The Enkomi Cup: macrophotographic damage assessment

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ABSTRACT: Macrophotographs of the Enkomi Cup have been examined to assess the cracking damage in the Cup metal, a silver alloy. The resulting interpretations and their implications indicate that the cracks are most probably due to long-term stress corrosion that stopped well before excavation and restoration. It is concluded that no additional restoration and conservation measures are needed.

Introduction

The Enkomi Cup is a high-status silver artifact found in a tomb during excavations in the 1940s on Cyprus. It is now in the Cyprus Museum in Nicosia (Acc No 11.2.176.200). It dates to about 1400 BC (Organ 1977; Schaeffer 1952) and stylistically shows Aegean and Mycenean links. The Cup is decorated with an artificially black-patinated copper alloy and superimposed gold alloy inlays (Giumlia-Mair 2012). Figure 1 shows the Cup effectively as-found in 1949, and in the cleaned and restored condition, together with indications of some of the long-term burial damage. Although not clearly shown in Figure 1, the Cup handle has a bifurcated 'wishbone' configuration with each half of the wishbone attached to the Cup wall by three silver alloy rivets. The Cup itself would have been worked up from a flat sheet of base silver. This would have been done using multiple cold-working and annealing cycles.

The inference that the sheet metal, and also the handle, were originally base silver comes from the green corrosion products. These were formed by selective leaching of copper from the Cup and handle to form a crust of copper carbonates (Organ 1977). This corrosion process left the original silver surfaces of the Cup and handle unscathed, as evidenced by Figure 1b. The selective leaching also changed the bulk composition of the Cup, lowering the copper content and raising the silver and gold contents. Two composition measurements, concentrating on the three major elements, showed the cleaned and restored Cup to have a nominal wt% composition of 87.6Ag, 9Cu, 3.4Au (Plenderleith 1956) and 86.5Ag, 9.5Cu, 4Au (Giumlia-Mair 2012). The original composition is unknown, but the copper content must have been significantly higher. From the reasonable assumption that a pinkish tinge would be avoided in the finished artifact, modern colour descriptions (Roberts and Clark 1979; Leusch *et al* 2015; Khan 2017) indicate that up to 20wt% Cu would not be noticeable, but more than 30wt% Cu would have been too noticeable. On the other hand, several cycles of working, annealing and descaling (pickling) during the final stages of manufacture would, if done, result in surface and near-

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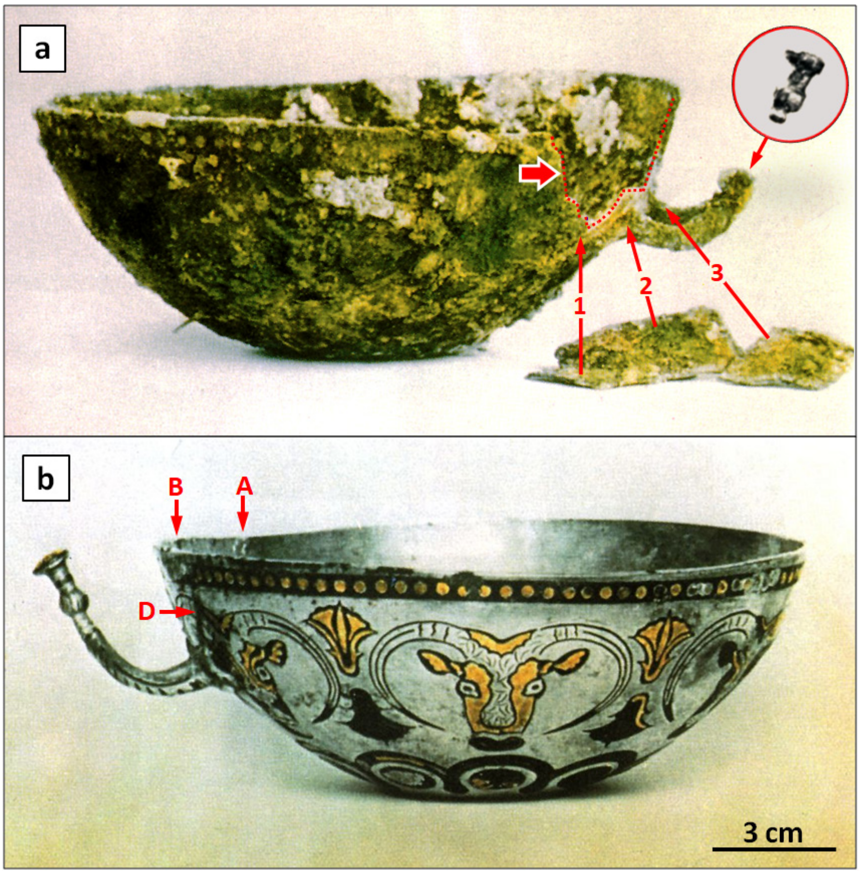

