WHITEPAPER

Enhance patient recovery with new biomaterials for individual 3D printed implants

KUMOVIS
a 3D Systems company

EVONIK
Leading Beyond Chemistry

INTRODUCTION

No other market segment showcases the benefits of **additive manufacturing** *as evident as in today's medical technology. Advanced 3D printing technologies open up new possibilities for* **individual implant design.**

High-performance biomaterials *provide* **new functionalities** *that enable* **faster bone healing** *through improved osteointegration between bone and implant.*

In this whitepaper, the specialty chemicals company for material design **Evonik** *and the technology provider* **KUMOVIS, a 3D Systems company,** *explore the infinite possibilities of additive manufacturing in medical technology for enhanced patient recovery.*

Additive manufacturing of PEEK polymers is a fast-growing field. As of today, FFF-printing is the leading technology for high temperature polymer 3D printing [6]. FFF opens the door to various possibilities for PEEK implants such as reduced material use and costs with design freedom for customization. Although FFF is a well-known additive manufacturing method, manufacturing with these high temperature polymers requires a competent heat management system in the print environment. Kumovis R1 printer provides a well-managed thermal environment in an integrated clean room for implant manufacturing at the point-of-care.

R1 Printer from KUMOVIS

In this study, VESTAKEEP® Fusion filament was investigated in detail via FFF-printing with the Kumovis R1 machine. Results were compared to the samples printed with virgin PEEK filaments (unfilled VESTAKEEP® i4). Beyond the VESTAKEEP® i4 benefits such as comparable mechanics to bone and imaging advantages to assess bone integration, VESTAKEEP® Fusion aims to enhance the bioactivity with the host bone to further promote improved implant fixation.

Goals of the study:

1. Printability evaluation of VESTAKEEP® iC4800 3DF in comparison to VESTAKEEP® i4 3DF (settings, handling, mechanical values, samples).
2. Possibilities of generating different surface structures via printing strategies to increase functionality and bioactivity via processing technology.
3. Investigating the availability of BCP on the surface of printed parts and bioactivity.

Evaluation of printability

Tensile Bars

- Printability was evaluated by printing tensile bars in XY- and ZX-direction. Printing parameters used are provided in Table 1.

Specimen	Tensile Bars	TLIF Cages
Extruder		
Nozzle Diameter	0.4	0.4
Extrusion Multiplier	0.96	0.95
Temperature Settings		
Nozzle Temperature (°C)	450	390
Bed Temperature (°C)	250	230
Build Chamber Temperature (°C)	200	200
Speed Settings		
X/Y Printing Speed (mm/min)	1600	1200
Other		
Build Volume (mm^3)	Ø 200x150	Ø 200x150

Table 1
FFF parameters used in this study for Kumovis R1.

- Tensile bar tests show a very high reproducibility with small variation.
- As expected, results vary slightly between XY and ZX printed samples, both delivering good performance with respect to e-modulus.
- As expected, VESTAKEEP® Fusion PEEK was slightly stiffer, that is expected behavior due to the added BCP.

	VESTAKEEP® iC4800	
	XY	ZX
Stress at Max (MPa)	93,0 ± 0,6	77,8 ± 2,4
Elongation at Max (%)	4,2 ± 0,05	3,5 ± 0,22
Elastic Modulus (MPa)	4180 ± 205	4260 ± 392

Table 2
Mean and standard deviations of the maximum tensile strength, elongation, and elastic modulus for XY and ZX tensile bars.

Spinal Cages

- Illustrating a realistic use case, a basic design for a TLIF spinal cage was chosen. Special features of additive manufacturing were included in the design such as porous structures were directly integrated in the design.
- One TLIF spinal cage design was printed in both materials with the same printer settings (Table 1). For these parts, similar accuracy was achieved for the i4 as well as iC4800.

- VESTAKEEP® Fusion was easier to handle and print while printing both materials with the same printing settings. Thus, the operating window of parameters becomes wider for the user and the processing window becomes more robust (warpage was also reduced).

Figure 1
Case study design for TLIF spinal cage with porous infill made from VESTA-KEEP® Fusion.

