Automated Production of High Repetition Rate Foam Targets

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Introduction

With the recent developments in laser technology there are an increasing number of high repetition rate systems that are available for utilisation by the plasma physics community for experiments investigating topics such as ion acceleration. One of the most interesting types of targets in the field is a low density polymeric foam that is on the order of 10-100 microns in thickness and can be used to investigate hole boring [1]. It is however difficult to manufacture thin foams in the numbers that are required to carry out these experiments on facilities such as Astra Gemini with the high shot rates available. Current manufacturing techniques rely on a manual fill of target geometries under a microscope with a syringe and then processing using a critical point dryer. This paper reports on a production method that uses a semi-automated dispensing and curing system to maximise the output of the drying process to produce targets that are technically challenging and previously difficult to fabricate.

Typical target geometries that have been requested to date have been foam densities in the range 10 to 300mg/cc and thicknesses in the range from 50 to 500 microns. For low rep rate experiments on facilities such as the Vulcan laser at the Rutherford Appleton Laboratory (RAL), there may be a need for 10's of targets but for med rep rate experiments, such as those on the Astra Gemini laser at RAL there may be the need for several 100's of targets. There is a trend within the community to require the more demanding thin and lowest density targets and these specifications are especially challenging to achieve for free-standing foams and may well be beyond the realms of existing technology and beyond the budgets of experimental campaigns.

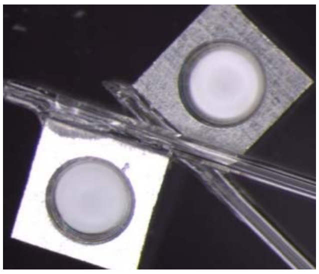

Figure 1a. Individual foam targets with washer supports for low rep rate experiments. Shot on the Vulcan laser at RAL, UK, May 2013.

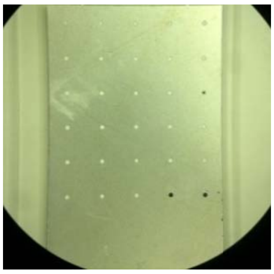

Figure 1b. Array based foam targets for med rep rate experiments. Shot on the Astra Gemini Laser, May 2013.

The physical structure of different foam types makes them more or less suitable for different experiments and can be quantified in terms of chemical composition, physical structure with pore size being a key factor, densities achievable in manufacture, machinability and quality. The last attribute, quality, can include uniformity, defects both in terms of high density inclusions or holes, and the presence of a higher density skin.

The chemical from which the foams are made as detailed in this report is trimethylolpropane triacrylate (TMPTA) and is composed of only carbon, hydrogen and oxygen. For some experiments the presence of oxygen prevents this type of foam from being used. However in the case of TMPTA the foam benefits from having no predefined pore size meaning that the density can be reduced without introducing complicating large voids. If pure chemicals are used and clean conditions are employed then inclusions of high density defects and skin effects can be minimised. The foam is not easy to machine so a support or mount is required which defines the shape and size of the final foam targets.

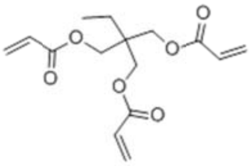

Figure 2. The chemical structure of TMPTA showing the 3 functional acrylic groups available for polymerisation.

Manual production

Foam production has an established process [2] that starts by producing a foam solution made up of 3 chemical parts: the material of the foam, a solvent and an initiator. The ratio of TMPTA to solvent defines the final density of the foam. A very small quantity of UV sensitive photo initiator is added which allows the foam to polymerise. The solvent and photo initiator are carefully chosen to only contain the same chemical elements as the TMPTA to avoid any chance of cross contamination. Some initiators as an example might contain high z elements such as chrome (Cr) or Iron (Fe). The foam solution is dispensed into cavities which could be individual mounts for single shot experiments or arrays for medium rep rate. The process is typically performed under a microscope due to the small size of the cavities and would typically take 10 seconds per cavity. For several hundred targets the filling stage could take a number of hours.

A mercury arc lamp or LED UV source is used to cure the foam. Over a time frame of a few seconds, depending on the power of the UV source, the clear solution will turn white. This is because the polymer network scatters the light that passes through and indicates that the curing stage is complete. The last stage involves removing the solvent and this is a challenging process to complete without damaging the foam as traditional drying of the foam by evaporation of the solvent would collapse the delicate foam structure. Consequently a Critical Point Drier (CPD) is used. In the CPD carbon dioxide is introduced into the exchange chamber at a high pressure (above 75 bar) and the temperature is controlled from around 20°C up to 40°C. At the higher temperature (and therefore pressure) the carbon dioxide behaves as a supercritical fluid displaying the properties of both a gas and liquid simultaneously. Once in such a state, the carbon dioxide can be vented off without any surface tension effects. When this process is complete, the foam is dry and ready to be used as a target. The solvent exchange stage takes around 2 hours but is highly dependent on the amount of foam material that is being processed and can take up to 8 hours.

