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Additive manufacturing process development for realization of Preburner Pump Impeller of LOX hydrocarbon based rocket engine using AlSi10Mg material

Rajeev Verma and A Alex***
** & ** Materials and Manufacturing Entity,*
Liquid Propulsion Systems Centre,Valiamala, Trivandrum, India,
Email: raazeev15196@gmail.com & Email: a_alex@lpsc.gov.in*

Abstract—Fuel pump of LOX hydrocarbon based rocket engine employs preburner impeller realized through investment casting process and made by aluminum alloy AJI4-BM-T6-3(Casting). The pump impeller is shrouded, centrifugal flow impeller with backward curved blades. It operates with inlet pressure provided by the inducer and delivers the fuel at the required flow rate and pressure to thrust chamber. The rejection rate of the realised hardware is high, due to the inherent casting defect. Hence an alternate route for realization of pre burner pump impeller is planned. The present study has been carried out to realise Fuel Pump Impeller of LOX hydrocarbon based rocket engine through Additive manufacturing process using AlSi10Mg material in place of conventional casting route.

Keywords:* AlSi10Mg, *LOX, Additive manufacturing, Powder bed fusion

I. Introduction

Additive manufacturing (AM), which is also known as 3D printing, refers to an evolutionary manufacturing technology that substitutes conventionally manufactured products, including castings, forgings, assemblies with parts consolidation, etc. Additive manufacturing enables the realisation of complex parts with reduced lead time, with minimum material, and empowers the designer to combine multiple process steps into a single design. On investigation it was found that preburner impeller which is at present realized through investment casting process are most amenable to be realize through additive manufacturing route. The pre burner pump impeller of size, ø 160 x 100 mm Length could easily fit into a 3D printer available .The AlSi10Mg powder; the basic feedstock is freely available and is being widely used for additive manufacturing. The vanes could easily be printed without supports by suitably orienting the parts. The entire part could be realized in one piece eliminating any further joining process. Available results on Additive Manufacturing gave the confidence that parts would be free of defects. Considering the advantages it was decided to realize the part by Additive Manufacturing. For development of fuel pump impeller through additive manufacturing, certain specimen are also to be developed along with the actual hardware for demonstration of mechanical properties and chemical compositions. This technical paper furnishes the details of the additive manufacturing process carried out for realisation of fuel pump impeller, its qualification requirement and discusses the properties of the hardware etc.

II. REALISATION OF PRE BURNER PUMP IMPELLER

A. Selection of Material

The pre burner pump impellers of the turbo pumps used in the LOX hydrocarbon based rocket engine were made from Cast AJI4-BM-T6-3. Due to non-availability of Cast AJI4-BM-T6-3 power material, AlSi10Mg powder materials is preferred which is equivalent to Casting AJI4-BM-T6-3 material. AlSi10Mg material is having high strength and good corrosion resistance, and is suitable for the applications involving thermal exposure up to 315^{o} C. The comparison of their material property as per standard is shown in the table 1

Table 1 AJI4-BM-T6-3 (Casting) Vs AlSi10Mg

Specification	АЛ4-BM-T6-	AlSi10Mg[1]
UTS, MPa	225	345
YS, MPa	-	207
% Elongation	7	5

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B. Manufacturing Plan

The conventional manufacturing of pre burner fuel pump impeller of the turbo pumps used in the LOX hydrocarbon based rocket engine relies on investment casting followed by subsequent machining to final shapes and dimensions. These subtractive manufacturing processes always inevitably result in a large amount of material waste, more machine hours, and long lead times. The Direct Metal Laser Sintering (DMLS) a type of powder bed fusion process was chosen, considering the size of the parts. The pre burner pump impeller of size, ø 160 x 100 mm Length exactly suits the bed size of EOS M290 printer. AlSi10Mg powders as well as the parameters for printing AlSi10Mg were readily available. The first and foremost step in AM is to convert the 2D model into 3D model. This model is converted into Standard Tessellation Language (STL) format and followed by slicing of the STL file into thin sections or layers for building. The preburner Pump impeller is realised through M/s. WIPRO 3D by powder bed fusion process. The realised hardware with supports is shown in figure1.

