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An investigation into the suitability of additive manufacturing techniques for neutron moderator vessels

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Abstract. Additive manufacturing (also known as rapid prototyping or 3D printing) techniques are increasing in popularity for several key reasons; greater freedom in possible geometry, reduced time of manufacture and connected to these are potential cost savings. ISIS has begun an investigation into the suitability of the various available techniques for the manufacture of neutron moderator vessels, in order to see if it can exploit these advantages.

It is however understood that additive manufacturing is by no means a perfect technique and part of the investigations will be to try and better understand how some of the disadvantages of the technique affect its potential application within the spallation neutron environment. Some of the main disadvantages commonly listed are; the grades of materials available/suitable for the process are limited, virtually no pre-existing material data from radiation environments, lower quality surface finish (directly from the manufacturing process), less familiarity with residual stresses in the material and questions over whether tight tolerances and consistent material thicknesses be achieved?

The work has been divided into two streams; one which utilises small samples to evaluate and compare different manufacturing and post-treatment techniques, the other that performs tests on a full-size representative moderator vessel. The complete programme of testing shall include the following tests; fundamental ‘neutronic transparency’, room temperature vacuum leak test, cold shock (using LN_2) and subsequent room temperature leak test, pressure cycling, a burst test, welding suitability and material data testing.

The investigations being conducted at ISIS are very much in the early stages and looking at fairly fundamental questions. Answering these will clearly guide the decision whether is it worth continuing with further investigation and development or if the currently available techniques do not produce materials that are suitable for use as moderator vessels.

This paper will present and discuss testing methodologies and results from planned tests in 2014.

1. Introduction

1.1 Additive Manufacturing

Recent years have seen the rise in popularity and number of applications of additive manufacturing (AM) techniques, which differs from traditional manufacturing techniques because material is added as oppose to being removed by the process. The range of technologies and techniques covered by this term are also referred to as 3D printing, rapid prototyping or rapid manufacturing. The techniques first came to prominence by producing products in a range of plastics but since its conception there has been a desire to develop the techniques to be applicable with metals. They are now a wide range of companies offering production services and manufacturing equipment in this field. AM offers several potential benefits when compared to conventional subtractive manufacturing techniques and these are:

- Greater freedom in possible geometry
- Reduced time of manufacture
- Potential cost savings
- Can be produced directly from CAD data

1.1.1 Metal Manufacturing Techniques. There are several AM techniques available for the production of metal components, although following some research and a preliminary tender exercise, the selection was reduced to two main techniques. These were selective laser melting (SLM) and direct metal laser sintering (DMLS). The key difference between these two fairly similar techniques is that in SLM, the material is fully melted rather than sintered, allowing different properties (crystal structure, porosity, and so on). Both techniques work by building up fine layers of material (in the form of a powder) that uses a laser to fuse the powder grains together (see figure 1). Once one layer is complete, the excess powder is removed and a new layer is applied. This process is repeated until the required geometry is achieved. As the technique builds components layer by layer, it allows highly complex and intricate geometry to be produced. The term additive manufacture stems from the fact that material is added and not removed as with conventional machining. AM techniques offer several potential benefits when compared to the standard conventional production techniques; greater freedom in possible geometry, potentially reduced manufacture time, potential cost savings and components can be produced directly from CAD data. These are benefits that clearly would interest to any designers of moderator vessels, but particularly of interest is the additional freedom in available geometry and the novel concepts this may allow.

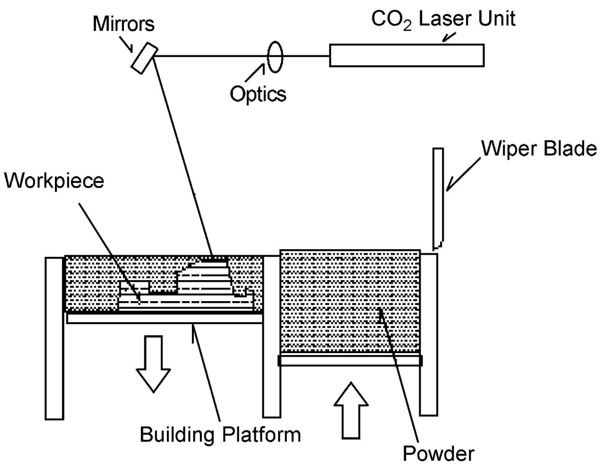

Figure 1. A schematic showing the principle behind AM techniques for the production of metal components [1]

