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In-situ shelling via selective laser melting: Modelling and microstructural characterisation

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ABSTRACT

This study focuses on the use of selective laser melting (SLM) to produce tooling (a shell) that is filled with powder and subsequently consolidated via hot isostatic pressing (HIPing) so that the tooling, rather than being removed, becomes part of the sample. The microstructures of the HIPed samples were studied using scanning electron microscopy (SEM) and electron backscattered diffraction (EBSD) to assess the bond between the shell and the consolidated powders. The columnar grains in the SLM-built tooling bonded with the powder although the grains in the tooling were found to be much coarser than those in the HIPed powder, leading to preferential failure in the tooling. However, failure occurred in a fairly ductile mode and reasonable tensile strengths and ductility were obtained. Finite element models were developed to define the required initial shape of the shell in order to obtain the correct geometry after HIPing. It was found that the final shapes predicted are consistent with the observations on HIPed samples.

1. Introduction

Additive manufacturing such as selective laser melting (SLM) and near-net-shape hot isostatic pressing (HIPing) are effective near-net-shape manufacturing technologies. Particularly, SLM has the capacity to fabricate complex freeform geometries directly from computer-aided design (CAD) models. One disadvantage of SLM process is that their building rate is usually low due to the processing limit on powder layer thickness [1–3]. As a result, it is time-consuming to build large parts especially when the parts contain large cross sections or thick walls. Net-shape HIPing, by contrast, could be more efficient in processing rate. However, it involves the design and preparation of capsules for powder filling as well as modelling to predict shape change during HIPing. The capsules or tooling are usually made of steels and need to be removed after HIPing either by pickling or machining which is expensive [4].

In the present work, we use a hybrid route, in-situ shelling route which combines the strengths of SLM and HIPing, which was initially suggested by Das et al. [5], more than a decade ago. The idea is to use SLM to prepare thin tooling with specific shapes which are then filled with powder and HIPed to required shapes. In Das et al's work [5], the focus was on microstructural development of the samples fabricated by SLS (selective laser sintering) plus HIPing. No report on the tooling design, shape change during HIPing as well as as-fabricated components was made. In this study, we use modelling to predict the shape change of the tooling during HIPing, which in turn creates feedback to the design of the tooling. Modelling on hot isostatic pressing has made significant advance in the past two decades. Shima and Oyane [6] proposed a plasticity theory for porous metals, which represents the basis for most of the powder consolidation modelling work. Cassenti [7] investigated HIPing modelling using an elasto-plastic large-deformation model with implicit thermal calculations. Later, Nohara et al. [8] and Abouaf et al. [9–13] developed and adapted constitutive equations to account for elasticity, visco-plasticity, and thermal effects, and to model the mechanical behaviour of the powder. Similar finite element (FE) models were also developed by Svoboda et al. [14–16], and Wikman et al. [17] who developed a combined material model that accounts for both granular and viscoplastic behaviours whereby the granular plasticity model accounts for the early stage of the consolidation and the viscoplastic model accounts for the intermediate and later stages of consolidation. Gillia et al. [18] further improved the viscoplastic model by taking into account the strain hardening effect of the powder material. Samarov et al. [19] developed a FE model to predict the final dimensions of shaped part produced by HIPing Ti–6Al–4V powder, using the constitutive equations for plastic yielding, without considering the constitutive models that describe other densification mechanisms. This was justified because more than 90% of density increase occurs within this instantaneous plastic yield mechanism. This model has relative concise formulation with fewer parameters involved as reported by Seliverstov et al. [20]. The developed model showed very good agreement of more than

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98% between the produced geometries and the predicted ones. Similar conclusion was reported by Wei et al. [21] who suggested that the creep mechanism does not play a major role in the powder consolidation during HIPing, for instance at the ramp up and cooling down parts of the HIP cycle. Khoei et al. [22] employed a constitutive model based on the double-surface plasticity to simulate the thermo-mechanical compaction process and to predict the relative density, temperature and stress distributions. However, the ability of the model to predict the shrinkage shape change was not presented.

Recently, constitutive models that account for densification mechanism by plasticity and creep were used to improve the prediction accuracy of HIP macroscopic models. Aryanpour et al. [23] used plastic–viscoplastic model to simulate the powder densification in HIPing. The results were validated against published 316LN stainless steel data and good agreement was found. However, the model prediction was only limited to the relative density. Similar model was used by Liu et al. [24] who investigated the influence of pressure on the densification behaviour of 316L stainless steel powder using a modified PERZYNA model. The model used to predict the shape change of a 2D cylinder with a relative error of about 7%. Though, these approaches are complex and need large computation time compare with pure plasticity models [19,22].