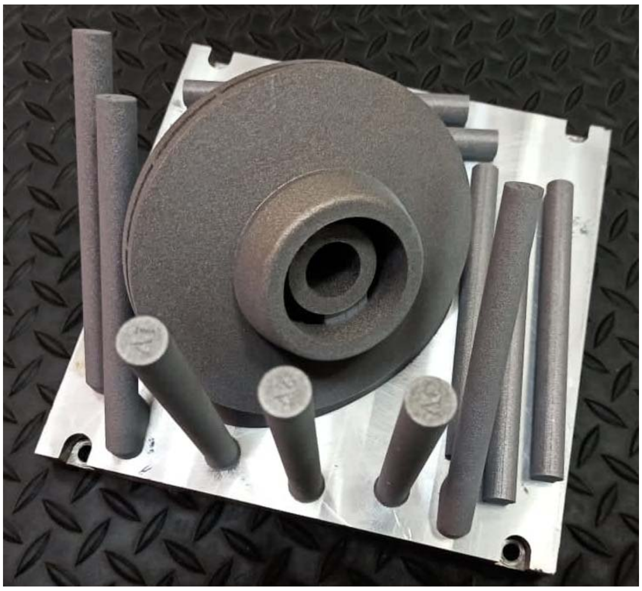

Figure 1 PBP Impeller along with specimens(X,Y,Z & 45^o- direction)

By suitable orientation the vanes was easily printed without supports. The process parameter used for realisation is listed in table 2.

Table 2: AM process parameters

Parameter	Process description
Material	AlSi10Mg grade
Powder size	20 – 45 microns
Layer Thickness	40 microns
Hatch width	0.4 mm
Machine	EOS M290

X-Ray Radiography is carried out to find out the internal flaws on the impeller and specimens. No significant internal defects are observed on radiography testing. The specimen required for the mechanical property evaluation are realised with same process parameter and feedstock from same lot.

III. Acceptance and qualification

To ensure the quality of the product, the feedstock powder used is virgin and characterization of feedstock is carried out before realisation. Fuel Pump impeller along with test coupons (X, Y, Z & 45^o) to XY plane direction (Z is build direction) are realised in a qualified machine with optimum process parameter using AlSi10Mg powder. After printing, preburner pump impeller along with the test coupons were stress relieved at 300° C for 2 hour and solution annealed at 530 °C for 6 hours followed by air cooling. Further, aeging is carried out at 160 °C for 6 hours followed by air gas cooling.

DOI: 10.13009/EUCASS2022-6188

A. Powder characterization

Variations in powder properties can have adverse effects on product yield. Accurate powder characterization enables consistent production of high-quality components with predictable properties. The Preburner Pump impeller along with test coupons (X, Y, Z & 45^o) to XY plane direction (Z is build direction) were realized using virgin AlSi10Mg powder sourced from EOS . A summary of powder characterization is given in Table 3 below.

Table 3: Summary of powder characterization

Test	Test method	Result
Chemical composition	ASTM F3318 - 18	As per specification
Oxygen, Nitrogen & Hydrogen	ASTM E1019[2]	Oxygen – 0.0984
		Nitrogen – 0.0029
		Hydrogen – 0.0023
Particle size distribution	ASTM B214[3]	<45 µm – 68.62 %
		>45 µm – 24.59 %
		>53 µm – 6.05 %
		>63 µm – 0.54 %
Flow rate	ASTM B213[4]	10sec/87.67g
Apparent density	ASTM B212[5]	1.28 g/cm3
Tap density	ASTM B527[6]	1.54 g/cm3

B. Specimen level qualification

To validate the soundness of specimen level, Non-Destructive Testing (DP & RT) of test coupons was carried out, followed by the mechanical testing in X, Y, Z & 45^o to XY plane direction (ambient temperature tensile testing and impact testing). Totally 12 number of round specimen of size ø14 x 160 mm are realized for properties evaluation. Each rod is cut in 2 segments, one for tensile properties evaluation and other for impact testing .The chemical composition analysis on specimens was carried out and it meets the specification. Microstructures of all the samples showed Si particles distributed around Al matrix, typical of AlSi10Mg in all directions.

C. Product level qualification

At product level validation, the parts are subjected to Non-Destructive Testing (DP & RT).Dye penetrate test is carried out in NDT LAB and common observations are found. Distributed surface porosities are observed on face of the impeller before machining and after final machining no relevant indications are observed. DP test is done at top & bottom hubs of the impeller and shown in figure:4
.

