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Over the rainbow? Micro-CT scanning to non-destructively study Roman and early medieval glass bead manufacture

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ABSTRACT

Desktop micro-CT scanner has become a standard piece of equipment for many materials science laboratories and is increasingly popular in the field of archaeology for the study of archaeological soils and small archaeological artefacts. The technique does have limitations which are reviewed. Then, the usefulness of desktop Micro-CT scanners for the study of archaeological artefacts is demonstrated in a non-destructive study of manufacturing methods of Roman and Early Medieval monochrome and polychrome glass beads. Differences in glass colours show up in these scans as differences in attenuation. The presence and distribution of bubbles and various inclusions (metal, opacifier) are also well visible. Shaft shapes and patterns of bubbles inside the glass make it possible in most cases to distinguish between drawn, wound and constructed (millefiori) beads and to study shaping methods. Shafts shapes also reveal shapes and dimensions of the mandrels used in bead manufacture. Decoration and construction methods are visualized and studied in virtual cross-sections and semi-3D rendered images of selected glass colours. Visible degradation processes - including fissuring, leaching (especially of opaque yellow glasses) and dissolution processes - are highlighted. The micro-CT scans demonstrate how quality of raw glass, base design and workmanship in bead manufacture have improved with time. Moreover, it shows how these scans may serve as basis to discuss the organization of workshops where simple or more complex objects were made from non-metallic raw materials, and the availability and distribution of different qualities of raw materials for these workshops.

1. Introduction

1.1. scanning in archaeology

Chemical, physical and microscopic analyses and recording are core and major parts of archaeological science studies. Since many techniques are destructive, choices have to be made between damaging scientific analyses on the one hand and preserving archaeological remains as source for future study and as cultural heritage on the other hand. Studying micro-spatial and micro-structural properties of artefacts often requires especially damaging approaches like making and analysing cross-cuts, petrographic slides, or thin sections. Even then, these techniques are limited by the fact that they provide a 2-D cross-section of what are essentially 3-D spatial properties.

X-ray Computed Tomography (CT) techniques in general have the dual advantage that they are non-destructive, and at the same time

provide possibilities for recording, studying and analysing the 3-D spatial characteristics of the materials or objects studied. “Normal” or medical CT scans have been sporadically applied in archaeological contexts, mainly for determining the content of blocks of soil from burial sites (Jansen et al., 2006) and cremation urns (Anderson and Fell, 1995; Harvig et al., 2012) without the risk of damaging vulnerable artefacts during excavation or for inspecting ancient mummies, in order to derive biographical information, detect signs of pathology or allow facial reconstruction (Lynnerup, 2010). The same techniques have also been used to study material properties and manufacture of artefacts – in particular ceramics (Applbaum and Applbaum, 2005) – but for this, usually higher resolutions are required. This higher resolution can be achieved using X-ray micro-CT scans.

In the last decade, the use of X-ray micro-CT has made it possible to study the internal structure of archaeological objects non-destructively, and at high resolution (microns). This non-destructive technique

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(Cantatore and Müller, 2011 and Cnudde and Boone, 2013) can be used to inspect the internal composition and 3-D structure of objects of a wide range of materials, including glass. This makes this technique extremely useful for studying the manufacturing techniques and material properties for non-metallic objects. X-ray attenuation is function of object thickness, material density and mass attenuation coefficient. The mass attenuation coefficient depends on the X-ray energy and the cube of the atomic number of the chemical elements present in the material. Thick objects made of metals with high atomic number like lead obstruct X-ray. Micro-CT is increasingly popular in the field of archaeology for the study of archaeological soils (Ngan-Tillard and Huisman, 2017) and small archaeological artefacts (Bertrand et al., 2012; Tuniz and Zanini, 2014; Barron et al., 2017). With repeated (time lapse) 3D-X-ray imaging, microstructural transformations caused by environmental changes imposed to archaeological artefacts can also be tracked (McBride and Mercer, 2012; Ngan-Tillard et al., 2015, 2016). Both degradation and conservation processes can be investigated (Bertrand et al., 2012).

X-ray micro-CT can be conducted at one of the few synchrotron facilities available worldwide, but also using a desktop micro-CT scanner. The latter has become a standard piece of equipment for many materials science laboratories and is readily accessible to archaeologists. Compared to lab-based micro-CT, synchrotron based micro-CT is faster and provides results with similar or often higher degree of detail. It is performed using a high quality parallel monochromatic beam which eliminates the beam hardening (white corona effect) that is inherent to micro-CT scans obtained with polychromatic beams.

Lab-based micro-CT scanners deliver scans which have a sufficient resolution for the study of small objects: between 5 and 10 micrometres for a 10 mm diameter object, i.e. about one to two thousandth(s) of the width of the object. With the development of local tomography, a higher resolution can be reached for larger objects in a given region of interest (Maire and Withers, 2014).

Sufficient X-ray attenuation contrast between the materials present in an artefact is a *sine qua non* condition for the conventional micro-CT technique used in this article. With the less common phase contrast X-ray micro-CT (Bertrand et al., 2012), even subtle contrasts in density can be resolved.

1.2. Limitations of CT scanning and post-processing

Several artefacts are inherent to X-ray tomography. Some can be mitigated during scanning by careful choice of appropriate scan parameters and by hardware filters. Others can be corrected for during reconstruction and post-processing of the scanned object (Cheng et al., 2017 and Cnudde and Boone, 2013). Remaining X-ray artefacts have to be understood in order not to mistake them for real features (see further below).

Reconstruction consists in combining radiographs recorded during the scan in order to model the object as a 3D matrix of voxels. Each voxel is assigned a grey value that corresponds to the local X-ray attenuation of the object. As reconstruction algorithms are expected to improve rapidly by integrating a-priori information on the object in the reconstruction or by fusing micro-CT data with other kinds of tomographic data (neutron tomography data, for example), both raw and reconstructed data should be archived to allow better reconstruction in the future. The size of the data sets (1–100's of GB per set) does require large storage capacity.

After reconstruction, the inner structure of the object can be visualized. The data can be further processed to improve image quality and segmented to extract selected features. These features can be subjected to a morphometric and spatial distribution analysis, in order to evaluate, for example, manufacture skills or extent of damage. The volume that they occupy can be represented to better understand their 3D depositional context and their surface can be generated and meshed, for producing 3D printed replicas, that can be manipulated for a closer

relation with the object and a better understanding of its use. Abel et al. (2011), for example 3D-printed virtual flints produced from X-ray micro-CT scans for detailed analysis of knapping styles. As the surface of a volume generated from micro-CT scans is oversampled, mesh simplification and smoothening are often required to allow 3D printing. This adds to the uncertainty of the final product.

