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The Metals' Family Tree and Their Separate Branches: an Experiential Journey

Abstract

Metals have been integral to people's lives for several millennia. We interact with them daily in many forms to fulfil a wide range of needs, from food preparation or elaboration of attire, to architectural components or means of transportation. We take for granted that one material meets these distinct challenges, but discovering metal's versatility has only been achievable through long-term engagement over a period of millennia. This enabled craftspeople to learn and understand their special characteristics, or properties, which both facilitate and constrain usage, with each metal having its own unique combination of properties. Due to this, craftspeople frequently employ multiple metals for a single artefact, melding together a desired package of properties. The significant differences between the metals and their recurrent use in combination thus calls for an intra-cross-craft approach.

Past metal production can only be fully understood by comprehending these properties. This knowledge comprises elements that can be transmitted discursively, but also those that can only be transmitted non-discursively, the latter being impossible to communicate in full without direct experience, which can be difficult to acquire. This paper proposes methods through which such direct experience of the properties of metals can be obtained, by inviting readers to participate in simple experiential activities using common household items. These properties are then discussed in an intra-cross-craft setting, using case studies to demonstrate how and why different metals are used together and the implications of these technical practices.

Keywords: metal, metal properties, metal production, intra-cross-craft, experiential, non-discursive knowledge transmission

Introduction

You are about to embark on a journey that explores the differing properties of metals through hands-on experience, which is designed to provide a taste of how craftspeople learn to work with metal by their acquisition of knowledge, both discursively, but especially non-discursively. Therefore, before settling down comfortably to read this paper, we advise you to have to hand as many of the following items as possible: a blunt pencil topped with an eraser, thick aluminium foil, a piece of cardboard, scissors, two stainless steel teaspoons, an empty can, a plastic beaker or old mug, a piece of paper, a collection of coins (both silver and copper if possible), a pen knife, a metal paper clip, a spring-loaded ballpoint pen, sellotape, a lighter or candle+matches, a pair of glasses, a weak acid (such as a fizzy soft drink, like lemonade or cola, vinegar, or lemon juice) mixed with a little table salt, some chocolate wrapped in foil and finally, something that can be used to make a soft surface (old newspaper, piece of felt, etc.).

Metals are all around us. We take for granted their special characteristics that contribute to the environment in which we live. Throughout the majority of history and prehistory, the family of metals have been an intriguing and practical part of daily life for human families. Despite this, if you asked a typical person what their definition of metal would be, chances are the answers you would receive would resemble "shiny, hard, heavy, light, strong, stiff, bendable material". Metals, therefore, seem inherently contradictory: hard but flexible, strong but fragile. Metals are also constantly changing, through their interaction with their environment. Yet all of this is due to specific characteristics, or properties, that belong to the metal family.

Understanding these properties is vital to the successful production of objects that incorporate metal. The characteristics of metal can both help and hinder the design and manufacture of a desired artefact, and they guide every step of the decision-making process. Any craftsperson, past or present, must not only understand these properties of metals, but also learn how to read, respond to, and work with them for every single individual piece of metal with which they interact. These skills of observation are vital for crafting artefacts and involve multiple senses; through engaging with metals, craftspeople are trained to look for certain signs, to feel and to hear the metal, in order to achieve their desired outcome.[1] Any discussion of metal-crafting in past societies is then, by definition, situated in the realm of sensory archaeology.[2]

Moreover, any discussion of metal-crafting and the use of metals in past societies must, ultimately, rest upon these properties of metal;[3] even sociopolitical- or symbolic-centred debates are founded on them. It has been posited, for instance, that the immutability of gold can help explain its attractiveness and the development of certain specific symbolic associations, such as its links to the divine.[4] The fact that pure gold does not tarnish is a distinctive characteristic of this metal, noticeably distinguishing it from other metals such as silver or iron, and is due to one special property that it shares with few other elements: exceptionally low chemical reactivity to its environment. However, there is little to no reason why archaeologists, along with the majority of the population, need to think about these properties of metals on a day-to-day basis, because we usually encounter such objects after they are finished, in other words after all the production decision-making is complete. We express no surprise that the material used to create the skin of an aircraft, aluminium, also finds a use in the kitchen as a food-wrapping solution; such choices of which metal to use are presented to us as self-evident, when they in fact emanate from the millennia-long engagement between human communities and the family of metals.

Given that metal-crafting in particular, both as a sole focus and in cross-craft studies,[5] has remained an important topic of study for archaeologists across many decades, awareness of these properties of metals has instead been acquired by individual specialists, to a varying degree, through dedicated material science textbooks,[6] ancient technology publications,[7] and experimental[8] and experiential[9] archaeology. The special significance of

[1] Kuijpers 2015.

[2] See Skeates, Day 2020 for a recent overview of sensory archaeology as a discipline and what this perspective can achieve, particularly by moving beyond the Western model of the five senses.

[3] This paper concentrates on the importance of the differing properties of metal for secondary metalworking, *i.e.* the manufacture of metal artefacts (metal-crafting), rather than primary metalworking, the obtaining of metal. Of course, the latter is also significantly influenced by the differing properties of metal, especially their degree of reactivity with their environment.

[4] For example, Betz 1995, 19; Whittaker 2008, 94.

[5] For example Nosch 2016, although the majority of cross-craft studies reference metal-crafting as an inspiration for other crafts, rather than exploring the impact of cross-craft interaction on metal-crafting itself.

[6] For example Brady *et al.* 2002; Cardarelli 2018. The majority of these are intended for general use, meaning that they concentrate on modern forms and uses of metal, but see, for example, Scott 2012; 2013; Notis 2014 for handbooks aimed at an archaeometallurgical audience only, as well as conservation handbooks, such as Selwyn 2004; Garside, Richardson 2021, which give information on a subset of metal properties relevant to their care in museum settings.

[7] For example Evely 1993; 2000; Hughes 1993. These publications collate information specifically useful to archaeometallurgists by concentrating on metals within past settings (sometimes referred to as 'heritage metals'), especially before the development of modern methods of metal-crafting that provide more precise control over their physical and chemical properties.

[8] There is no clear-cut boundary between experimental and experiential archaeology. However, the former tends to follow a more rigorous approach that employs standard elements of scientific methodology, such as control and isolation of variables, repetition of experiments, and integration of recording using high-quality equipment, to answer specific questions related to a technical process, whereas the latter more frequently assesses the role of people or other aspects that cannot be quantitatively measured, considering the process from a holistic perspective, and therefore the design of the experiments vary accordingly and usually follow a more relaxed protocol (Doonan, Dungworth 2013). In short, experiential archaeology is often a learning process, whereas experimental archaeology is more akin to testing. The two approaches are complementary. Experiential archaeology is often a prerequisite stage before further controlled experiments can be carried out, as it provides an opportunity to explore the range of factors relevant to a particular technical process. Recent examples of experimental archaeology investigating metal properties include Pingel 1995; Fang, McDonnell 2011.

[9] Unfortunately, experiential archaeometallurgy experiments are less likely to be published (Doonan, Dungworth 2013, 8). Recent publications that could be considered closer to experiential rather than experimental archaeology include Maragoudaki, Kavvouras 2012; Blackwell 2018.

experimental and experiential archaeology for obtaining and transmitting this knowledge has long been recognised and encouraged within archaeometallurgy, especially for primary metalworking (smelting).[10] Together, they fulfil a vital role, by allowing archaeologists to gain knowledge of the properties of metals that can only be transmitted non-discursively, information necessary for metal artefact production that cannot be communicated through words alone:[11] what exact shade of 'cherry-red' indicates that the metal is hot enough to work, or how much force is required for a 'single heavy blow'? It is worth noting that direct observation and participation also conveys and reinforces knowledge that can be transmitted discursively more effectively.[12]

Why, though, is it important for *archaeologists* to develop an understanding of the properties of metals? On the one hand, it could be argued that interdisciplinary research teams incorporating people with craft experience negates such a need, and indeed this solution is becoming increasingly widespread.[13] However, without this type of metallurgical knowledge, it is not plausible to begin designing meaningful research projects for certain forms of archaeology.[14] Moreover, lacking even a basic level of awareness, it is possible for interpretations to accidentally incorporate elementary mistakes that can have a significant bearing on the trajectory of future research. One of the most clear-cut examples stems from early experimental work on prehistoric bronze shields. The first in-depth study on this subject, published in 1962,[15] whilst a seminal and pioneering piece of research, also ingrained into the archaeological literature the belief that these bronze shields were essentially for show, and should be considered non-functional. It would come as no surprise to any smith that the thin, industrially produced copper sheet used for the shield replica was easily ravaged during these experimental tests, but they would be bemused as to why it was ever considered a suitable substitute material for the hammered bronze used in antiquity. Subsequent research using more accurate replicas[16] has demonstrated how misleading these early experiments were; however, it would take more than four decades for this interpretation to be challenged.

Furthermore, awareness of these properties and the role they play in the manufacture and use of metals opens novel research avenues that may lead archaeologists towards surprising interpretations and intriguing aspects that previously have been unintentionally overlooked. The need to employ metallurgical skill to fragment certain types of metal artefacts has relatively recently reached mainstream archaeological consciousness,[17] skill that is firmly founded on knowledge and familiarity with the properties of metals. This has considerable implications for our recognition and understanding of fragmentation as a deliberate action, replacing prior assumptions of a simple and perhaps even mindless task with carefully orchestrated scenes requiring the presence of specialists with expert knowledge and tools. Moreover, given how the senses act as a vital bridge between smiths and the properties of metals, sensory archaeology has an important role to play in explaining technological change, by providing a framework through which the vertical and horizontal transmission of knowledge can be more deeply explored.[18] This issue is especially poignant for ancient smithing, as many techniques routinely employed within modern metallurgy to exert direct control over the properties of metals, such as refining, were only slowly developed after many centuries of engagement with metals. The effectiveness of modern metallurgy is dependent upon its capacity to incorporate standardisation into every stage of the process, creating a streamlined *chaîne opératoire* with consistently replicable outcomes even at scale. This level of standardisation was simply impossible to achieve before the invention of these modern techniques, and has contributed to a radical change in societal perceptions of metals. Past smiths were, therefore, even more reliant upon their senses to successfully produce metal artefacts, especially since they did not have access to the sensitive measurement and analytical equipment which is equipment essential to modern metalworking today.

