Renishaw plc
New Mills, Wotton-under-Edge,
Gloucestershire, GL12 8JR
United Kingdom

T +44 (0)1453 524524
F +44 (0)1453 524901
E uk@renishaw.com

www.renishaw.com

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DfAM essentials - print parts efficiently and effectively



Additive manufacturing (AM) gives us tremendous freedom to create components with free-form and intricate features, designs which would be impractical - if not impossible - to produce conventionally.

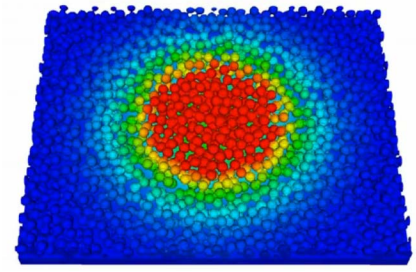
So AM gives us unfettered freedom to design anything we want, right? Well, not quite.

Like any manufacturing process, the various AM technologies have their capabilities and their limitations. In this post, we'll take a look at some of the key design for AM (DfAM) considerations for laser melted metal parts. We will consider feature size, surface finish, overhanging features, minimising supports, and avoiding component distortion.

Feature size

In machining processes, the size of detail feature that you can produce is limited by your choice of cutting tool. The cutting tool size determines the minimum size of holes and slots in the part.

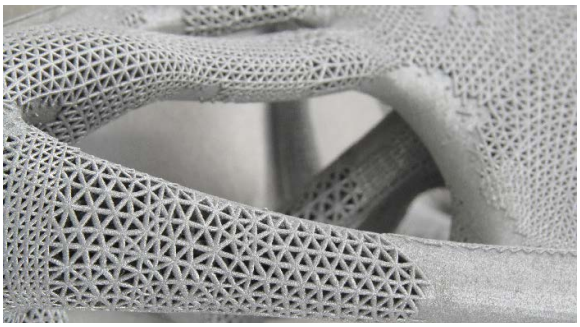
In AM, a similar rule applies, except that we tend to focus on the size of the solid elements that are printed rather than the gaps, with the tool size being the spot size of your laser. This spot heats the powder to create a weld pool, which cools into a solid structure once the laser energy is removed. The size of your spot, along with laser power and modulation, controls the size of the weld pool and hence the size of the structure that is built.



The image above shows how laser energy heats powder grains under the spot, and how this heat spreads into neighbouring powder. Sufficient energy must be transferred into the material to melt the powder in the central zone to create a fully-dense part, but with the consequence of some heat transfer beyond the laser spot perimeter. This heating effect also occurs downwards into the powder bed.

The minimum producible feature size is generally somewhat larger than the spot size due to this effect. The amount of sintering beyond the laser spot depends on the thermal conductivity of the powder and the amount of energy that is imparted.

For detailed structures such as lattices, strut dimensions down to 140 microns can be built using a 70 µm laser spot. Wall thicknesses as low as 200 µm can also be achieved.

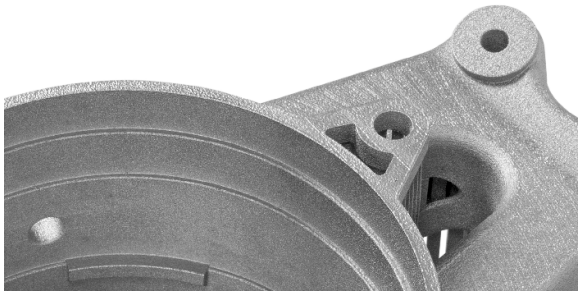


Surface finish

The intense heat of the focussed laser beam melts powder into a liquid which then cools into a dense solid. As we move away from the centre of the weld pool, the temperature drops, until we reach a point where powder grains soften but do not liquefy.

Some of these partially sintered grains will be captured by the molten metal and become firmly attached to the surface of the component. Others that are not so close to the heat source will not attach to their neighbours as they cool. This grain-by-grain welding, with some grains adhering to the part and others not, creates the characteristic textured surface of an AM part.

This effect is reduced somewhat by the partial re-melting that can occur when the next layer is processed, due to some of the heat travelling down into the layer below. This progressive melting and cooling of layers creates the familiar stripes on the component surfaces where the layers meet.



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The surface finish that is achieved is therefore largely driven by the laser power and modulation, the typical powder grain size and the layer thickness. Thinner layers tend to improve surface finish, but at the cost of longer build times. In a laser melting process, the surface finish (Ra) that can be produced on the machine (without any subsequent post-processing) using typical powder compositions, is normally in the range of 5 to 10 µm.