Figure 1: The Enkomi Cup. a) as excavated, with an inserted B&W image of the broken-off top part of the 'wishbone' handle (Plenderleith 1956); b) after cleaning and restoration. The images were originally hand-coloured (Organ1977; Schaeffer 1952) and lacked the red annotations: a) 1–3 are broken-off pieces and the outlined arrow points to the fracture surface profile in the cup wall; b) the letters A, B, D indicate barely visible cracking locations.

surface copper depletion and a silvery lustre when polished (Lechtman 1984).

The paragraphs above contain some uncertainties about the Cup's manufacture owing to limited information, except for the decorative black and gold inlays (Giumlia-Mair 2012). However, an essential detail directly related to subsequent long-term burial damage is the near-certainty that the final step was riveting the handle to the Cup. That is to say, there would not have been a final annealing treatment. The silversmith would not have recognized a need for one, see the discussion section of this paper, and may also have wished to avoid possible damage to the decorations.

The main purpose of this paper is to discuss the damage that the Cup has sustained from long-term burial and whether there are particular aspects that could be relevant to its ongoing conservation. This discussion is possible owing to macrophotographic evidence obtained as a spin-off from two recent examinations of the Cup (Giumlia-Mair 2012; Hart 2015). We note here that taking samples from the Cup is out of the question, as is usually the case for such valuable artifacts. Nevertheless, the interpretation of visual observations is sometimes sufficient, even for modern engineering components (Kishore 2021).

Restoration at the British Museum

The corrosion crust was removed from the Cup and handle by immersion in a boiling aqueous solution of formic acid for 20 minutes, after which patches of residual cuprite (Cu_2O) and reduced copper were removed by locally applying concentrated ammonia (Plenderleith 1956). Although not specified by Plenderleith (1956), the adhesive used to reattach the broken-off pieces of the Cup and handle would have been a cold-setting epoxy resin. This is inferred from Werner (1962), who provided a contemporary description of the advantages of epoxy resins: (i) achromatism and transparency, (ii) strength without brittleness, (iii) good adhesion to silver, and (iv) ambient temperature curing with low shrinkage. Werner (1962) also summarised a method of applying the adhesive to a very fragile bowl, by brushing viscous liquid epoxy over the inside of the bowl and allowing it to set. A complete description of this necessarily complicated restoration was given previously by Organ (1959).

Returning to the Cup, it was restored from the inside by applying the liquid adhesive sufficiently to re-attach the broken-off pieces and also reinforce a severely cracked but still attached piece. These observations will be discussed further below.