Surface properties

After good printability of VESTAKEEP® Fusion was demonstrated, surface properties were further assessed since the surface is known to highly affect osseointegration. For this purpose, surface roughness of different 3D printed parts were measured. The surface roughness of 3D printed PEEK is obviously higher than machined PEEK and for medical applications increased surface roughness favors cell growth, thus delivering better bone attachment [8].
It is possible to obtain further engineered special surface properties that are not available by traditional manufacturing methods such as injection molding without additional time and cost intensive post processing.
Improvement of the new bone formation was studied via tailored surface properties generated by 3D printing compared to traditional manufactured smooth surfaces.
The average surface roughness of 3D printed PEEK and VESTAKEEP® Fusion was on the same order of magnitude and varied between 13-15 microns.
A much more pronounced effect was achieved by modification of the printing strategy (Figure 2), by which a 4-fold increase of average roughness Ra was achievable, providing a significantly higher surface area availability for cell growth.

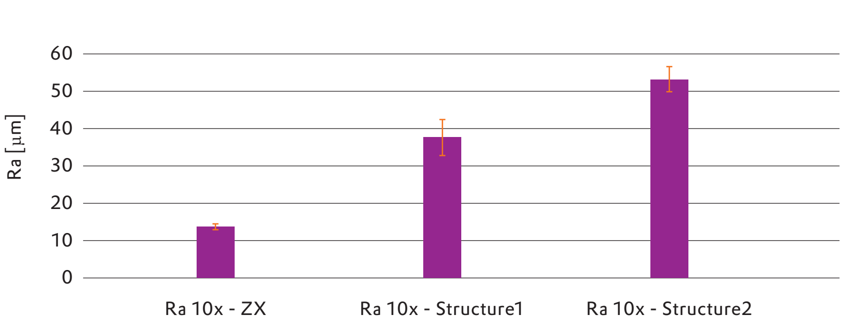

Figure 2
Average surface roughness Ra for different printed surface structures for VESTAKEEP® Fusion.

Combining the different features that can be achieved via additive manufacturing of an increased surface roughness with porous structure is illustrated in Figure 3. These features in combination with the osteoconductive properties of the VESTAKEEP® Fusion material are a combination of design and functionality for an optimal bone on growth and good mechanical fixation.

Figure 3
Sample for TLIF cage with porous structure and increased surface roughness.

Bioactive Surface

Besides the processability and the design options, the bioactivity of the surface is essential to achieve a fast bone on-growth; for this, the presence of calcium phosphate from the BCP additive on the surface represents bioactivity.

1) SEM

SEM images were made to assess the BCP particle distribution inside and on the surface of the material. Figure 4 shows the printed surface. The SEM pictures clearly show the individual layers that are very accurate and consistent. Peaks and valleys create perfect grooved area for cells to grow in. This investigation demonstrates that additive manufacturing offers an important advantage to modify the surface properties that will favor stronger bone integration.

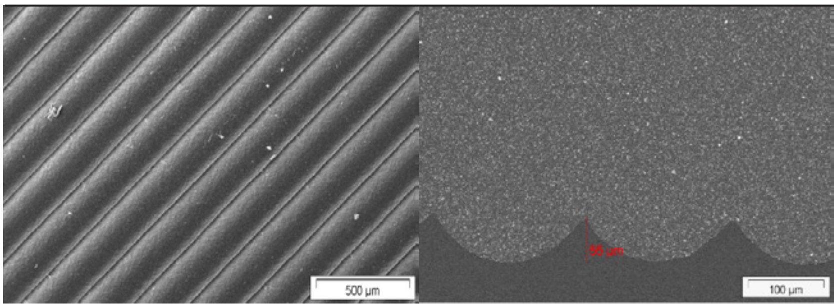

Figure 4
SEM pictures of printed VESTAKEEP® Fusion.

Figure 5 shows a closeup view on the printed surface. The individual BCP particles are clearly visible on the surface of the sample which is similar to the particle view inside the printed parts.

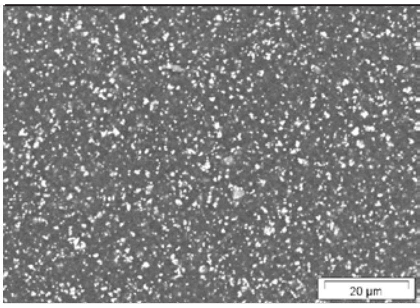

Figure 5
BCP particles (white) on printed samples. 1000x magnification: BED-C detector

2) Calcium phosphate on the surface (with acid etching)

Furthermore, the presence of BCP on the surface of the printed samples was chemically analyzed. Samples were etched in 0.1M HCl for 24h at room temperature. These conditions are known to dissolve the calcium phosphate. Since PEEK is not affected under these conditions only the calcium phosphate that is available on the surface can be dissolved. After etching the elemental components of calcium and phosphate were analyzed via ICP-MS.
In the analysis, calcium as well as phosphate could be detected in the supernatant of the acid etched liquid and thereby proving that the BCP is accessible on the printed PEEK surface.

