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Procedia Engineering 132 (2015) 70 – 77

Procedia Engineering

www.elsevier.com/locate/procedia

The Manufacturing Engineering Society International Conference, MESIC 2015

Analysis of Factors Influencing the Mechanical Properties of Flat PolyJet Manufactured Parts

P. Gay[a], D. Blanco[a,]*, F. Pelayo[a], A. Noriega[a], P. Fernández[a]

[a]*Department of Construction and Manufacturing Engineering, University of Oviedo, Gijón 33203, Spain*

Abstract

In Additive Manufacturing (AM), parts are manufactured layer-upon-layer. This strategy affects the mechanical properties of AM parts, since they cannot just be assimilated to those of parts manufactured by traditional methods. The PolyJet AM technology uses UV energy to cure layers of photopolymer that are stacked one on top of the following. The amount of energy that reaches each layer is related to several aspects of the manufacturing procedure, such as jetting head displacement strategy or UV irradiation pattern. This work aims to analyse the relative influence of configuration parameters on the relaxation modulus E(t) of flat parts manufactured using PolyJet technology and orientated on the XY plane. Evolution of material properties with respect to time has been used since parts shall present viscoelastic behaviour. Four factors have been evaluated: part spacing along X axis (Δx) and along the Y axis (Δy), orientation of the part within the tray (φ) and surface quality (Q). Influence of Q has been included since material properties could be modified by UV shielding effect. Experimental results have pointed out that Y-spacing and orientation φ both affect E(t).

Peer-review under responsibility of the Scientific Committee of MESIC 2015

Keywords: Additive Manufacturing; PolyJet; Mechanical Properties.

1. Introduction

The ASTM F2792-12a standard defines Additive Manufacturing (AM) as “the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing

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* Corresponding author. Tel.: +34 985-18-2444
E-mail address: dbf@uniovi.es

Peer-review under responsibility of the Scientific Committee of MESIC 2015
doi:10.1016/j.proeng.2015.12.481

methodologies". Consequently, AM processes allow the manufacture of very complex shapes, as well as regular geometries. Nevertheless, this layer-stacking strategy conditions the mechanical properties of AM parts, introducing a certain degree of anisotropy, so they cannot just simply be assimilated to those manufactured by traditional processes. Since AM processes are relatively new, there is still a lack of knowledge on current mechanical behaviour of AM parts [1], which can be a drawback for the industrial adoption of these technologies. This deficit is one of the main challenges that AM processes must face in the future, since achieving reliable industrial-level applications is a prior objective nowadays.

In present work, focus has been put on the PolyJet process. This process uses ultraviolet (UV) radiation for curing layers of jetted acrylic photopolymer. The jetting head is formed by a matrix of jetting orifices disposed along the Y axis, and is mounted on a carriage that allows for X forth-and-back displacements and alternate transverse (Y) relocations. Additionally, the manufacturing tray can move in the vertical (Z) direction, after each layer has been successfully manufactured (Figure 1).

Once the slicing software has split the 3D geometry of a CAD model into a collection of 2D geometries, they shall be manufactured from bottom to top. In a particular layer, the 2D shape is analysed and a CAM code is generated in order to synchronize jetting head displacements with correspondent material deposition. Thus, during forth movement, each orifice in the jetting head coordinates the projection of photopolymer droplets with its instant position, so that an area correspondent to the theoretical shape of the 2D geometry is covered by material. Simultaneously, an UV lamp on the carriage cures the photopolymer, and this curing procedure goes on along back-and-forth movements. Once the layer geometry has been cured, the tray descends a length equal to the layer thickness along the Z axis, and this procedure is repeated until the part is completed.

According to this description, it seems clear that the amount of energy that reaches each layer is related to several aspects of the manufacturing procedure, such as jetting head displacement strategy or UV irradiation pattern. Moreover, some researchers have pointed out that actual parts could have slightly different mechanical properties than those reported by the manufacturer [2]. Thus, factors affecting the degree of curing of the photopolymer layers shall influence the mechanical behavior of the part.