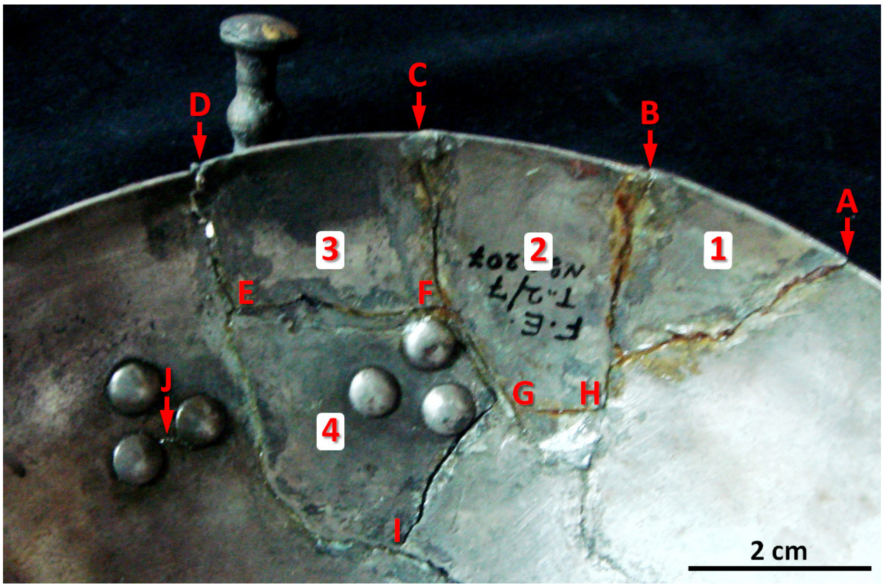

Figure 2: Partial view of the inside of the Cup. The red letters A–I refer to significant cracking locations; J appears to be a small crack between two rivets; the numbers 1–3 refer to the three broken-away pieces and the number 4 to the severely cracked but still attached piece. Also visible are the old and now yellowish-brown adhesive used to re-attach pieces 1–3 and partially re-attach piece 4, and a modern colourless adhesive (the wider irregular surface flanking the cracks and especially visible below the crack segment GH) superimposed on the old adhesive and continuing further into the Cup. The basic image is © A Giumlia-Mair.

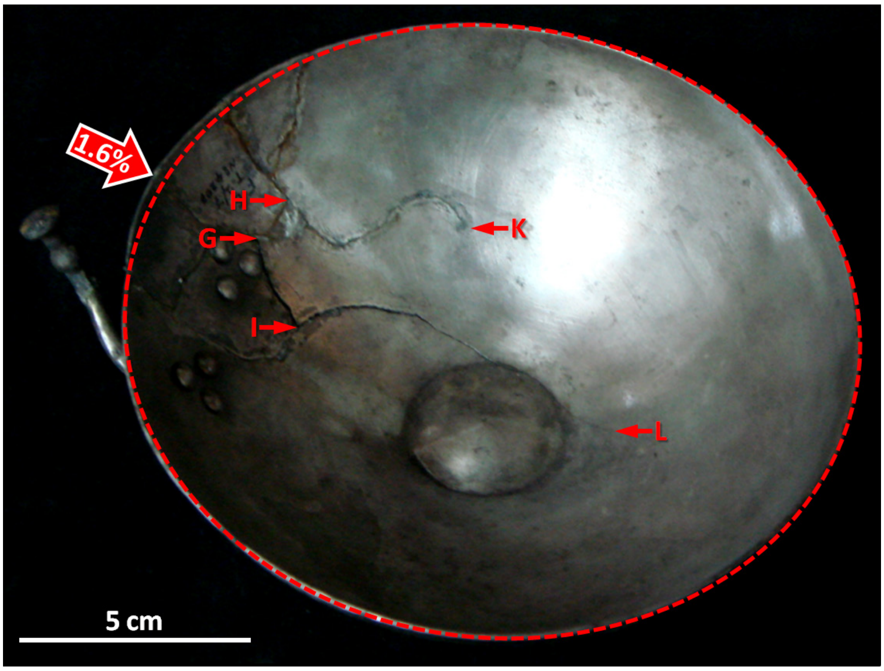

Figure 3: Inside view of the Cup. The letters H–G–I point to two cracked segments displaced from the local concave profile of the Cup, and the letters K and L point to crack arrest locations. The dashed ellipse indicates the perfect contour of the Cup rim before the long-term burial damage. This ellipse allows visualizing the deformation-induced distortion at the Cup rim: a maximum of 1.6%, equivalent to a horizontal displacement of 2.5 mm. The basic image is © A Giumlia-Mair.

Figure 4: External views of the large crack running from G to I and then to L (cf Figure 3). The right-hand image shows Cup wall displacement from G to I and a yellowish-brown smear of the old adhesive accidentally deposited on the external surface. The inset (to the left) shows that the crack from I to L is at least partly open. The right-hand basic image is © A Giumlia-Mair; the basic image used for the inset is from © C Hart 2015. The inset has been circularly cropped, re-orientated and very approximately matched in colour tones for compatible viewing with the overall view.

