Robotics and Computer-Integrated Manufacturing 37 (2016) 23–32

Contents lists available at ScienceDirect

Robotics and Computer-Integrated Manufacturing

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

Investigation of part distortions as a result of hybrid manufacturing

Zicheng Zhu*, Vimal Dhokia, Aydin Nassehi, Stephen T. Newman

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

ARTICLE INFO

Article history:
Received 7 March 2014
Received in revised form
13 May 2015
Accepted 17 June 2015

Keywords:
Part distortion
Hybrid manufacturing process
Fused filament fabrication
Additive manufacturing

ABSTRACT

In today's society, the customer driven markets has led to the rapid developments and continuous evolution of manufacturing technologies. The ability to accurately produce complex parts, and to reuse and remanufacture used parts is becoming more prevalent, requiring more efficient and rapid methods to be developed. One such method being currently developed is the hybrid process combining additive, subtractive and inspection processes for the manufacture of complex part geometries from any given raw material in terms of shape and size. A major element of the hybrid process is decomposition of a part into a number of subparts, which are additively manufactured and machined in sequence. However, the residual stresses resulting from the temperature difference between the solidified material (i.e. already manufactured subparts) and the material being deposited (i.e. new subparts being built) leads to part distortions, which significantly reduces the dimensional accuracy of finished parts. This study investigates part distortions that take place in the additive manufacturing process under the context of hybrid manufacturing. A method for conducting this investigation was first proposed. A mathematical model was developed, identifying the influential parameters that contribute to part distortions. These parameters were then incorporated in the experimental design by employing the Taguchi design of experiments strategy. Distortion behaviour arising from thermally induced stress was experimentally explored, indicating that part length, height, and layer thickness have significant effects on part distortions.

1. Introduction

The 21st century demand for innovation is leading towards a revolution in the way products are perceived [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. [2,3]. Additive manufacturing (AM) 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. Nevertheless, surface quality and accuracy impedes its further development for producing end user products with high accuracy [4]. Computer Numerical Control (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 [5,6]. 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 [7].

A typical configuration of the hybrid processes is the combination of additive and subtractive processes [3]. Integrating CNC machining with AM processes may provide new solutions to the limitations of additive processes [8] due to the high accuracy, improved quality and speed that machining processes offer. In addition, the capability of the AM processes in producing complex part geometries can be utilised. Jeng and Lin [9] 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. Song and Park [10] utilised two gas metal arc welding guns for deposition of different materials, and CNC milling to finish machine the deposited injection moulds. Karunakaran et al. [11] used face milling to machine each slice built by metal inert gas and metal active gas welding. Ruan et al. [8] and Ren et al. [12] 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. However, one of the major problems of these hybrid processes is the rapid contraction of the material after it is deposited. The new material is deposited onto the part that has previously been built or machined. The contraction of the newly

* Corresponding author.
E-mail address: Zicheng.Zhu@bath.edu (Z. Zhu).

http://dx.doi.org/10.1016/j.rcim.2015.06.001
0736-5845/

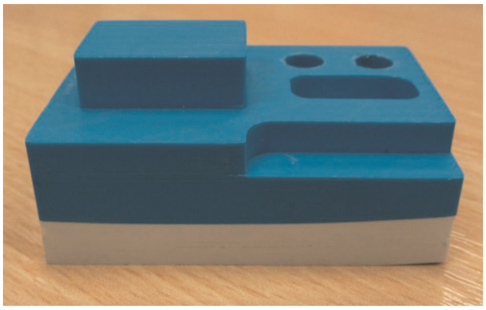

Fig. 1. Part distortions in continuously depositing new material. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

deposited material can induce residual stresses and distort the final product shape, significantly reducing the part accuracy. An example can be found in Fig. 1, where the new material (blue part) was built on the white part that had been previously made. The heat was dissipated during deposition of the blue part. As a result, the rapid temperature reduction after the blue material was extruded caused the material to quickly solidify and contract, which consequently pulled up the white part.

Therefore, this study is aimed at investigating the distortion behaviour in the additive process under the context of hybrid manufacturing. The related research on part distortions in individual additive processes was first reviewed in Section 2. A novel concept of the hybrid process consisting of additive, subtractive and inspection processes was proposed. The part distortion behaviour in this specific hybrid process was then investigated. A mathematical model was developed, which was used to select process parameters in the design of experiments (DoE) stage. The experiments were conducted and finally the results were statistically analysed, identifying the relationship between the distortion behaviour and the process parameters.