It is however understood that AM techniques are by no means a perfect solution and part of the investigations carried out by the team at the ISIS were to try and better understand how some of the disadvantages of the techniques affect its potential application within the spallation neutron environment. Some of the main disadvantages that cause concern for moderator designers are; the grades of materials currently commercially available as well as suitable for AM process are limited, there is virtually no pre-existing material data from radiation environments to base lifetime calculations or irradiation damage effect estimations on, AM techniques produce a lower quality surface finish (directly from the manufacturing process) when compared to machining, there is less familiarity with residual stresses in the material and there are questions over whether the tight dimensional or geometric tolerances and consistent material thicknesses often required by the design of moderators, can be achieved.

1.2 ISIS moderator vessels

The ISIS facility operates two target stations with a total of six moderators (excluding pre-moderators). As these moderators are optimised for a variety of scientific requirements they vary in geometry, size and moderating material. Target station 1 (TS1) currently features four neutron moderators; one liquid hydrogen (LH_2), one liquid methane (LCH_4) and two poisoned ambient water moderators. They are arranged in the configuration shown in figure 2, below. They are positioned above and below the TS1 target and serves a varied suite of neutron instruments. Target station 2 (TS2) operates with 2 moderators; a decoupled solid methane and a coupled liquid hydrogen moderator. These are again arranged above (decoupled) and below (coupled) the target.

ISIS has an on-going programme looking at improving operational and scientific performance of the current moderators and developing the 'next generation' of moderators for the facility. One of the driving factors in looking at AM techniques for the potential production of moderators vessels was to give the ISIS neutronics team greater geometrical freedom for their moderator concepts.

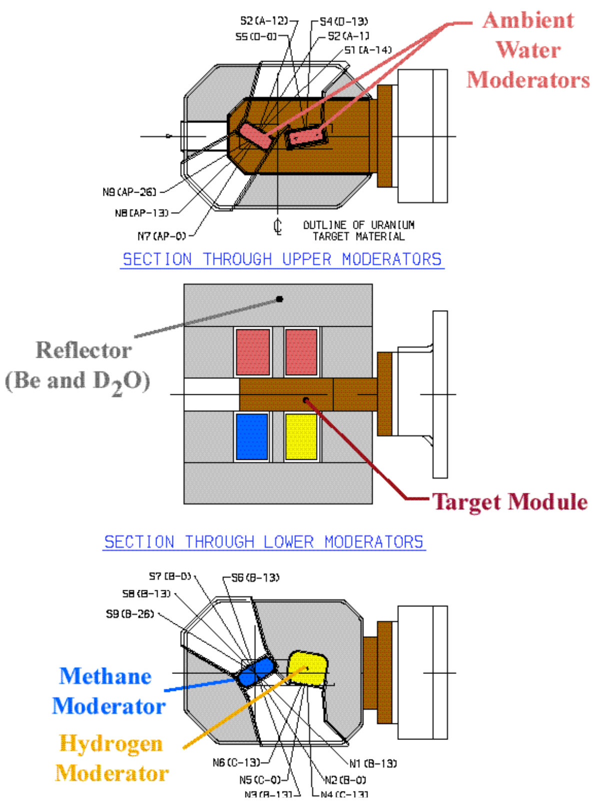

Figure 2. Showing the layout of the ISIS TS1 moderators

2. Assessing the suitability of additive manufacturing

The aim of the initial part of the investigation was to try and develop understanding of components made via AM techniques, to address some of the disadvantages listed in the introduction and to try and provide answers to some basic fundamental questions, namely, can we produce a vacuum leak tight vessel, can it withstand working pressures seen at ISIS and are the neutronic transmission and scattering characteristics of these components acceptable?

Two 'streams' of testing were pursued in parallel; one focussed more on mechanical performance and property testing and the other with a neutronic behaviour focus. These two testing streams are discussed in more detail in the paragraphs below.

2.1 Mechanical property testing

The first part of the investigation was a basic proof of technology test by having a full-scale TS2 decoupled moderator vessel (including pipe connections) manufactured (see figure 3) using an AM technique, in this case, SLS. With this successfully achieved a test procedure was drawn up. The procedure laid out the basic tests to be carried out and covered leak checks, pressure cycling, cold shock followed by a room temperature leak test, a burst test, weld tests on the samples machined out of the vessel following the burst test and mechanical property testing also carried out from sample taken from the ruptured vessel.

