Review

Technological Insights into the Evolution of Bronze Bell Metal Casting on the Korean Peninsula

Chun-Soo Won 1, Jae Pil Jung 1,*, Kwang-Sik Won 2 and Ashutosh Sharma 3,*

1 Department of Material Science and Engineering, University of Seoul, Seoul 02504, Korea
2 National Intangible Cultural Heritage No. 112, Seupji-gil 35, Deoksan-eup, Jincheon-gun 27815, Korea
3 Department of Materials Science and Engineering, Ajou University, Suwon 16499, Korea
* Correspondence: jpjung@uos.ac.kr (J.P.J.); ashu.materials@gmail.com (A.S.); Tel.: +82-10-95345040 (A.S.)

Abstract: Bronze cast bells have been designed and developed for hundreds of years, with the worldwide spread of several faiths and religions such as Buddhism, Catholicism, and Protestantism. The exceptional ringtones of bronze bell metals have scientific healing and cultural importance. In this review article, we highlight the evolution of bronze bell metal over the decades, its composition, and the complex fabrication technologies used to date. Furthermore, we overview ancient and modern casting alloy technology, especially bronze bell castings in Asia. The bell shape, materials, and alloy casting technology have undergone dramatic change over the years. For comparison, we include different bronze cast bells and their characteristics produced from the Middle Ages to the present times. Based on the data obtained from the bell casting technology surrounding the Korean Peninsula, the major trends in the evolution of bronze bell castings and long-standing traditions of mold materials and alloys are described. In the present review, the effects of different elements on bell materials are qualitatively overviewed, with an assessment of the material and casting properties, service life, and bell sound. We also highlight the challenges of conventional bronze casting and possible solutions for future investment castings and rapid prototyping of bronze bells.

Keywords: cast alloys; bells; silicon; bronze; 3D printing; wax casting

1. Introduction

With the progress of humanity, bronze cast bells have occupied nearly all facets of human life. Bronze bells have been an important component of the life of societies irrespective of the historical traditions and customs they represent. The historical bronze bells stem from the 19th century BCE. These bells were believed to be a signature of religious customs, morning prayers, Buddhism, and pieces of art [1]. In this journey, humans learned the process of casting materials into definite shapes at high temperatures, which is metal forming, which is still used today. Casting technology has been known to man for many centuries and employed to shape tools for daily life. Cast weapons were mainly used in war and in protection against dangerous animals, as temple bells, as household products, and as art [2,3].

Bells are used either singly, doubly, or in combination with several bells as instruments, which are usually hit by a wooden block or shaken by hand or in a clock-operated system. In small cities, temple bells are hung in a church tower to wake the citizens for morning prayers. Bells were also part of various ceremonies and weddings or used in ships as a sign of imminent danger [4]. Figure 1 shows a typical temple bell structure with different body parts.
The various parts of a temple bell include the bell bottom, which has different shapes: round, smooth, scalloped, etc. Lip and sound rings are located below the body. The upper regions consist of the neck, shoulder, and crowns of the bell. Several descriptive bands and scriptures can be written over the body, which are related to the specific culture or history of that religion. The crown heads consist of hanging holes or some divine creatures such as a dragon as seen in most Southeast Asian bells [4,5].

2. Historical Evolution of Casting Bell Technology in Asia

2.1. Appearance of Bells in Asia

From the beginning of the human era, bells have been an important part of the everyday ritual practice of Buddhist monks and monasteries in South Asia. Both the Buddhist and Chinese Daoist customs promoted the casting of copper and bronze alloys. Consequently, further spread of this technology occurred in the inner Asian countries, including Korea and Japan. The beginning of the Bronze Age occurred at different times in different geographical regions. This evolution began in the 7th century and passed to Tibetan bells in the 8th century. Bronze casting technology evolved in Southeast Asia in about the 10th century BCE [5]. The beginning of the Bronze Age took place around the 10th century BCE on the Korean Peninsula and the 15th century BCE in Manchuria (a region in northeast China) [6].

Written inscriptions such as epigraphy were either engraved or cast into bells, which proclaim the representative religion to serve narrative purposes. Without any doubt, many examples that once existed in the last millennium have either been spoiled, damaged, or burnt during the past centuries. For example, the Nazis confiscated over 175,000 bells throughout Europe for copper and tin. Of these, 150,000 were destroyed [7]. The Tsar Bell in Moscow was damaged during a fire in 1737 [8] and the Chinese Xi’an Bell Tower built during 1384 was bombed by the Japanese in 1939 [9]. Most Korean bells were lost during Japanese colonial rule (1910–1945), which were later restored by Kwang-Sik Won [10]. Thus, most of the precious data related to the initial form of bronze cast bells, their size and shapes, and the casting technology is mostly found in Buddhist Asia [4,5].