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[10] Various research institutions and organisations worldwide regularly encourage, facilitate, and publish the results of participation in experimental and experiential archaeometallurgy, including the Historical Metallurgical Society, EXARC, and the UCD Centre for Experimental Archaeology and Material Culture.

[11] As observed by Kuijpers (2015, 138), the terms 'discursive knowledge' and 'non-discursive knowledge' have acquired many additional implied meanings. This paper specifically uses these terms in relation to the transmission of knowledge.

[12] These two modes of communication should be seen as inherently complementary, and even, to a certain degree, symbiotic.

[13] See, for instance, the wide-ranging research on gold-based objects in the National Archaeological Museum at Athens produced in collaboration with Akis Goumas, e.g., Konstantinidi-Syvridi *et al.* 2014; 2019; 2020; 2024; Papadimitriou *et al.* 2016; 2021.

[14] Dolfini, Crellin 2016, 81.

[15] Coles 1962.

[16] Hermann *et al.* 2020: 18–19, 51–54.

[17] For example, Hoffman 1999.

[18] Although sensory and perceptual abilities are essentially pan-cultural (Hinde 1998, 176), smiths are trained not only to understand the implications of what they sense, but also to heighten their capability to perceive according to the criteria prioritised within their own metal-crafting tradition.

Despite the best intentions of individual researchers, developing a holistic and deep understanding of the properties of metals to produce meaningful archaeological research[19] is far from straightforward. Smiths gain this knowledge through repeated encounters with metal, an opportunity that few archaeometallurgists have the time or funding to embrace. Furthermore, the majority of experimental and, to a lesser extent, experiential archaeological projects aim to elucidate specific issues related to metal artefact production, rather than provide a general introduction to metal properties. The situation is even more difficult for archaeologists working chiefly outside archaeometallurgy who may, nevertheless, frequently consider metal artefacts in the context of cross-craft production or grave assemblages, as they could potentially have no or limited personal access or exposure to experimental and experiential archaeology.

Therefore, the aim of the first part of this paper is to attempt to impart some of the, especially non-discursively transmitted, knowledge vital to smithing, using a highly accessible form of experiential archaeology organised as a series of simple activities that involve basic household items. While the list of metal properties explored is not exhaustive and is mostly limited to those of greatest importance for metal-crafting in past societies, we hope that this guide will stimulate your curiosity to find out more.

The second part of this paper will delve more deeply into the way in which a smith thinks about the metal family and its properties, in particular by analysing why smiths choose to incorporate multiple metals into a single artefact through an intra-cross-craft perspective. Although the need for this approach within archaeometallurgy may initially appear counter-intuitive, it stems from the fact that each metal is best understood as a unique package of properties, due to the exact characteristics of its crystalline structure. Thus the knowledge, gestures, and equipment required to work with the different metals varies to the extent that the experience is akin to using completely different materials.[20] Since the combining of metals is one of the most powerful and common strategies through which a specific set of properties can be obtained, an intra-cross-craft approach is essential for understanding various aspects of decision-making by past craftspeople, including the ways in which metals can and cannot be used together. This will be discussed through several practical case studies that focus on the challenges and rewards of integrating multiple metals into a single artefact from an intra-cross-craft perspective.[21]

As this paper is based upon the experience of a single craftsperson, inevitably it is, to some extent, subjective. Therefore, we have purposefully focused here on general concepts with wide applicability that are, as far as possible, time agnostic. The individual properties of metals do not change over time, although continued human engagement has revealed more of them, as well as new techniques for controlling them. Nevertheless, some of the techniques discussed here, such as forging with a hammer,[22] will have been familiar to the early Neolithic pioneers of metallurgy, although the equipment and process have been refined and enhanced over the millennia.

Your guide during this journey is Dawn Hoffmann, a metal smith with over four decades of experience. Dawn works across an unusually wide range of metals: silver, gold, copper, brass, pewter, and bronze. She first studied with Fred Fenster and Eleanor Moty at the University of Wisconsin, Madison, during which time she also completed an independent study constructing a Mozart-era horn. This led to her being apprenticed to and working for a maker of French horns, Walter Lawson, for a number of years. She has continued to study and grow as a smith through intensive research, and hands-on learning through workshops and demonstrations given by blacksmithing guild meetings, conferences, and metal-smithing workshops run by various art/craft schools. Dawn feels that by producing beautiful utilitarian objects, mainly flatware (plates, *etc*.) and hollow-ware (jugs, bowls, *etc*.) as well as other household items, they have the presence to elevate the mundane: she aims to make practical, functional designs that speak with grace. One of her pieces, a sterling-silver punch bowl and ladle, forms part of the 1994 White House collection housed at the National Archives and/or Clinton Library. She is interested in replicating the practices in use from the Medieval and Early Modern Period through into the 18th century in North America and Europe, and how they were intertwined. Dawn is also a bookbinder, printmaker, and papermaker, and is working on a project to reproduce replicas of historical book furniture, as

[19] Kuijpers 2015, 138–139.

[20] Aulsebrook 2022, 100–101.

[21] This paper is not intended to provide a technical overview of metal artefact production. For further reading on this subject see, for example, Clarke 2013; Evely 1993; 2000; Fregni 2014; Untracht 1968. The number of citations within the remainder of this paper has also been kept to a minimum, to reflect the fact that the majority of the information discussed here has been accumulated by Dawn through her own personal engagement with metals and the world of metalworking, and contains a significant quantity of what is usually characterised as non-discursively transmitted knowledge.

well as to create original designs based on the ones held at the Folger Shakespeare Library,[23] and on books in the collections of the Library of Congress and the Dibner Library (part of the Smithsonian) both in Washington, DC. Metal fragments like these were also found in a well at Jamestown, in Virginia. As well as making metal artefacts, Dawn is a teaching artist and provides demonstrations, aimed at a wide range of audiences at various public events held at historical locations and arts venues, and public and non-public schools, to promote understanding of traditional craft techniques and their continuing relevance to the modern world.[24]

Part One: an Experiential Guide to the Properties of Metals

We welcome you to the first part of this paper, which provides an experiential exploration of the properties of metals. Treat this section as though you are present at a craft demonstration; it is not necessary for you to try all of these activities, but the more you can engage with, the more opportunities you will have to see, feel, and hear for yourself how metals function as materials. Please note, all the measurements used below are approximate, and there is no reason for you to bring along a ruler! As the purpose of this section is to shine light on the non-discursively transmitted knowledge necessary for metal artefact production in the archaeological past, it will concentrate on the properties that are most important for manufacturing metal objects, especially before the advent of modern machine techniques.

Malleability

Required items: a blunt pencil topped with an eraser, a spring-loaded ballpoint pen, a collection of coins (both silver and copper if possible), some chocolate wrapped in foil, thick aluminium foil, sellotape, scissors (or pen knife), something that can be used to make a soft surface (old newspaper, piece of felt, etc.), two stainless steel teaspoons, a piece of cardboard, and a piece of paper.

Let us begin by picking up the pencil and carefully looking at the metal ferrule that surrounds the eraser. Note the thinness of the metal and the dimples and lines incised in it that hold the eraser in place. Next dissemble the pen, and consider the spring that forms a fundamental part of the mechanism: its shape and again, the thinness of the metal. Do the same with the coins; take a moment to think about their design, if you can feel the shape of the motif with your fingers or perhaps any ridges around their exteriors. It is astonishing that one type of material can take all these different forms, and yet we take this for granted. Malleability, the willingness of metal to be formed into new shapes, is perhaps the most exciting, and certainly one of the most useful, properties of the metal family tree. The extreme malleability of certain metals, like gold and aluminium, make it possible to stretch them out very thinly into foils, to one-tenth of a micrometer (0.1 μm) in the case of gold. This requires hammering, or more recently rolling, the metal many many times. Unwrap the chocolate and note the thinness of the foil wrapper, and how responsive it is to pressure, making it easy to transform it into new forms to suit any chocolate shapes without tearing.[25]

The ability to shape metal in this way has been exploited not only to create different shapes but also to decorate artefacts. Embossing is one popular method, where the metal is worked from both the front (chasing) and the back (repoussé) to create relief decoration (Fig. 1). To have a go at embossing yourself, you will need a 5 x 5 cm square of aluminium foil, a soft surface, a pen (retracted) and a blunt pencil. First, lay your foil on top of the soft surface, and experiment with using the pen and pencil (both ends) as tools to press the foil down into the soft surface. Try applying different pressures. Then, starting from the centre, use one of your tools to create a depressed circle, at least 2 cm in diameter. Aim to press gently, but consistently, and repeat multiple times to create depth without ripping the foil. Now turn the foil over. You should have a protruding circle. You can better define its edge by running your tool around its perimeter, pushing the metal back the other way. You can also add extra details, like line-and-dot filler decoration, by pushing the metal from the front.

The ability of metals to be formed into wire (Fig. 2), that is their willingness to be transformed through tensile stress (being pulled) rather than compressive stress (being squashed), is often referred to as ductility. Making the pen spring required a metal that is both ductile (to make the wire) and malleable (to form the wire into a spring).

Not all metals are so malleable; to change the form of iron or steels, for instance, the metal must be heated. The glow emitted by the metal indicates its temperature. Steel must be heated until it is yellow-orange (roughly

[22] Martin 2023, 20–24.

[23] The online catalogue of their book bindings and furniture can be found here: https://luna.folger.edu/luna/servlet/BINDINGS~1~1 (accessed 21/10/2024).

[24] More examples of Dawn's work in various media can be found at: https://dawnartdesign.com/ (accessed 21/10/2024).

[25] This property is the foundation of gilding, which in prehistory means the covering of artefacts with hammered metal foil, as

Fig. 1. A, B – adding chasing to a repoussé design, with pitch bowl supporting the work, using a hardened steel tool and metal surface; C – wooden and steel dapping blocks with punches, the resulting pieces are shown on the left-hand-side of the photo (photo by Kent Heimer/Dawn Hoffmann).

