victrex

ADDITIVE MANUFACTURING FILAMENT FUSION PROCESSING GUIDELINES

CONTENTS

Industrial Additive Manufacturing Grades

Victrex AM™ Filament

VICTREX AM portfolio includes two filaments for the fusion fabrication process:

- **VICTREX AM™ 450 FIL which is based on VICTREX PEEK 450G™.**
- **VICTREX AM™ 200 FIL which is a PEEK copolymer, based on the Victrex LMPAEK™ polymer.**

Material properties are provided on the technical data sheets on www.victrex.com/data sheets.

Granule Grades

Direct granule extrusion additive manufacturing machines are becoming more prevalent in the market, particularly for large area printing. For large area printing, short fiber-filled versions are generally the most suitable due to the size of the parts produced.

Smaller, more precise direct extrusion machines, like the Arburg Freeformer, are also becoming increasingly available. For these machines, granule grades of the VICTREX AM™ materials are being introduced.

Most of the guidance in this document still applies to direct extrusion additive manufacturing. Future updates will include filled materials. Contact us for information on granules.

PEEK Printing is hard. VICTREX AM™ 200 is easier.

Printing using traditional PEEK, like VICTREX AM™ 450, is challenging and requires specialised machines and knowledge due to the thermal shrinkage, crystallisation shrinkage, speed of crystallization, and high temperatures.

VICTREX AM™ 200, made from the LMPAEK™ PEEK co-polymer, is easier to print but still requires careful attention to achieve optimal results. Tips to improve printing are in this guide. Two pathways to printing PAEK are described: route 1 for directly printing crystalline parts in hot chambers >150°C, and route 2 for printing amorphous VICTREX AM™ 200 in chambers < 150°C.

Optimised Printing Profiles from Machine Makers

Some machine manufacturers have created profiles for VICTREX AM™ 200, VICTREX AM™ 450, and PEEK. Starting with offered print profiles for VICTREX AM™ 200 or VICTREX AM™ 450 is preferable, as the profiles are optimised for the equipment and software.

If a custom VICTREX AM™ 450 profile is unavailable, a generic PEEK profile may be used, especially for printing on a high chamber temperature machine (>150°C). It is not recommended to print VICTREX AM™ 450 PEEK on a low chamber temperature machine as it typically results in weak parts.

VICTREX AM™ 200 is more versatile and can be printed on lower chamber temperature machines with effective results.

Invibio Medical Grades

Victrex materials are not approved for medical implant applications. Victrex' medical business, Invibio, has developmental grades, and implant grades (available only to Medical Device Manufacturers). Visit www.Invibio.com for more information. Filaments made from PEEK-OPTIMA™ polymers process similarly to VICTREX AM™ 450 FIL.

Summary & Quick Reference

If you are new to printing high temperature polymers like Poly Aryl Ether Ketones (PAEK), It is recommended you read the detailed sections below. As a quick start, here are suggestions for the most important settings:

	VICTREX AM™ 200 FIL	VICTREX AM™ 450 FIL
Nozzle Temperature	380-400°C (340-425°C possible; no higher than 450°C)	380-400C (380-425°C possible; no higher than 450°C)
	VICTREX AM™ 200 FIL provides a wider melt temperature window than VICTREX AM™ 450 FIL.	
Nozzle/Tip selection/Machine components contacting the melt	Avoid copper, nitride coated, and aluminium components. Make sure the internal surfaces are as smooth as possible.	
Drying Temperature	120°C overnight; Higher temperatures possible but not recommended on the provided polycarbonate spool.	
Chamber Temperature	Route 1: Crystalline printing. Both VICTREX AM™ 200 FIL and VICTREX AM™ 450 FIL can be printed crystalline in high end machines >150°C chamber temperatures. Typically, 175-200°C, to as high as 250°C, though geometric replication will suffer.	
	Higher chamber temperatures will yield higher interlayer strength. This comes with a trade-off of surface, bridge, and overhang quality.	
	Route 2: Amorphous printing, < 150°C, typically 100-140°C; Starting suggestion 135°C. Lower than 100°C is possible but not suggested. Parts will be amorphous and not look like the typical PEEK part. Amprphous parts may be carefully annealed to crystalline.	Route 2: Amorphous printing is not recommended for AM450.
	When printing amorphous, lower temperatures will result in lower strength. Being too close to Tg at 155°C can result in inconsistencies.	
Bed Temperature	At least 100°C, and typically +20-40°C over chamber temperature, but not higher than 140°C for amorphous printing. (i.e. Route2)	

Summary & Quick Reference Continued

<table>
<tr><th></th><th>VICTREX AM™ 200 FIL</th><th>VICTREX AM™ 450 FIL</th></tr>
<tr><td rowspan="2">Print Speed</td><td>Typically, 10-40 mm/s, though VICTREX AM™ 200 FIL can be printed >100mm/s. (in some machines)</td><td>Typically, slower than VICTREX AM™ 200 FIL, within the range of 10-40mm/sec</td></tr>
<tr><td colspan="2">Profiles can be optimized for speed or strength. 10-20% stronger parts have been observed with slower printing of VICTREX AM™ 200 FIL, while parts printed as high as 100 mm/s still had useful strength.</td></tr>
<tr><td rowspan="3">Support Materials</td><td colspan="2">Self-support is possible, however VICTREX AM™ 200 FIL and VICTREX AM™ 450 FIL bonds strongly to itself, so removal can be difficult. Optimisation required.</td></tr>
<tr><td colspan="2">Break-away: Support materials designed for PEI, PEEK, or PEKK have been used successfully for VICTREX AM™ 200 FIL and VICTREX AM™ 450 FIL.</td></tr>
<tr><td>Soluble supports only possible for VICTREX AM™ 200 FIL route 2 amorphous prints.</td><td>Printing amorphous to use soluble supports is not suggested for VICTREX AM™ 450 FIL.</td></tr>
<tr><td>Annealing</td><td colspan="2">Minimum of 170°C for 2-3 hrs, with 1-2°C /min heating and cooling, or 20°C higher than the maximum use temperature if higher. Using a weighted sand or gypsum bed can significantly reduce deformation and is recommended if practical</td></tr>
</table>

Drying

Filaments should be dried before use. A drying temperature should be at least 100°C. Recommended drying conditions are 120°C overnight per spool. Drying at higher temperatures is possible but it will require re-spooling of the filament on a different bobbin from the one supplied, more explicitly a metal spool. High drying temperature should not exceed 150°C. VICTREX AM™ FIL grades is provided on polycarbonate spools which may start to deform if exposed to temperatures higher than 120°C. Ideal moisture content after drying should be below 0.05% as determined via a moisture specific analyser such Computrac Vapor Pro XL from Brookfield Ametek.

