SCALING UP ADDITIVE MANUFACTURING

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With noticeably growing interest from industry, coupled with an increase in accessible and large format hardware configurations, underpinned by feature-rich, multi-axis tool pathing software solutions, Directed Energy Deposition (DED) is now coming of age and starting to prove itself as a viable tool for the manufacture of large parts and structures.

TWI Ltd has been at the forefront of DED developments for over 18 years and has seen, first-hand, a growing appetite from its industrial members to consider DED as a viable manufacturing option to produce both pre-existing and new component designs. Hence, this recent surge in global interest comes as no real surprise. This article gives an overview of TWI's journey towards large scale part production, focusing on laser-based directed energy deposition (DED-LB) and will conclude on some future trends and programmes.

Laser-based directed energy deposition

DED is a metal additive manufacturing (3D printing) process which uses a focused energy source, such as a laser, plasma arc or electron beam, to melt either a jet of blown powder or a wire feedstock from a nozzle, forming a solid bead of material which is fully fused to the underlying substrate or previously deposited material.

TWI currently operates five DED-LB systems from its state-of-the-art facility based in Rotherham, South Yorkshire. Two are multiple axis robot systems and the others are four and five axis gantry systems including one of the UK's largest systems. All are powder feed compliant, two can interchange between powder and wire, and all are complimented with integrated and fully interpolated two-axis workpiece positioning systems. TWI also offers the extreme high speed laser application (EHLA) process. This gives a step change in deposition speed from a few m/min for DED to several hundred m/min, and is currently used to complement TWI's sizeable activities in the application of metallic coatings and for component repair, but is also driving early developments towards high speed metal additive manufacturing.

The DED-LB journey begins

TWI started its journey in earnest on what was then considered to be 'large' scale DED back in 2010 when it was involved in an EC FP7 funded project called Merlin (expectations on scale were not quite as they are today). The intended component demonstrator was part of a helicopter combustor casing assembly made from Inconel 718, and at the time of planning for DED-LB manufacture, it was considered large for metal AM because it would not quite fit into a then standard powder bed fusion (PBF) build platform; the part being 320 mm in diameter and 100 mm tall (see Figure 1). The geometrical requirements were also very challenging for DED, including an 800 µm wall thickness (±100 µm), diameter and circularly variations of ±1.0 mm and <1% respectively, and a surface finish in range 12-15 µm Ra.

The task was without precedent, and it took nearly two years to develop the process parameters, the tool pathing strategy, and even the CAM software to drive multiple axis deposition. Commercially available software with enough flexibility to support the planned development route proved difficult to find at the time.

The strategy was to spin the substrate and build the wall by depositing a single pass melt bead defined by a helical toolpath, whilst tipping the substrate along the way to ensure the wall section directly under the melt pool was coaxially aligned to the vertically orientated nozzle, removing the need to support any overhanging features. The part also had to be manufactured in a single operation i.e. with no breaks or any discontinuous use of the laser. This approach is now widely used in DED.

There were several reasons for this approach. Firstly, using the positioner to rotate the substrate relative to the nozzle, rather than moving the nozzle around a circular path, created a cylindrical wall with a better dimensional consistency and surface finish. Secondly, continuous operation and laser exposure was necessary to minimise in process deformation, caused by process induced thermal hoop stresses, which were found to be most significant in the wall section closest to the substrate or atop of the open-ended cylinder during cooling. The deformation comes in the form of a reduction in cylinder diameter and would make any restart difficult without creating a seam or witness mark visible on both sides of the wall. Terminating a thin cylindrical wall with a flange helped to pin the geometry and resist any deformation during cooling.

The choice of nozzle, powder particle size distribution (PSD) and the speed and volume of powder feed into the melt pool played a pivotal role when trying to achieve a thin wall with good surface finish. A PSD of +20-45 µm was selected alongside a suitable coaxial nozzle (supplied by Fraunhofer ILT, Germany) that was able to produce a tight powder-gas beam focus with a core diameter of ~0.9 mm. This arrangement gave a material deposition rate of 150 g/h, forming a weld bead 800 µm in width and 200 µm in height (height of bead above the base metal which governs the pitch of the helical toolpath). The build time was 7 hours to deposit nearly 1 km of weld track, giving a final component weight of 800 g and a deposition material efficiency of 75%.