Image processing and image quantification allow to derive valuable information from micro-CT scans. Even when using high performance computers equipped with fast graphic cards, they can cost 10 to 100 times the data acquisition time (Maire and Withers, 2014) which is about 60 min for small beads! Checking the results of each step of the image processing such as feature segmentation and separation over a whole object is particularly time consuming.

In brief, the models resulting from micro-CT scans have a high spatial and density resolution but are also tainted with uncertainty related to each phase of the scanning, from data acquisition to surface generation, as well as to the scanned object itself and the environmental conditions of the scan (Cheng et al., 2017). Quantification of uncertainty in micro-CT scans deserves more attention.

One must also be aware that, despite being classified as a non-destructive method, X-ray micro-tomography has been reported to alter visibly the colour of some materials, including antique glasses. Colour changes in glasses occur mainly around the impurities that glasses often contain. Some are reversible by exposure to UV light (Bertrand et al., 2012; Bertini et al., 2014). The photon beam sent by bright X-ray sources can also cause non-visible radiation-induced damage at the atomic level. By ionizing the material, it can affect results of future investigations (Bertrand et al., 2012). As the X-ray beam interacts with electrons around the nucleus of atoms, it is more likely to impact analyses based on the number of electrons trapped within the atom such as thermo-luminescence and optically stimulated luminescence-dating (in contrast to e.g. ^{14}C -dating, which relies on the number of neutrons contained in the nucleus of Carbon atoms). Fast electrons generated by X-ray radiation can produce secondary ionization that can degrade molecular bonds in matter. Organic compounds are thought to be among the heritage artefacts the most vulnerable to structural alteration by X-ray radiation (Bertrand et al., 2012). Ongoing research aims at monitoring radiation induced damage and determining tolerable doses of radiation for a wide range of materials. The task is complicated, in particular for composite archaeological artefacts (Bertrand et al., 2012). In any case, all information allowing the calculation of the dose of X-ray to which an artefact has been subjected should be archived so that possible bias on future analyses can be evaluated (Bertrand et al., 2012; Zappala et al., 2013).

1.3. Application in archaeological glass

Archaeological glass artefacts are arguably among the most complex of the non-metallic archaeological artefacts: To a basic, compositionally more or less homogeneous glass, variability is introduced by colourants and decolourizers, giving different properties to differently coloured glass. Opacifiers basically cause the formation of specific minerals in the glass, causing additional small-scale variability. The plasticity of the material at working temperatures allows manufacture of objects in which different types of glass are combined in detailed, complex and intricate 3-D designs. Finally, some types of glass are particularly sensitive to dissolution and fragmentation processes. Observing and understanding the resulting potentially extremely complex structures in (often relatively small) glass objects is not easy, especially if damage to the objects has to be limited.

All these aspects would theoretically be observable in micro-CT scans: As X-ray attenuation is strongly influenced by the concentration and atomic number of (especially the heavy) chemical elements glasses of different chemical composition – often related to colour – can be distinguished. This makes it possible to analyse the way that different glass colours are combined in polychrome objects. Moreover, impurities

and bubbles present in the glass mass can be visualized and the morphology of the surface and enclosed spaces like (narrow) bead shafts can be inspected non-destructively. Despite this potential, micro-CT has only been applied sporadically to the study of objects of glass or other vitreous materials: Gu et al. (2014) analysed Chinese faience beads using a synchrotron-based micro-CT scanner, whereas Cheng et al. (2017) applied synchrotron-based CT techniques to study Chinese polychrome glass beads. In their approach, the CT techniques were effectively used to create non-destructive cross-sections in order to study the geometry of the inside's objects. 3-D approaches were first used in vitreous materials in three studies from 2014, using segmentation and rendering techniques: Bertini et al. (2014) analysed scans of Iron Age Scottish glass beads acquired with a synchrotron beam line to study their manufacturing process. Huisman et al. (2014) used desk-top micro-CT scanning to study the material properties and quality of iron age glass beads. Schalm et al. (2011) studied the distribution of Man-ganese minerals in heavily degraded glass.

1.4. The present study

With the present study, we explore the potential of desktop micro-CT scanners for inspecting and quantifying the microstructure of small objects. We focus on a selection of glass beads that have come available for research in the last few years. Because of the inherent large complexity that is found in especially the elaborated polychrome glass beads, this study can be used as a benchmark of the potential of using micro-CT scanning for investigating a range of features of other (types of) archaeological artefacts. We test to what extent micro-CT scanning can be applied in the study of manufacture of glass beads.

Large numbers of glass beads are found in early medieval cemeteries in Western Europe (e.g. Matthes et al., 2004; see also Müssemeier et al., 2003, Koch, 1977 and Siegmund, 1995, 1998). Burials of women and children may contain several bead strings – commonly necklaces – that each could count many dozens of beads. The majority of these beads are made from opaque glass. They show a great variety in colour and technical level of manufacture – often within one string – ranging from small, simple monochrome ones to large and complex polychrome beads in which e.g. red, white, yellow, blue, green and black glasses are combined in elaborate patterns. Where the decoration consists of cross-sections of polychrome rods, these complex beads are commonly referred to as “millefiori”. Beads that are decorated by winding twisted polychrome rods are known as “reticella” (Davison, 2003). It is assumed that the simple, monochrome beads were made locally in various workshops, as in the Netherlands alone, four potential early medieval sites are known with indicators for the manufacture of simple monochrome glass beads: Maastricht (Sablerolles et al., 1997), Wijnaldum, (Sablerolles, 1999), Leiderdorp (Dijkstra et al., 2010) and Oegstgeest (publication in prep.); see Fig. 1.

The complex and elaborately decorated beads, however, are thought to be imported over longer distances from few specialised workshops. Although none of these workshops have yet been identified, it is generally assumed that they were based in the Mediterranean. Moreover, some bead types are thought to originate from even further away, e.g. the Indian subcontinent (Pion and Gratuze, 2016). The combination of beads may reflect social status, with imported complex beads associated with higher status. However, there may also be links with lifecycle events (beads gifted to mark e.g. birth, adulthood, marriage, motherhood etc.) or family relationships (inherited beads, or beads brought into the area with foreign brides); see Kars (2011) for a recent discussion.

Although the technological level of glass bead production plays such an important role in social-anthropological interpretation of bead assemblages, there have been few studies on the manufacturing process itself. One reason for this may be that in-depth study of traces of the manufacturing process would require damaging the beads in order to search for clues on the manufacturing process. Curators in general,

Fig. 1. Palaeolandscape reconstruction of the Netherlands in the early middle ages (800 AD; Vos and de Vries, 2013), with archaeological sites mentioned in the text indicated.

however, are reluctant to damage these colourful and appealing objects.

