Understanding the Bronze Casting Techniques in the Late Shang Dynasty Through the Solidification Process Simulation of Anyang Niuzun

Huan Yang[1]*, Minghui Fang[2], Yuling He[3], Junchang Yang[1]
1. Institute of Cultural and Heritage, Northwestern Polytechnical University, 127 West Youyi Road, Xi'an, P.R.China
2. School of Materials Science and Engineering, 127 West Youyi Road, Xi'an, P.R.China
3. Institute of Archaeology Chinese Academy of Social Sciences, No.1 North National Stadium Road, Beijing, P.R.China
*Corresponding address: e-mail: yanghuan2019@nwpu.edu.cn

Abstract: This study investigates the advanced bronze casting techniques employed in the Shang Dynasty's capital city, focusing particularly on the cattle-shaped wine vessel (Niuzun) from Anyang. To elucidate the casting techniques used in the creation of the Niuzun, and thereby assess the bronze casting technologies of the Shang Dynasty, this paper integrated advanced solidification theory with cutting-edge research methodologies from materials science. A suite of techniques, including three-dimensional modeling, mesh division, and software simulation, was employed to reconstruct the dynamic solidification process of the vessel. Through this study, we not only elucidated the dynamic solidification process of the bronze Niuzun for the academic community and obtained precise simulation results, but also uncovered numerous previously unrecognized technological features, such as the bronze patches and chaplets. These findings offer a novel research perspective and methodology for understanding the bronze casting techniques of the late Shang period.

Keywords: Yazhangniuzun, Solidification Theory, Gating and Risers, Piece-mold Casting

1 Introduction

Approximately 3,000 years ago, Chinese artisans adopted the distinctive piece-mold casting to produce thousands of bronze vessels, thereby marking the advent of China's unique Bronze Age. The artifacts unearthed from sites such as the Yin Ruins (the capital city of the late Shang Dynasty) and Sanxingdui are particularly noted for their exquisite craftsmanship. Zun is a highly representative type of bronze vessels of this period[1]. In 2000, a cattle-shaped Zun(*Niuzun*) was unearthed from a high- ranking noble tomb at the Yin Ruins, the capital of the late Shang Dynasty (FIG. 1). The vessel measures 40 cm in length, 22.5 cm in height and weighs 7.1 kg [2]. The shape of the cattle statue is accurate and vivid, reflecting the exceptional bronze casting technology of the late Shang Dynasty. In order to accurately understand its casting process and further observe the bronze technology of the late Shang Dynasty, this study employed dynamic simulation methods of solidification process, accurately simulating the filling and solidification process of *Niuzun*, and obtained many understandings about the casting technique of it.

Fig. 1 Niuzun of Yazhang Tomb

2 Experimental procedure

The main research methods of this paper include the observation of the casting traces, the establishment of a 3-D model, meshing, parameter setting, solidification process simulation , etc., to study the casting process of the *Niuzun*. The main task of the observation step is to identify characteristics of casting process, such as chaplets, mold join lines, welding and other technical features, so as to determine the mold sectioning and other casting details of the object. Another major task in this stage is to locate the pouring gate and riser of the mold cavity. The setting of the gate and riser will have a significant impact on the quality and defects of the bronze[3][4].

The three-dimensional model of the bronze was obtained by scanning modeling of the *Niuzun*. After extracting the geometric information of the *Niuzun* , UG software was used for reverse modeling, resulting in a CAD model for simulation. The alloy composition of the *Niuzun* was set as $Cu_{89}Sn_{10}Pb_1$, with the thermophysical property parameters of the alloy materials automatically obtained by ProCAST's built-in material database. The thermophysical property parameters of the cavity and the interfacial heat transfer coefficient between the mold and metal were obtained through actual measurements and calculations of clay mold unearthed at the Zhuangli foundry in Zhouyuan of Shaanxi province (early Western Zhou Dynasty). After completing these steps, the parameters and models were imported into the simulation software(ProCAST) for dynamic simulation of the solidification process.

