PRODUCTION OF LOW COEFFICIENT OF THERMAL EXPANSION COMPOSITE TOOLING MANUFACTURED VIA 3D PRINTING

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ABSTRACT

Additive manufacturing enables the ability to produce composite tooling molds in a rapidly and cost effective manner. This work has produced low coefficient of thermal expansion composite tooling based on Invar, ceramics and metal-ceramic composites that are functional in the temperature range of 180°C. Here, four main approaches have been considered. The first approach consisted on using a binder jetting technology to 3D print sand molds to cast molten Invar to produce tooling. The second approach consisted on printing a mold based on both silica and zirconia sand and infiltrating them with a polymer to yield a robust tooling. The third approach was based on transforming a SLA printed ceramic mold into a metal-composite system. The fourth technology was based on a Direct Energy Deposition System for attaching Invar upon a steel molding structure. This last approach could represent a promising technology for producing low cost composite tooling since only a small layer of Invar would be added to a non-expensive substrate. The results have shown that the aforementioned processes have successfully resulted on low CTE tooling molds and successful composite materials.

1. INTRODUCTION

Additive Manufacturing (AM) has become a continuous evolving technology in the manufacturing field [1]. The American Society of Testing and Materials (ASTM) defines additive manufacturing as “The process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies; Synonyms : additive fabrication, 3D printing, additive process, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication” [2]. Additionally, the

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advancement in the Computer Assisted Design (CAD) software has resulted in the junction of AM assisted by Computerized Designs [3]. With these developments, the AM technologies and applications have gradually evolved from their initial 'Rapid Prototyping-RP' applications, into actual design-manufacturing uses on structural components. This growth, has motivated the interest on producing composite tooling molds for the aerospace sector via additive manufacturing rather than using the traditional production methods due to the ability to create complex parts at lower costs with reduced leading times [4, 5].

On the other hand, the selection of material for producing tooling systems is a critical aspect that will define the thermal performance of the mold. Indeed, a low coefficient of thermal expansion (CTE) tooling is required in order to produce accurate, and high-quality composite sections [6]. The selection of materials with low CTEs for the 3D printing processes can be a difficult task because these such materials are either expensive or difficult to fabricate. However, the incorporation of AM methods, such as binder jetting, direct energy deposition (DED), and stereolithography (SLA) allow the fabrication of composite tooling molds with materials such as ceramics and Invar while maintaining the manufacturing costs considerably lower than traditional manufacturing methods [7].

Binder jetting is an AM method that is able to produce complex 3D parts in a layer by layer fashion from a computer aided design (CAD) software. In this process, a feed tray is used in combination with a roller to smoothly spread the powder across a building tray. A binder is then deposited on each layer in a pattern established by the CAD file. This process is continuously repeated until the part is built. Subsequently, the part is removed from the printer and cured to consolidate the binder and consequently the part [8]. A Post-processing step such as sintering of the cured state part, is then followed in order to induce a functional performance [8, 9].

In contrast, the DED process is a method that directly deposits and consolidate metal and ceramic powders using a high-powered laser into 3D parts based on a CAD file. In the DED process, the powder is fed into a conical nozzle via a carrier gas where it is propelled out of the tip and melted by the laser source. DED offers the capability of manufacturing functionally graded systems which could allow the production of low cost tooling molds by surface-cladding only the expensive metal with low CTE features upon inexpensive printed substrates [10]. Based on these characteristics, the aforementioned methods have motivated the manufacturing process of low cost composite tooling molds over traditionally manufactured tooling molds.

2. EXPERIMENTATION

2.1 General approach

The general working methodology in this research work was based on four different printing technologies. The first approach consisted on casting molten Invar-36 into 3D printed sand mold via binder jetting. Following the casting process, the silica mold was broken and the casting section was subjected to a sand blasting step for inducing a smooth surface area. The second method was based on printing the composite tooling mold directly on both silica and zirconia sand followed by a polymeric infiltration. Here, the resin infiltration allowed the production of a robust tooling system. The third approach was based on printing the ceramic tooling mold in a Stereolithogarphy (SLA) printer followed by a transformation process into a metal-ceramic structure. The last approach was performed in a Direct Energy Deposition (DED) unit and consisted on joining printed Invar-36 upon a lightweight printed steel substrate in order to produce a low-cost tooling mold. In more detail, the experimental methodologies are given below.

