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Qualification of rapid prototyping tools: proposition of a procedure and a test part

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Abstract Rapid prototyping machines are becoming faster at manufacturing machine tools. The processes of quality assurance impose the qualification of the production devices. A procedure and a test part are proposed for that purpose; intended for the family of processes of point-by-point layer manufacturing. Existing test parts only permit benchmarking and comparisons between machines: their capacity can be evaluated, but the test part analysis does not make it possible to establish the link between noted defects and their causes. The proposed process and test part permit the identification of the defects and whether their origins are machine or material linked. This paper describes the approach used to design the test part. Some preliminary measures were made on a test part, in order to discuss procedure and measurements.

Keywords Rapid prototyping · Layer manufacturing · Qualification of manufacturing tools · Quality assurance · Maintenance · Test part

1 Introduction

The 1990s saw the progressive appearance of rapid prototyping (layer manufacturing processes) within product development processes. Indeed, rapid prototyping has strongly contributed to the installation of simultaneous and then integrated engineering [1]. These concepts are based on a series of methodologies as well as some technological tools such as CAD-CAM.

Recently, the digital mock-up in the sense of a geometrical model became a common reference to all actors involved in the design process. This model permits testing and simulating of several alternative solutions. It also permits working simultaneously and coordinating different domains within the project group [2].

The transition from traditional design to an entire digital definition is necessary to quickly validate digitally and physically the concepts for new products [3]. The techniques of rapid prototyping contribute to minimizing the risks of project failures. Whereas conventional prototyping takes several weeks and is costly, manufacturing by layers takes only a few hours at a lower cost. The economic stakes are a key factor.

In this paper, one of the new requirements of layer manufacturing machine users is presented: it is about ensuring the industrial performance of their machines. Next, the problem of the selection of a production method and of its qualification arises.

Then, the defects normally found in these types of machine are presented. The solutions to find the origins of these defects are illustrated with a concrete case. Finally, the limitations of the procedure to qualify rapid prototyping devices are discussed.

2 Evolution of rapid prototyping and the necessity to ensure performance

The term rapid prototyping indicates the group of operations leading to the delivery of an object defined by the digital data in a short time without tooling [4]. By physical

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object, we refer to the models and the prototypes, objects of intermediate representations of the process of product development: cosmetic models, functional prototype for testing, rapid tooling, etc.

Market trends lead to innovation and to the reduction of the design and its realization duration, while putting operational products onto the market [5]. Rapid prototyping is one of the tools that participate in this “race’. Indeed, the prototype makes the validation possible on two levels: product and manufacturing process [6].

The future of rapid prototyping processes addressed the idea of rapid manufacturing obtaining parts known as “good material” [7–9]. Thanks to new materials and processes of implementation, new applications can be envisaged. Even if the latest developments of machines confirm this trend, the applications are still limited: Manufacturing speed, part size, surface finish and materials are too restrictive.

The technical and economic feasibility of rapid manufacturing has been studied [10]. Rapid manufacturing has its limitations and some significant advantages: the elimination of expensive mould manufacturing, the flexibility, the possibility of producing very complex parts and shapes, the possible combination of different materials within the same part. Existing examples tend to prove that these processes offer time and cost advantages over conventional technologies [11].

Rapid prototyping must not be used to the detriment of quality, which is the third important point to overcome. However, quality is not the maximum performance, but the accurate application of the specified performance.

One of the current challenges faced by manufacturers consists of a real industrialization of the rapid fabrication machines by layers and but also making them reliable, in order to integrate them to the manufacturing processes of average and large production lines [12].

However, this integration raises the problem of performance repeatability but also of the qualification of production tools [13, 14]. The quality assurance requires a control of the processes. It becomes necessary on one hand to qualify the rapid prototyping tools like any method of production necessitating conformity with a requirement, and on the other hand, to set up appropriate standards for the long term.

After satisfactory evaluation or testing, qualification is the acknowledgement of the aptitude of a process, of a production line, of a supplier or a component, to compete in a definite manner to obtain the quality of the final product. It is an effective tool to control the production [5]. The qualification can also make it possible to evaluate the capability of a new machine, to allow corrections and adjustments, to facilitate maintenance by the identification of drifts and their origins.

