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An integrated method for net-shape manufacturing components combining 3D additive manufacturing and compressive forming processes

Jun Jiang[a]*, Paul Hooper[a], Nan Li[a], Qinmeng Luan[a], Chris Hopper[a], Mani Ganapathy[a], Jianguo Lin[a]

[a]*Department of Mechancial Engineering, Imperial College London, Exhibition Road, SW7 2AZ, London, the UK*

Abstract

Additive manufactured (AM) or 3D printed metallic components suffer poor and inconsistent mechanical properties due to the presence of a large number of micro-voids, residual stress and microstructure inhomogeneity. To overcome these problems, a new forming process has been proposed, which effectively combines AM and compressive forming. The aim of this study is to prove the feasibility of this newly proposed method by providing preliminary results. Thus, we compared the tensile performance of hot-forged additive manufactured stainless steel 316L samples to none-hot-forged additive manufactured ones. Significant improvement in mechanical properties has been found in the tensile tests as well hardness test. In addition, our EBSD characterized grain orientation maps at each stage of the process revealed the corresponding microstructure revolution which provides insights into underlying mechanistic.

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Keywords: addtive manufacturing, compressive forming, net-shape forming, porosity

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1. Introduction

Additive manufacturing (AM) is defined as ‘a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies’ [1], which has been becoming an important commercial metallic material manufacturing technology over the last two decades [2]. AM opens up the possibility of producing parts with complex geometry from product design [3]. However, employing AM approach

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* Corresponding author. Tel.+44(0)207956778;
E-mail address: jun.jiang@imperial.ac.uk

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on forming high-end, high-value and safety-critical parts has been found to be technically challenging due to the presence of high content of process-induced micro-porosity, undesired inhomogeneous microstructure which significantly reduce the mechanical strength, ductility and fatigue life of parts [2-4].

We recently proposed to a new hybrid forming technique in that AM printing approach is combined with hot forging process. Using 3D printing approach to produce preform will reduce the cost considerably by reducing the material waste and increasing production rate, although the 3D printed microstructure contains defects and undesirable features such as coarse grains or texture, which cause reduction in mechanical performance and fatigue life. To overcome these issues, we propose to add a hot forging post-process to form the preforms into their final net shapes.

The main purposes of this study are to validate the proposed novel forming concept and to prove its feasibility through a set of systematic tests and characterization. In particular, we aim to identify the effects of hot forging and heat treatment post processes on the improvement of mechanical properties of 3D printed samples. The fundamental mechanisms of these post-processes will be revealed through characterizing the microstructure evolution through the entire manufacturing process.

2. Methodology

2.1. Sample fabrication and processing

An overview of our sample processing and testing program is shown in Figure 1. We produced two sets of 3D printed single phase stainless steel 316L samples using a Renishaw AM250 Selective Laser Melting Machine. Printing speed was varied using two laser exposure times of 88µs and 120µs to produce one set of samples at near fully density and another set with intentionally high porosity. These 3D printed samples have undergone three different post-processing routes in order to compare and study how each post-process affects the mechanical behavior~~s~~ of the formed samples. Note that the 3D printed sample geometry was designed to be over-sized compared to the standard tensile testing samples. This is because the sample geometry changes during the post processing. The post-processed samples were machined to their final shapes for standard tensile testing.

For each set of 3D printed samples, three batches were produced at various processing stages. The first batch of samples was directly 3D printed without any post processing. The second batch of 3D printed samples was heat treated at 900 °C for 30 minutes by furnace heating and followed by air cooling. The final batch of 3D printed samples underwent hot forging at 900 °C, and was subsequently subjected to the same heat treatment as the second batch. These samples were forged between the two flat disks by a hydraulic Instron test machine (2500KN) at a constant displacement rate of 10mm/s. A thickness reduction of approximately 30-40% was achieved.

