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Procedia CIRP 67 (2018) 203 – 208

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11th CIRP Conference on Intelligent Computation in Manufacturing Engineering, CIRP ICME '17

The use of self-replicated parts for improving the design and the accuracy of a low-cost 3D printer

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Abstract

Low-cost entry-level 3D printers suffer from reduced optimization, that is a consequence of development cost savings. A student challenge was used to modify four Prusa i3 machines with the aim of enhancing the design and performances by means of self-replicated parts. The challenge results were assessed through benchmarking of the four modified 3D printers, whose dimensional accuracy was evaluated by means of CMM measurements of 3D printed replicas of a reference part. The ISO IT grades related to the dimensional quality of the replicas were considered in the analysis of the CMM measures for the challenge assessment.

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Peer-review under responsibility of the scientific committee of the 11th CIRP Conference on Intelligent Computation in Manufacturing Engineering

Keywords: 3D printing; Prusa i3; dimensional accuracy; IT grades; GD&T.

1. Introduction

In recent years, the expiration of Sr. Scott Crump's patent for the technology of Fused Deposition Modelling (FDM) has boosted the diffusion of 3D printers. However, the widespread adoption of FDM technology, that is more popularly known as 3D printing, is a result of the availability of open-source systems and the birth of 3D printing communities, such as the one of the makers. The benefits of an open system and the sharing of information are reduced costs, availability of processing parameters for different materials, guides for assembling or self-repairing with a DIY (do it yourself) approach and readily printable 3D models.

The FDM process is very simple in its physical principle and can be assimilated to an automatic hot-glue gun. Instead of a stick of glue, a thermoplastic filament is heated and extruded through a nozzle of the extrusion head of the FDM machine. The melted polymeric mass is subsequently deposited layer-by-layer on the printing bed along the trajectories of the extrusion head [1]. The deposited material cools down and solidifies right after deposition. The extrusion head can comprise multiple nozzles, one for each different filament and material. Commonly two extruders are present, one for the part material and another for the support material. The support material is used to create a raft for the adhesion of the part on the printing bed, but also to create support structures for overhanging features that would not be supported along the building direction because of the absence of part material in the previous layers.

The simplicity of the FDM process and the low cost of polymeric filaments has driven the development of a huge number of low-cost entry-level systems soon after the expiration of the main patent.

One of the first systems was the open-source DIY project called RepRap, that was started in 2005. Other FDM machines followed, but their architecture is based on a Cartesian structure with three degrees of freedom that controls the motion of the extrusion head in the building direction (Z-axis) and along the deposition path (X and Y axes) within each single layer.

The extrusion head of low-cost systems often has a unique extruder that can be heated up to a maximum temperature of about 270 °C to melt a thermoplastic filament. The most common materials used for the filament are ABS

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doi:10.1016/j.procir.2017.12.200

(acrylonitrile butadiene styrene) and PLA (polylactic acid). Open systems allow the using also of other materials without being bound to proprietary materials by the machine manufacturer as in the case of industrial systems.

Low-cost 3D printers are sold over the net at a price starting from some hundreds of euros for a kit that the users should assemble by their selves. On the one hand, the low cost has contributed to the rapid diffusion of 3D printers among the population thanks to their high affordability. On the other hand, the affordable price is a marketing choice that limits the investment for the machine development, resulting in simple and cheap mechatronics solutions. Thus, low-cost entry-level 3D printers suffer of the lack in optimization and advanced engineering solutions, which makes those machines difficult to be used by unexperienced users. Nonetheless, the performance of such systems can be improved by advanced users or amateurs exploiting the open architecture and platform.

As concerns mechatronics and automation, Politecnico di Torino has a partnership agreement with Comau S.p.a., a worldwide leading company for industrial automation that is part of the FCA group. Within this partnership, a Specializing Master course in Industrial Automation is offered to post-graduate engineering students that are selected and employed by the company with an apprenticeship contact. In the fourth edition of this Specializing Master, an optimization challenge of a Prusa i3 3D printer was proposed to the students. The apprentices were divided into four groups with the aim of promoting also team working and managerial competences as in a real work environment. Within the challenge students had to cope with limited budget for modifying the 3D printer, the timing of materials procurement and activities planning for respecting the assigned deadline.