Printing

Recommendations for printing parametres can vary from one system to another and the change of one parametre may require consequential adjustment of others. The following suggestions are given as starting points only and specific machine settings from the printer manufacturers should be followed.

> Filaments should be dry before printing

Figure 1. Filament should be dry before printing. Avoid spool distortion by drying at <120°C

Nozzle Temperature

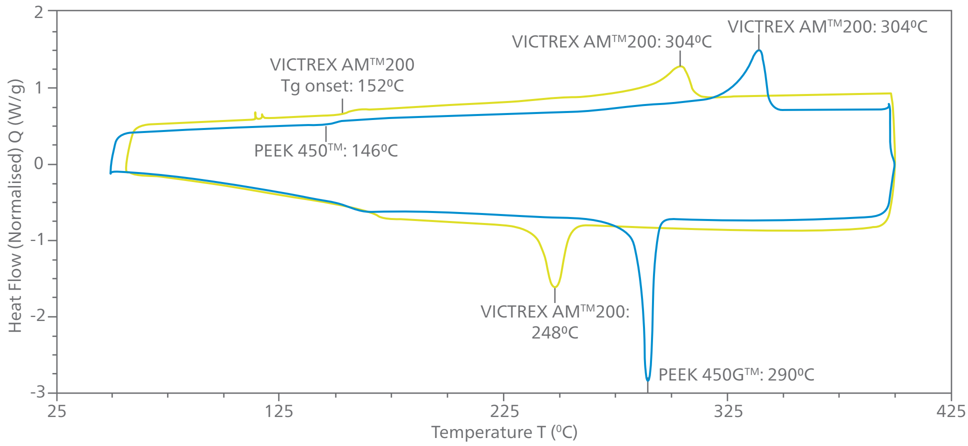

Figure 2. DSC thermal scan of VICTREX AM™ 200 and AM™ 450 polymers

VICTREX AM™ 200 FIL has a melting temperature of 305°C, while VICTREX AM™ 450 FIL has a melting temperature of approximately 340°C. For successful filament deposition, a high degree of remelting of the filament needs to occur in the nozzle. Hence, It is recommended starting optimisation at least 50°C higher than the melting temperature of the filament. The most common working range for VICTREX AM™ 200 FIL has been so far 380-400°C, however lower nozzle temperatures should work because of the lower melting temperature of this polymer.

For both materials, nozzle temperatures should be set considering thermal degradation limits of the intrinsics materials, and higher temperatures may contribute to shorter tip/nozzle life. In an analytical lab set up, the LMPAEK™ polymer in VICTREX AM™ 200 filament has a similar degradation temperature to VICTREX PEEK, of approximately 570°C (Table 1).

For VICTREX AM™ 450 FIL, 380-400°C is the recommended starting point for optimisation, with possible higher temperatures. Higher temperatures will give stronger parts, lower temperatures will give longer tip life.

Test	Onset Temperature (°C)
VICTREX AM™ 450 in Air	572
VICTREX AM™ 450 in N2	576
VICTREX AM™ 200 in Air	566
VICTREX AM™ 200 in N2	570

Table 1. Degradation onset temperature of VICTREX AM™ 450 and VICTREX AM™ 200 in air and inert atmosphere (N2) when subject to heat ramps. PLEASE NOTE It is recommended STAYING WELL BELOW THESE TEMPERATURES DURING PRINTING

Nozzle Temperature

There is little variation between onset degradation temperature in air and in an inert atmosphere for both VICTREX AM™ 200 and VICTREX AM™ 450. However, the degradation mechanism may be different in the two environments. Printing will likely take place in air.

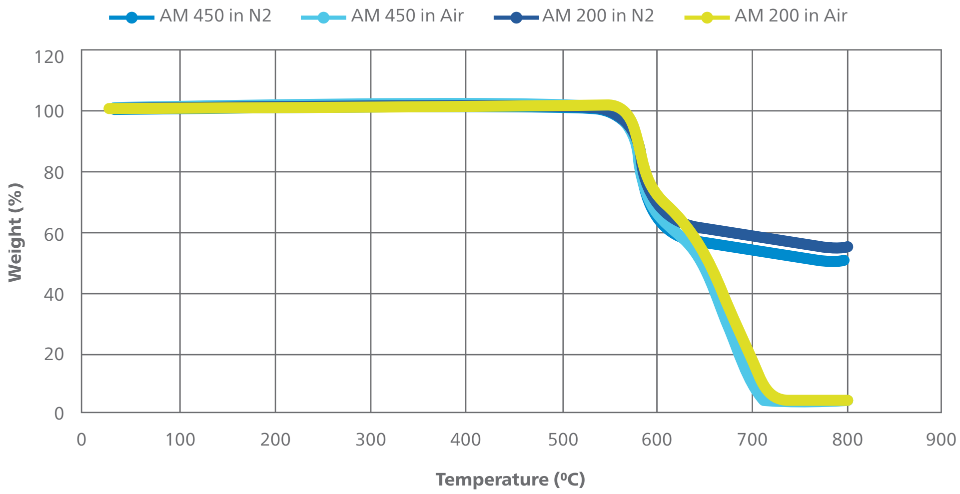

Figure 3. Thermogravimetric results of VICTREX AM™ 450 and VICTREX AM™ 200 in air and inert (nitrogen N2) atmosphere. Similar degradation onset temperature but different scission mechanism in the two conditions.

Please consider at these onset temperatures, polymer degradation is so catastrophic to cause weight loss. In reality degradation phenomena like chain scission, branching, etc. will occur at much lower temperatures. Therefore, we do not recommend using any temperature above 450°C.

The acceptable melt process window is 40°C wider for VICTREX AM™ 200 LMPAEK™ filament (~355-450°C) than VICTREX AM™ 450 PEEK filament (380-450° C). Higher nozzle temperature, i.e. higher than 400°C, may yield to increased flow or higher interlayer bonding. However, there will be side effects, such as higher thermal gradients in the building environment, the polymer will have to cool down further before becoming solid, etc.