Although the material deposition rate is somewhat low and perhaps uninspiring on first glance, it would however be an immense challenge, if at all even possible, to achieve a net shape part with the same precision and consistency at a higher material deposition rate. Therefore, and as with all DED processes, a balance always needs to be sought between material deposition rate and the amount of deformation and post build machining that can

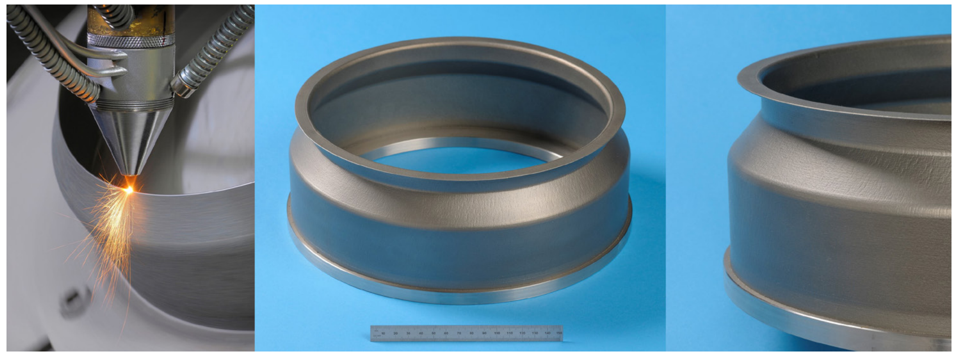

Figure 1: Inconel 718 Helicopter combustion casing built as part of the Merlin EC project in 2013. The image shows the part in the as built condition (the part was subjected to a light bead blasting to remove excess powder). The annular ring at its base is a 12 mm thick substrate.

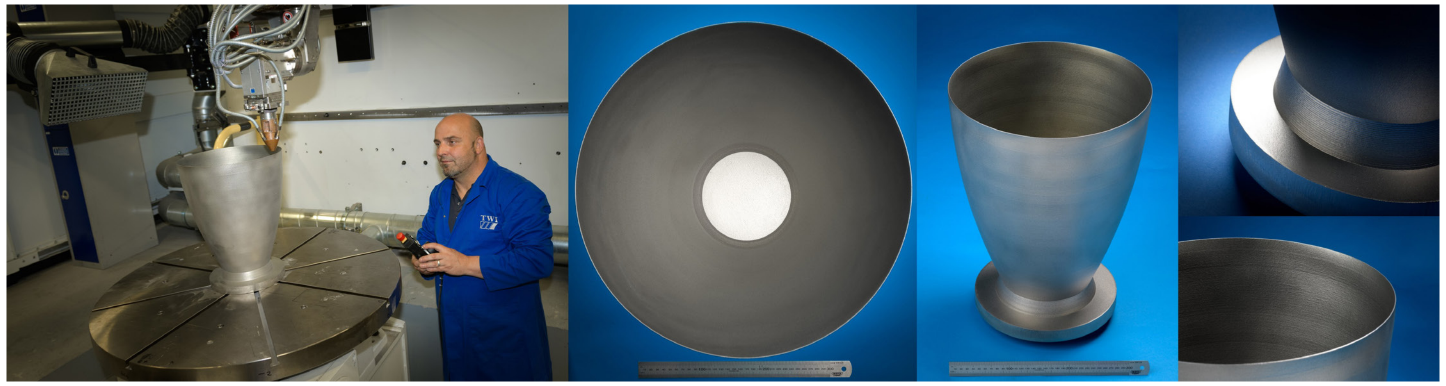

Figure 2: Inconel 718 rocket nozzle, standing 420 mm tall with a wall thickness of 1.3 mm. Photographed in the as-built condition (the part was subjected to a light bead blasting to remove excess powder).