Beads from three burial sites in The Netherlands were available for this study: Amersfoort (Roman), Borgharen and Lent (both Merovingian). The beads range from monochrome simple – sometimes even slightly clumsy – to polychrome complex and elaborately decorated ones. The Roman period beads at face value seem to be least well manufactured, and therefore form a good comparison with the Medieval beads. Micro-CT scans of these beads were used to study various aspects related to manufacturing processes, many of which are not apparent on visual inspection only. The (processed) results of these scans were used to derive material properties, manufacturing methods and degradation processes. We compare the quality of workmanship and of the glass used in manufacture of the beads, and discuss the implications for workshop organization. We conclude with an outlook on the wider application of micro-CT scans in archaeological artefact research.

2. Materials and methods

2.1. The studied beads

Eight cremation burials were found in 1989 in Amersfoort during the excavation of a settlement site. This location lies some 20 km north of the border of the Roman Empire at the Rhine in *Germania Magna*. Among the burial gifts were a bowl of decorated Samian ware and remains of Roman glass and metal objects. Based on the typology of the Samian ware bowl, the burial ground would date from the early third century AD at the earliest. One of the burials, with the cremated remains of a 35–52 yr old woman and a 12–16 yr old child, contained a set of 11 beads, seven of which were glass (the others were bone and bog iron ore). They comprise three black melon-beads, two spherical beads and two tiny (3 mm) torus beads (Snieder, 1996). All beads, except one of the melon beads, were analysed. At least one bead of each type was selected for this publication (see Table 1 for an overview of the beads analysed).

The Borgharen burial ground consists of a group of Merovingian inhumation burials within the remains of a Roman villa. The 6th–7th

Table 1

Beads used in this study and their characteristics.

		ID	Shape	Length (mm)	Decoration	Colours
Lent		5 - 19	Spherical	14	Millefiori	Blue, yellow, white, red
	5 - 27	Spherical	13	Millefiori	Blue, yellow, white, red
	9 - 21	Seven-sided rod	24	Millefiori	Blue, yellow, white, red
	26 - 29	Biconical	12	None	Blue
	26 - 32	Dumbbell	7	Encased metal	Dark grey
	41 - 15	Cylindrical	27	Polychrome bands (Reticella)	Red, yellow, green
	41 - 16	Spherical	12	Bands	Red, yellow
	41 - 19	Cylindrical	18	Polychrome bands (Reticella)	Red, yellow
	41 - 8	Parallelepiped	19	Chevrons	Red, yellow
Borgharen		1269-5	Spherical	7	None	Yellow
	1735	Spherical	14	Lenses	Grey/white, blue
	1732	Spherical	7	Bands	Yellow, orange
	1740	Cylindrical	16	White parallel bands	Red, white
Amersfoort		5	Melon	10	None	Black
	7,8	Spherical	8	None	Orange-black
	11	Torus	3	None	Orange

century AD burial pits were dug through the remains of one of the Roman buildings that had a hypocaust floor. After discovery, several of the burials were excavated in 1995 and 1999. Worries about looting and degradation processes on this site led to field campaigns in 2008, 2009 and 2012 during which an additional 7 burials were excavated - see [Lauwerier et al. \(2012\)](#) for the excavation report. The burials were

richly furnished with burial gifts of various kinds; one of the burials (feature 47) contained 208 glass beads. Based on the typology of [Siegmund \(1995, 1998\)](#), they date between 530 and 610 AD (group E). Due to post-burial disturbance – probably by burrowing animals – the original order on necklaces or other strings could not be determined anymore. All beads were analysed with hand-held XRF, the results of

Fig. 2. Field photographs of burial 9 in the Lentseveld cemetery. A: Complete burial; B: Close up of cranial region with polychrome glass beads. Note the two elongated (heptagonal) millefiori beads, one of which (9–21) was investigated further in this study. Photographs: Nijmegen Municipality.

Fig. 3. Micro-CT scan results of Amersfoort bead no. 5. A: Volume rendering. B: Orthogonal cross sections. The shaft of the bead is visible in the centre (s). Cavities (c) and inclusions (i) are indicated. C,D,E: 3D representation of the shaft (C) combined with the representation of voids (D) and inclusions (E).

which are reported in [Lauwerier et al. \(2012\)](#). A set of four beads of various types was selected from burial 47 in order to test whether micro-CT scanning would provide additional useful data on bead manufacture. They are Siegmund types S33,3 (1269–5), S33,7 (1732), S35,13 (1740) and Koch 3,5 (1735); see [Table 1](#).

In 2011 the Lentseveld cemetery was discovered just outside the village of Lent, lying at the north bank of the river Waal, directly across from Nijmegen. This hitherto unknown cemetery is the second Merovingian cemetery that has been excavated in the village of Lent and dates approximately to the 6th century AD. It has been investigated almost completely and consisted of at least 55 inhumation graves and 24 cremation graves. Most of the inhumation graves were well conserved and contained many grave gifts, including strings of glass and amber beads. In total, more than 1000 beads were found in 30 graves (21 woman's and 9 child burials). Because most beads were still in their original position, many of the strings and necklaces could be reconstructed (see [Fig. 2](#)). Standing out within this collection of beads, many of which are relatively simple of design with dominant red and

yellow colours - are elaborately decorated polychrome rounded and elongated beads made with the “millefiori” and – in two cases - “reticella” techniques. Another string consists of biconical green and grey/black to metallic annular beads. Nine of the beads of different types from Lent were selected for further analysis. They include relatively simple beads: spherical (41–16) and parallelipedic (41–8) beads with ribbon and chevron decoration respectively and a biconical bead (26–29). Other beads are more elaborated, e.g. a cylindrical bead with a red-yellow covering pattern (41–19) and a dumbbell-shaped transparent one with incorporated metal (26–32). And some are polychrome and more complex, like the two spherical (5–19 and 5–27) and one elongated heptagonal (9–21) millefiori beads as well as the large cylindrical reticella bead (41–15); see [Table 1](#).

2.2. Methods

The micro-CT scans of the beads were all recorded using a Nanotom (General Electrics) equipped with a 180 kV X-ray tube and a diamond

Fig. 4. Micro-CT characteristics of the various colours. A: Different glass colours in heptagonal millefiori bead Lent 9–21 as they appear in micro-CT scans. Different colours give different X-ray attenuation, whereas yellow and white opaque glass contains many small highly attenuating inclusions. B: Pattern with variable X-ray attenuation levels in monochrome blue-green biconical bead Lent 26–29, probably due to heterogeneous glass composition. White rounded inclusions are globules of metallic lead.

target. For most beads, 1440 X-ray 2D projection images were acquired on a flat panel CCD detector (field of view 2200×2200 square pixels) obtained from incremental rotation of the scanned object over 360° with a rotation step of 0.25° . At each step, 6 radiographs with an exposure time of 500 ms each were recorded, 1 radiograph was skipped and 5 radiographs were averaged to increase signal to noise ratio. The detector was shifted automatically during scanning for reducing the influence of defect pixels on the panel detector. The resulting radiographic projections are grayscale 16-bit tiff images with grey histogram values in the range of 0–65536. The scans were acquired using a high voltage of 90–160 kV, a current of 80–190 μ A, and a voxel size of 3.5–12.5 μ m. Despite the small size of the objects, a high voltage was necessary to penetrate the glasses rich in heavy chemical elements. The highest voltages were used for the largest beads. A thin copper filter was inserted between the X-ray source and the beads to block the weakest rays of the polychromatic beam and attenuate the strongest ones. In this way, beam hardening was reduced and the detector was preserved from direct impact by very high energy rays. The beam parameters were adjusted so that the average detector saturation reached not more than 100% saturation in an empty field of view to avoid over-exposure and exceeded 10% after passage through the bead. Scanning parameters per bead are available as supplementary information 1.

