Investigating the tool marks of stone reliefs from the Mausoleum of Cao Cao (AD155–AD220) in China

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1. Introduction

Stone reliefs also called as pictorial stones or stone-carved pictures (Pearlstein, 1984), prevailed in the Eastern Han Dynasty (AD25–AD220) as decoration of mortuary architectures, and marked the flourishing of Chinese stone pictorial art. Different decorative topics including historical stories, life customs, religious beliefs, and astronomical phenomena (Yu and Xin, 1981; Wang, 2001; Xin, 2008) were carved on stone surface to show off the status and wealth of tomb occupiers. Those profuse images vividly exhibit the social life in the Han dynasty. Thus, the stone reliefs are referred to “the pictorial epics of Han history” (Jian, 1983). Most research about stone reliefs has focused on interpreting its prominent historical and cultural value of stone reliefs (Shih, 1960; Sun, 1999; Nickel, 2000; Wu, 2006; Wei, 2007).

Stone reliefs in the Han Dynasty represent a new development stage of stone carving art. Because the filial piety was encouraged in the Han dynasty, people extraordinarily concentrated on decorating the mortuary architecture to show their great miss and respect to the death. Thus, the stone carving techniques in the Han Dynasty made a further progress, and it also had a great influence on the later stone carving art (Li, 1965; Jiang and Wu, 1980; Xin, 2008). However, the carving techniques of ancient stone reliefs are little known due to the lack of detailed literature records and excavated engraving tools. Although some attempts have been made to disclose carving techniques and manufacture process of stone reliefs in terms of modern carving practice and textual information from the inscriptions (Xin, 2008; Zhen, 2010), tool marks analysis has never been reported up to our knowledge. Tool marks analysis has proved to be a successful method to investigate the carving techniques of quartz cylinder seals (Sax and Meeks, 1995), Chinese jade (Sax et al., 2004, 2007), Roman microquartz gemstones (Rosenfeld and Dvorachek, 2003), as well as inscribing and finishing processes applied to Chinese bronzes (Strahan and Fenn, 2007; Li et al., 2011). It is possible to recognize the use of various techniques from the characteristic morphology of tool marks on worked artifacts (Sax et al., 2007). Thus, tool marks analysis could provide an ideal way of investigating the carving techniques of stone reliefs.
Optical microscope and scanning electron microscopy (SEM) are main methods to observe tool marks. The preparation of detailed silicone moulds of carved features facilitates the examination of deeply carved parts of the object, which are difficult to view directly and often preserve the original tool marks. The observation of those silicone moulds under the SEM provides much information about the carving techniques (Olsen, 1988; Sax and Meeks, 1995; Sax et al., 1998). The digital microscopy system with extended depth of focus (digital microscopy-EDF) has a function of three-dimensional reconstruction (digital microscopy-3D) technology and provide a direct method of assessing the fine detail of carving features including depth without using silicon moulds. It can also show the profile features and other 3D information of the observed carving features. This method has been applied successfully to disclose the processing marks of turquoise bead (Yang et al., 2008), analyse rice phytolith (Wu and Wang, 2009) and clarify man made incisions on Paleolithic stone artifact (Peng et al., 2012). In this paper, a digital microscope with EDF and 3D image reconstruction technology is used to investigate tool marks on stone reliefs, and particularly to measure three-dimensional model of tool marks and analyse the characteristic of the longitudinal and cross-sectional profiles of depth along the lines, which will help further understand the carving techniques of stone reliefs.

2. Materials and methods

Six representative fragments of stone reliefs (hardness 3–4 in Mohs’ scale) were selected from the Mausoleum of Cao Cao in Anyang city, Henan province. Cao Cao (AD155–AD220), as one of the greatest politicians and strategists in China history, is the highest officer in the late Eastern Han Dynasty. The Mausoleum of Cao Cao was extensively excavated in 2009, and thousands of fragments of stone reliefs were discovered and thought to be from parts of his sarcophagus (Institute of Cultural Relics in Henan Province, 2010). Although the pictorial stone were broken by grave robbers, the elegant patterns on the fragments are well preserved in Fig. 1.

Tool marks on six different stone reliefs were observed and analysed under a digital microscope (VHX-600ESO, Keyence, Japan). By the extended depth of focus (EDF) technology, the digital microscope could provide a high accurate image (digital microscopy-EDF image) and three-dimensional model by composing and superimposing images captured at different focus positions. The images were recorded at different focal depths with the automatic movement of objective lens. In the software of the digital microscope, the 2D pictures could be used to correspond to the related 3D models after that the EDF technology is applied to 3D reconstruct the selected areas; when a line is selected on the 2D pictures, the corresponding depth profile on the 3D model will be presented. Thus, the 2D profile pictures or 3D model could provide direct information of the tool marks. More detailed principles of digital microscopy with EDF have already been introduced by Wu and Wang (2009). The criteria established by Sax et al. (1998) for recognizing different tools and techniques were used in this paper to interpret the carving technology of the stone reliefs. Several characteristics of the carved features were considered: the topography, the shape in plan view (assessed from directly above a carved feature), the cross-sectional depth and the longitudinal depth profiles. The terminology “longitudinal profile” and “cross-sectional profile” developed by Sax and Meeks (1994) were used to describe the variation in depth of an engraved line along and across its length respectively. It is usually possible to distinguish between individual tools (Sax et al., 1998). By considering the full set of characteristic morphology of tool marks, it is also possible to distinguish different carving skills.