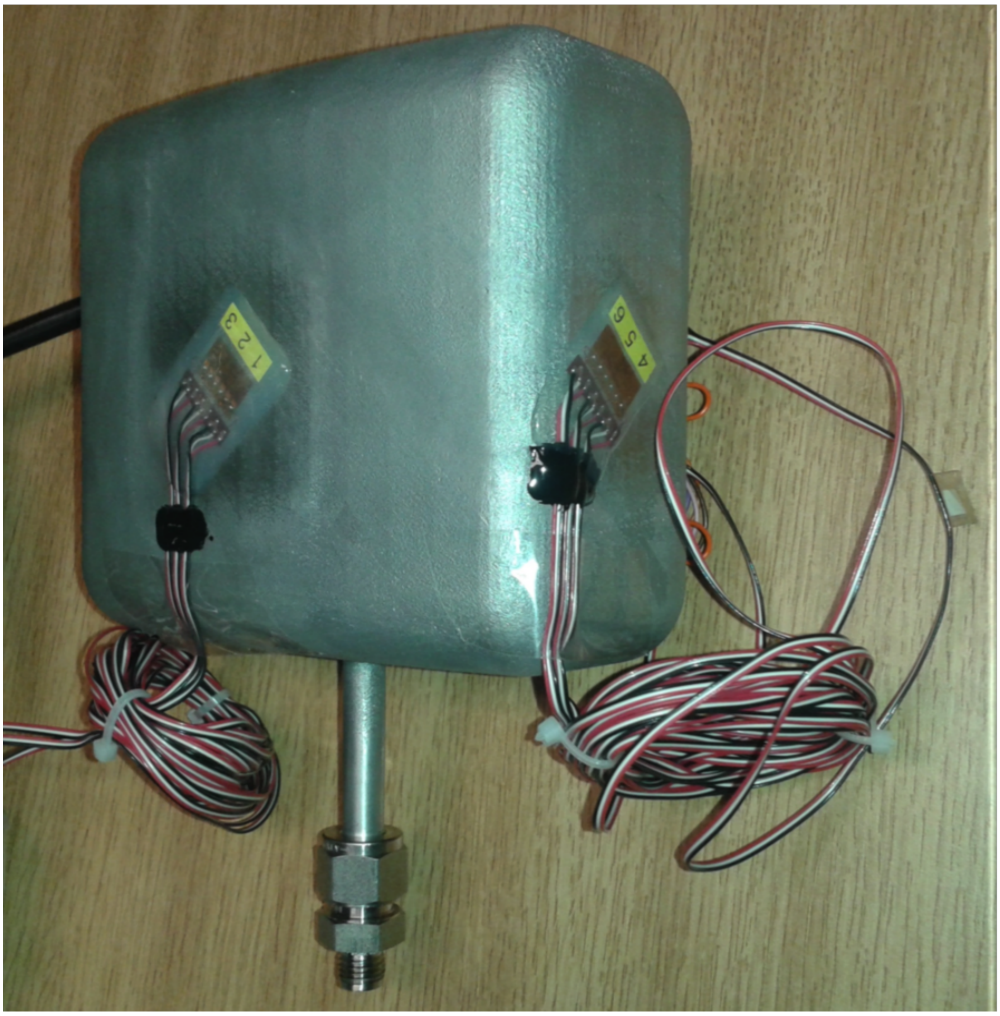

Figure 3. *Additive manufactured (AM) TS2 decoupled moderator can with strain gauges applied, before cyclic pressure testing.*

2.2 Neutronic testing

The focus of this part of the investigation was to assess the impact, if any, of the variations between aluminium vessels made by conventional techniques and those made by AM techniques. Some of the postulated differences might arise from; the material grades readily available for use with AM processes, different internal stresses generated from the manufacturing and post treatment processes the orientation of the metals grains and crystallite sizes.

