euspen's 17th International Conference & Exhibition, Hannover, DE, May 2017
www.euspen.eu

E-beam sterilization of microstructures in titanium surfaces for medical implants

Sebastian Winkler[1], Marleen Dietze[2], Jan Edelmann[1]

[1]*Fraunhofer Institute for Machine Tools and Forming Technology IWU, Chemnitz, Germany*
[2]*Fraunhofer Institute for Organic Electronics, Electron Beam and Plasma Technology FEP, Dresden, Germany*

sebastian.winkler@iwu.fraunhofer.de

Abstract
Due to its biocompatibility titanium is the metal of choice for most medical implants. The surface in contact with the human body may be equipped with a functional microstructure for various purposes such as bone ingrowth. All implants must be sterilized before operation. Among other processes, the sterilization by low energy electron beam (e-beam-sterilization) offers a lot of advantages. The non-thermal sterilization works with short process times (milliseconds) and without microbicide gases. The radiation sterilization is a regulated process according to DIN EN ISO 11137, which describes a killing effect of microorganism after the validation of a dose of 25 kGy. In principal it is possible to sterilize all material classes, electronic devices and different geometries, so that the low energy e-beam-sterilization is a suitable method for multifunctional implants. The sterilization of surface microstructures with low energy e-beam-sterilization is challenging because of the limited penetration depth.
The influence of high aspect ratio microstructures on low energy e-beam-sterilization was investigated experimentally. A microhole array with 230 µm hole diameter served as a model structure and was manufactured in the titanium surface by electrical discharge machining. Other surface microstructures were generated by laser machining and blasting. All samples were contaminated with 10^7 CFU/sample Escherichia coli (E. coli) K12, sterilized by e-beam and incubated in a culture medium in order to prove that the sterilization was successful. The microhole depth was varied to determine the critical depth for low energy e-beam-sterilization.

keywords: microholes, microstructures, titanium, implant, sterilization, electron beam irradiation

1. Introduction

Medical implants such as pacemakers or hip joints are becoming increasingly important as the population grows older. The design of the implant surface highly influences both wanted and unwanted interactions with the human body. Functional microstructures on the surface are used for improved biocompatibility, bone ingrowth or controlled friction behaviour. Various manufacturing technologies such as cutting, blasting, laser machining and electrical discharge machining (EDM) are used for surface modification. [1, 2]

For the sterilization of medical implants different methods such as steam sterilization, gas sterilization and e-beam-sterilization can be applied. The gas methods use toxic chemicals in a long time process (~11 h) to sterilize medical products. Steam sterilization cannot be used for thermosensitive materials and components such as electronic devices and polymers. The low energy e-beam-sterilization provides the advantage to sterilize a multifunctional implant in one step because material changes and loss of function occur rarely at the sterilization dose of 25 kGy. The possible limitations of low energy e-beam-sterilization lie in complex microstructures with cavities and undercuts, because the penetration depth is limited by the low acceleration energy. Nonetheless, it is desired to keep the acceleration voltage as low as possible because lower voltages mean more compact and less expensive systems. [3, 4]

This paper presents an experimental investigation of the potentials and limits of e-beam sterilisation when applied to complex surface microstructures and microholes.

2. Surface microstructure manufacturing process

The Titanium alloy TiAl6V4 is a common material for medical implants and has been selected for all experiments. The sample shape was designed for the biomedical equipment as a blank with a diameter of 13 mm and a thickness of 1 mm.

A 9×9 microhole array with spacing of 1 mm between two holes was used as a model geometry for determination of sterilization behaviour. The holes were manufactured with micro-EDM on a Sarix SR-HPM T1-T4 machine. A carbide metal electrode with a diameter of 200 µm and orbiting motion was used, resulting in a hole diameter of 230 µm ± 10 µm. Two different hole depths of 240 µm ± 15 µm and 400 µm ± 15 µm were manufactured. Figure 1 (left) shows a front view and Figure 2 a cross section of the microhole array.

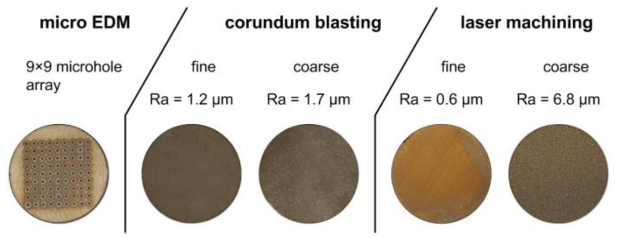

Figure 1. Titanium samples with structured surfaces

Surface microstructures were produced by corundum blasting and laser machining (Figure 1). For the corundum blasting a particle size of 10 µm (fine) and 105 µm (coarse) was used. All surfaces were analysed with a Keyence VK-9700 confocal laser scanner (results in Figure 1).

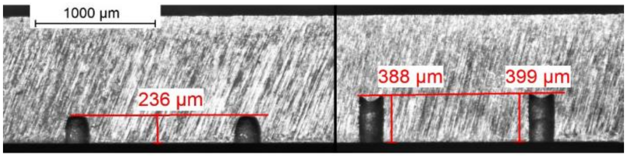

Figure 2. Cross section of microhole arrays

3. Contamination and low energy e-beam-sterilization

The experimental procedure for investigation of e-beam-sterilization is specified in Table 1. After pretreatment (cleaning and thermal sterilization) the samples were contaminated with *Escherichia coli (E. coli)* K12, followed by controlled drying and packing in desinfected polyethylene (PE)-film.