Fig. 2. A – drawing wire through a drawplate; B – various sizes of supporting T-stakes, mushroom stakes, wooden, steel and urethane forming blocks; C – a selection of various sizes and weights of hammers (all based on the traditional forging hammer with a cross peen and a round-faced hammer face); D – anvil for cold forging non-ferrous metals, samples show pattern and stages of making a spoon (photo by Kent Heimer/Dawn Hoffmann).

Fig. 3. A – hot forging iron at yellow-orange heat; B – iron in the coal fire and on the anvil before forging; C – cold forging silver using the cross peen face of the same type and weight of forging hammer to spread the metal (note the shinier anvil); D – two stages of raising a copper sheet over a T-stake using a cross peen raising hammer (photo by Kent Heimer/Dawn Hoffmann).

1100–1250 °C) before it is possible to hammer it into shape (Fig. 3). Hotter temperatures (white-yellow or even white-hot) increase its malleability, and pass into the range required for welding (see below).

Forging is the general term used to describe changing the length, width, or thickness of the metal being worked, which is usually received by the smith in the form of a standardised shape (bars, rings, *etc*.).[26] Sinking is when the metal sheet is stretched downwards into a new shape, whereas raising (Fig. 3) uses compression stress to change the direction of the angle of the metal (from a flat sheet into a bowl form, for example). Using these techniques, the scale and type of work can range from making a tiny rivet to raising a bowl or teapot, or from forging a gate to making its hinge.

You can have a quick experiment with forging, using some aluminium foil, two spoons and a piece of cardboard. Cut out a 5 x 5 cm piece of foil; if you want to be able to compare the before and after effects, carefully trace around it on a piece of paper. One of your spoons will be the anvil, laid on the cardboard with the back uppermost (you might want to tape it in place), the other is your 'hammer', which you will use with the back facing downwards, so that the foil will be squashed between the two convex surfaces. Starting about 1 cm away from the point and working towards it, hammer the metal so that you stretch it towards the point. It will be noisy! Try to take care not to rip the foil. Of course, with such a thin piece of metal the results will not be radical, but if, after trying this at all four corners you then compare the foil to your original drawing, you should be able to see a slight bulge at each of them.

You can try out sinking as well, using some cardboard, a spoon and some aluminium foil. Cut out a 5 x 5 cm piece of cardboard and cut a 2 x 2 cm hole in the centre. Make two more of these, stack them so that the holes align and tape them together. Cut a 5 x 5 cm piece of aluminium foil and place on top, then securely tape it down around the edges. Start pressing the foil down into the central hole with the back of the spoon, using steady pressure to slowly stretch the metal downwards into the hole. You should end up with a slight bowl shape. This technique is often used to begin the manufacture of a hammered bowl or other hollow-ware products.

As you have experienced, when forming metals in this way, there always needs to be some kind of support underneath the material in order to prevent it from collapsing, and to squash it in-between the hammer and the supporting tool. Anvils take many forms, from the well-known blacksmith-type anvil to a silversmith's T-stake or mushroom stake, or a tinsmith's bick-iron or edge-tool roller (Fig. 2). Depending on the metal being worked, the thickness and hardness of the metal, and the amount of movement required by the craftsperson, the supporting tools can be made of many materials, steel tools being the most common nowadays (hardened and non-hardened steel), but also wooden hollowed-out forms, hard plastics, chaser's pitch (pine rosin, tar, plaster, or brick dust and oil-based supporting material), antler or bone, and various clays (Fig. 1). Hammers, too, take many forms, usually based upon two typical faces: one

opposed to the much thinner gold leaf employed today, as attested at the Chalcolithic Varna cemetery (Renfrew 1986, 149).

[26] See, for example, the wide range of semi-products (raw iron ingot forms) known from prehistoric Europe, the shapes of which were used to indicate the quality of the metal (Berranger,

a variant of the rounded flat face, and the other a rectangular face, known as a cross peen (Fig. 2). The shape, size, degree of roundness, edge profile, and weight greatly vary the impact the hammer has on the metal, and how the metal compresses and moves beneath the repeated blows.

Strength, Hardness, and Brittleness

Required items: a blunt pencil topped with an eraser, thick aluminium foil, two stainless steel teaspoons, a pen knife, a piece of paper, a metal paper clip, and a collection of coins (both silver and copper if possible).

Two other exceptionally important properties of the metal family tree are high tensile strength and hardness. The majority of metals are much stronger and harder than many other common materials; they better resist forces that could pull them apart and are less likely to deform upon impact. This provides them with the toughness and durability needed to use them for so many different purposes, from tool heads to suspension bridges. You can test the strength of metals by using one end of the paper clip to poke holes in the paper; even though the wire of the paper clip is very thin, it can perforate the paper without bending.

However, increased hardness comes with a cost because harder metals are generally more brittle. This is one of the most influential reasons as to why different metals are suitable for different tasks. Test out the relative hardness of the collection of metal objects you have gathered by using them to scratch each other. Which metals were more readily marked? These are softer metals. Your steel penknife should be able to mark all the other objects, whilst remaining unmarked itself. The decorative technique of engraving relies on these differences in hardness (Fig. 4).

Resistance to abrasion is important for many applications in which metals are involved, such as tools for filing or ball bearings used to ensure the continued smooth operation of a mechanism. Nevertheless, the ability to abrade softer metals has been exploited for various purposes, one of which you can try for yourself. First, rub the edge of a silver coin over a sheet of paper and observe if there are any markings (most likely there will not be due to the smoothness of the paper). Now, rub the pencil eraser on the piece of paper, leaving the eraser crumbs in place. Try rubbing the silver coin edge over these crumbs onto the paper. You should be able to leave a mark on the paper more easily this way. Before the invention of the graphite pencil, thin lead, copper, tin, and silver rods, so called 'metalpoint' styli, were used for drawing. The paper or substrate had to be treated beforehand to create a rough surface which abraded the metal to leave a trail. This treatment was a painted-on ground containing a mineral grit. The grit in the eraser created a little bit of roughage that was enough to abrade the edge of the coin in a similar way to the painted-on ground used for metalpoint substrates.[27]

Now take the paper clip, open up its first joint and keep bending that small sliver of wire back and forth until it breaks. If you look closely at the end of the paper clip, you will see the crystalline structure of the metal at this break point. What happened? Why does the paper clip initially bend, but eventually snap? You have just witnessed 'work hardening' in practice. The crystalline structure of the metal has been stretched and compressed beyond its cohesive capability. The individual metal grains are no longer able to slip past each other with the same ease, due to faults accumulating in the structure. Work hardening always takes place when the crystalline structure is distorted; for example when we change the shape of a piece of metal through hammering, rolling, or die-forming. Due to the trade-off between hardness and strength discussed above, the loss of malleability through repeated bending of the paper clip causes it to become increasingly brittle until it snaps. You can test the increase in hardness by scratching your coins once again with the now work-hardened paper clip, to see if this increases the ease and extent to which you can mark the coins.

Work hardening can be beneficial and is often incorporated into the *chaîne opératoire* of certain objects deliberately. Toughening tool edges, whether on a knife blade or a snowplough, is one example;[28] another is using stamping to produce a coin or spoon, so that it does not bend readily and keeps its shape. If you pick up the pen knife and whittle the lead end of the pencil, you are taking advantage of a work-hardened tool edge. Try to bend the largest coin in your collection with your bare hands; what you are experiencing now is the power of work hardening and the associated loss of malleability. For iron and steel, hardness can also be increased through a special process of heating and rapid cooling (quenching), with a further cycle of heating (tempering) used to scale back the associated gain in brittleness without compromising the additional hardness. Like work hardening, this can be selectively applied.

Fluzin 2012). As mentioned above, forging metal to change its shape is one of the earliest known techniques.

[27] Although it has been suggested that the reason why modern pencil cores are still known as 'leads' is because the first graphite deposits were mistaken for lead metal, it is also plausible that this name came about because the pencil directly replaced the most widely used form of metalpoint styli, which were made of lead.

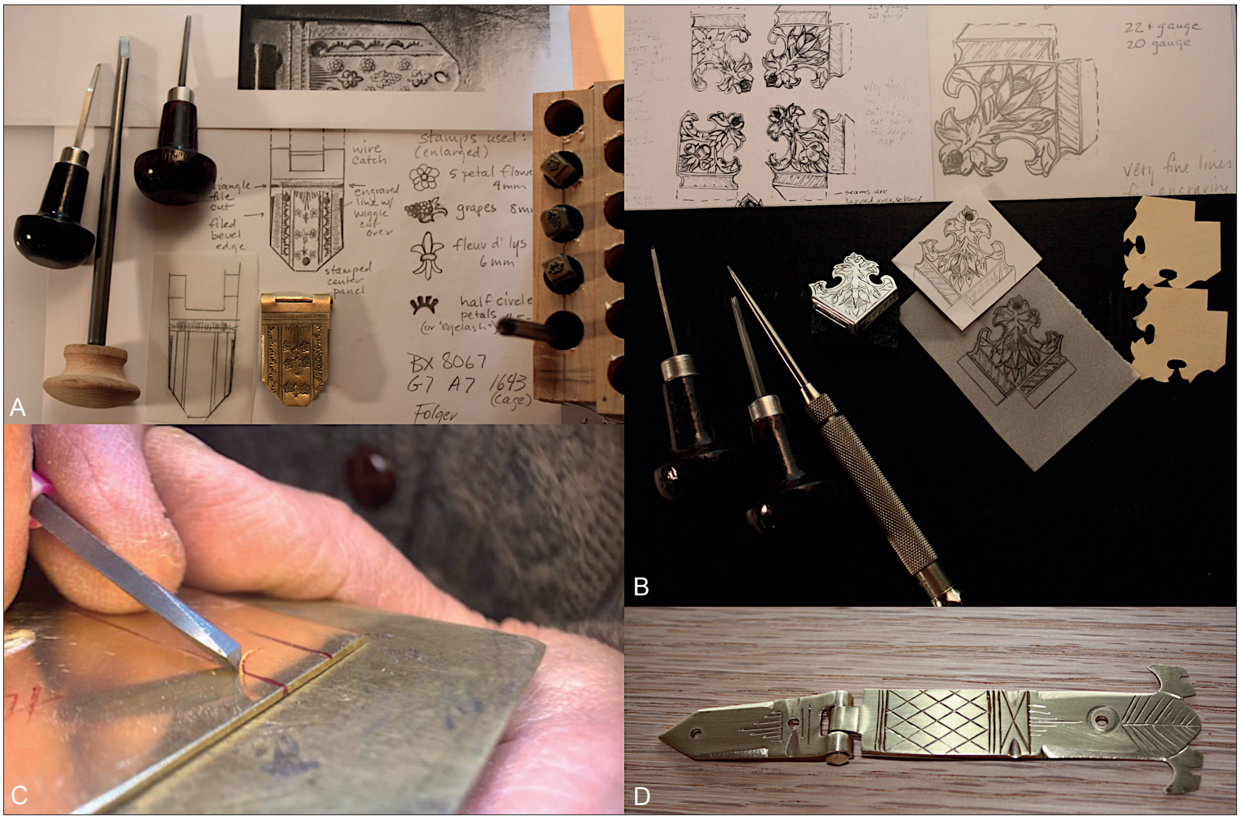

Fig. 4. A, B – patterns and tools used to scribe and engrave book furniture, with examples of formed and engraved work; C – close-up of engraving a line; D – common design of traditional book furniture forged at widest part, filed and engraved, hinge section formed and bent, stem riveted at both ends to prevent dislodgement in use (photo by Kent Heimer/Dawn Hoffmann).

