Markforged Mark Two: Part 1

In the first of a two part review, **Al Dean** gets hands on with Markforged Mark Two, the next generation of the Boston-based 3D print start-up's product line. Here, he looks at the basics of how the 3D printer works

TECH-SPECS

- » MarkForged Mark Two
- » Nylon Filament + Single Strang Fibre
- » 320 x 132 x 160 mm build volume
- » 575 x 322 x 360 mm machine dimensions
- » 13kg weight
- » 0.1mm layers
- » Nylon + Fibre (Carbon, Kevlar, Glass)
- » Material spool containment, build plates, model removal + clean up tools
- » 1 year return to base warranty
- » Price from $5,499/£3,890 + VAT
- » markforged.com

Markforged caused a bit of a stir when it debuted its Mark One machine a couple of years ago. While much of the 3D printing industry was going nuts for ever cheaper, ever crappier desktop 3D printers, the company came out of nowhere (well, out of the auto-sport industry) and delivered a desktop sized 3D printer that not only looked like it was a product intended for engineers and designers (rather than the yoda head brigade), but also had more than a few secrets up its sleeve.

Markforged's products are centred on the idea that alongside nylon materials, it's also possible to build in layers of fibre. That alone got the company some serious attention and some serious investment.

What differentiates Markforged's process from other fibre re-enforced composite capable printers is that the fibre is a continuous strand, rather than chopped short strands.

That gives you superior mechanical benefits and the range of materials available are growing. But before we get onto the subject of composite reinforced parts, we need to deal with how the system works.

The reason for this is that we quickly realised that the Mark Two is a rock solid printer without factoring in the composites angle, so we're going to look at how the system works with just the base nylon material in the first part, look at the set-up and build process, then look at the benefits of composites in the second part. Make sense? Good. Let's go.

THE MACHINE AND SET-UP

The Mark Two arrives in a clearly labelled box and unpacking it is pretty simple. You'll need a decent space around the machine as the cover tilts right back over the casing. You'll also need to find room near the unit to accommodate the Pelican Case that holds the nylon filament spool (Nylon is pretty hydroscopic in filament form, so the case keeps things close to air tight).

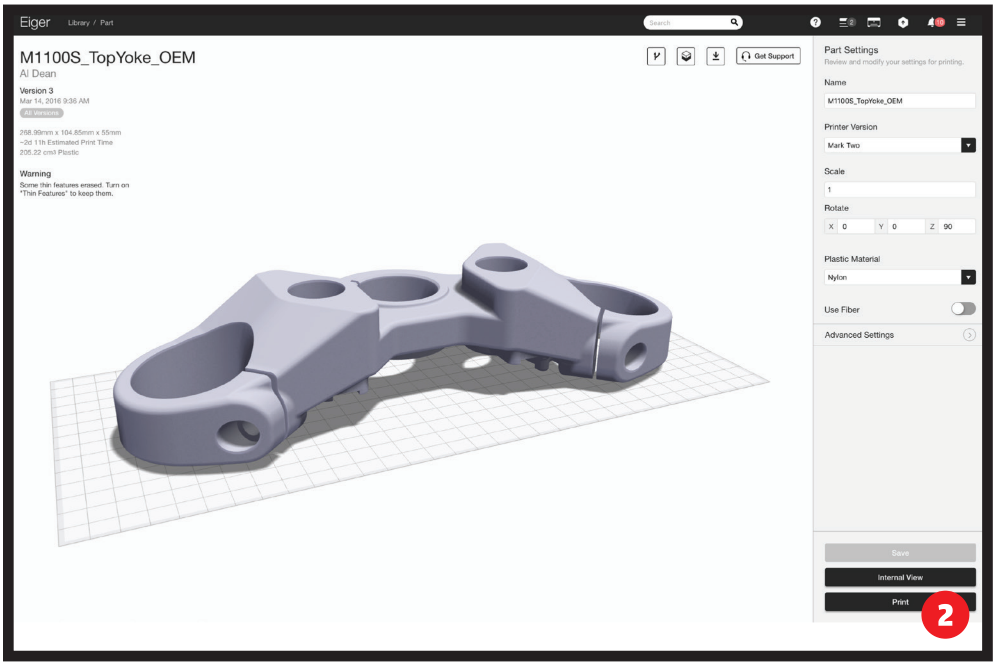
Connectivity is with a simple power unit and you have a choice of wireless or ethernet – we ran with wireless as it made life much easier for set-up in a corner of the workshop. You'll also find all of the accessories in the accompanying box and we'll step through those next as you set-up the machine.

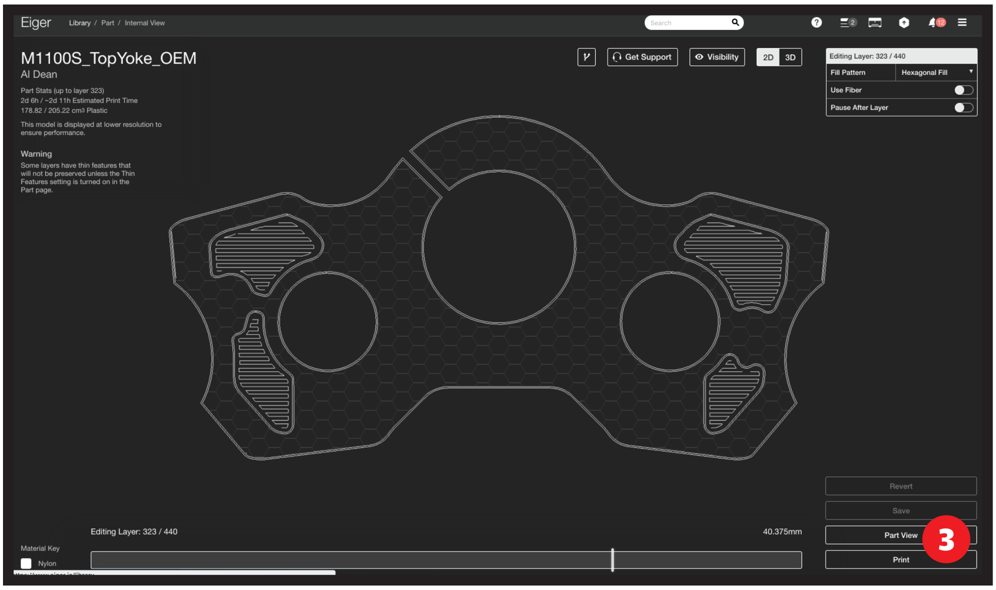
There's a powerswitch on the rear of the unit and it'll boot up. You'll immediately notice that the small touch screen at the front of the inside comes to life.