2. Review of the related work on part distortions

Although there is no research reported on part distortions for hybrid processes, a number of efforts have been made on the investigation of the effects resulting from various process parameters in relation to part distortions for individual additive processes.

Nickel et al. [13] examined the effect of deposition patterns on the resulting stresses and deflections in the Shape Deposition Manufacturing (SDM) process. Both finite element analysis and experiments show that the deposition pattern has a significant impact on the deflection of the manufactured part. The interaction between the process parameters and material properties also influence the deflection. Material properties such as dynamics of polymerisation related to the amount of volume shrinkage in the Stereolithography (SLA) process was investigated by Wiedemann et al. [14]. They further identified that the dynamics of polymerisation can be used to optimise hatching strategies for reducing internal stress, which in turn diminishes the curl development of the part surface. Dalgarno [15] carried out a structural analysis, modelling the curl development of the parts in the Selective Laser Sintering (SLS) process. Double sintering the first two layers was found to be an effective way to reduce the curling level. Sonmez and Hahn [16] developed a thermo-mechanical model investigating temperature and stress distributions in each layer in the laminated object manufacturing process. A large roller diameter and slow roller speed are recognised as beneficial for laminate bonding, and it is suggested that these two factors could contribute to part warpage. Zhang and Faghri [17] developed a physical model where melting a mixture of two powders with significant different melting points was explored. It was found that the porosity of the part contributes to the shrinkage, leading to distortions. The shrinkage phenomenon accelerates the melting process while the material is at fixed solid phase. Chin [18] studied the thermo-mechanical relationship between droplet columns and adjacent droplets in the SDM process. The established model shows that the process-induced pre-heating has noticeable impact on the reduction in thermal gradients and residual stresses, which consequently reduces distortions. Xu et al. [19] studied the distortion deformation of the plate parts and developed a mechanical equivalent model of resin phase change shrinkage in the SLA process. Yang et al. [20] developed a scale factor in three dimensions to compensate the distortions of the SLS components caused by the material phase changes during the laser sintering process. The Taguchi method was applied to maintaining dimensional accuracy against the changes in the build positions and part size. The accuracy was improved by up to 24% compared with the counterparts made by other commercial machines.

A number of research activities have been carried out, identifying the effects caused by the deposition patterns. The raster pattern with lines oriented 90° from the long axis of the rectangular block produces the lowest deflections [13]. Klingbeil et al. [21] identified that when depositing in a raster path, material should not be deposited parallel to the longest part dimension. This is because the curvature is the greatest parallel to the deposition direction and depositing parallel to the longest part dimension would result in greater warping deflections and loss of tolerance. The raster pattern with lines 45° and concentric pattern generate low and uniform deflection but the part produced by using the former pattern shows better mechanical property in terms of stiffness and bonding strength between adjacent layers [22]. The deflection and mechanical properties of the part by using Hilbert curve and Octagram spiral remain undeveloped. An initial study has been conducted, showing Hilbert curve and concentric patterns generate smaller substrate deflections, compared with raster 0° [23].

Wang et al. [24] simplified the factors that affect the part deformation phenomenon and therefore proposed a mathematical model where only temperature, length of cross-section and layer thickness were considered. By theoretically analysing the model, linear and non-linear relations between these factors have been obtained, indicating that the changes of each factor significantly influences the part accuracy. Zhang and Chou [25] developed a comprehensive finite element model, which is able to simulate the Fused Deposition Modelling (FDM) process involving mechanical and thermal processes. Experiments were also conducted and the results were compared with the simulation results, revealing that scan speed is the most significant factor followed by the layer thickness. In slicing Computer Aided Design (CAD) models, the inconsistent layer geometry containment where all the approximated extruded square-edged layers do not correspond to the minimum circumscribed volume results in systematic distortion [26]. Chen and Feng [26] proposed a layer contour generation approach, creating the minimum circumscribed extruded layered geometries. Along with the developed marching algorithm, which generates the boundary contour for each layer, the systematic distortion in AM parts can be eliminated. Yu et al. [23] explored part distortions, interior quality and mechanical properties of the laser solid forming manufactured parts by using four deposition tool path patterns, namely raster, offsetin (offset from the inside to the outside), offsetout (offset from the outside to the inside) and fractal. Both finite element analysis and experiments show that the part distortions are primarily influenced by the transient temperature gradient arising from deposition patterns. The smallest deformation was obtained when using fractal pattern followed by offsetout. Vatani et al. [27]