One of the constraints of the challenge was that most of the parts used for the mechanical modifications of the machine should be fabricated by the same 3D printer using a self-replication approach. Each group worked independently and four new printers were developed and presented with the names of Fluo, Ghostprinters, Metallica and Print-Doh. In order to assess the effectiveness in terms of performance improvements achieved by each team through the machine modifications, a benchmarking study about the dimensional accuracy was carried out.

The aim of this paper is to present the results of the challenge by summarizing the benchmarking analysis after the description of the improvements applied to the original Prusa i3 machine.

2. Description of Prusa i3 and modifications

The i3 postfix in the machine name indicates the third iteration of the design by Josef Prusa. The machine comes with the standard Cartesian architecture and all its parts are open-source similarly to the RepRap project. This 3D printer has a minimal mechanical structure, that comprises two rails for the elevation of the printing bed along the Z-axis and two rails for the motion of the extruder head orthogonally to the bed along the X and Y directions.

The four machines modified by the four groups during the challenge look quite different from the original Prusa i3 as well as from each other. The modifications mainly focused on mechanical and electrical aspects, also taking into account ergonomics and related safety issues. Aesthetics was also enhanced to mimic marketing purposes.

Although the four groups worked independently, their printing experience and testing of the original Prusa i3 machine led all teams to consider the need for the following improvements:

- introducing a holder for the filament spool and a guide to drive the filament in order to reduce the probability of jamming during the extrusion process;
- cutting down the time for bed levelling by using suitable components like a nut or a knob;
- protecting the power cables with the use of chains or tubes made of polymeric materials with the additional result of avoiding the interference with movable parts of the machine;
- increasing the stiffness of the rails by adding rigid components with the function of anti-wobble devices to support the motion of the printing bed and extrusion head.

The four modified printers are shown in Fig. 1.

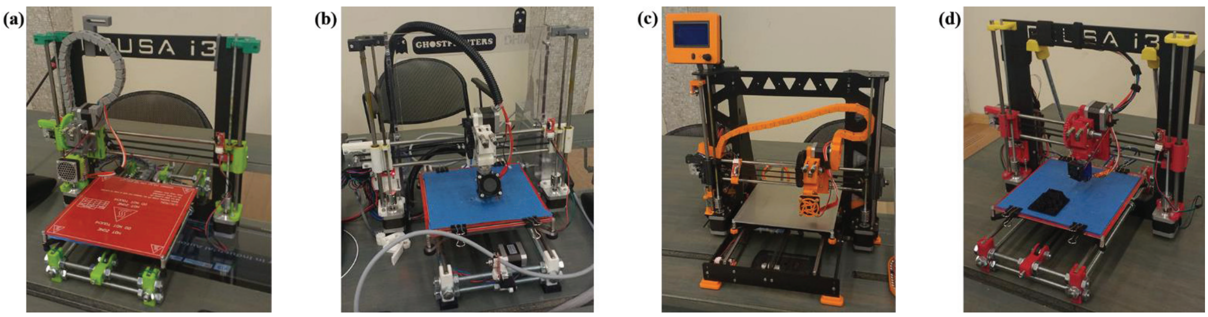

Fig. 1. Picture of the Prusa i3 printers modified by the four teams of apprentices: Fluo (a), Ghostprinters (b), Metallica (c), Print-Doh (d).

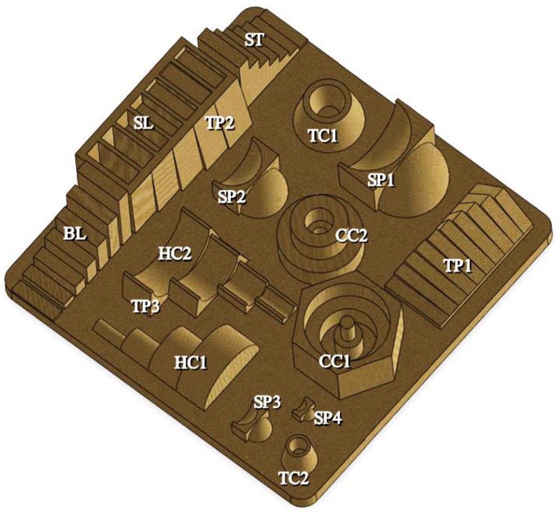

Fig. 2. CAD model and geometries of the reference part.[2]

3. Benchmarking study

Different benchmarking studies have been proposed and used in the literature for the comparison of several Additive Manufacturing (AM) technologies and machines. These studies [2-14] are based on the use of reference artifacts comprising different geometrical shapes. However, only a few works [2, 4, 10, 11, 13, 14] summarize the results of the benchmarking by expressing the dimensional accuracy of the printed replicas of the reference part by means of ISO IT grades.

