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The Effect of Hot Forging on the Mechanical Properties ofAdditive Manufactured 7075 Aluminium Alloy Preform through Crack Closure

Fu Lun Tan[1], Kai Soon Fong[1,#], Zhiguang Zhu[1], Fern Lan Ng[1] and Min Hao Goh[1]
1 Singapore Institute of Manufacturing Technology, 73 Nanyang Drive,Singapore637662
Corresponding Author / Email: ksfong@SIMTech.a-star.edu.sg, TEL: +65-6826-6111, FAX: +65-6777-1711

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Additive manufacturing (AM) has become a research hotspot since the first introduction of the layer-by-layer 3D printing technique, mainly due to the benefits of near net shape production, zero die cost, low buy-to-fly ratio, and flexibility for complex components creation. However, in the metal AM production, especially for 7000 series aluminium alloy, the mechanical properties are adversely affected by the presence of defects like porosities, cracks, oxidation, and evaporation of volatile alloying elements. In this study, we proposed a potential solution to enhance the mechanical properties of aluminium alloy, which is by sequential hybrid AM, combining the selective laser melting (SLM) and forging processes. One benefitof choosing the hybrid route is the reduction of forging steps as would have been required in the traditional forging process, in which a near net shape preform can be formed by SLM, while the poor mechanical properties of SLMsamples can be simultaneously improved by forgingto achieve near forged properties. To minimize elemental evaporation, the highest laser scanning speed and the lowest laser power were selectedfor the SLM process, but at the expense of developing severe hot cracking in the material. To close the cracks, the SLM fabricatedpreformis subjected toforging at the temperatures of 200 ºC and 400 ºCwith solution heat treatment performed either before or after forging, followed by a final artificial aging heat treatment. Under the observation of Scanning Electron Microscopy (SEM), it was found that forging before heat treatment will lead tobetter crack closure and overall defect reduction. From the results of the tensile tests, forging significantly improved the mechanical properties of the alloy, resulting in better yield strength, ultimate tensile strength, and elongation of 279 MPa, 349 MPa, and 5.2 % respectively than the as-builtpreform. Hence,hybrid AM with subsequent forging can be considered a promising solution to enhance the mechanical properties of AM products by greatly reducing the density of cracks.

1. Introduction

Selective laser melting (SLM)is one of the most promising additive manufacturing(AM) techniques to fabricate a near net shape, complex and high-performance metal component with great efficiency [1].Meanwhile, aluminium alloysexcel as lightweight structuralmetalsamong other metal alloysbecause oftheir high strength-to-weight ratio, corrosion resistance,formability, and machinability, indicating their potentiality in SLM production[2,3]. However, the aluminium alloys produced by SLM have exhibited inferior mechanical properties, due to the presence of different malicious defects such as porosities, cracks, balling, satellite, oxidation etc., especially for the aluminium 7000 series[4,5].These defects are caused by solidification-induced residual stresses, high oxidation, high laser reflectivity and high powder agglomeration and large composition fluctuation [3]. These undesired defects have jeopardized the overall performance of the SLM-ed aluminium alloys, therefore limiting their applicability in many aspects[4,5]. Hence, various hybrid AMroutesare innovatively introduced to enhance the poor mechanicalproperties of metal alloys derived from the AM production process bypore and crack closure, work hardening, crack density reduction etc. [6-8].

It is difficult for AM parts to achieveforged properties and this can be potentially overcome by introducing a forging step in a hybrid AM route that could create a near net shape component with improved local property[9].To our best knowledge, hybrid AMand forging studiesare limited and have been mainly investigated onsteel-base[10-12] and titanium-base alloys[9,13].Therefore, this study aims to investigate the effect of hybrid AM and forging processeson the crack/defect reduction andthe mechanical properties of AA7075.The influence of SLM processing parameters on the crack morphology is investigated and the optimum processing parameters to achieve minimum elemental evaporation are determined.The effect of the forging temperatures and solution heat treatment sequences on the crack closure and mechanical properties is investigated.Lastly, the microstructure in the vicinity of the crack is investigated after hot forging and the different heat treatment sequences.

2. Experiment

2.1SLM Process

AA7075 preforms of cubic shape (18×18×18mm) were fabricated by SLM process using the 3D Systems ProX 300 machine at the scanning speed range of 50 to 400 mm/s and the power of 170 W and 300 W. The layer thickness and hatch distance were maintained at 30 µm and 100 µm, respectively.