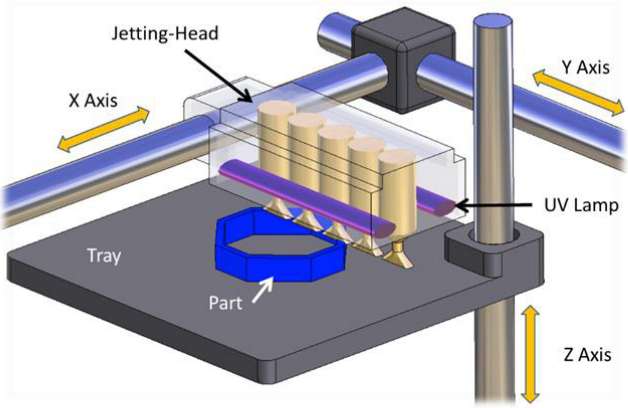

Fig. 1. Schematic representation of the PolyJet system.

The variability on mechanical properties of parts manufactured using PolyJet has been studied by Kesy and Kotlinski [3]. These authors have evaluated several mechanical parameters (such as the tensile strength or elongation at failure) in test bars manufactured with different orientations in the working space. They have found notable differences between orientations, and had related this effect to variations in the amount of UV energy that reaches the different zones in each part. In particular, these authors remark the importance of a comparatively higher density and hardness values (related to a higher degree of curing), found in edges that were built parallel to the X axis.

A research by Barclift [4] have revealed that over-curing caused by parts distribution within the tray could also lead to noticeable differences between mechanical properties of parts sharing common geometries. These authors relate the differences between materials properties to the manner in which the PolyJet machine patterns UV light during processing. They also suggest that, when printing multiple parts that require multiple print paths, UV irradiation pattern does affect in different way different zones among the manufacturing tray and, consequently, some parts could be over-cured depending on their location.

This conclusion is consistent with a fundamental study on stereolithography parts characterization [5], where it was set that the UV exposure time is the main parameter affecting the final material strength. Moreover, it has also been established that slight variations in temperature may have significant influence upon mechanical performance of this type of materials, which are expected to have a viscoelastic behaviour at normal ambient temperatures [6 and 7]. In this sense, a previous research by Blanco et al. [8] has characterized time-dependence of material properties by means of the relaxation modulus E(t). It has also been found that surface slope (characterized through the inclination angle of part surface with respect to the Y axis) has also great influence upon material properties. Moreover, a shielding effect upon UV curing caused by support material was also described.

Summarizing, previous research has pointed out the difficulties on modelling mechanical properties in AM parts, due to both layer-upon-layer nature and UV radiation pattern strategies. Since a complete characterization of 3D part behaviour shall present great complexity, it seems reasonable that initial studies should be focused on simplified manufacturing conditions.

2. Experimental procedure

2.1. Materials and equipment

A test bar with a nominal thickness h of 2 mm, width w of 12 mm, and length l of 50 mm has been designed for testing purposes. Dimensions were selected to facilitate working with the test specimens during mechanical properties evaluation. Test geometry has been designed using Solid Edge CAD software and then converted to Standard Tessellation Language (STL) format using a 0.001 mm conversion tolerance. Parts within this study have been placed laying on the tray, so that thickness is oriented parallel to the Z axis. This decision is also consistent with the manufacturer own recommendations, since printing of tall objects is highly time-consuming.

Manufacturing of test specimens has been carried out in a Stratasys Objet30 machine, with tray size 300 x 200 x 150 mm. A RGD240 acrylic photopolymer has been selected as construction material, whereas gel-like photopolymer FullCure 705 has been used for supporting structures. Support material is used for stabilizing subsequent model sections and can be easily removable after manufacturing is completed using a water jet. Layers are 28 µm thick, whereas common resolutions in both X and Y directions are approximately 42 µm (600 dpi).

2.2. Experimental planning: factors and levels

Four factors have been considered in present work: part spacing along the X axis (Δx), part spacing along the Y axis (Δy), orientation of the part within the tray (φ) and surface quality (Q). The complex relation between manufacturing strategy and UV irradiation pattern suggests the presence of non-linear effects. Therefore, it should be mandatory to include a high number of levels for each factor. Nevertheless, possible interactions should be difficult to isolate, since some factors are, in fact, dependent (i.e. orientation may affect the minimum distance between adjacent parts in both X and Y directions). Taking these considerations into account, the one-factor-at-a-time (OFAT) experimental strategy has been used.

This approach provides an independent analysis of each factor, without considering possible interactions. On the other hand, it allows for an increase in the number of levels for each factor, without compromising the cost of the experimental program.

