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Dimensional accuracy analysis of Direct Metal Printing machine focusing on roller positioning errors

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Abstract

Despite of the great deployment of Direct Metal Printing (DMP) technology for additive manufacturing, there is still an issue in the dimensional evaluation of built parts. To establish (or define) a reachable dimensional accuracy value in this kind of technologies is an arduous work due to the wide variety of factors involved. The high flexibility allowed by this technology (regarding geometry, materials, strategies, form and size of the powder particles, post-processing method, etc.) causes a high grade of uncertainty on the final part quality. This uncertainty not only affects the surface roughness or the mechanical properties, but also has a high impact on the dimensional accuracy, and this without considering ulterior post-processes. This paper analyses the geometrical and dimensional accuracy of DMP machines focusing on the positioning error of the leveling roller. Another objective of this survey involves the design and validation of a prismatic test part dedicated to characterize the positioning accuracy of a given DMP printer. The analysis is carried out by determining the positioning errors of the printed geometries according to several printing orientations, both in the directions of the roller (metal dust-feeder) displacement, within the roller itself, as well as in the height direction. The high number of prismatic features manufactured onto the built-up plate, and the uniform spatial distribution of these features, allow for obtaining values of the manufacturing repeatability within the machine working volume, providing the deviations with regard to the nominal model as the variability achievable in the different printing directions.

Keywords: Direct Metal Laser Printing; Additive Manufacturing; GD&T analysis; 3D Printing Accuracy

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1. Introduction

Direct Metal Printing (DMP) is an additive manufacturing technique aimed at producing a completely functional part, as it occurs in 3D metal printing. Therefore, part dimensional accuracy stands out as one of the most important aspects to reach this objective. In fact, although there already exist many research studies about the accuracy achieved in metal 3D laser printing and other additive techniques [1,2], the vast majority of them are focused on the surface and dimensional finishing of the components [3,4]. Such type of studies pursues to find the geometric limits achievable in 3D metal printing [4], avoiding the incorporation of reinforcements or the building of supporting structures, both on the outer and inner regions of the manufactured part (using Computerized Tomography for inspecting the inner features [3-5]). However, the influence of other key factors is obviated, such as:

- Some of the additive manufacturing techniques from metal powder use a roller that spreads the powder homogeneously over the printing bed (build-up plate). In turn, this roller compacts the powder before the laser melts the powder selectively following a specific strategy. The effect of the roller on the positioning accuracy of the parts on the printing bed has not yet been studied properly.
- Moreover, after laser sintering, the part is heat treated in order to improve its internal density and to relieve the residual stresses produced in the printing process, which has an obvious influence on the final part accuracy.
- Several post-processing operations are required that involve not only the separation of the individual parts from the build-up plate (by sawing, wire-EDM, diamond-wire cutting, etc.), but also the enhancement of the surface finish of the printed parts (by shot-blasting). In other cases, specific regions of the printed parts are machined in order to ensure their assembly and interchangeability (re-drilling, hole reaming, etc.).

In this paper, only the first mentioned factor is analyzed, studying the positioning error of printed geometries depending on the printing orientations; both in the directions of the roller movement (X axis), according to the same axis Y, and as well as in height (Z axis).

2. Selection of test part and comparison methodology

In this work a test part has been designed by combining different planar surfaces in several cubes, which are the simplest existent 3D geometries. This kind of entity is easily and unequivocally assessable from the metrological point of view. A combination of planar surfaces in different machine building orientations allows a fast dimensional evaluation, which is used for analyzing the influence of the positioning accuracy of the roller on those geometries. For instance, the positioning errors in the direction of the leveling roller movement, as well as in the perpendicular direction to that movement, are obtained from the dimensional analysis of the vertical faces of cubes. Analogously, the precision with which the cubes are manufactured, in the vertical direction (or printing direction), is also obtained from the analysis of the horizontal faces.

