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Microstructure characteristics and acoustic properties of laser repaired Chinese bronze bells 2300 years ago

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ABSTRACT

Six broken Chinese bronze bells, unearthed from Jiu-Lian-Dun tomb of the warring states period 2300 years ago, are repaired successfully in shapes and acoustic properties by laser welding. The tone pitches of repaired bells are harmonious and well coherent with those of nearby bells. The investigation shows the weld metal has a good consistency with base metals in both microstructure and chemical components, which is the main mechanism to recover the bell's acoustic property. Besides, both the microstructure of weld and base metal are dendrites consisting of pro-eutectoid α-Cu and the eutectoid (α-Cu + δ-Cu_6Sn_5) between the dendrite arms.

1. Introduction

In November 2002, a set of Chinese chime from the tomb of Jiu-Lian-Dun Chu of the warring states period 2300 years ago were unearthed in Zaoyang, Hubei province of China, which are significant artifacts for the studies of metallurgy and culture of ancient China. However, six bells were broken because of the tomb collapse, as shown in Fig. 1, and one of bells even cracked to pieces as shown in Fig. 2b. It is well known that the Chinese chime is one of the oldest percussion instruments of China and played for the important occasions such as war, sacrifice. Each bell can make two tones by striking bell frontal and side face respectively. Nowadays, except for famous Zeng-Hou-Yi set-bells, most of other unearthed sestet-bells all have some broken bells owing to the collapse of tombs and environmental erosion, which are fatal to the chimes' rhythmic fluency and integrity.

In the past years, cementation and soldering after orthopedic procedures have been the main joining methods to conserve thin wall bronze antiques with slight breaking and deformation [1,2]. However, those conventional methods are hardly to repair the thick wall bronze antiques with serious deformation and cracking because the low strength joint cannot bear the deformed stress during orthopedic procedures. Besides, as the joint materials are different with base metal, the musical properties disappear after the repair. Therefore, how to repair the broken bells both in shape and acoustic properties have been a puzzle for many years.

With good joint properties such as strong joint strength, narrow seam and metallurgical joining, laser welding is a good joining method for nonferrous metal materials and has made a few achievements in conserving bronze antiques [3–6], but so far all limited in repairing bronze swords [3]. For broken musical instruments, similar work is scarce. The study is unquestionably important to introduce laser welding to recover large numbers of broken musical antiques in the world. Based on the detailed process studies and acoustic tests on imitate bells, the laser repairing method of bronze set-bells has been developed by our team. Moreover, the broken bells unearthed from Jiu-Lian-Dun Chu tombs are successfully recovered by this method, and the acoustic properties and microstructure characteristics of laser repaired bells are studied to reveal the sound recovery mechanism.

2. Experimental procedures

The laser employed in the experiment is a 5 kW CW CO_2 laser (Rofin-Sinar TR050). Laser beam is focused on the weld surface with a focal length of 286.5 mm by a reflective mirror and the laser spot diameter is 0.6 mm. The laser power used is 2.5 kW, and welding speed is 0.8 m/min. The average wall thickness of the welded bells is 2.5 mm. The shielding gas is argon and carried by a 6 mm diameter paraxial copper tube with the flow rate of 10 l/min. The chemical ingredients of bell base metal (BM) and filler powder are shown in Table 1.

The welding procedures are as follows:

- First, use orthopedic clamps to fix the deformed or broken bell and hold its complete shape,
- Second, clear the welding positions,

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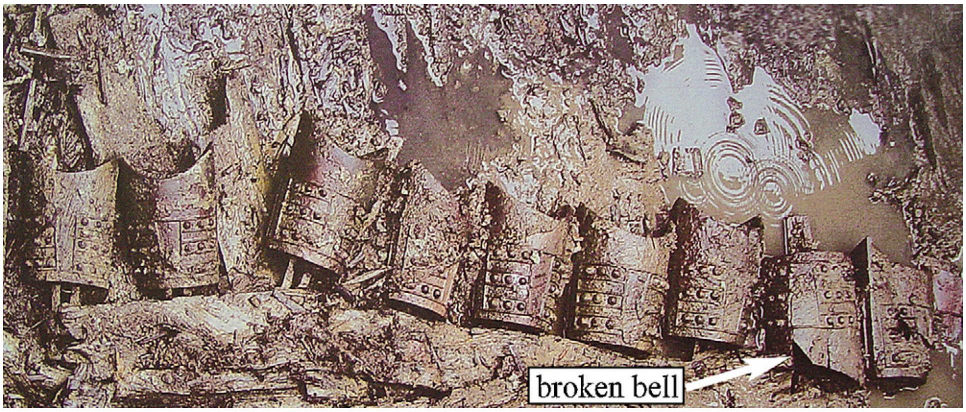

Fig. 1. Picture of unearthed site of Jiu-Lian-Dun Chinese chimes.

