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RESEARCH

Debunking Deterministic Narratives of Technological Development Through Experimentation: A Critical Review of the Prehistory of Tin Bronze Alloying

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Abstract
The currently accepted narrative on the prehistory of bronze alloying technology follows deterministic, outdated assumptions of technological progression that ignore the role of contextual and performance factors in the decision-making processes, thus neglecting human agency. In essence, it is expected that newer techniques were overarchingly more advanced than older ones and hence replaced them. The validity of this narrative should be challenged and revised. A critical analysis of worldwide literature exposed that, contrary to predictions of the accepted theory, (1) the oldest alloying techniques persisted for centuries after newer ones were invented, and (2) several techniques usually coexisted in the same contexts. We hypothesised that these counterintuitive findings could be explained by differences in performance between techniques, (dis)advantageous at different settings. To obtain empirical information on the performance of techniques and test for behaviourally relevant performance differences between them, a series of alloying experiments were conducted. The results show that all techniques can produce objects of broadly equivalent quality while offering different trade-offs during production. Therefore, every technique—or a combination—can be advantageous under certain conditions, and there are no grounds to support a linear trajectory of substitution. These results debunk the traditional narrative and predict that co-smelting and cementation techniques were more frequently practiced in the past than hitherto assumed. Our propositions prompt a readjustment of explanatory models of bronze production organisation, trade, and consumption while opening unexplored research paths for archaeology and the history of technology.

Keywords Co-smelting · Cementation · Co-melting · Experimental archaeology · Performance matrix · Technology

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Introduction

Traditional histories of technology explain technological development as a rather simple, unilinear process that Pfaffenberger (1992) denominated the Standard View of technology. These narratives start with the discovery of rudimentary technologies and their irrevocable evolution into more advanced ones. During the last few decades, however, archaeologists have welcomed alternative explanations of technological change that integrate a holistic understanding of technological choices within their socio-economic and environmental settings (e.g. Adams, 1999; Amati *et al.*, 2019; Boyd & Richerson, 1985; Buchanan et al., 2017; Dobres, 2000; Dobres & Hoffman, 1999; Eerkens & Lipo, 2014; Henrich, 2001, 2009; Killick, 2015; Kim, 2001; Martinelli, 2004; Nelson, 1991; Östborn & Gerding, 2015; Roux et al., 2018; Sáenz-Samper & Martinón-Torres, 2017; Scholnick, 2012; Valcárcel Rojas et al., 2010). Despite this general rejection of unidirectional models of technological development, remnant ideas remain scattered across currently accepted explanatory theories not only of the past but also of the present (Zuboff, 2019).

Questioning the validity of these enduring unilinear views can generate new anthropological insight into past societies and expose under-explored research arenas. These knowledge gaps reveal flaws in our received wisdom and promote targeted research to generate more robust explanations of technological change. Whether it leads to the adjustment of previous assumptions or the proposition of radical alternatives, this process can trigger a cascade effect when reconsidering related aspects of the role of technology within a given society. Thus, challenging assumptions ultimately contributes to a better understanding of the complex relationship between technological and societal change across time and space.

A prominent example of a largely accepted linear narrative of technological progress is the prehistory of tin bronze making. Since the alloying technique used cannot be inferred by looking at finished objects, a greatly relevant question has been systematically overlooked: how was bronze in fact made, and why? Explicitly or implicitly, explorations of this topic portray a gradual substitution of alloying techniques over a few millennia, from the presumed simplest technique to that considered the most advanced one. This picture is, to say the least, unrealistic, because it does not consider the influence of environmental, socio-economic, and performance factors in the decision-making processes of bronze making. In accepting it, we are also neglecting the agency of those who made bronze.

Besides its appealing simplicity, two reasons have contributed to the endurance of this perspective. Firstly, we lack a systematic compilation of all the available data on the use of bronze alloying techniques in the past. This would allow reassessing the traditional view in the light of the recent acceleration of archaeological science research. Secondly, some core assumptions of the traditional narrative cannot be challenged while we lack an empirical understanding of the performance implications of alloying techniques.

Against this background, this paper revises this deterministic narrative of technological development and discusses the derived implications. To this aim,

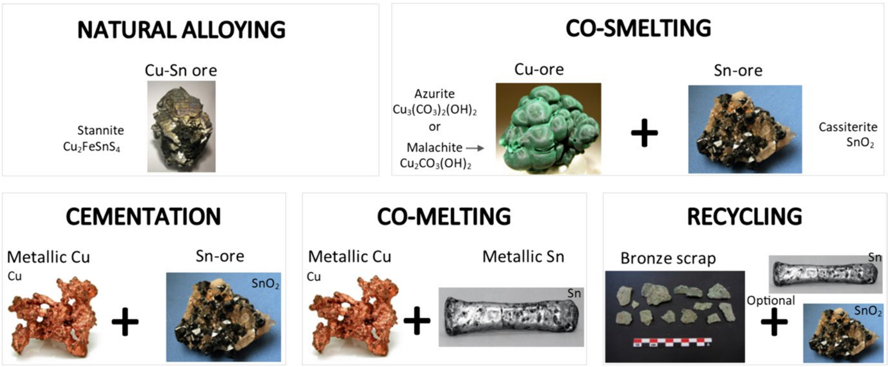

Fig. 1 Tin bronze alloying techniques used in Antiquity (bronze scrap by JML; stannite and malachite by R.M. Lavinsky (CC-BY-SA-3.0); cassiterite by R. Bottrill (CC-BY-3.0); copper by J. Zander (CC-BY-SA-3.0); tin (CC0-1.0)

a critical literature review and a series of alloying experiments that identified performance differences between techniques are presented. The resulting observations from both approaches expose a remarkable knowledge gap in the prehistory of bronze alloying technology development that opens new paths of enquiry on contextually explaining alloying technique choices over time. It is argued that this unexplored research field can lead to a re-evaluation of current models of bronze production organisation in Europe and beyond.

The Accepted Narrative vs the Archaeological Evidence

The Accepted Narrative on Tin Bronze Alloying Development

Bronze is an alloy of copper (Cu) and tin (Sn). Although other Cu alloys have been documented, bronze is an important metal used for both utilitarian and symbolic artefacts in much of the world since the Bronze Age (~3rd–1st millennium BC depending on the area). Besides recycling, four techniques were used to produce bronze in Antiquity (Fig. 1): natural alloying, co-smelting, cementation, and co-melting. All of these metallurgical reactions could be conducted within open shallow crucibles heated from the inside (with the charcoal mixed with the metalliferous charge) or in small open pits with a clay lining (Montes-Landa et al., 2020; Wayman, 1993). They entailed variable reducing conditions, temperatures between 1000–1200 °C, and heterogeneous reactions (Bourgarit, 2007).

Natural alloying denotes the smelting of polymetallic Cu-Sn ores. These ores can be selected deliberately or also be used unconsciously when trying to produce Cu, resulting in a low-Sn bronze instead. As natural alloying is constrained by polymetallic ores availability, it has a low incidence in the archaeological record (Charles, 1978; Moorey, 1994; Wertime, 1978). The co-smelting of oxidic/carbonate Cu-ores mixed with the mineral cassiterite (SnO_2) is usually considered the most rudimentary technique used to intentionally produce bronze. Alternative pathways are the cementation of metallic Cu with cassiterite,[1] and finally, the co-melting of metallic Cu and Sn. Importantly, bronze was also obtained through recycling, i.e. the melting of pre-existing bronzes. Because of the easy oxidation of metallic Sn, additional cassiterite or metallic Sn can be added during recycling to compensate for expected losses.

The traditional allocation of these techniques in a continuum from 'rudimentary' to 'advanced' (from natural alloying through co-smelting and cementation to co-melting) is likely influenced by their apparent occurrence in the archaeological record in such chronological order (see the "Use of Tin Bronze Alloying Techniques in Antiquity" section). This, coupled with the long-standing traditional view of a linear and staggered development of metallurgy (Budd & Taylor, 1995), has served to sustain received wisdom that cementation would always replace co-smelting, and that co-melting would always substitute the other two. However, as the parameters used to define 'rudimentary' and 'advanced' have never been clearly defined, it can only be inferred that co-melting is considered the most advanced technique based on implicit assumptions on its greater complexity (as it required prior smelting of the two metals separately) and the possibility of acquiring a better end-product with it (as each metal could be refined and weighed as required) (Clark, 1952; Healy, 1978; Herdits et al., 1995; Moorey, 1994; Muhly, 1985; Pigott et al., 2003). Crucially, the alleged superiority of some techniques over others has not been empirically demonstrated, and more remarkably, it has not been thoroughly tested in accordance with the technical affordances of ancient metallurgists (e.g. type of infrastructures and material access). Moreover, the near impossibility of inferring specific alloying techniques from the analyses of objects has made it difficult to challenge these assumptions (but see Alcalde et al., 1998 and Radivojevic et al., 2013 for examples of objects purportedly resulting from natural alloying).

During the last few decades, advances in archaeological science have allowed the identification of individual alloying techniques through the compositional and microstructural analyses of bronze slag (see Supplementary Information 1). This has promoted a progressive increment of bronze slag analyses, with results scattered in numerous papers. Surprisingly, this growing body of data has not been synthesised to address the history of bronze alloying. As a result, the standard linear narrative has remained unquestioned. To start revising this linear narrative, it is firstly necessary to confront it with the most recent evidence.

Use of Tin Bronze Alloying Techniques in Antiquity

Over the last few years, researchers have considered a range of microstructural and compositional features to reverse engineer bronze-making residues. However, the criteria employed for their interpretation have never been clearly defined or

[1] *Sensu stricto*, cementation implies the interaction of gaseous Sn with solid Cu. In practice, Sn mainly interacts as a liquid with molten Cu (Rademakers and Farci 2018), and only isolated gas–solid reactions occur (see EX-CEM-1 below).

systematically discussed together. This is important because scientific consensus on how to recognise alloying techniques is needed, especially since by-products of the same technique can have different microstructures and compositions (Rademakers & Rehren, 2016).

To overcome this limitation, a critical evaluation of all features used to characterise bronze slag samples as by-products of a specific technique was conducted. Table 1 presents a reference summary, but a more detailed discussion of each feature is available in Table SI1.1 (in Supplementary Information 1). These standardised criteria were then used to conduct a critical reassessment of all the available literature on bronze slag, spanning 54 case studies across the world. A summary of the key findings is offered in the main text here, but all published samples are discussed in detail in Supplementary Information 2, where further references and discussion on the limitations of this dataset are provided. During this reassessment, some samples were assigned to a different alloying technique than proposed by the original investigators, but this should not be taken as a dismissal of previous work: reclassification of samples was only possible thanks to the good documentation of the published finds. We acknowledge that the (re-) classification of these samples may be subject to revision with additional evidence, including further analyses and contextualisation. Nonetheless, the material evidence is sufficiently robust as a baseline to justify our research and further discussion. Importantly, in the data below, the earliest example of a given technique does not necessarily mean that it was invented there, that it had not been used before, or that it was the only technique used at that time.

Natural alloying is the earliest technique documented. It has been found in the earliest contexts with attested bronze production: in 5th millennium BC layers from the Balkans (Radivojevic et al., 2013) and in 3rd millennium BC contexts at Bauma del Serrat del Pont (Spain) (Alcalde et al., 1998; Montes-Landa et al., 2021). Remarkably, for the former area, bronze production by natural alloying was discontinued gradually by the end of the millennium, and tin bronze produced using cassiterite only appeared ~1500 years later (Radivojevic et al., 2013). This already provides an excellent example of a non-linear development path. Furthermore, evidence of 2nd millennium BC activity at the Deh Hosein mine (Iran) shows the exploitation of this polymetallic Cu-Sn outcrop whose isotopic signature is consistent with Luristan bronzes dated to the 3rd–1st millennium BC (Nezafati et al., 2009). Thus, further research should confirm if any of these artefacts were made from naturally alloyed bronzes.

