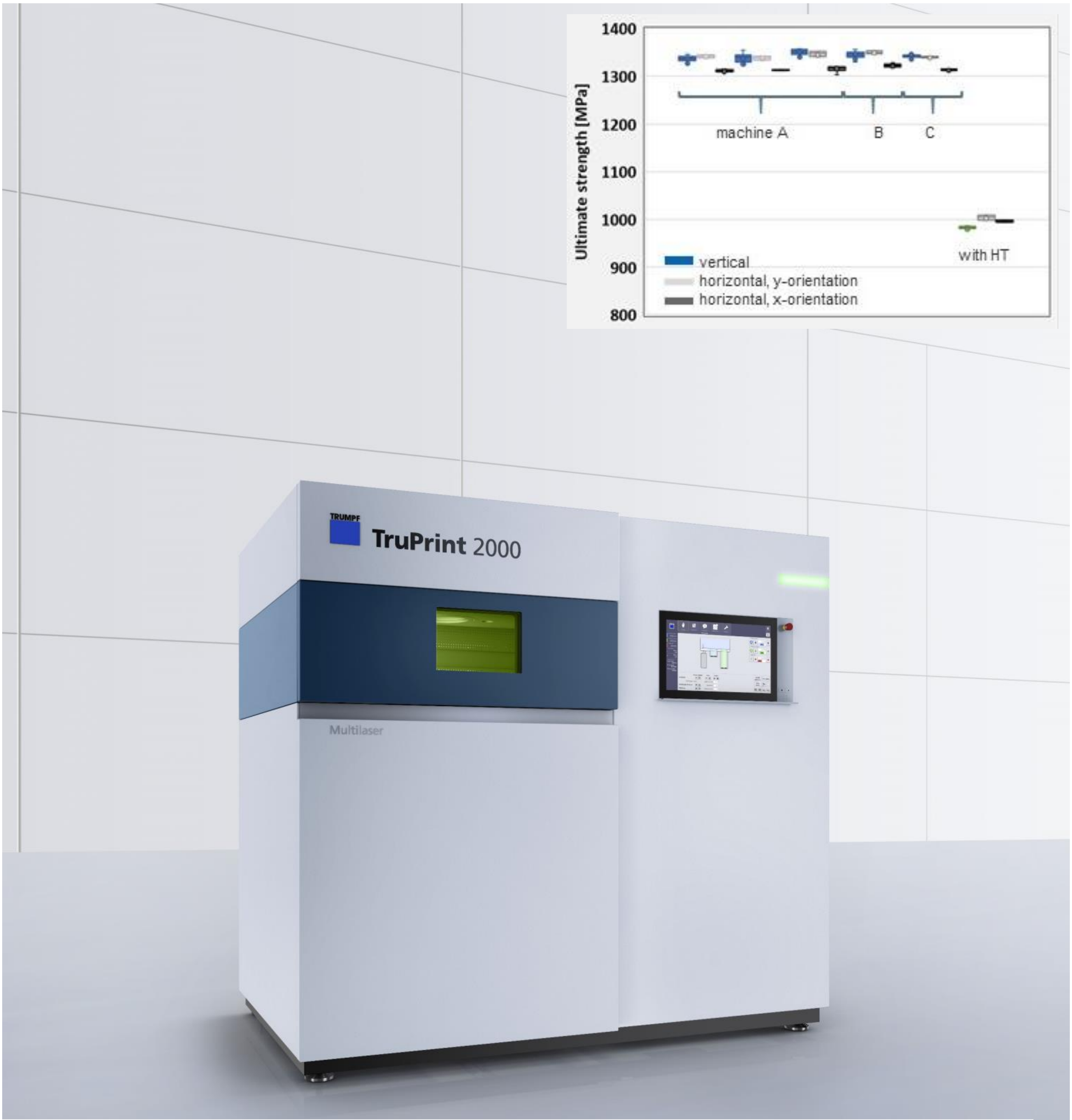

TRUMPF

Whitepaper

Premium Part Quality: Homogeneity and Repeatability on the TruPrint 2000

Contents

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Abstract

Robustness of machine and process as well as repeatability of part properties are the most frequently mentioned requirements for additive manufacturing by industrial users. This is particularly relevant for industries with certified processes such as aerospace and medical technology. In recent years, TRUMPF has taken this need into account in the further development of its Laser Metal Fusion (LMF) respectively Powder Bed Fusion (PBF) machine portfolio. It is well known that the shielding gas flow has a significant influence on the process stability on the entire build platform. Therefore, one of the main focuses in the development of the TruPrint systems was the design of a gas flow concept that ensures both temporally and spatially constant process conditions and is also robust with respect to manufacturing tolerances. This ensures not only the homogeneity of part properties in a machine, but also consistency from machine to machine. This flow concept serves as a reference for the entire current TruPrint product portfolio. However, the analysis of the part properties with regard to homogeneity and repeatability is decisive for the final evaluation of the quality of the flow concept. In this study, the methodology and results of process stability evaluation for the TruPrint 2000, as a representative of the current TruPrint series, are presented. In addition to the very good part properties in terms of density, surface quality and mechanical properties, the results also show very good homogeneity of these properties across the entire build platform as well as very good repeatability both from build job to build job and from machine to machine.