Sometimes, though, work-hardening can be undesirable. The increasing brittleness of the metal can threaten the successful production of an object. However, malleability can be restored through a process known as 'annealing'. Annealing involves heating up a metal object to a temperature that enables the crystalline structure to reset within the new shape.[29]

Certain metals, like lead, tin, and related alloys (pewter, Britannia metal), never work harden at room temperature. Their melting points are close enough to room temperature so that distortions to their crystalline structure can be healed without a smith needing to initiate a cycle of annealing. Furthermore, these metals soften, *i.e.* become more malleable, by being worked. This is because of the way in which their crystal faces are formed, with easily displaced bonds enabling increased slippage between individual crystals (strain softening). These metals, therefore, are easy to work yet stay soft, and will continue deforming during use or further working.

Finally, the deformation/shaping of metals also helps increase their resistance to bending. This is evident on the thin ferrule that attaches the eraser onto the pencil; most likely there are ribbed grooves or another form of texture, as well as indentations. This textured surface is not just for decoration, as the changes in the direction of the thin metal sheet strengthens its resistance to bending (in limited ways) and helps it to hold the elements of the pencil in place.

Lustre and Smoothness

Required items: thick aluminium foil.

Pick up some of the aluminium foil and admire the way in which it reflects light. Shine, or lustre, is one of the most obvious visual properties of the metal family tree. All metals can be brought to a shiny polish; however, the method for doing this varies. Iron requires grittier, harder sanding or scrubbing to achieve a smooth finish

[28] As seen on archaeological examples through metallographic analyses; see, *e.g.*, Mödlinger, Trebsche 2021.

[29] Annealing leaves characteristic traces in the microstructure (annealing twins), which have also been observed in archaeological artefacts; see, *e.g.*, Mödlinger, Trebsche 2021.

and tougher polishing compounds because of its hardness, whereas softer metals often need very little scrubbing and require a soft polish compound. In the past, gold and silver would be finished by rubbing a soft pumice stone to smooth the surface and then were burnished with a polished hard stone (*e.g.*, agate or haematite) to achieve a shiny surface. Today they are more likely to be treated with sandpaper of coarser to finer grits, followed by a series of coarser to finer polishing compounds (using a buffing wheel) to achieve a shiny finish. Whilst certainly aesthetically pleasing, lustre has other uses and benefits as well. Mirrors are an obvious example.[30]

If you run your fingertips lightly over the aluminium foil, you can appreciate how smooth metals can be. This smoothness again can have uses and benefits beyond visual beauty; mechanisms, for example, rely upon having components with smooth surfaces, and damage to this smoothness can cause them to fail.

Reactivity: Oxidation and Patinas

Required items: a collection of coins (both silver and copper if possible), a plastic beaker or old mug, and a weak acid (such as a fizzy soft drink, like lemonade or cola, vinegar, or lemon juice) mixed with a little table salt.

Take a look at your collection of coins. Do specimens of the same denomination all look the same? Perhaps their colour is slightly different or some of them are more dull. What you are observing are the effects of oxidation and corrosion, caused by reactions between the metal and its environment, including air, water, soil, and various chemicals. Initially, this can cause discolouration of the surface and pitting, which compromises lustre and smoothness. However, some degree of reflectivity, on metals like copper and silver, is retained if the metal remains smooth enough. An example of this is the bronze roof on Dawn's workshop, which still brightly reflects the sun even though it is now brown from acid rain that has made a skin of corrosion, known as a patina, on the polished surfaces. Patinas can be produced intentionally, using chemicals to speed up the reaction, and these can be used decoratively to create interesting contrasts between shiny and dull surfaces or in colour.[31]

Over time, corrosion products can build up on the surface. These do not share the same properties as their parent metal. One of the most extreme examples is iron, which transforms from a greyish hard metal into rust, a reddish brittle substance. Indeed, as mentioned above, one reason why gold has been so valued over millennia is because of its inertness, meaning that it does not tarnish. Annealing also causes these reactions to speed up, because of the application of heat, but luckily there is a way to remove corrosion products from the surface and continue making an artefact: pickling.

You can test pickling yourself with an oxidised (dirty-looking) coin and weak acid of your choice (*i.e.*, a fizzy soft drink like coke or lemonade, lemon juice, or vinegar) mixed with a little table salt. Drop the coin and your acid into the plastic beaker/old mug, and leave for a few minutes before checking to see what has happened.

As well as being an essential part of annealing metals, pickling is also the concept that lies behind the etching of metals; acid is selectively applied to remove a small proportion of the surface, creating a decorative pattern or even a plate of text.

Heat: Conductivity and Resistance

Required items: a metal paper clip, a lighter or candle+matches and thick aluminium foil.

Metals are superb conductors of heat, making them the material of choice for thermal exchange, such as radiators and cookware. You can test the former yourself if you unfold the rest of the paper clip and carefully hold it in the flame of the lighter for a few moments. You can also do the same with a small piece of aluminium foil (*e.g.*, 5 cm x 2 cm) and a candle; very quickly you will see the metal visibly sag. Use pliers if you are worried about burning your fingers! Do not leave the metal in the flame too long, otherwise it will start to melt. If you do want to experience melting, it is better to use a thin strip of aluminium, and ensure you use pliers to hold the other end. You will see the metal sag, curl up into a ball and then drip.

The melting point, the temperature at which a solid will become a liquid, varies between every metal. The melting point of mercury is so low that it is liquid at room temperature. However, a number of metals have exceedingly high melting points, including gold (1064 °C), iron (1538 °C) and tungsten (3422 °C). This in itself can be a useful property; if you have a lighter, you can observe that the areas closest to the flame are made of metal, especially chosen to resist damage from such proximity to the heat source.

Conversely, the ability to melt metals can also be a beneficial property. Molten metal can be cast into shape

[30] For recent research into the production of mirrors, see Thomas 2024. For a case study of the societal impact of the introduction of metal mirrors on past societies, see Alvarez 2023.

using a mould, providing an alternative method through which metal artefacts can be made.[32] Broken and obsolete metal objects can be melted down and the material reused again.[33]

Sonority

Required items: stainless steel teaspoon, an empty can, a collection of coins (both silver and copper if possible).

Drop one of the spoons on a hard surface or a few of the coins together, and listen. Metals are sonorous: they make a sound when struck or otherwise vibrated. Now try tapping the empty can with the spoon. It should be possible to make a ringing noise. The quality of the sound varies according to the type of metal, its form, and the way in which it has been worked; metals clink, jingle, rattle, chime, crash, clank, tinkle, *etc*. Although obviously of great use for the manufacture of bells and musical instruments, this property is also significant to craftspeople. As you have experienced when trying out forging, the process of hammering metal is noisy. As the metal work hardens, the note produced by repeated blows to the metal changes. A smith can thus use the sound the metal is producing to gauge the degree of work hardening, and therefore when it is necessary for the metal to undergo a round of annealing to re-soften it. This occurs before any visible changes to the metal, like cracking, thereby enabling smiths to avoid damaging the objects they are making.

Integrating Properties

So far, this guide has focused upon the individual properties of metal that are of the greatest significance to craftspeople. Of course, this is by no means a comprehensive list, but there is no space here to enumerate every single one. Weight, for instance, influences the selection of aluminium to make airframes and lead to make fishing-net sinkers. The density of lead makes it an excellent choice for radioactive shielding. The main three magnetic metals, iron, cobalt, and nickel, are used for many purposes, from fridge decoration to MRI (magnetic resonance imaging) scanners. Metals are also good conductors of electricity and thus form the core of the electricity grid, from domestic copper wiring to power station transformers. Every time you switch on a light or charge your phone, you are taking advantage of the electrical conductivity of metals. There are hundreds of further examples that could be listed here.

Rarely is a particular metal chosen for a specific task based on one property alone; it is the combination of properties unique to each metal that drives the selection process. The metal used for the paper clip must, for example, be ductile enough to be drawn into a thin wire, and malleable enough to be formed into the shape of a clip, but strong enough to resist snapping even with repeated use, and hard enough to prevent deformation if dropped on the floor.

The range of applications for metals can, therefore, be significantly widened if two or more metals are used together. In this way, different properties can be integrated to create objects with characteristics that could not be replicated using a single metal. This is also the case for non-metal materials. Make a thorough examination of the pair of glasses or the ballpoint pen. Look at the role that each metal piece has and how these components are joined together to make the whole. To function properly, both of these objects have to be made of multiple types of metals and incorporate other materials. Hammers, with their wooden handles for comfort and hard steel heads, spoons, with their steel bodies for strength and heat-proof handles, a finger ring with a stone set into it, or a computer integrating metals, plastics, and silicates, are all examples of using multiple materials to mix and match desired properties. Pick up and consider again your pencil, with its graphite lead encased in a wooden barrel and its eraser ferrule made of metal. These are just a few daily examples that readily come to mind.