Figure 2: DP test of PREBURNER PUMP Impeller

X-Ray Radiography is carried out to find out the internal flaws on the impeller and it is challenging to carry out 100 % RT for Impeller which is having complex features. In view of that five sets of exposure views are plans with 29 exposures which

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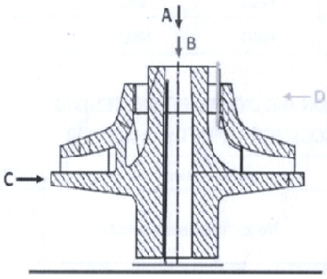
cover 90% of the impeller (RT shooting plan is shown in figure 5).No significant internal defects are observed on radiography testing (shown in Figure 6).



SN	Shooting View	No. of Shots	Targeted Area
1	A	1 (D4) + 1 (D7)	Double Wall
2	B	1	Central Cylinder
3	C*	4	Bottom Hub + Centre Cylinder + Top Cover
4	D	7	Top Outer Cover

* *Film kept outside*

Figure 3 Radiography Shooting Plan – SC PREBURNER PUMP Impeller

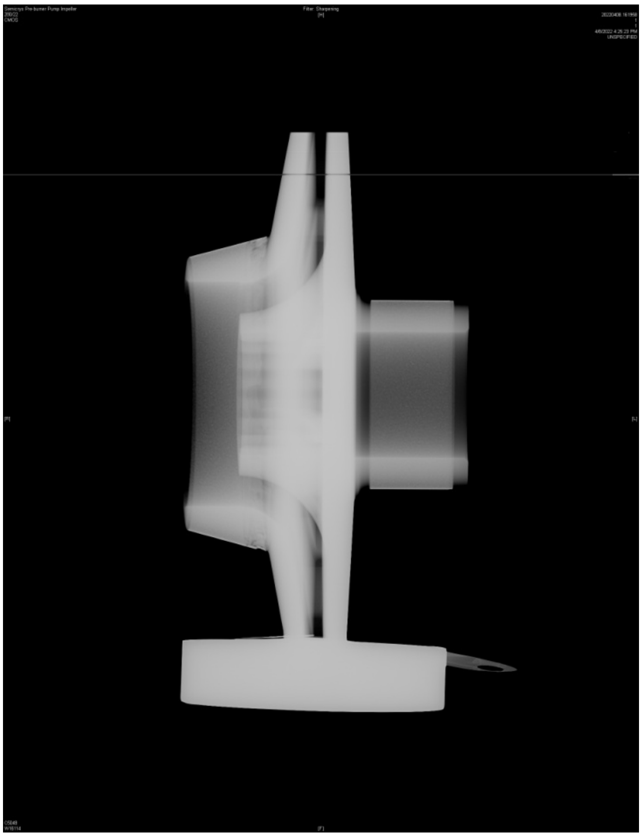


Figure 4 Digital Radiography Observations – SC PREBURNER PUMP Impeller

In order to see the internal surfaces like surfaces of vane, videoscopy is carried out and found that some of the surfaces are rough. It is also observed that material is deposited at the flow path inside the area of the vanes. Subsequently it is remove during machining using fitting operation at accessible surface. Videoscopy inspections are also carried out in all accessible flow path area after machining and no projection/ are observed. Dimensional inspection is carried out and meeting the requirement. At present product level PREBURNER PUMP Impeller Spin test completed successfully @26210 rpm for 140 sec and it is cleared for conducting cold flow test at the turbopump assembly level. Impeller assembly during Spin test is shown in figure:5

DOI: 10.13009/EUCASS2022-6188

Figure 5 Spin testing of PREBURNER PUMP Impeller

IV. RESULTS AND DISCUSSION

A. Chemical composition

The chemical compositions of the additive manufactured printed part sample are presented in Table 4. Variations in powder properties can have adverse effects on product yield. Accurate powder characterization enables consistent production of high-quality components with predictable properties. The pre burner pump impeller were realized using AlSi10Mg materials powder sourced from EOS . The AlSi10Mg powder used for printing the part and same chemical composition of the materials is evaluated by using OES & it meets the specification

Table 4: Chemical composition analysis of the AlSi10Mg coupon printed by additive manufacturing