The earliest co-smelting slag known so far comes from Early Bronze Age sites (2nd millennium BC): Bauma del Serrat del Pont (Alcalde et al., 1998), and Santa Maria de Matallana (both in Spain) (Rovira, 2007). Then, the first available cementation evidence dates to the Late Bronze Age (late 2nd-early 1st millennium BC). In Europe, the relevant sites are Cerro de San Cristobal (Spain) (Merideth, 2001) and perhaps Entre Águas 5 (Portugal) (Valério et al., 2013). In Africa, Pi-Ramesse (Egypt) is the only example so far (Rademakers et al., 2018a, 2018b; Rehren & Pusch, 2012). In Asia, Site 41–Supsa–Gubazuli (South Caucasus) also has cementation residues (Erb-Satullo et al., 2015). Although bronze recycling has been practiced since the beginning of bronze production, evidence of cassiterite addition

Table 1 Key analytical features to be looked for in archaeological bronze slag to establish the bronze alloying technique used

Key analytical features	Cu-ore addition	Sn-ore addition	Cu metal addition	Sn metal addition	Recycled bronze addition
Relic Cu-ore	Diagnostic	Not relevant	Counter-diagnostic	Not relevant	Counter-diagnostic
Tiny Cu metal prills	Indicative	Not relevant	Counter-indicative	Not relevant	Counter-diagnostic
Impurities related to Cu-ores (phase type, association, impurity type, amount)	Might be diagnostic	Not relevant	Might be counter-diagnostic	Not relevant	Might be counter-diagnostic
Relic Sn-ore	Not relevant	Diagnostic	Not relevant	Counter-diagnostic	Not relevant
Acicular Sn oxide crystals	Not relevant	Indicative	Not relevant	Counter-indicative	Not relevant
Impurities related to Sn-ores (type of phase, association, type of impurity, amount)	Not relevant	Might be indicative	Not relevant	Might be counter-indicative	Not relevant
Ca-Sn(-Si) compounds	Not relevant	Indicative	Not relevant	Counter-indicative	Not relevant
Sn-Fe compounds	Not relevant	Indicative	Not relevant	Counter-indicative	Not relevant
Relatively clean glassy matrix	Counter-diagnostic	Not relevant	Indicative	Might be indicative	Indicative
Large metallic Cu prills/masses	Counter-indicative	Not relevant	Indicative	Not relevant	Counter-diagnostic in the absence of deoxidation microstructures
Impurities related to Cu metal addition (phase type, association, impurity type, amount)	Counter-indicative	Not relevant	Indicative	Not relevant	Not relevant (but impurities might be part of the bronze mass)
Pure Sn metal prills	Not relevant	Counter-diagnostic*	Not relevant	Diagnostic	Not relevant
Small standard deviation of bronze prills composition	Counter-indicative	Counter-indicative	Indicative	Indicative	Might be indicative when reducing atmosphere controlled
Large deoxidation microstructures	Not relevant	Not relevant	Not relevant	Not relevant	Indicative
High-Sn bronze prills	Indicative	Indicative	Indicative	Indicative	Counter-diagnostic unless cassiterite/Sn was added
Consistent with:	**Co-smelting**	**Co-smelting, cementation, or Sn ore addition to recycled bronze**	**Cementation or co-melting**	**Co-melting, or addition of Sn to recycled bronze**	**Recycling (with or without Sn-ore or Sn addition)**

(Counter-)diagnostic (orange and green), conclusive if present; (counter-)indicative (light orange and light green), not conclusive in isolation. (*) Assuming a single-step co-smelting operation (see main text and Supplementary Information 1 for further discussion on this parameter).

to recycled metal can only be traced back to the Late Bronze Age too (e.g. Senhora da Guia de Baiões, Portugal) (Figueiredo et al., 2010).

The earliest co-melting use in Africa is documented at Pi–Ramesse in the Late Bronze Age (Rademakers et al., 2018a, 2018b; Rehren & Pusch, 2012). For Europe, co-melting has not been registered until the Iron Age (late 1st millennium BC) at Carmona (Rovira, 2007), La Fonteta (Renzi, 2013; Renzi & Rovira Llorens, 2016), and Emporion (all in Spain) (Montes-Landa et al., 2020). In Asia, possible co-melting evidence was dated to the late 1st millennium BC at Khao San Kaeo (Upper Thai–Malay Peninsula) (Murillo Barroso et al., 2010).

Besides the seemingly staggered introduction of these techniques under the scarce available data, co-smelting remained in use well after cementation and co-melting were introduced. Equally, cementation was not replaced by co-melting. Moreover, although natural alloying broadly disappears after co-smelting was developed, the Late Bronze Age slag from Mušiston (Tajikistan) shows its potential persistence to test polymetallic ores (Berger et al., 2022).

Co-smelting operations have been recorded until the fifth century BC at Puig de Sant Andreu–Ullastret (Spain) (Rovira, 2011a, 2011b), Isthmia (Greece) (Rostoker et al., 1983), and Emporion (Spain) (Montes-Landa et al., 2020). In Iberia, cementation was already widely used by then (e.g. Merideth, 2001; Rovira, 2007), and co-melting had just been introduced at Emporion (Montes-Landa et al., 2020). Potential Late Roman co-smelting slag needs further assessment (e.g. Tayma, Saudi Arabia) (Liu et al., 2015).

The most recent cementation residues analysed so far are dated to Roman times, at Hengisbury Head (UK) (Northover, 1987) and Philippolis (Bulgaria) (Rademakers, 2015). At this time, co-melting was likely well known by the Romans. Interestingly, cementation remained in use as recently as the 17th century AD, when it was used in Jamestown (USA) to test the viability of American cassiterite (Veronesi et al., 2019).

Finally, the most recent co-melting evidence comes from the 17th century AD Rooikrans (South Africa) (Miller & Hall, 2008). Arguably, modern bronzes are manufactured by melting metals too, but this review focuses on bronze alloying using preindustrial installations.

This compilation of evidence also highlights the coexistence of techniques in the same production contexts/sites. This phenomenon was noted by Wayman (1993), but it has received little attention since. During the Late Bronze Age, several techniques coexisted at Senhora da Guia de Baiões (Portugal) (Figueiredo et al., 2010), Pi–Ramesse (Egypt) (Rademakers et al., 2018a, 2018b; Rehren & Pusch, 2012), and possibly at Entre Águas 5 (Portugal) (Valério et al., 2013). During the Iron Age, the coexistence of techniques occurred at Emporion (Montes-Landa et al., 2020), El Castru (Farci et al., 2017), La Fonteta (all in Spain) (Renzi, 2013), and possibly Hengisbury Head (UK) for Europe (Northover, 1987). In Gordion (Turkey) (Rademakers & Rehren, 2016; Rademakers et al., 2018b) and Khao Sam Kaeo (Upper Thai-Malay Peninsula) (Murillo Barroso et al., 2010), the coexistence of techniques was also documented during the late 1st millennium BC. In fact, coexistence is the norm for all sites where the publication reports detailed data for more than one sample. Two exceptions exist: Castelejo assemblage (Portugal) with inconclusive results (Merideth, 1998) and Remosterkloof 3 samples (South Africa), which indicate a single technique, although in an assemblage that is much more recent than the bulk of the case studies reported (1000-1300 AD) (Bandama et al., 2015).

The reader will note that when referring to the co-existence of techniques, recycling has been conceptualised a technique by its own. Therefore, instances of co-existence of recycling with any other active alloying technique (e.g. the case of Senhora da Guia de Baiões, where recycling has been identified together with co-smelting) are also considered part of this identified trend. The reasoning behind this choice is discussed in the next section.

Clashes Between the Accepted Narrative and the Archaeological Evidence

The endurance of co-smelting and cementation in the archaeological record over millennia, and the coexistence of techniques within the same contexts/sites, seem at odds with the standard narrative, which predicts a deterministic replacement of techniques according to their attributed advantageousness. However, if we accepted the assumption of co-melting as the most advanced technique, one could still explain the observed patterns within the current framework. Arguably, the perdurance of the oldest techniques might be due to a delayed awareness of the superiority of the newer ones (although this vision would entail condescending assumptions of prehistoric metallurgists as unable to effectively recognise advantageous innovations). In the same vein, technique coexistence might be claimed to result from biased sampling strategies: researchers systematically targeting the beginning of the adoption curve of a new technique, which inevitably overlaps with the decline of a more established variant. In the light of the body of evidence, however, this would seem special pleading.

There is a more parsimonious explanation to explain the absence of replacement and the coexistence of techniques. This would simply require challenging the core assumption of the standard narrative, namely that co-melting is universally superior. If we consider that the various techniques offered different adaptive advantages (for example in metal losses, savings in charcoal or time, or precision in the composition of the desired alloy), as opposed to co-melting outperforming the rest in all parameters, the predicted linear trajectory of substitution could no longer be sustained. Instead, different techniques—or a range of them—could have been more advantageous under different conditions, and the oldest technique(s) could have been retained in those settings where they performed sufficiently. Thus, contrary to the accepted narrative, this alternative view confers agency to past metallurgist over their decisions and takes into account the role of environmental, socio-economic, and performance factors in technological choices.

Importantly, when considering all of this, the inclusion of bronze recycling as a technique itself is relevant in this hypothesis. This is because bronze recycling could offer specific performance advantages, such as time and fuel savings, and represent a more straightforward or less costly alternative to fresh ore/metal acquisition. Recycling was a conscious choice when practiced, so we must not overlook its presence in the archaeological record without questioning what it means. Thus, under the proposed hypothesis, the co-existence of recycling with another technique would imply that metallurgists were not using the 'most advanced technique available', which is precisely what the reasoning behind the linear model demands. Instead, this co-existence pattern highlights that metallurgists were evaluating and acting according to the different performance possibilities that both alternatives offered to produce a good-enough end-result on each occasion. This favours a non-linear development of technology, and because of this, the co-existence of recycling with other active alloying technique(s) contributes to calling into question the discussed linear model of technological progression.

Testing this alternative hypothesis requires empirical data on the purported performance differences between techniques. Only on this foundation can we explicitly ask: why did modern alloying techniques not replace ancient ones over millennia? Is this pattern rooted in different advantages offered by each technique, or in a very protracted awareness of the 'superiority' of co-melting? These questions demand a theoretically informed experimental archaeology program to clarify performance differences between techniques, as a starting point to address more complex issues related to patterns of selection, and to identify the key factors driving technological decision in a given setting.

Contextualising Alloying Technique Choices

Studies of technological choices in other realms usually consider environmental, socio-economic, and performance factors to explain decisions. Several of them can affect choices at the same time.

Examples of environmental factors (including geographic location) driving technological decisions abound (e.g. Buchanan et al., 2017; Nelson, 1991; Scholnick, 2012). In the case of alloying techniques, ore availability and ease of access can promote/discourage the selection of specific techniques. The influence of socio-economic factors in technological decisions is also well documented (e.g. Adams, 1999; Amati et al., 2019; Boyd & Richerson, 1985; Dobres, 2000; Dobres & Hoffman, 1999; Eerkens & Lipo, 2014; Henrich, 2001, 2009; Killick, 2004, 2015; Kim, 2001; Martinelli, 2004; Östborn & Gerding, 2015; Roux et al., 2018; Sáenz-Samper & Martinón-Torres, 2017; Valcárcel Rojas et al., 2010). Aspects, such as cultural and personal preferences; the connectivity degree between groups; the socio-political context, demographics, and beliefs; the prestige system; the technological tradition; the permeability to innovations; and the way in which a technology is culturally transmitted, can condition choices in the acquisition of raw materials and the processes of transmission and rejection of techniques.