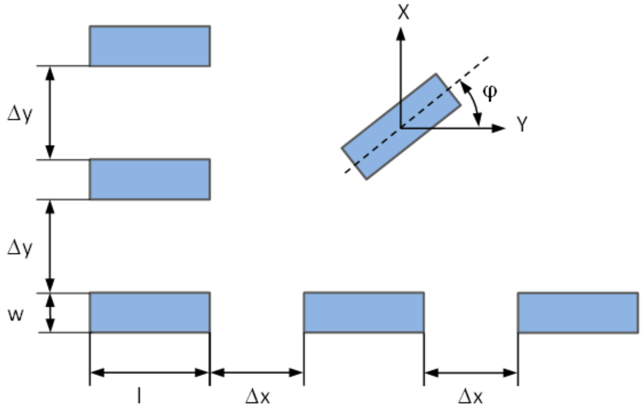

Fig. 2. Factors regarding distribution pattern.

As a result, four independent experimental series have been defined.

- Part spacing along the X axis ranges from a minimum distance of 5 mm to a maximum of 60 mm. The minimum value has been selected in order to avoid superposing of support material of two adjacent parts, whereas the maximum one has been selected regarding tray dimensions (300 mm in the X direction) and test specimen dimensions. Four levels where therefore considered for the first experimental series: 5, 20, 40 and 60 mm. Since spacing conditions the maximum number of parts that could be manufactured within the same tray, three-part trays shall be manufactured in all levels. Moreover, it was decided that each specimen should be replicated four times, in order to obtain averaged values of the mechanical properties. This means that, for each level, four independent trays, containing three test specimens each, shall be manufactured. This leads to manufacture 48 specimens in this experimental series.
- Part spacing along the Y axis share the same minimum limit with X spacing. However, maximum limit could have reached an 80 mm value, since test part width allowed for a higher spacing than the previous factor. Nevertheless, the same limits and levels (5, 20, 40 and 60 mm) previously defined for the X direction spacing had been used for convenience. Consequently, results from the second experimental series could be easily compared to those of the first one. Equivalent decisions have been taken regarding number of trays and number of parts in each one, so four trays containing each three parts shall be manufactured, and 48 test specimens were planned for this experimental series.
- Due to symmetries involved, orientation of the part within the tray can be limited for testing purposes between 0° and 90°. Test specimen already have 180° symmetry and, due to manufacturing strategy, possible differences in UV curing between zones of the same part are expected to be distributed in a specular pattern, on parts oriented symmetrically with respect to the YZ plane. According to this consideration, test specimen rotated 90° are expected to present identical mechanical behaviour. Since non-linearity has been previously observed [8] in parts with different slopes with respect to the Y axis, it has been decided that at least seven levels shall be defined for the third experimental series: 0°, 15°, 30°, 45°, 60°, 75° and 90°. Four replicates were planned for this experiment, which means that a total 28 test specimens shall be manufactured.
- Finally, surface quality on PolyJet parts can be related to roughness profile but, in the particular case of flat surfaces parallel to the XY plane, differences in roughness shall be almost negligible. Nevertheless, the PolyJet technology offers two options for surface finish: glossy and matte. Unsupported surfaces can be manufactured using either option, since matte finishing can be obtained by applying a thin coating of support material over a glossy surface. On the other hand, supported surfaces are always matte, since contact between support and construction materials cannot be avoided. It is not clear how this additional coating should affect the mechanical properties of matte surfaces, when compared to glossy ones. Therefore, both options have been considered in the fourth experimental series. Four replicates were again planned for each level, so a total 8 parts shall be manufactured.

2.3. Evaluaton of mechanical properties

The relaxation modulus E(t) has been used as characterization parameter for the viscoelastic behaviour, since it allows representing not only the modulus magnitude but also its evolution with time. A RSA3 Dynamic Mechanical Analyser (TA Instruments) has been used to evaluate E(t). This equipment is capable of applying either static or oscillating loads, which are instantaneously registered with a load cell. Measurements of E(t) were conducted using a three-point bending tool under controlled laboratory temperature (20 °C), since the measuring device is equipped with a temperature-controlled chamber. The specific level of strain (0.1%) was produced under an instantaneous strain step, and was kept constant during the stress relaxation test.