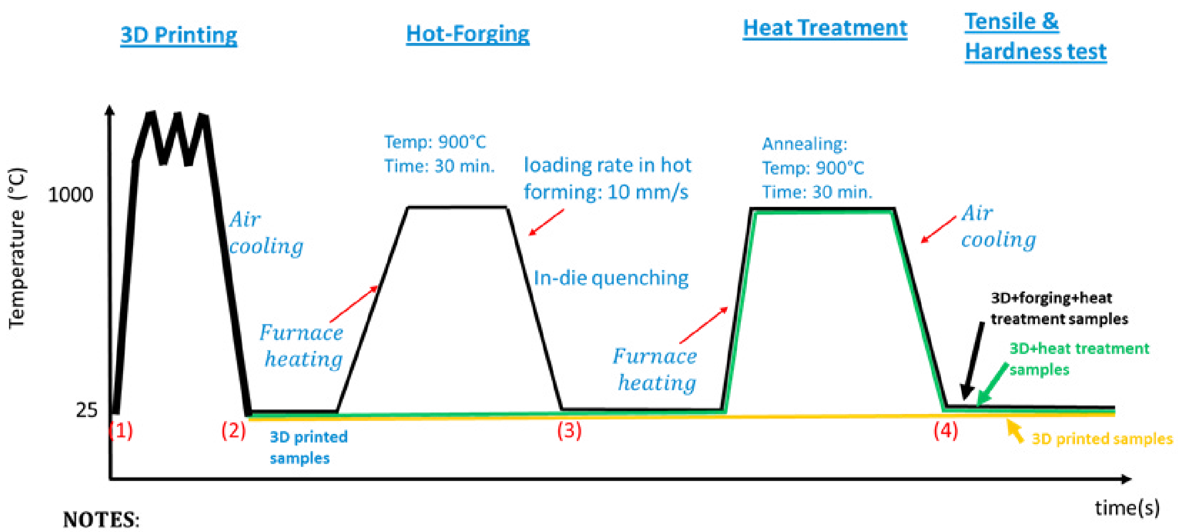
2.2. Mechanical tests

2.2.1 Tensile test

Conventional tensile tests were carried out to measure the tensile properties of machined samples. These samples were stretched at a constant displacement rate (2mm/min) using an Instron 5585H testing machine. A 250KN loadcell was used to record the applied load, and strain was measured by tracking the displacement of the machine crosshead.

2.2.1 Hardness test

To confirm our tensile measurement, we also conducted conventional hardness tests which should give us a quick and approximate examination of the strength of all prepared samples. The strength of samples typically has a linear correlation with their hardness. All hardness tests were carried out using a Zwick ZHU Vickers hardness testing machine at a HV10 load setting.



NOTES:
A – microstructure examination at stage (3) for both 3D printed and hot forged samples;
B – microstructure examination and hardness tests will be carried out at stage (4) for both 3D printed and hot forged samples (after machining).

Figure 1. Material processing diagram of three types of 3D printed samples undergoing three different post-processes. These processing routs are indicated as black, green and yellow lines in the figure.

2.3. Microstructure characterization

The machined samples were cut along the forging direction to reveal their microstructure. The sectioned samples were ground progressively using silicon carbide paper from 800 grit to 4000 grit. Twenty minutes colloidal silica polishing was used as the final stage to achieve a mirror surface finishing with minimum induced deformation.

Zeiss Axio Lab.A1 optical microscope (OM) and Hitachi 3400 SEM based Bruker e flash electron backscatter diffraction (EBSD) were used to characterize porosity and grain distributions respectively.

3. Results and discussion

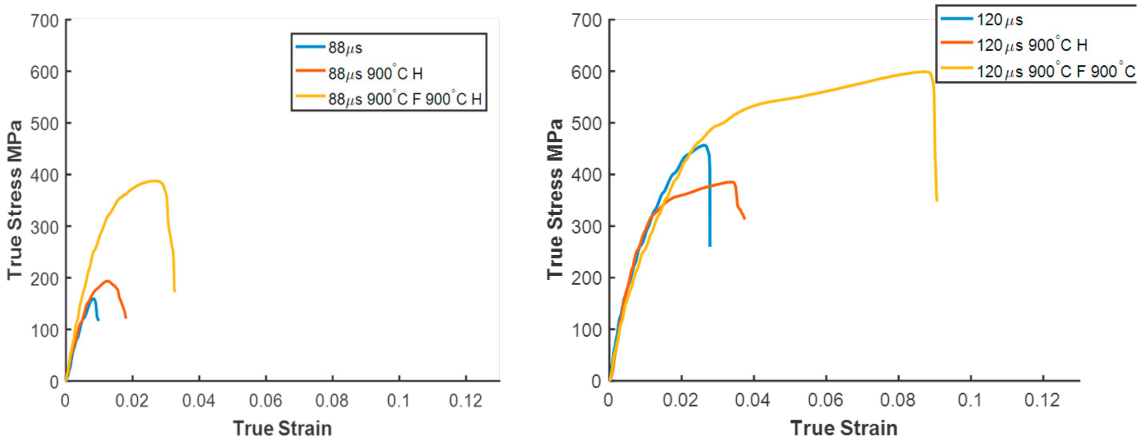
3.1. Tensile test

Conventional tensile tests have been carried out on all prepared samples. Their corresponding true stress strain curves are shown in Figure 2. The 3D printed samples display a poor tensile performance. Given that >98% powder consolidation has been achieved; notably low yield strength, ultimate strength and elongation are seen for both fast (88μs) and slowly (88μs) 3D printed samples. Comparing the fast and slowly printed samples, the fast ones only have half the strength and ductility of the slowly printed ones.

A remarked improvement in mechanical properties can be seen by combining the hot forging post process. For the fast printed samples, the tensile strength and ductility have been increased more than 200%. Even for the slowly printed samples, not only was strength increased by approximately 50%, but ductility also increased 500%.

