Thinking through Molds: Metal Flow and Visualizing the Unseen

Andrew Lacey and Pamela H. Smith
Making and Knowing Project, Columbia University, New York, NY, USA

Until techniques like those described in this article were available, clues to how molten metal behaved inside a mold had to be sensed from phenomena occurring outside the mold, including how fast the mold filled, metal splashes, and cracking. But sixteenth-century sources show that the flow of metal through the mold was visualized in advance during the construction of the mold itself. This article focuses on evidence from an anonymous sixteenth-century source that demonstrates such thinking through molds about the unseen.

Visualizing the Invisible

Today, when metal founders and sculptors visualize the flow of molten metal through a mold, they imagine it entering the thickest part of the mold, rushing, propelled by its own weight, into the mold's farthest corners. The anonymous author-practitioner of a remarkable late sixteenth-century French manuscript (Ms. Fr. 640) considered a well-constructed mold in combination with the heat of the metal when imagining such metallic flow.[1] This individual viewed the mold as a vehicle to propel molten metal through the narrowest parts of the mold, racing through delicate channels into larger parts, attracting and drawing the substance into the mold's tiniest interstices along the way.

Until recently, the behavior of metal inside a mold was imagined and sensed from outside. Theophilus's twelfth-century account of molding large bells directs a bell founder to heat the mold to red-hot before carefully pouring metal into the mold, and "while this is going on lie down close to the mouth of the mold and listen carefully to find out how things are progressing inside. If you hear a light thunderlike rumbling, tell them to stop for a moment and then pour again; and have it done like this, now stopping, now pouring, so that the bell metal settles evenly, until that pot is empty." This continues until the metal is visible in the mold's pouring cup, or gate.[2]

No matter how much care was devoted to making a mold, an overly hot fire, a cold wind, or other unexpected occurrences could cause a mold to crack or the molten metal to cool and congeal too quickly, ruining the final cast. All such contingencies had to be visualized and thought through in constructing a mold, a process that involved sourcing and preparing the mold materials, forming the mold, constructing the casting infrastructure around the model (gate, sprues, and vents), arranging (and constructing) the furnace, alloying and "treating" the metal (with fluxes and substances), and, finally, heating and casting the metal. The Italian mine manager and metalworker Vannoccio Biringuccio (ca. 1480–1539) opined that "the greatest labors of both mind and body are required for its [casting] operations in the beginning, middle, and end." The fact that the behavior of metal within a mold was invisible heightened the urge to open the mold after a pour to see the success of a cast. This moment of metalworking led Biringuccio to note that "the mind is held in suspense and fear regarding the outcome; the spirit is disturbed and continually anxious," but despite this he concluded that "it is indeed true that these labors are endured with pleasure because they are associated with a certain expectation of novelty, produced by the greatness of art and awaited with desire, particularly since the artificer sees that it is an art pleasing and delightful even to ignorant men. As a result, as if ensnared, he is often unable to leave the place of work."[3]

That anxious moment of complete invisibility and uncertainty between pour and reveal in casting metals has led to deep consideration of and extensive experimentation with the factors that influence the flow of metal into a mold. This type of thinking through molds and casting is evident in many documents like Biringuccio's *Pirotechnia* (1540) and the aforementioned Ms. Fr. 640. Of the more than nine hundred entries in that latter manuscript, more than a third are devoted to casting, mostly of small items, especially of plants and animals cast from life in plaster and medals cast in earth-filled frame molds. The unknown author-practitioner called these earths (including plaster) *sable* (sand) and focused on the trials of sands with significant preoccupation. He used a great variety of metals including gold, silver, copper, and copper alloys like latten and what he calls *bronze* and *metal*. He also experimented extensively with tin, lead, and various alloys of the two, as well as alloys derived from available coins. Ms. Fr. 640 is by no means a recipe book, with its observations, first-hand trials, and directives put down in occasionally chaotic order. In fact, its many contradictions, lacunae, and trailing and unfinished passages can sometimes prove to be an advantage over the highly rhetorical polish of some published texts, at least for the historian attempting to visualize a metal worker's thinking with and through their molds.