A 3D Systems ProX DMP 100 machine has been used to manufacture the part. The machine uses a fiber laser of 50 W and 1070 nm of wavelength, in a Nitrogen (or Argon) controlled atmosphere at 6-8 bar. The metal powder deposition is carried out by means of a roller that extends a powder layer 30 μm thick. The maximum printable volume available is 100x100x100 mm with a repeatability of 20 μm in the 3 axis and accuracy of ±0.1-0.2% with a ±50 μm minimum. The material selected for manufacturing the test part was a 17-4 PH stainless steel, which is a precipitation hardened steel alloyed with Cr, Ni, Cu, Si, Mn and Nb, and whose yield strength is 620 MPa in its "as-built" condition, and reaches 1100 MPa after the subsequent heat treatment.

Measurements on the test part have been carried out with a CMM (DEA Global Image) with Renishaw SP25® scanning probe and a 2 mm diameter ruby tip, whose Maximum Permissible Error is MPE_E [μm] = $2.2 + 0.003 \cdot L$ (ISO 10360-2[6]). In addition, several techniques have been applied to compensate the usual errors in CMM measurement, such as multiposition measurements and repetition of measurements. Fig. 1 summarizes the methodology used in this work based on four steps, which were:

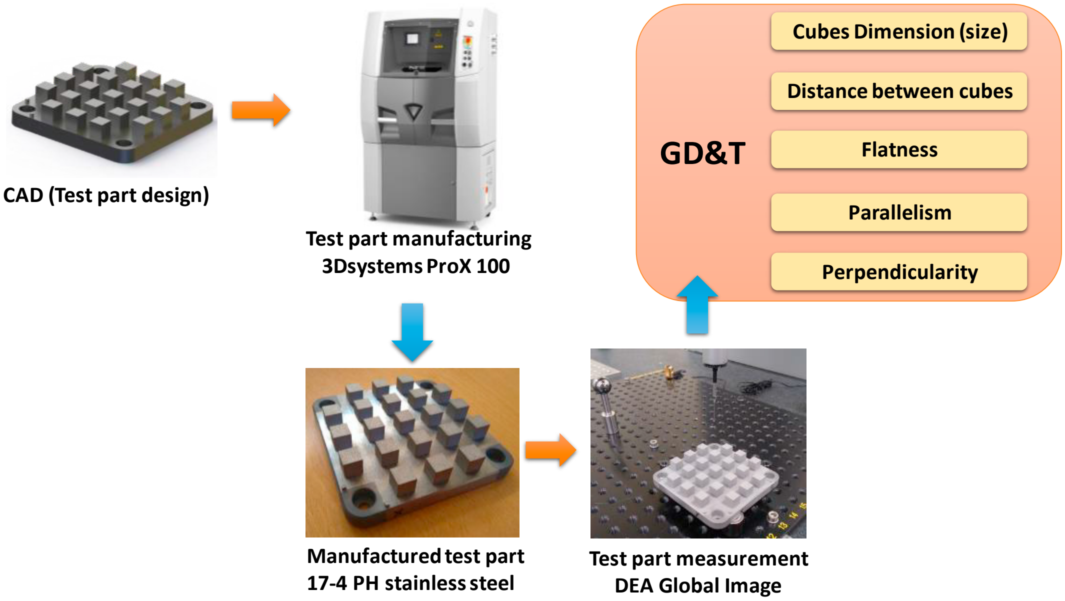

Fig. 1. Experimentation Methodology

- Test part design. This part has a geometry based on planes. Planes have been positioned on the printing bed in parallel and perpendicular directions to the compaction roller. Test part meets the restrictions of the machine and allows to characterize its limits. Also, the part is easily measurable by CMM. It consists of 21 cubes distributed regularly on base plate of 100x100x10 mm. Each cube has nominal dimensions of 10x10x10 mm, with distances between cubes of 10 mm for X and Y axis (X is the direction of the roller movement). Fig. 2 shows the cubes distribution in 5 rows and 5 columns. The identification of each cube consists of 2 digits, the first one represents the column that by agreement is increasing in the direction of roller movement whereas the second digit represents the number of rows, within the length of the roller.