Last, performance characteristics of alloying techniques might have affected choices too (McGuire & Schiffer, 1983; Schiffer, 2004; Schiffer & Skibo, 1987; Wejnert, 2002). These are the 'behavioural capabilities that an artifact (in this case alloying technique) must possess in order to fulfil its functions in a specific activity' (Schiffer & Skibo, 1987: 599). While socio-economic and environmental factors are site- and time-specific, performance characteristics are cross-cultural. However, their incidence is mediated by contextual socio-economic and environmental factors, which dictate the acceptable thresholds of performance at each time (i.e. what is considered good-enough). For example, the production of high-quality weapons would demand using a technique able to target a ~12–15wt%Sn composition, as this range provides optimum hardness and toughness. Thus, when techniques are contextualised in a given setting, it becomes possible to evaluate if one of them was (dis)favoured based on its performance characteristics (Schiffer, 1996). The rejection of a technique might occur when its performance levels are unacceptable under specific conditions (Skibo & Schiffer, 2008).

This approach is not only useful to understand technological rejections but also instances of coexistence. The coexistence of techniques with different performance advantages might be indicative of diversified demand that translates into diversified production strategies within the system. For example, higher-end items, presumably consumed by the elites, might require a technique with a more accurate control of the alloy as opposed to commoner items that could be manufactured within a broader range of compositions considered good-enough. If the market catered for both ends, the coexistence of techniques could be expected.

However, we should not by default assume competition between techniques (i.e. one technique being better than other for a given end) (Schiffer, 2001). Two techniques offering different performance advantages can perform well-enough within a specific setting too (Killick, 2004). If so, coexisting variants might be complementary if selective pressures are weak on those aspects of performance where they differ. Complementary use implies not only that the differences in performance between each alloying technique are behaviourally significant (Schiffer & Skibo, 1987)—also relevant for competing variants—but also that these differences offer divergent good-enough trade-offs within their context of use. Therefore, each alloying technique is differently advantageous for the same end (McGuire & Schiffer, 1983).

Understanding the impact of performance characteristics in decision-making requires evaluating how different techniques perform against different parameters through a performance matrix (Schiffer, 2004). Table 2 presents an attempt at formalising a performance matrix for bronze-making techniques. The performance characteristics listed there are mostly related to efficiency, but quality concerns or more practical aspects that might compromise efficiency are also included. This allows an evaluation of the base-line performance differences between techniques. Importantly, Table 2 assumes that if metals were used in cementation and co-melting, these were smelted on-site rather than being readily available by other means (e.g. trade). It also assumes a target batch of a few hundred grams. Both parameters are generally relevant for early bronze-making traditions, but this performance matrix may be modified to suit different scenarios with alternative production strategies, usually present in later contexts.

The multiple blank spaces in the matrix prevent evaluating performance differences and highlight the need of empirical data, especially because technique selection was likely based on more than one parameter (Schiffer, 2004). As performance characteristics are cross-cultural, these can be explored by experimental means. If the performance matrix provided is modified to fit a different scenario (see above), this should also entail a relevant modification of the experimental strategy followed to explore the performance characteristics under investigation.

Experimental Aims

The blank spaces of Table 2 exposed the performance aspects that need to be experimentally explored to effectively understand performance differences between techniques:

Objective 1: Number of Operations Required by Co-smelting and Cementation to Produce the Necessary Amount of Homogeneous Bronze

Co-melting requires three operations: Cu smelting, Sn smelting, and alloying of both. However, the archaeological evidence reviewed (see the "Use of Tin Bronze Alloying Techniques in Antiquity" section) makes it impossible to ascertain whether co-smelting and cementation required one or two operations for alloying: one to produce bronze prills and a second remelting stage to allow casting of a mass. The scarce experimental literature is inconclusive: previous experiments either obtained bronze prills of varied compositions that needed remelting, or metallic masses with highly cored microstructures perhaps requiring a second melting operation to homogenise the alloy (Adriaens et al., 2002; Berger et al., 2022; Gowland, 1912; Herdits et al., 1995; Johnson et al., 2015; Lackinger, 2011; Lackinger et al., 2013; Rademakers & Farci, 2018; Rostoker & Dvorak, 1991; Rovira, 2011b). Some techniques might be able to only produce a homogeneous bronze mass of a few hundred grams, only suitable for the manufacture of small objects. A second remelting operation entails further Cu and Sn losses, and more time and charcoal.

Objective 2: Approximate Time and Charcoal Required by Each Technique

Smelting usually takes longer than melting, but it is unclear if these differences are behaviourally relevant when alloying. The amount of metal produced also affects this parameter, and longer operations require more charcoal. For this evaluation, it was assumed that all techniques can be conducted with broadly comparable infrastructure. Therefore, equipment manufacture/maintenance is considered a fixed time commitment comparable for all.

Objective 3: Metal Loss Differences and Alloy Accuracy

It is unclear if all techniques entail comparable Sn and/or Cu losses, and if the amount of metal being produced affects this parameter. When these concerns are mentioned in the literature, they are usually linked to Sn recovery, assuming that co-smelting and cementation allow a poorer control of the resulting alloy (Clark, 1952; Healy, 1978; Herdits et al., 1995; Moorey, 1994; Muhly, 1985; Pigott et al., 2003).

Table 2 Performance matrix for bronze alloying techniques

PERFORMANCE CHARACTERISTICS AND RELATED PERFORMANCE ASPECTS		CO-SMELTING	CEMENTATION	CO-MELTING	EXPLANATION
Minimise Cu losses	Number of operations necessary for alloying				Experimental objective 1.
	Independent Cu smelting related losses	+	-	-	If Cu smelting for cementation and co-melting operations happened on-site (as opposed to obtaining Cu metal e.g. via trade), some Cu was likely lost in the slag and fumes. If not, all techniques would score equally.
	Remelting of the products of the independent Cu smelting (ingot as result)	=	=	=	Early prehistoric crucible-based smelting of Cu and Sn involved two steps: one to produce metallic prills, and another one to melt them to create the desired item (Figueiredo et al. 2016; Rovira and Montero-Ruiz 2013; Shugar 2003; Timberlake 1994; Yener et al. 2003). This would be applicable to the acquisition of the metallic Cu and Sn necessary for cementation and co-melting operations. However, the second remelting step seems unlikely if Cu or Sn smelting took place on-site. This is because (1) using an ingot reduces the metallic surface exposed to the other alloying element, (2) the second operation wastes time and charcoal, and (3) extra metal losses are incurred when cutting an ingot in chunks to be alloyed. Thus, if cementation or co-melting were used, it would be more efficient to directly alloy unconsolidated prills/masses resulting from previous smelting operations if these metals were smelted on-site. Importantly, material losses derived from metal cutting might be relevant for cases where metal was obtained as large ingots rather than smelted on-site Cu.
	Cu lost during alloying operation				Experimental objective 3.
	Cu-ore losses during preparation	=	=	=	Comparable losses are expected if the independent smelting of Cu occurs on-site for cementation and co-melting operations. If not, co-smelting would score lower because the other techniques would not require this step.
Minimise Sn losses	Number of operations necessary for alloying				Experimental objective 1.
	Independent Sn smelting related losses	+	+	-	See same parameter for Cu above.
	Remelting of the products of the independent Sn smelting (ingot as result)	=	=	=	See same parameter for Cu above.
	Sn lost during alloying operation				Experimental objective 3.
	Cassiterite losses during preparation	=	=	=	Comparable mineral losses are expected if the independent smelting of Sn for co-melting operations occurs on-site. If not, co-melting would score higher than the other two techniques.
Minimise charcoal consumption	Number of operations necessary for alloying				Experimental objective 1.

Table 2 (continued)

	Time to perform the alloying operation				Experimental objective 2.
	Independent Cu smelting	+	-	-	If Cu smelting for cementation and co-melting operations happened on-site (as opposed to obtaining Cu metal e.g. via trade), extra charcoal is needed for this operation. If not, all techniques would score equally.
	Remelting of the products of the independent Cu smelting	=	=	=	See same parameter above.
	Independent Sn smelting	+	+	-	If Sn smelting for co-melting operations happened on-site (as opposed to obtaining Sn metal e.g. via trade), extra charcoal is needed for this operation. If not, all techniques would score equally.
	Remelting of the products of the independent Sn smelting	=	=	=	See same parameter above.
	Temperature needed	=	=	=	Smelting theoretically requires higher temperatures (and therefore more charcoal) than melting, but within the temperature range typical of crucible metallurgy (between 900-1200ºC) it is difficult to make accurate adjustments. Generally, temperatures around 1100ºC are aimed to instead. This can be broadly guessed by the colour of the fire (yellowish-orange).
	Reducing atmosphere need	=	=	=	Given the relatively high free energy of oxidation of tin, reducing atmospheres would be required in all cases, therefore likely involving similar amounts of charcoal.
Minimise time	Number of operations necessary for alloying				Experimental objective 1.
	Independent Cu smelting	+	-	-	If Cu smelting for cementation and co-melting operations happened on-site (as opposed to obtaining Cu metal e.g. via trade), extra time was devoted to this operation. If not, all techniques would score equally.
	Remelting of the products of the independent Cu smelting	=	=	=	See same parameter above.
	Independent Sn smelting	+	+	-	If Sn smelting for cementation and co-melting operations happened on-site (as opposed to obtaining Sn metal e.g. via trade), extra time was devoted to this operation. If not, all techniques would score equally.
	Remelting of the products of the independent Sn smelting	=	=	=	See same parameter above.
	Time to perform the alloying operation				Experimental objective 2.
	Preparing Cu-ore	-	+	+	Based on the size of the Cu-ore relics in co-smelting and Cu smelting slag (e.g. Montes-Landa et al. 2020, 2021), smaller Cu-ore fragments were used in co-smelting operations, probably to maximise the surface in contact with cassiterite/Sn. Finer crushing required more time. If independent Cu smelting for cementation and co-melting operations happened on-site, less time would be required to prepare the Cu-ore in these cases. Equally, beneficiation of the ore, if applicable, would be relevant for all cases.

Table 2 (continued)

	Preparing cassiterite	-	-	+	The size of the cassiterite fragments used in co-smelting and cementation operations is expected to be smaller than the cassiterite fragments used in Sn smelting operations conducted on-site. Smaller fragments would maximise the surface in contact with Cu-ore/Cu, favouring Sn absorption during alloying. This requires more preparation time. Beneficiation of the ore, if necessary, would be relevant for all cases.
Targeting a composition accurately					Experimental objective 3.
Minimise impurities that affect performance of the alloy		-	+	+	Cementation and co-melting might allow using a purer metal, as independently smelting Cu and Sn in advance should help to get rid of impurities such as Fe that can affect the end-product. However, to avoid Fe impurities, it is also necessary to maintain a temperature <1200ºC (Craddock and Meeks, 1987). The selection of very pure Cu-ores, the potential beneficiation of dirtier minerals, and the slag formed during co-smelting could help to acquire a pure-enough metal for a given purpose too. Therefore, behaviourally relevant differences in performance might not be obvious in many cases. However, specific elements such as Pb in Cu-ores can end in the bronze produced in relevant amounts, and affect its properties. In these cases, co-smelting would present a disadvantage.
Ease					Experimental objective 4.
Necessary amount of bronze produced in one operation					Experimental objective 1.