Compared to many desktop 3D printers, the user's interactions with the machine are nice and simple – everything is done from this panel.

The first step is to connect it to wifi or plug in the ethernet cable to your network. Once it acquires an internet connection, the machine will update itself to the latest firmware. Again, this is a breeze and the machine handles everything for you – no messing around with SD cards or other such contraptions.

Once that's complete, you then start





❶ With it's aluminium casing, the MarkForged certainly looks more the part in a design or engineering office than most 3D printers at the desktop level

❷ Markforged Eiger's 3D view showing one of our test parts on the machine bed. Global settings are adapted here

❸ If you want to optimise the internal structure of the part, you switch to the internal view. This allows wall, floor and roof layers, as well as internal fills to be adapted on a layer by layer basis

to set-up the machine. As you'll discover, the system guides you through the whole process, whether that's feeding the filaments through the machine's casing (again, pretty simple) as well as adding in the build platform and levelling it.

Bed levelling is something that's worth paying a lot of attention to. The build plates are solid aluminium billet with a special coating to help adherence of the model. Getting this dialled in is critical to efficient model building.

Unlike some FDM machines, the Mark Two uses a three point magnetic location mechanism to hold the build plate in place. Adjustment is carried out using thumb screws beneath each of these locators. The system guides you through the process and using these on-board prompts along with the shims/feeler gauges, it's done in minutes.

Depending on the material you're building with, you'll need to level the bed against the nylon nozzle, then the fibre nozzle. There is a little fine tuning involved, but once done, you'll have it dialled in and ready.

It's worth noting that bed levelling isn't required for every build. MarkForged recommend that if you're building with fibre, you need to level the bed every couple of jobs, but if you're just running with nylon, then it should remain pretty consistent for 10 or so job – and our experiences back that up.

Last step before you start your first print job is to coat the build platform with the supplied glue. If you're looking to invest in this machine, you might want to track down some of this stuff as it's quite hard to come by in the UK – Elmer's Invisible Glue.

This helps the model stick to the platform and gets you a solid result, so it's worth the effort.

MARKFORGED'S SECRET SAUCE

Now that the machine is ready, you're then ready to start doing the set-up work on your first build job. Unlike some older generation 3D printers, Markforged machines use a cloud-based pre processing and job management system (If you take on the Enterprise bundle, this is also available for non-networked environments). You securely log-in to the system and pair it with your printer (it's capable of handling multiple machines).

What you're presented with is a clean environment where you can set-up each part you want to build as well as print jobs (which is a platform that contains multiple parts). To begin, you upload your STL data to the sytem.

As you'll see in Figure 2, the interface is clean and shows you the part and a reference for platform size. Here, you can rotate, scale and arrange your part. You also have the ability to define the global parameters of the parts.

As default, the Eiger has a good set of parameters set-up for the number of wall layers, the infill density and style (there's a couple of options in terms of geometry) and top and bottom layers.

While those defaults are excellent, it's also possible to expand the options and dive into the global details. This allows you to add more strength to the outer skin of the part or to vary the infill density.

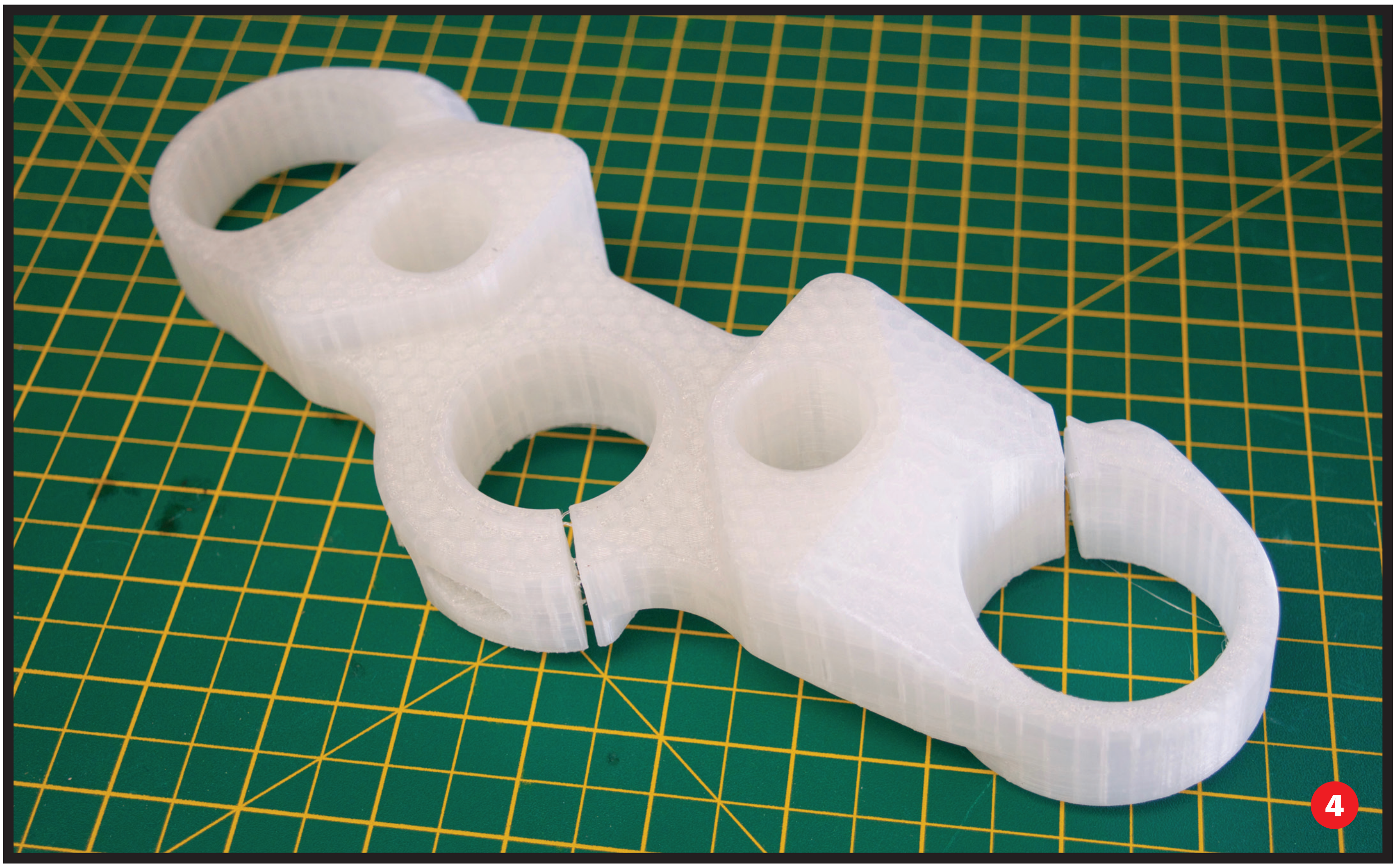
If you then want to dive into the options further, you can also then switch to the "Internal" view. This gives you full control over what's happening inside your build. While this is predominantly aimed at the lay out of fibre content (and we'll cover this in the second part), it can also prove useful with pure Nylon parts without fibre content.