It is not recommended using a nozzle temperature above 450C

Nozzle Temperature

Temperature is not the only factor contributing to polymer degradation. It also matters how long the material is kept at high temperature, this is called residence time. The higher the temperature, the shorter the residence time becomes. When the residence time for a given temperature is exceeded, the polymer will start to degrade and "carbonise". Symptoms include black material and clogging in the nozzle. One symptom may be black specks or spots appearing in the printed part in increasing frequency.

In more severe cases, prior to complete nozzle clogging, you may notice increasing amounts of under-extrusion, sometimes requiring increasing the extrusion multiplier, after long hours of printing on the same nozzle. Observing this change is a good sign that a clogged nozzle may be imminent.

1. It is good practice to record the nozzle life (odometre) and associated nozzle temperatures to develop a better understanding of your particular setup with our materials.

2. Consider starting with a fresh nozzle for long, sensitive prints, until you know the typical nozzle life in your particular setup.

3. Another mechanism that may lead to premature clogging and nozzle life is the nozzle and melt flow path design in the machine. See the Nozzle selection section.

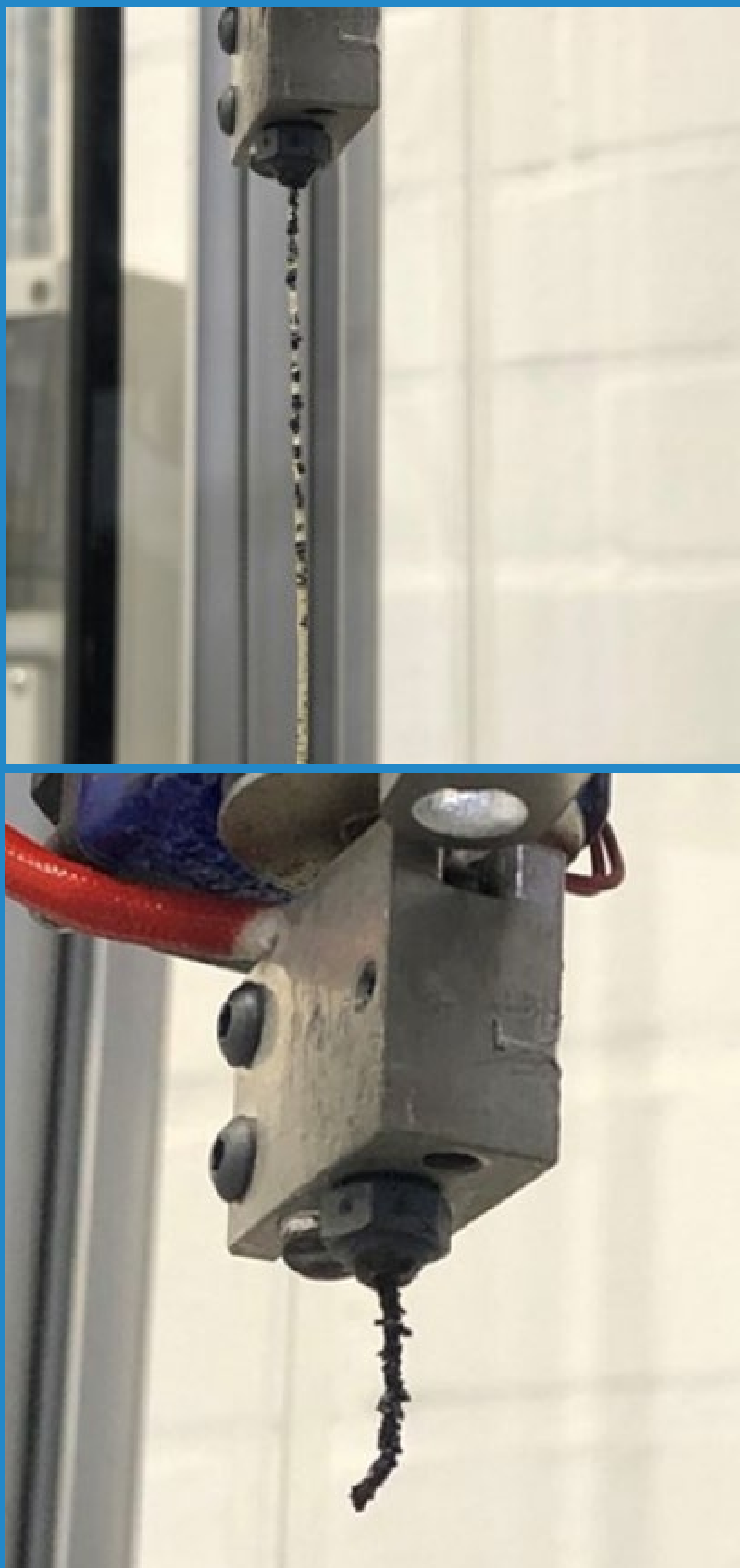

Figure 4. Examples of carbonisation in the extruded filament of a PAEK beige material

Nozzle Temperature

The recommended general residence time for Victrex materials is 1 hour at 360°C and 30 minutes at 380°C in processes like injection moulding. At higher temperatures typically seen in 3D printing nozzles, >380°C, the residence time will be lower. Testing by Victrex has shown that although in static conditions VICTREX AM™ 200 did not noticeably degrade at 400°C for 30 minutes, other tests with elevated shear stress in the melt and tests with complex print-retract cycles typical of 3D printing observed some signs of degradation at 30 minutes, or carbonization build up in printing nozzles, respectively. (See also Nozzle Selection and Design)

Please keep this in mind when setting nozzle temperatures and considering lowering it if the print job is paused for some reasons. Please keep also in mind that nozzle set temperatures may not relate exactly to the temperature the melt sees due to a number of factors including thermocouple location within the printer, print speed, etc., so we would recommend, if safely possible, to double-check the temperature of the polymer as soon as it is extruded from the nozzle, when you start to familiarise with printing with Victrex materials.

VICTREX AM™ 200 will give you more options for tuning deposition than VICTREX AM™ 450

Nozzle Selection and Design

Another mechanism that may lead to premature clogging and nozzle life is the nozzle design and melt flow in the machine. High temperature polymers like VICTREX AM™ 200 and VICTREX AM™ 450 can bond to metal under certain circumstances. Once that happens, the material ceases to flow in that location and residence times increase locally, leading to char build up in the nozzle.