3. Results and discussion

3.1. First experimental series: Δx.

The averaged values of E(t) for parts manufactured with the same Δx have been calculated using 12 parts each, plus two measures of the same part. Figure 3 shows the evolution of E(t) in a 5 seconds period. The viscoelastic effect can be clearly seen, since E(t) roughly drops a 15,8% during the first second of load appliance. Reduction in E(t) slows down as time passes, as is usually observed in viscoelastic materials. As a reference value, it can be observed that this reduction reaches a 25% along the measuring period. This reduction is nearly equal for all tested levels of Δx.

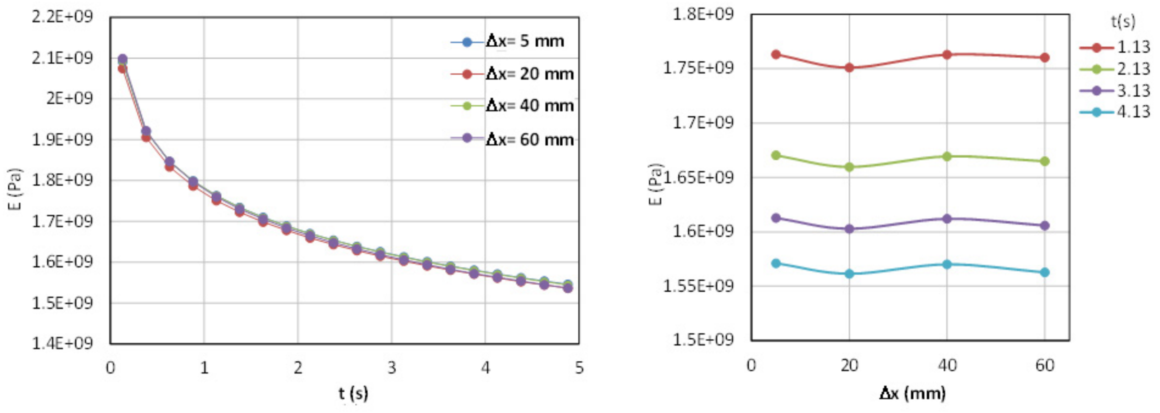

Fig. 3. Relaxation modulus for different values of Δx at four selected instants.

Results also indicate that spacing between adjacent parts in the X direction has no significant influence upon E(t). In fact, those differences are almost negligible, since differences between levels are below 1.2% in every case. Moreover, after 1 s, these differences do not significantly vary with time, and a 0.6% stabilized value can approximately be obtained for each of the four instants (1.13 s, 2.13 s, 3.13 s and 4.13 s) represented in Figure 3.

3.2. Second experimental series: Δy.

Calculation of E(t) for parts manufactured with the same Δy have also been obtained following the same procedure as in the Δx experiments. Figure 4 shows the evolution of E(t) in a 5 seconds period. Whereas the viscoelastic behaviour of the material can be easily observed in Figure 4, neatly differences between different levels can also be observed.

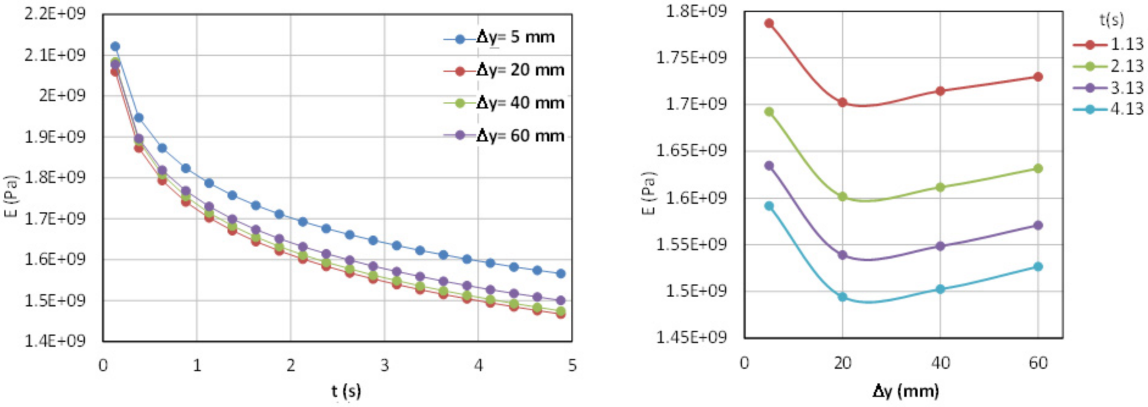

Fig. 4. Relaxation modulus for different values of Δy at four selected instants.