The heat treatment process moderately increased the mechanical properties of the fast printed samples as seen in Figure 2 (a). This may be caused by accelerating the thermal diffusion process to increase the homogeneity of microstructure, particularly for powder bonding processes. On the other hand, as seen in the Figure 2(b), the tensile strength of slowly printed samples after 900 degree heat treatment dropped by ~ 30%, although the ductility increased slightly. As the slowly printed samples have reach ~100% consolidation, this softening effect might due to grain growth which reduces grain boundary volume fracture, and thus the hardness effects of pinning dislocations.

In hot forged samples, the dislocation density hardening mechanism may not be significant, as the forged samples were subsequently subjected to heat treatment. This treatment should considerably reduce the total dislocation density, prior to the tensile tests.



(a) **(b)**

Figure 2. True stress strain plots of 3D printed samples with different printing speeds: (a) 88 μm (fast) and (b) 120 μm (slow) respectively. In each plot, the three curves correspond to three different treatments including 3D printing (the blue curve), 3D printing and 900 °C heat treatment (red) and 3D printing, 900 °C hot forging and 900 °C heat treatment (yellow).

3.2. Hardness test

Conventional hardness tests were conducted on all six types of samples. The averaged hardness measurement from each sample is plotted in Figure 3. Slowly printed samples show superior hardness than fast printed ones. For the fast printed samples, materials are hardened by post heat treatment and hot forging process. Nevertheless, the forged and subsequently heat treated samples have the highest hardness value, which is ~50% higher than solely heat treated samples. On the other hand, the hardness of slowly printed samples decreases slightly by heat treatment, but improved considerably after the hot forging process. The observed hardness results agree well with our tensile testing results and confirmed our observations.

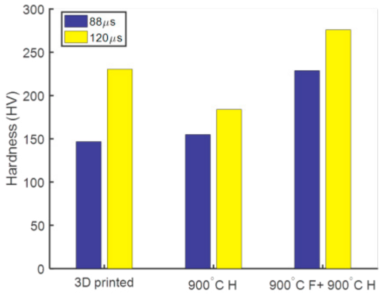
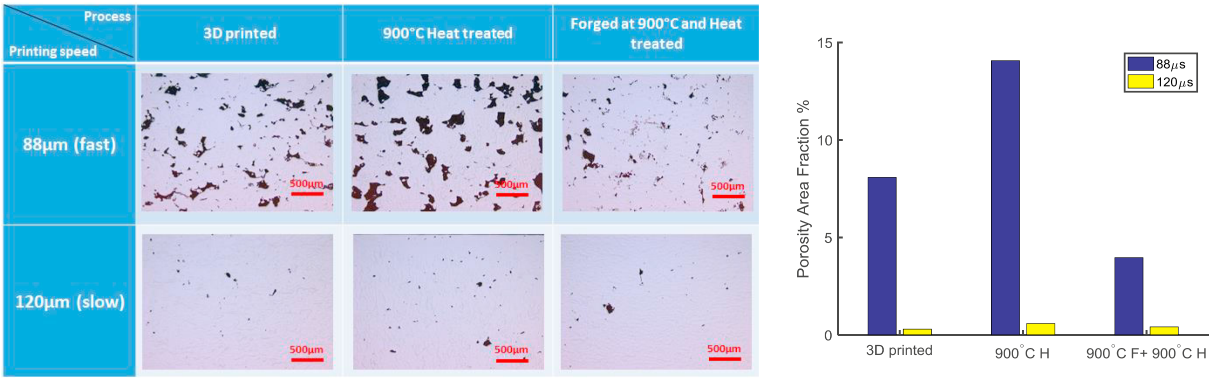


Figure 3. Mean values of conventional Vickers hardness of fast (blue) and slow (yellow) 3D printed samples for three different treatments, namely direct 3D printing, 900 degree C heat treating after printing, and 900 degree C forging (900°C H) and 900 degree C heat treatment after printing (900°C F+900°C H). For each bar, the mean hardness value was determined by taking the average of measurements taken at four different locations.