Introduction

The study of homogeneity and repeatability is being conducted with a TruPrint 2000 with Fullfield Multilaser (2 x 300 W) system. The system has a platform size of 200 mm in diameter and is equipped with the new flow concept of the TruPrint series. The flow concept was designed taking into account all the relevant criteria, such as efficient removal of fume, uniform flow velocity, no turbulences, etc., to ensure constant process conditions. Considering these criteria, the basic concept was transferred to other machines with smaller and larger platform sizes. Therefore, the results obtained in terms of process robustness are considered representative for the latest additions to the TruPrint portfolio. The evaluation of process robustness is based on a comprehensive study of the homogeneity and repeatability of the attainable part properties. The study has been conducted for the material TiAl6V4ELI. The TruPrint 2000 has an inert powder handling system and is therefore very well suited for processing reactive material like Ti-alloys, among other materials. This material has wide application in aerospace and medical technology, industries in which reliability and repeatability of part properties are particularly important. In addition, the mechanical properties of TiAl6V4 specimens are sensitive to deviating process conditions, especially when the specimens are analyzed without post-heat treatment. The specimens for the study are build up with the standard beam diameter of 55 µm and a layer thickness of 40 µm. This results in very good detail resolution and surface quality of the parts, which is required for implants with filigree lattice structures or precision parts for aerospace applications, among others. The process parameters used yield a theoretical build rate of 16 mm^3/s per laser beam, thus 32 mm^3/s for the build process in multilaser operation. The platform temperature has bee set to 200 °C.

Figure 1: The TruPrint 2000 Fullfield Multilaser system has been chosen for the study, as a representative of the new TruPrint portfolio

Methodology

Build job configuration

Cubes with an edge length of 10 mm for the determination of density and surface roughness as well as vertically and horizontally oriented cylinders for the determination of mechanical properties under static load (tensile tests), distributed on the build platform, are produced as test specimen. The arrangement is shown in figure 2. For the analysis, 14 cubes, 12 vertically oriented (in build direction z) and 10 horizontally oriented tensile test specimens were used from each build job. One cube at the gas inlet side and one cube at the gas outlet side (representing expected best and worst process conditions, caused by the gas flow) have been taken for CT analysis. The remaining specimens shown in figure 2 were used only for more in-depth internal analyses. The TruPrint 2000 has the option of fullfield processing for each laser beam. For the study, a fixed assignment of lasers per part was chosen. In the lower picture of figure 2, the assignment of the individual test specimens to the respective laser beam is color-coded.

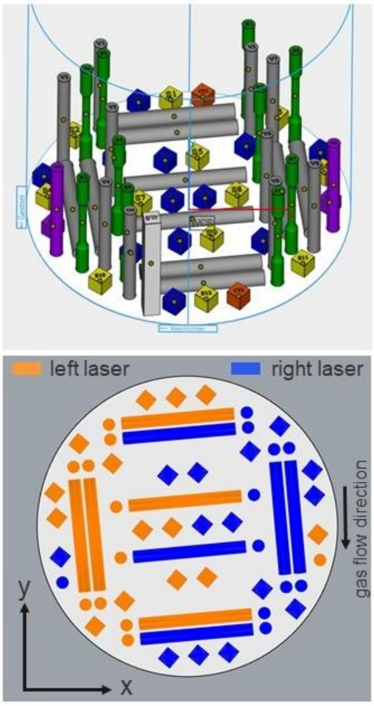


Figure 2: Build job configuration and laser assignment of the build jobs, used in the study

Methodology

To investigate a possible influence of the laser beam incidence angle on the part quality, a cube and a vertically oriented tensile specimen on the right and left edge of the build platform were assigned to the opposite laser beam in order to obtain the maximum incidence angle for these specimens. The distribution of the test specimens over the build platform and the defined assignment of the laser beams to the test specimens make it possible to detect a possible position and/or laser dependence of the part properties.

Machine capability

In the first step of this study, the general suitability of the machine and the parameters are checked for achieving the properties required by the standard F3001 for Additive Manufacturing of TiAl6V4ELI with Powder Bed Fusion and the more demanding AMS4928 for conventional manufactured and annealed TiAl6V4 products. For this purpose, the build job described above is set up and then subjected to heat treatment at 920 °C for 2 hours.

Repeatability systematic

The general procedure for repeatability testing is graphically illustrated in figure 3. A distinction is made between build job to build job repeatability in one machine and machine-to-machine repeatability of a build job. For build job to build job repeatability, the build job is built three times in succession in machine A. For machine-to-machine repeatability, the build job is built once on each of three machines. The build job to build job repeatability serves as a reference for evaluating the machine-to-machine repeatability. In this way, it can be determined to what extent the consistency of the process conditions across different machines deviates from that within one machine. The machines used for the study are located at three different sites with three different operators in two European countries. The same (already used) powder and the same build job file were used for all build jobs. The used powder was analyzed for oxygen and hydrogen content after each of three build jobs, and compliance with the TiAl6V4ELI specifications was checked. No increase of O or H content was measured.

The analysis of all build jobs for the repeatability study is performed without heat treatment to prevent possible variations in part properties from being compensated by heat treatment and thus not being detected.