A number of simple precautions were also taken to obtain good quality scans. The beads were laid down on a block of foam fixed on top of a glass rod that was fastened inside the scanner turning stage in order to avoid X-ray interference with the mounting platform and facilitate

separation of the beads from the glass rods on the scans. To prevent any movement that would blur the reconstructed objects, the beads were secured with a light tape. The more vulnerable ones were inserted inside a plastic sheath and immobilised with a soft plastic film.

Visual inspection of the beads by the naked eye before and after scanning revealed no discolouration of the opaque, semi-opaque and transparent glasses. Alteration at the atomic level cannot be discarded without further study.

Reconstruction of the acquired 2D projections into a set of XY slices perpendicular to the axis of rotation of the object during scanning was performed using StudioMax, 2.0 (Volume Graphics). The reconstruction was generally performed at twice the resolution of the acquired images to keep the size of the data sets under 3.5 Gigabytes and facilitate post-processing. Like this, scans with a resolution equal at least to one thousandth of the bead diameter were obtained. Additional beam hardening correction of the 3D volume and denoising of the 3D volume with a median gaussian filter were also accomplished with StudioMax. It should be noted that since most beads are heterogeneous and never perfectly spherical nor cylindrical, full beam hardening correction is impossible. The XY slices were exported in 16-bit tiff format for visualization and analysis with AVIZO 9.3 and 9.4 (Thermo Fisher Scientific's). Sets of XY and XZ slices were cut from the 3D volume of each bead and were scrolled through for a visual exploration of the bead. Each voxel on a slice has a specific grey value. The grey value is a measure of the linear X-ray attenuation coefficient of the materials present in that voxel. It depends on the local density and the atomic number of the chemical element(s) present in the voxel, together with the incident photon energy. The lighter the voxel colour is, the higher the material attenuation is. Highly attenuating materials cause X-ray diffraction and are associated on the scans to bright star artefacts and black shadow zones, not to be confused with real cavities. Such streak artefacts cannot be easily corrected but are easily recognizable on scans.

Volume rendering was used to opacify more or less the digital bead representations and observe their external shape in relation with attenuating inclusions that they might contain or inspect their shaft, voids and any region of interest. Impurities and bubbles present in the glass were separated from the glass matrix by interactive thresholding. Bubbles connected to the exterior of the beads or their shafts were discarded in this process. Adjacent bubbles were not separated from each other. The images were cleaned with a despeckled filter. The smallest objects of the size of 3 voxels were considered as noise and discarded in the shape analyses. The quantification of the shaft morphology required a number of processing steps (separation of the shaft from the exterior of the bead, interactive thresholding, a sequence of erosion, filtering, and dilation, determination of the orientation of the shaft maximum inertia axis, and realignment of the shaft axis parallel to the vertical axis) before the 2D ferrets of the shaft could be measured in the xy planes at 10° spacing along the shaft length and minimum, maximum and average ferrets profiles could be drawn. In order to separate the shaft from cracks and other flaws connected to the shaft, a sequence of erosion, filtering and dilation (Gonzalez and Woods, 2008) was necessary.

In order to determine which colourants and opacifiers were used, additional analyses were done on the beads using hand-held XRF. Other analyses, including SEM-EDX and gamma-ray decay analyses are in progress on the Lent beads. These will be reported separately. In the present study, we will superficially refer to these results where it concerns discussion on or identification of the colourants.

3. Results and discussion

3.1. What can be seen in scans

A range of different properties of the glass beads could be discerned using micro-CT scans. Examples can be seen in Fig. 3 and

Fig. 5. Characteristics of the shafts of various types of beads. A: typical round, tapering shaft of bead Borgharen 1732, seen in cross-section. Differences in attenuation in the glass mass are due to colour differences. Note a thin band of decreased attenuation on the outer surface of the light grey glass, probably due to leaching. The lighter colours on the shaft surface and adjacent bubbles may be due to reactions between glass and the parting layer. B: Enigmatic six-sided shaft cross-section in Amersfoort bead 8; the heptagonal shape in the centre changes to elliptical near the ends of the shaft. Note also some large air bubbles and a network of fissures. C: 3-D rendering of the shaft of bead Borgharen 1732 (figure A,B). D: Shaft of bead Lent 41–8 with small tapering angle. E: Shaft of heptagonal millefiori bead (Lent 9–21; See Fig. 4A), showing a cylindrical shaft with burr-like extensions. They are voids – connected to the shaft – that formed due to incomplete accommodation of the glass blocks used to construct this bead. F: Roughly cylindrical, irregular shaft of spherical millefiori bead 5–27, with no clear imprint of mandrel or rod. G: Shaft of (drawn) bead Lent 26–29 (see Fig. 4B). The centre of the shaft is wider, probably because this is the location of the bubble present before the glass was drawn (b). Broken lines indicate the orientation of the shaft on both sides of the bubble, showing they do not align. H: Shaft of bead Amersfoort 11, showing that it is dotted with bubbles. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

supplementary information 2: Firstly, the scans provided a detailed image of the overall shape of the bead, including the shape of the shaft, with resolution at a few micrometres. These shapes could be studied in cross-section, by using volume rendering (Fig. 3A and B), or 3D thresholding (Fig. 3C). Moreover, the scans revealed the presence, size, shape and distribution of bubbles and cavities (Fig. 3D) as well as of diverse types of inclusions that may be present in the various types of glasses (Fig. 3E), up to a few micron in size. Grey values of the inclusions depend on their type, and differ between incorporated mineral grains, metal fragments and opacifiers (see also Huisman et al., 2014).

