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Determining the required cleanliness level using synthetic test contamination

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Determining the required cleanliness level using synthetic test contamination

P Brag[1*], V Piotter[2], K Plewa[2], S Umbach[3] and M Herzfeldt[4]

[1] Department Ultraclean Technology and Micromanufacturing, Fraunhofer IPA, Nobelstr. 12, 70569 Stuttgart, Germany
[2] Institute for Applied Materials - Materials Science and Engineering (IAM-WK), Karlsruhe Institute of Technology, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany
[3] Department of Machine Elements and Engineering Design, University of Kassel, 34125 Kassel, Germany
[4] IST Prüftechnik GmbH, Schloss-Rahe-Str. 12, 52072 Aachen, Germany

*Corresponding author: patrick.brag@ipa.fraunhofer.de

Abstract: As electrification in the automotive industry progresses, the demand is rising for test particles with specific properties. More and more new applications are also being developed, such as processes for validating cleaning steps, contamination tracking or determining cleanliness limits. This article describes how test particles can be reproducibly manufactured in all three dimensions by micro milling. In addition, it explains how the dimensional accuracy of these free-form surfaces can be analyzed with computer tomography.

Keywords: Technical cleanliness, Synthetic test contamination, Particles, Computer Tomography.

1. Introduction

Technical cleanliness has been an established quality feature in the automotive industry for many years. However, defining component cleanliness still causes problems for companies today due to the lack of standardized regulations. Too strict or inadequately specified cleanliness limits can be a disadvantage for both the manufacturer and the consumer [1].

The required level of component cleanliness can be determined empirically by fault injection testing. This method calls for particles with defined characteristics. Due to their diversity, naturally occurring particles are technically impossible to reproduce identically, see figure 1. Consequently, to come as close as possible to the original particles, the material, quantity, shape, and size of test particles are selected to match the respective application scenario.

The production of synthetic particles for tribological studies on gearboxes was first outlined in the year 1990 [2]. From today's point of view, these manufacturing and analysis methods are technically outdated. This article describes how test particles can be produced and analyzed according to the latest state of the art. The application of synthetic test contamination is not limited to electronic components nor the automotive industry.

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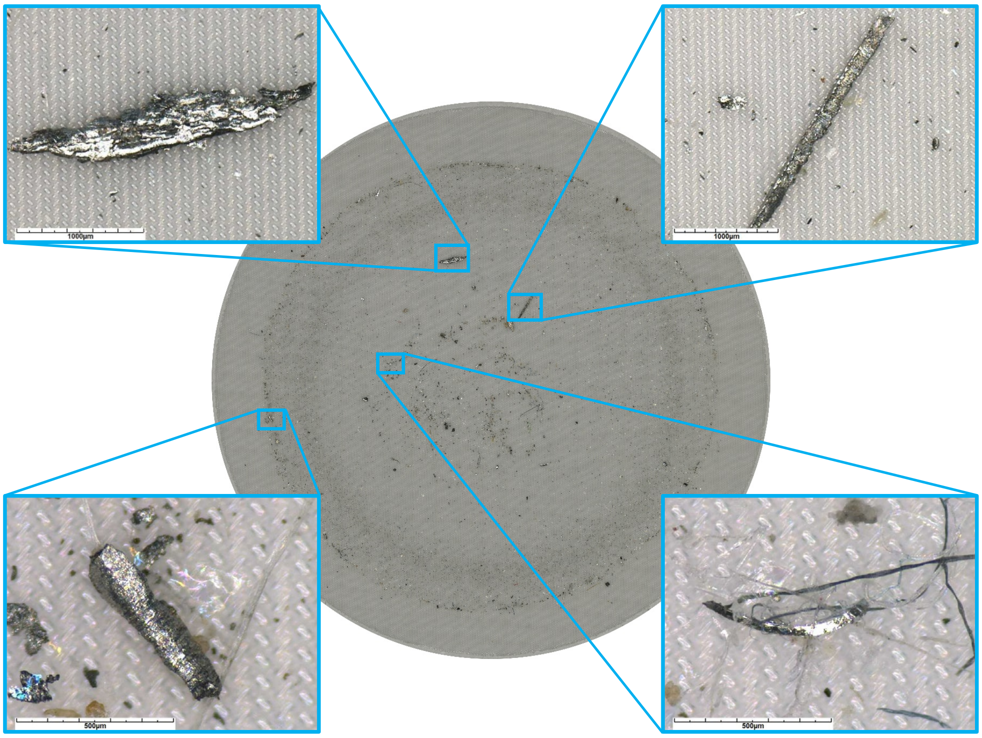

Figure 1. Analysis filter membrane of an aluminum die-cast transmission housing.