One excellent example is being able to pause the build process at a specific layer. Why might you want to do that? The answer is pretty simple. As the Mark Two is a nicely sealed unit and the mechanics of the system mean that the build tray removal and subsequent relocation is both consistent and accurate, you can pause the build at a specific time and add additional parts to the build.

For instance, there's the ability to add in fasteners, such as brass inserts, into the part, then have it complete the build. The set-up for this is a case of making sure you plan where the fastening features are going in your 3D model, then ensuring that you leave enough room to fix those fasteners in place.

The trick here is to get it dialled in, make sure that you can add the parts you want in and that the top of them remains flush with the top of the partial complete build. Otherwise you'll end up with a machine crash as the nozzle catches it.

> "The interface is clean and shows you the part and a reference for platform size. Here, you can rotate, scale and arrange your part"



If you get that right, you start the build, have the machine pause where you need it to, remove the build plate from the machine, add your hardware, then snap it back into place and complete the job.

While fasteners, bearings and location hardware are the obvious uses, there's the potential for much more here.

With the rise of greater use of sensors, these could also be factored into the build, so the part comes off the machine ready to go. Yes, it'll take some testing and experimentation, but it's entirely possible.

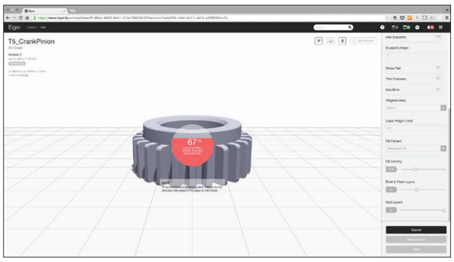
POST PROCESSING

As with all single material build machines, MarkForged's machine needs some attention when it comes to post processing parts. The parts are, unless you're lucky, going to have some form of support structure in placement, so they'll need to be removed manually. But if you're clever in your placement and orientation, this can be reduced to a minimum.

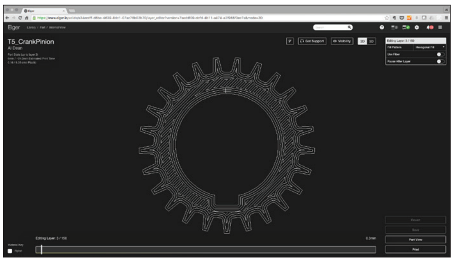
In terms of getting the parts off the plate, it's simple and you're given all the hardware you need. The build plate will

4 Our largest test part – a triple tree yoke bracket – a two day build that came out exactly as required

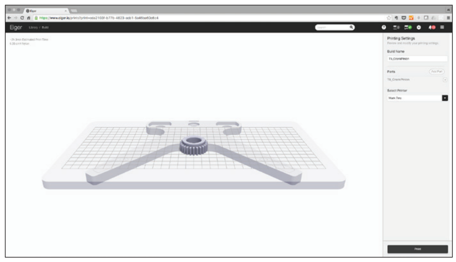
MARKFORGED MARK TWO: BASIC 3D PRINT SET-UP PROCESS



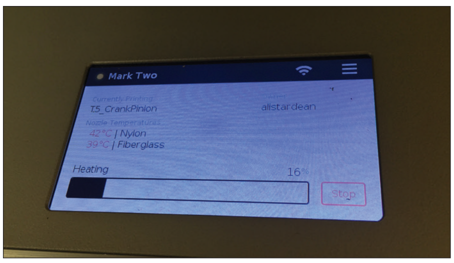
1 Log into Eiger.io, upload the STL file and define the key overall parameters for the build process; these include fill density and style, roof/floor/wall layer coun.



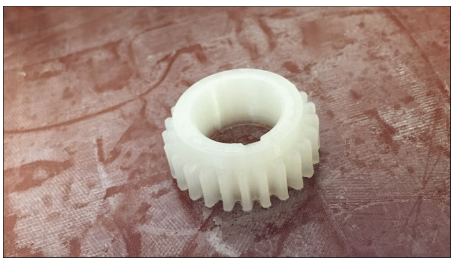
2 Switch to the Internal View mode and inspect the internal build details of the part to ensure it'll perform as you require – fill can be varied on a layer by layer basis.