In the benchmarking analysis of the modified Prusa i3 machines, the procedure and reference artifact defined by Minetola et al. [2] were used. The geometry (Fig. 2) of this reference part comprises a large number of geometric features with different sizes as to cover multiple ranges of the ISO basic sizes, accordingly to the indications provided by Moylan et al. [15, 16]. In addition to this, the part geometries do not require support structures for their production and all of them can be measured using a Coordinate Measuring Machine (CMM) with the vertical shaft of the tip as the unique probe configuration.

Finally, the artefact is relatively small, since it has overall dimensions of 110 mm x 110 mm x 33 mm. For this reason, it fits into the building volume of the Prusa i3 machine as well as in the one of many other 3D printers. This characteristic allows for future extension of the benchmarking analysis to other FDM machines.

3.1. Fabrication of the reference part

Each team had about three weeks for the definition of the machine modifications and the related bill of materials. During this first phase, students had the opportunity to test the original Prusa i3 machine to detect its weaknesses and select what changes could be applied using the assigned budget of about 450 euros. After the reception of the ordered pieces, about one month was spent for the application of the changes and mechanical assembly. Another month was available for the teams to optimize the printing parameters for the PLA material on the modified printers.

At the end of the project, one replica of the reference artifact was produced by each of the improved machines. The replica was fabricated in the middle of the printing bed using a diverse colour of the PLA filament on each machine to distinguish among the teams (Fig. 3). Each group selected the printing parameters to achieve the highest part quality basing on the experience made during the process optimization phase. These parameters are summarized in Table 1. The choice of the process parameters was left completely free, so different manufacturing times are a consequence of the selected nozzle diameter, extrusion speed, deposition speed, layer thickness and infill strategy.

3.2. Measurement procedure

After manufacturing, the dimensional accuracy of the replicas was measured at the Department of Management and Production Engineering of the Politecnico di Torino. Measurements were carried out using a coordinate measuring machine (CMM) by DEA model GLOBAL Image 07.07.07. The accuracy of the CMM is consistent with the dimensional tolerance of 3D printed parts, since the machine has a declared volumetric length measuring uncertainty MPE_E [17] of 1.5 + L/333 µm, where MPE is the acronym for Maximum Permissible Error and L is the measured length.

The four replicas were measured in the as-built condition following the methodology proposed by Minetola et al.[2].

Finishing or polishing operations were not applied to the replicas in order not to alter the accuracy resulting from 3D printing. The average value of three measurement replications is then considered for each geometric feature of the reference part. Particularly care was paid during the definition of the part reference system for the dimensional

Table 1. Process parameters adopted by the teams for the production of the replicas.

	Fluo	Ghostprinters	Metallica	Print-doh
Nozzle diameter (mm)	0.4	0.2	0.3	0.4
Color of filament	Green	White	Black	Red
Thickness of the first layer (mm)	0.30	0.20	0.30	0.30
Layer thickness (mm)	0.20	0.15	0.20	0.25
Infill density	25%	15%	20%	25%
Infill strategy	Skirt/linear	Concentric	Skirt/honeycomb	Honeycomb
Build time	about 5.5 hours	about 9.5 hours	about 6 hours	about 5 hours