Any roughness on the interior of the nozzle, eddies or hang ups in the flow path, and certain metals and coatings can shorten tip life. Copper and copper alloys should be avoided in parts in continuous contact with PAEK polymers because they can cause sticking and degradation at Victrex material processing temperatures. Care should also be taken with nitride coatings and aluminium components. (See also Printer Considerations)

It has also been observed that prints requiring many starts, stops, and retractions (e.g. more complicated parts), may be more sensitive to carbonization and shorter nozzle life than simple parts with few retractions. This will be dependent on nozzle temperatures and specific nozzle and machine design; therefore it is a good idea to track nozzle odometres and associated temperatures to develop an understanding of what you can expect from your particular setup with VICTREX AM™ 200 and VICTREX AM™ 450.

Avoid copper, copper alloys, nitride coatings, or aluminium in the nozzle and melt path

Victrex is always interested in learning more about your experiences with nozzle temperature and nozzle life. Please report any observations and experiences pertaining to tip life, unexpected clogs, and insights for improved performance to the Victrex AM team

Extrusion Consistency (moisture check)

Once the initial nozzle temperatures are set, trial extrusion of the melted material using the manual head feed or purge function should show a consistent smooth string that has no bubbles or roughness to the touch. Such bubbles or pitting could point to moisture in the material and may require further drying prior to print. Removing moisture is important to improve the quality of the printed part.

Extrusion Thickness Check

More checks can be carried out such as measuring the extrusion thickness with a micrometre to check the extrusion feed rate vs thickness. This can relate to layer build thickness (example 0.25 mm) and the nozzle extrusion thickness (example 0.50 mm) showing that there will be good Z layer adhesion or fusion. These parametres are part of the tuning process to improve part quality and Z direction strength.

First and foremost, extrusion thickness should be consistent. Note that extrusion checks should be done after filament feed mechanism calibration, also called E-step calibration. E-step calibration checks to make sure that a printer asked to push a certain length of filament through the nozzle does so accurately. Procedures will vary by machine. There are numerous tutorials available online and from your machine manufacturer.

Extrusion Line Width Check of Print

To measure the width of the extrusion during print requires a sample build where this can be measured by a visual device to determine the correlation between correlation between nozzle size, layer height, and extrusion multiplier slicer settings and observed line width in the print itself. These are factors that can affect the part quality and strength especially when producing thin walls where it requires the lines to merge during build and prevent side wall delamination.

The first step in line width calibration is to confirm that the desired line width used by your slicer in planning the tool path is in fact the line width delivered to the bed. The second step is to consider the line width suitable for your objective. If you are using a profile provided by your machine manufacturer, its likely this includes the optimisation setting.

Part strength may often be improved by increasing line width for a given set of conditions, while aesthetic quality and print speed can be improved by reducing line width for the same conditions.

Your machine maker may have advice and procedures for your particular machine.

Chamber Temperature

VICTREX AM™ 200 FIL is based on Victrex LMPAEK™ polymer, a slow crystallisation PAEK, with glass tansition temperature of 150°C.

- **Route 1 – By setting the chamber temperature above 150°C, VICTREX AM™ 200 FIL can readily be printed crystalline.**
- **Route 2 – If the chamber temperature is instead set below 150°C, VICTREX AM™ 200 FIL will be printed amorphous.**

Amorphous parts are translucent and of amber colour (part on the left Figure 5) and tend to have a crystallinity content measured via Differential Scanning Calorimetry (DSC) lower than 10%. Crystalline parts are opaque and beige (part on the right Figure 5) and usually exhibits crystallinity content higher than 20%, close to 30% when measured via DSC. Higher chamber temperatures will often result in stronger parts in terms of interlayer adhesion when printing amorphous with VICTREX AM™200 FIL.

VICTREX AM™ 450 FIL is based on a standard fast crystallisation PEEK polymer with glass transition temperature of 143°C. It is recommended printing VICTREX AM™ 450 FIL crystalline (Route 1). Amorphous or low chamber temperature printing is not recommended for VICTREX AM™ 450 FIL or any other fast crystallising PEEK filament. Attempts at using lower chamber temperatures < 140oC (Route 2) for VICTREX AM™ 450 FIL may still result in crystalline or partially crystalline prints and are generally weaker than VICTREX AM™ 200 FIL printed under the same conditions.

Figure 5. Amorphus and Crystalline parts in VICTREX AM™ 200 (Parts courtesy of INTAMSYS)

Two Approaches to Printing PAEK

Route 1: Crystalline Printing

This route requires a high chamber temperature so only a limited number of printers may be capable.

Recommended chamber temperature is at least 20°C above the glass transition temperature of the polymer, so a chamber temperature of 175°C is recommended as a starting point for VICTREX AM™ 200 FIL. 180°C is recommended as a starting point for optimisation for VICTREX AM™ 450 FIL. At present, there are no high temperature soluble supports tolerating temperatures above 150°C. Only breakaway supports are an option when printing in high temperature environments. Annealing post-print may still provide a benefit when printing in this mode by maximising crystallinity, relieving internal stresses and for use at high service temperature.

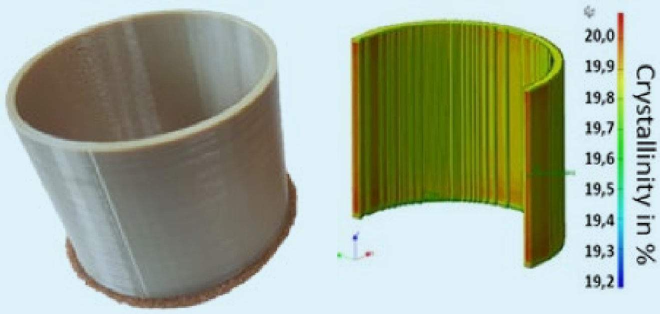

Figure 6. Crystalline Printed samples of VICTREX AM™ 200 courtesy of Xioneer and Digimat AM crystallinity simulation by Hexagon using their VICTREX AM™ 200 material card.

Route 2: Amorphous Printing

Recommended chamber temperature should be at least 20°C lower than the glass transition temperature of the filament. So maximum chamber temperature in this mode should be around 140°C .

VICTREX AM™ 200 FIL can be successfully printed at temperature as low as 60°C, or even lower. It is worth noting that LMPAEK™ polymers like VICTREX AM™ 200 FILh, typically with carbon fibre added to additionally improve shrink and warp resistance, have been printed successfully in large area additive manufacturing systems in open rooms without the need of heating chambers. Properties may differ though. This printing route may be accessible to a larger number of commercially available printers, and it enables the use of soluble supports.