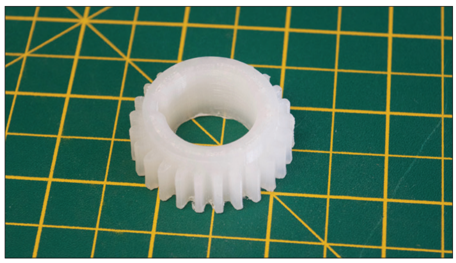
3 Next step is to add either add the job to the queue or to start the build process. Once your build plate is prepped (with a coating of the magic purple glue) you can start



4 The machine will then kick into life. It'll download the build file, preheat the machine and fibre, then start. This can all be monitored on the machine or remotely



5 An hour or so later, your part is ready. You'll get notifications to tell you and then the machine will cool down and your part will be ready to be removed



6 Once your part is cooled, it's pretty trivial to remove the component from the build platform, do a little finishing up and it's ready for whatever you intended it for

> **As the Mark Two is a nicely sealed unit and the mechanics of the system mean that the build tray removal and subsequent relocation is both consistent and accurate, you can pause the build at a specific time and add additional parts to the build**

also need a bit of clean up once the jobs are complete – then you pop it back in ready for the next.

The end result of parts without fibre are excellent. It's a filament based machine, so isn't particularly suited to very fine detail but to mark it down for this would completely miss the point of the Mark Two. It's a machine that gives a lot more than you might be forgiven for expecting from its desktop size.

Some clever engineering means that you've got a whopping 320 x 132 x 160mm. One of our test pieces (it's a triple tree fork bracket) fitted on the build platform in one piece – a first for desktop sized machines.

If you're looking at producing smaller parts, then it means you've got enough room to get a good sized batch complete in one go.

Build speed is also good and the controls you have over the process means that if you're wanting a quick sanity check for size and feel, rather than a more structural part, you can dial back the infill and get your part out of the machine much quicker.

IN CONCLUSION

While I'm going to give the full set of conclusions in the second part, it's also worth noting that the software infrastructure that goes alongside the system really is first class. The fact that it's cloud-based means that you have a resource that's available wherever you need it. You can set-up jobs where you want to, rather than on a local machine. Multiple users can submit jobs to the queue whenever they need and yes, it gives you a full set of monitoring and notification tools as well. This is clearly a machine that has potential for short batch manufacture.

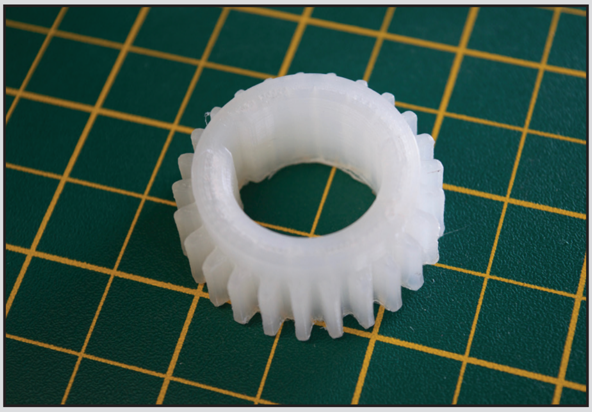
It's also worth noting that the system also has a very slick version management and file handling infrastructure. Each change is managed, and it's possible to branch a model and upload new STLs – so experimentation with both geometry and build parameters is done in a nicely managed environment.

Of course, what really makes this machine unique is the fibre capability and we'll be exploring that next in the second part of the review. But as we said at the outside, purely focussing on that would do this machine a disservice. As a pure nylon build machine, it's outstanding. MarkForged have also just released a new material that offers a single build material, onyx.

This gives you a black nylon fill with micro carbon fibres. If this is an indication of where Markforged are going with the Mark Two (and subsequent models) then it looks like excellent news for all.

Take a look over the page where we explore how you set-up fibre enforced print jobs and discover where the Mark Two really comes into its own.

INTRICATE



Test part: Gear

Challenge: This small component is small (diameter is 40mm), with a number of key internal features and the teeth need to be functional for testing.

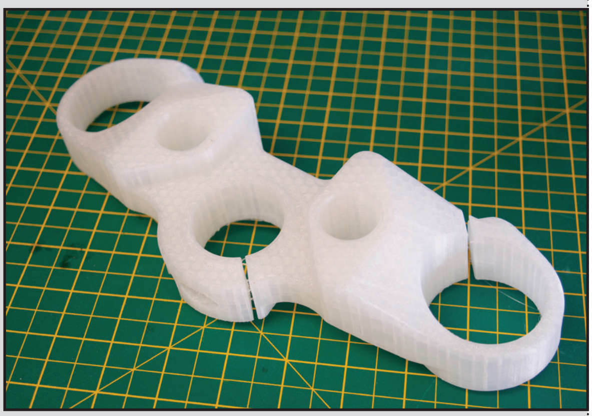
Material usage:
Nylon @ 6.35 cm3 (including supports) – built with solid in-fill for maximum robustness

Build time:
2 hour 3 minutes (@0.125 mm) + Solid in-fill

Cost: £1.08

Results: This is a part that needs dimensional accuracy and robustness to test with other mechanism components. The results were a solid part in a couple of hours and minimal clean up time.

BULKY & TALL



Test part: Ducati yoke (two part build)