In this paper, some simulation experiments using modern steel carving burin and seal stones made of pyrophyllite (hardness 2–3 in Mohs’ scale) were used to testify carving skills applied in ancient stone reliefs. The burin was pushed into the seal stone to engrave straight and curved features. The seal stones were also ground with rotary grinding device or in a non-rotary way, for example, file and sand paper. Although the experiments were made on seal stone and the carving tools are surely sharper and harder than Han tools, the previous study inferred that characteristics of the longitudinal and cross-sectional profiles were not strongly dependant on materials (Sax et al., 2007). As the detailed impressions of carving tools bear the evidence of carving skills, the carved features of modern carving skills provide useful information for interpreting skills of carving on the stone reliefs. Through a comparative analysis, the various carving skills and tools used in engraving ancient stone reliefs may be characterized.

3. Results and discussion

To create one stone relief, several steps were required. The first stage was working the flat smooth upper surface, the second stage was creating recessed background areas, and the third stage was engraving decorative lines to form the main features of the decorative design.

3.1. Polishing and grading marks

It’s of primary importance to grind a flat smooth upper surface. Before carving the stone reliefs, the stone should be firstly ground for engraving linear designs, or it would be difficult for the later work to create an impression that the patterns raised above the background plane. Grinding and polishing are different techniques, but sometimes they have overlapping definitions and functions. As shown in Fig. 1, the upper smooth surface had a low luster than the recessed surface, which was not polished at all. Stones should be fine shaped by grinding with either a non-rotary or a rotary tool. When examined under the digital microscope, it is shown that the polishing marks of extreme fineness are perfectly parallel to each other in large scale. Besides, the lines are very dense and the distance between the two parallel lines are between 50 and 300 μm (Fig. 2). According to our grinding experiments, the grading marks of non-rotary tools were typically multi-directional and crossed each other, and the grading marks of rotary tools were parallel to each other (the results are not listed in this paper). Such traits are similar to those of grading marks on the bronze arrow and the
3.2. Tool marks of lowering the background

The lowering marks can be clearly seen in the recessed surface iii (Fig. 1a, b). When observed under the digital microscope, the end of lowering marks iii (Fig. 1a) between a straight edge of the raised upper surface and two engraved curved lines are seen at 30× magnification in Fig. 3. The mark is characterized by straight line with the width of about 0.3 cm (Fig. 3). The depth is about 80 μm. These characteristics appear to have been produced using flat-headed burin or chisel 0.3 cm wide. Besides, the white areas near the straight edge of the recessed area are deeper than the green areas nearer the curved edges (Fig. 3), so we can know that the direction of working was from the curved edges to the straight edge. Moreover, the 3D micrograph of a lowering mark iii (Fig. 1b) recorded by digital microscopy-EDF also shows that the trace is square (Fig. 4). The yellow area is higher than the blue area, and the width of the rectangular strips is also about 0.3 cm, so a small flat-head tool may be used for lowering the background. From what have been discussed above, we know the tool is very small indicating that the tool should be of high hardness and toughness. According to the historical records and archaeological evidences (Han and Ke, 2007), people have mastered the technology to manufacture multiple-refined steel in the East Han Dynasty. Therefore, ancient stonemasons may use flat-head steel tools to lower the background.

3.3. Tool marks of engraved lines

Engraved lines form the main features of the decorative design on the stone relief carvings (Fig. 1a and b). Most are curved (50–150 μm deep and around 500 μm width) and some are thinner and straight (around 30 μm deep and 250 μm wide); concentric circles (around 50 μm deep and 500 μm wide) were also engraved. Firstly, the longitudinal profiles of depth along the end of engraved lines were observed and analysed by digital microscopy-EDF at magnification up to 200×, and it’s found that the longitudinal profiles of depth along the curved lines are similar to those of straight lines. The curved feature in position i (Fig. 1a) is shown in Fig. 5a and b, indicating that the curved line is very thin with the width of about 100 μm and very shallow with the depth of about 20 μm (Fig. 5a). Besides, this line has a linear longitudinal profile which looks angular not concave (Fig. 5b). Previous researches showed that the end of the straight and curved lines will have a curvilinear longitudinal profile when the wheel was used to engrave the jade or bronze (Sax et al., 1998, 2004; Strahan and Fenn, 2007). Thus, the lines were not engraved by a rotary incising wheel. On the other hand, the smooth engraved lines are of shallow depth (Figs. 1, 6 and 8). In accordance with previous research results (Wulf, 1966; Sax et al., 1998), the chisel was worked by repeated light hammering that would cause the rough lines present with irregular cavities. This feature was not shown in the longitudinal profile of ancient engraved lines. Besides, the depth of the curved line is very shallow. Hence, the chisel is impossible to be used to engrave the lines. The modern engraved lines which were engraved by burin were similar to the ancient engraved lines (Figs. 6–9). Therefore, the line was likely to be engraved by the burin which was a kind of common tool used in engraving stone.