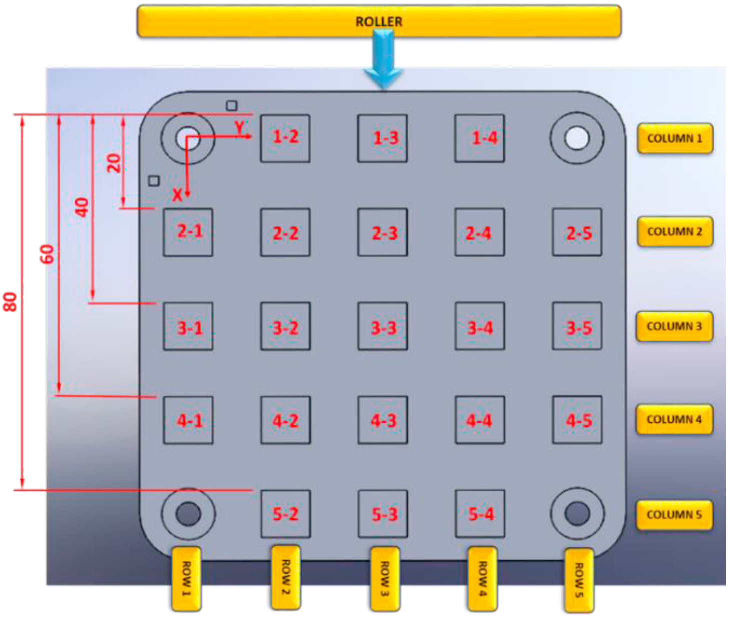

Fig. 2. Machine axis, roller movement direction and cubes distribution

- Test part printing. The CAD design of the test part is transferred to the DMP machine through a STL format. Optimal process parameters, established by previous studies [7], were selected to achieve a good print quality.
- GD&T (Geometrical Dimensioning & Tolerancing) part measurement with high accuracy. Data of dimensions, distances, parallelisms and perpendicularities are obtained. Following the established axes X and Y, distances from the outer face of the initial cube, in each row-column, to the same face of the adjacent cube (following the direction of the row or column) have been measured.
- Analysis of the measurement results. CMM measurement results are compared with the nominal CAD dimensions to calculate the deviations of the main dimensional and geometrical features. Finally, graphs showing these deviations are plotted.

3. Experimentation and results

In order to study the errors or defects given by the leveling roller of the printer, a geometry based on parallel and perpendicular planes to the roller has been designed. The differences between the designed part (CAD) and the manufactured part (measured by contact in CMM) could give us relevant insights about the printer accuracy with regard to the leveling roller behaviour. As can be seen in Figures 2 to 5, the part is made up of 21 cubes uniformly distributed over the available area of the Pinter machine. Once the part is manufactured with the best parameters recommended by the manufacturer for maximum quality and for a specific material (new powder, laser power, atmosphere, geometry without gaps, etc.), it is subsequently measured with the CMM.