A series of simple geometry samples were manufactured using both major AM techniques for metal, SLS and DMLS. Coupled with this were two variations in temperatures at which these techniques were carried out, two different post-manufacture heat treatments and two post-production surface treatments. The full list of samples and the processes applied to them is shown in Table 1. Included in the test were two samples of conventionally machined aluminium 5083 grade to act as a reference to the current material used at ISIS for the moderator vessels. The samples were provided in individual, marked bags to ensure some element of a 'blind test'. It is worth noting that compared to all the AM samples the conventional aluminium samples were very easy to spot, even by an untrained eye.

The samples measuring 20 x 20 x 4 mm were then put onto the LOQ instrument at ISIS, allowing small angle neutron scattering (SANS) measurements to be taken.

Table 1. A Table listing the information on the different AM specimens tested as part of the neutronic tests

TS-1 AM Test Samples

Sample Code	Source	Alloy	Process	Post Treatment	Surface Treatment
A	3T	AlSi10Mg	Direct Metal Laser Sintering (Hot Worked*)	None	None
B	3T	AlSi10Mg	Direct Metal Laser Sintering (Hot Worked)	None	Ceramic Blast
C	3T	AlSi10Mg	Direct Metal Laser Sintering (Cold Worked)	None	None
D (D2)	3T	AlSi10Mg	Direct Metal Laser Sintering (Cold Worked)	Stress-relieved (300C for 2 hours)	None
E	R12	5083	Machined	None	As machined (0.8)
F	R12	5083	Machined	None	As machined (0.8)
G	TWI	AlSi10Mg	Selective Laser Melting	None	None
H	TWI	AlSi10Mg	Selective Laser Melting	Stress-relieved**	None
I	3T	AlSi10Mg	Direct Metal Laser Sintering (Cold Worked)	Stress-relieved (300C for 2 hours)	Light Ceramic Blast
J (C2)	3T	AlSi10Mg	Direct Metal Laser Sintering (Cold Worked)	None	None
K	TWI	AlSi10Mg	Selective Laser Melting	Stress-relieved**	None
L	TWI	AlSi10Mg	Selective Laser Melting	Stress-relieved**	None

an anneal

*At 3T, there are two different process options. The product can be ran at 200C whilst sintering and hence, is stress relieved during the process. If cold worked, the process runs at room temperature and internal stresses are produced during sintering. 3T would then normally advise customers to have further heat treatments, like sample D.

** All TWI parts were created using the same parameters, parts 1-5 (G) are un-heat treated and parts 6-10 (H, K, & L) are heat treated. The stress relieve was an anneal for 2 h at 300 °C (572 °F).

3. Results

The aim of the initial part of the investigation was to try and provide answers to the questions of 'neutronic transparency' and mechanical viability.

3.1 Mechanical property testing results

A TS2 decoupled moderator vessel was successfully manufactured in aluminium using an AM technique (see figure 3) in 2012. The vessel has since been leak tested at room temperature with a mass-spectrometer to 5×10^{-8} mbar.litres/s, before it was subjected to a 'cold shock' test (submersion in liquid nitrogen). The leak test was then repeated, with identical results. This shows that despite some initial reservations, the AM technique was able to produce and acceptably leak tight vessel.

The vessel was twice cycled from atmosphere up to 6 bar(a) and while strain readings were taken from two strain-gauge rosettes; one positioned in the centre of one of the large faces and one positioned in the centre of a smaller side face. These data gained was used to calculate a maximum principal at the centre of the larger face (worst case) of 91MPa.

3.2 Neutronic testing results

It was felt that the easiest way to demonstrate clearly the observed differences between the various test specimens was to use the graph shown in figure 4 below.