The tool may be held perpendicularly or obliquely to the surface being worked. So, there are two basic carving skills when using burins to engrave the stone. One is the oblique attack technique.
that the tip of a burin keeps an oblique angle on the surface in engraving process; the other is the upright attack technique that the blade is nearly vertical to the surface in engraving process and the tip of the tool doesn’t nearly lean on one side of the line, whether the tool may be hold obliquely or vertical to the working surface along the direction of the line.

3.3.1. Tool marks of straight lines
Thin straight lines appear by eye to have been engraved with even continuous edges like modern soft stone relief carvings. The fine details of the straight line are seen in position ii (Fig. 1b) at 200× magnification by the digital microscopy-EDF technology, which both sides of the feature have small diffuse discontinuous edges (Fig. 6a) and the cross-sectional profiles of straight lines present a “U” shape (Fig. 6b). The characteristic of modern carved straight line engraved by the upright attack technique (Fig. 7) resemble with the straight lines of the stone reliefs. Thus, the stonemasons should engrave the straight lines by the upright attack technique. Because the burin engraves the stone uprightly, the two sides of the line would endure the pressure of the burin, so micro fracturing will appear around the impacted area on both sides of the line. When the tool was held obliquely or vertical to the working surface along the direction of the line, it all produce “U” shaped cross-sectional profiles. Besides, tool marks analysis could not provide the detailed information to judge the tool direction. So it is difficult to infer that the tool was held obliquely or vertical to the stone in the direction of the line when the upright attack technique was applied to engrave the straight line.

3.3.2. Tool marks of curved lines
In contrast to the similar characteristics presented along the sides of straight lines, different characteristics are seen on the opposite sides of curved features. The fine details of the curved line in position i (Fig. 1a) are seen in the micrograph at magnification up to 200× by the digital microscopy-EDF (Fig. 8a). One side of the curved line having a more diffuse and discontinuous outline than the other side. The cross-sectional profiles of curved line look like a “\( \sqrt{ } \)” shape (Fig. 8b), and the characteristic of modern curved line engraved by the oblique attack technique (Fig. 9) resemble with the curved lines of the stone reliefs. As the tool obliquely from one side of the intended line, so more extensive micro fracturing around the area of impact were created than at the opposite deeper side of the line, where cleaner fracturing occurred. Thus, the curved lines should be engraved by the oblique attack technique. As shown in Figs. 8 and 9, the working angle between the tool and stone of ancient engraved lines and modern engraved lines are similar. The burin was hold at an angle of about 35° to the contact surface by the ancient craftsman (Fig. 8).

3.3.3. Tool marks of concentric circles
There are two concentric circles in Fig. 1. The fine details of one concentric circle in position ii (Fig. 1a) are seen in the micrograph at magnification up to 200× by the digital microscopy-EDF (Fig. 10a),
and both sides of the feature have small diffuse discontinuous edges which is similar to straight lines. The shallow depth is around 50 μm. The cross-sectional profile of the circle present a wider “U” shape than those of straight lines under the digital microscope (Fig. 10b), but the cross-sectional profiles of curved lines have a “V” shape. Therefore, the concentric circles should be also engraved by an upright attack technique. Besides, there was a centre hole in stone relief (Fig. 1a) and the distance between both circles were equal. Since the tip of the tool was vertical to the surface in engraving concentric circles, then this tool used for engraving the circle should be similar to some kind of “h” formed compasses. No East Han compasses were excavated, and only the image records from the stone reliefs are found. According to the famous stone relief “Fu Xi and Nu Wa” (Wu, 2006) (Fig. 11) found in the Wu Liang
The stone reliefs represent the highest attainments of the Han Dynasty art for the combination of the graphic art and engraving art. The investigation of the tool marks on the stone reliefs showed that the stone were ground firstly to obtain a smooth surface for engraving designs, then some flat-head tools were used to lower the background and different skills were applied to engrave the decorative lines.

The study about the fragments belonged to late Han Dynasty has increased our understanding of the engraving tools which were rarely concerned in previous work. Through the observation about the characteristic morphology of tool marks, we predict the small steel tool may be used for lowering background. The burin may be used in engraving the lines. Furthermore, the “h”-formed compasses may be used to engrave the concentric circles. The results provide some useful information for the study of Chinese ancient engraving tools.

The results of examining carved features also provided some useful information about the carving skills around 1800 year ago. The observation about the cross-section of lines suggested that the stonemasons were using to engraving the curved lines by an oblique attack technique and engraving the straight lines by an upright attack technique. The burin was held at an angle about 35° to the contact surface if the oblique attack technique was applied to engrave the decorative lines. The results enriched our understanding about the development history of Chinese stone carving art.

In this paper, the 3D reconstruction function based on EDF technology was applied to examine tool marks. The observation using digital microscope can easily show the detailed characteristic morphology of tool marks and reveal more intuitive information about carved features. The 3D reconstruction function based on EDF technology provides a new useful method for investigating tool marks.

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