



Joining by forming of bi-material collector coins with rotating elements

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ABSTRACT

This paper presents a novel manufacturing process for producing innovative bi-material collector coins with free-rotating inner elements. The inner elements are fabricated using additive manufacturing, enabling the creation of coins with complex and intricate geometric details that would be unattainable using conventional wrought materials. The outer elements (rings) are metallic, and this study addresses the challenge of securely connecting them to the inner elements through force-closed mechanisms formed during the coin minting process. Finite element modeling, combined with experimentation on bi-material (polymer-metal and metal-metal) coins, is employed to analyze material flow, assess minting forces, and evaluate contact pressures at the force-closed joints. The analysis ensures that adequate destructive forces are required to separate the inner elements from the rings and provides insights into selecting the appropriate process parameters for simultaneous coining and joining. The successful production of the first bi-material collector coin prototypes with free-rotational inner elements validates the overall development.

Introduction

The history of humanity is linked to the development and perfecting of coin minting because money has always been the preferred medium of exchange for people to trade products and services with each other. The oldest coin in the world is believed to be the 'Lydian Lion' (Fig. 1a), created from electrum, an alloy of gold and silver, around the VI century BC using hand-made blanks and dies by artisans. The first industrial revolution and the development of steam-power coining presses paved the way for the mass production of coins made from copper instead of gold and silver and the establishment of modern mints. Over time, coin minting evolved into an advanced net-shape forming process as a testament to human progress and advancement. Nowadays, in coin minting, a disk (coin blank) is compressed between two dies while it is retained and positioned by a collar (side ring) to create well-defined imprints of the dies on their opposite faces (Fig. 1b).

In contrast to circulating coins, collector coins are typically produced in limited quantities, with extreme quality requirements regarding sharpness, detail, and finishing. They are intended for collectors rather than for everyday use and carry a higher value than circulating coins due to their rarity, unique features, or historical significance. Collector coins,

when fabricated from precious metals such as gold, palladium, platinum, and silver, are also used for financial investments, as their intrinsic metal value and potential appreciation make them attractive choices for investors seeking tangible assets (Grill and Gnadenberger, 2006).

Looking ahead, the global coin collection market is poised for substantial growth, with an estimated US\$18.1 billion in 2023 projected to rise to US\$43.9 billion by 2034 (Value Market Research, 2024). This optimistic outlook is driven by a rising interest in numismatics and an increasing appreciation for the aesthetic and investment value of collector coins. As a result, mints are racing to introduce innovative, disruptive, and technologically advanced products to meet demand (Pragana et al., 2024). Coin minting, in turn, is evolving into one of the most complex and challenging metal forming processes.

One of the innovative manufacturing trends in collector coin minting is the integration of new materials such as polymers, ceramics, and composites with precious metals (Fig. 2). This integration requires advanced joining technologies to connect materials with substantially different physical, chemical, and mechanical properties and must be carried out preferentially during the coin minting process.

The internationally awarded 'Chinese Porcelain Vase Qing Dynasty'

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collector coin produced by the Mint of Poland (2016) and featuring porcelain reliefs on the reverse side of a gold coin (Fig. 2a) does not fulfill the abovementioned integration objective because the different materials are not connected during coin minting.

Joining by forming, a subset of ‘joining by plastic deformation’ (Mori et al., 2013), used in the fabrication of bimetallic coins (Fig. 2c) by means of form-closed joints (Fig. 2c) resulting from the plastic deformation of the ring into a groove placed on the outside edge of the center (Vahteristo et al., 1992), could, in principle, fulfill the abovementioned integration objective.

However, it cannot be used for connecting polymers, ceramics, or composites with metals due to the former’s brittleness or elastic recovery limitations.

In bi-material coins with polymer, ceramic, or composite centers and metallic rings, for example, form-closed joints tend to fail due to cracking of the centers during plastic deformation of the rings into the grooves on the outer edges of the centers. Reversing the arrangement to fabricate bi-material coins with metallic centers and polymer, ceramic, or composite rings also leads to failure due to the cracking or recovery of the rings from inside the grooves on the outer edge of the metallic centers after unloading (Afonso et al., 2019).

However, the connection of different materials, such as polymer inner elements with metallic rings during coin minting, is possible using force-closed joints (Fig. 2d) in which connection is not ensured by interlocking (as in form-closed joints) but by interface contact pressure between the inner element and ring materials after unloading (i.e., by residual stresses) (Afonso et al., 2019). In what follows, the term ‘inner element’ will be used instead of ‘center’ to cope with geometries other than circular.

The ‘Gothic’ collector coin produced by the Mint of Portugal (2021) was the first to use this technique, combining a polyvinyl chloride (PVC) inner element with a silver ring (Fig. 2b). It showcases the potential of force-closed joints to foster creativity in collector coins through the combination of the textures and colors of diverse materials. Unlike regular coins that circulate in daily transactions, collector coins such as the ‘Gothic’ are designed for display. This key difference in use means that potential durability problems caused by environmental conditions (e.g., exposure to harsh environments) and the frequency of handling, which could lead to physical wear and abrasion and surface damage or loss of details in some materials, are not relevant.

However, to fully realize this potential, it is crucial to develop new coin designs that offer greater flexibility in shaping the elements, which

have been limited to basic geometries. In this context, the role of advanced technologies, mainly additive manufacturing, cannot be overstated because they unlock the door to greater customization, thereby adding value to the creation of collector coins (Pragana et al., 2023).