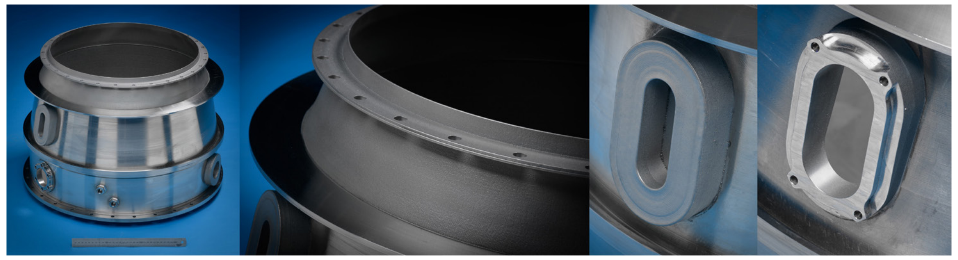

Figure 3: Inconel 718 turbine engine casing, 600 mm diameter and 450 mm tall, with the addition of internal and external flanges and bosses. The lower two tiers have been machined. The third tier and selected bosses are left in the as-deposited condition.

be tolerated. In addition to a finishing operation, DED parts will require a stress relief heat treatment prior to removal from the substrate. Additional heat treatments e.g. solution annealing, are also recommended to homogenise and enhance mechanical properties.

DED-LB technology development

In the intervening years, TWI has worked, both directly for its members and in collaboration with wider industry, to successfully manufacture a wide range of thin-walled (0.5 mm -1.8 mm thick) axis-symmetric components up to 550 mm in height and 1500 mm in diameter. This includes a number of different sized gas turbine components and rocket nozzles; all of which exhibited similar challenges and outputs to the helicopter casing discussed previously, but principally showed that large scale is feasible and in process distortion was manageable.

One variation worthy of note was an increase in material deposition rate to 280 g/h for the manufacture of the rocket nozzle shown in Figure 2, forming a weld bead 1.3 mm in width and 300 µm in depth. This increase became possible because of a thicker wall and a steeper wall orientation meaning a larger pitch of the helical toolpath could be used with little detriment to surface finish.

When moving away from thin-walled components, but still in the context of additive manufacturing, higher material deposition rates of 1-2 kg/h are achievable with laser and powder, particularly when used with a suitable nozzle. But no matter what the geometry, a higher material deposition rate will again come at the expense of lower feature resolution and surface texture, and will run the risk of greater levels of slumping, thermally-induced distortion and generally larger microstructure grain growth (through the need to use a high laser power).

Through continued use of TWI's CAM software, large scale and more feature rich components have been developed and manufactured. One example is a representative geometry of an aero engine casing (see Figure 3). This particular part contains walls and flanges ranging in thickness from 1-2 mm for a single pass track weld, and >12 mm using a combination of spiral and helical tool path forming tacks side by side as well as one on top of the other. This approach creates a good surface consistency by allowing gradual changes in nozzle position relative to the rotating substrate.

During the manufacture of this part, a number of observations and challenges were observed which are worthy of note here. Firstly, it was difficult to predict distortion behaviour of the part during manufacture because of a lack of robust design tools for DED. Hence, a balance had to be found through iterative experimentation between the deposition rate and heat input and the required feature resolution (e.g. wall thickness) to minimise both distortion and finish machining e.g. the uppermost flange on the part shown in Figure 3, which was deposited onto a 1.4 mm thick wall, had to be built with a low material deposition rate of 130 g/h. Ultimately, all walls within the part that had surface deposited flanges and bosses had to be built with a generous oversizing to ensure a suitable resistance to any thermally induced distortion; an approach clearly detrimental with attempts to minimise post machining and material waste.

For reference, the maximum material deposition rate used in the manufacture of the part was 500 g/h (measured at the nozzle), the average being 350 g/h. TWI has estimated around 25-30% of material was removed during finish machining to achieve net shape of selected features.

With regards to machining, a single stage finish machine was not possible because access for the cutting tool was difficult or blocked by certain features. Hence, an appropriate sequence of material deposition and machining steps had to be choreographed. This had to take place with additional intermediary stress relief heat treatment steps, to prevent tool chatter during machining, that would otherwise be caused by warping and distortion of the part as material is removed.

Future trends

Despite the obvious challenges, DED will no doubt increase its market share in metal AM, driven by its process flexibility and large-scale capability. It is also very clear that industry are currently confronting these issues with great vigour, continually introducing new and exciting advances in hardware, software and processes. In support of this, TWI is working on DED training programmes, CAM software and much needed design rules alongside industrially driven projects geared towards part production at multiple meters scale. This includes current projects developing DED maturity into a viable alternative manufacturing method for cast, forged and fabricated parts.

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