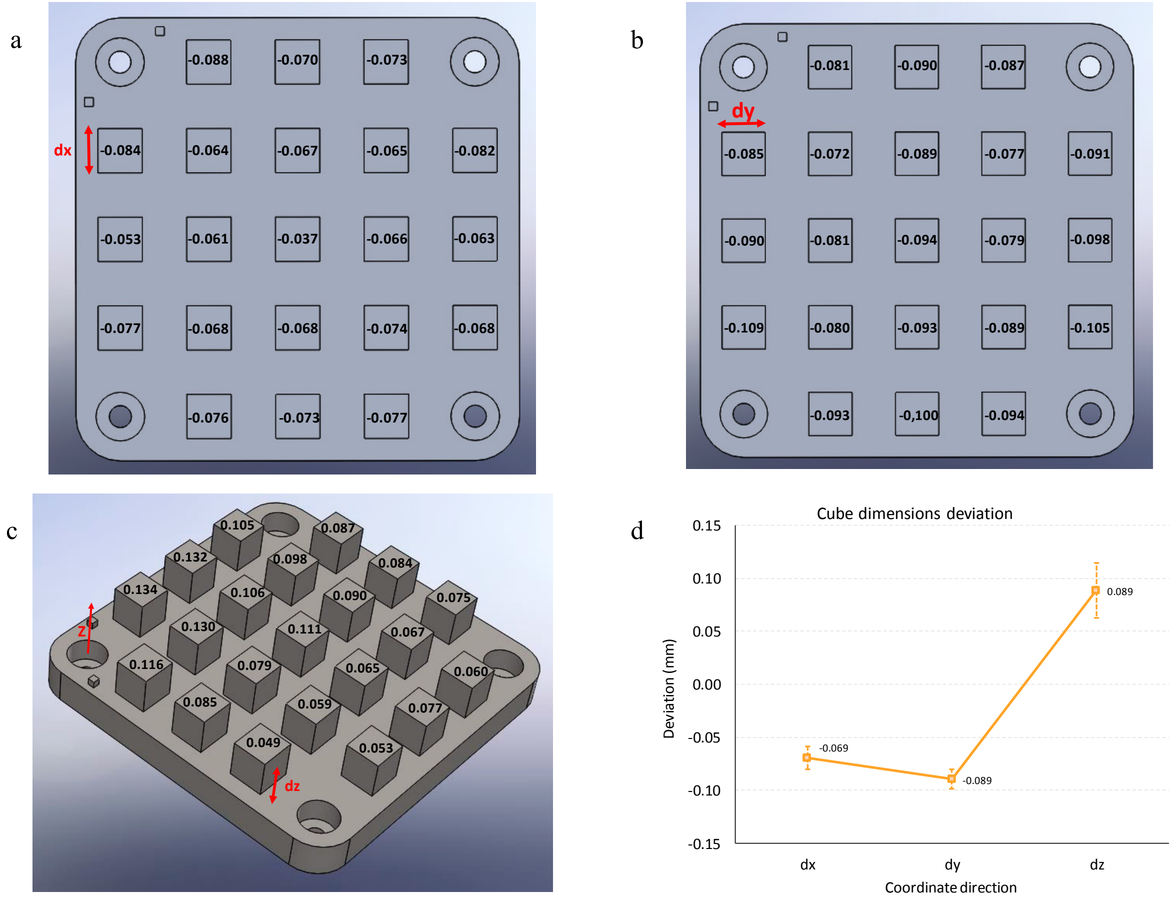

Fig. 3. Deviations of cube dimensions. (a) Deviations in X direction; (b) Deviations in Y direction; (c) Deviations in Z direction; (d) Average deviations in X, Y and Z directions

The proposed evaluation method involves probing multiple points on the different planar surfaces of the cubes. The software used with the CMM has been the PC-DMIS, which allows to perform an initial qualification of the probe, and to program the scanning paths with optimal scanning parameters (movement speed, scanning speed, pre-contact and pre-travel distance, safety planes, etc). Each planar face of the cubes was probed with 100 points to create a corresponding measured plane, enough density to reveal any geometrical deviations.

In Fig. 3, the measurement results in the different axes directions can be observed. In the case of the deviations in Z direction (dz), the reference plane (datum) was the built-up plane. This direction allows for analysing not only the upper face deformation (flatness error) but also the parallelism between the upper faces and the build-up plate. The build-up plate was measured before and after printing the 21 cubes, in order to take into account the distortion caused by the printing process. The orientation of the coordinate system of the CAD and the CMM were matched with an automatic alignment, using the built-up plate and two of its clamping holes (to construct the X and Y axes) as datum elements. Next, the different studies carried out will be detailed, beginning with the dimensional analysis, continuing with the flatness and ending with the parallelism between faces.

3.1. Dimensional survey

The dimensional survey allows for knowing the positioning error of the machine, taking into account both the actual size dimensions of each cube and their deviations from their nominal position.

Fig. 3 shows the results obtained in the dimensional study of the cubes. These results show an average deviation in the dimensions of the cubes of -0.063 mm in the X direction of the machine and -0.089 mm in the Y direction. Therefore, in X e Y directions the machine builds the cubes with lower dimensions than nominal ones. However, in the vertical direction (Z), the average deviation from the nominal one is 0.089 mm. Therefore, the machine builds the cubes in the vertical direction with a greater dimension than the nominal one. Error bars represent twice the standard deviation (2σ) obtained from the analysis of the measurements performed on all the cubes. The values of 2σ for the X and Y directions are very similar between them (around 0.020 mm) while in the Z direction the value of 2σ increases to 0.060 mm.