For safety reasons, It is recommended a printer with an enclosed chamber, even if the chamber has limitation on the temperatures which can be reached. If the chamber is unheated, a heated bed is necessary to provide some heating of the chamber above ambient conditions. Printing at low temperature will yield amorphous parts. For higher mechanical performance, thermal stability and chemical resistance, crystalline parts are required and therefore It is recommended post-print annealing of the amorphous parts.

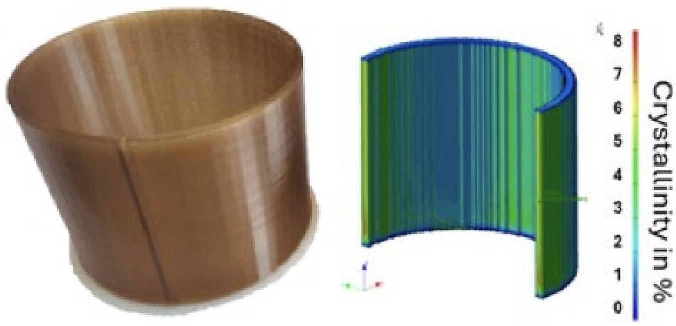

Figure 7. Amorphous Printed samples of VICTREX AM™ 200 courtesy of Xioneer and Digimat AM

Build Plate Temperature

Heated beds are desirable when printing additive manufacturing (AM) grades, to improve adhesion to the bed and reduce warping. Bed temperatures are usually at least 100°C and set equivalent to, or higher than the chamber temperature. Bed temperatures 20-40°C above the chamber temperature can be used as a starting point for optimisation.

Please consider that when printing amorphous the build plate temperature should be lower than 140°C. The use of AM glues has been reported to improve adhesion especially for PEEK. Deposition of rafts or skirts has also been used. It is common to have the first few layers deposited with higher temperatures and slower speeds to enhance good adhesion and part stability.

> Build plate temperature should be at least 100°C, and often +20-40°C over chamber temperature.

Sacrificial Sheet, Part Base Layer, and Z Level Flatness

Each 3D printing technology employs a distinct method for creating a substructure for part building, often utilizing a sacrificial build sheet that can be removed post-printing. Achieving optimal first-layer Z-level flatness is crucial for producing a high-quality part. Measuring the Z-level flatness of the base plate is a key procedure to ensure consistent material flow from the nozzle, preventing any inconsistencies caused by variations in the distance between the nozzle and the build plate during the creation of the first layer.

> The list of printing parametres reported here is far from being exhaustive, but it includes the most critical for the Victrex materials

Printing Speed

Polymers like VICTREX AM™ 200 FIL and VICTREX AM™ 450 FIL can be printed at various speeds. Most common speeds for VICTREX AM™ 450 FIL are around 10-30 mm/s, while VICTREX AM™ 200 FIL can be printed at much higher speeds, print speed may affect the interlayer bonding and ultimately strength of the final parts. Nozzle temperature and printing speed are directly correlated. So, if printing speed is high, a higher nozzle temperature may be required to transfer enough heat to the filament in a timely manner and vice versa. When using Route 2 for amorphous printing, it's essential to avoid excessive local heat build-up caused by short layer times. Depositing new melt too quickly over still-warm layers can keep temperatures elevated for too long, potentially initiating unwanted crystallization. See Slicing Considerations.

As explained earlier, the residence time for Victrex materials is 1 hour at 360°C and 30 minutes at 380°C. At higher temperatures, it will be lower. Please consider these values for printing parametres and in cases where printing will be paused, consider lowering the temperature.

Typical printing speeds are 10-30mm/s. For VICTREX AM™ 200, 20-40mm/s is common. VICTREX AM™ 200 can be printed as fast as 100mm/s or higher, but other settings will need optimized.

Post-Print Annealing

Route 1: Printing with the chamber temperature well above 150°C, results in crystalline parts without further processing. Depending on the crystallinity level achieved in printing, it may still be possible to increase the crystallinity of the parts by annealing.

Route 2: Parts produced with a lower temperature chamber, will be predominantly amorphous and will require post-print annealing to induce crystallisation, if crystalline parts are desired. We recommend annealing at least 20°C above the glass transition temperature of VICTREX AM™ 200 FIL, so at least at 170°C for 2-3 hours. Optimisation like higher temperature or longer holding time may be required according to the thickness, volume and size of your components. Gradual heating of the printed parts from room temperature up to annealing temperature (1-2°C/min) and gradual cooling down until to 130°C is recommended. After this temperature, controlled cooling can be switched off and let cooling occur naturally. Annealing in a media like sand, salt or gypsum will help to prevent distortion during annealing and preserve dimensional tolerance.

It is recommended annealing at a temperature that is 20°C higher than the maximum service temperature. Consider post-process temperatures such as painting, sterilization, or cleaning in addition to end use temperature when selecting the heat-set annealing temperature. The effect of annealing on printed crystalline and printed amorphous parts is shown in a small study carried out with a printing bureau reported in Table 2. Parts were printed in a Minifactory Ultra machine.

Tensile sample ISO 527-2-1A*	Strength (MPa) (%)	Elongation at break (%)	Modulus (MPa) (%)
ZX Printed amorphous/annealed (*)	2	-15	25
ZX Printed crystalline/annealed (*)	3	-5	4
XY Printed amorphous/annealed	10	19	5
XY Printed crystalline/annealed	9	5	4

Table 2. Effect of post- printing annealing on printed amorphous and printed crystalline parts in VICTREX AM™ 200 FIL. (3 repeats for each set. * Only 2 repeats)

The values represent the relative change compared with unannealed counterparts. Annealing may help to increase strength in the XY orientation by at least 10%. The increase in the ZX strength post-annealing in this small study was about 2-3%. Elongation at break may decrease as a result of annealing and increased crystallinity.

Post-Print Annealing

It is important to highlight that any part printed amorphous and annealed to crystalline state will be subjected to shrinkage due to crystallisation. This shrinkage is due to the transition from the amorphous to the crystalline state. This cannot be avoided, only estimated and counterbalanced by design. The dimensional change is usually a shrinkage in the XY direction and expansion in the Z direction.