2.2Forging and Heat Treatment Sequence

The as-built AA7075 preforms with maximum elemental composition retention were processed under four different conditions, in which two of the preforms underwent solution heat treatment at 470°C for 1 hour before forging at 200°C and 400°C (ST-F200 & ST-F400), while the other two underwent forging first before solution heat treatment (F200-ST & F400-ST). All samples underwent aging heat treatment at 120°C for 24 hours in the last processing step.

During the hot forging step done by AIDA 1100 model of servo press machine, the forging die was heated to the as-mentioned forging temperature. Simultaneously, the as-built sample was heated to the required temperature by an induction heating coil. Forging was done at astrain rate range of 1 s^{-1} and to a total strain in the range of 0.7~1.0. The forging axis was perpendicular to the SLM build direction.

2.3 Material Characterization

The samples were sectioned in the middle for hardnessand microstructure characterization.The sectioned surfaces were polished using diamond suspension gradually from 9 µm down to 1 µm andpolished by OP-S suspensionin the final step.

Thecrack morphologies in the sampleswere examined byoptical microscopy and scanning electron microscope (SEM). The microstructure characterizationwas conducted usingHelios Nanolab 600 Electron BackscatterDiffraction (EBSD) machine using a scan step size ranging from0.07 µm to 0.15 µm.The observation plane was parallel to the SLM build direction.

The effect of hot forging on the mechanical properties of the SLM fabricated AA7075 preforms was investigated by tensile tests and hardness measurements. The tensile tests wereconducted using the Instron 5982 machineequipped with a video extensometer at an initial strain rate of 1 x 10^{-3} s^{-1}.Miniature tensile bars were wire-cut from the samples and the gauge section length, width and thickness were 7 mm, 2 mm, and 1 mm respectively.The hardness measurement was performed using themicro Vickers hardness test machine.

3. Results and Discussion

3.1As-built Crack Morphologies and Compositions

During the SLM printing process, thelaser scanning speed and laser power were varied to determinethe optimum parameters which can minimizethe evaporation of key elements like Zn and Mg which areimportant for the formation of hardening precipitates during aging ofaluminium 7000 series alloy. In Fig. 1, the result shows that the elemental retention is improved at lower laser power and with increasinglaser scanning speed. This is because of the lower energy densitywhich is proportional to laser power and inversely proportional to laser scanning speed[14].

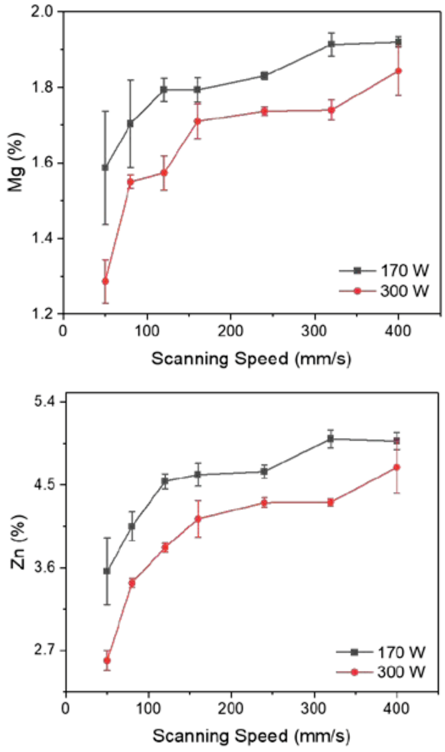


Fig. 1 Mg and Zn content at different scanning speeds and powers

Therefore, the highest scanning speed of 400 mm/s and the lowest power of 170 W are selected as the process parameters for the highest elemental retention but at the expense of more severe hot cracking as shown in Fig. 2. Hence, a subsequent hot forging step is introduced as part of the hybrid AM route to close the cracks and toimprove the mechanical properties of the SLM fabricated AA7075 alloy.

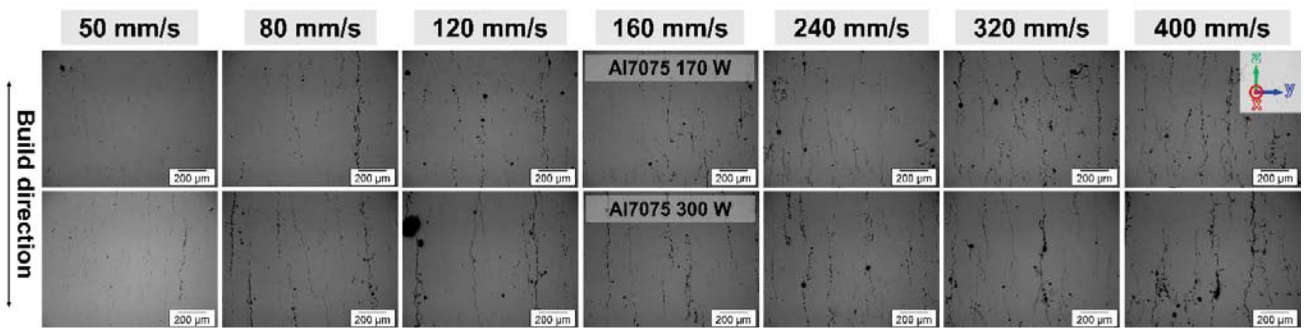


Fig. 2 Crack morphologies of SLM fabricatedpreforms at different laser scanning speeds and laser powers