2.2. Types, Geographical Distribution, and Characteristics of Bronze Cast Bells

Bronze temple bells are largely divided into Eastern bells and Western bells. Eastern bells refer to temple bells and Western bells refer to worship bells in churches or cathedrals.
There are various types of bronze bells around the globe that require our attention due to their historical importance, their production, and the specific roles they played. The history of bells passes from generation to generation because bells have a longer life and are used in numerous events, outlasting humans. In Asia, common bronze cast temple bells include both flat and scallop-edged bottoms [1,11]. The important temple bells found in Asia include the Chinese bell of the Zhou dynasty (770–256 BCE), the Japanese temple bell, the Kanzeon-ji bell of 698 BCE, and the Korean Sangwonsa Temple bell, founded in 725 BCE [12–14]. Common bells located in Europe differ in the shape of the bell bottom. These include Tuba Dei, the Royal Sigismund Bell, Maria Bogurodzica, Cracow bell, etc., which are mostly used in churches for morning prayers [1,4,5]. Japanese bells have a convex-type bottom while concave types are common in Tibetan temple bells. Other East Asian temple bells are flat-bottomed, an uncommon observation in Tibetan bells [5]. In Korea, bronze bells were first made in the Bronze Age (3300–1200 BCE). However, these bells did not produce a good sound and were not musical and were often used in horse trappings and shamanist ceremonies as a symbol of authority [5]. Apart from the composition, the sound of the bell mostly depends on its shape. For example, a circular shape allows a wave to travel around the bell’s perimeter. The standing waves generated around the circumference of the bell are responsible for the special tone of the ringing [15]. The first musical bells were made in China during 1116 BCE and were played in the orchestra and accompanied Confucian rites and ceremonies. The most famous Korean bells are big, shaped casting bells (pomjong) used in monasteries and Buddhist temples, which were introduced from China in the Tang dynasty [1,5]. However, utilizing other technology, such as papermaking and ceramics, the Koreans outperformed their teachers and developed exceptionally large and finely decorated bells in this era [5]. Papermaking of parts is generally used in metal castings to prevent melt leakage from the mold and prevent heat shrinkage [16]. Korean papermaking from mulberry has been used for printing, preparation of walls, and in ondol floors. The main sources of cellulosic fiber evolved as the ancient craft migrated from its origin in China to Korea and Japan, and then spread to Western countries [17]. Potteries such as ceramics were used on the bell surface to create engraved parts, which were filled with white and black clay, and various aesthetic decorations were produced over the bell [18]. Since Buddhist temple bells have different styles, varying from one country to another, they can be divided into Chinese bells, Korean bells, Japanese bells, Vietnamese bells, and Southeast Asian bells. According to the Gyeongju National Museum’s report (a world heritage site in Korea), the Korean bell is rated as having the most beautiful sounds and patterns. There are various reasons why Korean bells make such a beautiful sound. The first reason is its unique shape and structure, which filters out undesired noise. This bell sits lower than most of the other bells. The caved-in bottom creates greater resonance. The top of the bell is almost half the diameter of the bottom, which also helps to improve the sound clarity [19]. The Korean bell is considered as a masterpiece among other bells around the world due to its unique and beautiful shape and clear and long-lasting sound. In simple words, the bell rings and reverberates like a “Maengnoli phenomenon”, which is the sound of a heartbeat [20,21]. All these attributes led to its own scientific name “Korean bell”, demonstrating the excellent aesthetic sense and workmanship of our ancestors [22,23]. The sound of the Chinese bell is relatively noisy and has short resonance. Other bells such as the Japanese bell are similar to the Chinese bell and cannot produce beautiful sounds, causing fluctuation from deep inside [18–21]. Some of the popular bell types on the Korean Peninsula are summarized in Table 1.
The largest temple bells in Korea were produced during the Silla kingdom and are shown in Figure 2a. The unified Silla period witnessed significant development in arts and crafts, and large bronze bells were hung in Buddhist temples. The other oldest surviving bells include Sangwonsa Temple bell on Mount Odaesan near Pyeongchang and Songdok bell, also known as the Emille Bell, at the end of the Silla period (57 BCE–935 CE). The Songdok bell, made using a lost wax casting, weighs 19 tons (Figure 2b). This bell is housed at Pongdok Temple in Gyeongju and is thus called the Gyeongju bell of Korea [26].

The height of the Songdok bell is about 3.5 m with a diameter of 2.27 m and is decorated with lotus and heavenly creatures suspended through a signature dragon loop. Some of the bells that were larger than Songdok bells were, unfortunately, short-lived. In addition, the massive Hwangnyongsa bell, which had a record weight of 300 tons, disappeared. According to the historical records, these bells were either buried or disappeared with the temples due to heavy floods in early 1400. Some of the largest bells of Silla were taken away during the Mongol invasion [27,28]. After the Silla period, the Goryeo bell dates to the Goryeo dynasty (918 to 1392 CE), in which Buddhism continued to be the dominant religion of the state. Many examples of such bells exist in Japan today, being donated or captured during the Hideyoshi invasion in the 16th century CE. Goryeo bells are smaller in size than Silla bells, which were bronze cast and mostly decorated with dragons and heavenly creatures. Examples include the Naesco Temple bell in southwest Korea (1222 CE), which has lotus petals over the upper rim of the bell, a wider border around the nine-nodule squares, and four spheres accommodating the dragon suspension loop [29].

The above discussion makes it clear that primitive Buddhist temple bells were mostly founded in East Asia, specifically in China, Korea, and Japan. In contrast to Korean bells, Japanese bells are flat-mouthed (Figure 2c), with a few rare exceptions of the temple bell from Kasagi Temple, Kyoto, cast in 1196, which had a different form of scalloping, which has exactly the opposite rim shape to that of the Songdok bell [5,11,22,29]. A major difference

<table>
<thead>
<tr>
<th>Bell Name</th>
<th>Period</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silla bells</td>
<td>57 BCE to 935 CE</td>
<td>Silla art, gold crowns, tombs, Buddhist temples</td>
</tr>
<tr>
<td>Sangwonsa bell</td>
<td>725 CE</td>
<td>Mount Odaesan near Pyeongchang</td>
</tr>
<tr>
<td>Songdok bell</td>
<td>771 CE</td>
<td>Gyeongju National Museum, Korea</td>
</tr>
<tr>
<td>Hwangnyong-sa bell</td>
<td>553-645 CE</td>
<td>Gyeongju, Korea</td>
</tr>
<tr>
<td>Goryeo bell</td>
<td>963 CE</td>
<td>Toksu Palace Museum of Fine Arts, Seoul, Korea</td>
</tr>
<tr>
<td>Kasagi bell</td>
<td>1196 CE</td>
<td>Kyoto, Japan</td>
</tr>
</tbody>
</table>

Table 1. Some common temple bells that evolved on the Korean Peninsula, data from [5,24,25].

Figure 2. Important temple bells that evolved on Korean Peninsula. (a) Sangwonsa bell, (b) Songdok bell (Emille Bell), (c) Japanese bell, and (d) Chinese bell. Korean Buddhist ‘Emille’ Bell [26]. World History Encyclopedia. Last modified October 05, 2016. Retrieved from https://www.worldhistory.org/image/5838/korean-buddhist-emille-bell/ (accessed on 1 February 2022).
between Chinese and Korean bells lies in the shape of the bottom, being scalloped in Chinese bells (Figure 2d).