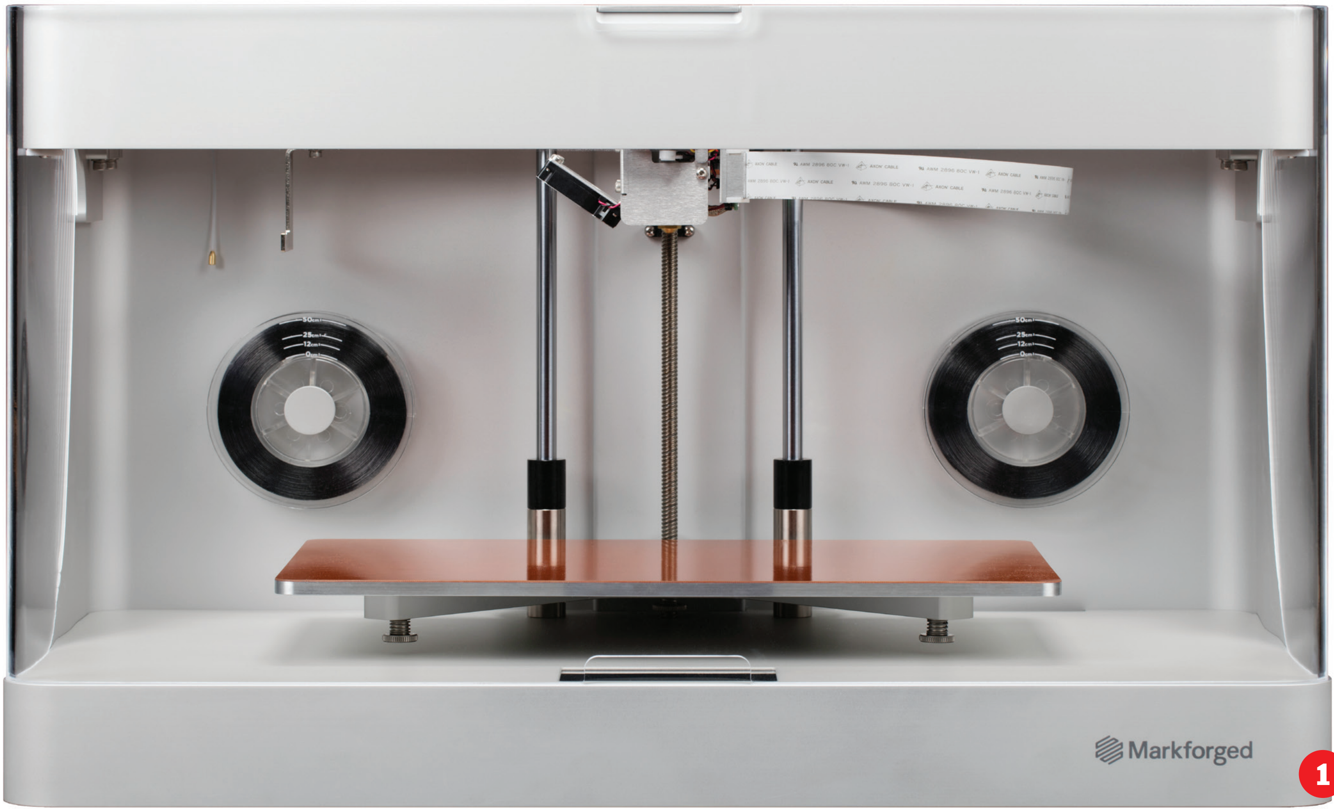
Challenge: This is a big part usually requiring that it's split into two parts. On the Mark Two, it maxes out the build chamber, but you get the whole part in one run.

Material usage:
Nylon @ 205.22 cm3 (including supports) with 25% in-fill density

Build time:
2d 11h (@0.125mm) – 25% in-fill density

Cost: £34.89

Results: This is a perfect use case for running the Mark Two with just Nylon. It's possible to build larger than normal parts, on the desktop, and get a good robust model for fit tests. If you need to add more rigidity, then the in-fill density can be pushed lower, but build time will increase.



Markforged Mark Two: Part 2

Following on from Part 1, where we looked at the basics of the Markforged Mark Two, **Al Dean** now turns his attention to the fibre composite capabilities of the machine, how it works, what end results it's capable of and the benefits it can bring

In part one, we looked at the basics of the Markforged Mark Two and found a desktop printer that provides a very workable build envelope of 320 x 132 x 160 mm with a nylon and composite filled nylon variant filament material. On that premise alone, the machine impressed us, both in terms of the end result and the consistency that's a trademark of the system. That said, the real interest in the Markforged machine has grown around its additional ability to add in single strand fibres (of a variety of types) to build composite parts. This is what we're going to explore in the second part in a little more depth.

Let's start by looking at how the machine enables the deposition of fibres as part of the build process first. The answer is that the Mark Two (as the Mark One before it) is a dual extrusion head machine.

You'll notice from photos of the machine that behind the build plate are two reels – these are the much smaller fibre reels. Both are held on with simple but strong magnets. The one to the right is purely for storage and the left is where the fibre feeds from.

As we mentioned in the first part, the calibration process requires that the user calibrate both print heads during set up. The fibre nozzle differs from usual filament extrusion heads in that it also includes a cutting mechanism for cutting the fibre once it lays each run of fibre.

So, now the mechanism is out of the way, let's talk about the really key factor – how to go about designing a composite part in the Markforged Eiger.io system.

COMPOSITE DESIGN IN EIGER

Eiger is Markforged's software connectivity and pre processing system. Because it's predominately cloud-based (there is an option to run this off line which we'll explore later), it provides some pretty serious compute power. And when it comes to pre processing an STL file for a composite build, that power will definitely be needed. So, let's start with the basics of how to take a part and prepare it for build in a composite manner.

As we covered in part one, the process begins by uploading the geometry to the system. Now in the global 'part' view, the user can define the overall parameters, such as the number of boundary layers (on both the walls together with the top and bottom of the part) as well as the overall in-fill (there's a choice of triangular, hexagonal or concentric) and the associated density. There is now the 'Use Fibre' toggle with which the system automatically constructs a sandwich panel type arrangement for the build.

It's at this point, a basic knowledge of composite design is handy. However, if you've not worked in this field, then it's worth getting hold of a good textbook.

To inspect what the system has done, switch to the 'Internal View'. This pops up the same part, but allows the user to inspect the internals of the part build scheme. The 3D view shows the whole thing, with the various layers, fibre layers (in blue) and any support structures needed.

At the bottom of the screen there's a horizontal widget that shows the make of the part layer by layer. The graph in that bar also shows how much fibre is being deposited and allows the user to make changes to that "group" of layers in one hit. That group can be expanded to add fibre to more layers or indeed, to reduce it to where it's needed most.

If the user would like layer by layer control, a switch to the 2D view allows a step through each layer at a time.