Estimates of shrinkage values in difference configuration have been generated using a calibration cube of size 20 x 20 x 20 mm printed within a Minifactory Ultra system. Condition of printing were 100% infill, +45/-45 raster angle, layer hight= 0.15mm, high cooling speed, nozzle temperature 400°C, plate temperature 110°C and chamber temperature 85°C. Cubes are printed with a skirt/raft.

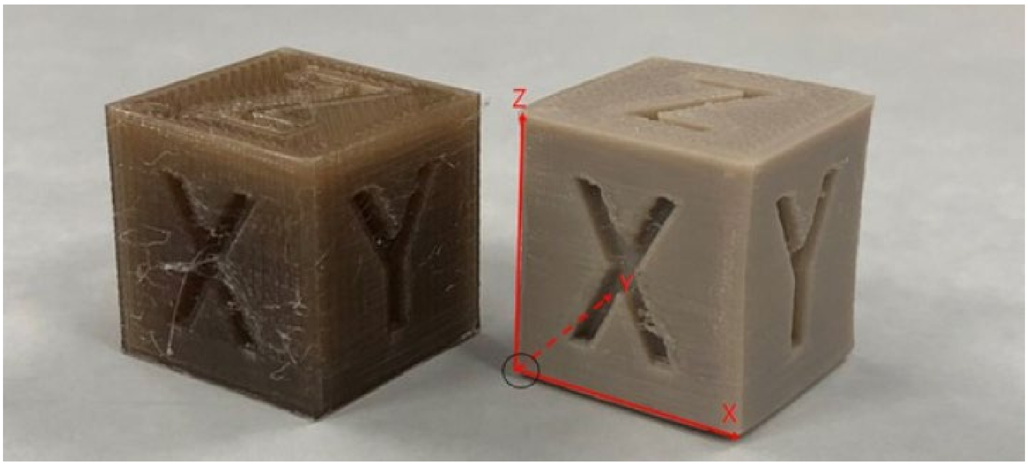

Figure 8. Calibration cubes used to estimate shrinkage values. Size 20x20x20 mm. Left amorphous cube as printed. Right crystalline cube via post-printing annealing at 175°C for 2 hours

In any manufacturing process, the fabricated component will deviate to an extent from the nominal dimension in the design file. This shrinkage is due to solidification of the polymer material from the molten liquid form. Estimates of the shrinkage from the melt when printing amorphous at 20, 60 and 120 mm/s are reported in Table 3. As shrinkage is not constant along each direction, three measuring points were taken for each direction parallel to X, Y, Z cartesian axes and averaged.

Shrinkage from design/ Amorphous	X (%)	Y (%)	Z (%)
20 mm/s	-1.0	-0.7	-0.7
60 mm/s	-1.0	-0.8	-0.8
120mm/s	-0.9	-0.5	-0.7

Table 3. Shrinkage values in VICTREX AM™ 200 FIL when printing amorphous from nominal dimensions.

There is little difference between the values at different speeds. Shrinkage are mostly around 1%.

Post-Print Annealing

Post-printing annealing can be carried out in air or in a media like an appropriately sized sand bath (parts should be surrounded by equal amount of a media all around). The two approaches yield to different amount of shrinkage in the crystalline parts and the shrinkage is due to crystallisation from the amorphous state. Values of crystallisation shrinkage for cubes printed amorphous and annealed in air are reported in Table 4.

Crystallisation shrinkage when annealing in air	X (%)	Y (%)	Z (%)
20 mm/s	-5.4	-5.0	7.2
60 mm/s	-4.4	-4.6	7.1
120mm/s	-3.5	-3.5	8.3

Table 4. Shrinkage values in VICTREX AM™ 200 FIL when printing amorphous and annealing post-printing. Annealing in air. Variations from nominal dimensions of the cube

Crystallisation shrinkage when annealing in air is 3-5% in X and Y directions and 7-8% expansion along the Z axis. As noted above, annealing in weighted media such as sand may reduce shrink and significantly reduce warp. Crystallisation shrinkage values for cubes printed amorphous at 20, 60 and 120 mm/s, and annealed in sand at 170°C for 2 hours are reported in Table 5.

Crystallisation shrinkage when annealing in sand	X (%)	Y (%)	Z (%)
20 mm/s	-2.6	-2.2	0.5
60 mm/s	-2.5	-2.4	0.5
120mm/s	-2.5	-2.4	1.1

Table 5. Shrinkage values in VICTREX AM™ 200 FIL when printing amorphous and annealing in sand post-printing. Variations from nominal dimensions of the cube

Crystallisation shrinkage when annealing in sand is 2-2.5% in X and Y directions and 0.5-1% expansion along the Z axis. It is evident that annealing in a media significantly reduces the amount of dimensional variation due to crystallisation. Victrex suggests annealing in a media to prevent large distortions especially for those parts that may have developed lots of internal stresses during printing. The improvement on reducing warp may be even more dramatic annealing in media rather than in open air.

There are other alternatives to reducing warp in annealed parts. Fixtures may be designed to hold the part in place during annealing. Support structures may be co-printed with the part to secure it through annealing. Combining model support structures with soluble support structures has also been demonstrated. These methods vary. These methods will not be discussed in detail in this guide as they are specific to a geometry and situation. Printing directly crystalline will also lead to some shrinkage, as in any other manufacturing process.

Post-Print Annealing

Crystallisation shrinkage when printing crystalline	X (%)	Y (%)	Z (%)
20 mm/s	-2.10	-2.33	2.07

Table 6. Shrinkage values in VICTREX AM™200 FIL when printing directly crystalline. Cooling speed was set low in this case.

Annealed in Open Air Annealed in Sand

Figure 9. Image credit: Xioneer Additive Manufacturing Lab

It is fundamental to highlight that shrinkage depends on many factors such as geometry of the parts and characteristics specific to the printing system as necessary and printing strategy. These values are therefore only an initial assessment of dimensional variation due to crystallisation shrinkage and it is recommended that users to carry out their own investigation. Victrex is actively working on this area, so please get in touch for comments and questions. Annealing has been found to increase the tensile strength in XY specimens (+10-20%) but has not always been found to significantly increase strength across the Z axis (please see Table 2).

The photo illustrates the importance of considering design during the annealing process. In this example, the part features very thin walls with large unsupported areas due to a low infill rate (<10%) and demonstrates excellent leak-tight printing. However, during annealing, the trapped air expanded, and the design lacked the necessary structure to resist this expansion and did not include intentional venting. To prevent issues with trapped air during annealing, it is essential to design with intentional vents, increase infill to reinforce the structure, add more shell layers, or use a combination of these strategies to address such situations effectively.

