beam input angle and heated area, and has initially identified that these two factors influence the machining efficiency. There is a possibility that future research will focus on these issues. Moreover, for a better understanding of HSTMP mechanisms, modelling of heat transfer is another potential major research topic.

Recently, cryogenic machining has drawn attention as both hard and soft materials can be machined under good machining conditions such as lower forces and temperature. Through the cooling of the cutting tool by liquid nitrogen, tool degradation can be reduced significantly and thus cryogenic machining can increase tool life (Shokrani et al., 2012). The improved surface finish, increased length of cut and reduced cutting force has also been reported.

In summary, cryogenic machining is under investigation and the majority of research focuses on turning of hard material but less attention is paid to milling and grinding operations which are also significant in the contemporary CNC manufacturing industry. There is also a lack of knowledge in the machining of soft materials with the exception of Dhokia et al. (2010b). These issues need to be further researched. With respect to high pressure cooling, research is likely to concentrate on the reduction in the high cost of coolant systems and the reduction of set-up times.

5.7 The importance of hybrid manufacturing research

As discussed above, the research of hybrid manufacturing has gained significant attention both in academia and industry. The reasons why hybrid manufacturing processes are needed can be briefly summarised in two aspects: (1) conventional manufacturing processes which have advantages and disadvantages; (2) some of the products that need to be made these days can no longer be manufactured by using individual conventional manufacturing processes or in other words, it is more reasonable to manufacture those products by using hybrid processes in terms of process capability, production time and costs. Some typical and representative examples are outlined below.

- Conventional deep micro-hole mechanical drilling of Inconel[®] 718 is a time consuming process. A noticeable improvement in terms of circularity was observed and 50% increase of MRR was reported, while using the hybrid process combining mechanical drilling with laser and ultrasonic vibration, respectively (Okasha et al., 2010; Liao et al., 2007).
- On the other hand, recast layer and spatter cannot be completely eliminated if an individual laser drilling process is used. The combination of laser drilling and ECM provides a solution to dramatically reduce recast layer (Zhang et al., 2009a).
- In order to increase tool life, reduce cutting forces as well as obtain better surface finish in mechanical milling, turning and grinding of hard materials (e.g. ceramics, H-13 mould steel, Ti and Ni-based-alloys and Inconel[®] 718), the concepts of ultrasonic assisted machining and thermally enhanced mechanical machining have

been proposed (Brecher et al., 2010b; Sun et al., 2010).

- EDM process has been widely used in the machining of tungsten carbide and stainless steels, but electrode deflection restricts its further development. Ultrasonic assisted EDM is capable of machining those hard materials with reduced electrode deflection effect (Jahan et al., 2010).
- Long production time is always the major concern in forming processes. Laser assisted sheet metal forming has shown the advantages in improving material formability and more importantly, reducing forming steps (Duflou et al., 2007), which results in reduced production time.
- Making mould inserts is not an economical process for low volume production, but now the costs can be significantly reduced by combining laser cladding and CNC machining (Jeng and Lin, 2001). The manufacture of components for gas turbines is another potential application area of this hybrid process (Nowotny et al., 2010). Furthermore, biomimetic robotics with embedded sensors and circuits can also be produced (Dollar et al., 2006), which was previously impossible without further assembly operations.
- Recently, a low cost process namely, cryogenic CNC machining, for the production of personalised shoe insoles has been developed (Dhokia et al., 2008), replacing injection moulding processes in the production cycle. This hybrid process has the potential to be widely used in low volume and personalised soft material product manufacture.

6. Conclusions

The initial purpose of developing hybrid manufacturing processes is to provide the advantages of constituent processes whilst minimising their inherent drawbacks (Karunakaran et al., 2010). Even though the specific consensus of hybrid processes definition has not been formed, the development of a hybrid concept is becoming wide spread and in this paper has been broken down into seven major research areas. The combinations of subtractive processes are mainly applied in the milling, turning, drilling and grinding of difficult to machine materials e.g. superalloys and ceramic. Due to the high surface quality provided by mechanical machining and EDM, they are the major contributors to material removal. With ultrasonic vibration or laser cutting, lower tool wear, higher surface integrity and shorter production times are achieved to some extent. Laser processing is still drawing considerable research interest in hybrid subtractive and transformative processes, whereas the use of the laser does not participate in cutting materials, but changing the microstructures of the materials. It enables conventional machining operations to remove the material more easily in terms of the lower cutting forces, longer tool life and higher material removal rate. However, these types of combinations cannot increase the flexibility of the processes, therefore, researchers employ rapid prototyping technology to flexibly build components with arbitrary shapes and then further machine the components for obtaining high dimensional accuracy.