Analysis

To determine the density, cross sections of the manufactured cubes were made and the density was determined by light microscopy using image analysis. In addition, the density, defect distribution, defect size and defect shape were determined on selected samples by CT analysis. The surface roughness was determined at 4 selected cubes by means of a perthometer on the 4 vertical walls of each cube as the mean value of four single measuring tracks at each wall. No surface processing was performed on the samples (“as built” sample condition). Tensile test bars according to DIN 50125 with L_0 = 25 mm were created from the manufactured cylinders by means of machining (turning). All tensile tests were performed centrally in a certified external laboratory (RTM Breda S.r.l. in Carré, Italy) according to UNI EN ISO 6892-1:2020.

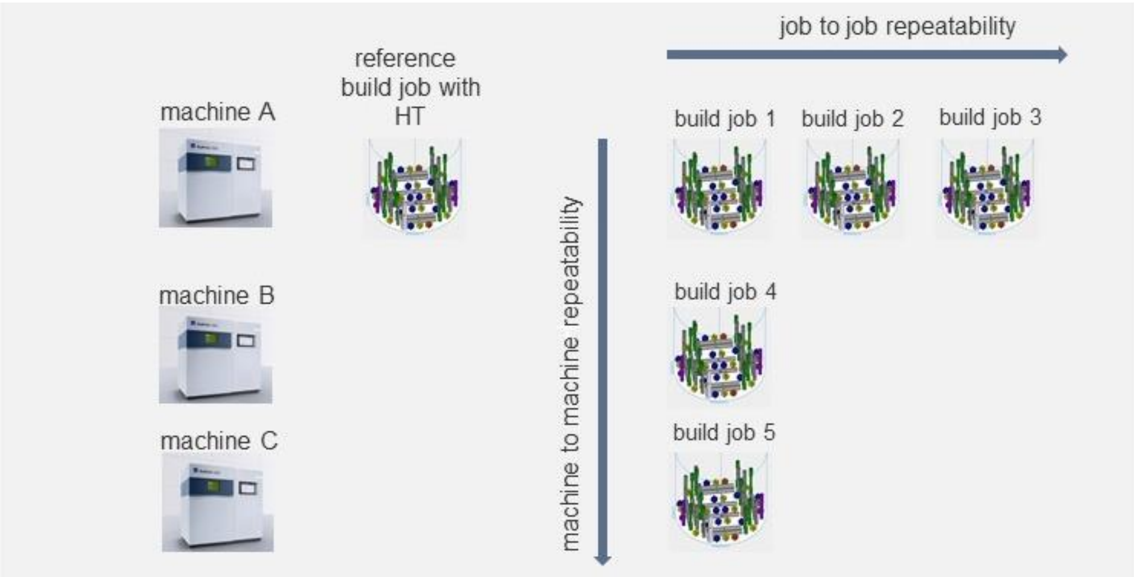


Figure 3: Systematic for build job to build job and machine to machine repeatability investigation

Results

Machine capability

The primary criterion for the capability of the machine and suitability of the parameters is the achievement of consistently high part densities across the entire build platform. Figure 4 shows the distribution of the density determined from the cross-section of the cubes across the build platform including the indication of the laser beam allocation. The result reveals a constant high density of δ > 99.9% with no discernible position or laser dependence, demonstrating that the primary criterion as a precondition for further analysis is fulfilled.