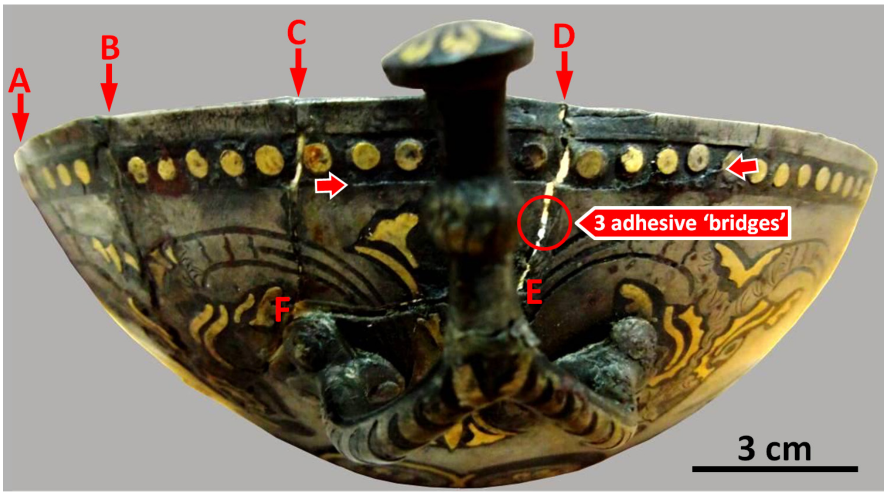

Figure 5: External view of the crack rim locations A–D and the coalescence of cracks CF, DE and EF that led to piece 3 breaking off (cf Figs 1 and 2). The long-term burial-induced cracking, deformation and distortion prevented neat attachments below the Cup rim, such that the CF, DE and CF crack surfaces are widely separated. Other notable details are the incomplete filling of cracks CF and DE by the old adhesive, accentuated by the presence of three adhesive bridges in crack DE; missing sections of inlay, whereby a trace and remnant between the white-outlined arrows just below the rim has the appearance of a narrow crack; and the misaligned top and stem of the handle. The basic image is © C Hart 2015.

Damage survey

A selection of some of the recent macrophotographs of the Cup and handle are presented in Figures 2–5. Table 1 classifies the damage into several categories and also records the presence of two restoration adhesives (old and modern).

Silver alloy damage

The combination of Figures 2 and 3 shows both an overall association of the main cracks with the region containing the two rivet clusters, and how the cracks coalesced into two single cracks that eventually arrested. This pattern and the wide CF and DE crack surface displacements visible in Figure 5 demonstrate that cracking began at locations A, B, C and D.

Figure 3 shows that restoration to optimise alignment of the rims of the broken-off pieces resulted in minor out-of-roundness of this rim segment. There are additional consequences: crack segment GI (Fig 4), and more clearly crack segments CF and DE (Fig 5), are displaced and have minor misalignments below the rim segments. All these features result from deformation and distortion during the long-term burial. Figure 5 also shows that the single-stem part of the handle is misaligned, especially the top 'cap'. This may have happened before burial.

Inlay and adhesive details

The two white-outlined arrows just below the rim in Figure 5 point to a region where the inlay has become detached, leaving a trace and remnant that under the photograph lighting conditions looks like a narrow crack. Many pieces of the gold inlays are also missing (Figs 1b, 4 and 5).

Figures 2 and 3 show the now yellowish-brown old adhesive and a modern colourless adhesive. As stated previously, the old adhesive is most likely a cold-setting epoxy resin, which would have been colourless when applied but has discoloured with age. The initial lack

Table 1: Classification of damage and restoration visible in Figures 2–5.

Figure numbers	Damage features: crack pattern	open cracks	crack arrest	detached inlay	deformation/ distortion	old adhesive	modern adhesive	missing gold inlays
Cup								
1b								•
2	•	•				•	•	
3	•		•		•	•	•	
4	•	•			•	• smear		•
5	•	•		•	•	•		•
Handle								
5		•			•			

of colour explains why the yellowish-brown smear indicated in Figure 4 was not noticed during restoration.