Sl No.	Elements	Weight (%)
1	Al	Bal
2	Si	10.3
3	Fe	0.113
4	Cu	0.0711
5	Mn	0.0022
6	Mg	0.231
7	Ni	0.110
8	Zn	0.0046
9	Pb	0.0014
10	Sn	0.0005
11	Ti	0.0150
14	V	-
15	Other each	0.016
16	Other total	0.04

B. Mechanical Properties

The mechanical properties of 3D printed components are dependent on the surface roughness and porosity which are significantly affected by the process parameters of the DMLS process. Test specimens printed along with the parts are oriented in such a way to ensure that tensile properties in any arbitrary orientation in the part are captured and reported. The mechanical properties of specimens in different orientations are shown in Table 5. Mechanical properties have been evaluated on samples representative of each orientation.

DOI: 10.13009/EUCASS2022-6188

Table 5: Mechanical property Evaluation of Specimen –Tensile Test[7]

Sl.No	Specimen Id	YS (MPa)	UTS (MPa)	% El (4D)	% RA
1	MME1421/21-X	237	302	14.1	15
2	MME1422/21-X	229	293	16.7	14
3	MME1423/21-X	250	312	17.6	13
4	MME1424/21-Y	209	273	14.8	14
5	MME1425/21-Y	238	305	12.9	15
6	MME1426/21-Y	239	306	16.6	13
7	MME1427/21-Z	232	294	15.8	13
8	MME1428/21-Z	245	307	17.1	13
9	MME1429/21-Z	275	313	14.5	13
10	MME1430/21-I	203	265	14.8	14
11	MME1431/21-I	224	287	17.5	13
12	MME1432/21-I	245	308	17.1	13

The tensile properties (0.2% proof stress, UTS, % EL, and %RA) of 3D printed AlSi10Mg material are found to be fairly consistent in all direction. Test results shows that mechanical strength of the AM AlSi10Mg obtained are comparable to the aluminium alloy AJI4-BM-T6-3.The strength of Additive manufacturing product is low however it is sufficiently above the margin requirement of the main fuel impeller. The engineering stress–strain curves obtained from testing specimens in different directions/orientations show the material behavior during tensile loading. The range of values obtained by testing specimens each from four different orientations shows very good consistency. It is also observed that the comparable strength has not affected the % elongation and % RA of these specimens. This also indicates that material is having good ductility. The representative engineering stress–engineering strain curves are shown in Fig.6