Thinking through Molds

It is perhaps an obvious point that a cast object should reproduce as closely as possible the model from which it was molded. This overarching aim is underscored by Ms. Fr. 640's author-practitioner in numerous life-cast experiments in which the goal was not just fidelity to the model but giving the cast an illusion of liveliness: "I cast a large lizard like a natural one."[4] While achieving this goal involved collecting plants or catching, keeping, feeding, and killing live animals, as well as the afterworking and painting of the cast, this article is concerned only with Biringuccio's "middle" part of casting, that is, thinking through the flow of metal in the mold.[5] Close study of the intensively written, revised, and annotated sections on mold making and casting in Ms. Fr. 640 reveals six main factors by which the author-practitioner thought and worked through metal flow in the mold: (1) the *materials* that make up the mold; (2) the *native properties of different metals* and their *transformation* by *alloying* and adding substances to make the metal *run*; (3) the *complex dynamic* between the materials of a mold and the metal cast into it; (4) the *regulation and workings of heat* with regard to the furnace, mold, and metal, especially in the moments just before casting; (5) the *environment* of molding and casting, which involves thinking about the water-holding potential of the surface on which molds are left to dry, open windows that let cold winds blow onto molds heating in a forge, as well as furnace construction, bellows operation, and wood type; and (6) arguably the most crucial factor, the *infrastructure* within the mold.[6] This last factor includes the positioning of the model itself and its subsequent careful removal to leave a void in the mold (*cave* or *creux*, or "hollow"); the gate (*gect*, or "cast") through which the metal is poured into the mold; the sprues (*filons*, or "veins") by which the void left by the model in the mold is "fed" (filled with metal); and the vents (*souspira[i]ls*, or "breathing holes") out of which the trapped air exits to make way for the inrushing metal. Only the optimal disposition of all six factors (and numerous lesser ones) will create a successful cast. Repeated trial of all factors—with the inevitable failures—are required to achieve such success. This experimentation informs an ever-fuller visualization of the likely flow of metal through the mold and allows for further mold construction that will withstand the many contingencies that befall each of these factors.

A complete discussion of these factors must be reserved for a longer essay; however, it is useful to note that the richest passages of first-hand experimentation found in Ms. Fr. 640 focus on trials with a stunning diversity of materials, including burnt felt from hats, human bones, and local earths from identifiable locations around Toulouse (where the manuscript was likely composed). Much testing is directed toward identifying and treating the native properties of metals: gold is "dry" and "tough," for example, while lead is "fat" (*gras*), and tin can be "brittle" or "sour" (*aigre*) if heated repeatedly. These inherent properties of metals can be transformed through alloying and adding "mixtures." A mixture for gold, for example, is composed of sal ammoniac (ammonium chloride), verdet (verdigris), borax, and saltpeter (potassium nitrate).[7] Alloying can, however, have downstream effects that must also be considered: for example, latten (copper alloy containing zinc or calamine) "is very capricious to cast," "and one ought not to leave it rest even a little bit outside the fire, like some do with silver, for it is immediately cold when it feels the air and the wind."[8] The author-practitioner also frequently referred to the dynamic between the properties of the mold material and those of the metal poured into it: the mold material, which might be "lean," "fatty," and "impalpable," interacts with the metal, for a "lean" sand can "drink" up the fat of a fatty metal.[9]

While a caster might see the heat of the molten metal as the most important factor in casting today, the author-practitioner considered the heat of the fire

Fig. 1
Ms. Fr. 640, fol. 124v, Bibliothèque nationale de France, Paris. Drawing of the mold of a life-cast lizard. The gate of the mold allows metal to enter the lizard's tail, with sprues carrying the metal throughout the mold. Vents run from the lizard's head to allow air forced out by the inrushing metal to exit through the gate end of the mold. Photo: gallica.bnf.fr.