Studies [15] confirm these needs. The results of the investigation relating to the practice and the needs as far as quality is concerned in the plastic industry highlight the need to qualify their production tools. Currently, the controlling of the cooling control of the processes results only from the expertise of the machinist. Finally, in the case where an industrialist calls upon a service provider in rapid prototyping using different processes, the problem lies in the choice of the service provider and the qualification of their tools.

3 Proposal for a correlation between the type of defects and the modes of observation

3.1 Qualification of manufacturing tools

Quality implies the improvement of the manufacturing process, which can be made possible if the origins of the defects are known, and if recurring defects (systematic) are identified. Thus, the qualification can be useful for quality assurance, but also for maintenance.

The qualification procedure must make it possible to identify and to quantify defects but also to determine their origins: measurements will be carried out with regard to the elements of the process. The procedure will make it possible to eliminate the parameters which are not dependent on the process.

The qualification procedures of conventional machine tools require to keep control of the displacements independently following the axes in order to be able to verify straightness, parallelism, perpendicularity, etc. In the same way, as far as experiments are concerned, it is necessary to vary machine parameters (which are often inaccessible in rapid prototyping tools). Indeed, for a lot of rapid prototyping machines, the control of these displacements is only possible by devising a special part; the interfaces of the machines only permit a few adjustments. Consequently, in order to be able to carry out a check of the performances of a rapid prototyping machine, we have to make a test part [16]. An indirect check is then possible.

3.2 Origin of the defects encountered on the prototyped parts

The defects observed by the users of rapid prototyping machines are linked to problems of machine geometry or material behaviour. The machine linked defects are more precisely linked to the mechanism or to the automatism.

A study [17] on a process implementing prototype and investment casting made it possible to emphasize the importance of material behaviour: the non-conformity between the digital and physical models was caused by the shrinkage of the material. In spite of taking into account the phenomenon of shrinkage in the modeling, the part obtained was not as good as specified by the supplier. This example highlights the need to know and to fully control materials supplied by manufacturers of rapid prototyping machines.

Many studies propose the use of test parts for shape geometric control [18–22]. A comparison of various test parts [16] highlighted the lack of features and possible measurements on each dimension, and the difficulty to obtain measurements due to very small distances between features.

All these parts are designed and developed with a unique objective which is to make a comparison between the processes or the machines. The correlation between the defects observed and their causes does not appear.

Some works [23–25] propose to quantify the geometrical defects, but also to identify and separate them from the origin of the defects observed. But they only allow measurements linked to tolerances. Defects are never quantified as linked to the manufacturing processes.

We therefore propose to correlate the cause and the effect, but also to quantify the observed defects. For the study proposed in this paper, a family of processes having common parameters has been identified. The processes were differentiated in a functional approach with the help of the inventory of functions to be achieved on the one hand and available technologies on the other. A process family of layer manufacturing, point by point, has been retained: laser polymerization (stereolithography), projection of material, deposit of fused wire.

A process is characterized by the "5 Ms": Means, Manpower, Methods, Medium, and Material. These influence factors modify the quality of the product. Within the framework of the qualification procedure, it is advisable to limit all the influence factors to a known field. We exclude all the independent parameters of the following processes:

- Upstream CAD: discretization and generation of STL file,
- Downstream: cleaning and finishing of the part (manual operations),
- Storage environment of the material or of the use of the machine,
- Ageing and storage of the part.

Thus, the common parameters to the rapid prototyping processes of the afore mentioned family are as follows:

- Displacements in plane XY: guidance and transmissions, slaving;
- Displacement of the platform (Z axis): guidance, layer thickness;
  perpendicularity of the axes between each other;
- Smoothing device: displacement perpendicular to X and Z; straightness (or cylindricality) of the device; rate of displacement;
- Behaviour of the material: during the transformation, the deposit, during the contact with the previous layer (in short run): the cooling rate, the shrinkage.

3.3 The correlation matrix

In order to minimize interaction between various sources of defects, the characteristics of the test part test should make it possible to differentiate the origin of the defects. The test part should give information on the straightness, perpendicularities, and parallelisms of the displacements, and also on material behaviour. But, this part must be constituted by only the necessary shapes so that it will be rapid and economic to manufacture.