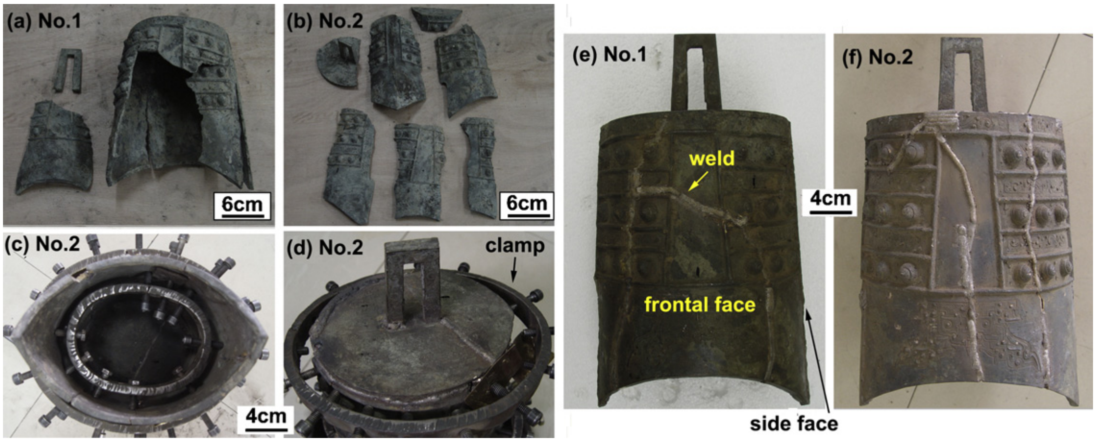

Fig. 2. Laser repair procedures for broken bells. (a) and (b) are the broken states of bell No. 1 and No. 2 respectively; (c) and (d) are the orthopedic and welding procedures for bell No. 2; (e) and (f) are the bell No. 1 and No. 2 after repair, respectively.

- Third, fill copper powder into the joint groove,
- Finally, weld the broken positions with optimized processing parameters.

After the welding procedures, a digital sound collection equipment which including a M-AUDIO MobilePre sound card and a Behringer ECM8000 microphone is employed to collect the bell sound. The acoustic properties are analyzed by the software General Music Analysis System Release 2.0. Microstructures and chemical ingredients distribution of the welds are investigated by the SEM/EDS analysis. The Vickers microhardness characteristics are measured on polished surfaces, using HV 0.1 and a load time of 15 s.

