Journal of Manufacturing Processes 15 (2013) 404–413

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

Technical paper

The development of a novel process planning algorithm for an unconstrained hybrid manufacturing process

Zicheng Zhu, Vimal Dhokia*, Stephen T. Newman

Department of Mechanical Engineering, University of Bath, BA2 7AY, United Kingdom

ARTICLE INFO

Article history:
Received 3 June 2013
Accepted 4 June 2013
Available online 16 July 2013

Keywords:
Hybrid manufacturing process
Process planning
Additive process
Subtractive process
Inspection

ABSTRACT

The application of state of the art manufacturing processes has always been constrained by the capabilities either from technical limitations such as limited materials and complex part geometries or production costs. As a result, hybrid manufacturing processes – where varied manufacturing operations are carried out – are emerging as a potential evolution for current manufacturing technologies. However, process planning methods capable of effectively utilising manufacturing resources for hybrid processes are currently limited. In this paper, a hybrid process, entitled iAtractive, combining additive, subtractive and inspection processes, along with part specific process planning is proposed. The iAtractive process aims to accurately manufacture complex geometries without being constrained by the capability of individual additive and subtractive processes. This process planning algorithm enables a part to be manufactured taking into consideration, process capabilities, production time and material consumption. This approach is also adapted for the remanufacture of existing parts. Four test parts have been manufactured from zero and existing parts, demonstrating the efficacy of the proposed hybrid process and the process planning algorithm.

1. Introduction

Manufacturing technology has gone through a number of evolutionary developments over the past decades [1]. However, due to the technological constraints of individual manufacturing processes, it is not always feasible to produce components in terms of material, geometry, tolerance and strength etc. [2]. Additive manufacturing methods provide the capability to automatically produce components with various part designs including complex internal features. However, a number of limitations hinder its further development, such as limited materials available, long production times, diminished surface quality and reduced dimensional accuracy, compared to computer numerically controlled (CNC) machining. On the other hand, CNC machining technology, a subtractive process, is typically used for hard material machining, due to high accuracy and the relatively short production times achievable. Nevertheless, certain features like internal cavities are still difficult to produce due to limited tool accessibility. In recent years, the on-going industrial trend towards energy efficiency and material consumption requires new technology to be developed. As a result, the concept of hybrid manufacturing begins to emerge [1]. However, none of these hybrid processes addresses the material consumption issue. Products that are out of tolerance are abandoned resulting in considerable waste and in turn, increased overall production and part cost.

Process planning techniques have nowadays been widely used in various domains of production. Generally, process planning comprises of the selection and sequencing of processes and operations to transform a chosen raw material into a finished component [3]. Nonetheless, the majority of process planning research focuses on machining technology. Furthermore only limited process planning approaches have been developed for the hybrid processes.

In this paper, a hybrid process entitled iAtractive, combining additive (i.e. Fused Filament Fabrication, FFF [4]), subtractive (i.e. CNC machining) and inspection, along with a reactionary process planning algorithm is proposed. This will provide the designer with enhanced manufacturing capability and flexibility. The process planning algorithm enables a part to be manufactured either from zero or an existing part. The major elements for realising such an algorithm are described in detail in the proceeding sections. Finally, two case studies were conducted. In the first case study, the test part consists of internal features has been accurately manufactured as one complete unit. Three identical parts in the second case study were manufactured from three existing parts with different features. These case studies demonstrate the efficacy of the proposed hybrid process and the process planning algorithm.

* Corresponding author. Tel.: +44 1225 386596.
E-mail address: V.Dhokia@bath.ac.uk (V. Dhokia).

1526-6125/$ – see front matter © 2013 The Society of Manufacturing Engineers. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jmapro.2013.06.006

2. Review of the related work

2.1. Current research on hybrid manufacturing processes

Combining CNC machining processes with additive processes may provide new solutions to the limitations of additive processes [5] due to the high accuracy, improved quality and speed that machining processes offer. Jeng and Lin [6] used a laser to melt the mixed powders (Fe, Ni and Cr) and once one cladding operation was accomplished, the surface of the cladding was milled in order to achieve the desired accuracy and maintain a flat surface for the next cladding operation, until the entire mould was produced. Liou et al. [7] and Zhang and Liou [8] incorporated a 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 times. Karunakaran et al. [9], and Suryakumar et al. [10] retrofitted a 3-axis milling, which was used to face mill each slice built by metal inert gas (MIG) and metal active gas (MAG) welding. However, there is no robust process planning approach developed. The hybrid process just deposits one layer followed by a face milling operation. Further layers are deposited and machined until the entire part is produced. Therefore, Karunakaran et al. [11] argued that the need to face mill each layer is the major barrier for reducing production time. Furthermore, Lanzetta and Cutkosky [12] utilised Shape Deposition Manufacturing process (SDM), which is the combination of material deposition and milling, to build smooth and sculpted 3D contours of dry adhesives which could be used to aid human and robotic climbing.