A correlation matrix has been defined [15]. It highlights the correspondence between the metrological observations that can be made on the test part and the different parameters linked to the process and to the material used. It is based on the analysis of the previous studies using the test parts, and on the inventory of influence factors depending on the machine and on the observation modes.

Each process parameter, which can be at the origin of a defect can be highlighted by one or more modes of metrological observation.

The advantages a matrix of this kind are as follows:

- Capitalization of the knowledge acquired during previous studies on the machines, on the defects observed, on the material behaviour;
- Identification of the necessary metrological measurements;
- Identification of the defects which interact, for the same mode of observation.

This matrix also leads us to propose the geometric elements for the design of the future test part allowing the identification of the origin of the defects.

Once the first matrix was diagonalized, three main high-density zones appeared. In order to highlight the multiple interactions between the measurements and the parameters, the number of modes of observations on the part was increased. In addition, this procedure has also led us to refine the parameters of the processes listed in the matrix. The final correlation matrix is shown in Fig. 1.

3.4 Proposal of a test part

Several influence factors can intervene on a defect which is identifiable by the same mode of observation. It is thus advisable to imagine the test part shapes, which make it possible to differentiate the origin of the defect. In addition, the test part must have simple geometrical shapes, perfectly defined and easy to control. It should require neither post treatment nor manual intervention; therefore, its forms should not require any supports. Finally, the test part

	observation modes / process parameters	Y Yaw	X Yaw	smoothing straightness cylindricality	X Pitch	Y Pitch	X Roll	Y Roll	Z Roll	Z Pitch	distorsion	Z Yaw	slaving interpol°	displac. speed	smoothing perpend Z	perpend. Z/XY	perpend. X/Y	position slaving	0/1	shrinkage	layer thickness Z
21	parall plans perp. to X - mesure along Y		x		.																
	parall plans perp. to X - mesure along Z				x																
22	parall plans perp. to Y - mesure along X	x				.															
	parall plans perp. to Y - mesure along Z					x															
4	straightness XZ along X				x		x		x												
3	straightness XY along Y					x	x	x			x										
1	flatness XY thick			x	x	x	x	x			.										
	flatness XY large			x	x	x	x	x			x										
2	straightness XY along X				x		x	x			x										
6	straightness YZ along Y					x		x	x												
5	straightness XZ along Z						x		x	x	x										
7	straightness YZ along Z							x	x	x	x										
9	concentricity (z axis)								x	x		x	x					x			
8	cylindricality (z axis)								x	x	x	x	x						x		
23	parall plans perp. to Z -mes. along X -thick plan									.	.	x									
	parall plans perp. to Z -mes. along Y -thick plan									x											
	parall plans perp. to Z -mes. along X -large plan										x	x									
	parall plans perp. to Z -mes. along Y -large plan									x	x										
19	squareness XY / Z														x	x	.				
20	squareness X / Y										x						x				
18	angles / X												.			x	.	.	.		
	angles / Y															x					
	angles / Z												x				x	x	x		
24	material homogeneity										x			x					x	x	
10	dimension between plans X																	x	x	x	
11	dimension between plans Y																	x	x	x	
15	thickness along X																	x	x	x	
16	thickness along Y																	x	x	x	
	roughness (plan non perp Z)																	x	x		
17	thickness along Z																			x	x
12	dimension between plans Z																			x	x

Fig. 1 Final correlation matrix

should allow measurements of repeatability, in order to avoid the production of several specimens [26].

A synthesis of the forms permits the definition of the completed test part (Fig. 2). It results from the matrix of the final correlation, the analysis of the interactions and it synthesizes the modes of observation to be carried out [15].

In order to simplify the part and to quickly manufacture it (due to cost considerations), we optimized the number of elements by arranging them in order to have the smallest surface at the base. Some elements are common to several series. However, it is necessary to respect the minimum encumbrance in order to facilitate access of the three-dimensional measuring machine.

In order to avoid the curling of the base surface, which sometimes occurs [16], the plate was recessed but rigidified (see Fig. 3).