Fig. 4 shows deviations of the relative positions of cubes with respect to their designed position in the CAD. Fig. 4a shows a minimum deviation in the direction parallel to the movement of the levelling roller (rows) of -0.008 mm and a maximum of -0.027 mm. Although this difference between deviations in the rows is not negligible, the values of them are close to a constant value around -0.016 mm. However, in the direction perpendicular to the movement of the levelling roller ("Columns" series in Fig. 4a), a decrease in the positioning accuracy of the cubes is very noticeable, as the roller moves away from the origin with a minimum deviation of 0.003 mm and a maximum of -0.067 mm. Similarly, the value of 2σ, whose values are not very interesting and do not offer conclusive results (it could be said that the variability is random) in the direction parallel to the roller movement (rows), while an increase can be appreciated again in variability of the cubes dimensions due to their location in farthest positions from the origin, in the direction perpendicular to the roller movement (columns). Fig. 4b shows deviations considering the nominal distances at which the cubes are positioned with respect to the initial (20, 40, 60 and 80 mm). In the figure, an increase in the deviation of the theoretical position of the cubes can be observed, both in the direction parallel to the roller movement (rows or X axis) and in the perpendicular direction (columns or Y axis). Again, there is a huge correlation between the deviation value and the location of the cube with regard to the origin. Therefore, a minimum deviation appears in the cubes located 20 mm from the origin, very similar for both the distribution in rows and columns, of the order of -0.015 mm. As the cubes are manufactured in positions furthest from the origin, it can be observed how this deviation increases; although in the case of row distribution the increase in the deviation is not very significant, a considerable increase in the deviation in the distribution by columns can be observed. The maximum deviation occurs in the cubes manufactured in the position furthest from the origin (80 mm), which have a maximum value of -0.024 mm in the distribution by rows and -0.056 mm in the distribution by columns. This supposes an increase in the deviation of the most distant positions, with respect to the theoretical distance, of 0.010 mm in the case of the distribution by rows and of almost 0.040 mm in the distribution by columns. The value of 2σ is almost constant in the distribution by rows whereas it is greater and increases in the distribution by columns.