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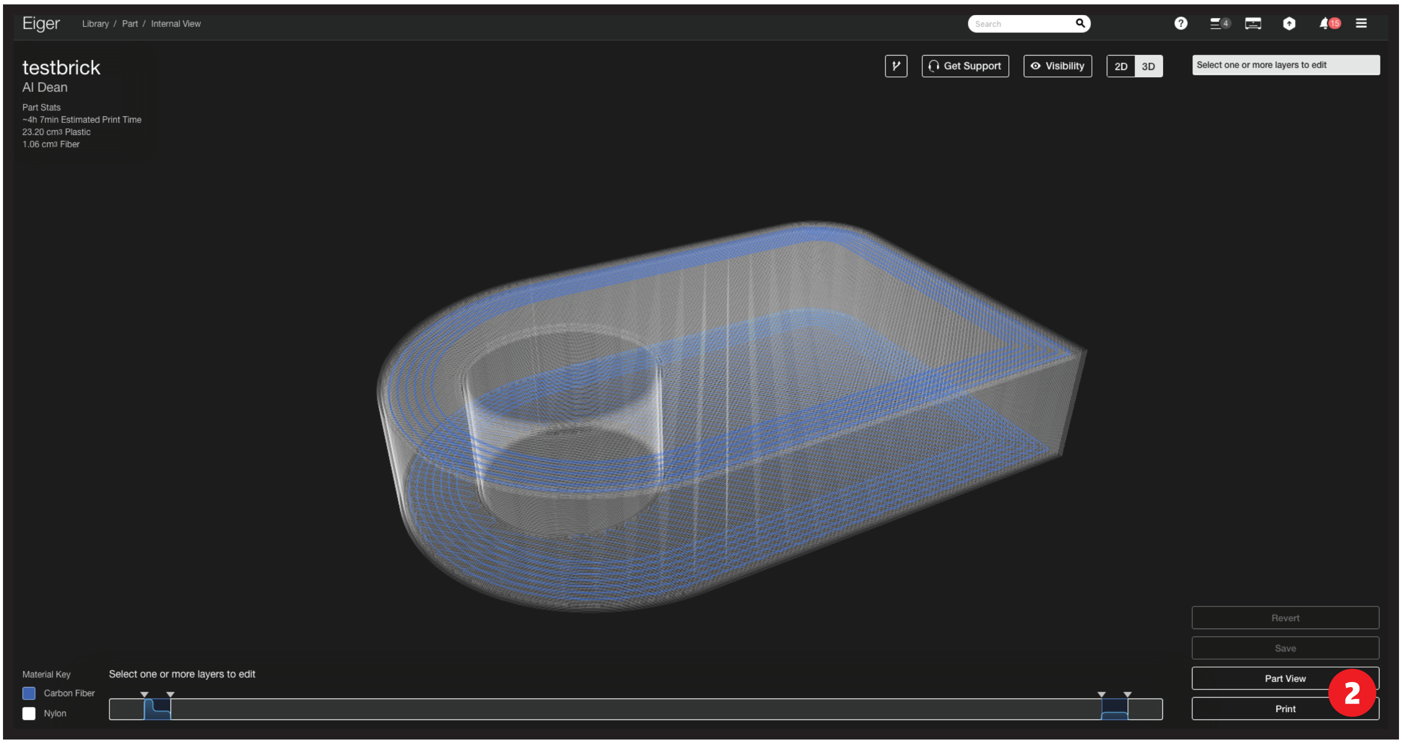
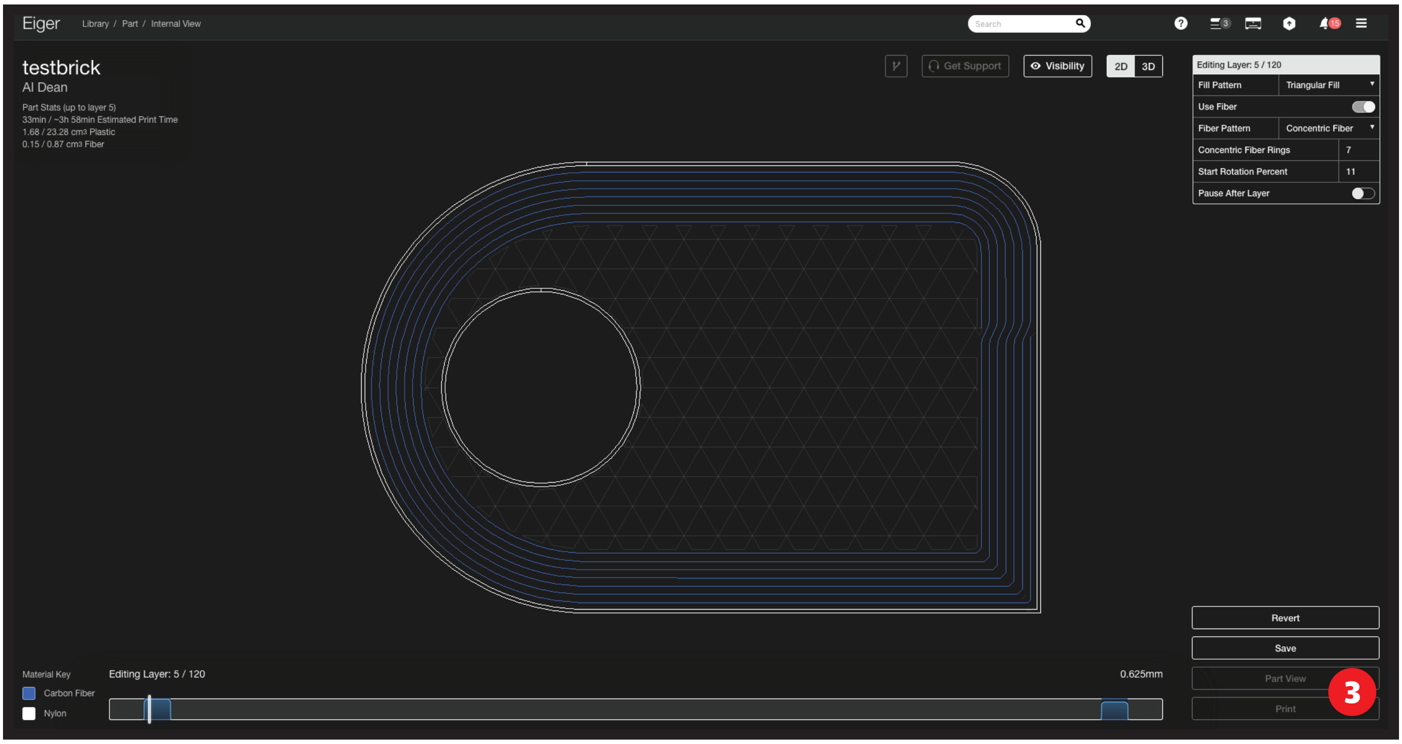




1 With its aluminium casing, the Markforged Mark Two certainly looks more the part in a design or engineering office than most 3D printers at the desktop level

2 & 3 Markforged Eiger's 3D internal view then the 2D view, showing concentric rings of fibre. Note the single strand running around the whole part's periphery

LAYER CONFIGURATION

When it comes to fibre layers, there are two key forms of fibre deposition. Concentric is just as you would imagine. It follows the outer profile of the part and fits a single strand of fibre inwards in rings from that outer boundary. If you take a good look at Figure 3, you'll see that the test part is defined with seven concentric rings.