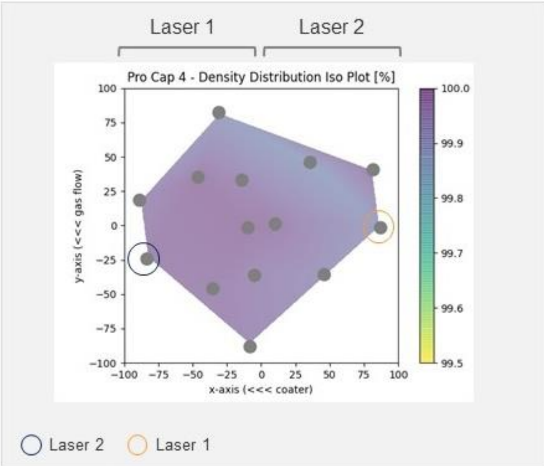


Figure 4: Homogeneous density results of δ > 99,9% across the entire platform

The further evaluation of the machine capability for the production of high-quality parts from TiAl6V4 is carried out on the basis of the tensile test results of the heat-treated specimens and their comparison with the standard requirements. For the analysis, 22 tensile specimens (12 vertically and 10 horizontally built tensile specimens) were examined. The scatter of the individual values shows a sufficiently Gaussian distribution, which is why the representation of the characteristic values tensile strength R_m, yield strength $Rp_{0.2}$, elongation at break A and necking is chosen as a Gaussian curve with indication of mean value µ and scatter width via the standard deviation sigma as well as 3-sigma (figure 5). To classify the values, the minimum requirement from the standards F3001 and the tougher AMS4928 are also plotted as the lower specification limits (LSL). The results show that for all mean values of the tensile tests specifics (R_m = 989 MPa, $Rp_{0,2}$ = 916 MPa, A = 19,8%, necking: 52,8%,) as well as each scatter width at -3sigma are clearly above the corresponding specification limits and thus fulfill the requirements of both standards well. From the plot, in principle, the c_{mk} value ($c_{mk} = (\mu - LSL)/3\sigma$) can be determined to describe the machine capability. The c_{mk} value is clearly above 2 for all characteristic values from the tensile test and thus fulfills well the condition for the use of a machine in series production. However, the c_{mk} value given here is only intended as an initial classification of the results, since a significantly larger database would be required to determine the machine capability according to the 6-sigma method. Nevertheless, the results show that the machine and parameters are best suited for reliably meeting the standard requirements according to F3001 and AMS4928 for the production of parts made of TiAl6V4. The values also show that the selected heat treatment results in a relatively ductile microstructure with an elongation at fracture of approx. 20%, which is well above the standard requirement of 10%. There is thus considerable scope for adjusting the mechanical properties to meet customer-specific requirements by adapting the heat treatment parameters. For example, by applying a lower heat treatment temperature (e.g. 840°C), greater strength can be set with a reduction in ductility without falling below the standard requirement.

From the presentation of the position-dependent values in figure 5 (only for vertically oriented tensile specimens) it can be seen that there is no dependence of the characteristic values either on the position on the build platform or on the laser assignment. This also applies in particular to the specimens at the right and left edges of the building platform, which were each built with the maximum angle of incidence of the laser beams.

Results

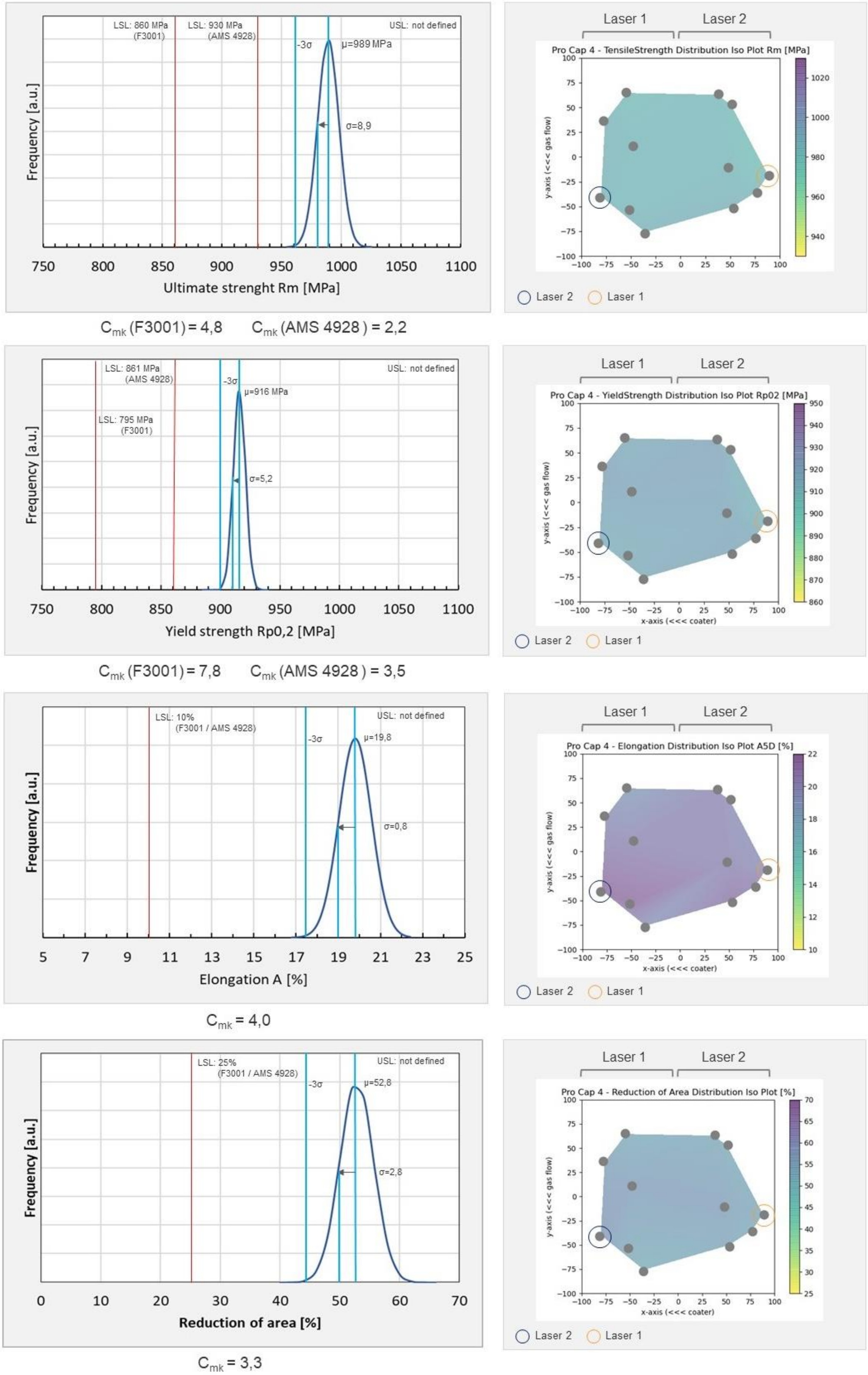


Figure 5: Mechanical properties of heat-treated samples.