2.1.1 Invar-36 casting on a printed sand mold

A mold and core system was designed based on a leading edge part requested by the Air Force (see figure 1). The negative mold was then printed in an ExOne S-max binder jetting unit located at Humtown Products (Ohio, US). Here, the mold was made of silica sand and held together by furan binder. Invar-36 ingots (with melting point of 1454°C) were heated to 1575°C, and poured into the 3D printed mold (see figure 2). Following the casting stage, the silica sand was broken and removed. A sand blasting post-processing step was required in order to have a smooth external working surface on the tooling mold.

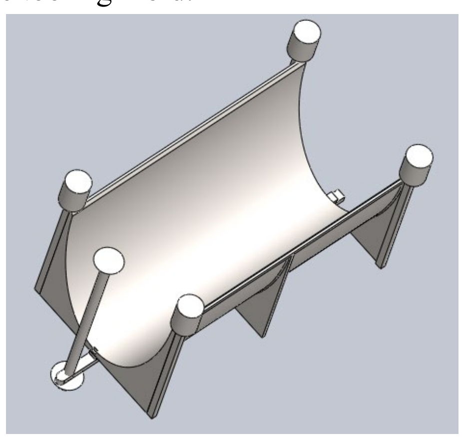

Figure 1. Leading edge section to be used as the composite tooling.

Figure 2. Casting process of Invar-36 (left). Casting part after removing the silica mold.

2.1.2 Polymeric infiltration of 3D printed tooling

In this approach, the tooling molds based on silica sand and zirconia sand were printed on the S-Max binder jetting machine and subsequently infiltrated with a 2 parts high temperature epoxy material under 20 in-Hg vacuum for 15 minutes in order to yield mechanically robust tooling systems (see figure 3). The epoxy used was a proprietary blend from BJB enterprises and it was cured following the supplier's recommendation protocol [11]. Here, small specimens were also infiltrated to characterize their mechanical and thermal properties. The mechanical testing consisted on the flexural and compression characterization of the materials following their corresponding ASTM's (C1161-13B and C1358-13, respectively). The thermal analysis consisted on measuring their coefficient of thermal expansion in a TA Q400EM instrument.


Figure 3. Polymer infiltration process. As-received printed part (left). Resin infiltration under vacuum (center). Final infiltrated part (right).

2.1.3 Printing process via SLA

A Formlabs 2 unit was used for printing the leading edge system using a proprietary fussed silica ceramic resin from Formlabs (see figure 4). After the printing process, the part was washed in isopropanol for 5 minutes and subsequently allowed to dry at room temperature for 24 hours.

Figure 4. Printed tooling part in a Formlabs 2 unit using a silica ceramic resin.

A burnout and sintering process was then applied to the part following the suppliers' protocol [12]. The sintered part was then transformed (by Fireline, Inc.) into a metal-ceramic composite tooling mold to yield a robust system. Here, the transformation reaction between the metal and the ceramic is given by:

$$(4 + x)Al + 3SiO_2 \rightarrow Al_2O_3 + 3[Si]_{Al} + xAl$$

2.1.4 Invar-steel hybrid structure via direct energy deposition

3D printed Invar-36 and stainless steel (SS) powder (PH13-8) were joined to produce a Hybrid structure. Here, a thin (4mm) 3D printed Invar-36 layer was attached to an also printed steel substrate in order to yield an Invar working section onto a large non-expensive metal substrate. Once the incorporation of Invar over steel was confirmed, larger slender composite samples were manufactured on the hybrid tooling.

Table 1. Printing DED parameters used in the Ambit system for printing Invar-36 and steel.

Parameter	**Value (Invar)**	**Value (PH13-8)**
Laser Power	395 W	375W
Transverse Speed	350 (mm/min)	205 (mm/min)
Deposition Offset (z-axis)	6 mm	6 mm

Controllable process parameters for the DED process included: laser power, powder mass flow rate, carrier gas flow rate, transverse velocity, and Z depth offset. The process parameters used for the deposition of Invar-36 on steel are provided in Table 1.