The integration of laser heating or ultrasonic vibration and traditional milling/turning/grinding processes has been identified as an effective method to improve surface quality and increase tool life [13]. In the laser assisted machining process, a focused laser beam is used as the heating source to irradiate the workpiece for improving the materials machinability. While the material is locally heated and softened, it is removed by a conventional cutting tool [14]. Dumitrescu et al. [15] attempted to use a high power diode laser, suggesting that higher machining efficiency and better metal absorption can be expected. Anderson and Shin [16] proposed a new configuration in which two laser beams simultaneously irradiate a machined chamfer and an unmachined surface adjacent to the chamfer, respectively. 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 workpiece [17]. Uhlmann and Hübert [18] 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. The tool was vibrating in a vertical direction while it was cutting material horizontally. However, in the experiments by Yanyan et al. [19], 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. [20] further developed a tool path generation algorithm for machining of ceramic components, obtaining better surface quality.

Other combinations of manufacturing processes are also researched. Zhu et al. [21] investigated the mechanical-electrochemical machining of small holes by ECM and grinding, where a metal rod with abrasives was used as the cathode tool to mechanically and electrochemically machine the workpiece part. Dhokia et al. [22] developed a novel cryogenic CNC machining method, which sprays liquid nitrogen onto the workpiece (i.e. soft elastomer) to rapidly reduce the material to its glass transition temperature. This increases the stiffness of the low-density workpiece, allowing it to be machined by conventional CNC machining methods. In the paper by Araghi et al. [23], a stretch forming process was employed for pre-forming rough shapes. An asymmetric incremental sheet forming (AISF) process was subsequently carried out to produce the final parts.

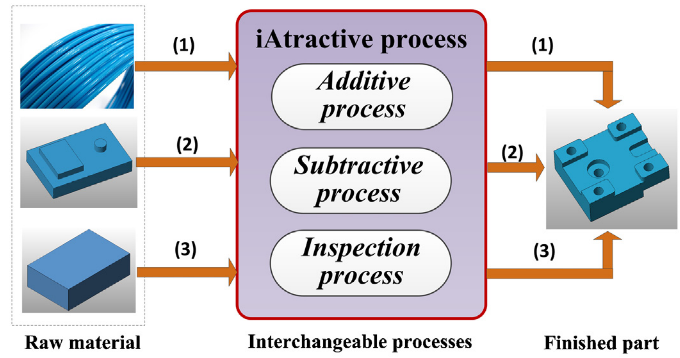

Fig. 1. Vision of the iAtractive process production.

2.2. Process planning for hybrid processes

Very limited research has been reported on process planning of hybrid manufacturing. This is because there has not been a need for it since manufacturing has been limited to singular independent processes. Kerbrat et al. [24] used a design for manufacturing (DFM) approach to analyse features in the design stage and subsequently identified which features would benefit from being made either by machining or additive process in terms of feature complexity. In the combination of additive and subtractive processes, a typical process planning approach is to face machine the top of each layer after it is deposited [6]. Hu and Lee [25] introduced a concave edge-based part decomposition method, which splits the part into a number of subparts to eliminate undercut edges during machining. Ruan et al. [26] developed a process planning approach that can generate non-uniform layer thickness and tool paths for laser cladding and CNC machining by taking into account tool collisions.

3. A novel concept of hybrid manufacturing process

The concept of hybrid manufacturing (iAtractive) currently being investigated at the University of Bath consists of combining additive, subtractive and inspection processes [27]. This is based on the need to reuse and remanufacture existing parts or even recycled and legacy parts; reduce the amount of material used; enhance the flexibility of CNC machining and improve the accuracy of FFF process. Incorporating an additive process releases design constraints often caused by tool accessibility issues in CNC machining. Using CNC machining capabilities the final part can be produced with a high degree of accuracy comparable to that of an entirely CNC machined part. Furthermore, dimensional information of the existing part can be obtained by using an inspection technique enabling the existing part to be further manufactured by an additive and/or subtractive process, providing new enhanced functionalities. This indicates that the iAtractive process is not constrained by raw material in terms of shape, geometry or features. The vision for the proposed hybrid process production is depicted in Fig. 1, where raw material can be (1) zero (filament for deposition from zero); or (2) an existing/legacy product; or (3) a billet. By using the additive, subtractive and inspection processes interchangeably, the given raw materials can be further produced to the finished part.

The iAtractive process is shown in Fig. 2 and is outlined as follows: (i) Raw material is first inspected by using a Coordinate