Broadly, the combination of additive manufacturing with sheet (Ambrogio et al., 2019), bulk (Meiners et al., 2020), and sheet-bulk (Merklein et al., 2021) forming processes has been explored since the late 2010s, with pioneering applications aimed at demonstrating its effectiveness to produce net-shaped or near-net-shaped parts in small to medium batch sizes which would have been very difficult or impossible to obtain through conventional forming processes alone.

This paper presents a new manufacturing approach for producing collector coins that combines metallic rings blanked from pre-rolled strips with customized, additively manufactured inner elements connected by force-closed joints during coin minting. The hybridization of coin minting with additive manufacturing allows the production of coins with complex and intricate contour holes featuring geometrical details that would be impossible to achieve in traditional coining using polymers, metals, or other wrought materials. Moreover, and to align with the current competitive landscape of Mints striving to produce innovative and disruptive collector coins, the complexity of the newly proposed coins is further enhanced by allowing free rotation of its inner elements.

The work uses finite element digital twins, a virtual representation of the physical coin minting process, to replicate the coin minting process in a virtual environment. Experimentation focuses on the additive manufacturing processes and strategies used to fabricate the inner elements, the final coin minting process where the inner elements and rings are joined, and the evaluation of the destructive forces required to separate the inner elements from the rings.

The fabrication of two bi-material collector coin prototypes, utilizing different combinations of materials and additive manufacturing techniques, demonstrates the effectiveness of this manufacturing route in producing innovative bi-material collector coins with free-rotating inner elements.

Methods and procedures

Hybrid manufacturing route

The hybrid manufacturing route to produce the innovative bi-material collector coins with free-rotating inner elements is

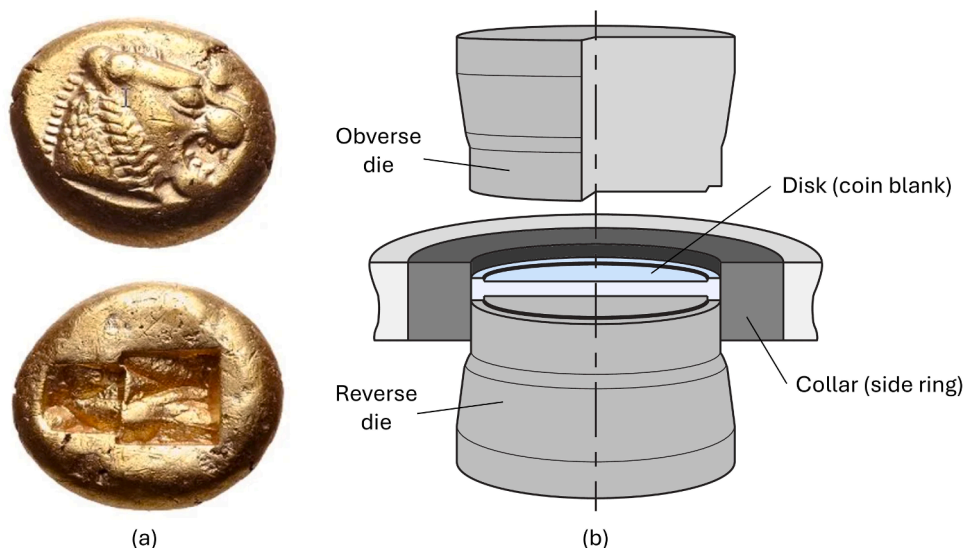


Fig. 1. (a) The ‘Lydian Lion’ coin (adapted from Markowitz, 2017) and (b) schematic representation and notation of the active tool parts of a modern coin minting die set.

schematically shown in Fig. 3a. It begins with the fabrication of the rings, which are blanked out from a pre-rolled strip and the construction of customized additive manufactured inner elements, designed with features that enable their free-rotating movement. Subsequently, the rings are polished to ensure the high quality of the sheared edges and surfaces, as is commonly done in the conventional manufacturing of collector coins. Polishing is not included in Fig. 3a because it is usually considered a post-blanking operation.

The inner elements and rings are then connected by a force-closed mechanism during coin minting in a conventional die set with active tool parts consisting of two dies containing the imprints to be transferred onto the surface of the coins and a collar.

The active tool parts of the coin minting die set, a pair of reverse and obverse dies with relief depths ranging from 0.08 mm to 1 mm made from an AISI D3 cold work steel that was heat treated by hardening and tempering to reach a hardness of 60 HRC, and a collar with an inner flat surface of 27.65 mm diameter made of tungsten carbide, were assembled in a tool with two (upper and lower) bolsters and an upper die holder (Fig. 3b). The tool was installed in an Instron SATEC 1200 KN hydraulic testing machine, allowing the acquisition of force vs. displacement data during the tests.

Additive manufacturing

In previous work, the authors (Pragana et al., 2020) introduced the hybridization of coin minting with additive manufacturing using Laser Powder Bed Fusion (LPBF) to produce metallic coins made from a single material. This paper takes a step further by proposing an innovative manufacturing route combining the two abovementioned processes to produce bi-material collector coin prototypes with inner elements and rings made from different materials and allowing free-rotation of the inner elements. This new manufacturing route to be applied in bi-material (polymer-metal and metal-metal) collector coins requires the involvement of different additive manufacturing processes and the development of new deposition strategies.