When those other materials are perishable, archaeologists can be confronted by metal artefacts that at first glance have no discernible use. Book furniture pieces are an excellent example of this problem; individual pieces have holes punched into them or are equipped with hinges, but they cannot function as a sieve or spoon, and are too small and lightweight to be a box or door hinge. Options only open up for exploration when you think about how these pieces might be used in conjunction with other media. The production of metal-based artefacts can, therefore, simultaneously be inter-cross-craft and intra-cross-craft.

There are two main ways in which metals can be combined with other metals. The first, joining, mimics the way in which metals interact with non-metal materials. The second, alloying, is specific to the metal family tree.

[31] See, for instance, the range of artificial patinas applied to Ancient Egyptian artefacts (Mohamed, Darweesh 2012).

[32] See Radivojević *et al*. 2021 for a discussion of the earliest known applications of casting.

[33] Contexts such as the Unexplored Mansion at Knossos, where broken artefacts were found in the vicinity of a hearth, provide archaeological evidence for metal recycling in past societies (Catling, Jones 1977, 57).

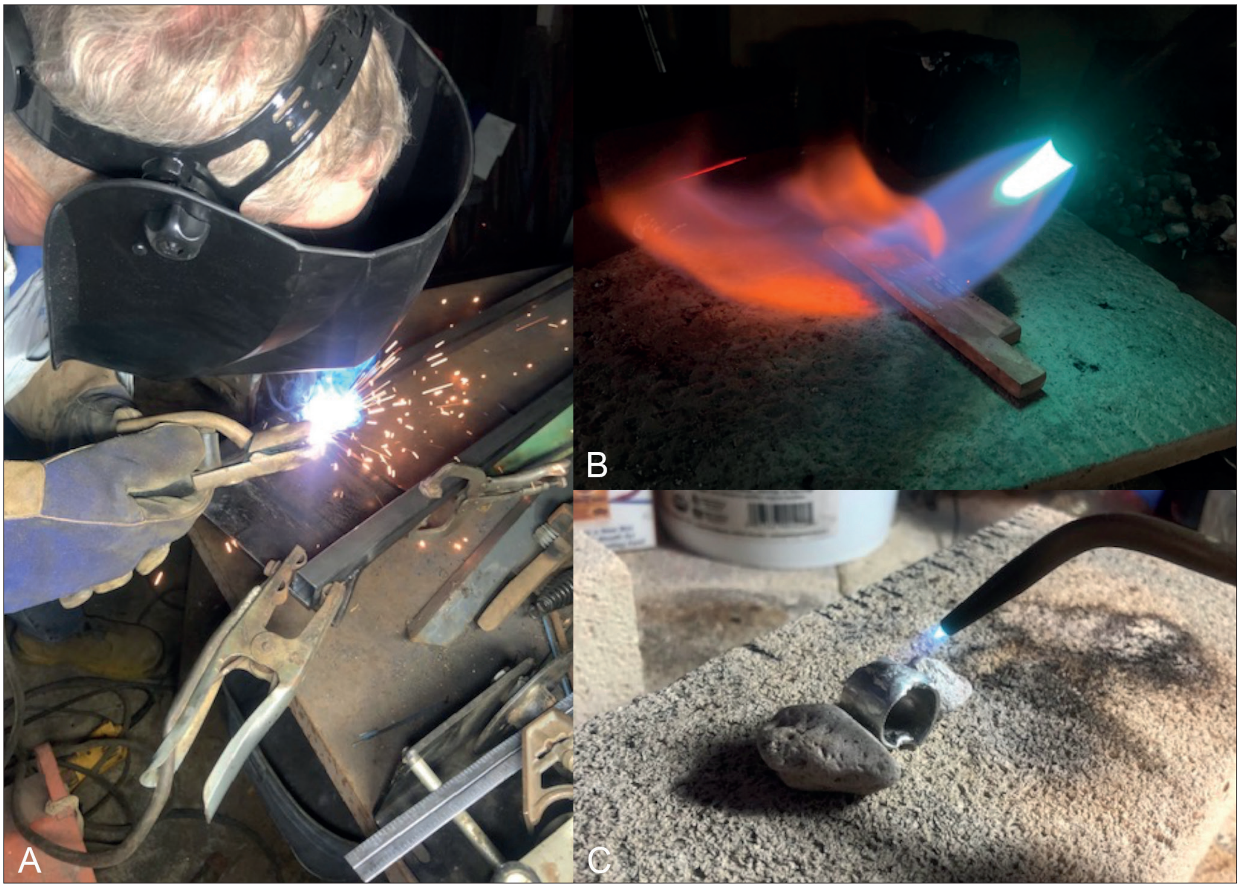

Fig. 5. A – Kent Heimer welding with an arc welder; B – brazing a piece of brass (note flame size); C – welding a piece of pewter with (a relatively cooler) tiny flame (photo by Kent Heimer/Dawn Hoffmann).

Joining

Required items: a blunt pencil topped with an eraser, a spring-loaded ballpoint pen, a pair of glasses, thick aluminium foil, scissors.

There are a variety of ways in which metals can be joined to each other and to non-metals: screws, nails, joints, welds, rivets, sockets, solders, *etc*. Your pencil ferrule, made of thin crimped sheet, is an example of how metal can be used to create a join between two non-metals. Some of these techniques, like nails, can be used for a wide variety of materials. Others, like soldering, can only be used to join metals to other metals. You will notice that some of these joining techniques, like nails, screws, and rivets, require an additional metal-based component.

The hot joining techniques, welding, brazing, and soldering (Fig. 5), take advantage of the property of metals to melt in order to create the join. These three terms refer to the temperature used during the joining process and, due to their varying melting points, this means different types of metals and alloys are used for the added joining materials. Welding makes the strongest bonds. When welding, the temperature used is hot enough to melt the welding rod and the pieces to be joined. This, of course, varies metal by metal. For pewter, the temperature for welding only needs to be 246 °C, but for steel, it needs to be much higher: 1760 °C. The welding rod is made out of the same material as the parent pieces. Whilst the temperature used for welding is situational, the temperature difference between brazing and soldering has a fixed definition. Brazing takes place at a temperature above 600 °C. The join cannot have any air gaps. The joining material (brazing compound) is an alloy that has some similarities to the parent pieces, but also contains metals that lower its melting point below that of the parent pieces. Therefore, only the brazing compound is melted. Soldering takes place at a temperature below 600 °C. Solder is primarily composed of metals with a low melting point, like lead or tin, and can be very different in composition to the parent pieces if used to join metals with a much higher melting point, like copper or silver. Solder, though, has the advantage that it can be used to patch gaps. Brazing and soldering are less risky techniques, because the danger of damaging the already-worked pieces whilst joining is much lower, but the joins they make are not as strong as welding.

You can have a go at making a rudimentary join yourself using two 5 x 5 cm pieces of aluminium foil. Make an 'L' shape along one edge on each of your pieces; the short leg should be quite shallow, between 0.25 cm and 0.5 cm. Hook the two short edges together with one facing upwards and the other downwards. Pressing sideways on the top piece will push both hooked folds together. This basic seam type is often used in tin smithing.

Alloying

Required items: stainless steel teaspoon, a collection of coins (both silver and copper if possible).

Another rather distinctive and important property of metals is their ability to be alloyed; elemental metals, like silver, copper, or iron, can be mixed with other metals or even, in the case of iron for example, other elements (in this case carbon to make steel) to form a new metal. In most cases, this new mixed metal will combine properties of its parent metals, sometimes simply augmenting or diminishing them, sometimes adding or removing desirable or undesirable properties.[34]

Take a look again at your collection of coins. The range of colours on display is well beyond the natural palette provided by pure metals. Alloys, as well as certain surface treatments, are used to create new colours, as well as to mimic more precious metals, like silver, through alloys of copper and nickel, for instance. Gold-coloured coinage includes brass (copper and zinc alloy) or bronze (copper alloyed with tin).

Now turn your attention to the stainless steel teaspoon. To function well, a teaspoon must stay corrosion-free despite being exposed to difficult environments, like being plunged into boiling water. Steel, itself an alloy of iron and carbon, is made more resistant to corrosion through the addition of zinc, chromium, nickel, and molybdenum. Hardening metals and making them less vulnerable to corrosion are two of the main reasons for using alloys. A finger ring of pure silver would be worn out much sooner than a similar cousin made with sterling silver; alloying the silver with copper to create sterling silver adds durability. Sterling silver, however, the same as pure silver, will still tarnish, and it is now being surpassed by the newest mainstream silver alloy, argentium: a modern tarnish-resistant silver alloy, which stays bright due to the addition of germanium. Gold also is alloyed to add hardness and durability. Copper is often alloyed with tin or zinc to make bronzes or brasses that can take wear and resist weathering to a greater extent than pure copper.

However, this does not mean that alloys are 'better than' pure metals. It is important to pick the correct metal for a specific task. Brasses can fatigue faster in some working conditions and do not necessarily transmit electrical impulses as well as pure copper. Pure gold, which would be too soft for most jewellery, can be used to make leaf and coatings that are more resistant to corrosion. A high-carbon steel may be too brittle and hard for certain tool usages that would be better served by a softer mild steel. There is a place for all of these variations.

Just as individual pure metals can be joined together to take advantage of their unique characteristics, so the same can happen for alloys. When making a modern axe-head, a soft mild steel may be used to form the outer part of the sandwich around an alloyed high-carbon steel. The high-carbon steel, the harder and more durable material, only needs to be exposed on the very edge of the axe-head to make the axe function well. Alone, the mild steel would not hold up to the cutting and splitting of wood. With the harder high-carbon steel sitting in-between the mild steel sides, it does a fine job of providing density and weight to the tool head. Alloying, therefore, acts as a method through which a particular package of properties can be fine-tuned for a certain purpose.