With the trend of producing hybrid products, hybrid additive processes technology

has been proposed, which is aimed at the fabrication of multi-material parts. Similarly, hybrid transformative processes emerged due to specific demand, for example, the formability of high-strength sheet metals for making complex thin shapes. In summary, new kinds of combinations are still emerging, which extend to broader application fields. There is a major need to establish the relationships between constituent processes and their respective control systems. This will largely determine the development of hybrid processes in the future. In addition, breakthroughs in individual processes can promote an advance in hybrid processes developments. The authors believe that for hybrid manufacturing processes to be fully realised, a number of future research advances, need to be addressed, namely i) integration with other processes; ii) need for new process planning methods (Xu et al., 2011); iii) modelling representations of hybrid process capabilities (Nassehi et al., 2011); and iv) additional standards.

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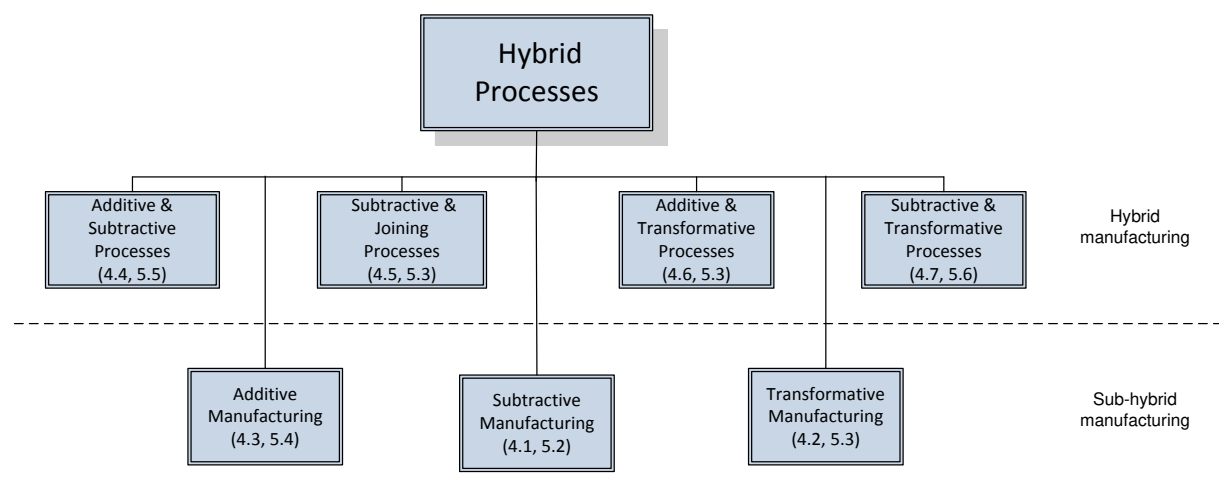


Figure 1 – classification of major hybrid processes research areas (corresponding section numbers are in brackets)

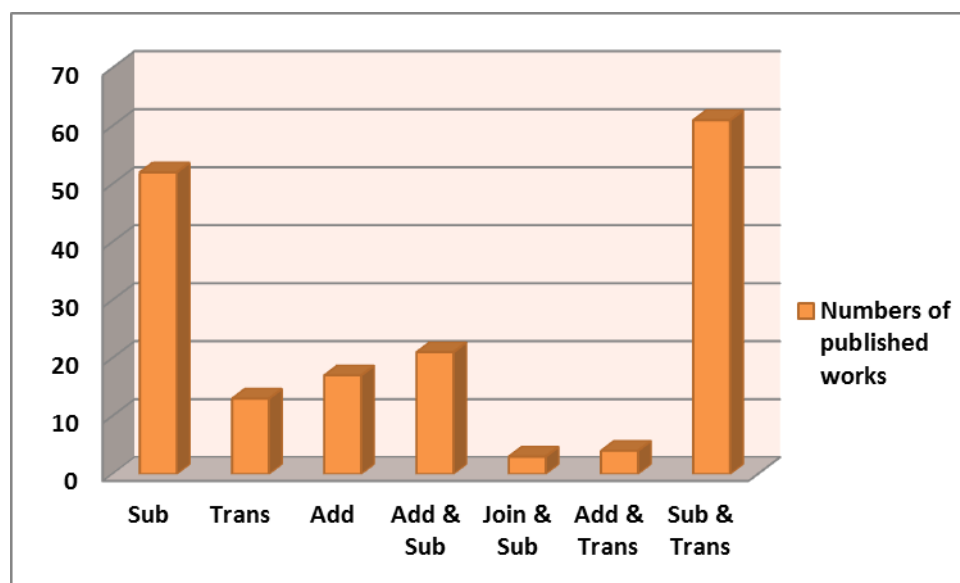


Figure 2 – Distribution of the collected hybrid research papers