4 First implementation of the qualification procedure

4.1 Standard conditions

Some instructions are listed in order to guarantee standard conditions of realization and homogeneity in the manufacturing procedures. They lay down the utilization conditions of the rapid prototyping machines, the storage conditions of materials, and of the finished part.

In the same manner, a procedure is put forward to guarantee an identical working procedure whatever the machine or the machinist, in order to free itself from the dependent parameters of the method.

The correlation matrix and the analysis of the interactions enable the drawing up of a list of the measurements to be carried out.

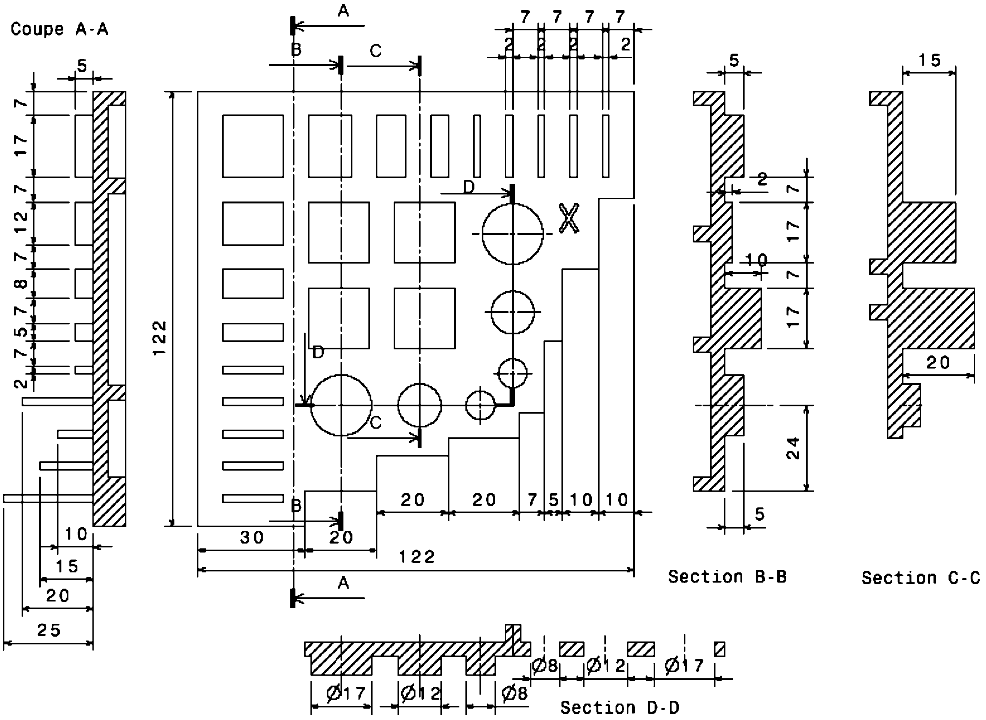
Finally, a procedure document is provided in order to carry out measurements necessary for the test part exploitation and to guarantee an identical procedure whoever the machinist.

4.2 Processing the results

On the one hand, the theoretical CAD dimensions and the measured dimensions are compared; on the other, the importance of the geometrical defects is highlighted. The correlation matrix indicates the link between the measurements and the influence factor(s).

Some measurements make it possible to quantify only one defect. However, for the matrix to allow a complete resolution, it would require that each influence factor correspond to an observation mode. When differentiation is not possible between the various factors which can intervene on an observation mode, the analysis will at least permit to determine globally if the defect originates from the machine or if its origin is linked to the material.

Fig. 2 Scale drawing of the test part



4.3 Application and first results

The realization of a test part has been entrusted to a service provider. The STL file and the documents specifying the standards conditions were provided.

After the realization of a test part in stereolithography (Fig. 4), measurements were taken using a three-dimensional measuring machine. The observations in this paragraph mainly aim at highlighting difficulties and at improving the measurement process and the test part.