3.2Sequence of Heat Treatment on Crack Reduction

The effect of the heat treatment sequence on the effectiveness of the crack reduction is investigated, while the SEM images of the cracks that remained in the samples forged at 400°C are shown in Fig. 3. These are remnant cracks from SLM as-built conditions which were partially closed up by forging butnot yet undergone complete solid-state bonding and are termed as "crack closure line" here.

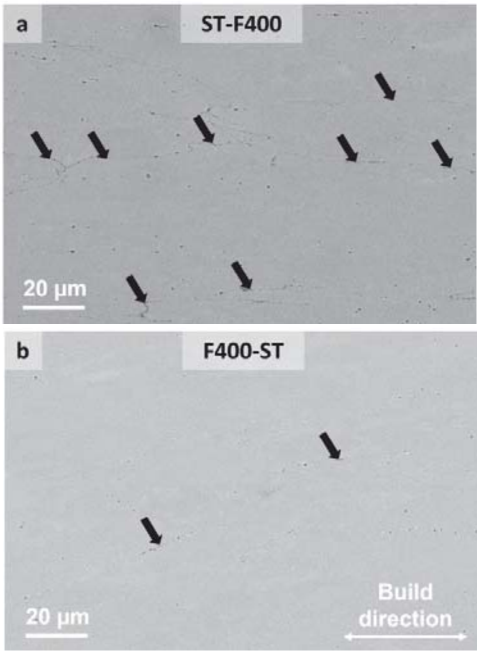


Fig. 3 SEM images of crack closure lines (remnant cracks)for samples (a) ST-F400, (b) F400-ST

As shown in Fig.3, the 'heat treatment – forging' sample has a higher density of crack closure lines (indicated by black arrows) and appeared to be more continuous as compared to the 'forging – heat treatment' sample. The solution heat treatment will contribute to the increase of defect density as the porosities tend to coalesce and form cracks during heat treatment [5]. Moreover, the crack propagation is accelerated when the trapped gas has expanded during solution heat treatment.Therefore, performing the solution heat treatment process first will cause the crack density to increase prominently, hence leading to difficult crack closure by the forging process.

3.3Mechanical Properties

3.3.1Hardness

The Vicker hardness values of each sample are depicted in Fig. 4. Usually,a lower hot forging temperature leads to higher strength due to grain refinement by dynamic crystallization, work hardening and low dynamic recovery. Thesubsequent solution heat treatment after forging promotes static recovery and grain growthwhich softens the alloy.

According to Fig. 4, the F400-ST sample shows marginally higher mean hardness. This contradicts that higher hardness should be observed in the samples forged at lower temperatures and when forging was performed after solution heat treatment.This suggests that hardness measurement alone is not enough to differentiate the

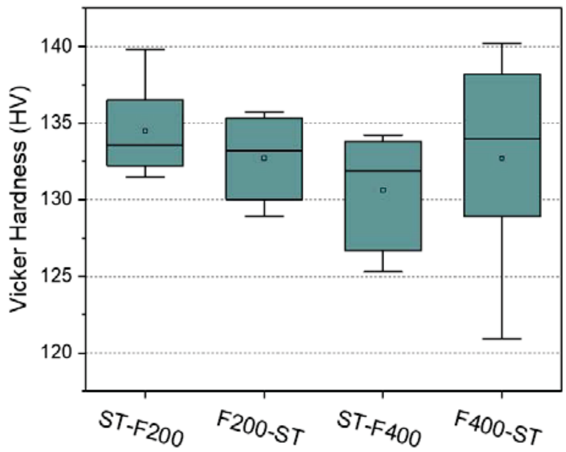
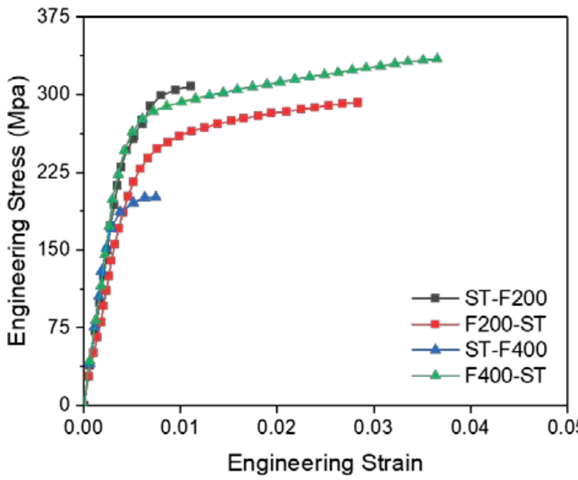