The polymer inner elements used in the bi-material (polymer-metal) collector coins were constructed by fused deposition modeling (FDM) using an Ultimaker S3 3D printer with a PLA (polylactic acid) filament of 2.85 mm diameter and 0.4 mm nozzles. The metallic inner elements

used in the bi-material (metal-metal) collector coin prototypes were constructed by laser powder bed fusion (LPBF) using a DMG Mori Lasertec 30SLM 2nd Gen. machine equipped with a 600 W laser inside a chamber filled with 99.9 % argon. The feedstock material used was the AISI 316 L stainless steel with a powder size of 15–45 μm .

Fig. 4 illustrates the deposition strategy for constructing the polymer's inner elements that was obtained from the open-source Ultimaker Cura software (Ultimaker, 2019). The strategy involves layer-by-layer zigzag patterns with 100 % infill. The overall geometry of the elements consists of a core and a shell connected by thin rods that support the construction. After material deposition is complete, the inner elements are removed from the build platform and the core is twisted along its axis, a motion indicated by the arrows inside the dashed circles of Fig. 3a (center). This twisting motion is transferred to the supports, breaking them and releasing the core, allowing free-rotating movement without detaching it from the shell.

The deposition strategy used in LPBF was similar to that of FDM but for a different geometry, which will be shown later in the paper. Table 1 summarizes the overall parameters for constructing the polymer and metal inner elements.

Coin minting

The connection of the inner elements to the rings through a force-closed mechanism during coin minting was analyzed using specially designed inner elements without free-rotating features. As mentioned in the previous section, the inner elements were made from two additively deposited materials - polylactic acid (PLA) and AISI 316 L stainless steel. In contrast, the rings were made from a single material - wrought UNS C36000 copper alloy - supplied in pre-rolled strips with 3 mm thickness.

While the geometry and dimensions of the inner elements remained constant, the dimensions of the rings were varied to accommodate different clearances i during coin minting. Additionally, the maximum coining force F_{max} was adjusted to assess its combined effect with the clearance i on the final shape and effectiveness of the force-closed joint.

Table 2 summarizes the experimental conditions applied during the coin minting tests.

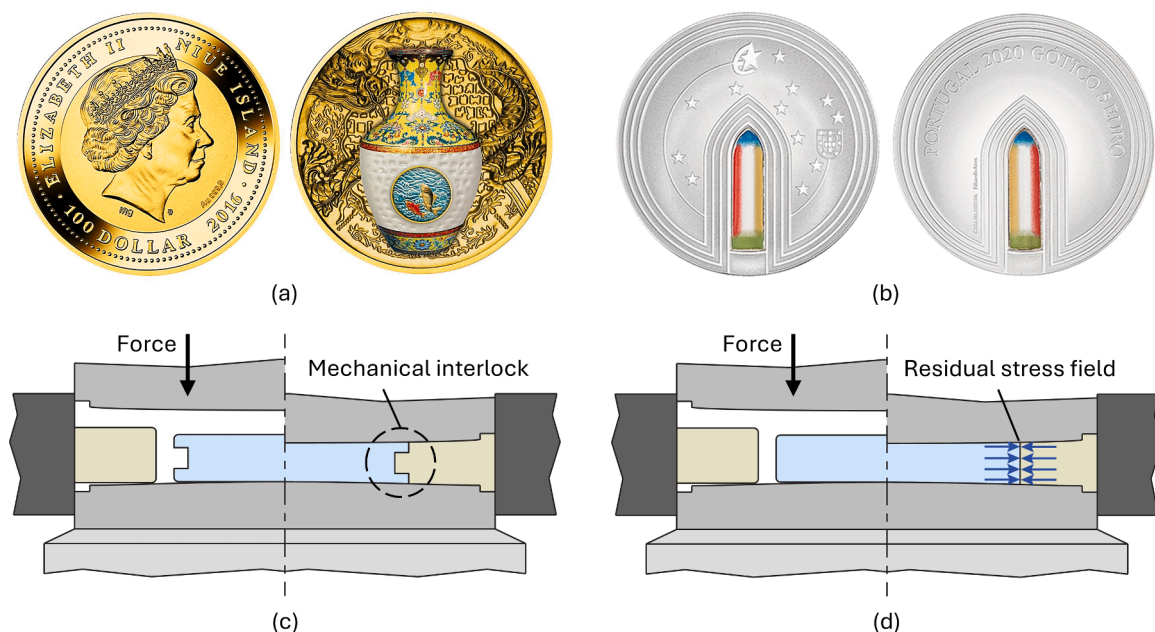


Fig. 2. Bi-material collector coins: (a) 'Chinese Porcelain Vase Qing Dynasty' (Mint of Poland, 2016), (b) 'The Gothic' (Mint of Portugal, 2021). Schematic representation of joining by forming connections used in bi-material collector coins based on (c) form-closed and (d) force-closed mechanisms.