and its regulation in the furnace and gave much consideration to the temperature to which the mold must be heated just before casting. A mold had to be hot enough to cause the metal to race through the mold without congealing, but not so hot as to fracture the mold or cause a metal such as lead or tin to become porous. The author-practitioner noted the numerous signals given by the mold and metal to indicate when all is ready for casting, such as when the mold glows red, when the molten metal behaves in a particular way (boils, throws off sparks, or turns smooth and shiny like a mirror [red copper]), or when the metal turns a particular color ("when [lead] is very hot, it becomes blue, let it then pass this color & rest a little before casting" or "when gold reaches its perfect heat, it is green like an emerald").[10]

Infrastructure

Long entries in Ms. Fr. 640 deal with the casting infrastructure of the mold, which, as noted, is crucial in the production of a good cast. The author-practitioner devoted ample attention to casting infrastructure of small life-cast insects, amphibians, and reptiles, as well as medals. The construction of the infrastructure, as documented in this manuscript, begins with the positioning of the model in the mold, which is critically important in creating a lifelike cast, as the body of the animal or plant will itself form a channel for the metal when burned out or removed from the mold. The gate through which the metal enters the mold is the subject of numerous comments and entire entries in the manuscript ("a means to make the gate for small female lizards" and "advice concerning the gate," among others).[11] For the most delicate of things like small

Fig. 2
Ms. Fr. 640, fol. 125r, Bibliothèque nationale de France, Paris. Drawing of the branched gate of a mold for life casting "small female lizards." Photo: gallica.bnf.fr.

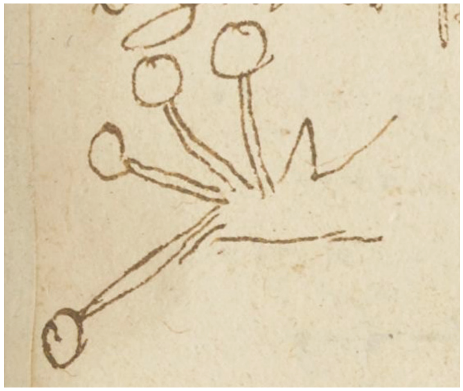

Fig. 3
Ms. Fr. 640, fol. 133r, Bibliothèque nationale de France, Paris. Drawing of wax balls placed at the ends of lizard toes for molding a life-cast lizard. When the wax is melted, the resultant void draws the metal through the lizard toes to reproduce the delicate details of the lizard's foot. Photo: gallica.bnf.fr.

female lizards or carnation blossoms, the author-practitioner constructed the gate on the thinnest part of the model: the tail of the lizard or the stem of the plant. As the author-practitioner noted, "When the tail, which is delicate and closer to the gate, comes out well, the rest will also come out well."[12] Because the tail "is so delicate and thin that the metal would run with difficulty, especially when [the tail] is curled," sprues must be formed that channel the metal directly to other parts of the mold "in order that the metal goes more easily from one part to another & promptly runs everywhere" (fig. 1).[13]

The gate can also be divided "in two or three branches thus when it approaches the molded thing, and always make holes in the gate" (fig. 2).[14] In addition, grooves or notches should be made in the gate "for this breaks up the fury of the metal." Additionally, one must also make "conduits of wax around the legs & around the contours of the body which are a little long, & they will serve as feeders for the molded thing."[15] In discussing metals, the author noted that such channels into the mold's delicate parts "attract" the metal and "feed the figure better."[16] Wax balls at the end of the toes of a lizard also help draw the metal through each delicate digit to feed it full with metal (fig. 3).[17] Finally, one's vents must come "from the head, which is in the bottom, toward the gate."[18]

Making Visible the Invisible

By filming metal flow through molds constructed according to the author-practitioner's instructions described above, Andrew Lacey and Siân Lewis not only made the flow of metal through a mold visible for the first time, but were also able to assess the details of Ms. Fr. 640 and give insight into the logic of the author-practitioner's instructions for constructing molds. The first of two experiments chosen for this article involved creating a plaster mold of a lizard that was then X-rayed during the casting process with bronze.[19] In the second experiment, Lacey constructed a lizard mold of thermal glass into which pewter (an alloy of tin and lead, following the manuscript) was cast and Lewis filmed the metal flowing through the mold.