3. Bronze Alloys and Temple Bells

As discussed earlier, bells have been used in musical idiophones and have been known to humankind since the primitive ages [3]. The materials used for casting bells cover a wide range of elements. Primitive bells were cast using copper (Cu) or iron (Fe) sheets. In Southeast Asia, especially some parts of China, the production of iron occurred as early as 600 BCE. After the Iron Age, it gradually spread across the Korean Peninsula, where it is hard to locate the end of the Bronze Age, unlike other parts of the world. Bronze cast products continued to be made in large quantities even after people had adapted to working with iron. It was predicted that until the advent of the 2nd century CE, cast iron bells were more popular than bronze bells [30]. One such example of a cast iron bell is the iron bell of Jeondeungsa Temple (164 cm × Ø 100 cm) in Korea, which is similar to most Chinese bells. According to the inscriptions engraved over the bell, the bell belonged to China in around 1097 BCE [31]. At present, the major component alloy of temple bells is Cu-Sn alloy. A specific composition of 78 wt.% Cu and 22 wt.% Sn is widely known as bell metal [32,33]. Bell bronze is a structurally complex alloy, and the quality of bells mostly depends on the casting parameters and technology used for their fabrication [34,35]. The quality of cast bells is assessed using their acoustic properties, vibrations, and frequency analysis. The acoustic vibrations are also affected by the present porosity and structure of the cast alloy [36].

Copper alloys account for more than 90% of the materials used to make bells in both Eastern and Western countries and these materials are very limited to the extent that these bells are intermittently made of Fe and Cu-Ni. According to Strafford, it is believed that the production of cast iron (Fe-C) bells started in 1857 with the development of cast steel. However, Fe-C alloys were not suitable due to their poor sound and short life. Many ancient bronze castings included Ni as an impurity (<1%) associated with copper ores [37]. However, as Ni > 1%, this effect becomes noticeable, and it is believed that ancient men developed a certain type of copper bronze containing an appreciable amount of Ni [38]. Previous works pioneered by Audy et al. [34,37] showed that Ni < 2 wt.% is the recommended fraction for obtaining a balanced set of castability, strength, and sound quality properties of a bronze cast bell. This is due to the characteristics of bells that must make a sound. Among these materials, bronze is the most used material for bells because of its clear and resonant sound. The important characteristics of bronze are (a) the tone determination according to the speed of sound and loudness, (b) damping ability, and (c) toughness. Most world-famous bells, such as the American Liberty Bell and the Korean Emille Bell, are made of bronze [11,39]. The strength and sound of bronze depends on the content of tin. Eastern bells, characterized by their loudness and low notes, have a tin content of 12–18% while clear, high-pitched Western bells have a tin content of 20–24%. The tin content of Western bells is higher than that of Eastern bells [40,41].

3.1. Composition of Bronze Bells

The generated sound quality and functioning of bells depend on the cast alloy composition, their methods of fabrication, and inherent cast defects. In other words, the quality of the cast bell is highly dependent on the material type, shape, and methodology. Mostly, temple bells are composed of bronze castings. The major bell alloys include bronze, brass, cupronickel, and iron. Bronze accounts for more than 80%, and the chemical composition of bronze used for bells is reported to contain various metals such as Zn, Sb, Ni, and Pb in the Cu-(10–25)%Sn system. This trend does not differ much between the East and the West [34]. Table 2 shows the materials of the ancient Buddhist temple bells (Eastern bells). It can be seen that the tin contents of the same oriental bells, Japanese bells, are similar to those of Korean Buddhist temple bells.
Table 2. Chemical composition of some temple bells surrounding the Korean Peninsula [11].

<table>
<thead>
<tr>
<th>Name of Bell</th>
<th>Chemical Composition (wt.%)</th>
<th>Impurity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cu</td>
<td>Sn</td>
</tr>
<tr>
<td>Sangwonsa bell</td>
<td>83.87</td>
<td>13.26</td>
</tr>
<tr>
<td>Seonrimwon bell</td>
<td>80.2</td>
<td>12.2</td>
</tr>
<tr>
<td>Silsangsa bell</td>
<td>75.7</td>
<td>18.0</td>
</tr>
<tr>
<td>Bell of the Joseon dynasty</td>
<td>80.1</td>
<td>12.2</td>
</tr>
<tr>
<td>Japanese bell</td>
<td>82.1</td>
<td>9-13</td>
</tr>
</tbody>
</table>

The successful casting of bells is largely based on tin bronzes. Previous studies have shown wide variation in the composition of tin bronzes (Cu-Sn) used for the construction of temple bells. The compositions of the different bells shown in Table 2 were mostly analyzed for various alloying and impurity elements. The important bronze bells surrounding the Korean Peninsula are summarized in Table 2. Most of these bells contain Pb and Zn as alloying elements except Seonrimwon bell, which contain sulphur. The compositions that were not detected are not shown in Table 2. Traditionally, bell bronze consisted of numerous other alloying elements, for example, Pb, Ag, Zn, Sn, Bi, Sb, Fe, As, Ni, Si, S, and P [11,34,41,42]. Among these elements, Pb, Zn, Ni, Ag, Sb, and Fe are important alloying elements. In addition, Bi, As, Si, S, and P are impurities trapped within the bronze melt during melting with coke and charcoal [34].

In the search for a better bronze alloy composition, bell makers have experimented with a range of different alloying elements in various fractions. The alloy composition, however important, is not the sole factor used to assess a bell’s properties. The problem of meeting the demands concerning the material properties becomes even more complicated as additional variables, thus far neglected or impossible to control, are considered. The requirements that need to be met by the bell alloy are as follows: (a) easy melting/casting, (b) high casting quality, (c) uniform and homogeneous bell surface properties, (d) durability, and (e) nice generated sound. Therefore, the casting technology used in bell preparation is a matter of secrecy in different bell foundries.