Symbols are used to indicate which technique(s) performs better (+) or worse (−) in relation to each other

However, there is arguably no conclusive evidence to support this statement in the experimental archaeology literature. The scarce reported data on this parameter for co-smelting (Berger et al., 2022; Rovira, 2011b) and cementation (Adriaens et al., 2002; Herdits et al., 1995; Lackinger, 2011) does not permit evaluating if the deviation from the original aimed composition differs between techniques, and whether any differences would have been mechanically and/or visually perceptible.

When no direct comparison between objects is available, colour differences are perceived within broad sensate categories based on mechanical and visual properties of the material: 'red copper' (<5wt%Sn), 'yellow copper' (5–12wt%Sn), 'gold copper' (12–20wt%Sn), and 'silver metal' (>20wt%Sn). Although bronzes can be visually different within each category, they can be worked according to the same recipe(s) and would perform equally well for the manufacture of small, simple objects (Kuijpers, 2017). Importantly, if different techniques produce bronzes in different compositional ranges, it might be possible to infer the technique used based on the compositional and statistical analyses of large datasets, as suggested by Rovira and Montero-Ruiz (2013).

Objective 4: Experiential Understanding of Techniques

Each technique likely requires different levels of skill or skill-sets, which possibly influenced their selection. An experiential evaluation, even if subjective, might bring interesting insight. When assessing this, it is necessary to consider the alloying operations as well as (for cementation and co-melting) the previous independent smelting of Cu and Sn if conducted on-site.

Experiments Design, Materials, and Methods

The experiments' design directly derives from the discussed blank spaces of the performance matrix (Table 2). Given that the structure of the performance matrix took into account early bronze-making strategies, the experimental design also considered such scenarios: furnace design, type of crucible, etc.

Four co-smelting (EX-COS), four cementation (EX-CEM), and two co-melting (EX-COM) experiments were conducted, together with one malachite and one cassiterite smelting. The latter two are summarised in Supplementary Information 4. Each alloying experiment aimed to produce 101.97 g of bronze with 84.55wt%Cu and 15.45wt%Sn, except for EX-COM-2 (expected 111.8 g of the same alloy; the charge was adapted to the weight of the Sn fragment available). Table 3 summarises other variables tested.

Bronzes with ~9–15wt%Sn are widely documented during the Bronze Age throughout Europe. The selection of the highest end of the range as the experimental target allowed for some minor Sn losses, given its higher oxygen affinity. The specific wt%Cu and wt%Sn were also appropriate for a straightforward weighing of the charge. The ~100 g of bronze aimed at allowed to maximise resources while producing the metal necessary to manufacture small common prehistoric objects (arrowheads, awls, etc.). The results allow inferences for operations involving comparable amounts of bronze, but they might serve as indicative of technique performance when handling larger amounts of metal too.

Supplementary Information 3 summarises the characterisation of the malachite, cassiterite, metallic Cu, metallic Sn, and charcoal used (composition and preparation). Time spent in crushing ores and charcoal, and in cutting metal was recorded together with the related losses. These data might be useful for future research. Cassiterite was beneficiated because of the great presence of impurities.

As independently producing Cu would have required more resources, pure Cu sheets (0.5–1 mm thickness) were used instead. They were cut using metal snips to a crescent moon shape (~ 6 × 2 mm) to maximise the surface in contact with Sn/cassiterite. This would be the closest resemblance to the potential use of small Cu prills/masses from an independent Cu smelting operation, in consistence with the two-step Cu/Sn smelting operations usually registered in early prehistoric settings (Figueiredo et al., 2016; Rovira & Montero-Ruiz, 2013; Shugar, 2003; Timberlake, 1994; Yener et al., 2003). The Sn ingot used was provided by co-author ST and cut in chunks using a rotatory diamond blade.

The crucible variable needed to be constant; furthermore, to directly compare the efficiency of each technique, it was undesirable for the charge to react with it. Modern crucibles made of a refractory fabric (see Supplementary Information 3 for compositional information) were deemed the best option. These were open shallow hemispherical crucibles with an inner diameter of 12.7 cm, an inner height of 4.8 cm, a total height of 5.2 cm, and a wall thickness of 0.8 cm. In shape

Table 3 Summary of variables explored and experimental results

	g malachite	g Cu	g cassiterite	g Sn	g bronze expected	%Sn expected	Crucible	Lid	Charge set up	Charge in furnace (mins)		Charcoal (kg)	Ingot/mass of metal (g)	Other (g)	Total metal recovered	Metal loss (g)	Metal loss (%)	%Sn resulting	Unreacted Cu bits (g)
										>1000°C	Total								
EX-COS-1	150		20		101.97	15.45	Yes	No	Three layers of mixed charge separated and covered by charcoal powder layers.	33	42	6.3		94.5	94.5	7.5	7.4	8.8	
EX-COS-2	150		20		101.97	15.45	Yes	No		45	50	11.2	57.4	40.1	97.5*	4.5	4.4		
EX-COS-3	150		20		101.97	15.45	Yes	No	Mixed charge in a single layer covered by charcoal powder.	36	46	6.5	91.6	6.6	98.2	3.8	3.7	12.2	
EX-COS-4	150		20		101.97	15.45	Yes	No		44	50	6.3	94.6	4.5	99.1*	2.9	2.8		
EX-CEM-1		86.22	20		101.97	15.45	Yes	No	Cassiterite added after melting Cu; covered by charcoal powder	37	40	5.4	60.5	27.3	86.3	15.7	15.4	0.1	
EX-CEM-2		86.22	20		101.97	15.45	Yes	Yes	Mixed charge in the same layer covered by charcoal powder	28	46	3.8		Unreacted charge					
EX-CEM-2(B)	Use of product of EX-CEM-2									22	31	5.4	90.6	4.3	94.9	7.1	7.0	9.1	
EX-CEM-3		86.22	20		101.97	15.45	Yes	No		35	47	4.5	95.7	2.8	98.5	3.5	3.4	12.5	
EX-CEM-4		86.22	20		101.97	15.45	Yes	No		39	48	3.4		Unreacted charge					
EX-CEM-4(B)	Use of product of EX-CEM-4									40	48	6.7	94.6	0.1	94.7	7.3	7.2	8.9	
EX-COM-1		86.22		15.75	101.97	15.45	Yes	Yes		21	28	5.2	96.7	0.2	97.0	5.0	4.9	16.3	4.3
EX-COM-2		94.53		17.23	111.8	15.45	Yes	No		42	48	4.9	108.7	0.7	109.4	2.4	2.1	15.8	1.6

*Includes visible oxides

and size (but not composition), these were the most similar ones to prehistoric open crucibles (e.g. Murillo-Barroso & Montero-Ruiz, 2012). A new crucible was used for each operation to avoid contamination.

Instances of bronze alloying within relatively complex structures have been documented (e.g. Orfanou et al., 2022). However, the general lack of evidence for early bronze-related metallurgical structures in early bronze-making contexts inspired us to build the simplest possible metallurgical pit, which was likely the most widely used. These structures would leave little or no trace over time (Figs. 2 and 3). Thus, a ceramic tuyere (4 cm diameter) was secured to the pit using clay and attached to a single bag bellows (see Supplementary Information 3 for detailed description). It should be noted that there are no tuyeres remains for many prehistoric metallurgical contexts, so it is likely that blow pipes were used instead in many cases. Using blow pipes was unfeasible given the great effort that it would have imposed on the team, as well as for health and safety considerations.

The metallurgical pit was preheated to 1100–1200 °C before introducing the crucible with the charge. Temperature checks were carried out every ~10 min to ensure temperatures > 1000 °C. Charcoal was added as needed, including fresh and recycled from previous experiments. Only fresh charcoal addition was monitored and thus reported, as it was not possible to reweigh recycled hot charcoal. The bellows power was maintained at a normal pace (one blow every 2 or 3 s) until the last 5 min, when it was increased to the maximum capacity of the operator to promote the coalescence of the metal into an ingot. When the operation finished, the crucible was removed from the pit and left to cool down covered with a flat tile to prevent oxidation. Casting was avoided to facilitate a consistent evaluation of cost-effectiveness, as it often involves spills and failures that entail variable metal loses.

The resulting materials were taken to the Pitt–Rivers Archaeological Science Laboratories (University of Cambridge) and inspected under desk-based magnifying lenses. Visible metallic/mineral remains were collected with tweezers. Prills < 0.5 mm were sometimes observed among co-smelting by-products, but they were impossible to collect with tweezers. Given their small size, these losses do not affect the

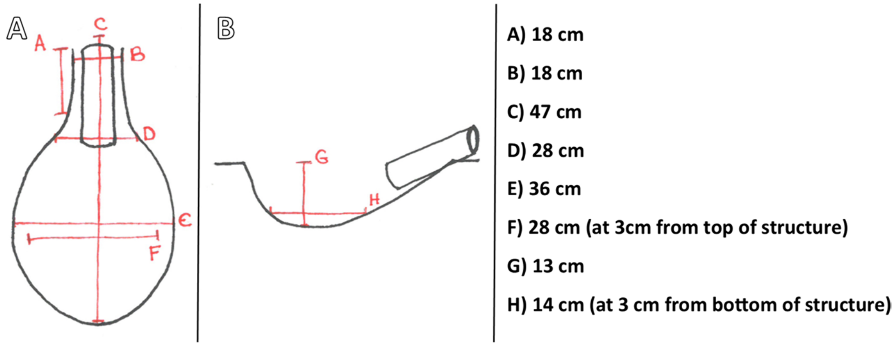

Fig. 2 Sketch of the metallurgical pit. **A** Top view. **B** Section

Fig. 3 The metallurgical pit before being used (**A**) and during use (**B**)

calculations presented below. Materials were photographed, weighed, and described (see Supplementary Information 4). A Canon Ixus 105 or a Leica M205C stereo microscope (for small specimens) was used to take photographs. The different scales used for weighing were precise to the second decimal place when measuring grams. Measurements were taken with electronic callipers or microscope software.

Compositions of the resulting metal masses were calculated based on their weight. Although materials were thoroughly dry-cleaned with brushes, they sometimes include some oxides and charcoal residues that might alter the result slightly. Thus, to account for the small potential errors related to this, only one decimal is offered in tables related to alloying composition calculations. It is acknowledged that minute differences in compositions, when calculating charcoal weight or when reporting losses of raw materials, are not perceptible by human senses and are likely irrelevant to the considerations made by ancient metallurgists. Therefore, while detailed numbers are provided in the presentation of results, the discussion uses round figures.

Results

Table 3 summarises all results and variables explored, and Supplementary Information 4 presents detailed descriptions of all operations and by-products. In the following paragraphs, 'ingot' is understood as a mass of metal that has coalesced at the bottom of the crucible. When indicated, these might include some oxidised residues.

Co-smelting

Co-smelting operations lasted 42–50 min. The fresh charcoal spent was ~6 kg for each except for EX-COS-2 (explanation below). In EX-COS-1 and EX-COS-2, the mixed charge was arranged in different layers separated and covered by charcoal powder. For EX-COS-3 and EX-COS-4, all the mixed charge was introduced within the crucible in one layer and covered by charcoal powder.

EX-COS-1 produced prills of varied compositions (judged by colour) and sizes (down to <1 mm diameter) (Fig. 4A and B). It entailed a 7.4% metal loss. For EX-COS-2, the metallurgical pit was maintained very hot (hence the higher charcoal input) to promote the coalescence of prills into an ingot; the outcome was a spongy mass ranging from yellow (bronze) to red (Cu) with a denser bottom (Fig. 5A). This indicates that an ingot was forming when the operation stopped. Metal masses, prills, and altered cassiterite chunks were recovered (Fig. 4C and D). EX-COS-2 entailed a 4.4% metal loss.