4.3.1 Observations on thicknesses

The influence of shrinkage can be observed thanks to the following shapes of the test part (Fig. 3):

- Shrinkage being a function of thickness [17], the planes of increasing thickness and constant height make it possible to dissociate the influence of shrinkage and that of defects of the machine (independent of thickness);
- The planes of increasing height and constant thickness make it possible to observe the influence of height on flatness. Indeed, the "crater" phenomenon resulting from a hot point is a thickness function of material [17]; cooling is slower for thick features and for the center of massive parts. The influence of material and that of machine defects are thus dissociated.

Figure 5 shows the deviation (i.e., the difference between theoretical and measured distance), according to the thickness, for features along X, Y, and Z.

Fig. 3 Test part (CAD definition). Legend: 0 Reference plane. *1* Planes YZ of increasing thickness (height=5 mm). *2*- Planes XZ of increasing thickness (height=5 mm). *3*- Planes YZ of increasing height (thickness= 2 mm). *4*- Planes XZ of increasing heights (thickness=2 mm). *5*- Planes XY (27×27 mm), of increasing heights. *6* Boring and cylinders of increasing diameters. *7* Steps along the base to measure the dimensions in X and Y

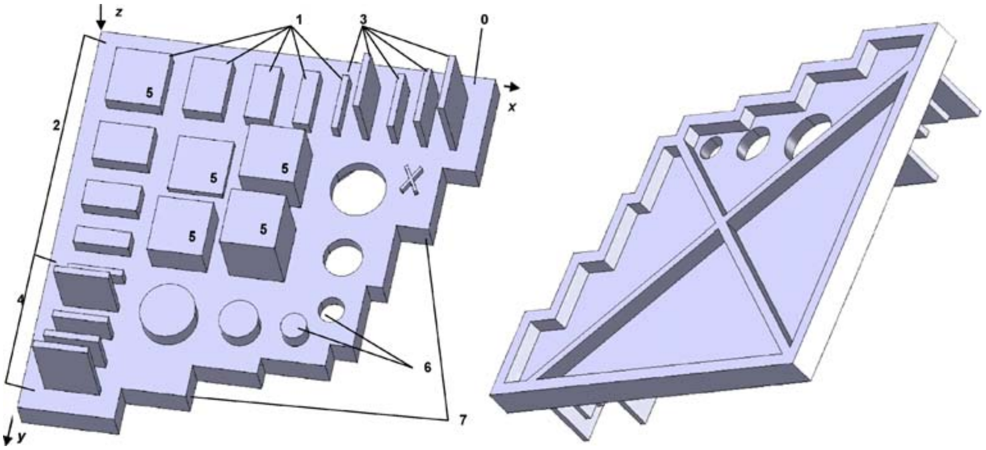


Fig. 4 Resin test part realized by laser stereolithography

Along the X axis of the completed part, we note that the deviation between the theoretical and measured value is significant (0.33 mm on average). The deviation is a little more significant along the Y axis (0.39 mm on average). These deviations vary little relating to the thickness of the forms and are positive (the obtained dimensions are higher than the theoretical ones).

On the other hand, along the Z axis, the deviation is negative (the obtained dimensions are lower than the theoretical ones) and this deviation increases with the thickness of the plane. The deviations are however less important than those of the X and Y axes, and vary between 0.12 and 0.29 mm.

According to previous works [19, 17], shrinkage increases with the thickness of the material. In the case of dimensions along X and Y, the observed deviations cannot be attributed to shrinkage since the gaps are positive. These defects are thus rather attributable to the problem of compression, which will confirm the negative deviation in Z. Once completed, every layer is smoothed, which can cause the compression of lower layers, which are not totally solid yet.

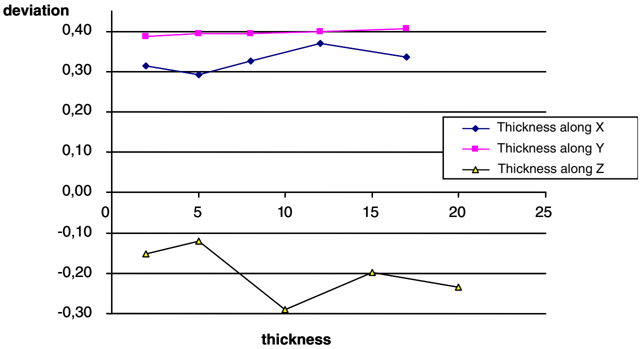


Fig. 5 Evolution of theoretical deviation measured according to thickness

The measurements taken on the circular shapes and the plane profile also confirm the hypothesis of compression. This poses the problem of the controlling of the cooling of the material [27].