Discolouration of the old adhesive (Fig 2) also reveals that restoration to re-attach pieces 1–3, and partially re-attach piece 4, was sparingly done along the edges of pieces 1–3 but not along the crack segment GI. Nor was the old adhesive applied along the crack segments IL and HK (Fig 3). Additional evidence of this minimal approach is provided by Figure 5, which shows incomplete filling of cracks CF and DE.

Discussion

As stated in the introduction to this paper, the main purpose is to discuss the damage sustained by the Cup (mainly the cracking but also some local deformation and distortion) and determine the relevance of the damage, if any, to its conservation. Before this can be done, it is necessary to describe the types and causes of cracking that have found been to occur in ancient silver artifacts. The cracking is designated as embrittlement because silver alloys, including ancient and historic ones, are normally ductile and malleable (*eg* Taylor 2013).

Ancient silver embrittlement

There are essentially three kinds of ancient silver embrittlement:

- General corrosion, manifested as the slow conversion of the metal surface to silver chloride (AgCl) in high-purity alloys (Gowland 1920; Organ 1977; Scott 1996), and copper corrosion products in base silver alloys, *eg* copper carbonates as in the case of the Enkomi Cup (Organ 1977). Strictly speaking, general corrosion is embrittling only when much of the underlying metal is lost, for example the lyre from the Royal Graves at Ur (Organ 1977).
- Selective corrosion: interdendritic in castings (Scott 1996); intergranular in mechanically worked and annealed artifacts (Vaníčková *et al* 2007); and both intergranular and transgranular in artifacts retaining considerable amounts of cold-work after finishing (Wanhill 2013; Wanhill *et al* 2008). The study of six corrosion-embrittled high-silver artifacts of widely different age and provenance has led to the conclusion that the intergranular and transgranular corrosion and resulting embrittlement are due to stress corrosion cracking (SCC; Wanhill 2013). Except for fully annealed artifacts, *eg* a Romanesque kaptorga (Vaníčková *et al* 2007), the stresses are residual stresses owing to retained cold-work and externally applied stresses from the soil weight during long-term burial (Wanhill 2013).
- Certain elements cause intergranular microstructural embrittlement of silver and silver alloys (Gowland 1920; Sisco and Smith 1951; Thompson and Chatterjee 1954). The latter authors investigated accelerated (elevated temperature) age-embrittlement of Ag-Pb and Ag-Pb-Cu alloys. This study was prompted by the brittleness and chemical compositions of ancient silver coins that originally would have been ductile. Thompson and Chatterjee (1954) concluded that lead precipitation from supersaturated solid solution in the silver matrix resulted in embrittlement. However, atomic segregation to grain boundaries is most probably sufficient to cause embrittlement (Wanhill 2002; Wanhill *et al* 1998).

A synergistic combination of SCC and ageing-induced microstructural embrittlement is possible. However, only one artifact, an Egyptian vase, has until now been reported to have this combined damage (Wanhill 2011; Wanhill *et al* 1998). The vase metal is very fragile and owes its current survival to extensive non-reversible restoration with an organic material functioning as an adhesive, and also as a filler where large pieces were missing (Wanhill *et al* 1998).

Further, it is important to note that the metal adjacent to and remote from general corrosion and SCC is normally not embrittled. In other words, the undamaged metal retains its normal mechanical properties unless becoming microstructurally embrittled. Even so, age-induced microstructural embrittlement, although intrinsic and resulting in generally fragile artifacts, does not necessarily destroy them. An example is a partially cracked but otherwise well-preserved Roman kantharos (Wanhill 2011; 2018). It is also fortunate that microstructural embrittlement appears to be less prevalent in ancient silver artifacts (Wanhill 2018).