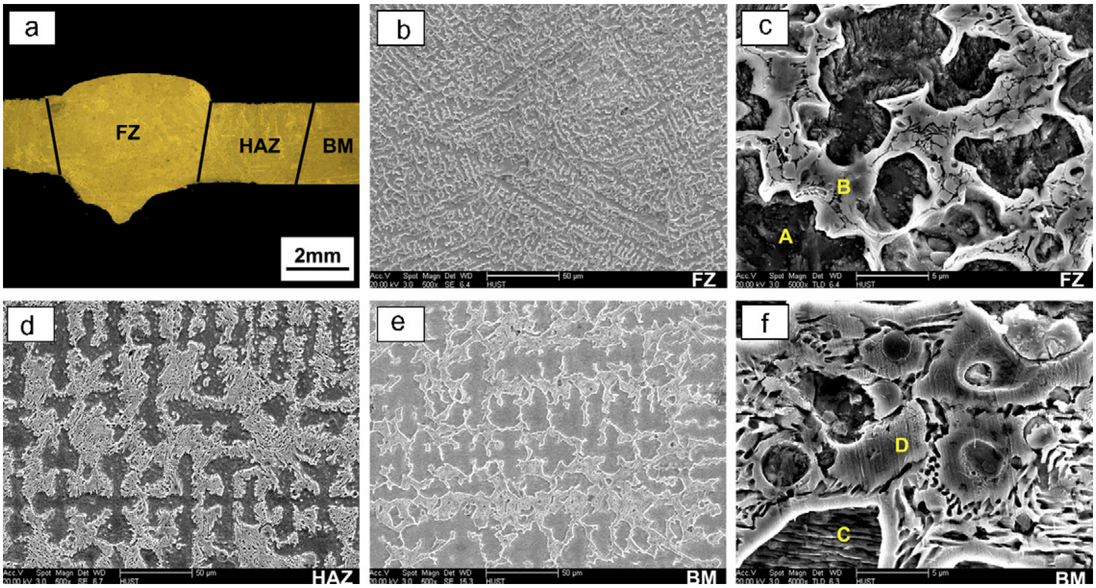

Fig. 3. The weld shape and microstructure of laser welded bronze bells. (a) Appearance of whole weld seam; (b) FZ at magnification 500×; (c) FZ at magnification 5000×; (d) HAZ at magnification 500×; (e) BM at magnification 500×; (f) HAZ at magnification 5000×.

Table 1
The chemical compositions of base metal and filler powder (wt%).

Materials	Cu	Sn	Pb
Base metal	78.88	16.54	4.58
Filler powder	75.36	18.13	6.51

Table 2
Components of FZ and BM, the test positions are presented in Fig. 3f.

Compositions	Sn	Cu	Pb	O
A (FZ α-Cu)	11.98	80.64	6.16	1.22
B (FZ eutectoid)	24.81	55.96	16.48	2.75
C (BM α-Cu)	10.33	82.95	4.75	1.96
D (BM eutectoid)	27.17	59.33	10.94	2.56

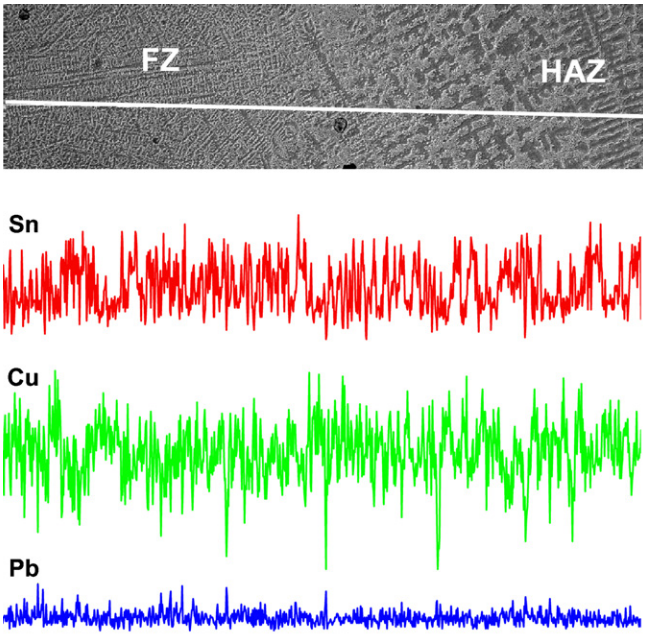

Fig. 4. EDS line scanning of weld seam from FZ to HAZ.

3. Results

3.1. Shape recovery of laser repaired weld

Fig. 2 presents the repair procedures of two worst-broken bells defined as No. 1 and No. 2, respectively. It can be seen the serious deformed and fractured bells were restored in good shape and sizes. The weld seam is narrow and beautiful, which keeps the original patterns on bell surface to the greatest extent.

3.2. Microstructure and mechanical property analysis

As shown in Fig. 3a, the weld seam is narrow, the widths of the fusion zone (FZ) and heat affected zone (HAZ) are 4 mm and 2.5 mm, respectively. Besides, the good metallurgical joining between weld and BM can be found, which guaranteed the joint strength of laser repaired bell behaves strong enough to hold the deformation stress during the orthopedic procedure. The strong joint strength may led to make the shape recovery of broken bells stable and durable. In fact, the heaviest bell with the weight nearly 30 kg just cracked at the junction between the handle and top wall. However, after repair, it can be suspended by the handle safely for musical performance.

As shown in Fig. 3b–f, the microstructure of FZ, HAZ and BM all are dendrites. The EDS test results as shown in Table 2 confirmed the dark dendritic arms are pro-eutectoid primary α-Cu, and the bright with the bone-shape between dendritic arms are eutectoid (α-Cu + δ-Cu_6Sn_5) [7]. There are small differences in the dendritic arm spacing between FZ, HAZ and BM, in the sequence of which the sizes are about 8, 20 and 12 μm respectively. The microhardness distribution agrees with the microstructure characteristics. The average hardness of FZ and BM are almost same, which are HV200 and HV205 respectively, but that of HAZ decreases to HV160 owing to the coarse grain size and over-aging of this zone. However, since HAZ is narrow enough, the influence of microhardness decrease in HAZ do not significantly affect the joint strength owing to the restraint effect from weld seam to BM. As a result, the joint strength of laser repaired bells is strong enough to bear their own weight and the striking force during the musical performance.