Further inspection shows that this is a single strand (the point where it moves to the next ring is circled in red). Interestingly, the system knows that this point is a potential area of weakness, so if there are multiple layers at the same settings, Eiger will automatically move this transition point around the part, so there's good overlap.

The other option is isotropic. As you'll see from Figure 4, this is a more linear approach to fibre layout. What's interesting here is that, firstly, it fills the complete layer where possible with a single strand, but secondly and more importantly, the user has explicit control over the angle of that deposition. Just as in more industrial, established composites design, the user has full control over this layer by layer. Of course, global parameters can be defined (to rotate each layer by 45 degrees for example), but if the user wants to dig into it and truly optimise a design, then this can be done layer by layer if needs be.

To further complicate things, it's also possible to combine the two, as shown in *Figure 5 on page 7*. Again, the user has full control over the global and individual layers, rotation, number of rings and so can really go to town.

Once the part is in a fit state, it's ready to print and this follows the usual process of aligning it on the print bed, preparing the machine and either selecting the part from the print queue (on the machine) or sending it to print directly.

The rest is pretty much the same. The system goes away, does its thing and sends a notification when it's done. Then it's a case of removing the parts, cleaning up the print bed for the next job and removing any supports.

END RESULTS WITH FIBRE

Composite design is a complex business, whichever way you cut it and whatever method you're using to build the parts. When it comes to 3D printing, the complications are there, but your use is also restricted in a couple of ways.

Foremost, there's the linear nature of the beast. The 3D print process requires that all of the fibre deposition is done in a single plane. We're not talking about fibre plies laid over a former here. This is strictly 2D in nature. That means that the benefits that will be derived are inherently limited to both the user's imagination and ingenuity, as well as the form of the part and how it is arranged on the print platform.

That said, there's huge potential here to be creative and find ways to not only improve a part for prototype's sake (you can get a much lighter weight, but stiffer part than most 3D printers), but there's also potential for end use parts.

While many of Markforged customers aren't talking about their use of the machine yet, the ones that are have a couple of things in common. One is that they're using the machines to provide end use parts to either go into the field or to support production. It's found a home in jigs and fixtures, as parts can be made that would typically have a finite lifespan or are sacrificial, but require something a little more sturdy than your typical 3D printer is capable of.

Others are building low-volume components that are suited to the mix of a nylon base material with the added mechanical and thermal benefits of fibre reinforcement.

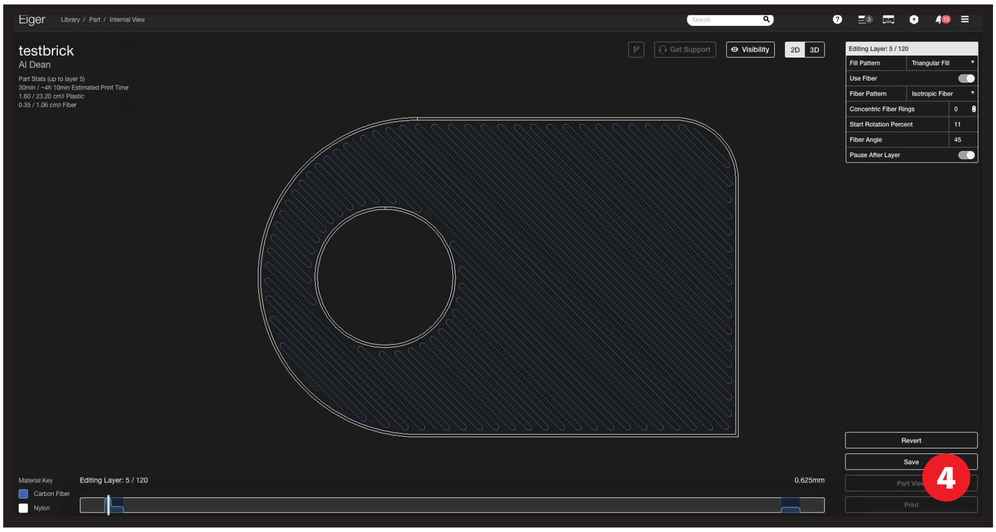
At present, Markforged has two core materials. The standard Nylon is a good core to start with, then the team has just introduced the Onyx material that boosts Nylon's properties with micro carbon fibre in fill.

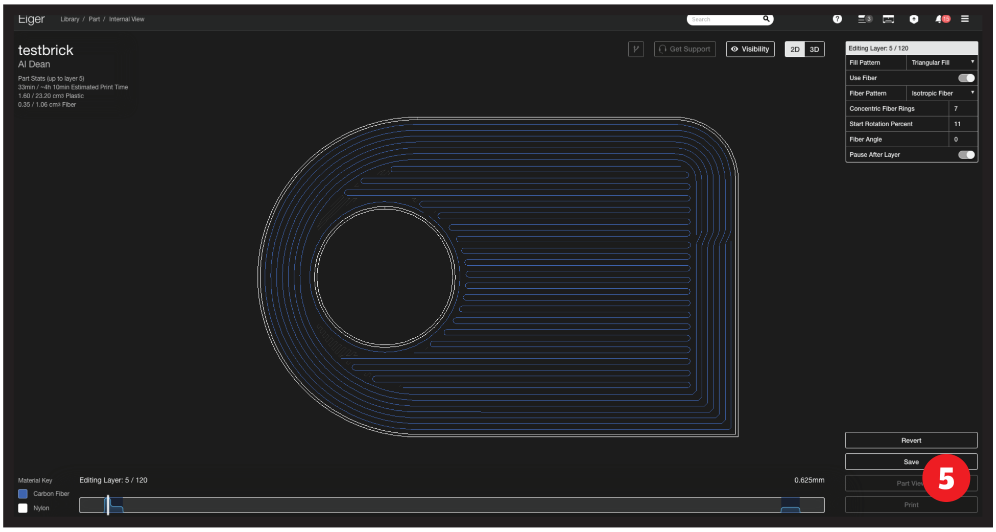
Then you get into fibres. Glass fibre is the cheapest (we'll get onto costs shortly), then there's Kevlar and Carbon fibre. There's also a new high temperature glass fibre for applications over 105°C, with a heat deflection point of 150°C.