Summary

This marks the end of the experiential guide to the properties of metals. We hope that this brief set of basic activities has provided a useful glimpse of the vast landscape of both the discursively and non-discursively transmitted knowledge that surrounds smithing, which plays such an important role in learning to predict the behaviour of different metals during production. We have stressed how smithing, particularly in past societies, should be viewed as a multi-sensory engagement with each individual piece. This need to build a relationship in order to achieve a successful outcome may help explain why tradition and cult practice are just as relevant to the overall human-metal story as technical innovation and experimentation.[35]

It is time now to consider, from an intra-cross-craft perspective, how the different packages of properties represented by each type of metal relate to each other, and the impact this has on metal artefact production through actual case studies.

[34] It is possible that this practice of deliberately alloying two metals together (rather than using an alloy found in nature) dates back as far as *c.* 4650 BC (Radivojević *et al.* 2021, 21).

[35] Budd, Taylor 1995.

Part Two: Working with Multiple Metals

As has been discussed already, within the family of metalworking disciplines there are many similarities and overlaps. However, at the same time there are also enough differences between the metals, in terms of their properties, to warrant their own fabrication practices undertaken within individualised workshop settings. After the more general discussion of metal properties in the previous section of this paper, it is now time to consider how an understanding of these various characteristics can inform us of which materials, processes, and tools would be best-suited for the job at hand. Therefore, this section is built around following the thought and decision-making processes that underlay the manufacture of nine objects that Dawn has produced. These specific case studies, which cover both ferrous (iron-bearing) and non-ferrous metals, will demonstrate some of the parallel and contrasting working conditions required. The case studies comprise both replicas and private commissions.

As mentioned above, Dawn has an interest in the history of her craft, and often draws inspiration from the material culture of past societies. She produces all her pieces by hand, although making use of modern tools and facilities (bottled fuel torches, motorised buffing tools, *etc*.). Such technology brings many benefits, in particular decreasing the time and physical effort required, while increasing the degree of control over many critical procedures, like the application of heat. However, fundamentally the underlying processes (forging, soldering, *etc*.) are the same, even if the technique itself may have changed. Moreover, the properties of the metals themselves remain unaltered; our improved understanding of metals and technological progress may enable Dawn to reproduce certain archaeological artefacts in a different way, but her work is ultimately rooted in a millennia-old craft, and offers archaeologists another experiential source through which a fuller appreciation of the complexities of metals can be grasped.

As an artist as well as a smith, even though Dawn concentrates on the production of utilitarian artefacts, she has a greater degree of flexibility in terms of the design process that may not be applicable to the majority of past craftspeople. The possible exception to this is the category of specialists identified by Kuijpers as 'virtuosos' who, although rare, had an outsized impact on their craft, by exploring the limits of materials, creating original objects, often laden with ideological and political meaning, and using unconventional techniques.[36] Therefore, a general overview of her decision-making during the design process will still shine light on an aspect of metalworking of relevance to the study of past production, as well as providing insights into the range of additional constraints on smiths beyond those imposed by outside circumstances.

Decision-Making during the Design Process

When Dawn sets out to make a piece, her first thought is about its utility. Does it need to support weight in some way, or will it be under compression? It is crucial that the metals can physically do what is required of them in order for the object to function well. Already, based upon Dawn's extensive experience, the answers to these questions can start narrowing down the types of metals that can be used. Other things that she gives immediate consideration to is who will use it, and how and where will they use it. Scale is another important factor: what size does the piece need to be in order to perform well? Metals often have limits of performance depending on their thinness or thickness, which must be taken into account. She also thinks about the qualities she wants the piece to express: gracefulness, lightness, strength, sturdiness, openness, solidity, or a combination of these, or any of the many other possibilities. These considerations alone may be enough for her to whittle down the possible candidate metals, in terms of exact alloy mixes, to just a handful, identify how many different materials would be required, and how they would interact with each other. Even at this early stage, it is already important for Dawn to think about the finish, as each metal has its own distinctive type that presents advantages but also vulnerabilities. Will the piece be used predominantly indoors or outdoors (or both)? Its intended environment can impact the rate of oxidation and corrosion, as can many other factors that must be taken into account. Does the piece need to be food-safe? Will it be subject to much wear? Does the surface need to be decorated, or will the design be inherently visually satisfying or arresting enough that the form alone will carry the work? For the latter, perhaps counter-intuitively, simple shapes are often the hardest to execute well, as ensuring the correct flow of a line by hand can be challenging. Again, these factors can considerably narrow the range of favourable choices, and have a bearing on which materials are required and how they will interact with each other.

For Dawn, the process of translating the qualities she seeks into practical manufacturing choices requires inspiration, which she personally experiences as a lifting up of spirit: this process varies in tempo, sometimes requiring years of patient observation, and to her is analogous to

[36] Kuijpers 2018, 563.

watching the unfolding of a flower, petal by petal, as each element falls into place. Boundaries are not just set by the properties of the metals, but also restrictions on time, cost, tools, and the cultural expectations of clients, amongst many other factors.

Sometimes, Dawn has found that the design and methodology come together before working directly on the metal. Therefore, she has a full mental template of the likely process before she starts. In other situations, the work in progress seems to point out alternate ways to solve a problem of manufacture and the design is improved upon while the object is being made. Thus, the *chaîne opératoire* shifts during the process of manufacture. In certain cases, it is simply not clear whether a specific task is required until that moment is reached. For instance, if a piece has become really super work-hardened then it could begin cracking if left in a highly stressed state. This is particularly likely for brasses. The piece would need to be annealed, and perhaps gently worked over again in order to strike the right balance between hardness and stress to avoid deformation during use. Often, only after the piece is considered complete will it become apparent whether it requires additional work like this. Therefore, to achieve the best outcome, the exact *chaîne opératoire* used emerges through the relationship between the smith and the individual piece.[37]

Some metals can only withstand a certain quantity of working before they fail, so even the complexity of the design has a direct bearing on the choice of metals. Nowadays, there are a very wide range of alloys, each with a very well-understood specification of properties, from which smiths can select the most suitable type. As one moves further back in time, the range of different metals available decreases. We see past smiths creatively experimenting with metals, pushing to see what they were capable of and exploring new possibilities.[38] We also see them having to compromise, and work within the limitations of what was available to them at the time.

Choosing a Chaîne Opératoire

Fundamentally, each metal has its own specific repertoire of techniques. Although the underlying concept may be the same, with shared facilities, tools, and methods, details of the execution vary. Annealing is a good case. Both copper alloys and steel work harden, and thus require annealing. For copper alloys, this involves a separate process that has been described in detail above. For steel, annealing occurs when it is placed in the fire in preparation for the next round of hot-working, and pickling and/or quenching do not occur until the piece is finished.

Each metal has its own variant of how volume can be achieved. Many metals are now regularly spun on a lathe with varying degrees of depth, after first being annealed. The earliest known evidence for this technology is a Ptolemaic rock relief (c. 300 BC).[39] Silversmithing often works the entire continuous surface of the metal, changing its direction to form the desired shape. The same style of working is often employed for copper alloys. In contrast, forging bar stock to change its thickness, length, and direction, with multiple pieces added in, is the common production sequence applied to iron. Tin-smithing techniques create the volume and shape required by concentrating on the formation of edges and joints on pattern parts that are then fixed together to create the whole. Similarly, construction techniques use multiple pattern pieces, but a wider variety of joining methods: welding, riveting, folding, and soldering. The assembly sequence can be affected by which metals are involved when using heat for these joins. Those joins that use harder solders and brazing compounds need the most heat and must be worked first, otherwise already-completed joins that involve a solder or compound with a lower melting point may end up coming apart.

These unfinished brass dividers (Fig. 6), which have mortise-and-tenon riveted leg ends made of Damascus steel, combine blacksmithing and whitesmithing. Although the former term is familiar, and refers to the use of fire, 'whitesmithing' denotes a manufacturing process without fire, and relies upon using a file to provide the final shape to the metal. This, though, still entails a great deal of work: filing, checking the fit, filing again, checking from every angle; slow careful work until the smith is eventually satisfied with the result. Both the brass and the steel were whitesmithed in order to fit the two parts together. The process for making the Damascus steel could hardly be more different. It is made of multiple layers of a nickel-steel alloy and carbon steel, twisted to form the patterning. To achieve this, the layers were repeatedly cut and forge welded back together (at 1760 °C), and then forged back into a bar shape after twisting. Forge welding is all about heat and pressure, and the only added material is a flux to prevent oxidation and keep the joins clean. Steel was chosen for durability. It appears regularly in classic drafting/writing sets because of its hardness

[37] The rigid adherence by past craftspeople to a specific *chaîne opératoire*, despite substandard outcomes in terms of quality, may indicate limited knowledge of the range of available techniques or the prioritisation of another factor, *e.g.* time, standardisation, or tradition.

[38] Kuijpers 2018, 563.

[39] DeVries *et al*. 1980, 52.

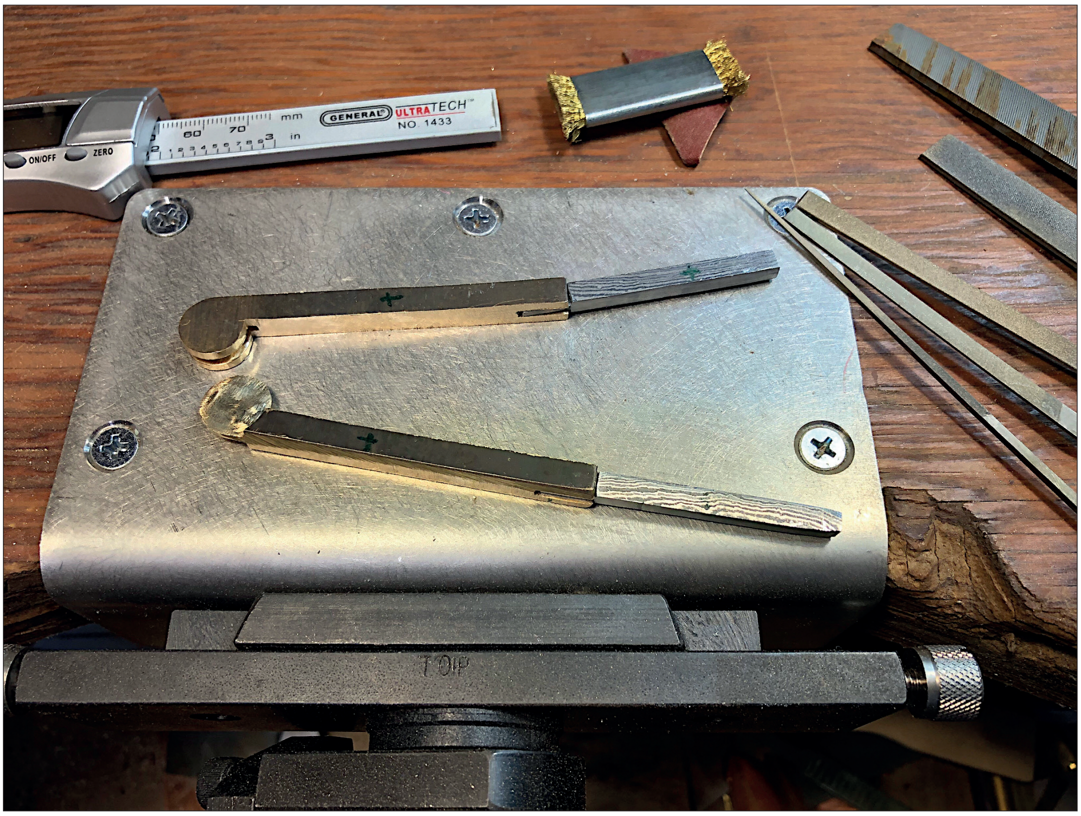

Fig. 6. Pair of brass and Damascus steel dividers in progress, during whitesmithing stage. (photo by Kent Heimer).