EX-COS-3 produced a bronze ingot (yellow, pale pink) with a redder area richer in Cu (Fig. 5B). Next to this area, Sn prills were coalescing, indicating that a slightly longer process would have encouraged a more homogeneous Sn recovery. A total of 6.6 g of small prills were also recovered (between 6 and <1 mm diameter). Occasional semi-dissolved cassiterite chunks and one small fragment of semi-reacted malachite were observed. EX-COS-3 losses are estimated at 3.7%.

EX-COS-4 produced a spongy 'ingot' (Fig. 5C), suggesting that a metallic mass formed, but that it started oxidising soon after. A total of 4.5 g of metallic prills (between 3 and <1 mm diameter), and occasional semi-dissolved cassiterite chunks were also recovered (Fig. 4E). EX-COS-4 entailed a 2.8% calculated metal loss, but the ingot includes Cu oxides, so slightly higher loses are presumed.

EX-COS-1 and EX-COS-3 were the co-smelting experiments yielding the largest metal amounts, so the average resulting alloy could be estimated. Considering the higher affinity of Sn for oxygen and the amount of Sn and high-Sn prills recovered separate from the metal mass, it may be assumed that most of the material lost was Sn. If the composition of the resulting metal is calculated considering all the metal produced (ingot + prills/masses), EX-COS-3 and EX-COS-1 would have resulted in ~12.2wt%Sn and ~8.8wt%Sn bronzes, respectively.

Cementation

Cementation operations lasted 31–48 min. Fresh charcoal input remained ~4.8 kg in all cases. In EX-CEM-1, cassiterite was added after the Cu was molten, but it did

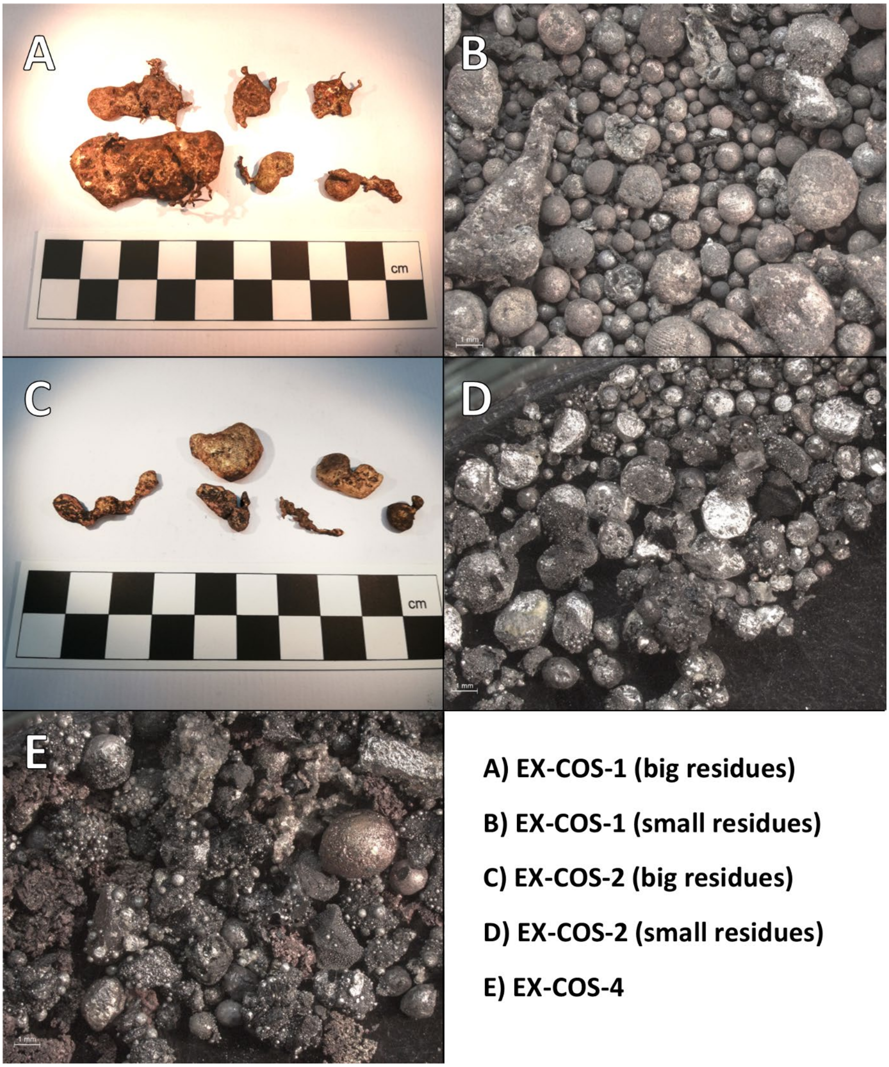

Fig. 4 Residues from co-smelting operations (small scales = 1 mm)

not penetrate the charcoal layer, so it did not reach the molten Cu. An ingot was produced (Fig. 6A). Half of it is a metallic mass, but the other half is made of partially fused Cu bits. In some cases, they have a yellow surface tint (Fig. 6B), which indicates that some cementation proper occurred (gas–solid interaction). Some metallic prills and masses were also recovered (~3–4 mm diameter). EX-CEM-1 presented a 15.4% metal loss (i.e. pure Cu), consistent with the cassiterite addition failure.

For EX-CEM-2, EX-CEM-3, and EX-CEM-4, the mixed charge was introduced in a single layer and covered by powdered charcoal. EX-CEM-2 produced an unreacted conglomerate (Fig. 6C), so it was rerun as EX-CEM-2(B) after re-introducing

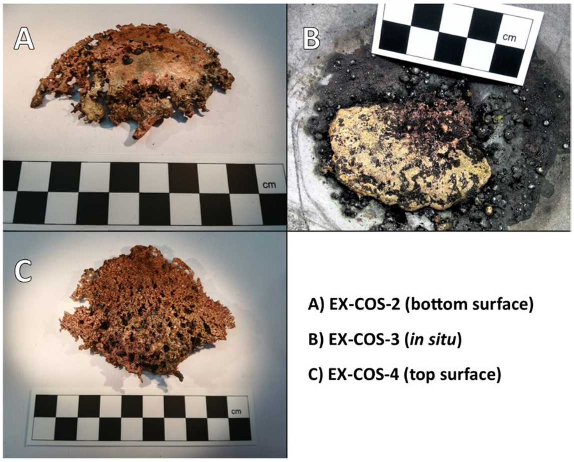

Fig. 5 Ingots from co-smelting operations

the unreacted materials in the crucible, which was covered by a lid. This created a bronze ingot (Fig. 6D) as well as metallic prills of different compositions (~ 3–4 mm diameter). EX-CEM-2(B) lost 7.0% of metal.

EX-CEM-3 produced a bronze ingot and a small amount of prills (Fig. 6E and F), most of them of Sn (~1–3 mm diameter, only a few < 1 mm). EX-CEM-3 lost 3.4% of metal. Finally, EX-CEM-4 also initially resulted in an unreacted conglomerate, so it was rerun too. EX-CEM-4(B) was progressing satisfactorily until the crucible content was accidentally spilled. The shape, size, and yellow appearance of the spillages (Fig. 6G) show that a liquid bronze mass that would have solidified into an ingot had formed. Other metallic prills of various sizes (between ~1.5 cm and 1 mm diameter, Fig. 6H) were also recovered from the ground, mostly made of Cu (red) and bronze (yellow), although some Sn prills were observed. A total of 7.2% of metal was lost, but this result would have been possibly closer to EX-CEM-3 had the crucible not fallen. Some of the smallest residues were likely lost.

Assuming that the metal preferentially lost was Sn, the estimated average compositions of the metals from EX-CEM-2(B), EX-CEM-3, and EX-CEM-4(B) are ~9.1wt%Sn, ~12.5wt%Sn, and ~8.9wt%Sn bronzes, respectively. The lid used in EX-CEM-2(B) did not affect recovery. Importantly, residual cassiterite was very rare in cementation operations.

Co-melting

For co-melting operations, the mixed charge was all covered with charcoal powder. A flat tile functioned as the lid for EX-COM-1, which lasted for 28 min. It resulted in a bronze ingot (Fig. 7A). Only a couple of isolated Cu-based prills (~2 mm diameter) and 4.3 g of unreacted Cu bits were collected (Fig. 7B). Some of them are yellow, indicating that they absorbed some Sn.

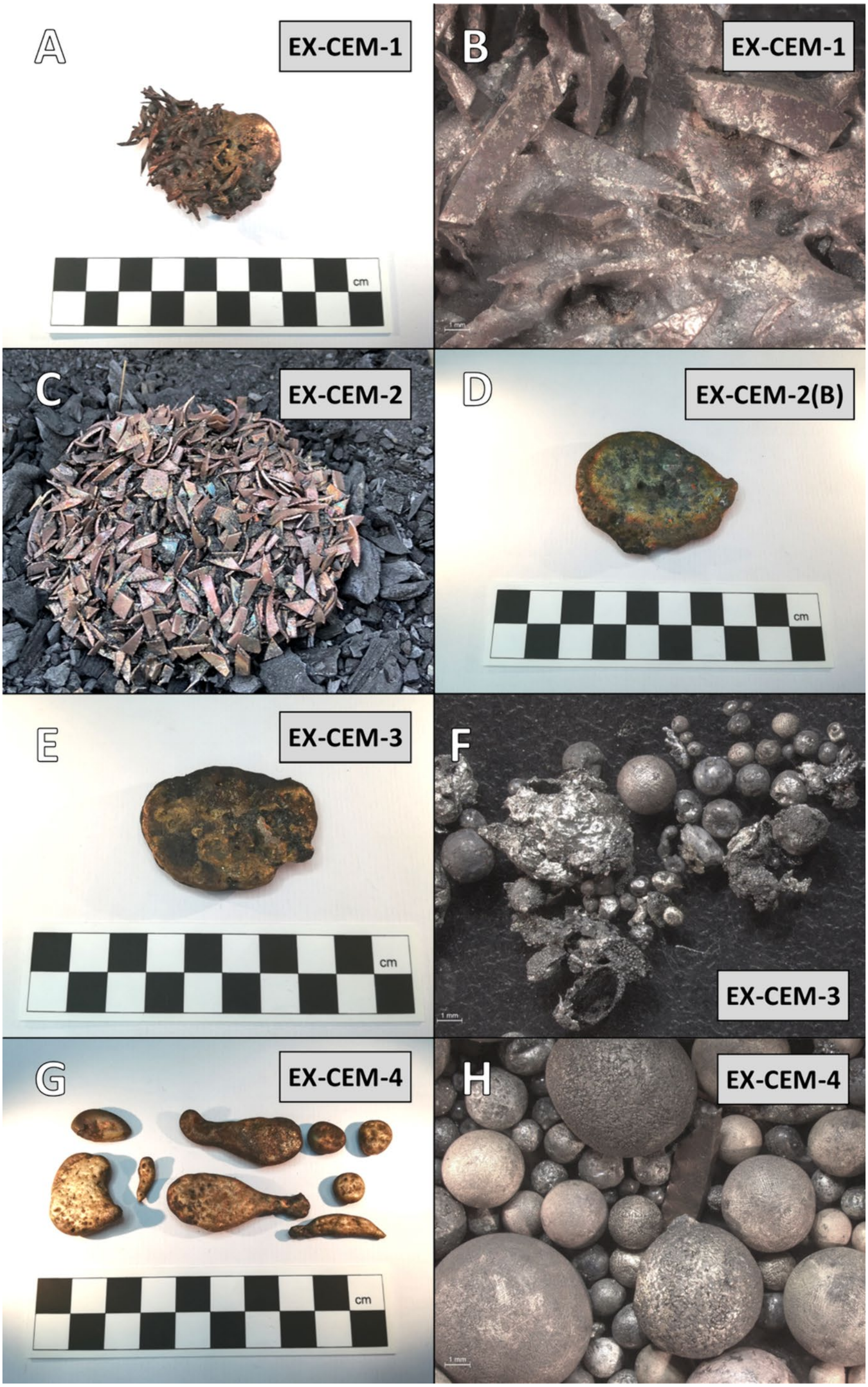

Fig. 6 Ingots and other resulting materials from cementation operations (small scales = 1 mm)