3) *In vitro* tests

To strengthen the above findings on enhanced surfaces with BCP for better osseointegration, *in vitro* studies were conducted on 3D printed samples with human cell line. Primary human osteoblasts (HOB) were seeded on the samples to further assess the cytotoxicity. Cell viability (%) and cell adhesion were compared between the 3D printed samples. For both measurements, 5×10^3 cells of HOB were seeded directly onto the samples and incubated for 72 hours. To determine the cell adhesion, fluorescence intensity was measured after incubating the cells with the CellQuanti Blue reagent.

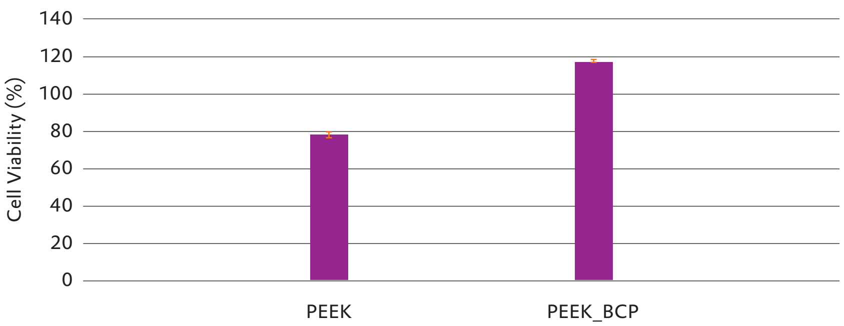

Figure 6
Relative cell vitality of HOB in direct contact tested with 3D printed samples. Dashed line indicates 70% cell viability that is in accordance with DIN EN ISO 10993 (approval of biomaterials as medical devices) (data normalized to negative controls (100%)).

Printed surface with VESTAKEEP® Fusion showed a statistically significant higher cell viability than the unfilled printed VESTAKEEP® i4 surface, proving the osteoconductive properties of VESTAKEEP® Fusion.
In addition to the quantitative investigations on cell viability, adhesion morphology of cells proliferated on the surface were visualized via fluorescence micrographs (Figure 7). A cell adhesion and differentiation can be observed for the printed surface of VESTAKEEP® Fusion.

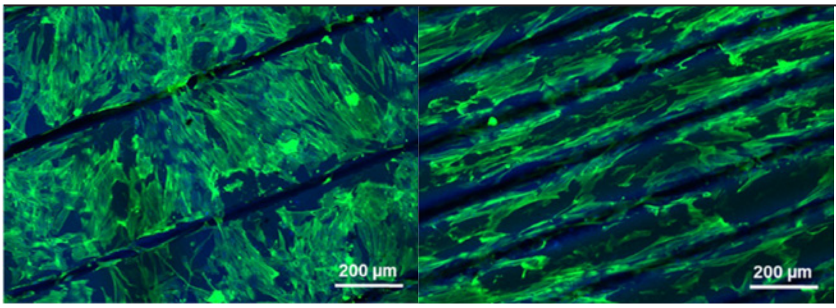

Figure 7
Cells observed on BCP surfaces (b&d) proliferated more compared to virgin PEEK surfaces (a&c) (cell skeleton stained green).

Left:
PG078 - PEEK_BCP_XY
Right:
PG079 - PEEK_BCP_ZX

SUMMARY

VESTAKEEP® Fusion Filament

VESTAKEEP® Fusion (aka VESTAKEEP® iC4800) is the next generation of PEEK Biomaterials for implant applications with osteoconductive properties that Evonik launched in 2020 [further reference on material, properties and advantages from press releases and Whitepaper Samaplast].
The material is bioactive since it contains biphasic calcium phosphate (BCP) that is uniformly compounded into the polymer matrix. BCP is a well known material and is proven to be the gold standard for artificial bone grafting [1-4]. The calcium phosphate at the surface triggers accelerated bone attachment and healing compared to virgin PEEK [5].
One of the unique features of VESTAKEEP® Fusion is that the calcium phosphate functional additives are not only present on the surface after machining of the material but are also available on the surface after injection molding [reference whitepaper]. Therefore, no secondary operations are needed after processing. Based on the encouraging findings with VESTAKEEP® Fusion in injection molding, VESTAKEEP® iC4800 3DF filament was created (1.75 mm diameter) and launched in Q2/2022 for its great potential in additive manufacturing for individual treatment of patients.

Literature

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