2. Production of synthetic test contamination

Using a Kugler Microgantry GU2, particles made of 42CrMoS4 were produced in lengths of 500, 700, 900, 1100, 1300, 1500, 1700, 1900, 2100 µm with a uniform width of 400 µm and a uniform thickness of 70 µm, see figure 2.

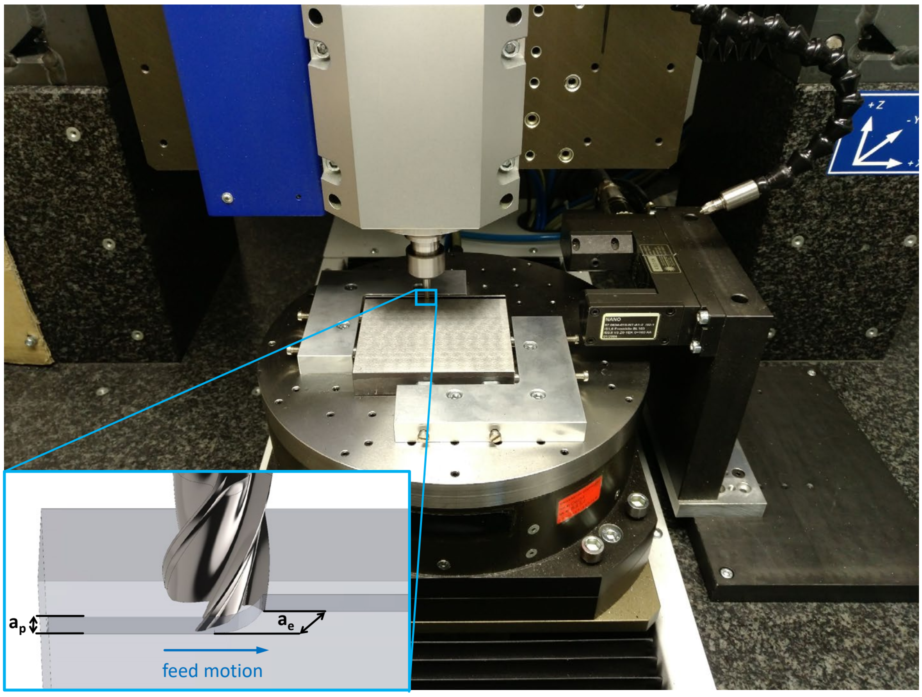

Figure 2. Chip-shape particle production on a Kugler Microgantry GU2.

Compressed air was used to cool the part and tool in order to lower the degree of wear to some extent. Milling parameters were optimized in several iteration loops by inspecting the generated particles with a light microscope.

The optimized milling parameters are summarized in table 1. For the particle sizes 500 µm to 1300 µm and 1500 µm to 2100 µm, the tool was not changed. For each particle size, three 10 cm long tracks were milled. The generated particles were collected in a beaker with the aid of the airflow.

Table 1. Optimized milling parameters.

Particle size[a] L x W x T (µm)	Tool	Spindle speed (min^{-1})	Feed rate (mm/min)	Feed per tooth (mm/tooth)	Cutting depth a_p (mm)	Cutting width a_e (mm)
500 x 400 x 70	Seco[b]	10,000	800	0.04	0.45	0.38
700 x 400 x 70	Seco[b]	10,000	800	0.04	0.65	0.39
900 x 400 x 70	Seco[b]	10,000	800	0.04	0.85	0.39
1100 x 400 x 70	Seco[b]	10,000	800	0.04	1.05	0.40
1300 x 400 x 70	Seco[b]	10,000	800	0.04	1.25	0.40
1500 x 400 x 70	Schreurs[c]	10,000	800	0.04	1.42	0.38
1700 x 400 x 70	Schreurs[c]	10,000	800	0.04	1.62	0.38
1900 x 400 x 70	Schreurs[c]	10,000	800	0.04	1.81	0.38
2100 x 400 x 70	Schreurs[c]	10,000	800	0.04	2.00	0.38

[a] Target dimensions.
[b] Seco Jabro Mini 920ML020-MEGA-T.
[c] Schreurs custom made, no. 651716.