3. RESULTS

3.1.1 Invar-36 casting on a printed sand mold

The casting process into a 3D printed mold successfully yielded a solid Invar mold capable of being used as a high temperature composite tooling (see figure 5). X-ray Powder Diffraction (XRD) were performed on the casting section, and a concentration of Ni-36% and Fe-64% was recorded in the sample. This result suggests that the casting parts was actually conformed of Invar-36. Also, the thermal analysis showed that the casting part has an average CTE of 3.93 µm/m°C (between 22 and 260°C) which is similar to the values found in literature for an Invar-36 (CTE of 3.6 µm/m°C up to around 200°C) [13].

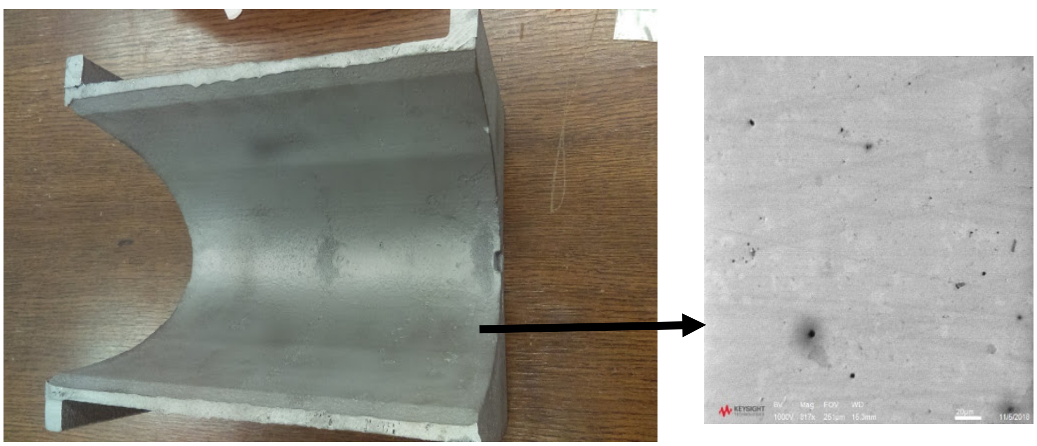

Figure 5. Casting Invar-36 part (left). Surface examination of the casting Invar (right), where it is observed some porosity due to some degasification during the casting process.

A metrology analysis was also performed on the final part (see figure 6), and it showed that the 68% - 91% of the lead edge tooling surface had 0.381- 0.762 mm (0.015”- 0.030”) tolerance for the intended application. From the determined CTE and the metrology analysis, it seems that this method can produce successful composite tooling molds.

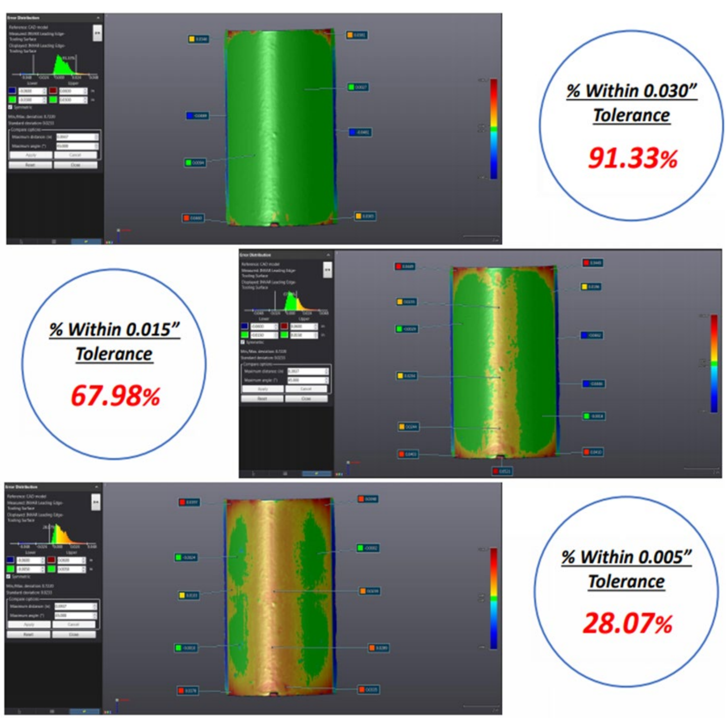

Figure 6. Metrology results of the casting Invar-36 part.