3.2. Micro-CT properties of the various glass colours

The scans revealed bulk glass masses with heterogeneous attenuating properties, probably due to differences in the concentration of various (relatively) heavy elements used as flux or stabilizer or as colourant, decolourant and/or opacifier. Additives can occur as component in the glass matrix, making it more attenuating, or – in the case of opacifying components – as small inclusions. A range of processes and additives are known to have been used to colour, decolour and opacify early medieval glass – see Rehren and Freestone (2015) for a recent overview. We will not focus on the chemical properties of this glass, or the specific components added to alter colour, opacity and workability in the present paper. This is subject of ongoing research. What is relevant for the present paper, however, is that the differences in chemical and mineralogical composition of the various glass colours result in different attenuations and variable presence of inclusions. As a consequence, the spatial properties of the different glasses used to make the beads studied here become clearly visible in micro-CT scans. Comparing the cross-section of a side of the elongated heptagonal

millefiori bead Lent 9–21 in Fig. 4A to the photograph of this bead in Table 1 demonstrates that most macroscopically visible colours are distinct in the cross section. This is partly due to differences in attenuation, which probably relate to the concentrations of elements like copper (Cu), iron (Fe) and especially lead (Pb) in the glass structure. In addition, the opaque white and yellow glasses contain considerable amounts of small inclusions that are most likely lead and lead-tin components that were meant to make the glass opaque and coloured. Similarly, the plate-shaped inclusions in bead Amersfoort 5 (Fig. 3B,E) are probably precipitates in some mineral form of the iron that was used to produce the opaque black colour. Most glasses with other colours and colourless glass look homogeneous in micro-CT scans. One exception is the green glass in biconical monochrome bead Lent 26–29: The image in Fig. 4B shows a large variation in its attenuation, indicating a heterogeneous glass composition. In addition, it contains globules (spherical inclusions) that were identified as metallic lead: The heavy material caused void artefacts (apparent cavities) in the micro-CT images, which are typical for heavy elements. Hand-held XRF confirmed that it was lead, whereas microscopic observations on a cut and polished fragment demonstrated that the metal was present in its metallic form (results of ongoing research). Metallic lead is unknown in ancient glass, and does not serve a specific function. As all the glass studied here seem to be leaded, making it better workable at lower temperatures, the lead inclusions may result from a (partially) failed attempt to produce leaded glass.

3.3. Bead manufacturing techniques

3.3.1. Tools used

The shape of the central shaft is determined by the methods and

Fig. 6. Graphs of shaft shapes. A: Distinguishing the different assembly methods using plots of the average surface shape (black line) and variability therein (grey fields). Mandrel – formed glass beads have a straight angled side with little variability. Drawn beads are widest at the centre, and have more variable shaft shapes. Millefiori beads typically are narrowest in the centre and show large variability. The red rings that cap these beads have a wider opening than the bead shaft proper. B: Average shaft shapes of all mandrel – formed glass beads. Bead 1735 shows extensive flaking on the shaft surface, disturbing the image. Note that G 41–8, G41–16 and 1740 have similar tapering angles. This might indicate that either these beads were made on the same mandrel, or that glass-making tools had uniform, standardized dimensions. C: Average shaft shapes of drawn beads. G26–32's shaft shape deviates because of modifications to the bead after initial forming; see below. Although AMF 7 has the same general shaft shape of the drawn beads, we cannot exclude that it was made on a mandrel and then shaped. D: Average shaft shapes of the two scanned complete millefiori beads. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

tools used to construct the basic bead. The shape of a shaft can become clear from cross sections (Fig. 5A and B), but segmenting and 3D representation as in Fig. 5C–G gives much more detailed information. Most beads show a tapered shaft see Fig. 5A + C and 5D. This is the negative of the mandrel (metal rod) used to make the bead. Tapered mandrels prevent beads from becoming stuck to them. The angle of the tapering varies considerably (compare e.g. Fig. 5C and 5D), as does the diameter. This demonstrates that the bead makers employed different tools to produce different beads.

A difference in attenuation in the glass around the shaft of Borgharen 1732 (Fig. 5A and B) as well as the bubbles around the shaft

of Amersfoort 11 (Fig. 5H) may indicate some kind of chemical reaction during bead manufacture. Both features may be related to interaction between the molten glass and the parting layer – a coating applied on a mandrel to prevent the glass to stick to (or react with) the metal. If this material contained clay or lime, this may have reacted with - or dissolved in - the glass.

In a more systematic comparison of shaft shapes, Fig. 6 demonstrates how the basic forming method of beads can be derived from the shaft shapes: Mandrel-formed beads (including reticella-decorated ones) have a tapered shaft with little variability. The shaft of the reticella beads widens at the ends because the decorative surface layer

Fig. 7. Patterns of deformation during glass shaping and forming. A, B,C: Borgharen bead 1740, showing swirls in wound glass. A: The red glass surface has zones with higher X-ray attenuation (h), showing a pattern that is incompatible with winding, and more consistent with winding a glass plate around a (tapered) mandrel. Note that the decorative white glass (w) shows many highly attenuating inclusions. B: Cross section, showing the winding pattern. C: Volume rendering of the less attenuating glass (i.e. darker grey in B). D: Elongated air bubbles due to forming (rounding off) of a drawn and cut bead. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

was made with a slightly larger central hole. Drawn beads have a more or less cylindrical form with more variability, and typically have a wider centre – although this shape can be obscured by later modifications. Finally, millefiori beads have the highest variability, with a more or less straight (G5-27) or a slightly tapered (G9-21) shaft.

The body of most mandrel-formed beads was probably made by winding a molten glass thread around it. Swirl patterns matching this may be apparent from the distribution of gas bubble in the glass, which in addition may have become stretched during the winding process (see below; Fig. 9C and Supplementary information C). Bead 1740 (Borgharen), however shows a different pattern: here, the cylindrical red glass in the oblique image in Fig. 7A and the vortex-like pattern in Fig. 7B show that the bead body was formed by winding an oblong or square piece of molten glass around the mandrel; maybe a remolten glass tessera. The shape of this piece, and its sharp edge are more clear from a 3D representation of the less attenuating glass in Fig. 7C (i.e. the darker grey in Fig. 7A).

Amersfoort bead 7 has strings of gas bubbles, some of them elongated, parallel to the surface (Fig. 7D). This may indicate that this bead was made by first making a cylinder of glass on a mandrel, and then separating off beads with a cutting implement. If the glass was drawn (see below), all bubbles should have been elongated. Its sister bead (Amersfoort 8) has a very irregular shaft that is locally heptagonal.