Due to the optimization measures, it was no longer possible to use a program code. Each time a path was milled, the workpiece, tool and surrounding work area were cleaned with a brush and compressed air. The workpiece, tool and beaker were also wiped inside and out with 2-propanol and cleaned again with compressed air. This proved to be necessary from the later analyses with the scanning electron microscope, see figure 3.

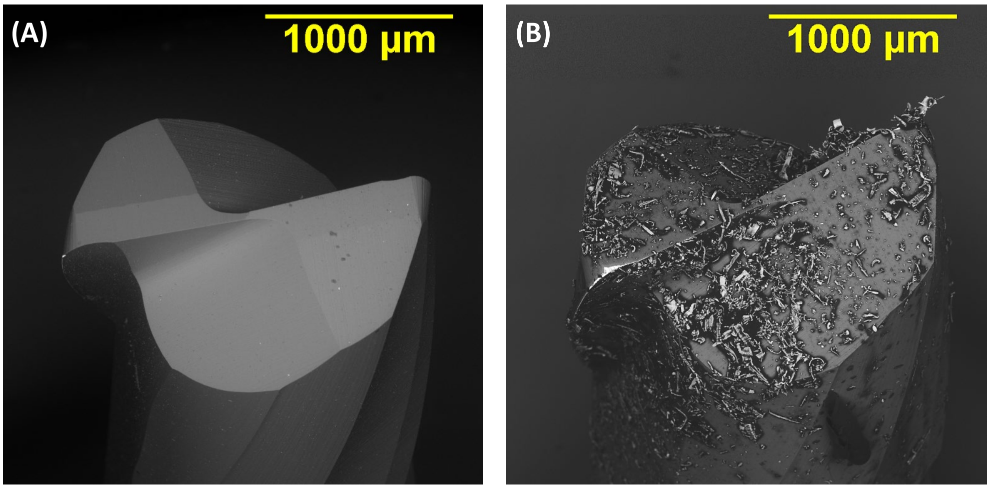

Figure 3. Seco Jabro Mini 920ML020-MEGA-T milling tool. **(a)** New. **(b)** After a single path.

3. Analysis

Microscopic methods for analyzing particles automatically have been established for more than 10 years [3,4]. The lengths and widths stated refer to the projected area of the three-dimensional object. This results in a measurement uncertainty that depends on the size and position of the particles [5].

Microscopes with an autofocus function can also measure the height of particles automatically. They use a small depth of field of the optics to calculate the distance between the background and the highest point of the particle [6]. While manufacturers may advertise the measurement of particle height as being three-dimensional, it is, at best, 2.5 dimensional.

A Bruker Skyscan 1172 micro computer tomograph (µCT) was used to determine the dimensional accuracy of the particles in three-dimensional space. Due to the chosen resolution of 1 µm per voxel and a rotation increment of 0.2°, the sample was exposed to X-rays for a relatively long period of time. It was initially thought that the thermally-induced drift of the samples was due to their insufficient fixation, so three different methods were used to hold them, see figure 4.

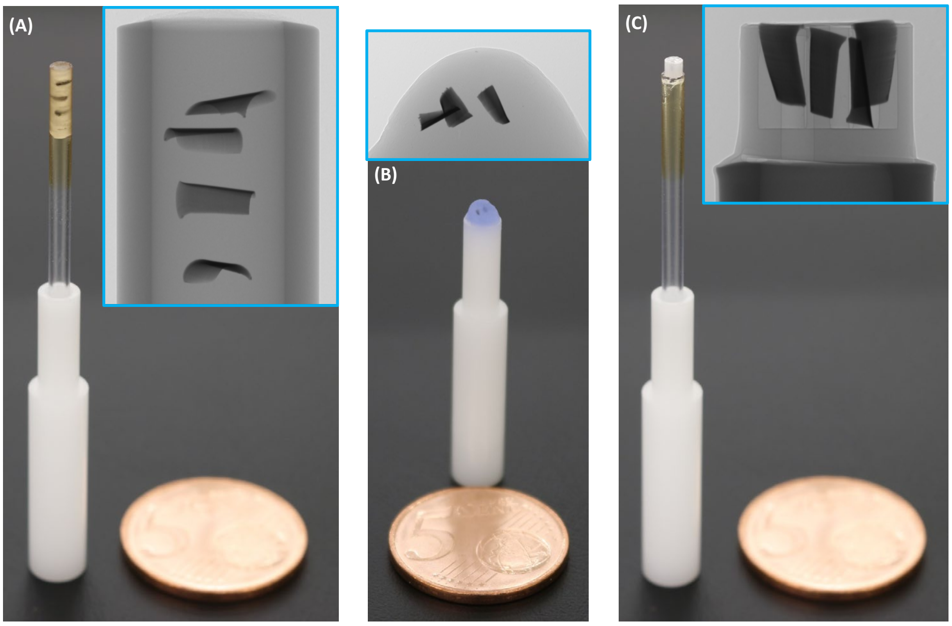

Figure 4. Sample holders. **(a)** Capillary pipette. **(b)** Plasticine. **(c)** Cylinder drum.