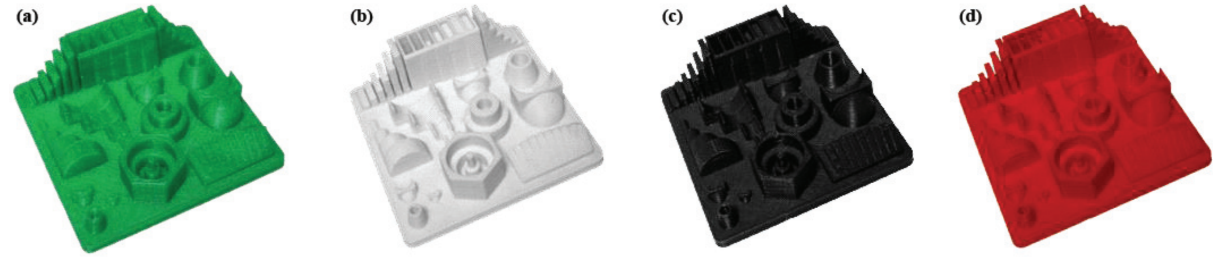

Fig. 3. Picture of the replicas of the reference part fabricated by means of the four modified machines: Fluo (a), Ghostprinters (b), Metallica (c), Print-Doh (d).

inspection with the CMM in order to avoid systematic errors [18, 19].

A minimum of ten probing points was used to measure each geometry of a replica with a tip of 2 mm diameter. Higher numbers of inspection points were measured on bigger features and each replication of the CMM inspection took about one hour.

The measurement results are analysed and converted into ISO IT grades accordingly to ISO 286 standard [20]. The standard tolerance factor i is used to define the values of standard tolerances corresponding to IT 5 – IT 18 grades for nominal sizes up to 500 mm. The tolerance factor i is expressed in micrometres by equation 1 starting from the geometric mean D of the range of nominal ISO sizes.

$$i = 0.45 \cdot \sqrt[3]{D} + 0.001 \cdot D \qquad (1)$$

The geometric mean D is computed by equation 2 from the extreme values $D1$ and $D2$ of each ISO range and it is expressed in millimetres.

$$D = \sqrt{D_1 \cdot D_2} \qquad (2)$$

The values of the standard tolerance factor i for the different ranges of ISO basic sizes are summarized in Table 1. For the classification of IT grades (Table 2), the number n of times that the dimensional deviation contains the tolerance factor i. For example, the IT9 grade corresponds to a minimum of $40i$ with $n = 40$ and it extends up to $64i$, that is the lower threshold for next grade IT10.

For a generic nominal dimension or nominal distance between features D_{jn}, the number n_j of tolerance units is computed by equation 3 and attributed to the corresponding range of ISO basic sizes.

$$n_j = \frac{1000 \quad \left| D_{jn} - D_{jm} \right|}{i} \qquad (3)$$

The value D_{jm} in equation 3 is the generic nominal dimension, so the absolute difference between D_{jn} and D_{jm} is the absolute dimensional deviation. Thu,s for each range of ISO basic sizes, a distribution of the number n of tolerance units is obtained. The maximum dimensional error of the 3D printer within each ISO range of basic size is then assumed as the IT grade corresponding to the n_{95} value of the 95th percentile of the distribution of the number n of tolerance units.

4. Results and discussion

The results of the benchmarking study of the four modified 3D printers are added to the ones of the previous study by Minetola et al. [2]. The two additional 3D printers are the Dimension Elite (Fig. 4a) by Stratasys and the 3D

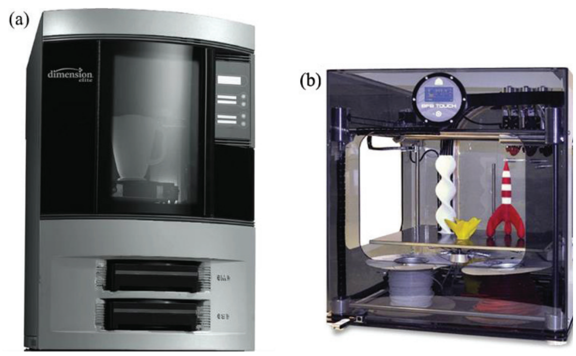

Fig. 4. Other 3D printers included in the benchmarking analysis: (a) Dimension Elite; (b) 3D Touch.

Table 2. Ranges of ISO basic sizes and corresponding tolerance factor i.

Range		Basic sizes							
Above	D_1 (mm)	1	3	6	10	18	30	50	80
Up to and including	D_2 (mm)	3	6	10	18	30	50	80	120
Standard tolerance factor	i (μm)	0.542	0.733	0.898	1.083	1.307	1.561	1.856	2.173

Table 3. Classification of ISO IT grades.