Bronze has a higher corrosion resistance than pure Fe, especially against harsh environmental conditions. The addition of Sn in Cu provides further strengthening of the Cu matrix and prevents mechanical damage to the bell when it is hit with a hammer, which in turn could degrade the sound. The alloying of Cu with Sn in moderation is preferred to avoid impact fracture upon prolonged striking of the bell. Additionally, Sn increases the sound amplitude; however, other elements such as Pb promote the castability but deteriorate the sound duration. A common Middle Age bronze bell composition falls within the range of 20–25 wt.% Sn; in recent times, lower amounts of Sn (10–15 wt.%) and Pb (1–3 wt.%) have been used [43]. The important bell compositions developed over the last decades are illustrated in Table 3. The ticks indicate the presence of a specific alloying element in the bronze cast bell.

Table 3 indicates that the material composition of bronze alloy has a significant impact on the mechanical and acoustic properties. According to the pioneering work of Audy et al. [34,37], the recommended concentration of Ni is less than 2 wt.% to achieve a high wear resistance, fatigue resistance, and castability of the melt. If Pb > 1.5 wt.%, the machinability, fluidity, and wear resistance are improved but at the cost of the sound quality. Additionally, if Sb > 1 wt.%, the brittleness increases, and the sound quality becomes poor. Other impurities such as p = 0.01 wt.% assist the deoxidizing properties of the melt during casting. When copper is melted, oxygen and other gaseous impurities trapped in the bell core cause further cracking after solidification. Thus, p = 0.01 wt.% is recommended for better bell casting. Based on these abovementioned factors, the most common bronze composition for optimum bell characteristics is recommended: ~20 wt.%Sn, <2 wt.%Ni, <1.5 wt.%Pb, <1 wt.%Sb, ~0.01 wt.%P, and Cu as a balance. There is large variation in differ-
ent bells’ composition in practice due to the different bell manufacturing practices [37,44–56]. Therefore, metallurgical analyses of bronze cast bells, including an evaluation of the mechanical properties, should be carried out in order to assess the quality of bells.

Table 3. Composition of bronze cast bells (Eastern and Western bells) and their possible effects on the mechanical properties. The tick mark (✓) indicates the presence of particular element in the casting.

<table>
<thead>
<tr>
<th>Alloying Constituents (wt.%)</th>
<th>Properties</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn Pb Zn Bi Ag Sb As Ni Fe S P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10–20 ✓ - - - - - - - - - - ✓ High tensile strength [37,44–49]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10–20 ✓ - ✓ - ✓ - ✓ - ✓ High hardness [44–46,49]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;23 ✓ &lt;5 ✓ - ≈1 ✓ ✓ ✓ - High brittle strength [44–46,49]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>≈23 ✓ &lt;5 ✓ - &gt;1 ✓ - ✓ - High wear resistance [49]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;23 ✓ &lt;5 - - - - ✓ High elongation [37,44,45,49]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;5 ✓ - - - - - - - - - Reduced elongation [43,44]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20–23 ✓ - - - - - - - - - Low elongation [37,44,46,48]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- - - - ✓ - - High toughness [21,22,24]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- - - - ✓ - - Fatigue resistant [51]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>✓ ✓ - - - - - - - - High fluidity [11,22,43]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- - - - - - - - - - Low fluidity [5,43,49]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- - - - - - - - ≈1 ✓ - - - Deoxidizing [43]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- - - - - - - - - - Reduced deformability [52]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- - - - - - - - ✓ - - Poor rusting resistance [44,45,53]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt;15 ✓ - - - - - - - - Poor crack resistance [43,44]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>✓ ✓ - - - - - - - - High machinability [43–46,49,54]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>✓ ✓ - - - - - - - - Poor castability [3,5,11,44]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;10 ✓ - - - - - - - - - Highly porous [2,44,45,54]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- - - - - - - 0.4–5 - - Reduced porosity [55,56]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- - - - - - - 0.5–2 - - Softening increased [45,55]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- - - - - - - 2–4 - - Structure stabilizes [45,55,56]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>≈20–23 - - - - - - - 2–4 - - Good sound quality [37,44–46]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt;1.5 &gt;1.5 - ✓ - - - - - Poor sound quality [37,44–46]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>✓ ✓ ✓ - - - - - - - Reduced melting point [37,43–45,47,48]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>✓ ✓ ✓ - - - - - - - Expensive [37,43–46]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>✓ - - - - - - - - - Cost-effective [37,43–46]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.2. Microstructure of Bronze Bells

The microstructure of bronze consists of an alpha (α) solid solution phase and an alpha + delta (α + δ) eutectoid phase, which is known to be affected by the Sn content and mold material. Here, the δ phase is Cu₃₁Sn₈₆, which is a brittle intermetallic compound. In the phase diagram shown in Figure 3 [42,57], it can be seen that the Cu₆Sn₅, Cu₆Sn₅, and Cu₃Sn intermetallic compound (IMC) phases can also be generated. Since these IMCs can cause cracks when the bell is used for a long time, it is necessary to suppress
their formation. For this purpose, the use of a lower content of Sn or an increase in the cooling rate is recommended to reduce the size of IMCs or suppress their formation by supersaturating Sn [37]. Annealing procedures have also been suggested to remove the brittle δ-phase of the Cu-Sn system [58,59].

An increase in the Sn content improves the technological properties of tin bronze, especially regarding the improved hardness, wear and friction properties [60].

Meanwhile, the mechanical characteristics of cast bronze have a maximum tensile strength at 17% Sn, elongation at 4–5% Sn, and maximum hardness at 32% Sn [59]. Regarding the material of actual bells, the higher the strength and hardness, the better. When the tin content is greater than 20%, the hardness increases but brittleness appears, so it is not only weak to fatigue after impact but segregation also easily occurs during solidification, so it is difficult to obtain uniformity in the material [61,62]. Therefore, the tin content of bronze Buddhist temple bells produced in modern times is around 15–17%, and the tin content is adjusted according to the size of the bells [63,64]. A typical bronze bell microstructure is composed of α-dendrites and α + δ eutectoid as shown in Figure 4a. The black dots correspond to the porosity in the matrix (Figure 4b,c). Others have also reported a similar microstructure in the past [65–67]. The role of the α + δ microstructure in the corrosion degradation mechanism of bronze artifacts was studied in the past using potential pH Pourbaix diagrams [67,68]. The results indicated that the porosity and brittle particles provide additional reaction sites and dissolution occurs through crevices and pores, which promotes the entire corrosion process.