Fig. 4 Vicker hardness values of different samples

strength improvement by the different processing sequences because cracks and defects were not fully eliminated in all these samples, which introduced noises and uncertainty in the hardness measurements. It is further noted that the error limits of the other

Fig. 5Tensile properties of different samples



results are within the range of F400-ST and the differences in hardness value are minimal.

3.3.2Tensile Properties

In Fig. 5, the 'forging – heat treatment' samples have exhibited better ductility mainly due to the better defect reduction and crack closure. Theoretically, the 'heat treatment – forging' samples will exhibit better tensile strength due to better preservation of grain size and minimization of recovery after forging.However, this was not the case because the defects and cracks were more difficult to eliminate in this processing sequence as shown in Fig. 3.

The ultimate tensile strength (UTS) and elongation of the as-built SLM preform are 45 MPa and 0.2 %, respectively [15]. Undoubtedly, forging has significantly improved the mechanical properties of the preforms.Also, the tensile properties of the F400-ST sample excel among all samples with the highest UTS of 349 MPa and elongation of 5.2 %.This result is in good agreement with the SEM observation of the crack closureas shown in Fig. 3, as the F400-ST sample has lesser crack closure lines compared to the ST-F400 sample. Samples that were solution-treated first have poorer ductility due to the higher density of defects and crack closure lines.

3.4Microstructures

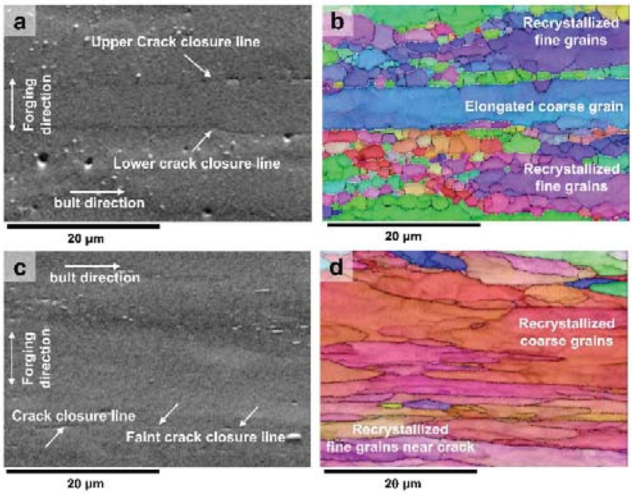


Fig. 6 Electron images and EBSD inverse pole figure maps of samples (a,b) ST-F400, (c,d) F400-ST

Fig. 6 shows the microstructuresin the vicinity of the crack closure lines. From the comparison of electron images in Fig. 6a and c, the ST-F400 sample shows more crack closure lines where the crack voids were much more visible as compared to the F400-ST sample. In Fig. 6b, dynamically recrystallized fine grains are observed in the regions above and below the upper and lower crack closure linesdue to the accumulation of dislocations which are unable to cross through the cracks. The grain in between the two crack closure lines remains coarse because stresses are more difficult to propagate into the region due to the proximity of the two initial large cracks in the preform.

In Fig. 6d, no fine grains were observed in the vicinity of the crack closure lines because the solution heat treatment was performedafter forging which promotes static recovery and grain growth. Despite the coarser grains observed in the F400-ST sample, the mechanical properties remain superior as compared to the ST-F400 sample. This suggests that the degree of crack closure due to the forging and heat treatment sequence has a more dominating effect on the mechanical properties than the preservation of fine-grained microstructure.

4. Conclusion

Hotforging is a potential method to significantly reduce the crack density of SLM-ed aluminium alloys. The 'forging – heat treatment' sequence is preferable due to better crack closure. A higher forging temperature will result in better mechanical propertiesdue to the better formability and uniform straining which leads to higher crack density reduction.The subsequent solution heat treatment promotes further solid-state bonding at the crack sites but results in static recovery and grain growth leading to grain coarsening.

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