3.1.2 Polymeric infiltration of 3D printed tooling

The vacuum infiltrated printed parts were successfully manufactured as shown in figure 3. Indeed, the infiltration-coating resulted on smooth surface finishing. The compression and flexural testing on the infiltrated samples was performed to ensure that the sections were robust enough to support the handling stages associated on the production of composite parts

The compression strength of the infiltrated and as-received parts are shown in Table 2, where it is observed that the polymeric infiltration resulted in a system considerable stronger than the non-infiltrated (as-received) parts. Included in the table, is the theoretical rule of mixture (ROM) calculation of the compression strength, were it observed that the predicted compressive strength of the silica and zirconia parts infiltrated with BJB resulted in 10.15% and 2.91% of error respectively. This suggests that a ROM can be used to predict the compressive strength of this type of infiltrated ceramic. Similar results were obtained on the flexural strength. Here, the epoxy infiltration resulted in a flexural strength at least 12 times higher than the non-infiltrated systems (see figure 7).

Table 2. Compressive results of the infiltrated and as-received printed ceramics in the S-Max-unit. Include are the theoretical compressive strengths determined from applying a simple rule of mixtures.

Material System	Compressive Strength Experimental	Compressive Strength Theoretical	Error
Zirconia as Received	3.2	-	
Zirconia BJB	56.4	54.7592	2.91%
Silica as Received	2.9	-	
Silica BJB	53.2	58.5989	10.15%
Pure BJB	141.8	-	

The CTE of the samples were also here investigated, and it was found that whereas the plain "as-received" ceramic parts yielded low average CTE values between the temperature range of 22 and 185°C (2.9 and 13.26 µm/m °C for the Zirconia and Silica, respectively), the BJB displayed a large CTE value (121.1 µm/m °C). This large value resulted in a CTE of 67.65 and 72.2 µm/m °C, on the infiltrated Zirconia and Silica parts, respectively. This suggests that although the infiltrated samples exhibited good mechanical performance, their CTE are relatively high, in comparison to metals used in composite tooling, such as Al 6061.

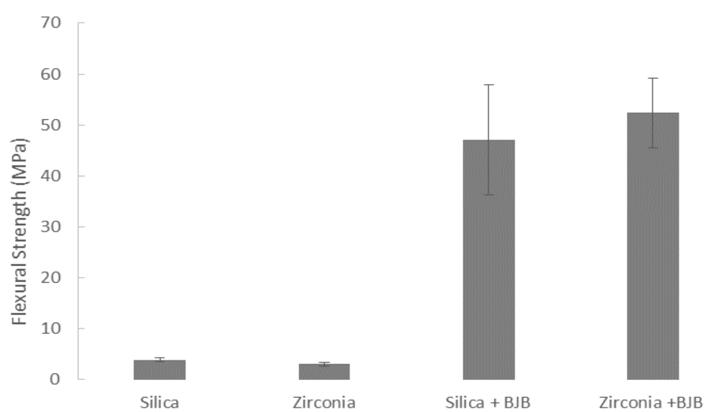

Figure 7. Flexural strength of the as-received and BJB infiltrated ceramics.

Although the CTE of the infiltrated ceramics was not as low as that shown by the as-received systems, carbon-fiber reinforced epoxy materials were still produced on the polymer infiltrated leading edge tooling molds. Figure 8 shows the 3 layers CF/Epoxy composite from Rock West Composites that were manufactured on the printed-infiltrated silica and Zirconia tooling molds. The composites shows a consolidated structure, with no apparent delamination or deboning. The composites were manufactured by subjecting the CF/Epoxy materials within the mold to 180°C for 2 hours, followed by a cooling process at room temperature.