3.3.2. Constructing millefiori beads

The body of the three millefiori beads that we analysed (two spherical and one heptagonal elongated) consists of fused wedge-shaped polychrome “blocks”. These blocks were cut from polychrome patterned glass rods and come in several types: Concentric patterns are combined with flower-like shapes in the elongated heptagonal bead (Lent 9–21; see also supplementary information B). Flower shapes are brought together with squared spirals in spherical bead Lent 5–27, whereas squared spirals are mixed with concentric patterns in spherical bead Lent 5–19 (Fig. 8). Krzyżanowska and Frankiewicz (2015) describe a process of making millefiori beads by pressing polychrome glass rod sections into a molten glass core. Our beads differ from these in that the core is missing. The cross sections in Fig. 8 show that our beads were rather assembled directly from the cut glass building blocks. The overall cylindrical shape of the shaft indicates that assembling was done around a (metal) rod or mandrel. This shape, the slightly tapered shapes of the polychrome blocks and the compressed bubbles close to the shaft (Fig. 8C) indicate that the blocks were assembled while they were made or kept malleable to some degree. Still, the ridges in the shaft-reconstruction of Fig. 5E and F make it clear that the blocks did not accommodate completely, and that some spaces were left between them.

The shaft shapes of the spherical beads (5–19 and 5–27; Fig. 8D and E) are, more irregular but may have been formed around a straight rod. Some deformation or shape modification seems to have happened in these beads after the rod or mandrel was removed from the bead. All three of these millefiori beads were finished with a red glass ring at both ends. It is interesting to note that this ring is made from massive opaque red glass in bead Lent 9–21 while it consists of transparent glass with a thin outer layer of red glass in beads Lent 5–19 and Lent 5–27.

3.3.3. Making reticella beads

Two beads from Lent (41–15 and 41–19) are completely covered by bands of opaque polychrome glass; in bead Lent 41–19 red and yellow, in bead Lent 41–15 a combination of red, yellow and dark-green. Fig. 9A shows a neat orthogonal cross-section through the core of bead Lent 41–15, and squared decorative bands that differ in attenuation. The bright white domains are opaque yellow decorations. The core of this bead is homogeneous, but contains a large amount of small spherical gas bubbles (Fig. 9B and C). Some elongated bubbles on the corners of the decorative bands mark incomplete accommodation of the bands with each other and with the core. The rest of the bubbles show a spiral pattern, also sometimes with some elongations, that relate to the creation of this core by winding around the mandrel (see above). The decorative bands consist of a red or green/black core, decorated by remarkably thin spirals of yellow and – in a few cases on the green/black glass – red glass (Fig. 9D,E and Supplementary Information D). Note that the herringbone pattern on the outside of the bead as only achievable if one rod was wound clockwise, and the other counterclockwise. The rods are quite homogeneous in thickness.

The decorative bands on Lent 41–19 however – consisting of red and yellow only – were made by twisting a red and a yellow glass rods around each other (Fig. 9F; see also Krzyżanowska and Frankiewicz, 2015) – again clockwise and counterclockwise. Here, the rods seem to have been of variable thickness. Fig. 9G shows that the core of this bead consists of at least two glass colours – as is apparent from the swirl with differences in attenuation around the shaft. This core may have been a reused polychrome bead, but it may also have been made from polychrome waste glass. The core is not round anymore – probably deformed by the application of the decorative bands – and the shaft has become off-centre (Fig. 9G). Comparing the two beads indicates that both were made with similar basic (“reticella”) techniques, but that the technical complexity of the design, the execution as well as the temperature control during manufacture of bead 41-15 was of a higher technological level. The way the decorations on the flat surface of this bead were fitted is admirable.

Fig. 8. Stacked patterned polychrome glass blocks in millefiori beads from Lent; A: Cross-section bead 9-21. Arrows indicate locations where one specific glass colour (i.e. opaque yellow) seems to have partially degraded. B: Lengthwise section of the same bead. C: Gas bubbles in millefiori bead G9-21 are flattened (“smartie-shaped”) close to the shaft, but spherical near the surface. This shows that the polychrome blocks were compressed on one side to create a tapered form to fit the shape of the bead. D: Multiple sections of bead 5-27, E: Multiple sections of bead 5-19. Broken lines in B, D and E mark the contact between two cross sections. The cross sections clearly demonstrate how the beads were assembled from blocks of polychrome glass. Note that the red rings on the outside are massive red in bead 9-21 (B) but formed by a red layer on a differently coloured core in beads 5-19 and 5-27 (D,E). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.3.4. Drawing and forming

Bead Lent 26–29 and Lent 26–32 do not show patterning typical for wound beads: The – quite heterogeneous – glass in bead Lent 26–29 does not only show banding parallel to the shaft (Fig. 4B). The air bubbles in the glass are also remarkably elongated, parallel to the shaft (Fig. 10A). This patterning is consistent with the bead being shaped by drawing (see above): According to Pion (2013), such beads are made by creating an air bubble in molten glass, and then drawing the glass in such a way that a cylinder with a central tunnel is formed, which can then be cut to form rough beads, which are subsequently hot worked to achieve the desired shape. This would also explain the misalignment of the two parts of the central shaft, visible in Fig. 5E.

Dumbbell-shaped beads with embedded metal foil, like Lent 26–32 (see also Fig. 10B) were made – according to Pion (2013) – by first

drawing two hollow cylinders of transparent glass. A slight difference in size makes it possible to subsequently coat a (smaller) cylinder with gold or silver foil, and then insert it in a slightly larger cylinder. The dumbbell shape was made by inserting a metal rod in the centre of the middle cylinder, and then rolling the heated, plastic glass over a crenulated mould to shape a long annular bead. Individual beads are made by breaking a section with two spheres from this elongated annular cylinder. The geometry and distribution of the bubbles observed in Lent 26–32 are in agreement with this manufacture technique. Elongated bubbles have been produced during glass drawing (Fig. 10C and D). The almost continuous interspace between the inner glass layer coated with the silver foil and the 2nd glass layer has resulted from the fitting of the inner cylinder in a cylinder of a slightly larger diameter. Remnants of the space between the two initial cylinders are preserved in the widest parts of the bead (Fig. 10D). The interspace has disappeared on the neck of the bead where the glass has been rolled on the ridges of the crenulated mould. The cylindrical shape of the narrow parts of the shaft (Fig. 10D; see also 6C) mirrors the shape of the rod used when forming the dumbbell-shape on a ridged mould. In Fig. 10D, the silver foil (white) encased between the two glass layers is clearly discontinuous. In the two spheres, the fissures between the fragments of silver are in dominantly perpendicular to the axis of the bead. In the neck and the lower extremity, however, they form an oblique parallel pattern. It is likely that the silver foil was torn – pulled and stretched to breaking point – during the forming of the annular shape. The silver foil fissure pattern in the spherical parts is in line with this; it matches the elongated cavities in the glass in the spherical parts of the bead that probably were stretched at the same time. The oblique parallel pattern in the neck and lower extremity – also visible in elongated pores in the neck and on the surface (Fig. 10B) – suggests that the neck was twisted while still plastic.