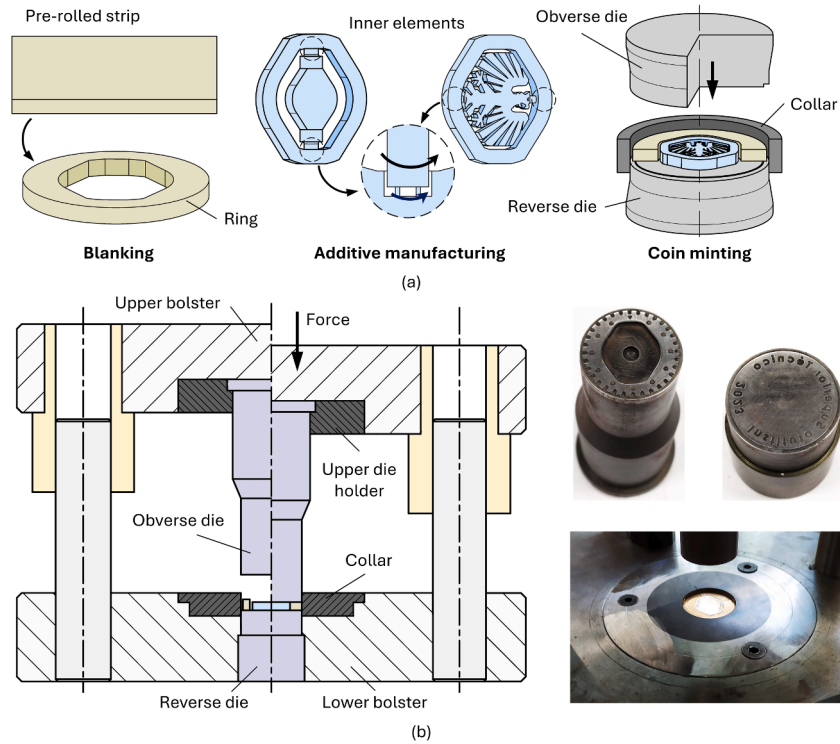


Fig. 3. (a) The hybrid manufacturing route used to produce bi-material collector coins with free-rotating inner elements. (b) Schematic representation of the laboratory tool system used to produce the collector coin prototypes with photographs of the active tool parts.

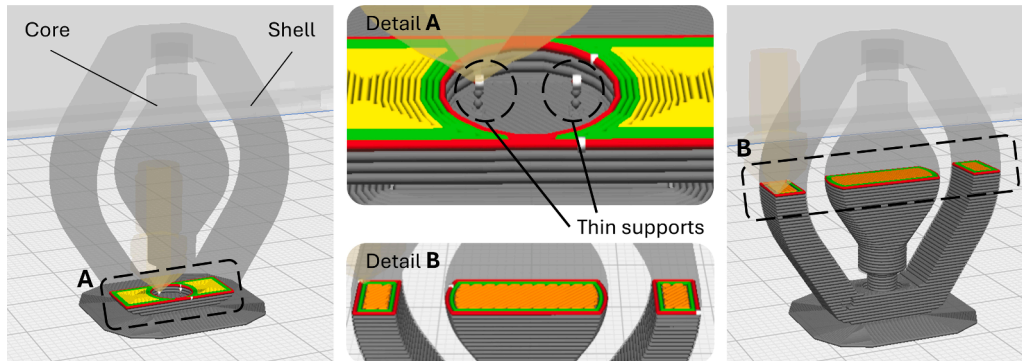


Fig. 4. Deposition strategy used for the construction of polymer inner elements. Detail A refers to the thin supports for enabling free-rotating movement, and detail B refers to the 100 % infill zigzag paths used in the layers.

Table 1

Main processing parameters used for constructing the polymer and metal inner elements through additive manufacturing.

Process	FDM	Process	LPBF
Material	PLA	Material	AISI 316L
Bed temperature (°C)	60	Laser power (W)	250
Printing temperature (°C)	200	Spot size (mm)	0.1
Print speed (mm/s)	30	Scan speed (mm/s)	750
Layer height (mm)	0.1	Layer thickness (mm)	0.05
Line width (mm)	0.4	Hatch spacing (mm)	0.1
Build-plate adhesion	Brim	Vector size (mm)	5

Material flow curves

Compression and stack compression tests determined the flow curves of the materials used in this work. The tests were conducted at room temperature using a special-purpose tool installed in the hydraulic

testing machine mentioned earlier.

Cylindrical test specimens, each 12 mm diameter, and 12 mm height, were fabricated from PLA and AISI 316 L additively deposited materials using the processing parameters listed in Table 1. Disk blanks with 12 mm diameter and 3 mm thickness were cut out from UNS C36000 copper alloy strips and piled up in sets of four disks to obtain stack compression test specimens.

Fig. 5 shows the material flow curves at ambient temperature resulting from the entire set of tests. It is worth noting that the flow curve of PLA neglects the strength differential effect because, during coin minting, the material is exclusively subjected to compression. Otherwise, tensile tests should also be carried out to distinguish between the flow curves in tension and compression.

Finite element modelling

Finite element digital twins provide a virtual representation of the physical coin minting process. They allow analyzing material flow and

Table 2

Summary of the experimental conditions used in coin minting with photographs of different inner elements and rings.