Cup crack pattern

The crack pattern mentioned in Table 1 and shown in Figures 2 and 3, began along the Cup rim at four locations. The crack origins A, B and C are offset to the left of the centreline between the two clusters of rivets. The cracks cross-linked and coalesced as they grew away from the rim, forming two longer cracks that eventually arrested. An explanation for this crack pattern is given here, relying on several assumptions:

- A combination of residual stresses from the riveting process and the weight of the soil (burial stresses) during long-term burial. The assumption of residual stresses remaining after riveting is the near-certainty that a final annealing treatment would not have been used. The silversmith would not have been aware of the modern concepts of residual stresses and stress

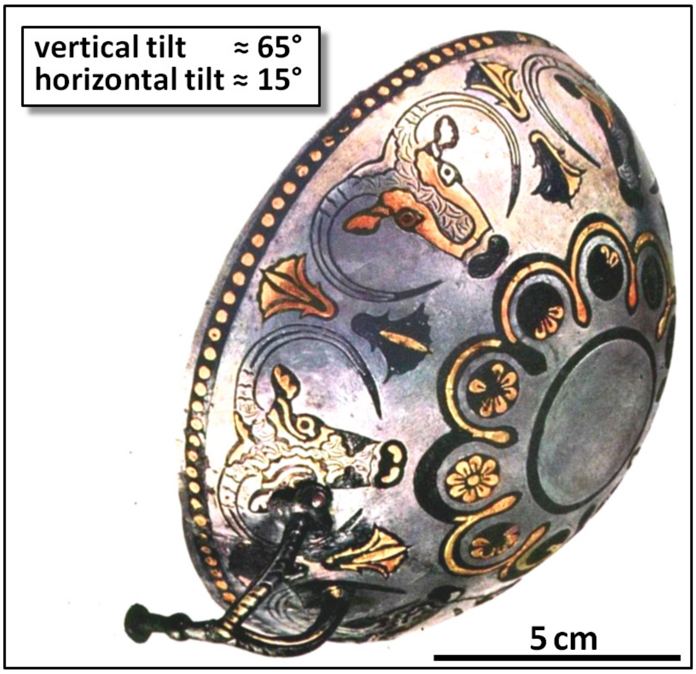

Figure 6: Suggested long-term stable orientation of the Cup during burial, based on the overall positions of the main cracks and their origins at locations A, B, C and D. NB: the horizontal tilt appears exaggerated in this representation. Original image: The APSIDA Repository of the UNESCO Chair on Digital Cultural Heritage at the Cyprus University of Technology.

concentrations (the rivet holes), but only that the handle had been attached without visible damage to the Cup.

- The predominance of burial stresses, since the Cup wall thickness is only about 0.9mm along and beyond the main crack locations A–D.
- The Cup orientation during long-term burial. To promote cracking from the rim and achieve the offset of the crack origins A, B and C from the area most influenced by residual stresses (*ie* the area surrounding the rivet clusters) it is suggested that the Cup was in a long-term stable orientation such as in Figure 6. Note that the suggested orientation also helps to explain why the Cup handle broke just above the wishbone, presumably owing to cracking induced solely by burial stresses.

Cracking details: identifying the type(s) of cracking

The Cup damage possesses several features that can assist in identifying whether the cracks are due to SCC or age-induced microstructural embrittlement, or both. Figures 1–5 and Table 1 provide the main observed features, namely several crack nucleation sites, the crack coalescence pattern, crack arrest, open cracks, and deformation and distortion. The following remarks about these features are derived from empirical knowledge about ancient silver embrittlement (Wanhill 2002; 2011; 2013; 2018; Wanhill *et al* 1998) and basic fracture mechanics (Janssen *et al* 2002):