Left diagrams: Distribution and specification limits (LSL) according to F3001 and AMS4928

Right diagrams: Distribution across platform position, lower limit of color range equates to LSL

c_{mk} value only for initial classification

Results

Repeatability

The following results of the repeatability investigations are presented in the form of boxplots. The first three boxes each represent the results of the non heat treated samples from the three build jobs in one machine A and thus show the repeatability from build job to build job. The next two boxes show the results from the other build jobs in machines B and C. By comparing all 5 boxes, the machine to machine repeatability can be determined and directly compared with the build job to build job repeatability. Box 6 in the diagrams shows in each case again the result of the heat-treated samples described above.

The diagrams in figure 6, (left column) show the results for R_m, $Rp_{0,2}$ and A from the tensile test (vertically and horizontally oriented). It can be seen from the plots that both, the respective mean values and the scatter range of all build jobs are constantly at a uniform level. The deviation of the mean values over the 5 build jobs in 3 machines is only 9 MPa for R_m, 14 MPa for $Rp_{0,2}$ and 0,8 % for A. The standard deviation σ within the single build jobs ranges from 12 – 16 MPa for R_m, 24 – 29 MPa for $Rp_{0,2}$ and 0,8 – 1,5 % for A. The standard deviation for all specimen of all 5 jobs is in the same range (14 MPa for R_m, 27 MPa for $Rp_{0,2}$ and 1,1 % for A). This shows not only the constant part quality within a single build job but also, and more importantly, the high repeatability across all build jobs. In particular, there is no discernible difference in machine-to-machine repeatability versus build job to build job repeatability within one machine. This underlines that the design of the TruPrint 2000 provides very constant process conditions for a correspondingly constant process result. The stability of the process conditions becomes even clearer when the results from the tensile tests are presented separately according to the direction in which the test specimens were built. As is well known, differences in strength between vertically and horizontally fabricated tensile

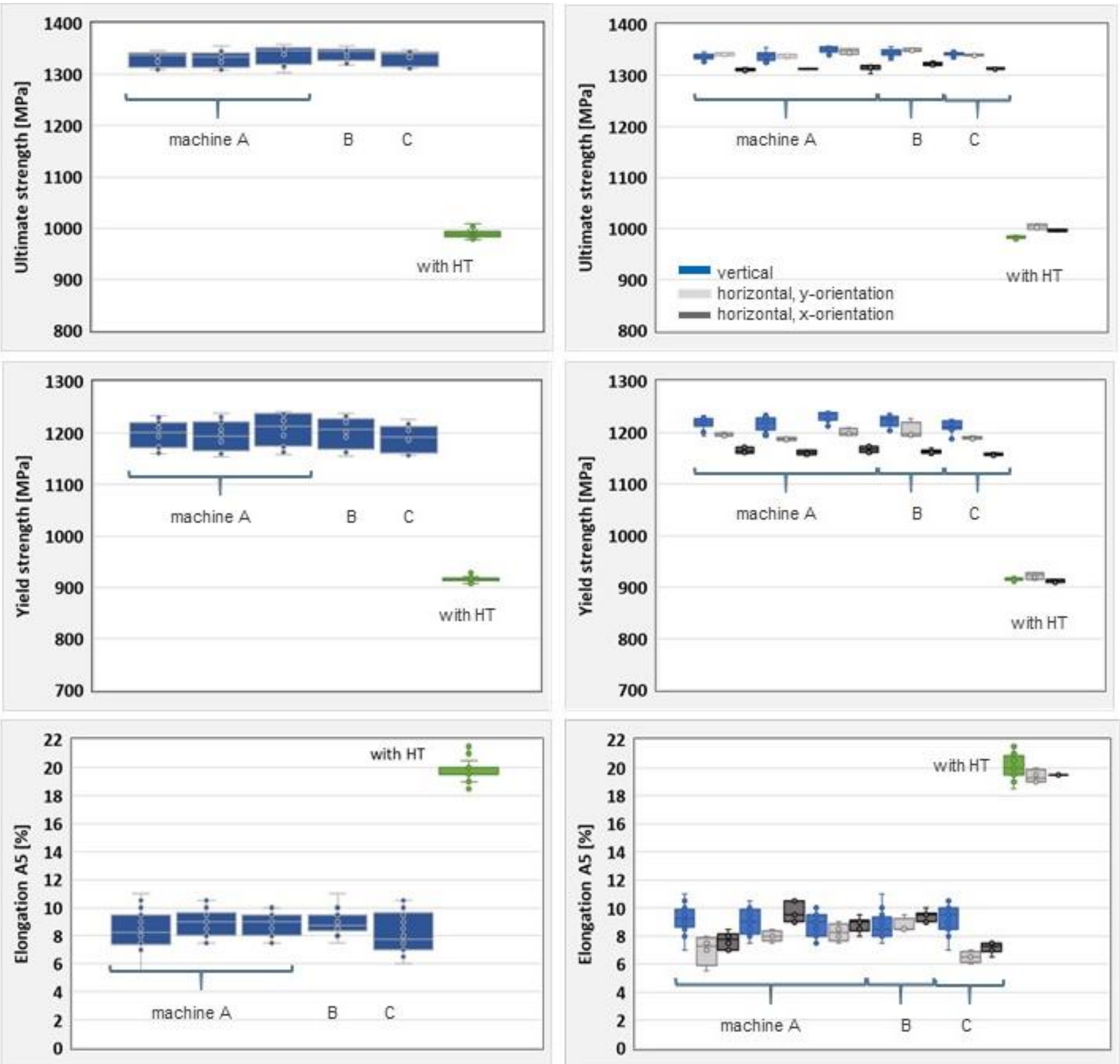


Figure 6:
Left column: tensile test results of 5 build jobs in 3 machines and the result of heat treated samples (green box)