Figure 3. Cu-Sn phase diagram [42].

An increase in the Sn content improves the technological properties of tin bronze, especially regarding the improved hardness, wear and friction properties [60].

Meanwhile, the mechanical characteristics of cast bronze have a maximum tensile strength at 17% Sn, elongation at 4–5% Sn, and maximum hardness at 32% Sn [59]. Regarding the material of actual bells, the higher the strength and hardness, the better. When the tin content is greater than 20%, the hardness increases but brittleness appears, so it is not only weak to fatigue after impact but segregation also easily occurs during solidification, so it is difficult to obtain uniformity in the material [61,62]. Therefore, the tin content of bronze Buddhist temple bells produced in modern times is around 15–17%, and the tin content is adjusted according to the size of the bells [63,64]. A typical bronze bell microstructure is composed of α-dendrites and α + δ eutectoid as shown in Figure 4a. The black dots correspond to the porosity in the matrix (Figure 4b,c). Others have also reported a similar microstructure in the past [65–67]. The role of the α + δ microstructure in the corrosion degradation mechanism of bronze artifacts was studied in the past using potential pH Pourbaix diagrams [67,68]. The results indicated that the porosity and brittle particles provide additional reaction sites and dissolution occurs through crevices and pores, which promotes the entire corrosion process.
Recently, Sarkar et al. studied the effect of quenching media on the morphology of the brittle phases in as-cast bell metal (78 wt.% Cu-22 wt.% Sn). The brittle δ-phase showed a needle-like structure. After quenching in oil and water media at 700 °C, the inter-dendritic region of all the samples differed. After comparison with the phase diagram, it was found that the dendritic structure of all three samples was in the α-phase while the interdendritic region of the as-cast sample was in the δ-phase; the β-phase was shown by the oil- and water-quenched samples [68]. The mechanical properties of the oil- and water-quenched samples were increased by 8% and 25%, respectively, after increasing the quenching temperature by 50 °C to above 700 °C due to the transformation of α- to β-phases by fragmentation of the dendrites. These results are consistent with several previous studies [69–72].

The binary phase diagram of tin bronze shows that the δ-phase solidifies first in the remaining Sn-rich liquid and other solute elements [73]. The interdendritic phases undergo eutectoid reaction to form an α + δ mixture, where δ is the brittle Cu31Sn8 compound. Rapid cooling prevents the generation of the brittle δ-phase and retains the α-solid solution. If the content of Sn is higher, i.e., 9–10%, the δ-phase inevitably forms, which impacts the mechanical strength and reduces the ductility of bronze. Some researchers have used high-temperature homogenization at 700 °C to improve the diffusion of brittle compounds into the α-phase, causing a single-phase state after fast cooling [74–76].

The composition of a bronze (80 wt.% Cu–20 wt.% Sn) bell was analyzed by Cekus et al. in a recent study [77] as given in Figure 5a–d. The compositional analysis showed that the test area A and B had α-fractions of 60% and 40%, respectively. Here, A and B refers to the “top” and “bottom” sections of the bell as shown in Figure 5a. The as-cast bronze microstructure consists of primary dendrites covered by α + δ eutectoid (Figure 5b–d), which is responsible for the sound quality of the bell. The eutectoid fraction was 40% and 60%, respectively, without taking into account the porosity. The microhardness of the α-phase in samples A and B was 132 and 135 HV. The microhardness of the δ-phase in samples A and B was 347 and 319 HV, respectively. The reduced mechanical properties along the thickest cross-section of the bell bottom did not affect the sound quality but did cause a decrease in the Sn content in the α-phase. The authors reported that this occurred to the differences in the melting, pouring, and solidification procedures of the alloys, i.e., a higher solidification time at the bell bottom creates a difference in the mechanical characteristics of the bell [77].
wax casting (LWC) or semi-permanent mold castings such as rotational molding or pep-set which can be used to develop cheaper and high-strength bell templates that can facilitate temporary molds produced by sand casting and plaster of Paris (POP) molds. Most bronze properties of bronze bells and the feasibility of a substitution for dedicated Cu-Sn bronze.

Al-bronze is characterized by an excellent hardness and strength. Previous authors have shown that castings made of CuSn$_20$ and CuAl$_{10}$Fe$_3$Mn$_2$ have similar acoustic vibrations, which can be used to develop cheaper and high-strength bell templates that can facilitate the desired curvature shape and acoustic characteristics without further additional tuning [36,62,79].

Similiar to tin bronze, aluminum bronze has also been used to enhance the acoustic properties of bronze bells and the feasibility of a substitution for dedicated Cu-Sn bronze. Al-bronze is characterized by an excellent hardness and strength. Previous authors have shown that castings made of CuSn$_20$ and CuAl$_{10}$Fe$_3$Mn$_2$ have similar acoustic vibrations, which can be used to develop cheaper and high-strength bell templates that can facilitate the desired curvature shape and acoustic characteristics without further additional tuning [36,62,79].

Figure 5. Microstructural analysis of an as-cast bronze bell. (a) The cut view areas of the test points A (top) and B (bottom) of the bronze cast bell. (b–d) Scanning electron microscopy and the elemental distribution in areas with increased Cu and Sn contents, respectively [77].

Low-tin bronze alloy depicts a single-phase microstructure and has better machinability, which is used to make thin sheets and artifacts [78]. Previous researchers have added Pb to compensate for the difference in the Sn content from the top to the bottom core of the bell. The addition of Pb improves the melt fluidity but remains undissolved and segregates in the solid state. The presence of Pb-spheroids and their size distribution contributes to the machinability of Cu-based alloys [78]. Pb is found as spherical aggregates along with the α and δ phases in the eutectoid. The microhardness of bronze bells varies between 160 and 200 HV0.5 due to the non-homogeneous microstructure ("harder" α + δ, α and Pb-globules, and porosity) [67].