However, the thermal drift occurred regardless of the type of sample holder employed. Using the reconstruction software NRecon 1.7.1.6, it was possible to transfer additional parameters from the hardware to the software, so that the displacement of the samples by a few micrometers could be eliminated with the aid of drift correction.

The particles were analyzed with the software VolumeGraphix StudioMax 3.0.5. Since no CAD models of the particles were available, it was not possible to perform a deviation analysis by comparing nominal and actual values. Instead, a reference particle was selected from each size class that had the least defects. A total of 9 reference particles – one per size class – were positioned in the coordinate system.

Subsequently, all particles of the same size class were matched up with the respective reference particle using the best-fit algorithm of StudioMax 3.0.5. To determine deviations in size, a section plane was placed at +150 µm on the z-axis (blue) and at +200 µm on the x-axis (red), see figure 5. This was repeated for all size classes.

Particle width and thickness were measured in the z-section plane (C) and particle length was measured in the x-section plane (D). In total, the µCT analysis was a very time consuming procedure so that only 90 particles (10 per size class) were scanned, reconstructed, aligned and measured. More than 200 µCT scans were required to do this, as only 3 to 6 particles fit into the image field (see figure 4) with the selected resolution and sample preparation method.

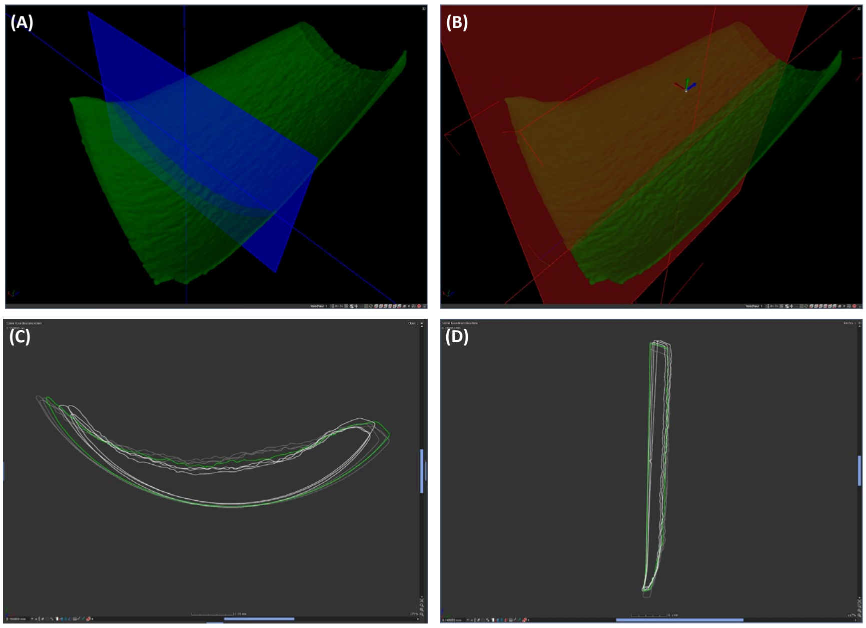

Figure 5. Analysis areas. **(a)** Z-plane. **(b)** X-plane. **(c)** Z-section plane. **(d)** X-section plane.