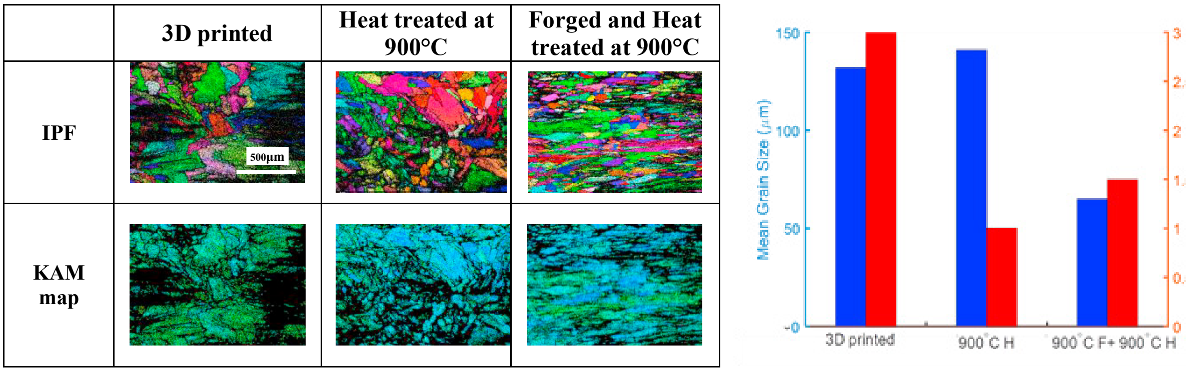
3.3. Microstructure characterization

Optical micrographs provide a clear overview of porosity distribution and development at each stage of the processing map. A summary of optical micrographs is shown in Figure 4 (a) and the corresponding porosity area fraction as a function of various processing conditions is illustrated in Figure 4 (b). Fast printing speed results in considerably higher area fraction of porosity than the slowly printed ones. This explains the inferior tensile performance as well as the hardness of the fast printed samples as seen in the Figure 2 and 3. For the fast printed samples, heat treatment seems to change the morphology of the voids to be more concentrated, rather than scattered. The hot forging process, however, effectively reduces the size and population of voids, and lead to a significant improvement in tensile properties. On the other hand, the slowly printed samples have a relatively small amount of initial void formation, and so the hot forging and heat treatment processes only reduce the void content slightly.



(a) (b)

Figure 4. (a) 10x optical micrographs of 3D printed samples using fast and slow printing speed and subjected to the three processes. Black regions indicate voids. The forging axis is along the vertical axis. (b) Bar plot of the estimation of porosity volume fraction of these six sets of samples. Blue bars represent fast printing samples while yellow bars represent slow printing ones.



(a) (b)

Figure 5. Crystal orientation characterization of fast printed samples: (a) the first row shows inverse pole figure (IPF) plots with respect to the vertical (forging) axis at various processed 3D printed samples whereas the second row reveals their kernel averaged miss-orientation(KAM) maps. Notes the same magnification and step size are used for all maps. The black dots corresponds to non-indexed points which might due to sample surface finishing quality (b) bar plots of map averaged grain size and KAM within the six maps shown in (a) after the three different processes.

A more detailed crystal orientation characterization was carried out on the fast printed samples. The grain size distribution and development are shown as inverse pole figures (IPF) in Figure 5 (a). In addition, kernel average miss-orientation (KAM) maps, which indicate stored geometrically necessary dislocation density within probed points, at various stage of the process, are also shown in Figure 5(a). A more quantitative map averaged bar plot is shown in Figure 5(b). It is very interesting to see that the hot forging process stimulated recrystallisation occurrence which refined grain size to ~a third of their initial sizes. Although some fine grains can be found in heat treated samples as well, these grains do not considerably change its map averaged grain size as seen in Figure 5(b). In addition, the 3D printed samples seem to have high content of dislocation density which may be generated due to the severe thermal stress caused by rapid and turbulent solidification processes. These dislocations are reduced during heat treatment process. However, hot forging induces additional dislocations, of which a small fraction still remain after subsequent heat treatment. This provides dislocation hardening and also indicates incomplete recrystallization. A higher temperature and longer incubation time are expected to form finer grain size and even better mechanical properties.

These EBSD provided insights reveal how the hot forging process alters the sample's initial microstructure, and explain the enhancement of mechanical properties for both slowly and fast printed samples.

4. Conclusions

To improve the mechanical properties and economic competiveness of 3D printed parts, a new forming process method combining 3D printing with hot forging and subsequent heat treatment is proposed. In this study we have tested and successfully proved the feasibility of this novel concept by using tensile and hardness tests together with optical and EBSD microstructure characterization on six types of 3D printed samples. The following conclusions can be drawn:

1. Fast printing speed results high porosity content and a considerably poorer mechanical performance when compared to slowly printed samples. High level of GND density is stored within the printed samples which might be caused by severer thermal stress gradient.
2. Subsequent hot forging process show significant improvements in the mechanical properties of the 3D printed samples. For example, the tensile strength of slow and fast printed samples has been improved by more than 200% and 50% respectively, and ductility by 300% for both cases.
3. The marked improvement observed is caused by two microstructure alterations, namely reduction of void content, and grain refinement as revealed by optical micrographs and EBSD grain orientation maps.
4. Heat treatment offers less improvement on mechanical properties when compared to the hot forging process. Our results indicate that heat treatment does facilitate bonding of pores and voids, but may also cause grain growth. These two competing hardening and softening mechanisms have to be carefully controlled to optimize material performance.

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