According to the metallurgy knowledgebase, casting is a material fabrication process in which molten material is introduced into a mold, allowing it to solidify within the mold, and then the mold is detached or broken to obtain the fabricated part. Castings are mainly used to make complex shapes that would be otherwise difficult or uneconomical to prepare using other methods, such as cutting, turning, or joining a solid [80]. In this section, we highlight the different methods used in casting technology.

Two major categories of metal castings include (1) expendable and (2) non-expendable mold casting technologies (Figure 6a). Expendable mold castings are permanent or temporary molds produced by sand casting and plaster of Paris (POP) molds. Most bronze bell castings utilize expendable mold castings with temporary pattern casting such as lost wax casting (LWC) or semi-permanent mold castings such as rotational molding or pep-set casting (Figure 6b). In this section, we discuss the casting technologies related to bronze cast bells in particular.

4. Metal Casting Technology

According to the metallurgy knowledgebase, casting is a material fabrication process in which molten material is introduced into a mold, allowing it to solidify within the mold, and then the mold is detached or broken to obtain the fabricated part. Castings are mainly used to make complex shapes that would be otherwise difficult or uneconomical to prepare using other methods, such as cutting, turning, or joining a solid [80]. In this section, we highlight the different methods used in casting technology.

Two major categories of metal castings include (1) expendable and (2) non-expendable mold casting technologies (Figure 6a). Expendable mold castings are permanent or temporary molds produced by sand casting and plaster of Paris (POP) molds. Most bronze bell castings utilize expendable mold castings with temporary pattern casting such as lost wax casting (LWC) or semi-permanent mold castings such as rotational molding or pep-set casting (Figure 6b). In this section, we discuss the casting technologies related to bronze cast bells in particular.
Metals 2022, 12, 1776

The traditional method of bronze casting using template molding expands the specified position of a mold during metal pouring. These template molds are considered improper because they do not take advantage of directional solidification [81]. The internal shrinkage pores inside the castings can disturb the sound vibrations in bells by introducing additional nodal points. Specifically, the casting technology of bronze bells can be divided into four methods, such as beeswax casting, rotational molding, polymer-set process, and LWC [82–85]. Among these, the rotational molding and beeswax casting methods are traditional casting techniques that have been used since ancient times. Beeswax remnants are not common in prehistoric European locations, with only a few exceptions to date [86,87]. The beeswax casting method was later used in Asia, especially in China and the Korean Peninsula, for the fabrication of bells, swords, and artifacts [88,89]. It is no exaggeration to say that almost all Buddhist bells in Korea were produced using the beeswax casting method from the unified Silla and Goryeo period [90].

4.1. Traditional Bronze Casting Methods for Bells

4.1.1. Importance of Beeswax in LWC

LWC or beeswax casting employs wax obtained from honey bees, an essential organic mixture of various compounds. The composition of beeswax differs quantitatively from different bee species [91]. The major components of beeswax include hydrocarbons, fatty acids, esters, and traces of a few unknown compounds [92–95]. Most recently, seven homologous series of beeswax have been used for identification, such as odd and even numbers of C- atoms (C17 to C35) (C22 to C34); odd numbers of monounsaturated fatty acids (C21 to C35) except HC29:1, HC31:1, and HC33:1; and monoesters (palmitate, (C34 to C50), oleate (C18:1–18, C18:1–20), and hydroxypalmitate with large chain alkanols (an isomer of C34 to C50)) [96].

Beeswax is believed to have specific importance in ancient technological, cultural, artistic, and symbolic areas as shown in Figure 7. The various applications of beeswax were summarized by Regert et al. in 2001 [97]. The last few years have shown new applications of beeswax as a glaze over pigment [98], a waterproof coating in ceramics [99,100], and an adhesive for a binding agent on Chinese turquoise-inlaid bronzes [101,102], in addition to its use as a sealing material for funereal homes [103]. With the development of lost wax metal castings, a significant amount of beeswax is required for the production of bronze castings using this method [104].
Figure 7. Application of beeswax in technological and artistic areas.

Beeswax has been used as a dental filling in Neolithic Slovenia [105]. Archaeological surveys have confirmed that the beeswax present in cooking pots is the remainder of beeswax castings [106]. Lamps or candles have played diverse technological, symbolic, and artistic roles in ancient times [107,108].

4.1.2. LWC Background

LWC is the most ancient casting technology for the production of cast artifacts, sculptures, bells, and swords. LWC is also known as investment or precision casting and has been widely known for centuries. The cast components have an excellent high surface finish, dimensional stability, and complex shapes (near-net-shape geometry) that are made possible when micromachining is not feasible or wasteful. Recent advancements in casting technologies have made it the most versatile casting method among the different casting technologies. According to Taylor [109], LWC originated in 5000 BCE when primitive men used it to fabricate tools for hunting animals.

Figure 8a–d shows the various cast objects used by primitive men to cast swords and pointed weapons using LWC. The assembled wax model was immersed in a clay mold followed by heating and squeezing of the wax out of the mold, leaving behind a hollow object that was filled with liquid metal. The solidified weapon heads were then detached and finished. Kotzin [110] mentioned the importance of this process in various jewelry, idols, and art castings for centuries. LWC has been found in various areas across the globe such as the treasures of the Pharaohs in Egypt, Inca tombs of South America, the ancient Etruscans, the Greeks in Europe, the Chinese Bronze Age, Indus Valley and Harappan civilization, etc. An example of a Harappan bronze sculpture, a creative dancing girl, is shown (Figure 8e). Later, this LWC was utilized to produce artifacts of Cu, Cu-Sn, and Au. The review by Kotzin states that LWC helped in promoting the cultural civilization of people across the globe. LWC offered solutions to various complex-shaped objects, undercut parts with a smooth finish, and fine details. In recent times, the use of LWC has continued to increase in the manufacturing of a variety of products.
4.1.3. Merits and Drawbacks of LWC

The various applications of LWC in the modern age include charger wheels, electronic gadgets, golf club heads, biomedical hip implants, and aerospace components for defense outlets according to Eddy et al. [111]. LWC has no metallurgical limitation on the products, including ferrous and non-ferrous alloys. No additional costly tools are involved in this process. However, LWC involves expensive manual labor to prepare the wax pattern and ceramic slurry.