Basic size		Standard tolerance grades													
Above	Up to	IT 5	IT 6	IT 7	IT 8	IT 9	IT 10	IT 11	IT 12	IT 13	IT 14	IT 15	IT 16	IT 17	IT 18
1 mm	500 mm	$7i$	$10i$	$16i$	$25i$	$40i$	$64i$	$100i$	$160i$	$250i$	$400i$	$640i$	$1000i$	$1600i$	$2500i$

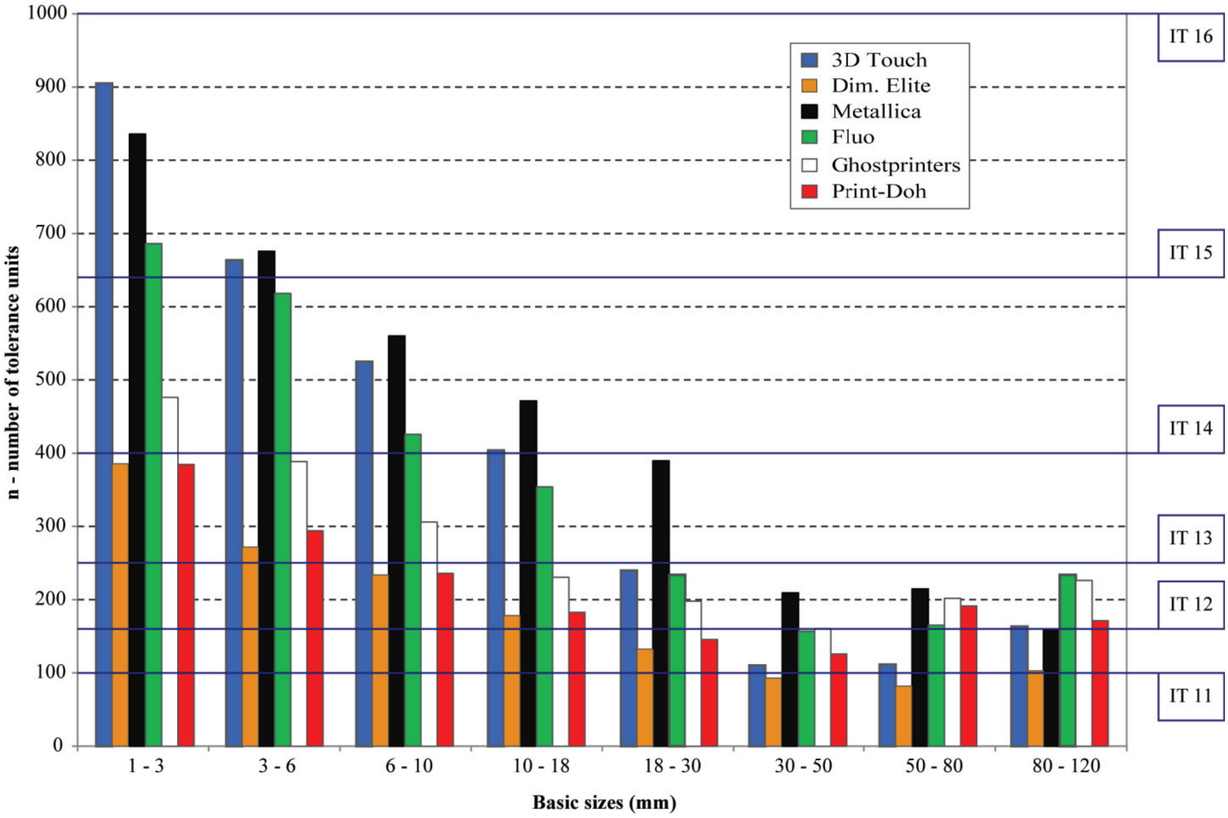

Fig. 5. Dimensional accuracy (95th percentile) of the compared FDM machines in terms of IT grades for different ranges of ISO basic sizes.

Touch (Fig. 4b) by BitsFromBytes.