Fig. 7. A – pewter pitcher with riveted walnut handle; B – in-progress embossed silver box inlaid with gold, with wired lid awaiting brazing, embossed decorative top, required tools (hammer, chisel, agate burnisher) on right, and sample of gold onlay on left; C – folding knife with blade of Damascus steel and decorated sheath of iron and bronze (photo by Kent Heimer).

and ability to keep a point. The two metals were joined together by riveting, because the temperatures that each need to reach for hot joining (welding, brazing, *etc.*) are too disparate.

This folding knife (Fig. 7) showcases the combination of steel and copper alloy in another way. The Damascus steel blade, formed of nickel and high-carbon steels, is housed in a patterned iron sheath. This sheath has then been overlaid with molten bronze for both colour contrast and texture.

Working with pewter is a very different experience to working with other metals. Unlike other members of the metals' family tree, pewter softens through being worked. Efficiency is therefore key. All hammering and direct shaping has to be kept to a minimum, so that the metal remains hard enough not to deform during use. This pitcher (Fig. 7) was made by what is known as the construction method. Flat sections were shaped and then welded together, and afterwards finished with light planishing. Low-temperature solder is very visible against the natural colour of pewter, so welding is used to avoid unsightly miscoloured seams. Casting is another good method for shaping pewter without overworking it. Pewter was originally a tin-lead alloy, and was not food-safe, despite being extensively used for dining and drinking equipment. There are now a number of modern lead-free pewter alloys, which have allowed the tradition of pewter tableware to be extended while adhering to current safety expectations. Their working properties are very similar to the original tin-lead pewter. This pitcher was made from a specific lead-free pewter alloy known as Britannia metal (92% tin, 6% antimony, 2% copper). The walnut handle is attached by a copper rivet, as a pewter rivet would not be durable enough.

Sometimes, it is possible to achieve a particular goal using multiple different techniques. The choice of which method to pursue is, therefore, influenced by the properties of the metal or metals involved. The decoration on this small in-progress box (Fig. 7), formed from the argentium silver alloy mentioned above, will consist of a combination of repoussé and chasing, enhanced with gold inlay to emphasise various details through colour contrast. There are many ways to attach gold to silver. In this case, using a technique that relied upon heating would have weakened the relief decoration, so there was a risk that it would have been deformed when applying the necessary pressure to adhere the gold. Instead Dawn used a Japanese method, whereby the silver is first scored with a small chisel to create a rough surface, then the gold is gently tamped down into place. The technique creates a mechanical join between the metals. This demonstrates that having a single solution to hand is rarely enough for craftspeople, modern or ancient. Exposure to and development of different techniques allows smiths to make the best choice for their desired outcome.

Metals and Tools

The choice of which metal to work with immediately has many other impacts. The hardness of a metal dictates what tools it can be worked with and, since this varies across the different members of the metals' family tree, this can have an important impact on the choice of metals, techniques, and equipment. There are other more subtle differences that affect the choice and treatment of tools as well.

Metals with low boiling points can be problematic for craftspeople. Metals are, as you have seen already in this paper, regularly heated during manufacture, especially when annealing and soldering. For those processes, both gold and silver require temperatures that exceed the boiling point of metals like lead and tin. If there are traces of such metals, even as alloys, on the gold or silver during heating, the base metals first alloy with the gold or silver, then vaporise. This leaves behind pitting on the surface of the precious metals, damaging their aesthetic appearance, and in the worst case scenario can sometimes even create holes. In workshops where, for example, both pewter and silver are being worked side-by-side, it is necessary to either impose strict tool hygiene protocols, to keep them free of residue and avoid accidental transfer, or even have two separate sets of tools available.[40] Separate working areas are required, and this can even extend to differentiating workshops by metal type to prevent this problem.

Working with different metals also leads to different relationships with tools in other ways. Dawn's blacksmithing friends often tease her about the shiny condition of her silversmithing anvil and T-stakes, since non-ferrous metals, such as silver and copper, will take on any unevenness, pitting, or roughness from the surface on which they are worked on. If there is any dust or scratch marks, or even just a little bit of grit on the tools or anvil and stakes, these will show in the surfaces of these softer metals. Iron and steel are worked hot and in workshops using equipment that has rougher surfaces. Iron too will take on impressions of tool cleanliness, but as it is rarely finished to a mirror polish this is not so problematic. However, finishing tools for all metals,

[40] The number of tools associated with a workshop may, therefore, have little correlation with the number of people present, and instead be linked to the range of tasks undertaken in the space and the number of different metals being worked.

including steel, need to be kept clean to prevent them damaging the surfaces they are being used on.

Metals and Fuel

Another factor impacted by metal type is fuel, which differs according to the varying temperatures needed for the required processes. Kilns are only utilised for highly specialised purposes, such as for bonding stacks of dissimilar metal pieces to make *mokumé-gane* billets (see below). Iron and steel call for some of the hottest working temperatures, usually achieved by using a coal or charcoal fire with forced air flow to raise the rate of combustion. Modern blacksmithing workshops, therefore, follow a more traditional model, due to this strong thread of continuity. Smiths working with non-ferrous metals may use a charcoal fire or, more rarely, an alcohol flame lamp, but often modern metalworkers turn to various gaseous fuels, including acetylene/air, propane/air, propane/oxygen, and acetylene/oxygen, sometimes in conjunction with a blowpipe so the smith can use their breath for finer control. The required size of the flame (torch head) and concentration of air/oxygen within the fuel depend on the process underway and the type of metal used.

For example, when Dawn welds pewter, she works with a tiny acetylene/air flame for which the blue section is no longer than 7 mm to 9 mm. This provides a temperature of about 246 °C. More heat than that would puddle the pewter sheet and burn holes into the piece before the weld could take place. When brazing silver she uses the same torch again, but with a much larger flame, extending from 25 mm to 65 mm depending on the size of the piece so that the temperatures range from 650 °C to 750 °C. There are different grades of silver-brazing compounds, formed from varying alloys, which match the required temperature; also to be taken into account are colour differences when matching materials.

Gaseous fuels allow for much more precise control over flame temperature, length, composition, and targeted position than previously possible. This has opened up new possibilities in terms of what is achievable with processes like soldering and brazing. It also leads to fewer mistakes. Such differences in fuel choices are the reason why, when conducting experimental archaeology, it is important to try to make the procedure as close to the past reality as possible. With experiential archaeology, when participants are gaining a feel for the overall process, this is less important. However, when testing, for example, a specific *chaîne opératoire*, using anachronistic equipment can prompt misleading interpretations.

Working with Multiple Metals

As is already apparent from this paper, working with two or more metals simultaneously can be necessary in order to create an object that satisfies the desired specification. However, metals do not have to be physically joined together in order to interact in an intra-cross-craft way. This serving set (Fig. 8), consisting of a copper tray with sterling silver handles, a silver sugar bowl, a silver spoon, and a silver creamer, provides another example of how metals can be used together in a complementary way. All the pieces in this set that will come into contact with foodstuffs are made of silver, which has antimicrobial properties and low reactivity, making it an excellent choice from a food safety standpoint. The tray is not intended to be used as a dining utensil so, although copper would have been a poor choice for the other objects in this set, due to its unpleasant and sometimes harmful reactivity with foodstuffs, other factors made it an appropriate option for the tray. The flatness of the tray would demand many rounds of annealing, because of the likelihood that it would become warped and too springy during the initial shaping process, which is easier to achieve with copper than silver because the former does not require additional flux. Copper as a material is less expensive than silver. Finally, the copper and silver provide a pleasing colour contrast. Therefore, although the selection of silver for the utensils was primarily dictated by food safety, the choice of copper was influenced by crafting, cost, and aesthetic considerations.

The advantages for using copper to make vessels are so significant that smiths have found a way to circumvent its inherent food safety issues. This is exemplified by Dawn's next case study, a cooking pot (Fig. 8), made from heavy-gauge copper. Copper is especially ideal for cooking, because it is such a good conductor of heat. The interior of the pot appears silvery because it has been tinned: using a low heat, pure tin has been wiped onto the surface. Tin is resistant to most chemical corrosion, hence its widespread use for food storage cans. For the handle a stronger metal is required than either tin or copper, and bronze was chosen because it is a poorer conductor of heat. Brass would have been a suitable choice too but, despite both being copper alloys, bronze forges more readily than brass. This is directly connected to the metals with which the copper is alloyed; the tin in bronze is more malleable than the zinc used to make brass. Finally, copper was selected for the handle rivet; being softer than bronze it provided a soft malleable connection between handle and pot, as well as creating a nice colour contrast. Riveting was especially chosen because of its mechanical strength, particularly because this join is put under a lot of strain when the pot is full. Attempting to use a brazing alloy would have triggered a reaction with the tin coating, which would have led to the slow decline of the join. This pot, therefore, partners copper with tin, but in two quite distinct ways. This is a useful reminder of how complex the relationships between members of the metals' family tree can be.