Clearance i (mm)	Maximum coining force F_{max} (kN)
0.1, 0.15, 0.20, 0.25	200, 250, 300, 350

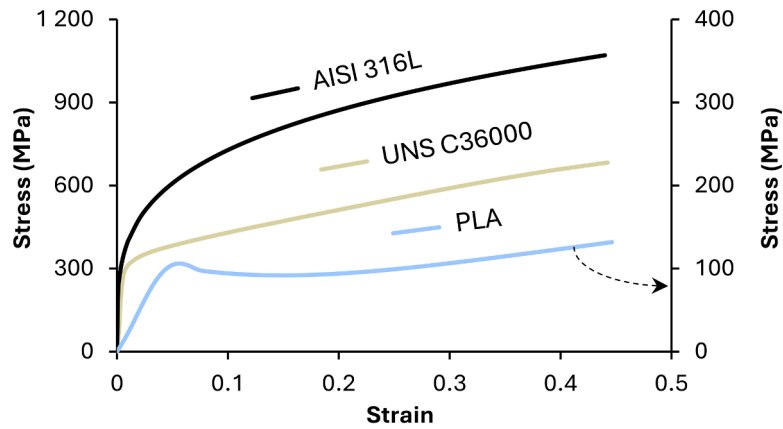


Fig. 5. Flow curves of the materials used in coin minting. Please refer to the stress scale of the right vertical axis in the case of PLA.

determining the required coin minting forces and contact pressures at force-closed joints, enabling the selection of the appropriate parameters without the need for exhaustive physical trials.

In recent years, commercial finite element software (e.g., Shirasaka, 2016) and special-purpose finite element software (e.g., Xu et al., 2008 and Li et al., 2017) have been used to create digital twins of the coin minting process.

This work used the in-house finite element computer software I-FORM (Nielsen and Martins, 2021), which has also been successfully applied to create digital twins of the coin minting process. The software is built upon the following modified weak form of Markov’s rate of energy variational statement to include contact and sliding with friction between the coin blanks and the active tool parts during coin minting,

$$\int_V \sigma'_{ij} \delta D_{ij} dV + \int_V \sigma_m \delta D_v dV - \int_{S_t} t_i \delta u_i dS + \int_{S_f} \left(\int_0^{|u_r|} \tau_f \delta u_r \right) dS = 0 \quad (1)$$

The software employs a control volume V with a sort of ‘updated Eulerian approach’ using the velocities u_i as the primary unknowns (Mattiasson, 2010). The first term in (1) involves the deviatoric Cauchy stress σ'_{ij} and the rate of deformation D_{ij} , representing viscous effects. The second term makes use of the hydrostatic stress σ_m and the volumetric rate of deformation D_v , analogous to hydrostatic effects on a viscous

fluid. The incompressibility condition of the velocity field $D_v = 0$ is relaxed using a penalty function K , where $\sigma_m = (K/2)D_v$.

The third and fourth terms in (1) refer to the tractions t_i applied on the boundary S_t of the control volume, and to the friction shear stress τ_f and the relative sliding velocity u_r acting on the contact interfaces S_f between the coin blanks and the active tool parts. Friction was modelled using the law of constant friction, expressed as $\tau_f = mk$, where k represents the shear flow stress and m denotes the friction factor. A value $m = 0.35$ was utilized based on a previous combined experimental and numerical investigation of the authors on coin minting (Alexandrino et al., 2018).

The computer implementation of (1) in I-FORM requires discretizing the coin blanks with hexahedral elements (Fig. 6) and results in a nonlinear set of equations that are solved using iterative procedures to minimize the residual force within a specified tolerance.

Two different discretization strategies were used. For collector coins with inner elements without free-rotating movement, two symmetry planes were considered (Fig. 6a) to reduce the total number of elements to approximately 8000 hexahedra. This allowed CPU time to be diminished by approximately 8 times compared to that of simulations using the entire geometry of the inner elements. These models were mainly used to investigate the contact between the inner elements and the rings during coin minting.

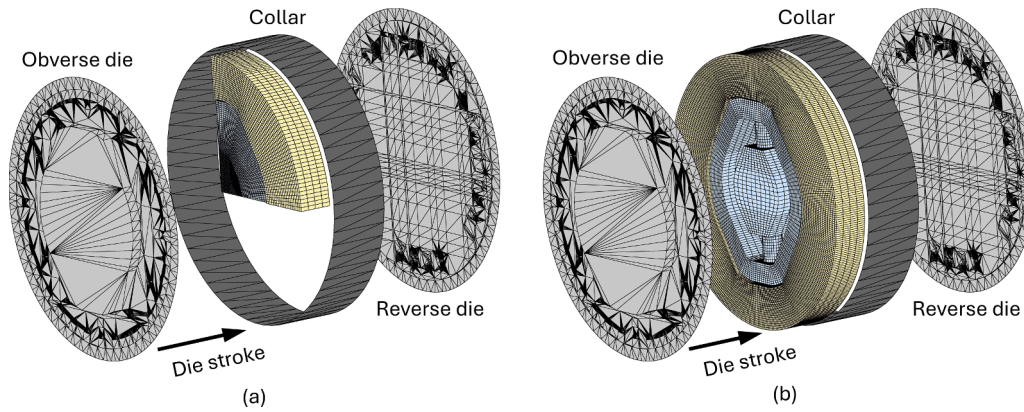


Fig. 6. Finite element models of bi-material collector coins with inner elements: (a) without and (b) with free-rotating movement.

No symmetry planes were considered when dealing with inner elements featuring free-rotating movement. This decision led to the creation of larger models, each comprising approximately 60,000 hexahedra (Fig. 6b). While this increase in mesh size and complexity was significant, it was a necessary step to thoroughly analyze the impartation of lettering and reliefs on surfaces during coin minting.