In this paper, several simple shapes including cylindrical and annular samples have been selected to try the in-situ shelling route. FE modelling is developed to predict the final shape of the tooling after HIPing, which is integrated to the design of initial shape of tooling. The microstructure and tensile behaviour of the SLMed + HIPed samples are also evaluated.

2. Modelling and experimental

2.1. Constitutive equations

In this investigation, a material model based on the modified Gurson's porous metal plasticity theory has been used. This material model defines the inelastic flow of the porous metal on the basis of a

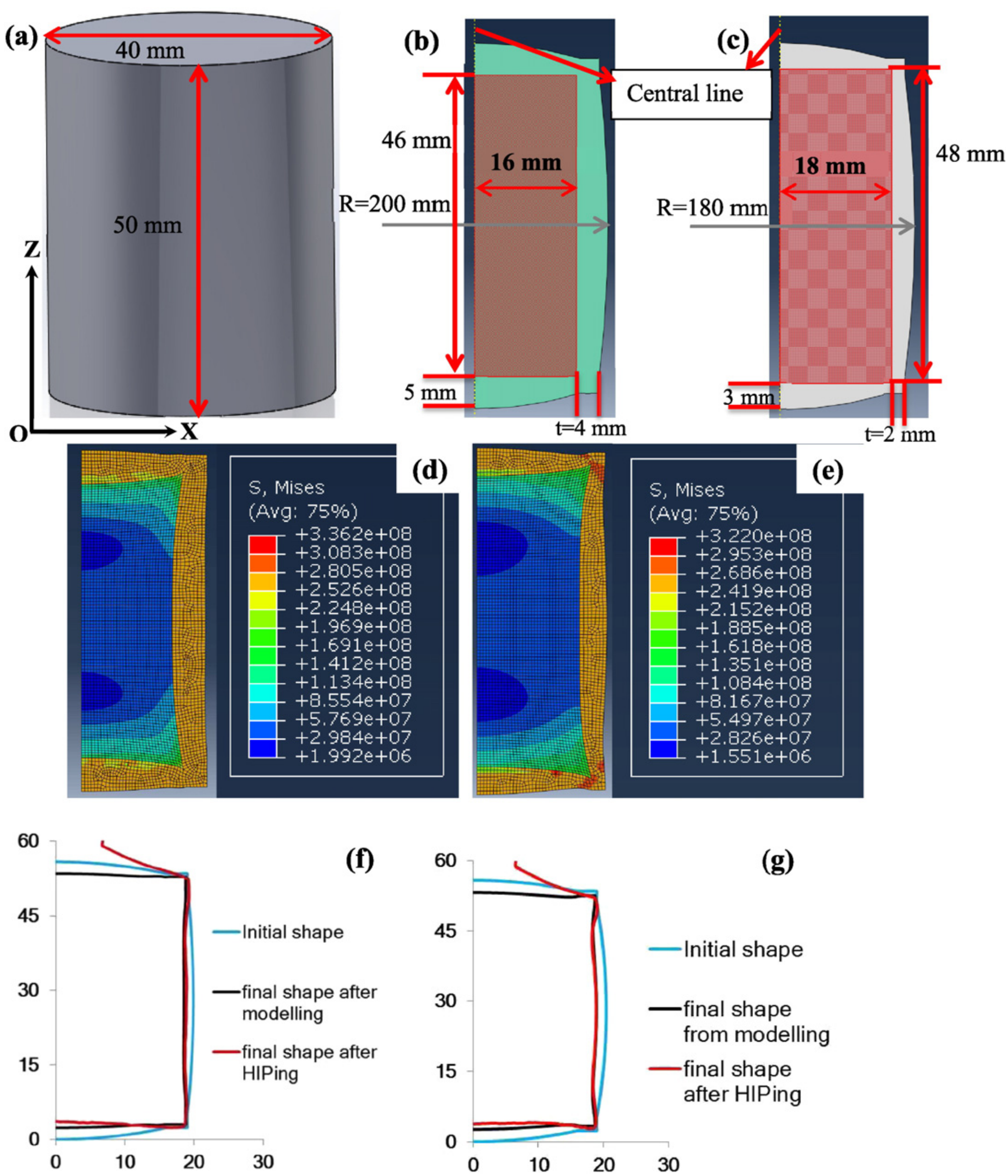

Fig. 1. (a) Specified final cylindrical sample to be fabricated via in-situ shelling route; (b) initial tooling shape with wall thickness t = 4 mm; (c) initial tooling shape with t = 2 mm; (d) predicted final shape after HIPing of the tooling shown in (b); (e) predicted final shape after HIPing of the tooling shown in (c); (f) shape change of the tooling with t = 4 mm during HIPing through modelling and experiments; (g) shape change of the tooling with t = 2 mm during HIPing through modelling and experiments.