The extensive investigations of LWCs carried out by Craig et al. [112] showed that the suitability of a wax pattern as a lost wax pattern depends on the following factors: (1) the lowest possible thermal expansion to match the desired dimensional accuracy; (2) a melting point that is lower than ambiance to prevent thermal distortions and cavitation issues; (3) high resistance to deformation at room temperature for easy handling; (4) high wettability and smoothness. (5) low viscosity to fill the thinnest sections of the mold during pouring; (6) easy detachment from the mold after casting; (7) ash free and should not leave any residue in the mold; and (8) environmentally safe. Other factors include the expenses, recyclability, availability, and toxicity when choosing a wax pattern. The efficiency of the lost wax can be achieved by employing additives, mixing it with different wax types, and optimizing the process parameters.

4.1.4. LWC for Bells

LWC using the beeswax method is the first ancient casting technique used in China around the 10th century BCE. It was introduced into Korea around the 3rd century BCE and was believed to be the origin of the modern LWC method. Beeswax casting is still a traditional method in Southeast Asia, Europe, and Africa. Craig et al. [113] studied the use of beeswax in dentistry at the University of Michigan and reported that the mechanical strength properties are especially important when considerable expansion occurs during investment casting for dental applications.

The beeswax casting method produces a model that is identical to the shape of the bell that is made of beeswax and overlaid with molding sand mixed with fine-grained clay and sand followed by drying [114]. After, the mold is heated to liquefy the wax inside, and liquid melt is poured into the space where the wax is dissolved. Beeswax is seldom
mixed with rosin, wood oil, or beef oil to soften the wax so that the outer plates rotate well [41,45]. The process flow of the beeswax method consists of pattern engraving, wax pouring, wax pattern plate production, core production, wax layer on the core, wax pattern plate assembly, casting sand, drying, wax removal, firing, melting, and casting.

Kissi [115] evaluated the casting of hollow artifacts produced by Ghanaian traditional metalsmiths and suggested that the use of liquid wax to produce hollow wax frames in POP molds should be used to ensure direct duplication of the master without the creation of parting lines in the inner walls of the model.

Hossain et al. [116] studied the physicomechanical characteristics of paraffin and beeswax to simulate the rocking behavior for water jet drilling and concluded that natural beeswax could be a good substitute for reservoir rocks. Giuseppe et al. [117] studied the thermos-mechanical properties of beeswax-halloysite nanotube (HNT) composites and stated that a slight decrease in the beeswax crystallinity occurred after the HNT addition. Zhang et al. [118] investigated the thermal behavior of four insect waxes and obtained a melting point of 70.34 °C and melting enthalpy of 168.1 J/g for beeswax.

Previously, Dong-Joo et al. [119] studied the influence of the temperature and cooling speed on the mechanical characteristics of a pressure cast thermoplastic composite. The results showed that the crystallinity decreased with the increased cooling rate, with the slowly cooled specimen having a high fracture toughness.

The patterns are engraved on stone, clay, or wood such as talc with an intaglio, and then the pattern is re-sculpted with wax (Figure 9a,b). The preparation of 3D patterns such as dragon string or a sculpture is created using the beeswax form (Figure 9c-e). Larger bells are difficult to make using the beeswax casting method, and it is presumed that the rotary method and beeswax casting method coexisted at the time [120]. Unfortunately, the key technology of this traditional method was lost during Japanese colonial rule and the Korean War. The demand for bells increased after the Korean War due to the rapid spread of Protestants, and the first bell manufacturing company was established in Korea in 1954, which used the rotational molding method learned from the Japanese [121].

![Figure 9. The fabrication process of a beeswax form [110,116]. (a) Pattern engraving, (b) beeswax pouring, (c) beeswax patterning, (d) plane beeswax form, and (e) beeswax bell form.](image)

Modern LWC for the *pomjong* bell was developed in the last few decades and was patented in Korea in 2004 [122]. The biggest difference between LWC and conventional wax casting is whether the model of the bell is made only with beeswax or a mixture of beeswax and FRP. In LWC, the bell frame is made of FRP—only the pattern part is separately made of wax—and the wax pattern is inserted into the FRP frame (Figure 10a–b). Although it is a simple process, it is important to know how to insert beeswax into the FRP bell mold and separate the FRP bell mold so that the molding sand does not break after coating with the casting sand.
When the model of the bell is completed using FRP and beeswax as shown in Figure 10c, unlike the traditional wax method, which uses clay and sand as the casting sand, in this method, ceramic materials such as zircon flour and chamotte sand (fire clay) are used as the casting sand, and colloidal silica is used as the binder. A slurry of colloidal silica and zircon flour is coated on the surface of the beeswax model and then chamotte sand is applied (Figure 10d). According to the size of the species, this process is repeated up to 30 times or more. After the casting sand coating is finished, the FRP and beeswax inside are removed and the outer shape is ceramicized through firing (Figure 10c,f). The finished outer frame is placed on the core, and a separately molded dragon string is placed on it to complete the form (Figure 10g,h).