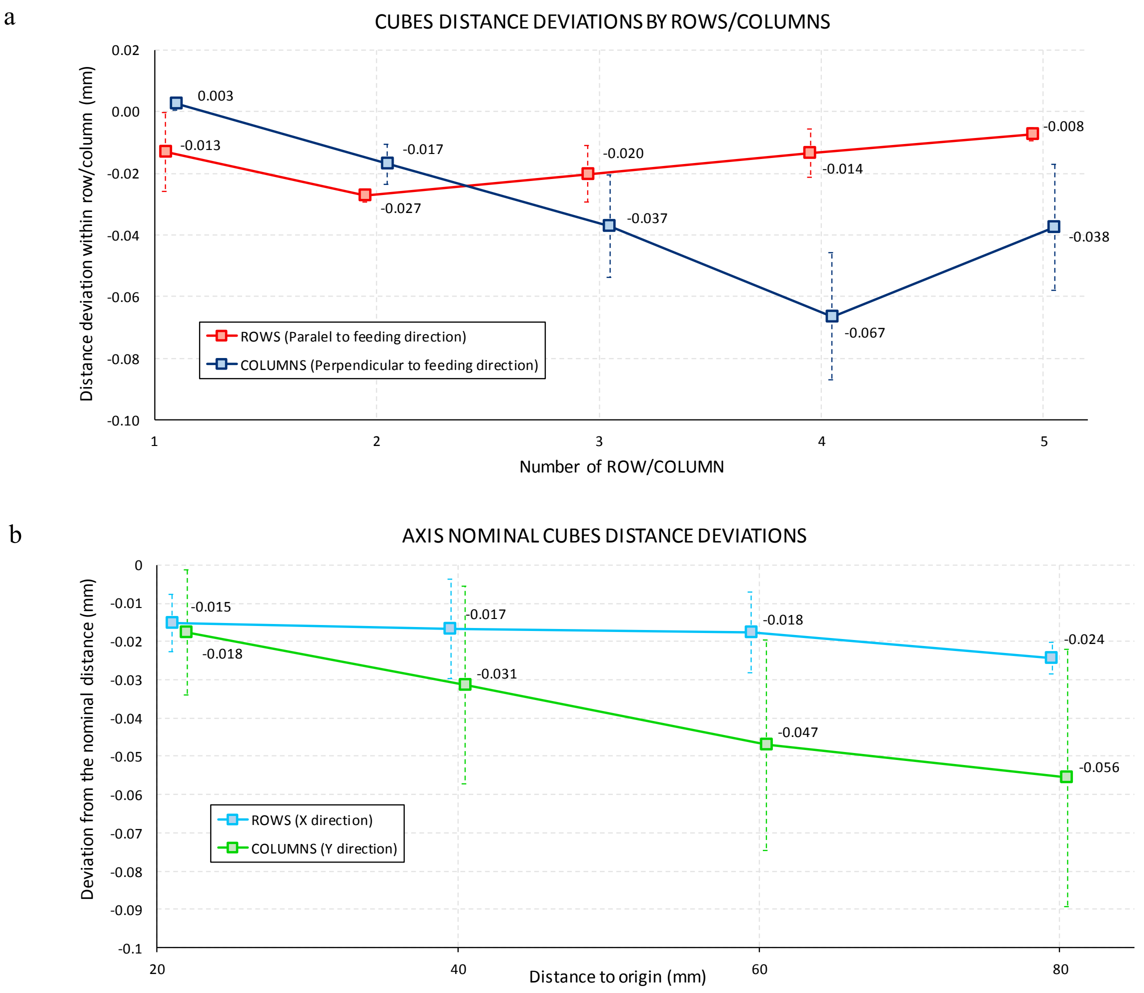

Fig. 4. (a) Cubes nominal distance deviations among them from the origin; (b) Cubes positioning deviations by axis nominal distances

3.2. Flatness survey

Regarding the form deviation survey, the flatness error was analysed according to the orientation of the planar surface and the mentioned nomenclature. Each face of all the cubes have been measured, taking a series of equal-spaced points on each of the faces. A reconstructed plane is obtained from each set of points by applying a best fit method. Then, the flatness deviation is evaluated in PC-DMIS® from the set of points and the reconstructed plane. Fig. 5 shows these flatness values for the different orientations (XY, XZ and YZ planes). The mean value of flatness deviation is smaller for the upper planes (XY) with an average value of 0.055 mm, while for vertical planes (XZ and YZ), the flatness deviations are higher and with identical average value 0.062 mm. However, the variability (2σ) is higher for the XY orientated planes than for the XZ- and YZ-orientated planes, practically the same.

3.3. Parallelism

The parallelism survey was focused in analysing the effect of the residual stresses that occur during the manufacturing process. Hence, the flatness values of the build-up plate have been measured before and after printing the cubes.