The active tool parts (e.g., the dies and collar) were assumed to be rigid objects and discretized with contact friction spatial triangles to automatically apply the boundary conditions associated with the moving obverse die and the stationary reverse die and collar (Fig. 6).

Results and discussion

Material flow

Material flow and the determination of contact pressures at the resulting force-closed joints were investigated using coin blanks with metallic rings made from a wrought UNS C36000 copper alloy and additively manufactured inner elements made from PLA, without free-rotating movement. The experimental and numerical simulation work gave insights into the influence of process variables, such as the clearance *i* between the rings and inner elements and the maximum coining force F_{max} (see Table 2).

Fig. 7 presents the results and identifies the three main deformation modes observed in the experiments, as shown in the accompanying photographs. These modes are significant as they provide insights into

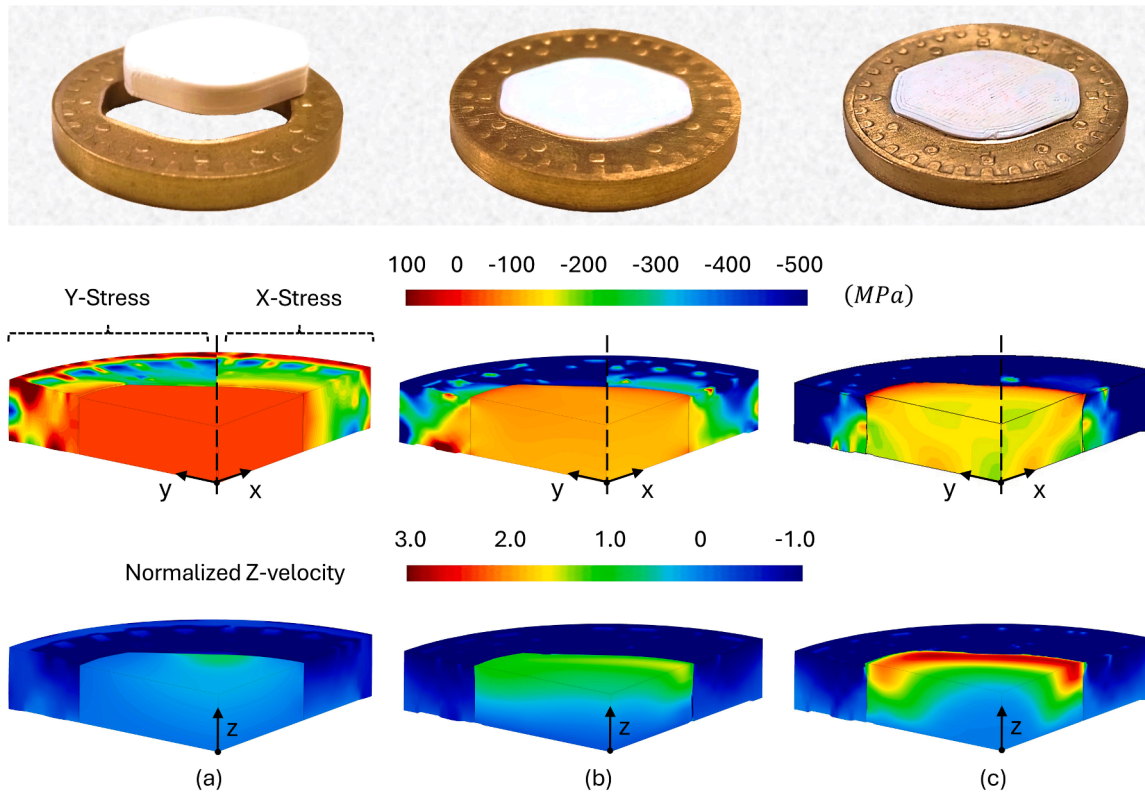


Fig. 7. The (a) first, (b) second, and (c) third modes of deformation that were experimentally observed and numerically replicated during coin minting of bi-material coins with inner elements without free-rotating movement. Note: The x- and y-stress distributions of (a) and (c) are plotted at the end of coining, while that of (b) is plotted after unloading. The normalized z-velocity is plotted at the end of coining for all the cases.

the conditions under which force-closed joints are formed and into the quality of the lettering and relief impartation on the coin surfaces.

The first mode of deformation (Fig. 7a) occurs under specific conditions of large clearance i , low values of the maximum coining force F_{max} , or a combination of both. In the example shown in Fig. 7a, corresponding to $i = 0.1$ mm and $F_{max} = 200$ kN, no force-closed joint was formed, and, therefore, no permanent connection was achieved between the inner element and the ring. The x- and y-stress distributions and the normalized z-velocity $v_z/|v_{obverse\ die}|$ at the end of coining confirm this by showing values around 0 MPa and a uniform upward movement of the inner element typical of free elements (i.e., without a force-closed connection). The small value of F_{max} is also responsible for the poor quality of the lettering and reliefs imprinted on the final coin surface.

The second mode of deformation (Fig. 7b) is typical of a sound force-closed joint and was achieved by increasing the maximum coining force F_{max} to 300 kN and slightly adjusting the clearance $i = 0.2$ mm. The corresponding x- and y-stresses at the contact interfaces between the inner element and the ring are compressive and range from 100 to 160 MPa, confirming the creation of a permanent force-closed connection. The non-uniform distribution of the normalized z-velocity $v_z/|v_{obverse\ die}|$ further supports this conclusion due to the connections that were created along the contact interface. Increasing the maximum coining force F_{max} is crucial for enhancing the quality of the lettering and reliefs imprinted on the final coin surface, as seen in the photograph (Fig. 7b).