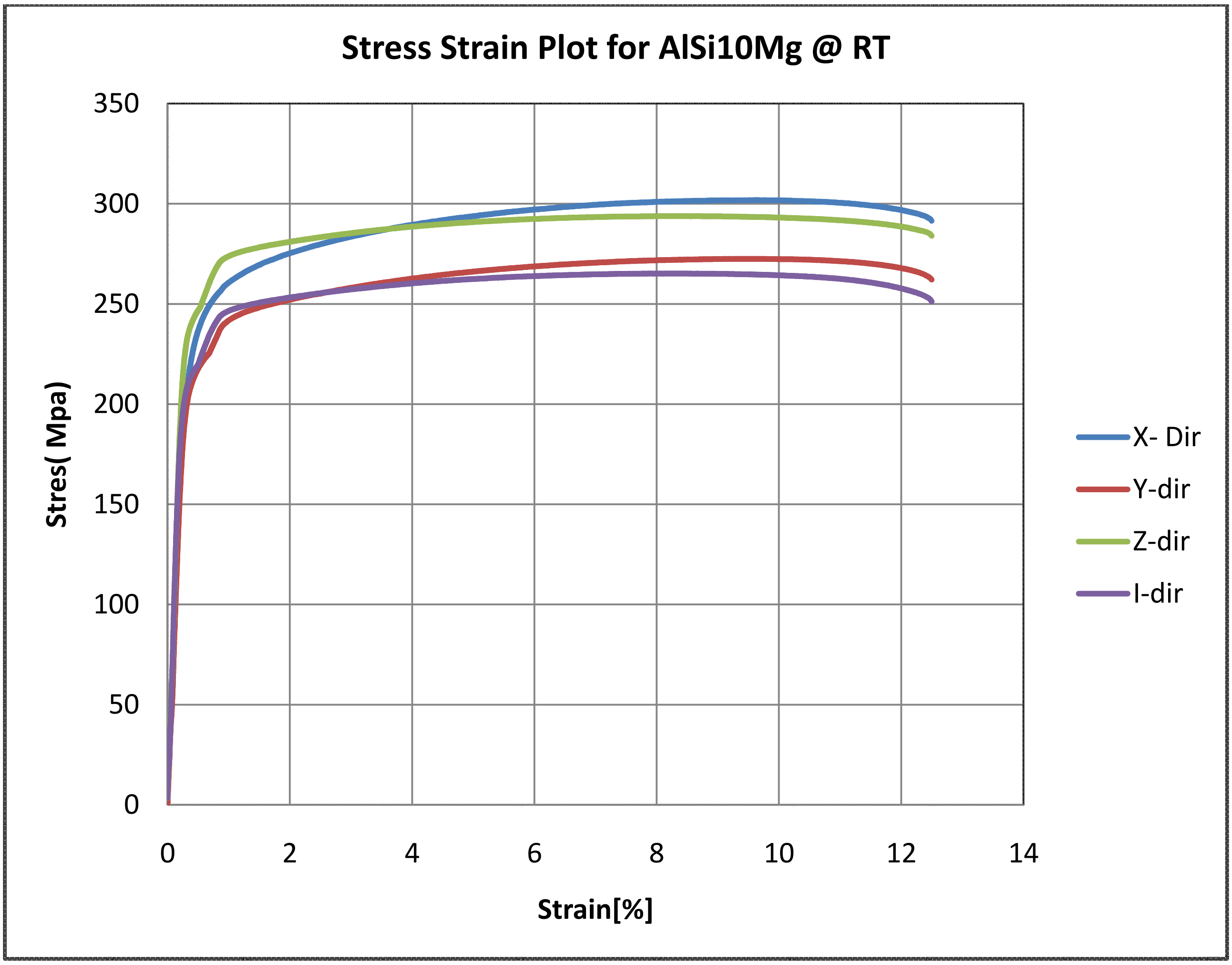


Figure 6. Stress- Strain Diagram for AlSi10Mg 3D printed specimen in X, Y, Z & 45°

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Hardness measurement on 3D printed AlSi10Mg material were stress relieved at 300° C for 2 hour and solution annealed at 530 °C for 6 hours followed by air cooling. Further, aging is carried out at 160 °C for 6 hours followed by air gas cooling. The hardness of specimens in each direction plane is checked and it is found that the hardness values were fairly consistent ranging from 108 to 125 BHN in all direction.