The sprue systems used in both experiments approximately followed the author-practitioner's sketch in the margins of folio 124v (see fig. 2), with the main gate and feeds directed into the tail of the lizard. The author-practitioner advised, "Be careful to not make your gate very wide, and do not forget to make in its conduit two or three holes and notches, and as your gate approaches the molded thing, divide it into three or four parts like fingers which are pointed and are not very deep. For the metal runs more gently without being hindered by vapors and fumes."[20] The gate or funnel divided into three feeds was common in art foundries until the late twentieth century, and evidence of it can be found on the underside of sculptures by Edgar Degas (1834–1917) in the collection of the Fitzwilliam Museum in Cambridge, England.

Experiment 1: Bronze Pour Filmed with X-Ray Technology

The effect of dividing the gate of the mold into three channels is immediately revealed by the X-ray video.[21] The author-practitioner's conception of metal flow and understanding of how evolving gases inside the mold might disrupt the flow of the metal results in his instructions to provide alternative channels for the metal to avoid choking the mouth of the mold. In the first experiment, in which Lacey cast bronze into the mold, the metal can clearly be seen filling all three channels of the gate and immediately impeding gases from escape (whereas the pewter poured into the second experiment's glass mold flows first down one gate leaving the other two free for evolving gases). The author-practitioner's advice to notch the lower section of the gate also shows his understanding of metal flow, for it results in the gate's roughened texture catching the metal dross, which would otherwise typically be deposited close to the bottom of the gate just prior to entering the cast, potentially clogging the gate.

Upon reviewing the footage, we noticed that the flow of metal was highly turbulent and produced metal-oxide smoke, which was violently released from the mold. In respect to latten, the author-practitioner suggested, "If you want to cast something fine & thin, the entire secret is to cast as hot as possible so that the substance boils. You will recognize that it is hot enough when it smokes a lot and while stirring it throws sparks."[22] This reference describes how the zinc component of latten rapidly oxidizes, causing clouds of billowing white smoke and a glowing peacock-hued aura to hover just above the liquid metal—quite mesmerizing to watch but highly dangerous to breathe in, and possibly the cause of the fever that Benvenuto Cellini notoriously suffered during his casting of *Perseus* (ca. 1545–54). As the metal's temperature increases, so does its volatility. This causes the metal to splash against the internal walls of the mold, potentially scaring the surface with a film of metal oxide. Meanwhile gases and smoke from the evolving metal oxides are forced upward into the downward flow of metal. The video shows that it is only when the metal reaches the halfway point inside the mold that the metal flow starts to calm and rectify, which is a far cry from the idealized gentle and controlled flow that we imagined would happen inside the mold before we could see the process in real time in these videos. The visual evidence gained from our experiments was crucial in understanding the realities of metal flow and showed that historic molds and casts were constructed by practitioners able—on the basis of repeated experimentation—to visualize and plan for the sometimes-chaotic flow of metal in a mold.

In particular, the video revealed an exceptionally rare event: the slow expulsion of air that was trapped inside a poorly vented and raised claw. Here, we saw that metal cast into a gas-permeable mold could push the gases directly through the wall of the mold. This event could only happen if the temperature and fluidity of the metal worked in conjunction with the temperature and permeability of the mold—part of the dynamic between mold material and metal that the author-practitioner repeatedly noted.[23]

Our footage of the bronze experiment revealed, however, a near-fatal flaw in the design of our sprue system. The speed at which the mold fills when directed through the thinnest part of the object (in this case the tail of the lizard) forced the inrushing metal to rise up the smaller sprues, causing a cascade of liquid metal to fall down the air vents and potentially to trap the escaping gas in the body of the lizard, thus interfering with the filling of the lizard's limbs. Crucially, the X-ray video also documents the results of the way the metal cooled: beginning under the true right arm of the lizard, a large void formed every few millimeters with increasing size and angularity along the central core of the body, until finally stopping at the midsection between the rear legs and the tail, indicating the point where the metal was last liquid before it entered a slush phase. Although this could have been a dramatic and potentially disastrous flaw, the void did not penetrate the outer surface of the cast, making the flaw itself invisible to the viewer and the cast appear whole.