Firstly, relative drop during the first second is slightly different from 5 mm spaced parts (15.8%) and other levels (17.4% for a 20 mm spacing, 17.7% for a 40 mm spacing and 17.7% for a 60 mm spacing). These differences are even increased during the 5 seconds period, where an average 28% reduction has been observed.

Results clearly indicate that spacing between adjacent parts in the Y direction do has a significant influence upon E(t). The minimum spacing (5 mm) provides the highest mechanical performance, whereas 20 mm spacing provides the lowest one. Differences between these two situations range from a 4.9% after 1.13 s of measurement, to a 6.4% after 4.13 s. In fact, observed differences tend to get higher with time. Increasing spacing value causes slight raises in E(t) values, and intermediate differences have been observed.

This behaviour should be related to differences in deposition and curing strategies, since the enveloped section that the jetting head must cover in a particular tray increases with Δy. As a result, the system automatically modifies the distribution of parallel passes to cover the whole required space. This circumstance is simultaneously altered by an algorithm that introduces slight displacements along Y direction, in order to randomize the use of jetting orifices. This algorithm has been apparently incorporated into the manufacturing sequence in order to avoid obstruction of jetting orifices, by achieving nearly-uniform use of each single orifice. Since Δy strategy is really complex and the user cannot modify the decisions made by control software, recommendations regarding this factor must be limited to use, when possible, minimum spacing along Y axis.

3.3. Third experimental series: orientation of the part within the tray (φ).

E(t) values for parts manufactured with the same φ orientation have been obtained from two-times-replicated measures of 4 parts. Figure 5 shows the evolution of E(t) in a 5 seconds period.

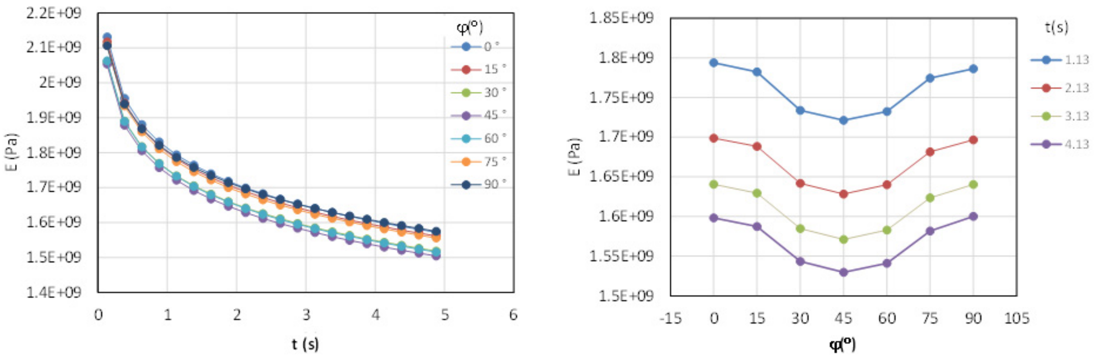

Fig. 5. Relaxation modulus for different values of φ orientation at four selected instants.

This factor shows a slight difference in E(t) values between the group of orientations closer to 45° and the group of orientations closer to the coordinate X and Y directions. Therefore, parts manufactured in a close-to-diagonal orientation present comparatively lower values of E(t) that those manufactured nearly parallel to the coordinated axis. Averaged differences between these two groups range up to a 3.5% within the measurement period, and they are increased the longer the load period is.

The graphic on the right in Figure 5 shows the evolution of E(t) in certain instants. The effect of E(t) reduction can be clearly observed in this graphic. Moreover, it can be also observed that its behaviour presents an almost-symmetry respect to the 45° orientation. Although lower values of E(t) could be expected for 60° and 90° orientations, similar to oriented-layered materials or in orthotropic behaviour [3, 8], a reinforced of the flat specimen lateral bands, due to higher degree of direct incidence of UV light, may be taking place [3].