Overhangs

In powder-bed processes, where shapes are built up layer by layer, the way these layers relate to each other is important. As each layer is melted, it relies on the layer below to provide both physical support and a path to conduct away heat.

When the laser is melting powder in an area where the layer below is solid metal, then heat flows from the weld pool down into the structure below, partially re-melting it and creating a strong weld. The weld pool will also solidify quickly once the laser source is removed as the heat is conducted away effectively.

Where component features overhang those below, then at least part of the zone below the weld pool will consist of un-melted powder. Powder is less dense than solid metal, so unsupported thin layers of newly welded metal can sag. Un-melted powder is also far less thermally conductive than solid metal, and so heat from the melt pool is retained for longer, resulting in more sintering of surrounding powder. In this way, overhangs are likely to exhibit a rough surface finish.

In the example above, layers of metal are being built up to create a profiled internal channel. Green layers will build OK, yellow layers will build but may suffer from poor surface finish, and red layers will distort. As we move up the curved left-hand edge of the channel and the overhang angle increases, the layers eventually become poorly supported, until we reach the horizontal overhang where the layers will sag and may fail.

The rule of thumb is that overhang angles greater than 45 degrees to the vertical should be avoided, with 30 degrees being preferable. Overhang angles greater than this will need supports.

Lateral holes

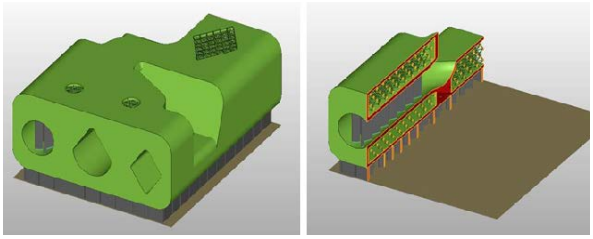
Holes in the side of AM components create overhangs. The scale of deformation in circular holes primarily depends on their diameter and also varies for different materials. As a general guidance, circles with a diameter less than 10 mm can be self-supported without causing visually noticeable distortion.

Minimising supports

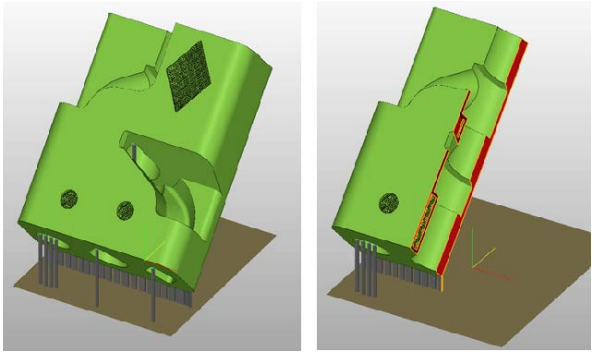
One answer to the problem of overhangs is to support the overhanging feature. However, supports are effectively waste and have to be removed after the build is complete: they enable the AM process to succeed, but add complexity and cost further down the process line.

So a key part of the DfAM process is to assess how to build the part with the minimum of supports. This means eliminating overhangs by angling the part, and by modifying the design of overhanging features such as holes, slots and channels.

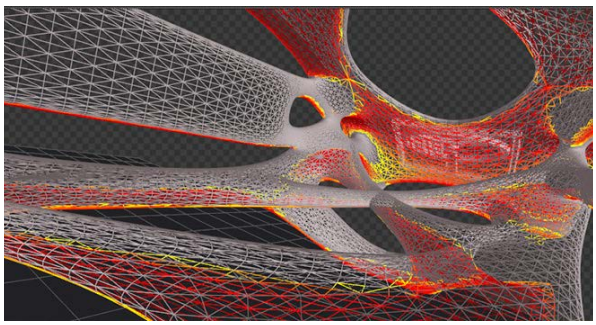
We are used to designing round holes because that is what we can most easily produce subtractively. Where roundness is critical, then it is best to orientate a hole so that its axis is vertical with no overhangs. If the hole must be in the side of the part, then consider whether it needs to be round or if it can be modified to make it more buildable - into a 'teardrop' or diamond shape, for instance. In the example below, the round lateral hole requires internal supports - the teardrop and diamond holes require none.



Orientation is another way to avoid supports, although this can come at the expense of additional layers and build time. In the image below, we have tilted the component so that none of the interior of the cylindrical hole requires supports, just those areas where it breaks out into the end face of the part.