Polymerisation process

When UV light of an appropriate wavelength is incident on the dissolved photo initiator molecules they split into two or more free radical parts. The free radicals can either recombine, but will split again under the UV, or they can react with the TMPTA monomer molecules but not the carefully chosen solvent. TMPTA has three functional groups containing a carbon double bond which are possible sites for a free radical to bond with. When a free radical reacts with a TMPTA molecule it opens up the double bond and forms a small chain at this point but leaves the other half of the double bond as a free radical which allows the chain to react with further TMPTA molecules creating longer and longer chains. Because TMPTA has three functional groups it is possible to have cross-linking between adjacent chains giving the overall polymer network rigidity.

Highly pure chemicals are key to the success of the polymerisation process because the free radical photo initiator parts or polymer chains will react with any impurity stopping the formation or growth of the polymer network.

Semi-Automated production

The most time consuming stages of the foam production process when making a large number of targets are the filling and curing steps. Given the regular spacing and grid-like nature of arrays it was proposed that a robot might be able to complete both of the steps quickly and simultaneously. The shot-to-shot variation in the foams should also be reduced by using pre-set dispensing values.

A 3 axis (x,y,z) robot with dispensing capability (figure 3) was used to prove the principle of automated production. The robot was controlled via a laptop and custom written software which allowed the integration of the UV curing stage using a digital signal to trigger an LED source.

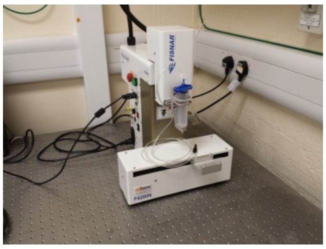

Figure 3. Dispensing robot with 3 axis stage. 4 mounting screws are available for custom made plates.

There were a number of challenges that needed to be addressed to commission the system to be suitable to make foam targets. An array mount holder, shown in figure 4, was designed to hold multiple arrays with an x,y positional accuracy of better than 200um. When thin (<150um thick) arrays were placed in the holder it was found that they could bow with a change in height of several hundred microns. In addition to the bowing different thickness array mounts could in practice be used and so it was decided that it was necessary to incorporate a feedback loop between the metal dispensing tip and the top surface of the metal arrays. The loop would trigger only when the tip touched the array and this position in z would then be set to zero. The tip could then be raised by a predefined amount before performing a dispense routine. The feedback loop allowed the system to cope with multiple target designs and built flexibility into the production process.

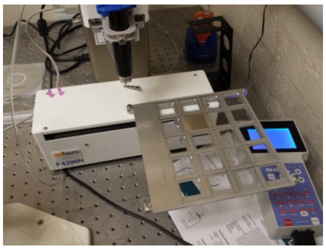

Figure 4. Holder plate with space for 20 array mounts. Positional accuracy was specified to be better than 200um in x & y.

It was discovered that when dispensing different liquids through a standard tip the physical characteristics of the liquid could yield surprisingly different results as shown in figure 5. For water, the droplet would form below the end of the tip. For the foam solution the liquid would climb up the outside of the tip. When dispensing into a shallow container there are obvious limitations if the liquid does not present itself at the end of the needle, especially if the foam solution is to be dispensed onto a very thin backing foil of a few 10’s of nanometers thick in which case any contact between the needle and the foil would damage it. It was decided to bend the end of the tip by 90° and use the wicking property of the foam solution to help with the filling procedure.

With the foam solution exposed proud of the needle it could be dispensed on one side of an array hole and the meniscus dragged over to the opposite side without the needle touching the fragile foils. To ensure such behaviour a gap was required between the tip and the array of the order of 50 – 100 microns which was possible to program using the contact feedback loop.

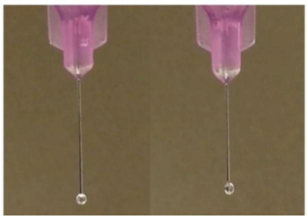

Figure 5. Left: A water droplet hangs below the end of the dispensing tip. Right: A foam solution droplet climbs up the dispensing tip.

Results

The height of the foam as produced by robotic fill and cure was measured relative to the flat surface of the array mount and was compared with a set produced using a manual fill. Measurements were taken using a white light interferometer which produced a 3D height map as shown in figure 6a. The height map was levelled and a lineout taken through the centre of a foam to obtain a measurement shown in figure 6b.