While a force-closed joint was also formed in the third observed mode of deformation, the use of a larger $F_{max} = 350$ kN with a clearance $i = 0.25$ mm, led to a substantial upward movement of the inner element, as indicated by the normalized z-velocity and by the high values of the x- and y-stresses at the end of coining. The implication of this is significant, as it compromises the geometrical integrity of the final coin, which shows material of the inner element on top of the ring surface (Fig. 7c).

Coin minting force

Based on the above-mentioned findings, the parameters for subsequent experiments were chosen as, $i = 0.2$ mm and $F_{max} = 300$ kN. Fig. 8 presents the experimental and finite element predictions of the force vs. die stroke evolution for a coin blank produced with these parameters. The agreement is excellent and the finite element cross-section details show the meshes at different die strokes.

The force vs. die stroke evolution of Fig. 8 can be divided into three distinct stages. In the first stage (Stage I), there is a sharp increase in force with minimal die stroke due to the initial contact between the ring and the obverse and reverse dies. In the second stage (Stage II), the force increases more gradually and steadily as the external diameter of the ring expands under uniaxial compression (refer to the finite element cross-section details, showing the ring material moving outwardly). The

third stage (Stage III) begins at a die stroke of approximately 0.12 mm, when radial contact between the ring and the collar is established. From this point onward, the ring material flows inward against the inner element (refer to the finite element cross-section detail), leading to a higher rate of force increase. This phase enables the creation of a force-closed joint between the two materials and ensures an accurate imprinting of the lettering and reliefs on the coin surface.

Destructive force

The effectiveness of the force-closed joints was assessed through destructive tests, where the inner elements were pushed out of the rings. These tests were conducted in an universal testing machine and provided valuable insights into the strength and reliability of the force-closed joints obtained with process parameters corresponding to the second and third modes of deformation.

Results for three different coin specimens are shown in Fig. 9, including photographs of the inner elements separated from the rings for three sets of process parameters, giving rise to deformation modes II and III. Results show that increasing the maximum coining force F_{max} or reducing the clearance i to improve the force-closed joints is ineffective in deformation mode III due to the compromised geometry of the joint. The process parameters associated with deformation mode II result in higher push-out forces, indicating more robust and reliable force-closed joints.

Coin prototypes with free-rotating inner elements

The previous sections on the fabrication of collector coins without free-rotating inner elements played a crucial role in determining the process parameters to achieve a robust force-close joint without compromising the geometrical integrity of the final coins. This final section of the paper, which delves into the use of free-rotating inner elements, further validates the previous identification of process parameters because the presence of a rotating fulcrum significantly raises the sensitivity of the overall assembly process.

Under these conditions, Fig. 10 illustrates the finite element evolution of z-stress (pressure) on the obverse side of two prototype blanks during coin minting with the process parameters corresponding to the second mode of deformation.

The results show a consistent increase in the compressive z-stresses towards very high values, peaking at around 1200 MPa. This pressure increase is crucial for the complete imprinting of the lettering and reliefs while ensuring the secure connection of the outer ring with the inner element by a force-closed mechanism. This is achieved without causing significant deformation of the inner elements, which could otherwise hinder their geometry or rotational movement. The process parameters were selected from the second mode of deformation ($i = 0.2$ mm, $F_{max} =$

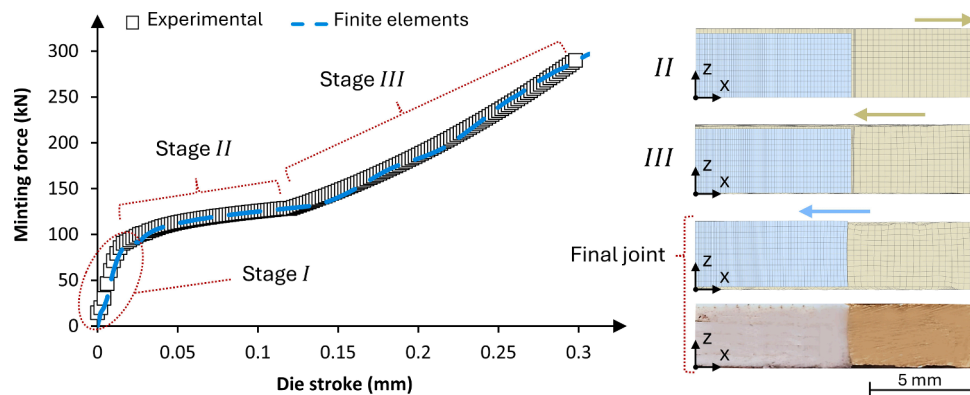


Fig. 8. Experimental and finite element predicted evolutions of the force with die stroke for bi-material (polymer-metal) coins having inner elements without free-rotating movement ($i = 0.2$ mm and $F_{max} = 300$ kN).