Right column: individual tensile test results for each build orientation

Results

specimens result from the grain growth during the solidification phase, which is preferably oriented in the build-up direction. In addition, however, differences also arise within the horizontally oriented tensile specimens. Due to the blocking of certain stripe angles to maintain processing against the flow direction of the shielding gas, there are differences in the scan vector length distribution and thus the average temperature level between x- and y-direction oriented horizontal tensile specimens (y-direction corresponds to gas flow direction). The effect on the strength values is shown in the diagrams in figure 6, right column. The diagrams show the clearly discernible difference in ultimate strength R_m and yield strength $Rp_{0,2}$ and somewhat less pronounced also for elongation at break A between the individual orientations. The scatter range within each orientation is significantly smaller compared to the already low scatter range across all specimens, shown in the left column diagrams. This makes it clear that the scatter width mentioned above is not only caused by a statistical variation, but essentially represents the width of the systematic, process inherent differences in strength due to specimen orientation. Although the gap between the strength levels of the different orientations is approx. 30 MPa, it is clearly resolved over all jobs and machines due to the very low statistical scatter within each orientation and the very constant mean value over all jobs and machines. The statistical scatter of the strength within the individual orientations is approx. two times lower compared to the scatter of the mixed orientations. (e.g. standard deviation for R_m ranges from 4-9 MPa within the single build jobs if considering only the vertical orientation).

No clearly separated orientation-dependent levels are shown for the elongation at break. Nevertheless, no difference in build job to build job behavior or machine to machine behavior is evident here either.

The systematic orientation-dependent differences of the microstructure and thus of the strength values are significantly reduced or even eliminated by the heat treatment and therefore not relevant for most applications. Again, this illustrates that the investigation of the repeatability by specimens without heat treatment shows a greater sensitivity compared to heat-treated specimens.

Overall, the orientation-dependent plot again illustrates the process stability and excellent repeatability of the mechanical properties from build job to build job as well as from machine to machine, since process-inherent systematic strength differences in the order of 30 MPa in the non heat treated specimen can be resolved clearly and reproducibly across all build jobs and machines.

Homogeneity

The low spread in mechanical properties within each build job suggests that no position dependence of part quality is to be expected even in the as-built condition without heat treatment. This is illustrated in figure 7 by the spatially resolved representation of the density and in figure 8 for the tensile test results (only for vertical orientation, the large extension in one direction of the horizontally oriented samples makes a position assignment unsuited). Starting from the first diagram on the left side in the figures for the position-dependent

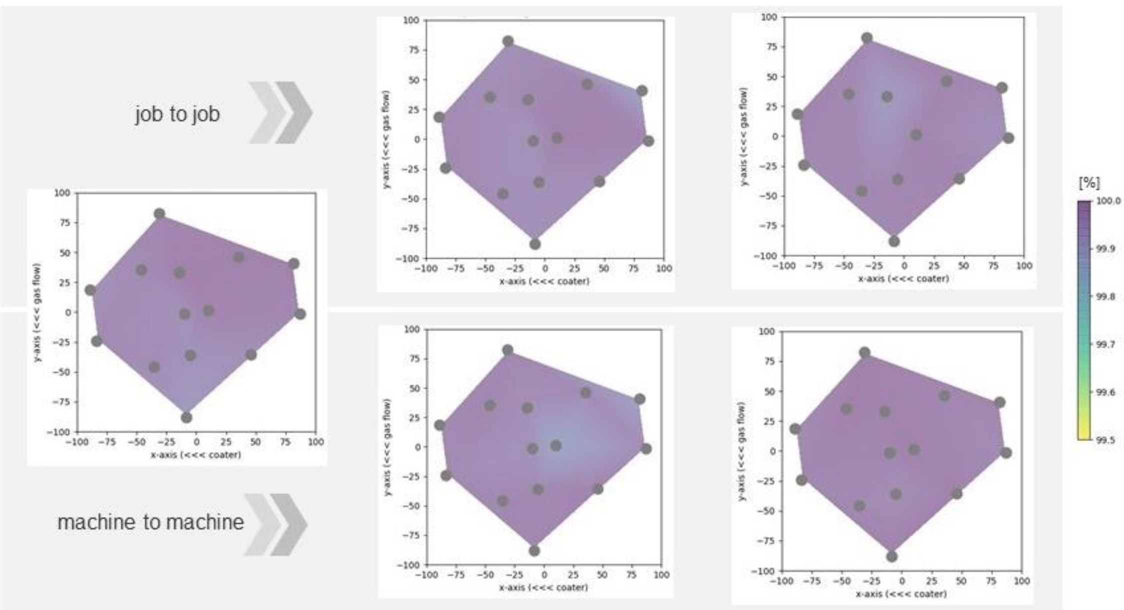


Figure 7: Spatially resolved representation of density (job to job and machine to machine)