The possibilities are expansive with this combination and the selection of material combinations will depend entirely on what the user wants the parts to do, their geometry and how they want them to perform – something which is very hard to quantify in the context of this review.

COST OF OWNERSHIP

Now. Let's talk turkey. How much does this bad boy cost? The answer is surprising, considering what it does. The base price for the Mark Two is $5,499/£3,890. That includes the machine, 1,000cm³ of nylon base material, 50cm³ of glass fibre, one set of nozzles and a single base plate. To my mind, that's a steal. But then it gets interesting. As you step up the range, the capabilities grow.





4 & 5 **The same part but with an isotropic fill, then a combination of both concentric and isotropic fill – all controllable, layer by layer**

The Mark Two Professional (at $8,799/£5,990) includes the machine, two build plates, three sets of nozzles, 2,000cm³ of nylon base material, 200 cm³ of glass fibre, then 100 cm³ of both carbon fibre and Kevlar.

If you want to go all in, then the Mark Two Enterprise bundle is $13,499/ £9,995. That includes everything in the Professional kit, but the material bundle changes: 1,000cm³ of Nylon, 100 cm³ each of glass fibre, Kevlar, carbon fibre and the new HSHT glass fibre. It also comes with 800cm³ of the Onyx carbon filled nylon too.

It's also worth noting that while the Standard kit gives you just the cloud-accessible Eiger platform, both the Professional and Enterprise kits allow you to run this locally, without the cloud-based infrastructure for the more security tight environments.

In terms of consumables, the machine comes with everything needed in terms of your first set of prints and experimentation (which I would imagine will be high as you get a feel for how best to use this machine). After that, as with every machine, there are parts that need to be replaced and additional materials to be purchased.

In terms of parts that will need to be refreshed, the nozzle sets are priced at £43. With most 3D printers, as soon as you start to work with more aggressive materials the nozzle life reduces. In contrast, the nozzle that Markforged supply is tougher than most, but are still a consumable at the end of the day.

The same is true of the print beds. These are priced at £129 each, but should last a good while with good care and maintenance.

As for the materials, these are pretty straightforward. The base Nylon is £170 for a 1,000cm³ reel. That's more costly than your typical filament, but this is a specialised material formulated to play well with other materials. The Onyx build material is £130 for 800cm³.

When it comes to fibre, it varies, as you would expect. All are supplied in smaller 50cm³ with glass fibre being the cheapest at £59, Kevlar £79, Carbon fibre £99 while the HSHT fibre hasn't yet been priced in the UK.

In our test parts, we found that the costs per part on the test builds were competitive with other professional level machines. Yes, as you add fibre, the price goes up, but with judicious design choices,

> **Those of us that have been around the industry for a while are tired of ever cheaper machines that do the same job. The Mark Two shows that the new age of 3D printing can bring something new and robust to the industry and push things forward – without breaking the bank**

this can be managed effectively. It's also worth noting that the build times also increase as soon as you start to factor in fibre, but that is to be expected.

IN CONCLUSION

It struck me while writing this part, that we've talked as much about the software tools as the actual Mark Two machine and this perhaps does it a disservice as it's an incredibly well engineered machine that has given us a 100% success rate with whatever we've thrown at it.

The reality is that when you have a reliable machine like the Mark Two, you're ultimately left with the hard work to do – and in this case, it's working with Eiger to make sure that your use of fibre reinforcement is exactly where and in whatever form you need it.

This isn't a simple case of choosing the best orientation angle for your model so you have the best surface finish, this is about making engineering decisions on the form of your part and a near granular level of control over where key material is placed.

Of course, you can just run with the defaults, choose whether or not to include a couple of layers of fibre where you need them quickly, and hit print but the Mark Two is capable of much more.

The results will depend on what you want your part to do and as such, it's a proper engineering tool and manufacturing system, one that can do things that no other system can at present.

That potential for experimentation is enabled by the Eiger system that's core to the whole experience. It's structured in a way that supports engineering and design decision making and experimentation (with its branching and version management tools). It also enables sharing and collaboration. But perhaps most importantly, it gives you granular control that is not often seen in 3D printing related software – down to the layer and sub layer level. It's this simple fact that makes the Mark Two an impressive solution and one that will find a home in a wide variety of companies and organisations.

As much as we've seen the explosion (and subsequent implosion) of hype surrounding 3D printing, we're only now starting to see truly unique machines and processes come online that give professionals a set of tools that support and benefit design and engineering. We're past the cost cutting and ever cheaper machines and into the realms of true innovation.

Those of us that have been around the industry for awhile are tired of ever cheaper machines that do the same job, just slightly less efficiently with questionable build quality and consumer priced, crappy materials. The Mark Two shows that the new age of 3D printing can bring something new and robust to the industry and push things forward – without breaking the bank.

So, although the Markforged Mark Two is impressive, when considering the cost of ownership, it becomes even more impressive. Yes, the Professional and Enterprise level bundles push the price up, but remember that for under 10 grand, you're talking about a machine that can build with advanced and an expanding range of materials. It still represents outstanding value for money.

There's much to get excited about – the machine is rock solid, performs consistently and has the potential to change how both prototypes and production (at low volume) are built. I couldn't recommend it more and trust me, your desktop will never be the same without one.