3.3.5. Shaping beads

Most beads have a smooth surface. As demonstrated by Krzyżanowska and Frankiewicz (2015) – heating and turning may suffice to produce a rounded shape and smooth surface for most beads. As the spherical millefiori beads (Lent 5–19 and 5–27) were not made – or at least finished – on a mandrel, they were probably shaped with a tool; their outer surface is somewhat rougher than the other – more simple – spherical beads. The heptagonal elongated millefiori bead (Lent 9–21) and the reticella beads (Lent 41–15 and 41–19) were probably rolled on a metal plate (marver) and compressed from the sides with a metal tool in order to obtain their flat surfaces and sharp edges. Next to the dumbbell bead (Lent 26–32; see above), only Amersfoort 5 has further surface modifications. Here, a donut-shaped spherical or rounded bead was incised with a chisel-like tool to form the melon-shape (see Fig. 3).

3.3.6. Applied decorations

The most common technique to produce polychrome beads is the application of thin coloured bands – usually of yellow or white opaque glass. (Note that the reticella technique, where the decoration is an integral part of the bead creation, was discussed above). Depending on the subsequent heat treatment, these bands may be proud (stick out of the surface) or may be completely sunken into the bead and flush with the bead surface. In cross sections, it becomes clear that proud bands do not sit on the surface, but are also partially sunken (Fig. 11A and B,C). This confirms that they were applied when the glass body was still plastic.

Bead Lent 41-8 has a pattern of chevrons (yellow on red). Such chevrons are typically made by drawing a glass rod or metal tool vertically over previously applied coloured bands. Cross-sections of this bead (Fig. 11D) show that the yellow was pushed far into the bead, almost reaching the shaft. This indicates that the chevrons in this bead were made using a thin metal tool (e.g. a knife) that was drawn through the glass bead when it was still plastic.

Fig. 9. Two examples of “Reticella” beads (A–E: bead 41-15; F–G: 41-19) that were constructed by winding decorative polychrome bands around a core. A: Cross-section showing how decorative bands have been wound around a core. Note some circular cavities where the bands did not accommodate completely (c). B, C: Cavity patterns from the side (B) and top (C), showing round bubbles in the core - spiral pattern can just be discerned in C -, and elongated cavities where the bands do not accommodate completely (c). D, E: Segmentation of the red (D) and yellow (E) colours in the bands, showing how the decorative bands were made by winding very thin (yellow) ribbons around glass cores of red (D) and green-black (not shown). A few red ribbons are interspersed with the yellow (black arrows). F: Red bands in the yellow- and red beads, showing how the decorative bands were made by twisting the two colours around each other. G: Cross-section, showing how these bands were wound around the core. Note the large difference in grey values and swirling pattern in the core. Contrary to the Reticella bead, the core has been deformed by the application of the bicoloured bands, and the shaft has come off-centre. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Bead Borgharen 1735 is decorated with transparent blue dots on a white opaque core. Cross-sections (Fig. 11E and F) show that these blue dots consist of small, shallow lens-like shapes that are sunken into the glass body. The first step in making this type of decoration was probably the application of small drops of blue glass on the surface of the bead. Subsequent prolonged heating and rotating (as shown by Krzyżanowska and Frankiewicz, 2015 for a different type of bead) would probably be enough to let these drops sink into the glass mass, and produce a smooth surface.

3.4. Evidence for damage and degradation

Several processes may damage or degrade glass beads. Damage may be associated with manufacture, with use and with post-burial circumstances.

The Amersfoort 7 bead is the only bead where a network of cracks runs through the whole of the glass body (Fig. 12A). This may be due to insufficient annealing: Glass experiences at least one step, but often multiple steps, of heating and cooling. These temperature changes need to be slow and homogeneous in order to prevent breakage. Glassmakers employ annealing furnaces for this, in which glass objects are placed immediately after shaping. Heated to the correct annealing temperature (which depends on the glass composition), the glass objects could subsequently cool down slowly in this oven. Not or insufficiently annealed glass objects are brittle, and often fracture upon cooling or during their functional life (Davison, 2003). The network of fissures in Amersfoort 7 is inconsistent with damage by impact (cf. Davison, 2003), and therefore probably resulted from incomplete annealing shortly after manufacture.

The cross section of Bead Borgharen 1732 in Fig. 5B shows that the outer few microns of the bead have lower attenuation than the rest of the bead. This difference may be compared to the differences in grey-value in SEM backscatter-images of fragments of partially degraded Roman glass (Huisman et al., 2008). This was caused by leaching of

sodium from glass with too low Ca concentrations. It is likely that the less attenuating surface in bead Borgharen 1732 was formed similarly by leaching. The loss of the surface of the opaque yellow glass in a millefiori bead in Fig. 8B is also probably caused by degradation and partial dissolution or disintegration of the glass.

Bead Lent 26–29 in Fig. 12B sports cavities and tunnels as well as an irregular surface with depressions and sharp highs. These patterns are consistent with dissolution processes. The tunnels suggest that this process of dissolution is at least to some extent caused or promoted by biological activity. The size of the tunnels, which are several hundreds of microns wide, make it most likely that fine roots have tunnelled through this bead, dissolving the glass. It is remarkable that most cavities, tunnels and surface depressions are concentrated in the least attenuating (darkest) parts of the bead. Probably, these are the parts with the lowest concentrations in lead, which may have made them more susceptible to dissolution processes – whether or not promoted by biological activity.

3.5. Quality classifications and workshops

From the outset, it was clear that the quality of the beads differed between the beads. Some are made with relatively simple methods, like the wound polychrome ones, or show evidence for sloppy work (e.g. cracking due to insufficient annealing). Other were made according to complex designs with exceptional levels of workmanship, like the millefiori beads and reticella bead 41-15. The micro-CT scans, apart from information on manufacturing methods, revealed various indicators for glass quality, especially homogeneity, bubble properties and inclusions.

In our present dataset, we see that simple, poorly made beads are in general made from worse quality glass. E.g. the simple beads from Amersfoort show rough workmanship (Amersfoort 5) and cracking due to insufficient annealing (Amersfoort 7,8) as well as large inclusions and numerous heterogeneous bubbles – a combination of low-quality

Fig. 10. Drawing and shaping patterns. A: Elongated gas bubbles in bead 26-29 indicating that the bead was drawn lengthwise. B–D: Bead 26-32; B: Outer surface of bead. Note the twist in the neck (indicated by arrows). C: Cross-section with segmented and rendered silver foil fragments (white) and cavities in the glass not associated with the silver. D: Cross-section with all cavities. The purple cavities in the spherical parts of the bead are in contact with the silver foil fragments. Note also the elongated bubbles that follow the twist in the neck-part. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

workmanship and low-quality glass. At the opposite side of the spectrum, the complex millefiori beads from Lent 5 and 9 and reticella bead 41-15 combine complex design and high-quality workmanship with high-quality (homogeneous) glass with no or only homogeneously small

bubbles.