Experiment 2: Pewter Pour Filmed in a Glass Mold

Our video of pewter being poured into a transparent glass mold revealed an entirely different picture.[24] The mold was assembled just minutes prior to the pour, so the overall temperature was high, as directed by the author-practitioner, and the pewter was heated much higher than normal. The liquid metal ran smoothly, highly fluid, pushing its way into the finest details of the mold. Its high density and relatively low metallostatic pressure meant that the flow of metal remained calm and focused, creating a single central stream that allowed the mold to fill up with limited turbulence or splashing. The three gates at the top did not fill up simultaneously as in the bronze cast, but provided a single route in for the metal and two (at least partial) routes out for the gasses, increasing the mold's ability to "breathe." The video revealed what could be expressed as a gentle and well-ordered transition in the filling of the void: a central well of

Fig. 4
Lizard cast in lead-tin alloy by Andrew Lacey, following the process described in Ms. Fr. 640, fols. 124v, 125r, and 133r. Here the results of the technique using wax balls at the ends of the toes is shown. Photo: Siân Lewis © 2021 Lacey Lewis (CC BY-NC-SA).

metal formed in the base of the mold, first filling upward into the body of the lizard then pushing outward through the vents. As the metal cooled, a substantial amount of liquid metal was sucked under pressure into the larger parts of the mold (such as the belly of the lizard), reducing any contraction in the resultant cast. Additionally, by following the author-practitioner's advice in placing small balls of wax at the ends of the toes (see fig. 3), the metal was allowed to pass just beyond the thinnest part of the lizard, where it would have otherwise congealed (fig. 4). Ultimately, although this experiment was less dramatic than the bronze casting, it provided insight into the logic of the author-practitioner's infrastructural design and instructions to heat the mold and metal much hotter than would be considered customary today.

Conclusion

The numerous descriptions in the manuscript clearly indicate that the author-practitioner had a deep practical knowledge of how metals moved and reacted in their molten states. Until methods like those described here enabled us to produce videos of the unseen spaces inside the mold, that knowledge had to be gathered from phenomena visible outside the mold, for example, the movement of molten metal when it is stirred or the revealing splashes that escape the mold. Additionally, the resultant casts provided a constant feedback loop in this active balancing of material properties and theoretical projections, helping to guide and refine each new experiment. Such thinking through aspects of metallic flow through the making of molds is an attempt to see what cannot be seen and, in turn, control it.

In the sixteenth century, many realms of study attempted to lay bare the unseen mechanisms and causes of things: in medicine, anatomies increasingly made visible the unseen interior spaces of the body; machine books illustrated the workings of internal gears; and in natural philosophy, a search for hidden or "occult" mechanisms replaced an elaboration of Aristotelian causes. At the same time, artist-theorists like Leonardo da Vinci (1452–1519) and Albrecht Dürer (1471–1528) proclaimed that art made visible what in the natural world was invisible. Long before the sixteenth century, however, the practices of founding and casting always necessitated an investigation of the unseen by thinking and working through molds.

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Andrew Lacey and Pamela H. Smith

Andrew Lacey operates his own studio-foundry in rural Devon and Wales in the United Kingdom. He is an artist, archaeometallurgist, and explorer of historical bronze culture.

Pamela H. Smith is Seth Low Professor of History at Columbia University, New York, and founding director of the Center for Science and Society and the Making and Knowing Project at the university.