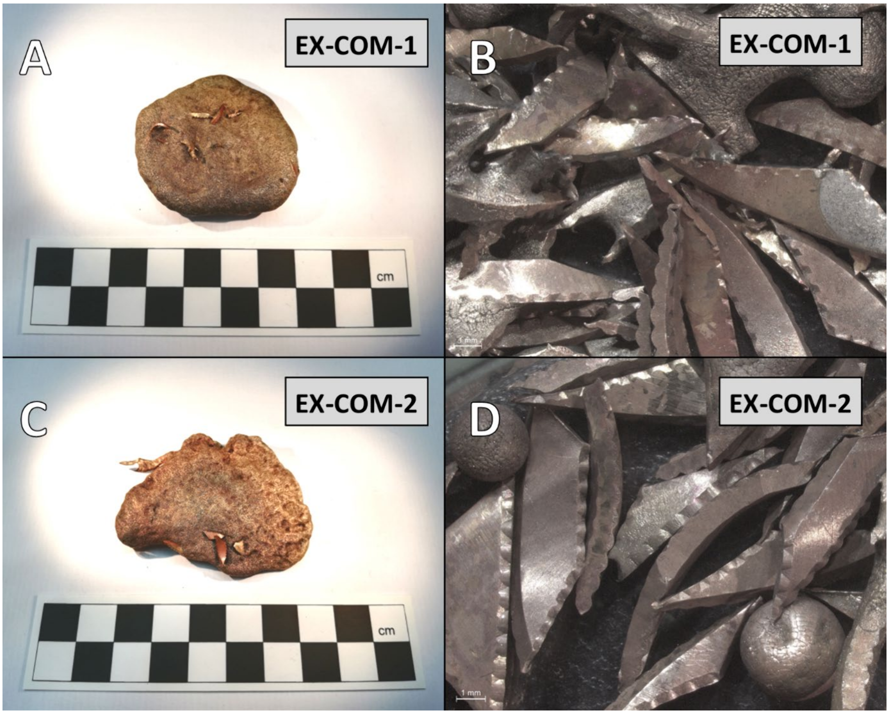

Fig. 7 Ingots and other resulting materials from co-melting operations (small scales = 1 mm)

EX-COM-2 entailed 48 min, allowing direct comparisons with co-smelting and cementation operations. It produced a bronze ingot, four Cu-based prills (~3–5 mm diameter), and some unreacted Cu bits (some of them yellow) (Fig. 7C and D).

Despite the time duration differences, both co-melting operations required ~5 kg of fresh charcoal. This is because EX-COM-1 was the first alloying operation of the week, so no recycled charcoal was available. EX-COM-2 had *ad hoc* recycled charcoal added on top of the recorded 5 kg, so overall, it used more fuel.

Co-melting operations resulted in metal losses of 4.9% and 2.1%, respectively. This corresponds to 5.0 g and 2.4 g of metal lost, respectively, which broadly fit the unreacted amount of Cu recovered at the end of both experiments (Table 3). Therefore, the metal preferentially lost in this case was Cu, and EX-COM-1 and EX-COM-2 produced ~16.3wt%Sn and ~15.8wt%Sn bronzes, respectively. The time increment for EX-COM-2 reduced the amount of unreacted metal by ~3%. Arguably, this does not constitute a significant saving in metal, but a considerable expense of extra charcoal during the extra time.

Comparative Evaluation of Performance Characteristics

Table 4 is an updated version of the performance matrix including the experimental results. It is important to remember that this evaluation assumes that the metallic Cu and/or Sn used in cementation and co-melting operations was smelted on-site (as opposed to procured readily in metallic form) and that it considers the manufacture of bronzes of a few hundred grams.

Number of Operations Required by Co-smelting and Cementation to Produce the Necessary Amount of Homogeneous Metal

Allocating the mixed charge together instead of in layers, like in EX-COS-3, can result in an ingot. EX-COS-4 and to some extent EX-COS-2 also show ingot formation, although constrained by unstable reducing conditions. If inexperienced operators such as ourselves could obtain an ingot after three attempts, more experienced people likely obtained a castable mass on almost all occasions. Furthermore, it must be considered that the co-smelting experiments produced many Sn prills, but that these are absent in archaeological co-smelting slag (see Supplementary Information 1 and 2; and confirmed by JML experience analysing > 200 prehistoric bronze slag samples which are in the process of being published elsewhere). If co-smelting was a two-step process, some Sn prills should have been found in archaeological co-smelting by-products. This supports that the coalescence of prills and direct casting after co-smelting was likely possible and easily achievable. This was probably more feasible for objects of a few hundred grams (arrowheads, flat axes, awls, etc.) because bigger items require a larger homogeneous mass of metal, seemingly at odds with the many small fragments of semi-dissolved cassiterite observed in the presented co-smelting experiments.

Direct casting was likely possible after cementation too. EX-CEM-2(B) and EX-CEM-3 produced metal masses potentially suitable for casting. The shape of EX-CEM-4(B) spillages also suggests the formation of a liquid mass. Unreacted cassiterite was rare or non-existent in cementation experiments so it could have been more appropriate for casting slightly larger objects than co-smelting, as it seems to facilitate Sn smelting and absorption.

Table 4 considers these observations by indicating no differences in the number of operations necessary for alloying itself.

Time and Charcoal Required by Each Technique

Co-smelting operations lasted 42–50 min. Only EX-COS-3 produced a proper ingot. A total of 10–15 additional minutes for EX-COS-4 and EX-COS-2 (and a better atmosphere control) might have resulted in homogeneous masses. Moreover, both the shortest cementation operation (EX-CEM-2(B), 31 min) and the longest one (EX-CEM-4(B), 48 min) produced ingots. The highest recovery rate (4% difference) was acquired in 47 min (EX-CEM-3). Finally, co-melting operations took 28 min

Table 4 Performance matrix for bronze alloying techniques (updated)

PERFORMANCE CHARACTERISTICS		CO-SMELTING	CEMENTATION	CO-MELTING
Minimise Cu losses	Number of operations necessary for alloying	=	=	=
	Independent Cu smelting related losses	+	-	-
	Remelting of the products of the independent Cu smelting	=	=	=
	Cu lost during alloying operation	+	+	-
	Cu-ore losses during preparation	=	=	=
Approx. score for minimising Cu losses		2	0	-2
Minimise Sn losses	Number of operations necessary for alloying	=	=	=
	Independent Sn smelting	+	+	-*
	Remelting of the products of the independent Sn smelting	=	=	=
	Sn lost during alloying operation	-	-	+
	Cassiterite losses during preparation	=	=	=
Approx. score for minimising Sn losses		0	0	0*
Minimise charcoal consumption	Number of operations necessary for alloying	=	=	=
	Time to perform the alloying operation	-	+	+
	Independent Cu smelting	+	-	-
	Remelting of the products of the independent Cu smelting	=	=	=
	Independent Sn smelting	+	+	-
	Remelting of the products of the independent Sn smelting	=	=	=
	Temperature needed	=	=	=
	Reducing atmosphere needed	=	=	=
Approx. score for minimising charcoal consumption		1	1	-1
Minimise time	Number of operations necessary for alloying	=	=	=
	Independent Cu smelting	+	-	-
	Remelting of the products of the independent Cu smelting	=	=	=
	Independent Sn smelting	+	+	-
	Remelting of the products of the independent Sn smelting	=	=	=
	Time to perform alloying operation	-	+	+
	Preparing Cu-ore	-	+	+
	Preparing cassiterite	-	-	+
Approx. score for minimising time		-1	1	1
Targeting a composition accurately		=	=	=
Minimise impurities that affect the performance of the alloy		-	+	+
Ease		+	-	-
Necessary amount of bronze produced in one operation		=	=	=

The scores highlighted result from adding 1 for each '+' and subtracting 1 for each '−' in every parameter affecting that performance characteristic. These scores could be easily modified by adding lines or grouping some of the parameters. Thus, the number offered should not be taken in absolute terms but as indicative of relevant or small differences in performance between techniques. (*) Independent Sn smelting losses are expected to be higher than Sn saved during a co-melting operation (see text for discussion) so this score should be taken with caution

and 48 min. Both attempts were deemed successful and the longest one recovered 3% more metal.

Overall, cementation and co-melting operations require a broadly similar time commitment, with cementation perhaps demanding slightly longer for a better recovery rate. Co-melting also recovers slightly more metal if left for longer. For ~100 g, 30 min would suffice for co-melting and ~45 min for cementation, although if Cu was introduced in larger chunks, slightly more time would be needed. Both techniques would still probably take less time than a co-smelting operation. Co-smelting probably requires >50 min to form a castable mass of ~100 g. The longer the time, the more charcoal is needed. Moreover, the larger the charge, the more obvious the time differences between techniques would likely become. Notwithstanding the shorter time required by cementation and co-melting, it is necessary to consider the time and charcoal involved in the prior smelting of the Cu and/or Sn for these operations, as reflected in Table 4.

Metal Loss Differences and Alloy Accuracy

The target composition was bronze with 15.45wt%Sn. Co-smelting and cementation attempts resulted in 9–12wt%Sn alloys, and co-melting operations in practically total recovery (~16wt%Sn). However, a sufficiently skilled person could easily produce our best co-smelting and cementation bronzes with ~12wt%Sn. These have only ~4% less Sn than the co-melting bronzes.

In this case, the resulting bronzes fall into two separate sensate categories ('yellow copper', 5–12wt%Sn; 'golden copper', 12–20wt%Sn). Although bronzes with >16wt%Sn are more difficult to work (Scott, 1991), it is important to note that both sensate categories include relatively large bronze composition ranges that differ in up to 8wt%Sn. Therefore, if the targeted alloy during these experiments had been slightly lower or richer in Sn, the co-smelting, cementation, and co-melting products could conceivably have fallen in the same sensate category. Even the product of a less skilled person performing co-smelting or cementation (i.e. our ~9wt%Sn alloys) differs from the co-melting compositions by only ~7wt%Sn, i.e. within the limits of sensate categories. All of this implies that the resulting products of the three techniques could have been perceived as similar, worked following the same recipe(s), and judged as good-enough for obtaining small and simple objects involving a few hundred grams of metal (Kuijpers, 2017). This is the scenario reflected in Table 4.

If larger bronze amounts are involved, co-melting could be more clearly advantageous to secure a homogeneous alloy within the appropriate compositional range, as co-smelting and cementation seem to be prone to more variability. The influence of larger metal pools in alloy accuracy needs to be further explored experimentally, whether these were obtained in larger crucibles or through multiple parallel operations.

The preferential loss of Cu in co-melting operations and of Sn in co-smelting and cementation experiments provisionally supports that co-melting could maximise Sn saving. However, unless the Sn needed was obtained via exchange, metal losses during the independent Sn smelting operation on-site and the later slag crushing process must be considered. Sn smelting losses registered in the experimental archaeology literature and through the analyses of archaeological Sn slag are generally higher than the Sn saving benefits of co-melting (e.g. Adriaens, 1996; Bandama et al., 2015; Berger et al., 2022; Chirikure et al., 2010; Earl & Yener, 1995; Figueiredo et al., 2022, 2016, 2018; Friede & Steel, 1976; Heimann et al., 2010;

Mahé-le Carlier et al., 2001; Malham et al., 2002; Miller & Hall, 2008; Tylecote et al., 1989). Berger et al. (2018) situate Sn recovery rates only between 12wt%Sn and 42wt%Sn during Sn smelting. Thus, co-smelting and cementation seem better options to make the most out of the available cassiterite. Considering this, the general score for co-melting in the Sn recovery parameter in Table 4 should be regarded with great caution.