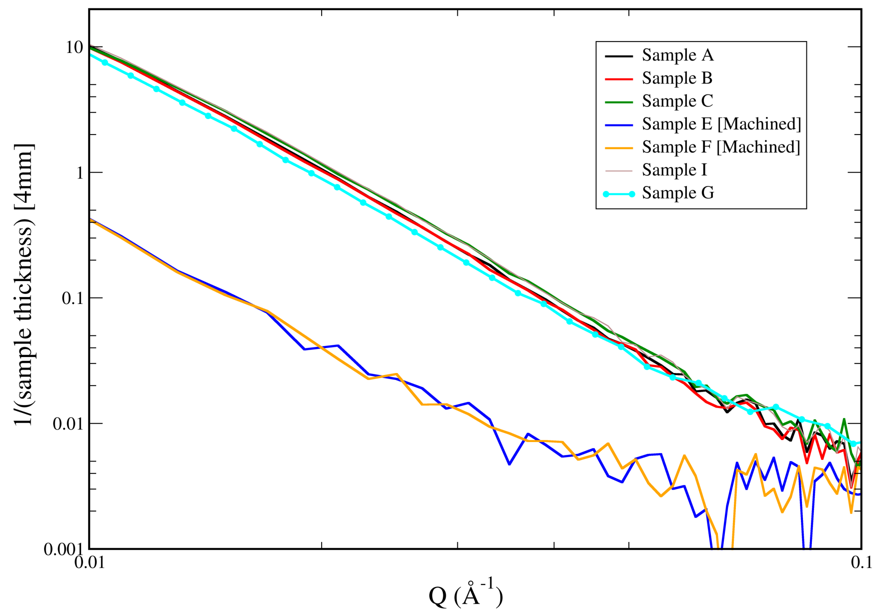

Figure 4. A graph showing the difference in small angle scattering between a representative selection of additive manufactured specimens and the standard machined aluminium reference specimens.

The graph illustrates that the AM specimens are significantly less 'transparent' to neutrons when compared to the two machine aluminium specimens. It is postulated that at least some of the observed difference may be down to composition differences between the AlSi10Mg grade used for the AM specimens and the Al5083 grade used for the machined specimens. Another postulated cause is the difference in inter-granular spacing and grain size.

Due to the log scale on the y-axis, it also shows that there is enough variation between the various specimens, to warrant further investigation (sample G can be seen to clearly sit below the lines of the other selected specimens displayed on the graph). In addition, with the postulated link to grain size being a potential contributing factor and there being several available techniques for altering grain size in the AM specimens (both larger and smaller) the team is optimistic that further improvements can be made.

4. Future work

4.1 Correlating finite element analysis results to empirical pressure testing data

In order to provide a high level of confidence in future simulation results, a finite element analysis (FEA) model has been created and work is continuing to ensure this is robust and fully mesh independent. The model is being benchmarked against the measured data gained from the repeated pressure testing. It was decided to finish this modelling work before carrying out a burst test on the full moderator can, in case additional pressure testing could provide useful secondary results.

4.2 AM vessel burst test

It is planned for the team to carry out a recorded (using high-speed cameras) and instrumented burst test on the AM vessel. This will provide insight into the mode and position of any failures as well as the total pressure required to burst the vessel. This information can be compared with similar results from similar previous tests carried on moderator vessels produced via conventional methods.

4.3 Post-burst test mechanical testing

Once the vessel has been burst, then samples will be machined out of the remaining material and used for a variety of mechanical property (e.g tensile testing) and welding tests. Again these results can be compared back to know references. The break will also expose the structure and how it fractures (either brittle or ductile).

4.4 Continuation of neutronic behavior characterization and viability testing

At the time of writing, ISIS, is currently in a planned long operational shutdown. Therefore there is no current access to beam time in order to carry out further SANS testing. It is planned that when the facility is running again that the observed, if only slight, differences between the two AM techniques that was shown by the first round of testing , will investigated further. It is also a potential that samples could be tested on ENGIN-X to look into possible correlations between internal stresses and neutron transparency. There is also the potential to develop the AM techniques to work with more standard engineering grades of aluminium, such as Al5083 and Al6061.

5. Conclusions

It is clear that there are some strong benefits offered by AM techniques that could be exploited by moderator vessel designers. What our initial investigations have shown can be roughly concluded as follows:

- Initial indications (leak tightness and max. principle stress) show technology is mechanically viable
- The effect of the manufacturing process on neutronic performance and suitability for radiation environments is yet to be fully understood – work on-going

There is much still to learn in this interesting and rapid developing field. ISIS is very open to joint projects and collaborations, so if you are interested then please feel free to contact the author.

6. Acknowledgements

The work presented here in this paper and in the accompanying presentation is the combination of a great deal of time and effort by a large number of ISIS' staff. I would like to acknowledge some of the main contributors to the project here (listed in alphabetical order); Stuart Ansell, Sean Higgins, David Jenkins, Eamonn Quinn, Colin Souza, Stephanie Thomas and Liam Whitelegg. It is due to the

dedication and commitment of its’ staff such as those listed above that ISIS remains such a productive and scientifically important facility.

7. References

[1] http://fabribles.com/community/forum/tech/49-direct-metal-laser-sintering-dlms