- Crack nucleation: Generally speaking, SCC frequently begins at several locations, while brittle fracture usually begins at a single location.
- Crack coalescence: SCC and brittle fracture often result in secondary crack branching in the direction of crack growth. However, brittle fracture does not usually proceed by crack coalescence in the manner illustrated by Figures 2 and 3. Note that this is a negative statement with respect to brittle fracture, rather than a positive one favouring SCC.
- Crack arrest: Both SCC and brittle fracture can arrest. However, the meandering of crack segment HK and the considerable length of crack segment IL (Fig 3) disfavour brittle fracture. Brittle cracks tend to be macroscopically straight and grow rapidly, developing kinetic energy that can be used partly to increase the crack length, even when the applied local stresses markedly decrease. Thus if the segment IL were a truly brittle crack the Cup would probably have fractured completely.
- Open cracks: Open cracks are typical of fractures with associated (sometimes very limited) plasticity, unlike brittle cracks, which tend to be narrow.
- Deformation and distortion: The fact that the broken off pieces 1–3 and still-attached piece 4 underwent deformation and distortion, visible especially in Figure 5, shows that the uncracked metal has not been microstructurally embrittled. Instead, this type of damage is most likely a consequence of SCC progressively weakening the attachment of the pieces, thereby introducing stress concentrations in

the uncracked and unembrittled metal ahead of the cracks and enabling localised plasticity-induced deformation. This scenario is plausible because the Cup wall thickness is only about 0.9mm at the main crack locations and therefore has low resistance to distortion.

Implications for restoration and conservation

The points above, taken together, mean it is reasonable to conclude that the cracking damage in the Cup is the result of SCC, and that the Cup has not undergone microstructurally-induced embrittlement. However, at the time of the Cup's restoration, in the early 1950s, it was thought that 'old silver is invariably much more brittle than silver that has been recently cast' (Plenderleith 1956, 217). This statement, based on much experience in restoring ancient silver artifacts, is understandable but not entirely correct. For example, part of the much later restoration of the well-known Khan Cup involved the reshaping of strongly deformed fragments supported by a rubber backing while applying light pressure with burnishing tools (Stawinoga 1997).

Although Plenderleith (1956) discussed heat-treatment as a general means of restoring the ductility of ancient silver, followed by careful reshaping, this would not have been an option for the Enkomi Cup owing to the risk of further damaging the gold inlays. Instead he chose the minimal approach using adhesives described above. This has been supplemented by a later application of a modern adhesive.

The main question arising from the present investigation is whether the results suggest additional reinforcement and/or care to be advisable. The answer is apparently no, for four reasons:

- The two final crack segments HK and IL grew well away from the area of assumed residual stresses encompassing the rivet clusters. Such residual stresses would anyway have been relieved by the earlier cracking of pieces 2–4 (Fig 2). It is assumed that piece 1 was too far way to be affected by residual stresses, and that the burial stresses and environment were responsible for its cracking and detachment.
- The final cracks both arrested. Given the time that the Cup was buried, more than 3,000 years, it is most likely that crack arrest occurred some considerable time before excavation, *ie* with a weight of soil still on the Cup.
- After excavation there are no stresses on the Cup and only a normal air environment in its communal display cabinet. This means that if the cracking during burial was SCC, as is most probable, there is no possibility of it recurring.
- Both the Egyptian vase (synergistic embrittlement) and Roman kantharos (microstructural embrittlement) mentioned above were investigated in detail (Wanhill 2011; 2018; Wanhill *et al* 1998) after small pieces of silver alloy metal became detached during careful handling and cleaning. These types of continuing damage have apparently not happened to the Cup.

Nevertheless, it is obvious that the Cup should always be handled with care, as befits its condition, rarity and high status.

Summary

An investigation of this kind, without detailed scientific evidence, cannot provide definitive conclusions. A summary stating the most probable interpretations of the findings has to suffice. Detailed examination and interpretation of the features shown in the macrophotographs strongly suggest that the silver alloy cracking sustained by the Enkomi Cup is due to long-term stress corrosion cracking (SCC) caused by internal residual stresses and burial stresses, in combination with the burial environment. Three pieces containing four crack origins broke off from the Cup but not before they were slightly deformed and distorted, indicating that the silver alloy was ductile, *ie* not microstructurally embrittled. Piece 4, still attached to the main part of the Cup, was contiguously cracked with pieces 2 and 3, and also slightly distorted. The final segments of cracking have arrested, most probably well before the Cup was excavated.

Given the findings, their interpretations and implications, and no evidence for subsequent detachment of small pieces from the Cup owing to microstructural or synergistic embrittlement, it may be concluded that no additional restoration and conservation measures are required.

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