Compression is different from the phenomenon of shrinkage. There is still shrinkage but it was not observed here; so we believe that there could be an internal machine compensation. Lastly, we could suppose that shrinkage is identical in the two dimensions of plane XY, but we note a difference between the average deviations on axes X and Y. That led us to believe it was a machine-linked defect.

A focus defect of the laser can cause the polymerization of a surface different from the one that was planned. Thus, the polymerization in the surrounding hot region can also be at the origin of the positive deviations along X and Y.

4.3.2 Observations on flatness

The profiles of the planes confirm the compression on their edges, and the crater phenomenon is absent. By observing the evolution of the flatness according to the thickness, along the Z axis of identical planes, we note that the absence of flatness seems to decrease when the thickness of the planes increases.

So, the problems attributable to the cooling of the material are not present. Study [17] observed an increase in the distortion when the thickness of the forms increases.

4.3.3 Synthesis

The differences between the manufacturing and theoretical large dimensions along the X and Y axes, increases with the dimensions. Moreover, these variations are positive, which does not correspond to the expression of shrinkage.

Furthermore, there is an offset between the deviations along X and Y axes. The part being symmetrical, this could be caused by a difference of machine behaviour.

The phenomenon of compression can explain the positive deviations on the diameters and negative deviations on the diameters of the borings. The order of magnitude of the deviations is identical.

So, dimensional deviations are of the same order of magnitude, whatever the dimensions. The phenomenon of shrinkage is not noted, certainly caused by an internal machine compensation.

The phenomenon of compression observed can implicate the controlling of the cooling.

5 Limitations of the procedure

The implementation of this procedure highlights the difficulty of a systematic identification of the exact origins of the defects. Nevertheless, the correlation matrix and the analysis of measurements allow us to identify at least the origin of the defect: machine and/or material behaviour.

In order to systematically correct these defects, we it is necessary to act directly on the process, but few adjustments are accessible to the machinist on the machines. In addition, the adjustments made by the machine on the material are not known.

To be able to correct the systematic defects of geometric origin, it is possible to correct the source file:

- method of positioning of the piece in the machine,
- simulation by finite elements and forecasts of anisotropic rate of withdrawal and introduction of a scale factor according to axes [28]
- method to define suitable cutting of the layer to increase precision [29].
- method of course for the laser beam [30]
- cooling of the part on specific parts at the time of manufacturing [27].

However, a modification of the data to compensate the defects related to the behaviour of material appears to be difficult. Indeed, the users of rapid prototyping machines have little information and no control over the material.

Thus the qualification of a rapid prototyping process seems difficult for the time being. The use of such a procedure would allow a more accurate reproduction of the manufacturer data in term of precision.

In a context of maintenance, it can also allow for a periodic control of the machines as well as the identification of drifts.

6 Conclusions

Certain rapid prototyping machines become direct parts of manufacturing equipment. Ensuring the industrial performance of such processes is a rather new requirement. The industrialists engaged in quality procedures need to qualify their processes. The procedures of qualification of the conventional machine tools cannot be applied, therefore the realization of a test part is necessary. The procedure and the test part have been tested with various machines. However, it appears that a qualification procedure based on a test part is somehow limited. Indeed, the influence factors of the defects are not systematically dissociable. Moreover, the corrections are difficult to implement. It is often impossible to intervene on the adjustments of the machines and on their behaviour. Accepting to modify the geometrical definition to obtain the desired result seems to be difficult to integrate within a qualification procedure because this amounts to acknowledging that the production process is not controlled. Finally, faced with the multiplicity of materials, more knowledge remains to be acquired to be able to control theses materials and to know their behaviour in more detail. Such a procedure is of interest to the users of machines in order to know the limitations of their processes: they can become aware of the origin of the defects and quantify them. In addition, they can detect the appearance of defects and the need for maintenance.

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