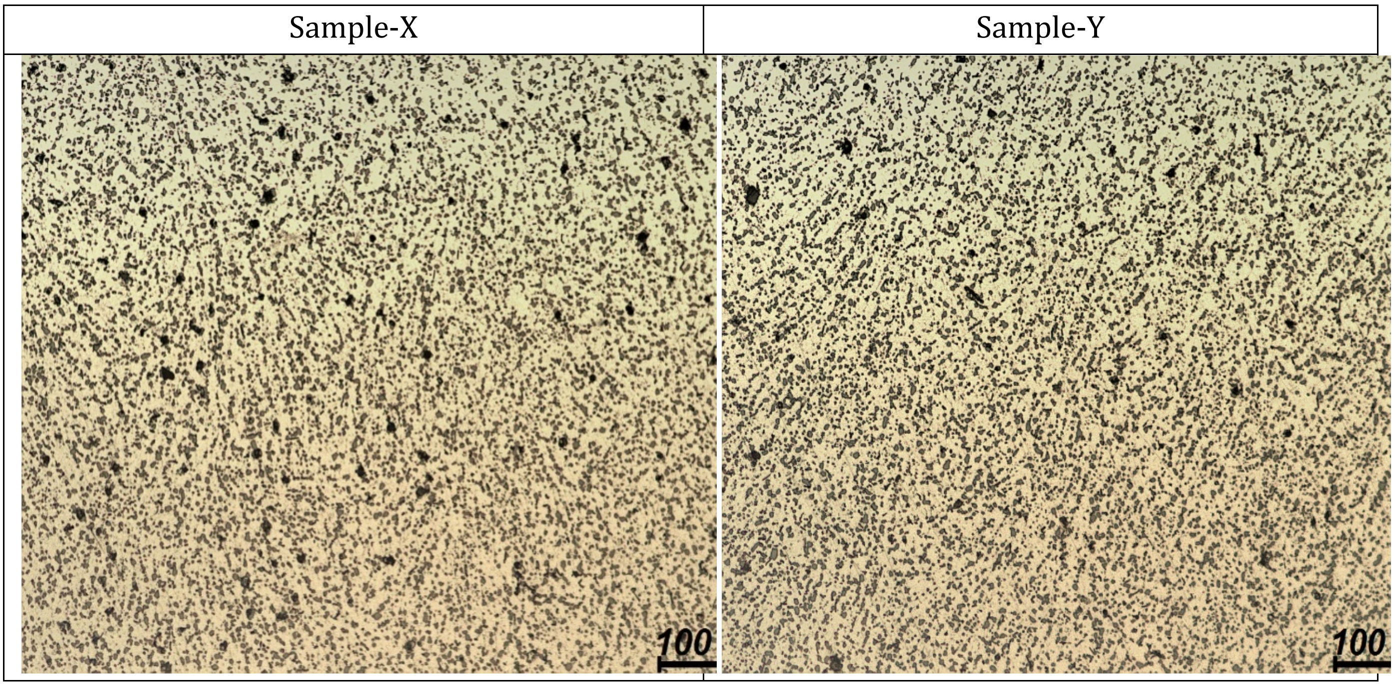
The room temperature Impact tests are carried out at Aerospace Materials lab of MME, LPSC. Achieved mechanical properties with 2mm V notch at room temperature are given in the Table7. It may be noted that impact value were fairly consistent in all direction. Dispersion of energy is minimum and properties of the material are maintained in all directions

Table 7. Mechanical property Evaluation of Specimen (Impact Test 2mm V notch at RT)

Sl.No	Specimen Id	Joule	Kgf-m/cm2
1	MME 1765/21	2	0.25
2	MME 1766/21	2	0.25
3	MME 1769/21	2	0.25
4	MME 1770/21	2	0.25
5	MME 1767/21	2	0.25
6	MME 1768/21	3	0.38
7	MME 1763/21	3	0.40
8	MME 1764/21	4	0.50

C. Microstructure

Micro structure samples were sectioned mounted and polished using different grades of emery papers. Final polishing was carried out with 1 micron diamond paste. The polished area was etched with suitable etchant to reveal the microstructure. The etched surface was then observed under optical microscope. The optical micrographs of coupons of aluminum fabricated through additive manufacturing are given in fig.7. Microstructure observed in X, Y, Z & 45° revealed fine Si particles distributed around Al matrix.