For the low energy e-beam-sterilization a state-of-the-art e-beam system developed at the Fraunhofer FEP Dresden equipped with an KEVAC Low Energy Accelerator was used (Figure 3). To control the absorbed radiation dose of 25 kGy a dosimeter film (Risø) was also irradiated and analyzed after the process.

After low energy e-beam-sterilization the samples were incubated in sterile nutrient broth in an incubator shaker for 24 h. If the low energy e-beam-sterilization was unsuccessful, the surviving microorganism grow, resulting in a turbid nutrient broth. In the case of success, the nutrient broth remains clear.

The experimental procedure was applied to seven different surfaces, summarized in Table 2 and partly shown in Figure 1. In addition to the three different surface types with two variations each, an untreated surface was investigated for comparison. For each surface five individual samples were used (Table 2). The complete experimental procedure was applied to three samples (*a*, *b* and *c* in Table 2). One sample was contaminated but not low energy e-beam sterilized to control the microorganism growth of the surfaces (*d*). With further controls the pretreatment step was validated (*e*).

Table 1. Experimental procedure

pretreatment	ultrasonic bath in 70 % ethanol (10 min)
	sterilization in autoclave at 121 °C (20 min)
contamination	samples exposed to E. coli K12 (ATCC 23716), (20 µL bacteria suspension, 10^7 CFU/sample)
	drying in laminar flow cabinet (130 min)
	packaging in desinfected 13 µm PE-film
e-beam sterilization	e-beam 90° to Ti-surface / atmosperic pressure / dosage of 25 kGy / voltage of 200 kV
incubation	samples exposed to 10 mL sterile standard nutrient broth I
	incubator shaker, 37 °C, 150 mot/min (24h)

4. Results and discussion

Table 2 summarizes the results of the sterilization process. For all surfaces the 3 samples (*a*, *b*, *c*) showed the same results, indicating good reproducibility. The results of the control samples (*d* and *e*) prove the reliability of the experimental procedure. During the low energy e-beam-sterilization of the samples, a film dosimeter was also irradiated. The evaluation verified the target dose application of 25 kGy.

There is no difference of sterilizing effectiveness between the corundum blasting and laser machining samples. Both microstructure types (fine and coarse) showed a clear nutrient broth after incubation. It can be assumed, that the titanium or microstructure themselves do not inhibit the bacterial growth and that the observed sterilization effect was solely achieved by electron beam processing of the samples.

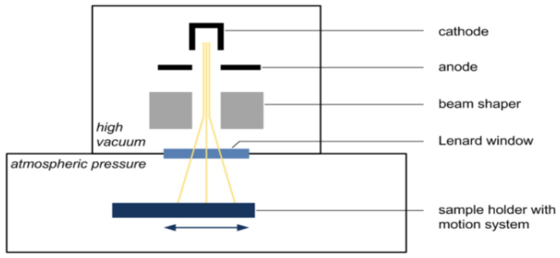

Figure 3. Low energy e-beam-sterilization system

The sterilization of samples with microhole depth of 240 µm was successful. The penetration was not efficient enough to attain the same result the 400 µm depth. From previous experiments with a bigger hole size it is known, that with increasing hole depth the dose in the hole bottom was reduced. The required dose for sterilization of the individual hole can be influenced for example by adjusting the impact angle. However, an altered impact angle results in a higher effort to achieve a homogenous dose distribution at the sample surface.

Table 2. Sterilization results

	samples	*a*	*b*	*c*	*d*	*e*
preatreatment						
contamination						
e-beam sterilization						
incubation						
untreated	-	○	○	○	●	○
microhole array	depth 240 µm	○	○	○	●	○
	depth 400 µm	●	●	●	●	○
corundum blasting	fine	○	○	○	●	○
	coarse	○	○	○	●	○
laser machining	fine	○	○	○	●	○
	coarse	○	○	○	●	○

culture medium ○ clear ● turbid

5. Conclusion

Low energy e-beam-sterilization was successfully applied to microstructured surfaces manufactured by corundum blasting and laser machining. As for microholes with diameter of 230 µm, the sterilization was successful for a depth of 240 µm, but unsuccessful for a depth of 400 µm. The results indicate that the low energy e-beam-sterilization process is limited when applied to complex microstructures with deep holes. The limit can be narrowed down to a hole depth between 240 µm and 400 µm or an aspect ratio between 1 and 1.5. Similar results can be expected for surface structures with comparable holes and aspect ratios, e.g. on surfaces generated by additive manufacturing. Further tests are needed to specify the exact limits. However, the sterilization success depends on the penetration depth of the e-beam, which can be increased with the e-beam parameters, for example the acceleration voltage.

References

[1] Zeidler H, Boettger-Hiller F, Edelmann J, Schubert A, 2016. Surface finish machining of medical parts using plasma electrolytic polishing. Procedia CIRP **49** (2016), S.83-87.

[2] Schubert A, et al. 2013. Enhancing micro-EDM using ultrasonic vibration and approaches for machining of nonconducting ceramics. Journal of mechanical engineering **59** (2013).

[3] Härtling T, Reitzig M, Mayer A, Wetzel C, Röder O, Schreiber J, Opitz J, 2012. Nondestructive testing of electron beam sterilization by means of an optically active marker material. In SPIE OPTO.

[4] Rögner F.H, Wetzel C, Röder O, Gotzmann G, 2009. Sterilization of surgical instruments using mini electron accelerators. Society of Vacuum Coaters 505/856-7188 (2009).