3.4. Fourth experimental series: surface quality (Q).

Calculation of E(t) for parts manufactured with the same Q have been obtained from two-times-replicated measures of 4 parts. Evolution of E(t) in a 5 seconds period can be seen in Figure 6. Mechanical behaviour is no significantly influenced by Q, since differences between E(t) are negligible. Moreover, the graph in the right of Figure 6 indicates that these differences decrease with time. Reduction of E(t) can be considered equivalent in both situations and similar to those obtained previously during the 5 mm Δx evaluation.

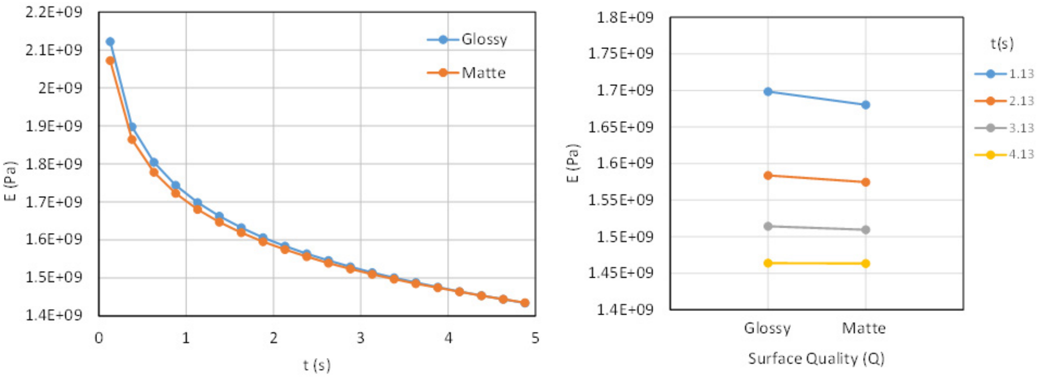

Fig. 6: Relaxation modulus for different values of Q at four selected instants.

Since no significant difference has been found, it must be concluded that, for flat parts oriented parallel to the XY plane, the addition of several layers of support material to provide a matte finish does not have influence upon final mechanical properties. Therefore, the possible reinforcement effect that additional UV radiation should have had upon material curing [8] is attenuated by support shielding effect, and the result is that no preferences could be stated upon the election of surface finish (within the limits of our experimentation).

4. Conclusions

Present work has dealt with the analysis of the variability of mechanical properties in PolyJet-manufactured flat parts, regarding its pre-defined distribution pattern on the manufacturing tray. The one-factor-at-a-time (OFAT) experimental strategy has been used in order to provide an independent analysis of four factors: part spacing along the X axis, part spacing along the Y axis, orientation of the part within the tray (φ) and surface quality (Q). A flat geometry has been used for testing purposes and later manufactured with a Stratasys Objet 30 machine. Subsequently, E(t) has been measured using a Dynamic Mechanical Analyser and a three-point bending tool. After data had been analysed, next conclusions can be formulated:

- Two factors, Δx and Q have shown no significant influence on E(t). Therefore, when defining part location along X axis or surface finish, no particular consideration should be taken into account regarding part mechanical properties.
- Δy does have a significant effect upon E(t), since differences above 6% where registered in a short (5 seconds) period. It can be assumed that these differences would grow constantly when parts are loaded during longer periods, so this result has to be taken in consideration. Our recommendation is that parts should be manufactured as closer as possible along the Y direction. Other options imply lower properties, due to complex material deposition and UV curing strategies.
- Orientation of the part within the tray can slightly modify material properties. It has been found that a 45° orientation causes a minimum in material properties, whereas maximum values are obtained when the part is oriented parallel to the coordinate axis. In fact, evolution of E(t) regarding φ seems to be symmetric with respect to the 45° orientation.
- It has been also checked that, in the particular case of flat parts oriented parallel to the XY plane, the addition of layers of support material on the upper surfaces to obtain matte finishing, does not affect the mechanical properties.

Results had allowed for a deeper understanding of the PolyJet process and how the relation between deposition/curing strategies and distribution pattern of parts could influence final part properties. Differences found for certain parameters could lead to introduce corrective factors in a future development of a viscoelastic model, which takes into account PolyJet manufacturing particularities in addition to photopolymer material characteristics.

Acknowledgements

The authors wish to thank the ARS:CEI_LAB platform and the Advanced Research in Additive Manufacturing (ARAMO) group for their support.

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