3 Result and discussion

3.1 THE OBSERVATION OF THE BRONZE

Through observation, it was found that the head and the horn are hollow. The head and the abdomen of the the vessel are separated by a thin bronze plate. The abdominal bottom is closed, and the foot cavities are not communicated. There is a square chaplet in the center of the two front feet, and a square-shaped inlaid bronze sheet can be seen on the wall below the head. Through the X-ray image, we found that there is another patch in the center of the bottom. The thickness of the patch is larger than the surrounding metal wall, with a clear edge, marking the first discovery of such a phenomenon in the bronzes of the late Shang Dynasty.

The four legs of the *Niuzun* are hollow, the edges of right forefoot and left hind foot are smooth, and the edges of left forefoot and right hind foot are thicker than the other two feet. The edge of the right hind foot is not smooth, showing traces of broken stubble, and the thickness of the wall connected with the body cavity is larger than the other three feet, which is speculated to play the role of the indirectly, so the right hind foot should be the pouring gate. A ring of copper liquid traces can be seen on the left front foot, which is seriously rusted and presumed to be a riser.

3.2 THE RESTORATION OF THE SOLIDIFICATION PROCESS OF NUNZUN AND THE OBSERVATION OF DEFECTS

In order to verify the previous inferred results of the sprue and riser, this paper simulated the solidification process of the *Niuzun* with the left front foot and the right rear foot as the pouring gate (shown by the arrow), and observed the differences in solidification time and defects between the two (Figure 2). The comparison revealed that when the right rear foot is used as the gate, the solidification time is shorter and the hole defects volume is minimized, which realizes the better performance of the object. This indicates that the craftsmen of the Shang Dynasty obviously made a better choice in the setting of the pouring gate of the *Niuzun*.

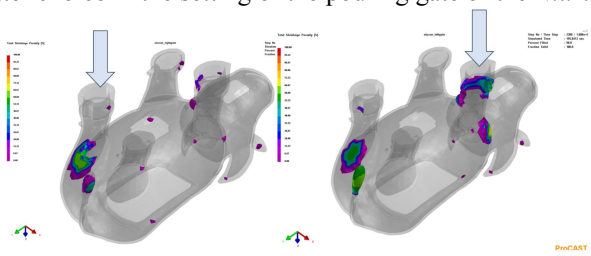

Fig. 2 Comparison of casting defects with different pouring gate settings

4 Conclusion

In this paper, the solidification research in materials science is employed to complete the reverse modeling based on the 3D scanning data of the objects. Through material assignment and finite element simulation of the bronzes and casts, the dynamic restoration of the solidification process of the *Niuzun* unearthed from Yazhang Tomb in the Yin Ruins is realized. The core data such as the solidification time of the objects are obtained, which provides an important reference for the follow-up research. The simulation results of the defects align well with the actual defect locations in the castings, which once again verifies the reliability and accuracy of the solidification simulation method.

It is found that the whole vessel of *Niuzun* adopts an equal wall thickness design, which significantly reduces defects and improves the quality of the objects[5]. After the observation of the object and the comparison of the casting simulation results, it is confirmed that the previous judgment that the pouring gate is the left rear foot is correct. The setting of the sprue and riser for specific objects by craftsmen in the Shang Dynasty achieved an optimal solution from the perspective of modern material science. Combined with the observation of the casting process and solidification simulation of the artifacts, this research found that the craftsmen of the late Shang Dynasty skillfully employed casting techniques such as metal chaplets, bronze patches, equal wall thickness design, and casting riser settings when casting large-scale artifacts. These techniques ensured the complete filling of the bronze *Niuzun* and improved the quality of the artifacts. It is with these technologies that a large number of bronze vessels of the late Shang Dynasty were cast and their exquisite appearance made a unique bronze civilization in ancient China.

References

[1] Ronggeng. Rong Geng's comprehensive discussion on bronzes. Zhonghua Book Company, 2012:47.
[2] Institute of Archaeology, Chinese Academy of Social Sciences. Shang Dynasty Tombs in Yin Ruins Garden Zhuang in Anyang. Beijing: Science Press, 2007:278.
[3] Jie Wanqi et al. Casting Technology. Higher Education Press, 2013:300-302.
[4] Fan Jinhui, Wei Bing, Wang Feng. Systematic study on hot spot of castings. Foundry Technology, 2000 (03): 5-28.
[5] Yang Huan et al. Observation and research on the phenomenon of equal wall thickness of ancient Chinese bronzes under the view of solidification. Jianghan Archaeology,2022,(05):108-116+144.