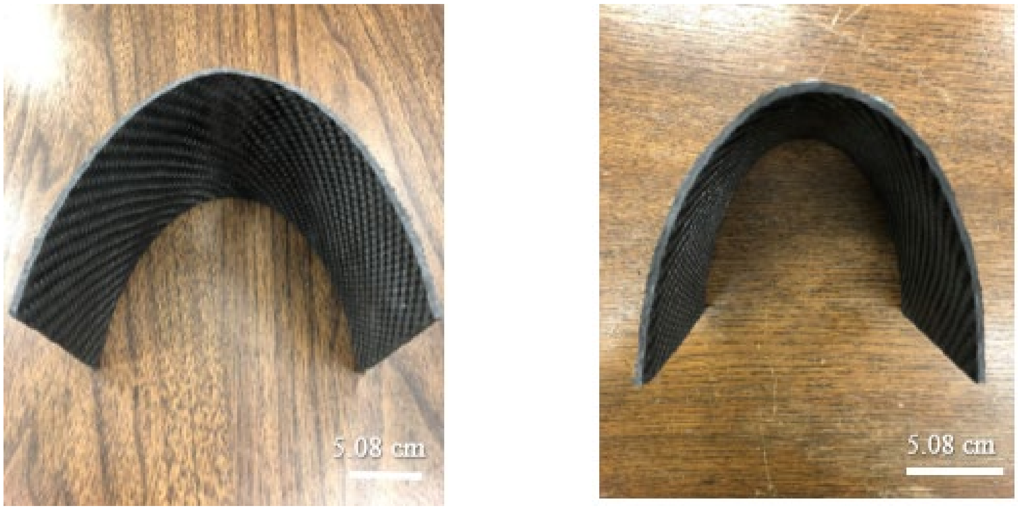

Figure 8. Lead edge composite parts formed on BJB epoxy infiltrated 3D printed ceramic tooling molds. Obtained from the silica sand mold (left). Obtained from the zirconia sand mold (right).

3.1.3 Printing process via SLA

As it was mentioned in the experimental part, the printed part was subjected to burnout and sintering process. Figure 9, shows the printed part following the sintering process. It can be observed that a smooth part was obtained. This section was subsequently subjected to a transformation process in order to yield a robust and consolidated tooling part.

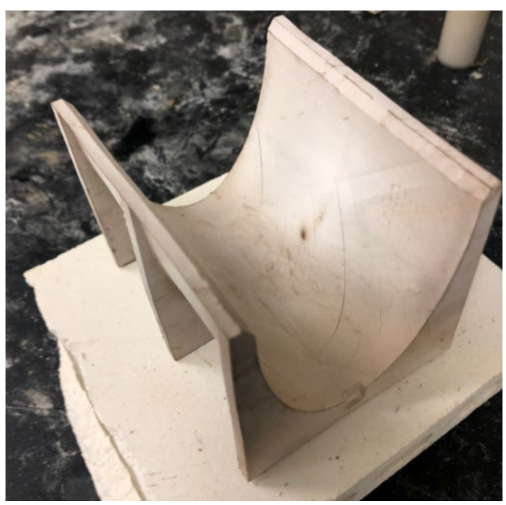

Figure 9. Sintered 3D printed leading edge part manufactured in a Formlabs 2 (SLA) unit.

Figure 10 shows the transformed part as well as the 3-layer CF/Epoxy composite material manufactured at 180°C for 2 hours, followed by a cooling process at room temperature. Figure

10 also shows a magnification of the edge of the composite, where it is observed that a well-consolidated composite was here obtained.

Figure 10. Transformed SLA printed part. Included in the figure, is the manufactured CF/Epoxy composite, as well as a magnification showing the consolidation.

3.1.4 Invar-steel hybrid structure via direct energy deposition

The direct fabrication of a hybrid Invar-36 / Steel substrate seems to represent a very promising technology, since the production costs are economically feasible as only a small amount of Invar is required for the manufacturing process of the actual mold. Figure 11 shows a part containing Invar-36 cladded onto a PH13-8 grade SS using an AMBIT DED system. From the figure, it seems that a good bonding can be achieved between these two metal. However, the extrapolation into large sections required the modification of printing codes that appeared to have resulted in a lack of bonding between the Invar-36 and the steel (see figure 12). In order to overcome this drawback, a welding process was performed at the interface of these materials resulting in a single solid leading edge part. A narrow CF/Epoxy composite was made on the welded Invar-steel part at 180°C for 2 hours, and it was observed that a successful composite was here obtained (see figure 13). A thermostability test was performed in the welded structure, by subjecting the system to 10 consecutive heating cycles up to 180°C. It was observed that after undergoing 10 heating cycles, the tooling molds remained without geometric deformation within 0.1 mm tolerance. Though promising, this process still needs refinement in terms of operating and process parameters in order to produce a functional part. Based on the CTE results, it was recorded that the deposited Invar retained its low average CTE of 1.2 μm/m °C which is significantly lower than the CTE shown by aluminum (~23μm/m °C) commonly used in tooling mold for composite materials. This technology is still being investigated and it is expected to serve as an exemplary method for producing composite tooling.