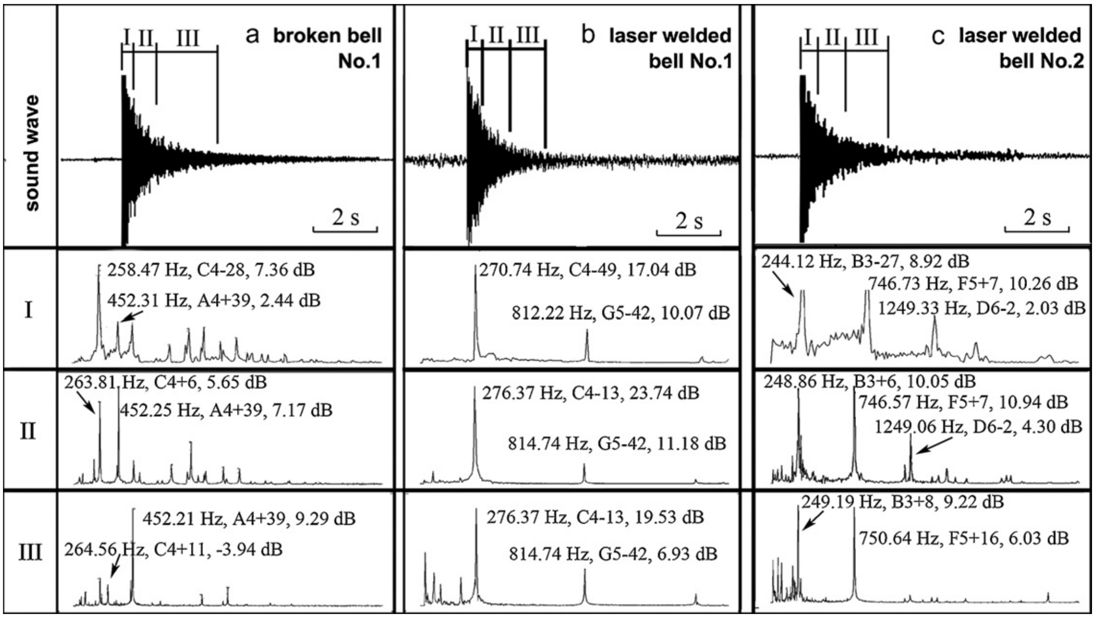

Fig. 5. Acoustic property results of bell No. 1 and No. 2. (a) Broken bell No. 1; (b) laser repaired bell No. 1; (c) laser repaired bell No. 2; I, II and III zones denote the pitch properties of begin, middle and last period during whole sound sustaining duration respectively.

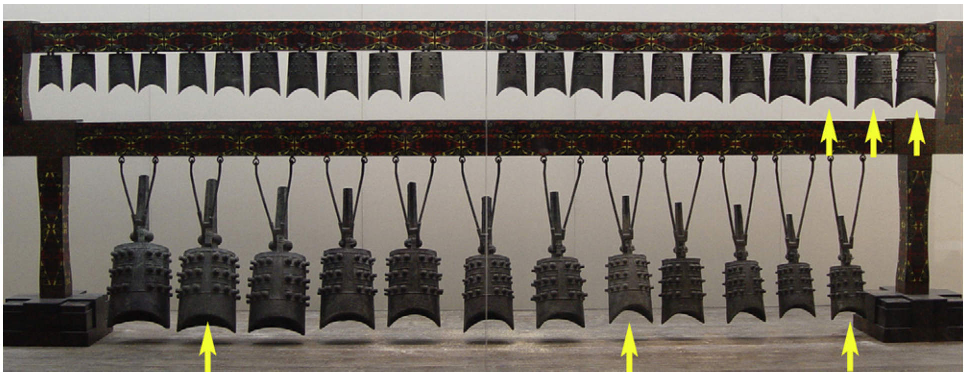

Fig. 6. A whole set of bells in Hubei Provincial Museum of China, the arrows point to the repaired bells.