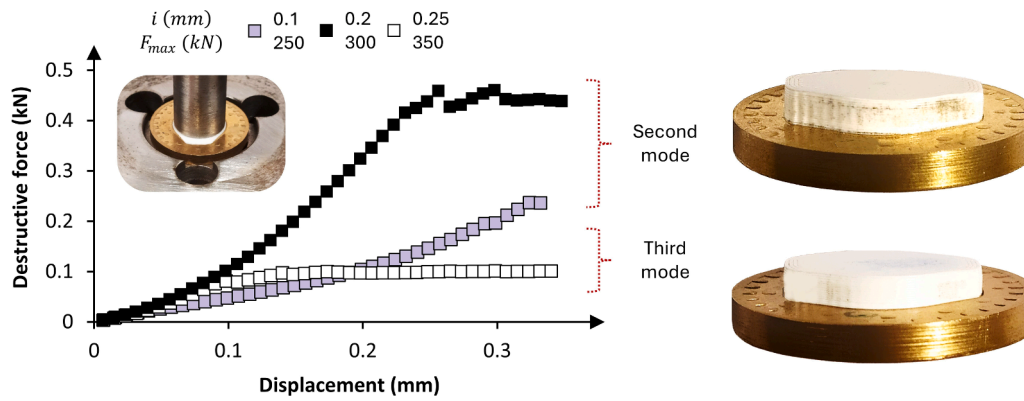


Fig. 9. Experimental evolution of the push-out force with displacement for coin blanks with different process parameters corresponding to the second and third modes of deformation.

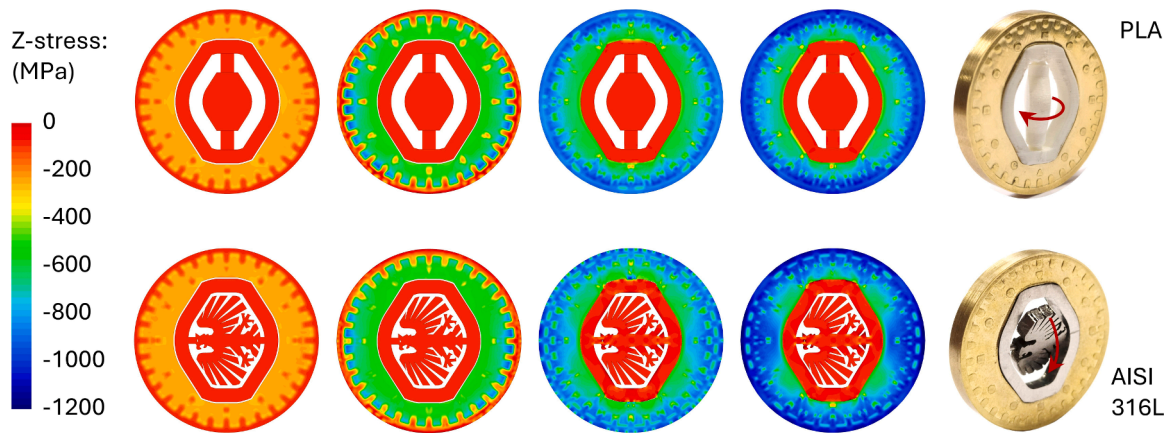


Fig. 10. Finite element predictions of z-stress (pressure) at 15 %, 50 %, 85 % and 100 % of total die stroke and final photographs (right-hand side) of coins with free-rotating elements built in PLA (top) and in AISI 316 stainless steel (bottom).

300 kN), validating the outcomes attained from coins without free-rotating movement that were analyzed in the previous sections.

The absence of pressure on the inner elements (as indicated by the red-colored areas in the z-stress distributions shown in Fig. 10) results from an intentional design decision, as detailed in Table 2. This decision was made to protect the rotational features from damage, a key consideration in the novel coin minting process. The photographs of the prototype collector coins shown on the right-hand side of Fig. 10 confirm the feasibility of the new proposed hybrid manufacturing route that integrates additive manufacturing with coin minting to produce collector coins with free-rotating elements.

Conclusions

The hybridization of coin minting routes by incorporating customized, additively manufactured inner elements has been successfully demonstrated, enabling the fabrication of bi-material coins with free-rotating parts. The utilization of polymer (PLA) and metal (AISI 316 L stainless steel) inner elements produced via distinct additive manufacturing processes and connected to wrought UNS C36000 copper rings, opens new possibilities for innovative, disruptive collector coin designs.

The connections were carried out during coin minting, where the compressive pressure required to impart lettering and reliefs is simultaneously used to create a force-closed joint between the inner elements and rings.

Results highlight that the quality of the final coins is highly sensitive to two critical factors: the initial clearance i between the inner elements

and rings and the maximum applied coin minting force F_{max} . When improperly controlled, these variables can lead to undesirable outcomes, such as loose inner elements or excessive deformation. However, by finely tuning these parameters, an optimal balance of deformation can be achieved (named as ‘the second mode of deformation’), which ensures both the integrity of the coin’s design and the secure locking of its components.

Finally, the work underscores the importance of employing finite element digital twins to simulate the coin minting process accurately. Digital twins helped predicting forces and explaining the three deformation modes observed, offering valuable insights to select the appropriate process parameters for producing sound collector coins with free-rotating elements.

CRediT authorship contribution statement

Pedro M.S. Rosado: Writing – review & editing, Investigation, Formal analysis, Data curation. **Rui F.V. Sampaio:** Writing – review & editing, Investigation, Formal analysis, Data curation. **João P.M. Praga:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ivo M.F. Bragança:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Carlos M.A. Silva:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Paulo A.F. Martins:** Writing – original draft, Supervision, Software, Resources, Methodology,

Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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