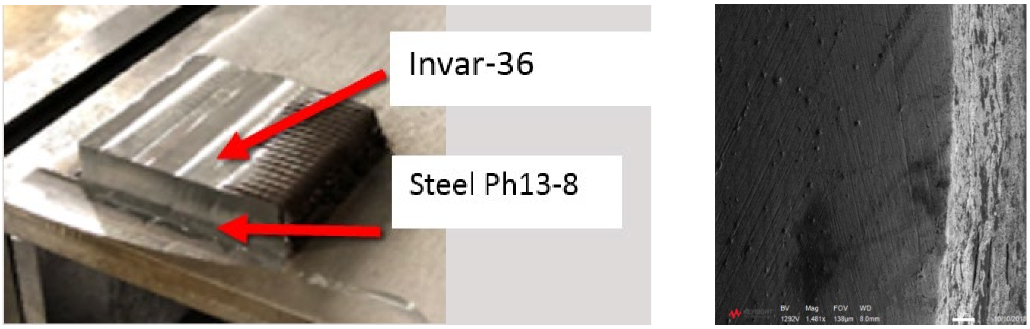

Figure 11. Cladding process of Invar-36 on steel (left). SEM micrograph showing the interfacial zone between the Invar and the steel.

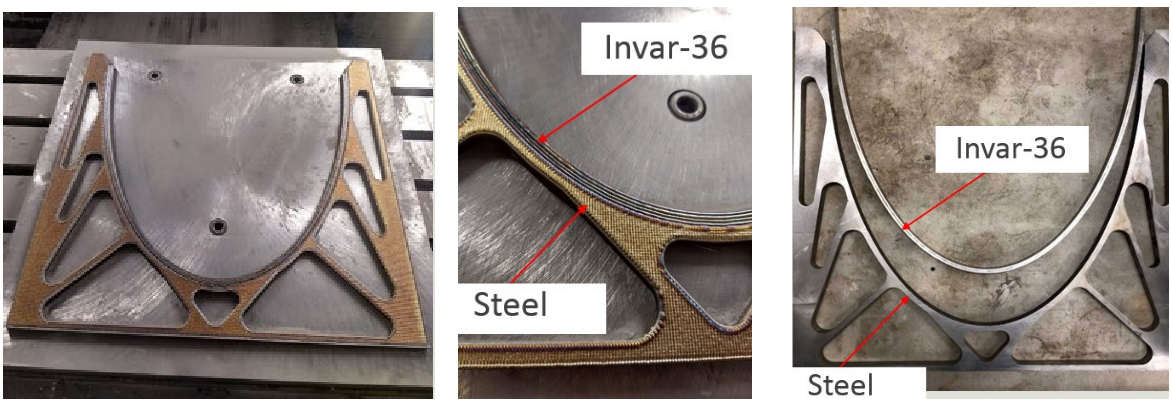

Figure 12. Cladding process in a large leading edge structure (left and center). De-bonded invar-36 from the steel substrate.


Figure 13. Welded Invar-steel structure (left). CF/Epoxy composite manufactured in the welded invar-steel structure (right).

4. CONCLUSIONS

Based on the current progress of the different technologies studied in this work, it is clear that additive manufacturing represents a promising technology for producing low cost composite tooling molds. Current results have shown that infiltrated printed silica sand can be successfully used as a direct mold for producing composites. A metal casting process on 3D printed sand mold has been successfully manufactured. The thermal and x-ray results have corroborated that the casting product was made of Invar-36. The most attractive and a high-risk technology seems to be the cladding of the Invar alloy on low cost metal substrates. Here, the use of Invar-36 on inexpensive steel substrate will ensure a low CTE tooling part with robust mechanical properties. Indeed, this technology is still under investigation, but it is expected to serve as an exemplary method for producing composite tooling.

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