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APPLICATION OF A HYBRID PROCESS FOR PRECISION MANUFACTURE OF COMPLEX COMPONENTS

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ABSTRACT: In recent years, hybrid processes have drawn significant attention due to their ability to capitalise on the advantages of independent processes whilst minimising their disadvantages. However, production of highly accurate and complex structures, such as internal features, without assembly is still considered to be extremely difficult due to limited tool accessibility. This paper introduces a hybrid process entitled iAtractive, combining additive, subtractive and inspection processes. A novel process planning algorithm is proposed, taking into consideration, tool accessibility, production time and dimensional accuracy. A test part with internal features has been manufactured as one complete unit, demonstrating the efficacy of this hybrid process and the process planning algorithm.

1. INTRODUCTION

The ever-increasing customer demand for increasing varieties of products have led to the rapid developments and continuous evolvement in manufacturing technology over the past decades (Zhu *et al.*, 2013a). 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. Additive manufacturing techniques, as one of the representatives of the new manufacturing methods, provide the capability with which to produce complex geometries, for example, internal features, which are virtually impossible to create with any other manufacturing process (Cheah *et al.*, 2005). Nevertheless, surface quality and accuracy impedes its further development for producing end user products with high accuracy (Vaezi and Chua, 2011). Computer numerical controlled (CNC) machining, on the other hand, provides the capability to generate components with extremely high levels of accuracy and surface finish, but it is still relatively difficult to machine certain complex geometries and shapes owing to tool inaccessibility problems (Yee and Shyan, 2008; Makki *et al.*, 2008). As a result, hybrid processes, which combine different processes together, have drawn significant attention due to their ability to capitalise on the advantages of independent processes whilst minimising their disadvantages. Despite the capabilities of individual processes continuously improving, such as reduced tool wear, the production of highly accurate and complex structures without assembly is still considered to be extremely difficult.

This paper introduces a hybrid process entitled iAtractive, combining additive (i.e. Fused Filament Fabrication, FFF), subtractive (i.e. CNC machining) and inspection processes. A novel process planning algorithm has been specially developed for the manufacture of complex part geometries. The major elements for realising this algorithm are presented. Finally, a test part with two internal pockets and a hole, which are traditionally impossible to produce using a conventional manufacturing approach, were manufactured as one complete unit.

2. STATE-OF-THE-ART IN HYBRID MANUFACTURING

Hybrid manufacturing technology has drawn significant attention due to its ability to make products in a more efficient and productive way (Pandey *et al.*, 2006). The combination of CNC machining processes and additive processes may provide a new solution to the limitations of additive processes due to the high accuracy and machining speed that machining processes offer. Two typical additive processes integrated in this type of hybrid process are laser cladding and arc welding. Jeng and Lin (2001) used a laser to melt the mixed powders (Fe, Ni and Cr). 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. 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. Very limited research has been reported on process planning of hybrid manufacturing. Kerbrat *et al.* (2011) used a design for manufacturing approach to analyse features in the design stage and subsequently identified which features would benefit from being made either by machining or additive processes in terms of feature complexity. Ren *et al.* (2010) developed process planning approach, which is able to generate toolpath for laser cladding and CNC machining processes by taking tool collisions into account.

3. A NOVEL CONCEPT OF HYBRID MANUFACTURING PROCESS

The concept of hybrid manufacturing (iAtractive) consists of combining additive, subtractive and inspection processes. 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 (Zhu *et al.*, 2013b). This indicates that the iAtractive process is not constrained by raw material in terms of shape, geometry or features. This paper only focuses on the capability of the iAtractive process on manufacture of difficult to machine structures i.e. complex structures. The vision for the proposed hybrid process production is depicted in Figure 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 processed to the finished nominal part.

Figure 1. Vision of the iAtractive process production.

4. A PROCESS PLANNING ALGORITHM (PPA) FOR THE IATRACTIVE HYBRID PROCESS

4.1 Methodology

The aim of this process planning algorithm is to generate the process plan from a given part design. The additive and subtractive processes are used interchangeably to accurately produce the complex part in the shortest time possible. Three factors have to be taken into account, namely, cutting tool accessibility, production time and dimensional accuracy. Figure 2 illustrates the various stages in the process planning algorithm. A given part is decomposed into a number of subparts. The viable build directions for each subpart are then identified followed by subpart merging. Subsequently the sequence of the additive and subtractive operations will be scheduled, which takes cutting tool accessibility into consideration. In certain scenarios the feasible sequence for producing the part cannot be found due to the capability of FFF and CNC machining processes. In this case, the merged subparts that lead to the failure in operation sequencing will be re-decomposed. Having obtained one sequence, other possible sequences will also be identified if the subparts have other viable build directions. This entire process is then applied to other part orientations, identifying other sequences that can be potentially used to manufacture the part. In the end, the production times for each sequence are estimated and compared, thus the most appropriate sequence is determined.

Figure 2. Flowchart for the major elements in the process planning algorithm.