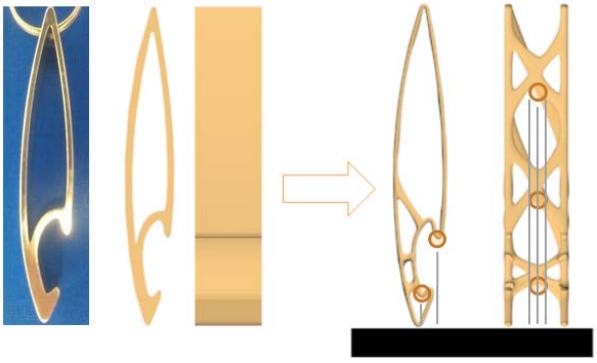
This optimisation of component design and build orientation can be tricky - eliminating supports in one area of the part through re-orientation can lead to supports being needed elsewhere. Renishaw's new QuantAM build preparation software provides instant visualisation of areas of the part that are unsupported, and can assist with support deployment.



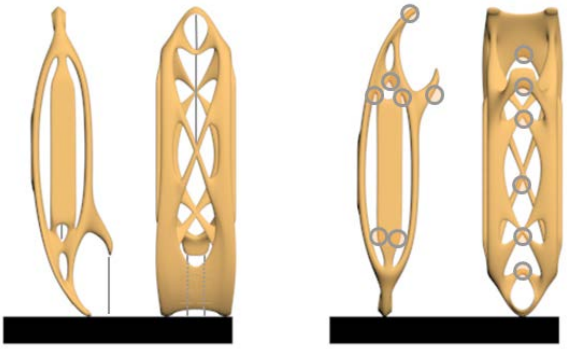
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Case study - eliminating supports

Let's look at an example of dealing with overhangs. Renishaw's AM beer bottle opener was originally conceived as the sleek design shown left (below). Our first attempt to optimise this part for AM involved eliminating weight by creating a more intricate structure shown below right. This resulted in several overhangs (circled in orange), necessitating additional support material (grey).



So we tried again, this time with some additional structures to minimise the supports needed (below left). But by inverting the part (below right), we were able to design a build with self-supporting overhangs (circled in grey), with just a tiny support to connect the bottle opener to the build plate.



And here they are on the build plate. Cheers!



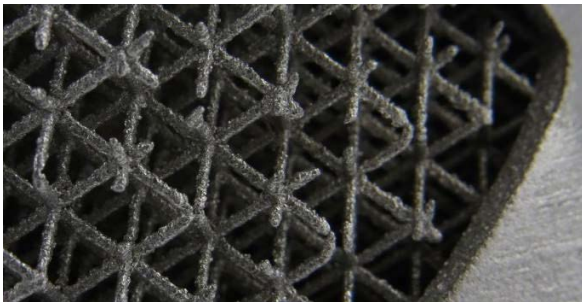
Residual stress and distortion

AM is essentially a welding process, although the beam spot diameter is smaller than with conventional welding and so the energy density is high. This can lead to stress in large cross sections or in parts with varying cross sections. That stress tries to break through the edge of the part, as shown below.

This stress can cause warping and, in extreme cases, can cause the part to pull away from its supports, or even to crack. Where thick sections have to be built, it is wise to select a thicker build plate to resist these bending forces.

In general, very thick sections are best avoided in AM parts, especially in materials such as titanium where melting temperatures and residual stresses can be high. Where possible, sections should be kept thin and consistent so that stresses in one area of the part do not distort the rest. Where blocks of material are essential, consider filling them with lattice to reduce stress, weight, material cost and build time.

Lattices can also be used to brace very thin walled structures that might otherwise warp due to stresses induced as they cool.



Summary

AM gives us huge freedom to design parts differently, but we do need to be aware of some of the characteristics and limitations of the process, so that we create parts that can be built successfully.

The DfAM rules described above are not too onerous in practice, and actually encourage us to consider ways to make parts that are lighter, faster to build, and more cost-effective.

Modern design and build preparation software helps enormously to find an optimum design, orientation and support strategy so that we can produce consistent parts economically.

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About the author

Marc Saunders, Director of AM Applications

Marc Saunders has over 25 years' experience in high tech manufacturing. In previous positions at Renishaw, he played a key role in developing the company award-winning RAMTIC automated machining platform, and has also delivered turnkey metrology solutions to customers in the aerospace sector.

Marc manages Renishaw's global network of Additive Manufacturing Solutions Centres, enabling customers who are considering deploying AM as a production process to gain hands-on experience with the technology before committing to a new facility.

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