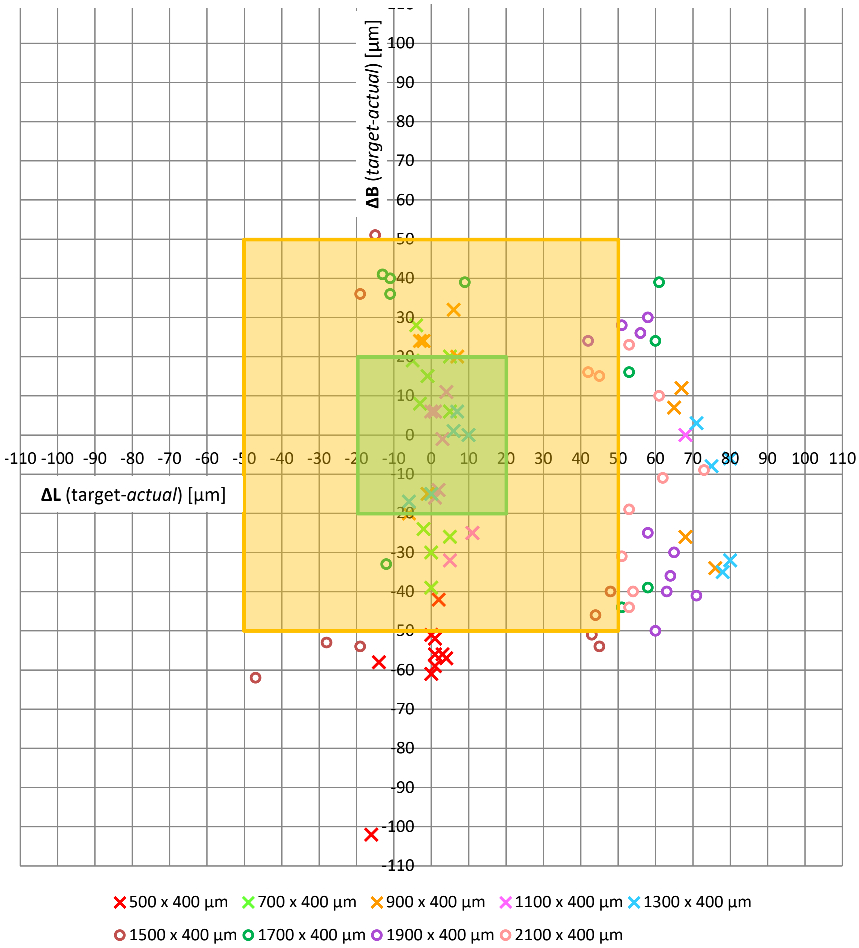

Figure 6. Diagram of the calculated deviations in length and width.

4. Results and discussion

Using the minimum bounding box approach, the smallest edge length of an irregularly shaped particle can be measured in each axis of space [7]. Since StudioMax 3.0.5 does not have such an analysis routine, the dimensions of the particles in the described z- and x-section planes had to be measured manually. Figure 6 shows the deviations from the particle target sizes in a length-width diagram. The yellow box in the diagram marks the wider tolerance range of ±50 µm and the green box marks the narrower tolerance range of ± 20 µm in length and width.

Despite the small sample size, it can be seen that the narrower and wider tolerance ranges were not reached. By carrying out further optimizations – e.g. reducing vibrations by stiffening the sample holder or cooling the workpiece and tool below freezing point – the wider tolerance range (TARGET ±50 µm) could probably be achieved.

Can the manufactured particles now be used for tests on a journal bearing test bench? This question can be better answered with the aid of the diagram in figure 7. For tests on a journal bearing test bench, a causal relationship must be established between the cause (particles) and effect (quantifiable damage). The power of the journal bearing tests depends, among other things, on the characteristics of the particles used. The further apart the size class or the narrower the tolerance range, the better the power [8].

If the particle length is in the range of -100 µm < L_{Target} < +100 µm, a size increment of 200 µm would be just acceptable for tribological studies.

If, on the other hand, the test particles are to be used to determine a cleanliness limit value – above which a system will reproducibly or demonstrably fail – then a size classification according to VDA 19.1 could also suffice [9,10]. This would allow greater size differences to be tolerated and reduce the effort involved to produce the particles.

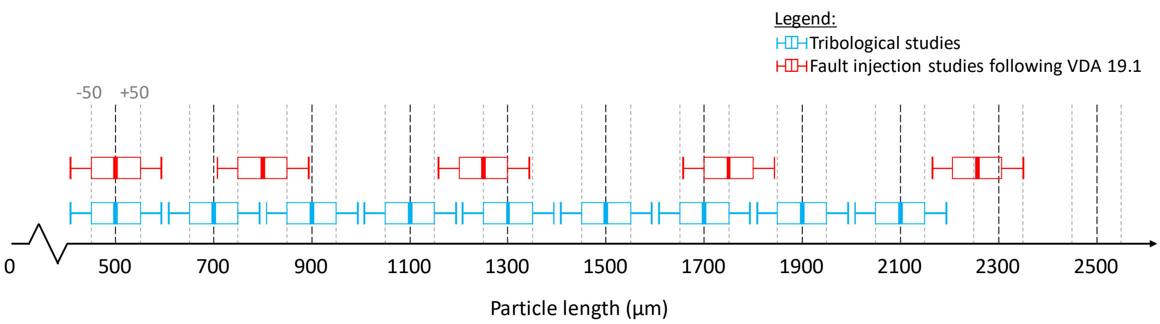

Figure 7. Different size increments for particles depending on the application.