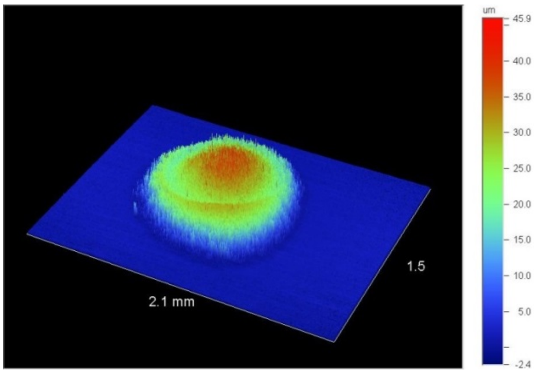

Figure 6a. 3D representation of a scan using a white light interferometer of a robotic filled foam.

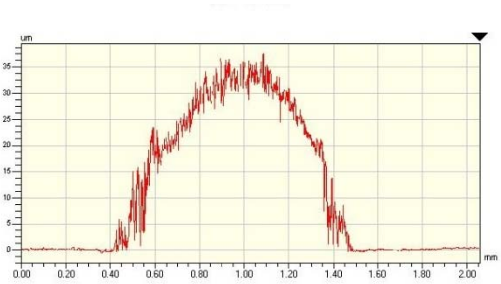

Figure 6b. A lineout taken through the centre of the foam scan to give a height profile above the level of the array mount.

The robot dispensing system has the ability to vary the amount of foam solution that it dispenses and therefore can vary the height of the foams above the mount. However for this investigation it was kept a constant to investigate variation over the range of positions using a common setting.

The results shown in figure 7 show the standard deviation of the height of the foams above the mount of 10.8um from the foams produced by hand and 6.7um from the machine made foams. Qualitatively the outline of the machine made foams in the plane of the fill plate (figure 8) is a skewed ellipsoid but mainly consistent across the array. The shape could be modified by using a different fill routine.

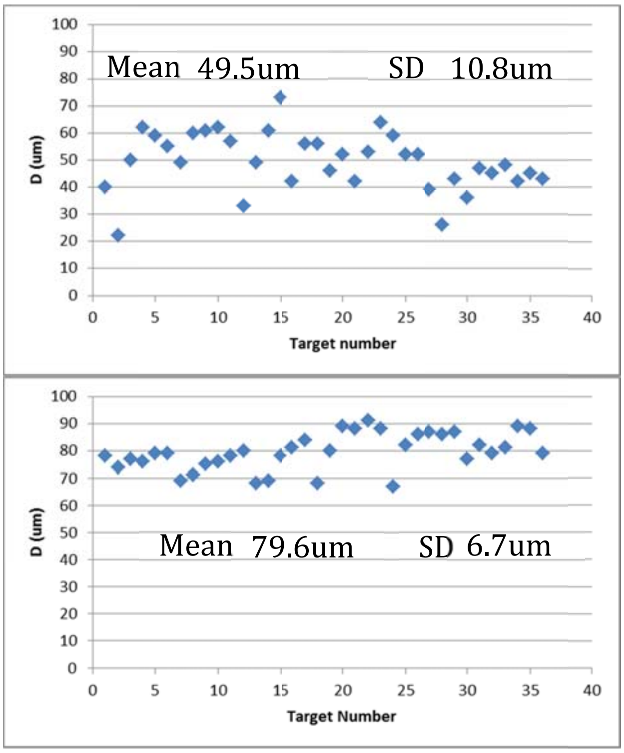

Figure 7. Results of the height of the foam solution measured relative to the array mount for manual fill (above) and machine fill (below).

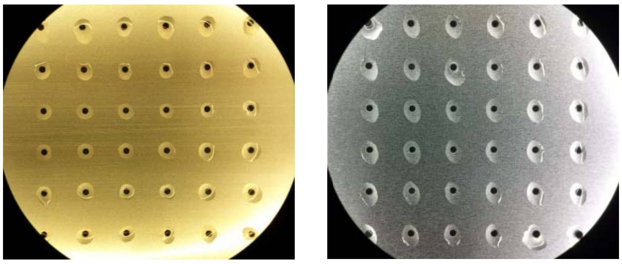

Figure 8. Left: Hand-filled array of foam solution. Right: Machine filled array of foam solution.

Conclusions

The robot has shown good results in improving the quality of foams production by reducing the target-to-target variation and with careful programming it is likely that the variation can be further reduced. The aim is to obtain a variance low enough that a whole batch of foams can be characterised by the measurement of only a few samples. The time taken to produce the foams has been significantly reduced. As more laser systems utilise the high repetition capabilities that are being developed a large number of arrays will be required. The demonstrated time saving in production will be essential in ensuring that the laser systems are not target limited. Over the next few years we will develop further target geometries in collaboration with user groups to further enhance the range of experiments that can be undertaken.

References

1. A P L Robinson et al, PPCF, (2009), 51, 024004
2. Nazarov W., Fusion Sci. & Technology 41, 193 (2002).