It is acknowledged that potential metal losses in slag have not been considered. Archaeologically, more evident metal losses in the slag are generally associated with co-smelting and cementation operations, which could accentuate the recorded experimental differences when compared to co-melting. However, it is worth remembering the small size of archaeological alloying slag (a few cm, often less), which is mostly made of molten ceramic. This suggests that metal lost in the slag when preparing big-enough amounts of bronze would not be significant.

Experiential Understanding of Techniques

Co-melting was experienced as the easiest technique, followed by co-smelting and then cementation. Co-melting provided good-enough results from the beginning. Equally, co-smelting easily produced metallic prills. After gaining some skills during the week, we left with the impression that a couple of extra attempts could have resulted in a proper ingot. Cementation was experienced as a technique very sensitive to minor changes. It was our impression that we needed to improve our skills if we wanted to keep working with this technique.

Ease, however, also needs to be evaluated according to the independent smelting of Cu and Sn necessary for cementation and co-melting operations. Although we only attempted each of them once (details in Supplementary Information 4), Cu smelting, despite being the first operation of the week, very easily produced metal. Sn smelting was the last operation of the week. By this time, we already understood the demands of the metallurgical pit, which had successfully produced bronze several times. However, Sn smelting was a disaster. Therefore, the difficulty of cementation might be somehow compensated by the ease of Cu smelting, whereas the ease of co-melting was strongly balanced by the difficulty of Sn smelting. These experiential, subjective notes were considered when filling in the 'ease' parameter in Table 4. Of course, a more developed set of skills gained over time regarding Sn smelting could have dictated otherwise. If so, the lower melting point of Sn would have likely facilitated the coalescence of Sn prills into an ingot. In the discussion section, it is further discussed how the progressive development of skills might affect the differences in performance between techniques.

Overall, the results summarised in Table 4 strongly support that, contrary to received wisdom, co-melting is not a very efficient option according to most parameters analysed, including Sn saving. This parameter is expected to be important in cassiterite-scarce areas. Moreover, when co-melting scores positively in a performance characteristic, there is usually another technique that can compete at the same level.

These experiments also support that co-smelting and cementation are broadly comparable in saving Sn and charcoal. Co-smelting saves more Cu and is easier than cementation. Cementation might be favoured instead when wanting to save time, and perhaps if Cu-ore impurities (Fe, Pb) are an issue to be avoided.

Finally and crucially, for the charge volumes tested, the quality of the bronze obtained is comparable between techniques. Thus, contrary to traditional assumptions, co-melting only seems clearly advantageous if metallic Sn is readily available (supplied in bulk via exchange) and when large amounts of metal are to be cast. From a methodological perspective, the end-products similarity means that it remains impossible to ascertain the technique used based on the compositional and statistical analyses of large datasets (contra Rovira & Montero-Ruiz, 2013); slag analyses remain fundamental.

We acknowledge that the number of experiments conducted is limited, that we experimented with a defined amount of metal, and that some of the experimental variables—namely the absence of slag due to the use of pure Cu-ores and non-refractory fabrics—do not fully resemble the prehistoric experience. If another type of Cu-ores was used, some minor/trace impurities derived from these would have likely ended up in the metal (e.g. Budd, 1991; Merkl, 2011). Thus, we emphasise the preliminary nature of this set of results that, nonetheless, serve to propose alternative and well-founded hypotheses to explain bronze alloying technique choices, as discussed in the next section. Such hypotheses must be further tested in a future, more comprehensive, series of experiments to expand and refine the performance matrix offered.

Discussion: Revising the Traditional Narrative on Bronze Alloying Development

In spite of the importance of bronze for prehistoric societies and of decades of research on bronze technologies, the historiography of bronze making is still dominated by simplistic, universal, unilinear models. These have tended to assume rather than test the performance inferiority of the oldest alloying techniques and their progressive, irrevocable replacement by newer ones: first co-smelting, later cementation, finally the culmination in co-melting. This explanation does not account for the role of socio-economic and environmental factors, neglects the agency of the decision-makers, and ignores key performance characteristics that might be relevant from a cost-efficiency point of view.

The critical literature review allowed us to isolate the microstructural and compositional features of bronze slag that must be considered to identify the use of a technique with a certain degree of confidence (see Table SI1.1) and to re-evaluate the characterisation of all the archaeological samples so far published (see Supplementary Information 2). The range of diagnostic features compiled in Table SI1.1 should promote scientific consensus when reporting analyses of bronze slag, ultimately helping us trace the use of alloying techniques more effectively. At the same time, the review allowed us to ascertain our real knowledge of bronze alloying techniques used in the past.

At the present state of knowledge, the archaeological evidence does not support the accepted model: the predicted replacement pattern does not occur, and several techniques coexist in the same contexts cross-culturally. Against this background, we hypothesised that different techniques (or a range of them) offer different trade-offs (e.g. lower metal losses, less charcoal and time investment, and a more suitable end-product), and hence were more advantageous under different contextual conditions (e.g. availability of Cu and Sn ores, wood resources for charcoal, time and labour, and size and quality of objects needed). Testing this hypothesis necessitated an investigation of behaviourally significant performance differences between techniques.

As performance characteristics are cross-cultural, a series of experiments recreating each alloying technique were conducted. These considered the manufacture of small- and medium-sized objects, by aiming to produce ~120 g of bronze with ~15wt%Sn using the simplest possible metallurgical installation—i.e. broadly relevant for early bronze metallurgical traditions practically everywhere. In summary, the three alloying techniques can produce a comparable final product whilst offering different trade-offs during production (Table 4).

Importantly, some of the performance differences determined in Table 4, like differential metal losses or easiness, might have varied over time as metallurgists improved their skills. Others, however, such as time commitments, charcoal investments or the ability to reduce ore-related impurities are more heavily dependent on practical aspects of the techniques themselves: e.g. the number of operations required by each technique, the different time needed to smelt or melt metal, and/or the type of ores available. Therefore, even if the presented experiments represent the 'beginners' side of the metallurgical skills spectrum for the evaluation of some specific parameters, they still reflect existent performance differences between techniques. These are especially relevant—but not only—for the early stages of bronze metallurgy development across the world. Further experimentation will refine our knowledge of the extent and variability of these differences. For now, it can be sustained that no one technique—or a particular combination of them—can be considered a cross-cultural better option. This debunks the deterministic linear narrative so far accepted and opens the door to contextually understanding these technological choices in relation to socio-economic and environmental factors.

A fundamental consequence of discarding the traditional narrative on bronze alloying technology development is that we can now expect a lower incidence of co-melting in the archaeological record, as this was the least advantageous technique in many of the analysed parameters. Co-smelting and cementation were likely more frequently practiced instead. Although further bronze slag analyses are needed, the archaeological data available appear consistent with this scenario (see Supplementary Information 2). These observations also nicely explain the general absence of Sn metal and Sn smelting slag in the European archaeological record during the Bronze Age and especially during the Early Bronze Age (Berger et al., 2018).

A lower incidence of co-melting could be expected particularly in settings where small- and medium-sized objects were produced, i.e. the types of objects found since the beginning of bronze metallurgy up until the Iron Age in practically all bronze-making traditions. If co-smelting and/or cementation were frequently practiced in these contexts, this should have important consequences for our interpretative models of production organisation. For instance, this situation compels us to consider the exchange of Sn in mineral rather than metallic form.

While evidence of Sn ingots transport is undeniable in different contexts (e.g. Beagrie, 1985; Berger et al., 2019a; Hauptmann et al., 2002; Wang et al., 2016), their relative frequency is low. Also, considering the scarcity of Sn-ore deposits in the world, the potential role of secondary sources not profitable today (Huska et al., 2014), and the general persistence of co-smelting and cementation in cassiterite-scarce areas attested by the literature review, the possibility of a parallel network of long-distance cassiterite exchange has not received enough attention. Scattered direct evidence might point to the actual existence of such scenarios: for example, at Bajo de la Campana shipwreck (Murcia, Spain), both Sn ingots and cassiterite were found (Polzer & Pinedo Reyes, 2009; Renzi, 2013; Roldán Bernal et al., 1995). Therefore, even if specific technological traditions might have conducted Sn smelting by the mines (therefore constraining the alloying technique choices available to the corresponding bronze makers), the aforementioned evidence suggests that mineral Sn provision networks existed at least during specific moments of Prehistory in some areas of the world. Their geographical and diachronic spread and relevance are, however, impossible to ascertain with the current evidence.

In this regard, researching case studies in the cassiterite-rich areas of Europe (and beyond) can be doubly useful. Firstly, it will allow an understanding of bronze alloying technique choices under presumably low pressures for saving Sn. Secondly, it will help grasping how these cassiterite-rich areas constrained the alloying technique choices at cassiterite-scarce places by dictating the state in which Sn was traded (mineral and/or metallic). Thus, regions such as Britain and Northwest Iberia, where cassiterite abounds and it was mined during Prehistory (Timberlake, 2017; Timberlake and Hartgroves, 2018; Carey et al., 2023; Taylor, 2022; Meunier et al., 2023; Rodríguez Díaz et al., 2013), must be investigated. The very preliminary archaeological evidence from these areas remains too limited to allow firm conclusions.

In the case of Britain, for instance, it is likely that cassiterite availability promoted the very early development of a true Bronze Age earlier than in the rest of Europe (~2100-2000 BC) (Pare, 2000). However, besides the growing evidence of cassiterite mining, only scattered small Sn slag nodules have been reported so far from Carloggas Downs (Cornwall) and Dean Moor (Devon). The former dates to the Early Bronze Age and the latter dates to the Late Bronze Age (Malham, 2010; Tylecote et al., 1989). This is insufficient evidence to support either a widespread use of co-melting with the resulting Sn (at least from the Middle Bronze Age onwards) and/or a generalised exchange of metallic Sn to other areas of the UK and beyond later on (Williams et al. 2023). The 40 Sn ingots of the Salcombe shipwreck (1300–800 BC) balance this situation (Wang et al., 2016) demonstrating the trade of metallic Sn at least during this time. We therefore do not argue that co-melting or Sn metal trade did not occur, or that they were not prominent at specific moments in time. Instead, we propose that other bronze alloying techniques might have coexisted with co-melting, and that cassiterite trading networks could have been developed in parallel during specific moments. In fact, the only site with conclusive analyses of bronze slag samples available so far in the UK (Hengistbury Head, Dorset) has provided evidence of cementation use during Roman times (Northover, 1987, and see Supplementary Information 2 for discussion of Iron Age materials from this site). This persistence of cementation is definitely striking given the long-standing bronze tradition in the UK. Thus, considering and testing the proposed hypotheses through more bronze slag analyses across Britain would enrich our insights on the complexity of the 'bronzization' process (Vandkilde, 2016; Williams et al. 2023).