4.2 Part decomposition for manufacturing

The aim of decomposition is to enable complex parts to be manufactured as one complete unit rather than producing a number of pieces and assembling them together. Internal features that would cause cutting tool accessibility issue are decomposed into a set of subparts based on primitives, which allows these features to be first produced to the required dimensions and tolerances. Subsequent features are then added. The decomposed subparts are named original subparts. The relationship between two original subparts is categorised as parent, child, twin and irrelevant. A subpart that has to be deposited onto another subpart is considered to be a child part. The output of part decomposition is a set of subparts, which will be further optimised and merged in the later stages.

4.3 Determination of build directions and sequencing of additive and subtractive operations

After decomposing the part into a number of original subparts, the build directions of these subparts will be determined. This is due to deposition tool collisions that may happen while depositing material on one certain direction or the specific operation sequence that is restricted by the limitation of the FFF process, i.e. features cannot be built without support. The major concern of determining the correct build directions is deposition tool collisions. The two neighbouring original subparts are merged into one subpart if they have the same build direction.

Build direction determination, subpart merging and operation sequencing form a feedback loop until all the viable sequences for manufacturing the part have been obtained. For a given orientation, a certain number of feasible sequences may exist due to some subparts that have multiple build directions. Other possible sequences that result from different orientations will also be identified. In addition, due to the accessibility of cutting tools and deposition nozzle that has been considered in the part decomposition stage, the original subparts are free to be produced without any constraint. However, more constraints are induced leading to further tool accessibility issues as a result of the number of original subparts that have been merged. In this case, the merged subparts that lead to the failure in operation sequencing will be re-decomposed into original subparts, releasing the constraints. The build directions of these re-decomposed subparts will be re-determined. These re-decomposed subparts will not be combined in the next stages. Figure 3 shows the sectional view of a part that has internal pockets. If subpart 1 and 2 were merged as they had the same build directions (denoted by the red arrows), the blind pocket would not have been machined. Therefore, the combination of subpart 1 and 2 has to be separated.

Figure 3. Illustration of part re-decomposition.

4.4 Production time estimation

Having obtained all the viable sequences, the production time for each sequence is calculated in order to decide the final operation sequence to implement. The total production time for manufacturing a part is defined as the sum of the time used in the additive, subtractive and inspection operations as well as switching time between additive and subtractive operations. Machining time estimation has been extensively researched and a method proposed by Maropoulos *et al.* (2000) is adopted in PPA. Since the part is decomposed into a number of small subparts with fewer features, the inspection time can be simply considered as constant at this stage. By contrast, the additive operations consume considerably longer time than that of other operations. Therefore, a build time estimation model has been developed (Zhu *et al.*, 2013b), which is depicted in Eq. (1), where T_a is the time used in a single additive operation, V is the part volume, H is the part height, ρ is the porosity and η is the intermittent factor which is defined for representing the ratio of nozzle deposition distance and repositioning distance. To this end, the most appropriate sequence, where the least amount of production time, is achieved.

$$T_a = 168.33 + 23.56V + 9.44H + 160.19V\rho + 78.17H\eta + \varepsilon \quad (1)$$

5. CASE STUDY

A case study was conducted to demonstrate the feasibility of the iAtractive process together with the proposed process planning algorithm for manufacture of difficult to machine structures. Figure 4a is a block with four connected pockets and a hole. All the corners (except the corner where the hole is located) are round corners with 3mm in radius but for better representation, they are ignored in Figure 4b. All the surfaces required finish machining. As a result, the part was decomposed into a number of subparts, which were then further merged into 5 subparts as shown in Figure 4c. The finished part is shown in Figure 4d. For illustrating the internal features, the part has been sectioned (see Figure 4e).

Figure 4. Manufacture of the test part.

6. DISCUSSION AND CONCLUSIONS

A number of inherent technical limitations of individual manufacturing processes stimulate this research on hybrid manufacturing. This paper introduced a novel hybrid process combining additive, subtractive and inspection processes in a serial manner. A novel process planning algorithm is proposed, which provides an intelligent solution to accurately manufacture products with difficult to machine structures, i.e. internal features. Based on the given part design, the part is first decomposed into a number of subparts, which are merged once their build directions have

been determined. The operations are then sequenced and the appropriate sequence is identified in terms of production time. The PPA acts as an enabler for flexibly and accurately manufacturing difficult to machine structures that are traditionally impossible to produce by either individual CNC machining or additive processes. The production time can be significantly reduced as compared to the method presented by Jeng and Lin (2001), since the redundant face milling operations for each layer has been removed. The manufactured products can be achieved with a high level of accuracy and surface quality comparable to that of an entirely CNC machined part, whereas some of the features manufactured by adopting Kerbrat *et al.* (2011) approach could still remain inaccurate. The case study demonstrated the efficacy of the proposed process planning algorithm, which indicates that the iAtractive process has better flexibility and capability as compared to individual additive and subtractive processes. However, as the PPA has been developed based on prismatic part manufacture, it is not currently applicable to manufacturing free form sculptured surfaces. The current PPA still requires human intervention and thus a fully automatic PPA system needs to be developed in the future, realising automatic part production.

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