DOI: 10.13009/EUCASS2022-6188

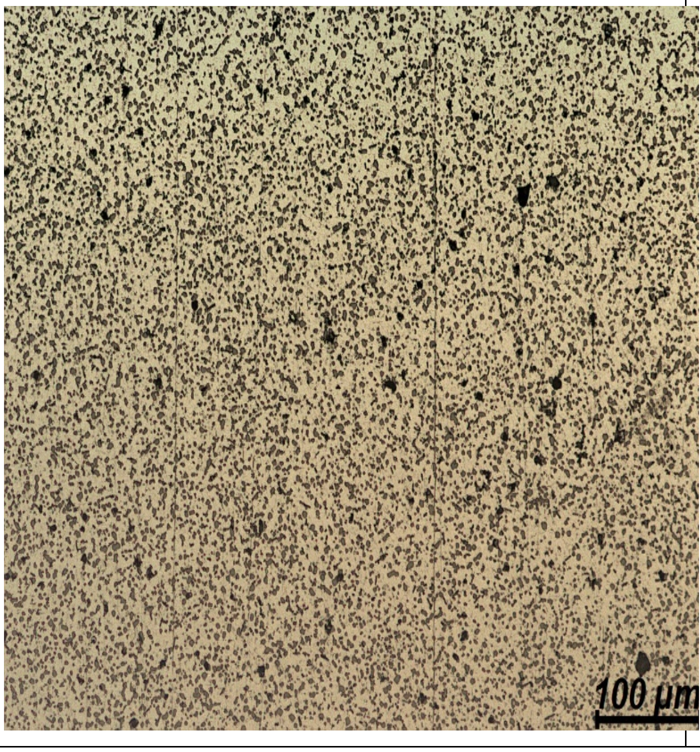
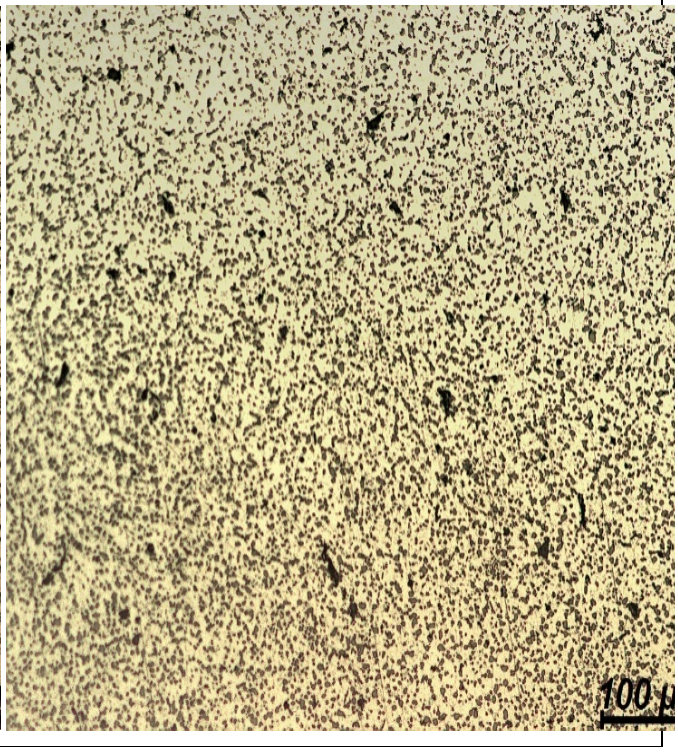
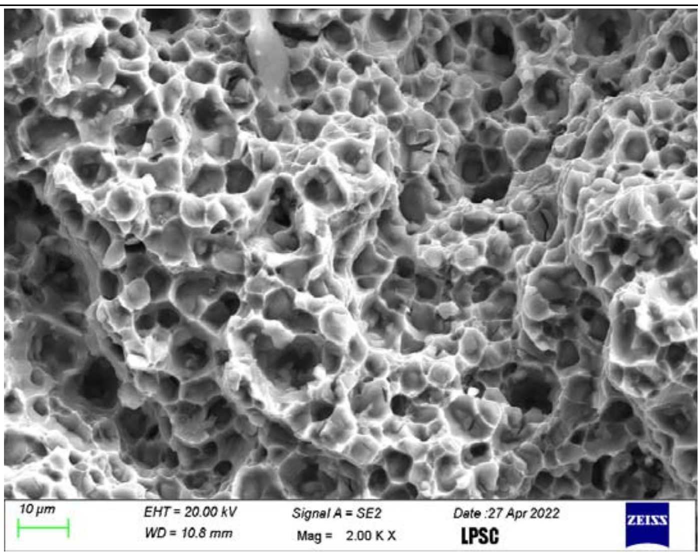
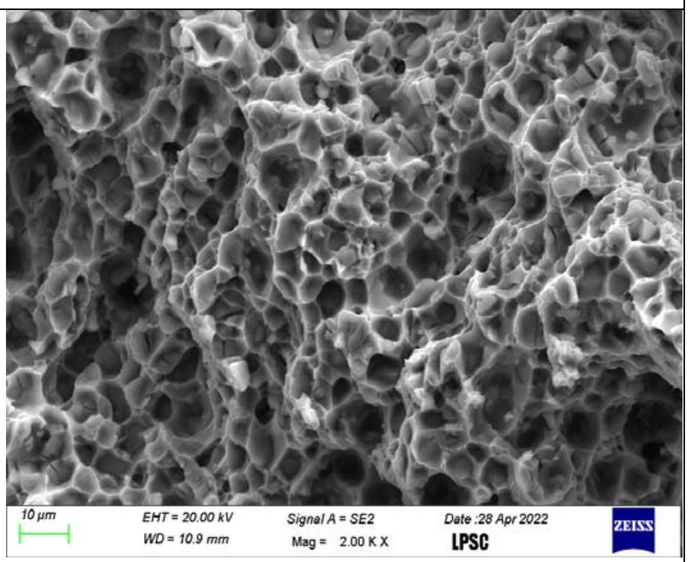
Sample-Z	Sample-I (45°)
	