Results

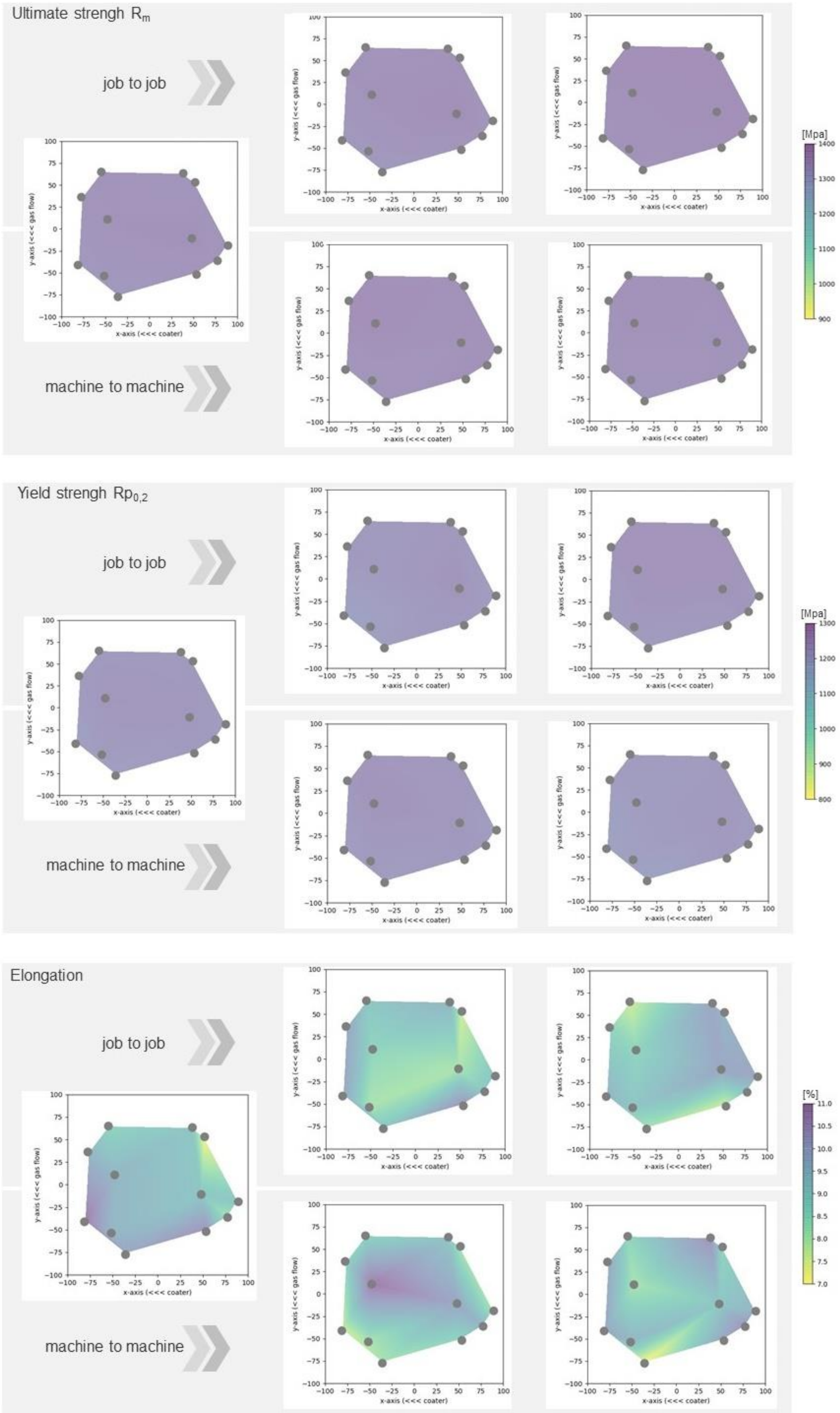


Figure 8: Spatially resolved representation of mechanical properties (job to job and machine to machine)

Results

representation of the results from the first build job, the following two diagrams of the upper row show the results from the further jobs of the same machine and the lower row shows the results of the build jobs from the further machines. Neither throughout the three build jobs in one machine nor in the build jobs of the other machines there is a discernable position dependence or laser dependence for the density and the mechanical properties, which again demonstrates the constant process conditions across the platform in all machines.

Surface roughness and defect characteristics

The results presented show the very good homogeneity and repeatability of the mechanical properties under static loading. Under dynamic loading, in addition to the mean part density, the surface roughness and the size, shape and distribution of the defects in the volume have a decisive influence on the fatigue behavior. The diagram in figure 9 shows the mean value and scatter range for the roughness Ra of all build jobs in the “as built” condition. The mean value of the roughness Ra is constantly between 6,1 µm and 6,7 µm for all build jobs and thus constantly at a very good level, which allows for direct use of the parts without any surface finish for many applications.

From the CT investigations of the cubes in “as built” condition, the volume defects are described via the distribution of the pore sizes, the pore spacing and the sphericity factor (figure 10).