The main difference to be considered is the material used for the fabrication of the replicas of the reference part. For the challenge, the four replicas were fabricated by a PLA filament on the modified Prusa printers, while ABS replicas were printed by means of the other two machines with specific parameters [2]. Therefore, the difference in the polymeric materials used to produce the replicas is disregarded in the analysis and the discussion of the benchmarking results that are summarized in Fig. 5. For each range of ISO basic sizes, the bars in the figure represent the IT grade corresponding to the n_{95} value achieved by each machine.

A general trend can be noticed while considering the variation of the IT grades along different basic sizes. In fact, as the ISO basic size increases, the IT grade decreases. This means that a better dimensional quality is obtained for bigger dimensions and sizes of the reference part geometries.

For larger dimensions the accuracy of the four improved machines is similar, whereas major differences are observed in the case of smaller dimensions. Among the modified machines, Print-Doh is the one with the best dimensional accuracy for all ISO ranges. The resulting IT grade for this machine is very similar to the one of the more expensive Dimension Elite by Stratasys. The Stratasys system is a professional 3D printer with advanced technical solutions and the unique machine with a hot working chamber among those compared. The hot working chamber is of paramount importance to compensate for the material shrinkage due to the fast cooling of the molten filament deposited in the building layer. For this reason, the best accuracy of the Dimension Elite machine for all ranges of ISO basic sizes is not surprising. On the contrary, the results achieved by Print-Doh are rather outstanding and impressive especially in the case of smaller basic sizes.

Among the modified 3D printers, Ghostprinters also achieved a good dimensional accuracy with a reference number n_{95} of tolerance units a little higher than that of the Print-Doh for all ISO ranges. Therefore, these two printers share the same IT grade for several ranges of the considered ISO basic sizes.

The other two improved Prusa printer, i.e. Fluo and Metallica showed a coarse accuracy with tolerance units n_{95} like those of the entry-level 3D Touch machine. Thus, these other three machines almost share the IT grade in each range of ISO basic sizes. However, Metallica has the worst accuracy with higher levels of n_{95} except for the two extreme ranges of dimensions, that vary from 1 to 3 mm and from 80 to 120 mm.

5. Conclusions

The low cost of entry-level FDM machine has recently contributed to the fast and widespread adoption at the amateur level. Nonetheless a reduced cost also constitutes a limitation for the optimization of these machines from the engineering point of view, resulting in poor dimensional accuracy of the printed parts.

For this reason, the scope of this work was to assess the dimensional accuracy of Prusa i3 printers that were modified through a student challenge of the Specializing Master in Industrial Automation of the Politecnico di Torino and Comau S.p.a. company.

Sixteen students were grouped in four teams with the aim of improving the performances of four original Prusa machines. The challenge led to develoment of four modified 3D printers named Fluo, Ghostprinters, Metallica and Print-Doh. These machines greatly differ one another as well as from the original Prusa i3 model.

The dimensional accuracy of the four printers was evaluated by a benchmarking study, that used a methodology based on a reference artifact previously proposed in the literature by some of the authors. The benchmarking results and comparison of the dimensional accuracy of the modified 3D printers are summarized by using ISO IT grades.

The best accuracy was achieved by Print-Doh, but results are very similar for the Ghostprinters machine as well. However, the reference part was built with higher productivity and thicker layers by the Print-Doh printer, so there is no need for adopting the process parameters of the Ghostprinters that resulted in longer built times. In fact, the difference in the accuracy of the compared 3D printers should be ascribed to the combination of the improvements and optimized manufacturing parameters that each team selected to produce the replica of the reference part.

The proposed challenge and its benchmarking results have demonstrated the possibilities for improving the performance of the low-cost 3D printers. In line with the idea of the RepRap project, the geometry of the reference part is downloadable in the open-source GrabCad library as an STL (Solid To Layer) model [21]. The aim is to promote the integration of the presented results with those of replicas manufactured using other FDM machines whose dimensional accuracy can be assessed by using IT grades.

Acknowledgements

The authors gratefully acknowledge Dr. Massimo Ippolito of Comau S.p.a. and all the students of the fourth edition of the Specializing Master in Industrial Automation of Politecnico di Torino. Special thanks are extended to the four team leaders Dr. Hadrien Bonaccorso, Dr. Marta Casassa, Dr. Veronica Fassi and Dr. Riccardo Ianni who provided specific details about the projects. Mention should also be made Mrs. Hilde Galati, who assisted the CMM inspection of the replicas.

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