Even if the knowledge gained can, in principle, be transferred to the particle width, it may not be forgotten that not all sizes of particles can be produced.

One limiting factor is the metal removal rate. Attempts to produce particles with a thickness of 100 µm and greater or a width of 600 µm or greater using the milling tool shown in figure 3 regularly resulted in tool breakage or cancellation of the job. To fabricate particles, the metal removal rate recommended by the tool manufacturer could be exceeded by a maximum of six times.

A second limiting factor is the milling tool itself. Its shape and characteristics have a direct impact on particle shape, with the result that a tool change can lead to unwanted deviations. To generate particles that vary only in length, for example, it is therefore advisable to use the same milling tool throughout the entire production process, see figure 8.

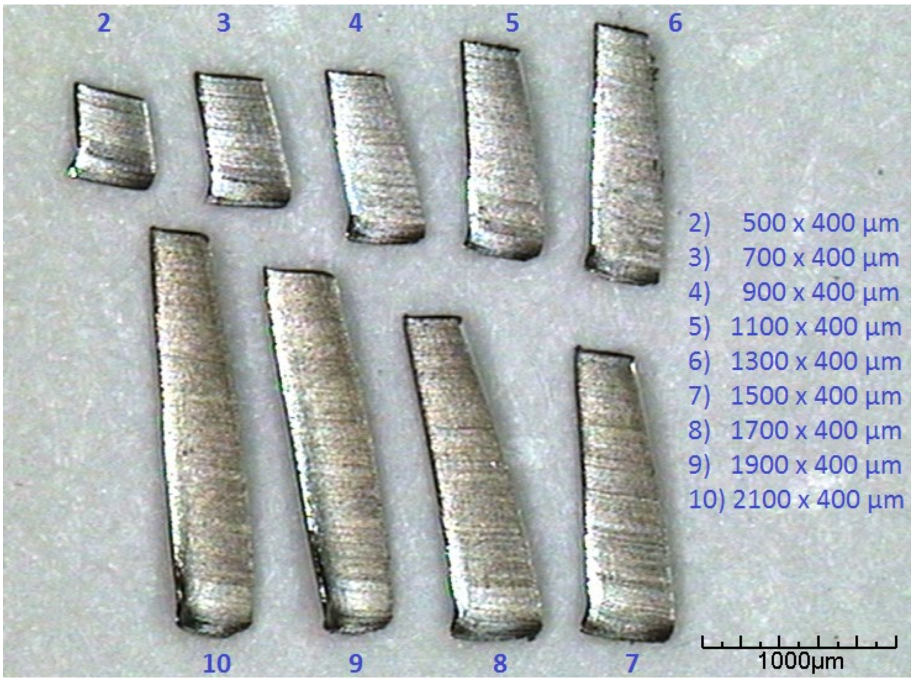

Figure 8. Particles with fixed width and thickness but varying lengths.

5. Conclusions

This article describes how and with which dimensional accuracy synthetic contamination can be produced by micro milling for use in tribological studies or for determining cleanliness limits with fault injection tests. After optimizing the milling parameters, the dimensional accuracy of the particles was analyzed in all three dimensions by micro computer tomography. Although the targeted tolerance range of ±20 µm was not achieved, the test particles were still suitable for use in tribological studies on a journal bearing test bench.

Further applications where synthetic contamination is used also exist, but these have a different focus and other particle characteristics. Cuboid particles, for example, which can be produced by laser cutting or etching, are more suitable for experiments on optical or electronic systems. In contrast, other regularly-shaped green bodies can be produced with very high accuracy by micro powder injection molding [11] and used as tracer particles to monitor production processes. Spherical or compact angular shapes are commercially available as abrasives and can also be used for tribological studies.

Apart from abrasives, which are easily obtainable in large quantities at a reasonable price, synthetic test particles are extremely time consuming and cost intensive to manufacture and thus still a niche application. In the electromobility sector, the automotive industry seems to be slowly recognizing the benefits, as evidenced by an increase in demand for synthetic test particles over the past five years.

Acknowledgements

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