Such a comparison between glass quality and workmanship indicators could potentially reveal hitherto unknown aspects of glass bead workshop organization: E.g. if simple, poorly made beads were made from the same quality glass as contemporaneous complex, well-made beads, it is logical to assume that all workshops had access to the same raw glass source. Here we see, however, that poorly made beads were made from lower quality glass.

If the glass beads were contemporaneous, it would be logical to assume that multiple sources of glass were available with variable quality. Better workshops would have had (easier) access to the better quality glass. We must keep in mind however, that the beads are diachronous: Our results rather seem to indicate that glass quality as well as the complexity and workmanship of bead manufacture increased from Roman to Early medieval time. The number of analysed beads is, however, too small to be certain about this trend. Moreover, the position of Amersfoort - just outside the Roman empire, - may also have played a role.

3.6. Outlook

The results of this study, as summarized in Table 2, demonstrate the potential contribution of desk-top micro-CT scanning to determining aspects of various manufacturing processes, including properties of some of the tools used. It shows that in most cases, the manufacturing method used to create the various beads can be identified. Amersfoort beads 7 and 8, however, demonstrate that it is not always possible to distinguish between mandrel-formed and drawn beads. Moreover, scans can serve to assess the quality of the processes and the workmanship that went into the manufacture of these artefacts. In addition, the scans reveal evidence for various kinds of damage and allow to study the impact of post-depositional degradation processes. Many of the manufacturing, damage and degradation processes are not apparent from macroscopic, visual inspection.

Taking glass beads as an example, in more general terms micro-CT derived features may serve as basis to discuss the organization of places or workshops where simple or more complex non-metallic artefacts were made, and the availability and distribution of different qualities of raw materials for these workshops. Moreover, they may provide clues to the evolution of raw material quality and workmanship.

While producing grey cross-section slices through non-metallic artefacts is straightforward and fast, separation and quantification of various components can be time-prohibitive. In this paper quantification is limited to the determination of the 3D volume of the whole beads and the 2D ferrets calculation of the bead shafts along the bead shafts. Successful bubble separation followed by a morphometric analysis (not done here) could reveal some thermodynamic aspects of the glass formation process as done in (Bertini et al., 2014).

Micro-CT scanning can become an indispensable tool in the study of archaeological artefacts as it has become in material sciences. Uncertainty in models generated from micro-CT scans will have to be quantified routinely, even if the task is complicated. For archaeological artefacts, specific attention is being paid to risks of visible and non-visible damage that could alter results of further investigation. A protocol defining best sequence of investigation techniques for the study of archaeological remains should be established.

Last but not least, appealing images and 3D animations (see supplementary documents) of small artefacts can be produced to illustrate hidden materiality aspects of the beads. Such material can be exhibited in museums and other heritage facilities to engage the larger public with collections of small, not always appealing, artefacts.

4. Conclusions

Micro-CT scans of a collection of different types of Roman to early medieval glass beads showed a range of features that could be related to

Fig. 11. Examples of differently applied coloured decorations. A: Spiral proud white band on red cylindrical bead (Borgharen 1740). B: Surface view of sunken yellow band in Borgharen 1732 C: Same without the coloured decoration. Showing the imprint of the yellow decorative glass on the red bead core). D: Yellow chevrons in Lent 41-8 The decorative yellow (lightest grey) is pushed far into the red, close to the shaft. This indicates that the chevron pattern was made using a sharp metal tool and not a glass rod. Note also the swirls in the rest of the glass. E,F: Borgharen 1735, showing decoration of transparent blue lenses in opaque grey-white core. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Fig. 12. Damage and decay features. A: Amersfoort 8, showing a pattern of fissures. B: Lent 26–29, showing dissolution features. Note depressions and sharp highs at the surface, and pores inside the glass. The latter are indicative for biologically promoted dissolution processes.

Table 2
Beads with forming characteristics (mCT results) and interpretation.

Site	ID	Shaft shape	Min. Shaft radius (mm)	Tapering angle	Indicators for parting layer	Forming/shaping method*	Polychrome decoration method	Damage and degradation
Lent	5–19	Irregular	3.6	–		Constructed	Mosaic	Slight dissolution of yellow
Lent	9–21	Irregular to tapered	2.2	–		Constructed	Mosaic	Slight dissolution of yellow
Lent	5–27	Irregular	3.7	–		Constructed	Mosaic	Slight dissolution of yellow
Lent	26–29	Widest in the centre	1.4	–		Drawn	NA	Severe dissolution and tunneling
Lent	26–32	Complex	1.2	–		Drawn + shaped	NA	
Lent	41–15	Tapered	3.8	1.2		Wound	Reticella	
Lent	41–16	Tapered	2.6	3.0		Wound	Applied bands	
Lent	41–19	Tapered	3.2	4.7		Wound	Reticella	
Lent	41–8	Tapered	2.3	3.0		Wound	Applied bands and cut	
Borgharen	1269–5	Tapered	1.8	–		Wound	NA	
Borgharen	1735	Tapered	5.2	5.3		Wound	Applied drops	
Borgharen	1732	Tapered	1.5	10.2	Reaction rim	Wound	Applied bands	Minor surface leaching
Borgharen	1740	Tapered	2.7	2.5	Reaction rim	Wound	Applied bands	
Amersfoort	5	Irregular	3.1	–		Wound + shaped	NA	
Amersfoort	7,8	Widest in the centre; 8 locally heptagonal	1.7	–		Drawn or wound + shaped	NA	Cracked
Amersfoort	11	Not clear due to bubbles	–	–	Bubbles	Wound	NA	

manufacturing process:

The 3-D distribution of the various glass colours could be studied because each colour had different X-ray attenuations, whereas mineral inclusions marked opaque glasses. Decorative silver foil embedded in a specific, dumbbell-shaped bead was also clearly discernible. The presence of metallic lead globules in one greenish glass bead was thought to result from a failed attempt of producing lead glass.

3-D patterns in inclusions, metal foil fragments and air bubbles give good indications of the forming and shaping processes. The shape of the central shaft gave clear clues on whether beads were shaped in a mandrel, drawn or assembled around a mandrel or rod, and revealed the dimensions of the tools used. The 3D pattern of the various glass colours brought to light the way the beads were decorated or, in the case of millefiori and reticella beads, assembled.

Although isolated cracks occur in many of the beads, a network of cracks in one of the beads probably resulted from incomplete annealing. Some of the beads showed evidence of surficial glass degradation. In one case (the failed lead glass), however, partial dissolution of the glass bead could be seen, with evidence that this process had been exacerbated by small plant roots.

On a more general note, micro-CT derived features may serve as basis to discuss the organization of workshops where simple or more complex objects were made, and the availability and distribution of different qualities of raw materials for these workshops.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.jas.2018.07.007>.

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