Equally, evidence from the Iberian cassiterite-rich belt is also scarce, but it points in the same direction. At Cerro de San Cristóbal (Extremadura, Spain), a site related to cassiterite mining activities during the Late Bronze Age, only cementation use has been identified so far (Rodríguez Díaz et al., 2001). Importantly, the general lack of slag and combustion structures at the site has been taken to suggest that the bulk of the cassiterite recovered was exported into Andalusia (Rodríguez Díaz et al., 2013), indicating mineral Sn trading networks. Besides this, two Sn ingots have been reported within two separate mining contexts in Galicia (Spain) ascribed to the Bronze Age (Monteagudo, 1954). Furthermore, Sn smelting slag has been recognised in only two sites across the Hispano–Portuguese cassiterite outcrops, at Outeiro del Baltar and Carvalhelhos hillforts. These Sn smelting operations were dated to the Iron Age (Figueiredo et al., 2018, 2022). Very importantly, at Outeiro del Baltar hillfort, which is very close to numerous cassiterite outcrops and Sn-bearing streams, Sn smelting activities coexisted with cementation and/or co-smelting during the Iron Age (Figueiredo et al., 2022). In parallel, the coexistence of co-smelting, cementation, and co-melting at the sites of La Fonteta (a Phoenician colony, Guardamar del Segura) and Emporion (a Greek colony, L'Escala) sites during the Iron Age supports the acquisition of both metallic and mineral Sn through exchange networks in these cassiterite-scarce areas, as no Sn smelting operations were identified at these sites (Montes-Landa et al., 2020; Renzi, 2013; Renzi and Rovira Llorens, 2016). This versatile scenario of exchange and use of both mineral and metal Sn in Iberia fits nicely with the aforementioned trade of cassiterite and metallic Sn documented at the Bajo de la Campana shipwreck during the 17th century BC.

Further bronze slag analyses are needed in Britain, West and Northwest Iberia (Portugal and Spain), Brittany (France, see Mahé-le Carlier et al., 2001 and Carlier et al., 2017 for prehistoric Sn production evidence), and other cassiterite-rich areas within and beyond Europe to further refine our discussion. However, the preliminary archaeological data available suggest that ancient populations still found somehow advantageous the use of co-smelting and/or cementation even in areas where the mineral resources would have allowed them to fully commit to the co-melting technique for the manufacture of all kinds of items. This supports the hypotheses raised by our set of experiments: that the specific performance advantages of the oldest techniques can explain their perdurance over millennia.

In the same vein, it is necessary to consider circumstantial evidence of copper production and exchange. Taking for example the production and exchange of copper across the Eastern Mediterranean during the Bronze Age (see Murray, 2023 for a comprehensive review), it is expected that most of this material ended up alloyed with tin through cementation or co-melting. However, at the same time, the co-smelting evidence found in 7th–5th century BC Isthmia (Rostoker et al., 1983) compels us to further analyse more bronze slag assemblages dated to the 2nd and

1st millennium BC to better understand socio-economic conditions that explain the survival of this technique. Alternatives to the more archaeologically visible models may have existed in some areas, and it is necessary that we start looking for them.

These findings urge us to understand how local socio-economic and environmental factors were interwoven with performance characteristics to shape bronze alloying decisions over time and across space. This includes paying attention to the inherited technological tradition, the value system, the level of social complexity, the trading networks that sustained production, the natural (un)availability of Sn ores, and the impurities associated to local Cu-ores, among other factors to be defined on a case-by-case basis (see the "Contextualising Alloying Technique Choices" section). Furthermore, when assessing this, it is fundamental to consider the incidence of bronze recycling in the technological system under study.

Recycling was likely practiced since the beginning of bronze metallurgy. Although targeted experimentation is necessary, it could be anticipated that for the production of small- and medium-sized objects, recycling would involve low time and charcoal commitments at the expense of some Sn evaporation during bronze melting, assuming that no extra cassiterite is added to compensate for the expected losses. Sn evaporation might affect particularly the quality of the end product if successive recycling rounds of the same metal batch are conducted. Besides, in cassiterite-scarce areas or in moments of unstable procurement networks, bronze recycling could have been an easy and good enough alternative to obtain new items of acceptable quality. This option might have coexisted with other alloying techniques, and the scrap metal transported in the Cape Gelidonya shipwreck supports this view (Lehner et al., 2020). Conversely, in cassiterite-rich regions, a high recycling rate might point towards alternative socio-economic conditions that favoured this choice, such as specific preferences of the technological tradition, concerns about environmental sustainability, or tight control of key outcrops by some groups.

A higher incidence of co-smelting and cementation in the past would also be relevant for the future of Sn isotopy studies for metal sourcing. Research on Sn isotopes shows that the isotopic field of some of the most important cassiterite deposits in Europe partially overlaps (Berger et al., 2019a; Haustein et al., 2010; Nessel et al., 2019), which severely compromises the use of this technique for provenance purposes. Moreover, experimental work has demonstrated that Sn isotope fractionation occurs during Sn smelting, leaving the slag enriched in heavier isotopes and hence unsuitable for cassiterite provenance. However, Berger et al. (2018) contend that it is still possible to provenance Sn metal if appropriate corrections are applied to the isotopic data, and his team implemented this recently with archaeological bronzes (Berger et al., 2023). The calculation of the necessary correction factor proposed by these authors, however, is based on analyses of experimental Sn smelting by-products. The problem is that, as mentioned above, most Sn experimental smelts yield a very limited amount of Sn out of the potential total recovery (e.g. Adriaens, 1996; Bandama et al., 2015; Berger et al., 2022; Chirikure et al., 2010; Earl & Yener, 1995; Figueiredo et al., 2022; Figueiredo et al., 2016, 2018; Friede & Steel, 1976; Mahé-le Carlier et al., 2001; Malham et al., 2002; Miller & Hall, 2008; Tylecote et al., 1989). Conversely, the above experiments show that Sn recovery is higher in co-smelting and cementation operations and that Sn vapour sometimes interacts with solid Cu during cementation. Both phenomena necessarily entail the fixation of more of the heavier (because more Sn is recovered) and lighter (because solid–gas interactions occur) Sn isotopes in the bronze resulting from a cementation and/or co-smelting operation, compared to smelted Sn used in co-melting ones. Furthermore, the multiple operations required by co-melting (i.e. Sn smelting and latter alloying) compared to the direct addition of cassiterite in co-smelting and cementation operations, would aggravate this situation.

As a result, it could be argued that different correction factors should be applied to bronzes made by co-smelting and cementation than to Sn metal or bronze resulting from co-melting. This seems to be supported by preliminary laboratory-based cementation and co-smelting experiments too (Berger et al., 2019b). Bearing in mind that the alloying technique cannot be inferred from finished objects, then Sn provenancing for small- and medium-sized bronze objects would be facing a likely dead end (or even for larger objects, if they were produced by multiple pours of smaller batches). Because these bronzes could be manufactured by any alloying technique, we would not know which correction factor to apply. As such, in line with a previous proposal (Martinón-Torres, 2018), the true potential for Sn isotopy of bronzes might be for technological rather than provenance studies: in cases where we are reasonably sure about the cassiterite source (and hence the original isotopic signature), isotopic analyses of the resulting objects could help inferences about the underlying alloying technique. Further targeted experiments are needed to clarify potentially different isotopic behaviours between techniques, as they may have an impact on the future of Sn isotopy and bronze provenancing, with implications on the models on mineral and metal transport and distribution.

All in all, this reassessment of the traditional historical narrative has exposed the fallacies of aprioristic assumptions and their inability to explain the development of bronze alloying technology. We are at present unable to offer a full alternative narrative because there is not enough empirical evidence. On a positive note, we now know what we need: a history built from the bottom up, based on properly contextualised studies. Furthermore, this paper provides a starting framework to formulate hypotheses and explanations.

Future research will require a dual strategy. On the one hand, more experimentation is needed to further refine the performance matrix offered in Table 4. This experimental plan should consider how the processing of larger metal pools could affect performance differences, and it could also be extended to include later stages (post-casting) of object manufacture. Further experimentation with dirtier Cu-ores and with less refractory ceramics can help explore the influence of slag formation on performance characteristics. As a side research strand, all the resulting materials could undergo microanalytical and isotopic analyses, to provide more robust references for the interpretation of archaeological materials. On the other hand, it is necessary to conduct further research on archaeological materials to be able to build an accurate narrative of bronze alloying development that considers the contextualisation of technological choices within their specific settings. This should entail (1) the microstructural and compositional characterisation of multiple slag samples from well-recorded sites, (2) their identification as by-products of a specific (or range of) alloying technique(s), and (3) the exploration of the relationship between the observed patterns of choice, and the specific socio-economic and environmental constraints. For numbers 1 and 2, Table SI1.1 can be a useful tool. For number 3, the performance matrix provided will be equally useful to ascertain how different contextual factors interacted with the performance possibilities offered by each technique, and how they dictated the acceptable thresholds of performance in each case. Ideally, archaeological case studies should include contexts of sole use of a given technique, as well as examples of coexistence of competing and/or complementary variants (see the "Contextualising Alloying Technique Choices" section). This would allow us to better understand how different (or similar) environmental and socio-economic factors can shape selection patterns across time and space.

The progressive aggregation of case studies will lead to a more truthful narrative of bronze alloying development that we should then integrate into our metal production organisation models. This is a large ambition that can only be achieved through collective, orchestrated research efforts. The gains may be significant, however, in fostering a new and fertile research arena for historical and anthropological studies of technology in society.

Conclusions

A critical analysis of the literature on the use of bronze alloying techniques in the past, combined with a series of bronze alloying experiments, exposed that the hitherto accepted narrative of bronze alloying technology development is fundamentally flawed. Co-melting of metallic Cu with Sn can no longer be considered the most advanced technique, and one that would be universally adopted once available. Instead, when manufacturing the small- and medium-sized objects that predominate in the archaeological record, co-smelting, cementation, and co-melting can result in a bronze of comparable quality, but each technique offers alternative trade-offs. No technique can be considered a cross-culturally better option, and their selection (of one, or a range of them) must have been dictated by the socio-economic, environmental, and performance factors relevant for a given context. This hypothesis can explain two peculiar patterns identified in the archaeological record: the absence of substitution of the oldest techniques by the newest ones, and the frequent coexistence of several techniques contemporaneously within the same contexts.

The rejection of the traditional narrative predicts that co-smelting and cementation use in the past was likely more frequent than typically thought, in detriment of the co-melting technique. If verified, this proposition should affect explanatory models for bronze consumption and production organisation, which typically do not consider the impact of bronze alloying techniques. For example, it would be necessary to reassess the provision strategies used to obtain the raw cassiterite that co-smelting and cementation operations require.

These experiments also suggest that co-smelting and cementation likely result in bronzes with Sn isotopic signatures different from those derived from co-melting operations. If so, different correction factors of the Sn isotopic signature of artefacts would be needed for provenance studies, depending on the alloying technique. This procedure would be challenging, however, since artefacts of volumes ranging from a ring to a dagger could be manufactured by any technique, and we are currently unable to identify the alloying technique through observations of finished objects. Thus, if co-smelting and cementation operations are confirmed to be more common than expected in the past, then the future of Sn isotopy as a tool for provenancing this type of items might be seriously compromised.

A more accurate narrative of Sn bronze alloying development inevitably calls for further systematic research on specific case studies, focusing predominantly on production debris. The exposed patterns of choice need to be contextualised within specific, and evolving, socio-economic and environmental dynamics, and assessed in relation to the performance matrix designed in this paper. This will enable us to contextually understand bronze alloying technique choices and their real impact in ancient societies, which in turn might entail the revision of current explanatory models.

This reassessment of the prehistory of bronze alloying provides yet another example of the risks of oversimplified, linear, and directional histories of technology (Erb-Satullo, 2020). It highlights the need of challenging technologically deterministic assumptions embedded in our interpretations, whose rejection has important consequences for our understanding of past human lives (Pfaffenberger, 1988). On the bright side, new areas of archaeological and theoretical enquiry are exposed, ultimately promoting a more holistic understanding of the past.

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Declarations

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