Fig. 8. A – silver service set with copper tray featuring silver handles; B – tinned copper cooking pot with brass handle (photo by Kent Heimer).

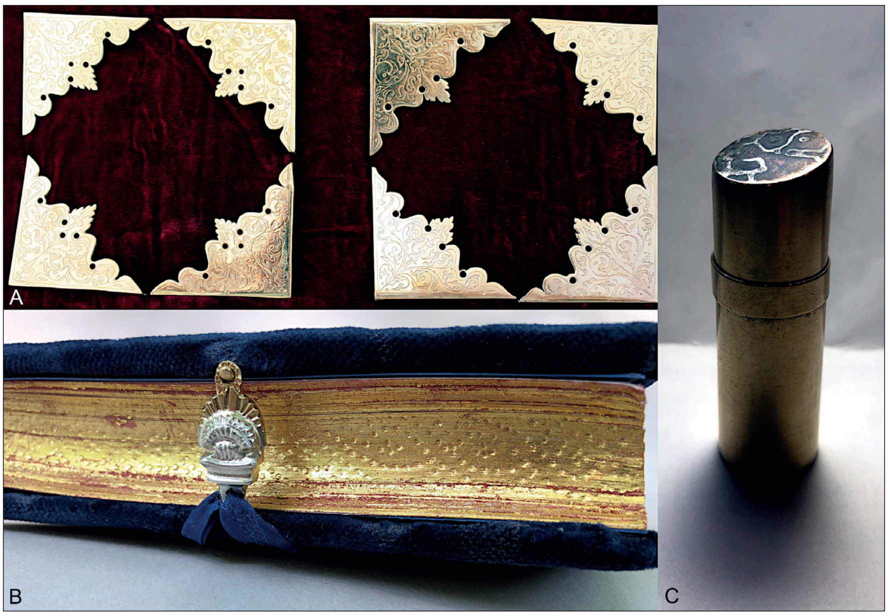

Fig. 9. A – reproduction gilt silver book furniture corner pieces; B – silver shell book clasp with brass back plate; C – perfumed oil box with *mokumé gane* decoration (photo by Kent Heimer).

Fig. 10. Three *mokumé gane* decorative boxes (photo by Kent Heimer).

Silver and brass can also partner well together, as demonstrated by this book clasp (Fig. 9). The clay/sand-cast sterling-silver shell was joined to the brass back-plate via diffusion; these two metals readily alloy together. The brass was then chased with a (harder) steel tool to echo and emphasise the grooves of the shell pattern. From a functional point of view, the brass is the better choice for the back-plate and peg because it naturally has a greater wear resistance compared to silver. From an aesthetic point of view, it shares the same golden colour as the gilt page edges, but provides an attractive contrast to the silver, making the shell stand out.

The dividers (Fig. 6) also incorporate multiple metals, the exact choice of alloys being founded upon a mix of traditional technical concerns combined with aesthetic considerations. This form of dividers was intended to be used to calculate locations whilst at sea by integrating observations with detailed physical maps. The use of brass for the hinge afforded a degree of resistance against corrosion stimulated by the salty maritime environment, whereas steel was favoured for the leg ends because its durability protected the sharpness of their points, ensuring the accuracy and increasing the use-life of the dividers. The hinge and legs will be joined together using rivets formed of red brass wire (with a high copper content), which is suited to this purpose and also provides colour contrast. The Damascus steel similarly adds aesthetic interest, and will be complemented by the use of a *mokumé gane* rod to make the large-diameter rivet that joins the brass hinge pieces together.

Damascus steel is just one example of how metals can be used together in an intra-cross-craft way specifically for decoration. The Japanese technique *mokumé gane* ('wood grain metal') layers together many metals which are then manipulated (*e.g.*, gouged or chiselled to reveal lower layers, deformed, then repeatedly hammered and/or re-rolled back into sheet) with the final stage being the abrasion of the surface, through filing and sanding, to reveal the pattern, which often resembles wood grain. Conceptually, it is the non-ferrous equivalent of Damascus steel. *Mokumé gane* is generally applied to decorative works, such as this small tubular box for perfume oil (Fig. 9) and these boxes made from copper and fine silver or brass (Fig. 10) because it is not food-safe, unless only silver, gold, and/or palladium alloys are used. The small tubular box (Fig. 9) incorporated many layers of sterling silver, brass, and copper alloys. The idea was to use a contrasting decorative surface to accent the sloped top of this simple form. Similarly, the use of an all-over pattern on the other decorative boxes called for a simple shape, with the top of these boxes calling attention to their details (Fig. 10).

Choice of metals can of course be guided primarily by the status of the patron or the receiver. In this case, the craftsperson must find ways to satisfy these requirements, even though they may raise difficulties during the production stage. This is exemplified by these silver and gold corner pieces (Fig. 9), which are reproductions of book furniture first made for the English queen, Elizabeth I (AD 1558–1603).[41] The selection of gold and silver were inevitable, because of the status of the recipient; only they would have been considered suitable metals capable of enhancing the splendour of the book. What is particularly intriguing is that mistakes were made in the engraving (which Dawn faithfully replicated), yet the pieces were still used for what was a very prestigious object. Dawn produced the corner pieces from fine silver (99% silver), engraved them by hand, burnished them with agate, and then gilded them.

Originally this was achieved through mercury gilding using pure (24 carat) gold,[42] a process in use from the Medieval era onwards.[43] Mercury gilding was applied to all manner of different objects, including steel armour and silver jewellery, as well as book furniture. Mercury is a very special member of the metals' family tree; the only metal liquid at room temperature, past artisans capitalised on its low density and boiling point to use it to deposit films of precious metals, like gold and silver, onto another metal surface. Mercury gilding required mixing and heating mercury with gold to form an amalgam paste, which was then wiped onto the surface to be covered. The object was then gently heated (340 °C) to evaporate the mercury, leaving behind a thin film of gold that was strongly bonded to the underlying metal.

Unfortunately mercury fumes are highly toxic, and mercury is rarely used in modern metalworking. Safer alternatives have been developed, although great care still needs to be taken when dealing with the fumes and chemical solutions required, including wearing protective clothing. This is one reason why electroplating is so popular now, but of course this process was not available prior to the 19th century AD.[44] Dawn was able to devise an alternative gold wipe to replicate the effect without resorting to mechanical gilding, by employing the basic principles of electroplating. She applied a plating solution containing 24 carat gold suspended in an electrolytic solution using a positively charged wand wrapped in a fibre cloth, and wiped it across the negatively charged silver piece. This wipe gave the same texture as mercury gilding, but without the danger of toxic mercury fumes. The plating solution used is still poisonous, as it contains arsenic, but using a wand rather than an immersion bath slightly lessened Dawn's exposure risk as less of the plating solution was required.[45]

Another important difference between modern and older gilding methods is that modern platers often sandwich a layer of zinc in-between the metals. This is to prevent the gold gradually self-alloying with the silver over time and becoming noticeably lighter in colour.

Finally, it is worth reiterating that metals are used in an inter-cross-craft, as well as an intra-cross-craft way, and often the metal itself only plays a supporting role. The entire design of this box (Fig. 11) revolved around the large slab of tiger's eye, which the client desired to be treated as the central feature. Both the shape and the colour of the stone was taken into account, with the patina applied to the copper made to match the rind/matrix of the material on the outer surfaces of the stone. Stones are often used in conjunction with metal, often for decorative purposes, such as for jewellery, but also for functional purposes, such as a handle. As an example, this replica of an 18th-century drawing tool, a porte crayon (Fig. 11), encloses the mineral graphite, which at the time was relatively rare and expensive, within a brass holder, produced by turning, and ornamented with hand-formed details, with a ring to hold the graphite in place.

This inter-cross-craft element can also be less visible in the finished piece. It is not uncommon for Dawn to

[41] The originals reside in the Folger Shakespeare Library (Washington DC), no. STC2099 Copy 3.

[42] Also known as 'fire gilding'. The process can also be applied to silver and is known as mercury silvering.

[43] Although Pliny describes a process of gilding using mercury, this was cold mercury gilding, a process that fell out of fashion once hot mercury gilding (fire gilding) was developed, which produced a better result (Vittori 1979, 35–36).

[44] Electroplating creates a differential charge between the object to be plated and the metal intended to plate it, with the latter held in solution (usually referred to as a bath). The positively charged particles of the covering metal are then drawn to the negatively charged substrate. Metals commonly used for plating in this way include silver, copper, and zinc chrome.

[45] The hazardous nature of certain metallurgical procedures, like fire gilding, means that completely accurate archaeological reconstruction of such processes, *i.e.* with little or no safety precautions, is not tenable.

Fig. 11. A – copper box with tiger's eye stone; B – reproduction brass porte crayon (photo by Kent Heimer).

begin 'making' a metal artefact by working with paper or clay, producing patterns or drawings for instance.

Final Thoughts

We hope that taken together the nine case studies discussed in the second half of this paper provide useful illustrations of the thought process that underlies decisions of which metals to combine and why. Although the use of modern knowledge, tools, materials, and facilities means that Dawn's experiences are not universally applicable to all archaeological contexts, the challenges presented by the working properties of the metals themselves are the same, and increased awareness of their implications can only improve our understanding of past metallurgical practices. This is just a small snapshot of the great complexity presented by the metals' family tree and the overwhelming number of opportunities they offer. The variation between the properties of metals is precisely the reason for using them together, even if this also precipitates new problems that need to be solved, as discussed here. Combining this vast potential with materials beyond their family tree has led to the endless possibilities that enable metals to enrich our lives in countless ways. For Dawn, this means she feels privileged to have had the chance to explore the variety of ways to exploit these special characteristics of metals, and to find ways to make useful and beautiful items for our world in which we live.

Author Roles

Dawn Hoffmann: concept, design of experiential guide, production of experimental pieces, writing of initial draft;

Stephanie Aulsebrook: extension and editing of text, referencing, bibliography, image editing.

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