Fig. 7 Optical micrograph of sample at 100X magnification

D. Fractography

Fractography studies of the tensile tested coupons were carried out on FESEM and high magnification images were captured in Secondary Electron mode. Fractography of the tensile tested coupons of AM AlSi10Mg realised through additive manufacturing are presented in Fig. 8.Fractography indicates ductile failure by micro void coalescence in all X, Y, Z & 45^{o} samples. Occasional isolated pores, varying from 4.5 to 14 microns, are observed. Shape of the pores indicates its formation by gas entrapment.

Sample-X(MME1422/21-X)	Sample-Y(MME1424/21-Y)
	

DOI: 10.13009/EUCASS2022-6188

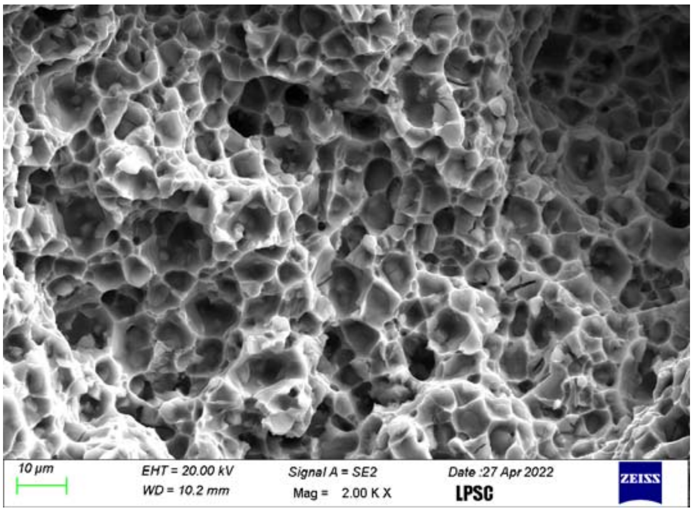
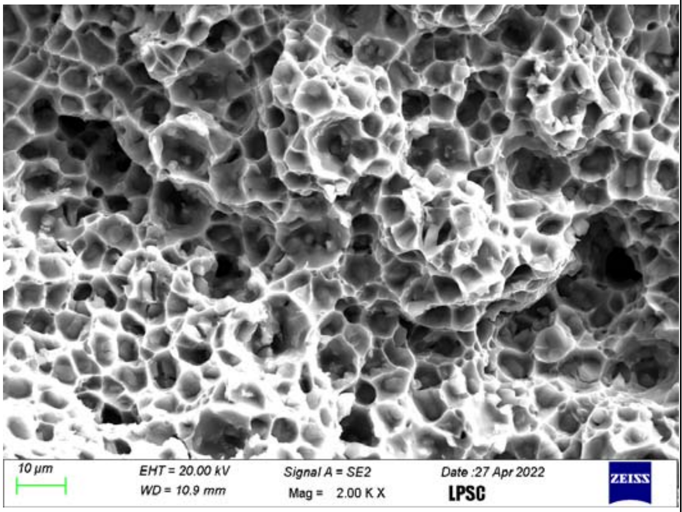
Sample-Z(MME1427/21-Z)	Sample-I (45°) (MME1430/21-I)
	

Fig. 8 Fractographs of AlSi10Mgtensile tested specimen

V. Conclusion

The mechanical strength of additive manufactured AlSi10Mg materials is significantly higher than the strength required to the Fuel Pump Impeller during operating condition. Additively manufactured Fuel Pump Impeller is now Spin tested successfully @26210 rpm for 140 sec at ambient temperature, which indicates that the hardware confirmed to system requirements and it is cleared for conducting cold flow test at the turbopump assembly level. It is found that Additive Manufacturing scores over casting in terms of time, quality, cost benefits and weight savings which are of prime importance in space sector. The Pre burner pump impeller realised using AlSi10Mg by the additive manufacturing route can be used as replacement for the impeller realized by the casting route using SS AJI4-BM-T6-3 material. Future scope lies in the application of design for additive manufacturing (DFAM) towards optimization.

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