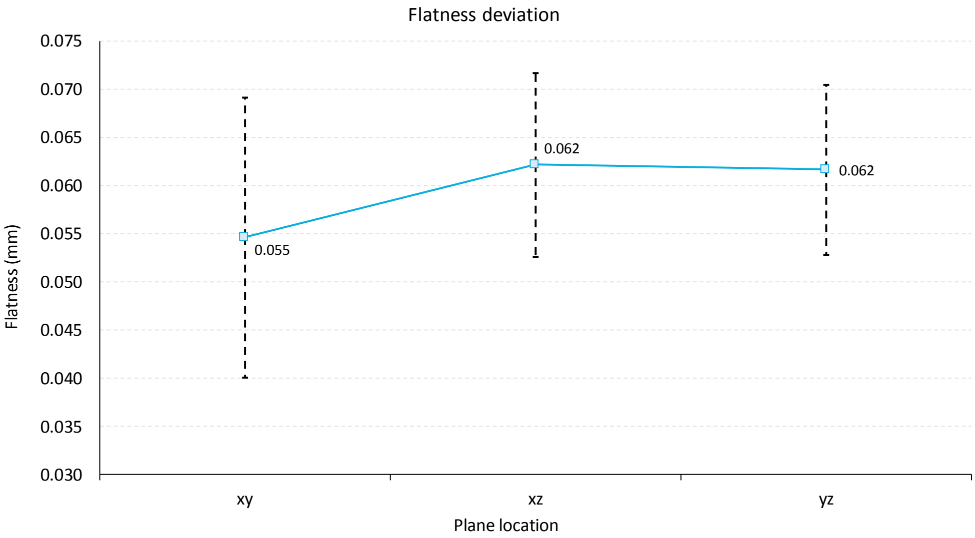

Fig. 5. Cubes flatness deviation

These data will serve as a reference (datum) to study the parallelism between the build-up plate and the upper faces of the cubes. This knowledge will provide a complementary study about the error of the machine once all the cubes are printed. In this case, the build-up plate was surface grinded before printing any cube, with a measured form error (flatness) of 0.011 mm. After printing all the cubes, the build-up plate was remeasured giving rise to a flatness of 0.041 mm. This increment in flatness is due to the distortions produced by the 3D printing process. Figure 6 shows the measured results for the parallelism between the upper faces of cubes with regard to the midplane of the build-up plate. As it can be observed, in the cube located closest to the origin, the deviation is greater (0.100 mm for columns and 0.081 mm for rows) and decreases when moving away from the origin. However, the deviation of the following positions is constant and of value around 0.070 mm. Regarding to the variability (2σ), a certain randomness can be observed in the value of the variability that can be due to the machine error itself.

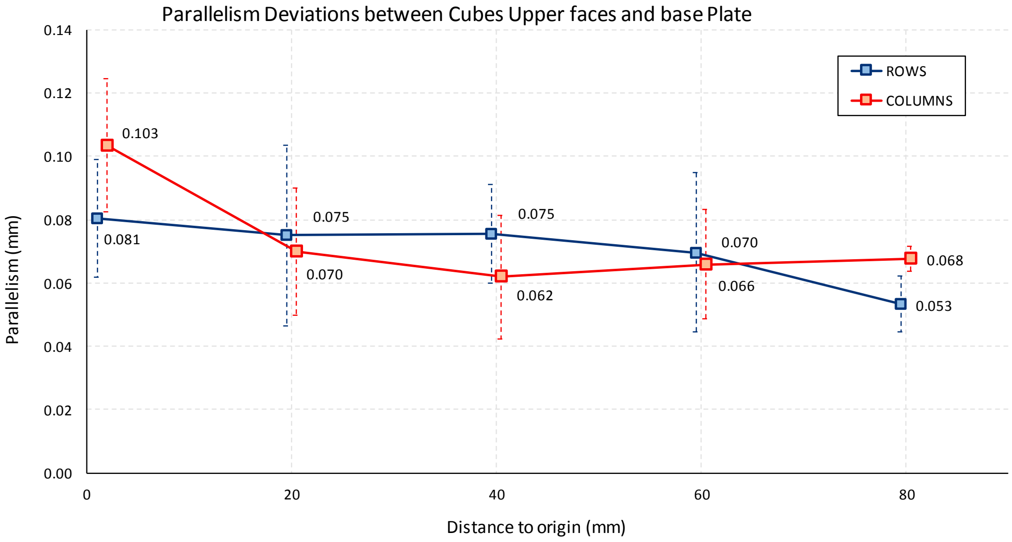

Fig. 6. Parallelism deviation of cubes upper faces with regard to the build-up plate midplane.

4. Conclusions and future works

After the experimentation carried out, several conclusions can be summarized regarding the errors derived from the Direct Metal Printing of a stainless steel part in the ProX 100 machine:

- The dimensions variability of manufactured cubes in the direction parallel to the roller is lower than the variability in the other directions, allowing to apply a correction to the machine more effectively in that direction. Corrections values of +0.060 mm, +0.090 mm and -0.090 mm in X, Y and Z respectively could be applied to the CAD design in order to enhance the accuracy of the parts.
- It can be considered that the flatness error of the manufactured surfaces is similar in any of the orientations XY, XZ and YZ, with an average value around 0.057 mm. On the other hand, the variability of the measurements is significantly greater in the XY plane.
- Regarding to the parallelism error, the variability is so high that no relevant conclusions can be extracted between the rows or columns comparison.

In view of the results, it would be interesting to design and build a test part with a greater number of entities located at more distances, and furthest from the origin and in the vertical direction, in order to obtain more representative and conclusive data on the positioning error and their variabilities.

An ulterior analysis should be carried out extending the comparison between the part “as built” and after applying several post-processing operations (shot-blasting, heat treatments, etc.)

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