1 A critical edition of this manuscript, with a full description of the manuscript and its genesis in Toulouse, France, as well as the many aspects of casting and metalworking that it treats, was published as *Secrets of Craft and Nature in Renaissance France: A Digital Critical Edition and English Translation of BnF Ms. Fr. 640*, ed. Making and Knowing Project et al. (New York: Making and Knowing Project, 2020), https://edition640.makingandknowing.org. For the writing of this article, the authors thank Siân Lewis for her crucial contributions in filming and thinking.
2 Theophilus, *On Divers Arts: The Foremost Medieval Treatise on Painting, Glassmaking and Metalwork*, trans. John G. Hawthorne and Cyril Stanley Smith (New York: Dover, 1979), 174.
3 Vannoccio Biringuccio, *The Pirotechnia of Vannoccio Biringuccio*, trans. and ed. Cyril Stanley Smith and Martha Teach Gnudi (1540; New York: Dover, 1990), 213–14.
4 Bibliothèque nationale de France, Paris, Ms. Fr. 640, ca. 1580s, fol. 131v.
5 On the preparatory stages of catching and feeding the animals, see Béla Demeter, "Mr Toad's Wild Ride: From Bestiary to Shop Manual," in Making and Knowing Project et al., *Secrets of Craft and Nature in Renaissance France*, https://edition640.makingandknowing.org/#/essays/ann_500_ad_20.
6 In particular, see Ms. Fr. 640, fols. 68–92, 106–65, and 169–70.
7 See Ms. Fr. 640, fol. 106r; and Emily Boyd, Jef Palframan, and Pamela H. Smith, "Making Gold Run for Casting," in Making and Knowing Project et al., *Secrets of Craft and Nature in Renaissance France*, https://edition640.makingandknowing.org/#/essays/ann_505_ad_20.
8 Ms. Fr. 640, fols. 154v and 136v.
9 Yijun Wang and Pamela H. Smith, "Fat, Lean, Sweet, Sour: Sand of Ox Bone and Rock Salt," in Making and Knowing Project et al., *Secrets of Craft and Nature in Renaissance France*, https://edition640.makingandknowing.org/#/essays/ann_012_fa_14.
10 Ms. Fr. 640, fols. 137r, 72v, and 124v.
11 Ibid., fols. 124v and 129v.
12 For extant sixteenth-century objects on which traces of this process are visible, see Pamela H.

Smith, “Lifecasting in Ms. Fr. 640,” in Making and Knowing Project et al., *Secrets of Craft and Nature in Renaissance France*, https://edition640.makingandknowing.org/#/essays/ann_511_ad_20; and Pamela H. Smith and Tonny Beentjes, “Nature and Art, Making and Knowing: Reconstructing Sixteenth-Century Life-Casting Techniques,” *Renaissance Quarterly* 63, no. 1 (Spring 2010): 128–79, esp. 153, 157.
13 Ms. Fr. 640, fol. 124v.
14 Ibid., fol. 125r.
15 Ibid., fol. 124v
16 Ibid., fol. 91v.
17 Ibid., fol. 133r.
18 For more on mold infrastructure construction in Ms. Fr. 640, see Giulia Chiostrini and Jef Palframan, “Molding a Rose,” in Making and Knowing Project et al., *Secrets of Craft and Nature in Renaissance France*, https://edition640.makingandknowing.org/#/essays/ann_022_sp_15; and Shiye Fu, Zhiqi Zhang, and Pamela H. Smith, “Molding Grasshoppers and Things Too Thin,” in Making and Knowing Project et al., *Secrets of Craft and Nature in Renaissance France*, https://edition640.makingandknowing.org/#/essays/ann_013_sp_15.
19 Andrew Lacey and Siân Lewis, “In Pursuit of Magic,” in Making and Knowing Project et al., *Secrets of Craft and Nature in Renaissance France*, https://edition640.makingandknowing.org/#/essays/ann_501_ad_20.
20 Ms. Fr. 640, fol. 125r.
21 For the X-ray of bronze pour into the lizard life-cast, see Andrew Lacey and Siân Lewis, “Imaging the Invisible,” 2015, https://vimeo.com/446827092. © 2021 Lacey Lewis (CC BY-NC-SA).
22 Ms. Fr. 640, fol. 82v.
23 See note 11 above.
24 For the glass lizard mold experiment, see Andrew Lacey and Siân Lewis, “Lizard Glass Mold Experiment,” 2019, https://vimeo.com/514271917/ccfecb6f54. © 2021 Lacey Lewis (CC BY-NC-SA).