Figure 10. Example of an annealed part where the trapped air occurred during printing cannot escape during annealing.
This similar issue can happen in molding because of inadequate venting.
Image courtesy of Xioneer.

Post-Print Annealing

Like for VICTREX AM™ 200 FIL, annealing of VICTREX AM™ 450 FIL may be required for optimising crystallinity, relieving internal stresses or use a high temperature. Recommendations for annealing VICTREX AM™ 450 FIL are based on PEEK annealing after manufacturing and are reported in the Victrex Finishing Guide and are also reported here for convenience.

It is important to highlight that these suggestions were carried out on parts manufactured with processes like injection moulding and machining, not 3D printing. Further optimisation may be required.

For optimising the crystallinity content:

- **Allow the component to reach an equilibrium temperature of 200°C**
- **Hold the part at 200°C. Holding time depends on thickness of the components each millimetre of wall thickness accounts for an hour**
- **Allow the component to cool at 10°C/min until the system fall below 140°C**
- **Switch the oven off and allow the component to finish cool down naturally**

Annealing for removing internal stresses can be carried out up to 250°C. Annealing for high service temperature will need to take place with the same mode as described above but at a holding temperature of at least 20°C greater than the maximum service temperature. Please consider that annealing may reduce ductility (elongation at break). Like for VICTREX AM™ 200 FIL, annealing in a media will minimise occurrence of distortion and we will recommend to gradually anneal and cool down the components.

Support Materials

The use of support material requires the use of a printer with dual nozzle.

At present there are no soluble support materials able to tolerate chamber temperature higher than 150°C, so in a crystalline printing scenario, breakaway support may be the only solution. To facilitate detachment and minimal marking of the part, some soluble supports can be used in minimal quantities between the component and the breakaway support when printing at high chamber temperature. There are a number of break-away support systems designed for PEEK, PEKK, and Ultem that work with VICTREX AM™ 200. When printing amorphous at lower temperatures, several soluble supports are commercially available, some via printer manufacturers themselves like 3DGence, Stratasys, etc. or via independent manufacturers like Xioneer, Aquasys, etc.

Photo used with permission from Xioneer. Design by Emerge in 3D on GrabCAD.

Support Materials

If available, please use printing profiles provided by machine manufacturers for model and support pairings as they are likely optimized to provide the best experience. Alternatively, contact the support material company for advice, or conduct your own experiments to determine settings that work for you. Support material needs to be able to handle the chamber temperatures without deforming, bond well to the print bed, and provide enough bonding to the model material both on model over support and support over model printing to prevent deformation during printing.

Combining self-support and soluble support has been demonstrated. In this method, separate removable support structures made from the model material, in this case VICTREX AM™ 200 FIL, are printed with a layer of soluble support between these semi-structure supports and the primary model. This method can be used to provide higher temperature resistant structure to the support system to resist deformations, or to provide some restraint or reinforcement to prevent distortion during annealing. Three nozzle machines may combine less expensive rigid support materials with soluble support and the primary model.

Victrex suggests working with its resellers who have experience with printing with our materials and/or to contact Victrex for further information. Contact Us

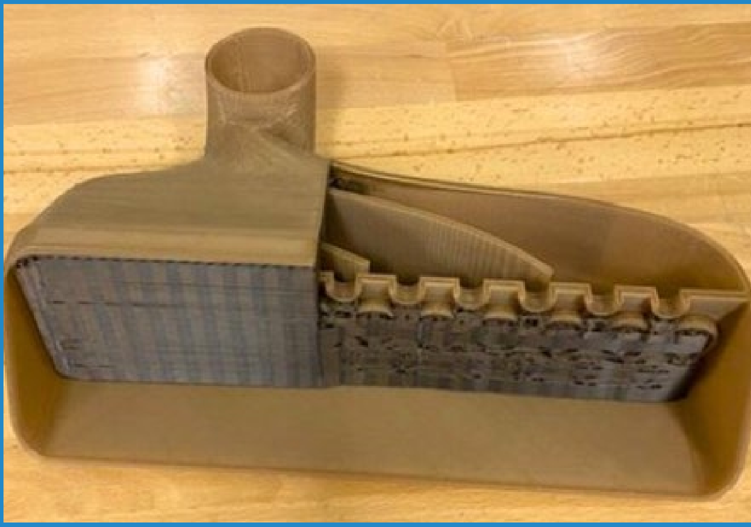

Figure 12. Image: VICTREX AM™ 200 on a Stratasys Fortus 450MC using Stratasys SR100 support.

Figure 13. Image: Model material delaminating from the support material and showing signs of deformation. (image source Xioneer)

Other Slicing & Profile Considerations

Route 2 - For amorphous printing, the temperature history of each layer and the surrounding layers can cause local crystallization of VICTREX AM™ 200 FIL. When the minimum layer time drops below a certain level, the next molten bead drops down on the still hot layer below and combined with the radiating heat from the print head may increase the time at temperature over the time required to crystallize the material.

Many slicers have minimum layer time settings that may be used to slow down printing to avoid depositing the next layer on top of the still hot previous layer. Cooling fans may also be deployed, as can printing multiple parts at the same time, or adding sacrificial towers to increase the average layer times.

Figure 14. : In this example, printing with Route 2 for amorphous printing of VICTREX AM™ 200, minimum layer time was not enforced and localized overheating occurred. The first symptom was local crystallization. As the print proceeded to the very top of the flange in the foreground, which rises higher than the flange in the background, layer time became so short that the polymer did not have time to cool enough to solidify. Image credit Xioneer printed on 3DGence

As a semi-crystalline polymer and a high temperature polymer that must cool more from the melt to room temperature than lower temperature materials, VICTREX AM™ 450 FIL and VICTREX AM™ 200 FIL will tend to thermally contract significantly. This will be greatest for VICTREX AM™ 450 FIL made from PEEK, because crystallization is triggered more easily before the part has solidified enough to resist deformation. This can be exasperated by aligning the raster angle across the longest dimensions and in a single direction as shrink will often be greatest in the direction of extrusion. Alternating raster angle, as is common for most slicers, will help, as will non-linear infill patterns such as hexes. Large thick sections with 100% infill are the most challenging, and bed adhesion will need to be maximized and brims may need used to resist delamination from the print bed. The slower crystallisation of VICTREX AM™ will provide improved success rates with large, thick sections.