By analyzing 2 specimens per build job, a total volume of 10 x 10^3 mm^3 was considered. The resulting size distribution shows the upper diagram in figure 10. The typical pore sizes are below 180 µm. (two pores have a maximum dimension of 230 µm). From the typical pore spacing (diagram in the center of figure 10), it can be seen that the samples do not have pore clusters (which would be evaluated as one large pore), as the pore spacing is typically larger than 1mm, which is significantly larger than the typical pore size. The sphericity factor as the ratio of the surface area of the defects to the surface area of an ideal sphere with the same extension is greater than 0.5 for all defects (lower diagram in figure 10), i.e., the defects are classified as roundish pores rather than lack of fusion defects, which tend to be characterized by a very flat, gap-like geometry and would be critical for fatigue under dynamic loading due to the notch effect.

The roundish pores detected here with an extension of less than 180 µm, on the other hand, are generally rather uncritical for fatigue behavior and are therefore generally tolerated in the small number present here.

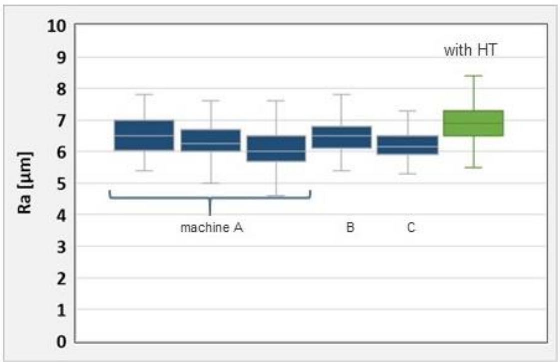
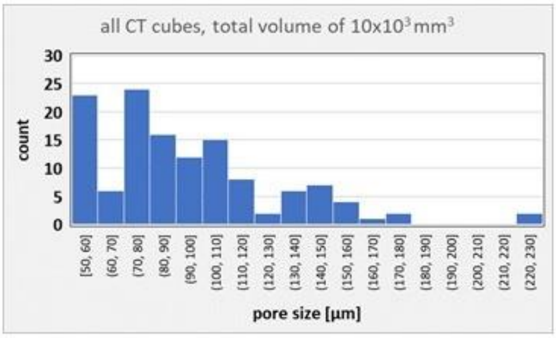
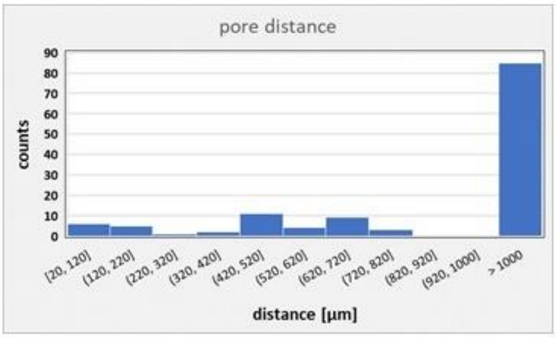


Figure 9: Surface roughness of the “as built” samples





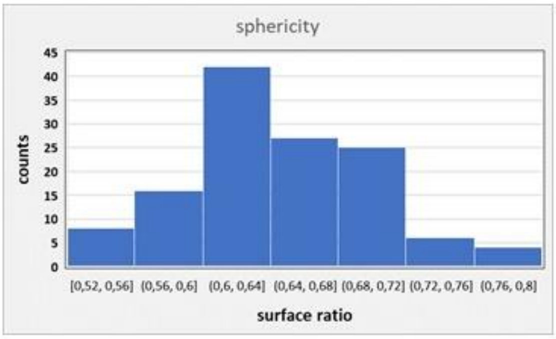


Figure 10: Results of CT analysis of the “as built” cubes for pore size distribution, pore distance and sphericity

Conclusion

The TruPrint 2000 is very well suited for the additive manufacturing of high-quality parts made of TiAl6V4. The parts show a density of >99.9%. The uncritical residual porosity is formed by round pores with maximum dimensions of typically below 180 µm in small numbers. The average surface roughness Ra is repeatably at approx. 6-7 µm ("as built" surface) on a very good level. The mechanical properties under static load (tensile test) of heat treated samples clearly meet the standard requirements according to F3001 and the tougher AMS4928 for additively as well as conventionally manufactured parts made of TiAl6V4.

At the same time, the quality of the parts from the TruPrint 2000 with Multilaser shows no position dependence or laser dependence, neither for heat-treated samples nor for samples without heat treatment.

Part quality can be produced with excellent repeatability, with no difference in build job to build job and machine to machine repeatability. The slightest process inherent differences in the microstructure and the resulting strength of non heat treated samples in the order of 30 MPa can be resolved clearly and reproducibly. This shows that the design of the TruPrint 2000 provides very constant process conditions for a correspondingly homogeneous and repeatable process result. Thus, the TruPrint 2000 provides an excellent technological basis for reliable and scalable series production using additive manufacturing. Due to the same concept of gas flow and optical system, this applies equally to all new TruPrint machines (new TruPrint 3000, TruPrint 5000), which is currently being experimentally validated in the same systematic as shown here. Furthermore, the results of multilaser processing of the single specimen will be added to this study soon.

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