It can be found from Fig. 4 and Table 2 that the alloying element contents are relatively stable except for Pb. In general, Pb is not a solid solution for Cu lattices thus cannot form electronic compounds with Cu. It prefers to segregate in the areas between dendritic arms as free phase in Sn–Pb bronze during crystallization, resulting in the big change of Pb content in FZ. The main influence of Pb is to improve the wear resistant property and the small difference of Pb content between the weld and base metals almost has no influence on bell acoustic properties.

The weld as a whole, shows a good consistency with BM in microstructure and chemical component, which makes laser repaired bells has the acoustic properties and beautiful tones as origin bells before broken.

3.3. *Acoustic properties of laser repaired weld*

Fig. 5 shows the acoustic properties of frontal face tone of bell No. 1 and No. 2 before and after repaired. As shown in Fig. 5a, the fundamental pitch of broken bell No. 1 changes with the sound sustaining and accompanies with many noises. In the sound duration from I to III zone, the loudness of initial fundamental pitch C4 gradually decreases from 7.36 dB to −3.94 dB, while that of initial second pitch A4 increases rapidly from 2.44 dB to 9.29 dB. That is, the roles of fundamental and second pitch exchange each other during the sound continuing. So the sound of broken bell No. 1 is unpleasant. However, the pleasant sound comes back after it repaired. As shown in Fig. 5b, the fundamental pitch of repaired bell is always as C4 during the sound continuing. Its loudness increases from 17.04 dB in I zone to 23.74 dB in II zone, and then decreases to 19.53 dB in III zone. While the loudness of second pitch has similar change with that of fundamental pitch and keeps lower than that of fundamental pitch. As a result, it plays a pleasant sound.

As shown in Fig. 5c, the acoustic properties of bell No. 2 before repaired are totally lost because it cracked to pieces. After repaired, it also plays a sound tone with clear fundamental pitch B3, second pitch F5 and a harmonic pitch D6. It can be found that the fundamental and second pitch of this bell is close in loudness. In the duration of I and II zone, the loudness of fundamental pitch B3 is slightly lower than that of second pitch F5. But in the total duration, the fundamental always keeps higher loudness, which in the range of 8.92–10.05 dB. The loudness of second pitch has an obvious drop in III zone, which decreases to 6.03 dB. The loudness of harmonic pitch D6 is always low and even disappears to harmonize the total sound. These characteristics indicate the totally broken bell No. 2 also recovered its acoustic properties by laser welding and plays a euphonious sound.

Moreover, the acoustic tests show the tones (frontal and side face tones) of laser repaired bells are beautiful and clear. Their tone pitches are harmonic and concerted to that of nearby bells, indicating the well recovery of acoustic properties. After smoothed and decorated old the weld seam, now the repaired bells are exhibited in Hubei Provincial Museum of China with other good bells as shown in Fig. 6, which raises strong effects in archaeological conservation.

4. Conclusions

The broken bells of Chinese chime from Jiu-Lian-Dun Chu tombs 2300 years ago have been successfully repaired both in shapes and acoustic properties by laser welding, which indicates the laser welding technology should be a good method for the conservations of broken bronze musical instruments.

Microstructures of the weld seam and base metal are dendrites consisting of pro-eutectoid primary α-Cu and eutectoid (α-Cu + δ-Cu_6Sn_5). The weld presents good intensity and consistency with base metal in both microstructure and chemical component, which are the key mechanisms for the recovery of acoustic property.

After repaired, the tones (including frontal and side face tones) of the six broken bronze bells are beautiful and clear, and their tone pitches are also harmonic and well coherent to the nearby bells.

References

[1] X.W. Yang, Sichuan Cultural Relics 5 (2006) 94–97.
[2] G.M. Zhang, P. Zhang, M. Zhang, Sci. Conserv. Archaeol. 16 (2004) 27–30.
[3] X.S. Ye, J.S. Zhang, J. Chen, Sci. Conserv. Archaeol. 15 (2003) 10–13.
[4] J.F. Ready, LIA Handbook of Laser Materials Processing, LIA, Orlando, 2001.
[5] X.B. Liu, G. Yu, J. Guo, J. Alloys Compd. 453 (2008) 371–378.
[6] Z. Sun, D. Pan, J. Wei, Sci. Technol. Weld. J. 7 (2002) 343–351.
[7] ASM Handbook: Alloy Phase Diagrams, ASM International, New York, 1992.