Other Slicing & Profile Considerations

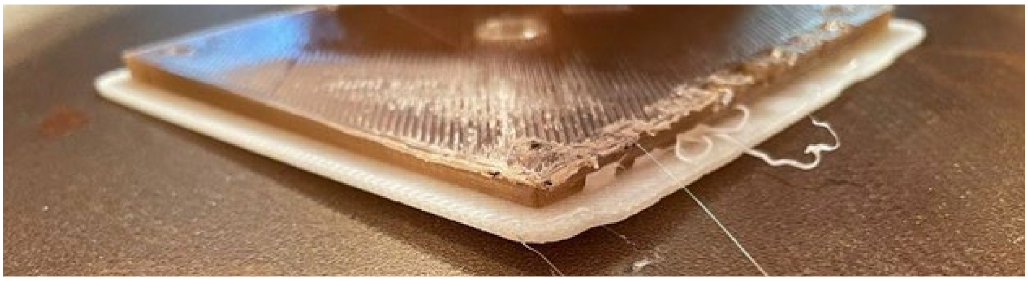

Figure 15. Image: a large thick slap delaminates from the print bed and interferes with the tool path. In this example, the raster angle was not alternating, and the adhesion to the print bed was compromised. (Image credit: Xioneer additive manufacturing R&D lab.)

Software is available to simulate the printing process to find trouble spots before sending the file to the printer. One example is Hexagon Digimat AM by Hexagon, which imports the g-code from the slicer, and applies thermo mechanical simulation to the process, layer by layer, to simulate how the time and temperature affects crystallinity and, the resulting shrinkage.

This software tool can be used to pre-deform a geometry for open air annealing, identify localized crystallinity as noted above, warn of geometry collapse from too high of temperatures, or warn of high interface stresses on the print bed that might lead to delamination. Software providers continue to improve their offerings.

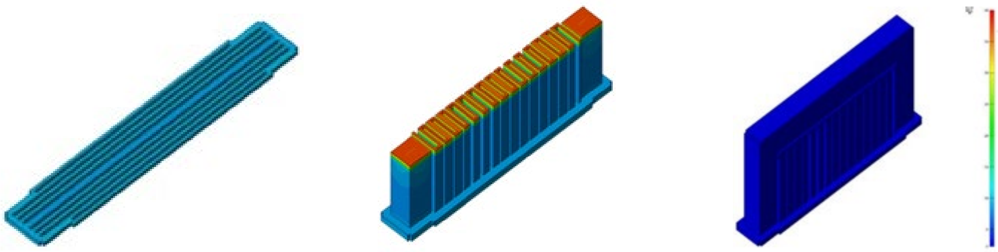

Figure 16. Image: Digimat AM simulation of VICTREX AM™ 200 FIL g-code showing layer temperature change over time, courtesy of Hexagon.

Design Considerations

Victrex does not currently provide a specific design guide for PEEK and LMPAEK. Tolerance and feature accuracy in filament extrusion. Filament extrusion depend on the combination of material, building strategies and parametres, and printer capabilities. Many design guidelines for filament extrusion fabrication with polymers are available online and may be supplied with your printing system. Please contact your printer manufacturer for more information.

For example, an online course on design for additive manufacturing is available from machine manufacturers such as Stratasys. Design for Additive Manufacturing Using FDM Technology Course

Printer Considerations

Copper and copper alloys should be avoided in parts in continuous contact with PAEK polymers because they can cause sticking and degradation at Victrex material processing temperatures. This applies to surface finishing of certain components as well. Care must be taken to ensure that Victrex materials do not cool and solidify in contact with the nitride coating; the bond between the polymer and the nitride coating is often strong enough to lift the nitride layer from the steel substrate.

Caution must be applied also with aluminium components as the heat treatment temperature of aluminium can be below the processing temperature of Victrex materials.

Some printers may be equipped with bed made of tempered glass. This has been reported to crack with high temperature polymers like PEEK. Metal replacement plates or carbon fibre reinforced plates have been reported to solve the issue. Please discuss this with the manufacturer of your systems.

References

1 Materials | Free Full-Text | Mechanical, Chemical, and Processing Properties of Specimens Manufactured from Poly-Ether-Ether-Ketone (PEEK) Using 3D Printing (mdpi.com)

2 Slow and fast crystallising poly aryl ether ketones (PAEKs) in 3D printing: Crystallisation kinetics, morphology, and mechanical properties - ScienceDirect

*Images Credits

Thank you to Hexagon, Xioneer, Stratasys, Digimat AM, and INTAMSYS, members of our AM Solutions Network, for providing images and parts for our processing guide. Your contributions have been invaluable in making this resource complete and informative.

We appreciate your support.

For More Information

www.victrex.com

Join our LinkedIn group, PEEK & PAEK for Additive Manufacturing, to connect and engage with fellow professionals and enthusiasts in the additive manufacturing community.

Join the group

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Victrex offers advanced PEEK & PAEK-based materials for additive manufacturing, including Victrex AM™ 200 and Victrex 450G™ filaments. These high-performance materials are designed for demanding aerospace, automotive, and industrial applications, providing excellent strength, chemical resistance, and thermal stability. These materials are optimised for 3D printing, enabling the creation of robust, durable parts.

Learn more at www.victrex.com

World Headquarters
Victrex plc
Hillhouse International
Thornton Cleveleys Lancashire
FY5 4QD
United Kingdom

tel +44 (0)1253 897700
fax +44 (0)1253 897701

Japan
Victrex Japan Inc
Mita Kokusai Building Annex
4-28, Mita 1-chome Minato-ku
Tokyo 108-0073
Japan

tel +81 (0)3 5427 4650
fax +81 (0)3 5427 4651

Europe
Victrex Europa GmbH
Langgasse 16
65719 Hofheim/Ts. Germany

tel +49 (0)6192 96490
fax +49 (0)6192 964948

Asia Pacific
Victrex High Performance
Materials (Shanghai) Co Ltd
Part B Building G
No. 1688 Zhuanxing Road
Xinzhuang Industry Park
Shanghai 201108
China

tel +86 (0)21-6113 6900
fax +86 (0)21-6113 6901

Americas
Victrex USA Inc
300 Conshohocken State
Road, Suite 120 West
Conshohocken
PA 19428
USA

tel +1 800-VICTREX
tel +1 484-342-6001
fax +1 484-342-6002

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