Previous bell manufacturers have attempted to produce large and small bells using a variety of materials: cast iron, steel, Zn and Al alloys, glass, China clay, or pottery. However, the alloy consists of about 80 wt.% Cu and 20 wt.% Sn is still regarded as the basic material for the production of bells, the so-called ‘bell bronze’ [123,124]. Despite many trials of replacing the costly Sn with other elements, no alloy with similarly good acoustic properties has been achieved so far [36,125]. There were incidents where some large-scale projects failed to combine these properties. Some bells cracked after a short time of use, e.g., the Aleksejevskij bell, which worked for only one year, and the largest bell in the world, the Tsar Bell, also known as Tsarsky Kolokol, with a mass equal to 250 × 10^3 kg, has never stricken a note. Since 2000, the largest and heaviest ringing bell in the world has been the Bell of Good Luck at the Foquen Temple in Pingdingshan city, China, whose mass is 116 × 10^3 kg [126,127]. The shape of bells has changed over the centuries [128–130]; nevertheless, their construction was designed to have suitable strength and divine sound using properly selected parameters, i.e., wall thickness, bell diameter, and the composition of the alloy, which are decisive concerning the sound tone and timbre [131–133]. The optimal mechanical strength is easy to achieve by increasing the bell wall thickness, but the relationship between the shape of the bell and its sound is hard to grasp, especially because the bell sound consists of a series of merged tones and overtones, which give the so-called strike tone [134,135].
4.2. Rotational Molding Method

4.2.1. Rotomolding Process

Rotational molding is also termed rotomolding or rotational casting. It is the most popular processing method for molding. It was first developed in the early 20th century, but it became popular after the 1960s when Lyondell Basell replaced vinyl plastisol resins with polyolefin resins [136]. The rotomolding process consists of four stages: charging, heating, cooling, and de-molding, as shown in Figure 11 [137–141].

![Figure 11](image_url)

**Figure 11.** (a) Rotomolding process and (b) thermal cycle for rotomolding of a semi-crystalline polymer [141]. There are seven steps in the thermal cycle profile.

The various stages in rotomolding are illustrated in Figure 11a,b. The various steps are as follows. The first step is mold charging, where the cast material is poured into the mold. The cast material is in the form of a powder, with or without additives, to achieve a uniform heat distribution. After charging, the mold is heated with uniaxial or biaxial rotation. The rotation speed is optimized, which is relatively low to achieve a uniform distribution. The uniaxial to biaxial rotation ratio is usually maintained at 4:1 to avoid the adherence of melt over the mold surface. After heating, the mold is cooled with air or water spray and the solidification of the cast sample follows. After solidification, the final cast product is detached from the mold and recovered [141].

4.2.2. Materials for Rotomolding

The numerous materials and their respective properties used as rotomolded cast products are summarized in Table 4. Rotomolding has also been used to prepare automobile prototypes. Although this method has the disadvantages of poor strength and degradation over time, the process is now becoming more popular due to the production of stress-free plastic products. Due to these challenges, suitable surface functionalization is exercised by choosing a suitable resin and additive polymer. The optimum process parameters in rotomolding can give rise to promising plastic products for industries. Rotomolding products are expected to increase in the near future [124,125].
Table 4. Various polymers and their properties needed for rotomolding [142,143].

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Moldability</th>
<th>Impact Strength</th>
<th>Advantage</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene</td>
<td>Excellent</td>
<td>Good</td>
<td>Low cost</td>
<td>Lower strength</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>Good</td>
<td>Poor</td>
<td>Better stiffness</td>
<td></td>
</tr>
<tr>
<td>Polystyrene</td>
<td>Good</td>
<td>Poor</td>
<td>Minimum shrinkage</td>
<td>Poor strength</td>
</tr>
<tr>
<td>Polyether ether ketone</td>
<td>Moderate</td>
<td>Poor</td>
<td>Rigid, fire safety</td>
<td>Expensive compared to polyethylene</td>
</tr>
<tr>
<td>Polyvinyl chloride</td>
<td>Good</td>
<td>Good</td>
<td>Easily paintable</td>
<td>costly than polyethylene, lower stiffness than polyethylene</td>
</tr>
<tr>
<td>Acrylonitrile butadiene styrene</td>
<td>Moderate</td>
<td>Good</td>
<td>Rigid and paintable</td>
<td>costly than polyethylene</td>
</tr>
<tr>
<td>Ethylene butyl acetate</td>
<td>Good</td>
<td>Good</td>
<td>Stretchable</td>
<td></td>
</tr>
<tr>
<td>Epoxy</td>
<td>Moderate</td>
<td>Poor</td>
<td>Thick and rigid, high impact strength</td>
<td>Highly expensive</td>
</tr>
<tr>
<td>Fluoropolymers</td>
<td>Good</td>
<td>Good</td>
<td>Chemical resistant</td>
<td>toxic</td>
</tr>
<tr>
<td>Nylon</td>
<td>Good</td>
<td>Good</td>
<td>Heat resistance, better impact resistance</td>
<td>Expensive</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>Good</td>
<td>Good</td>
<td>Transparent, tough</td>
<td>Harder moldability compared to polyethylene</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>Good</td>
<td>Good</td>
<td>Wear resistant</td>
<td>Higher cost than polyethylene</td>
</tr>
</tbody>
</table>

Rotational molding of temple bells is associated with the production of a core and an outer bell shape using separate rotating plates for the core and the external shape, their fixation on the central axis, and attachment of the casting sand while the rotating plate is rotating (Figure 12). To make the cross-section of the core, the outer shape should be cut exactly in half. The size must be decided by considering the shrinkage rate of the casting, and the difference between the diameters of the two rotating plates determines the thickness and shape of the bell. The core is fabricated using stacked bricks with a size slightly smaller than the actual core to be manufactured or by reinforcing bars to form the core (Figure 12a). A rotating plate is attached to the center for sand casting while rotating it (Figure 12b). Green sand is used as the casting sand mixed with clay as a binder. When the shape of the core is established, the surface of the core is smoothed, and then a graphite coating with water is painted and left to dry (Figure 12c,d).

Figure 12. The fabrication process of the bell core using rotational molding. (a) Building core bricks, (b) rotational molding, (c) mold wash coating, and (d) core drying [11].
When the core is completed, beeswax is applied while rotating according to the thickness of the bell, and then the surface is finely trimmed to finish. To improve the fluidity, beeswax is mixed with animal oil. After, the melted beeswax is pasted on a pre-patterned plate and inserted onto the surface of the wax model. The dragon strings are formed directly, with beeswax attached to the upper part and cast sand over the beeswax. To prevent cracking and improve the strength, broken earthenware fragments are also attached to the outer surface as reinforcements as the outer surface dries naturally. After complete drying, the outside of the mold is heated to melt the wax inside, leaving behind the bell core and outer part. The productivity of this method is low due to several complicated workflows. Raw sand is used as casting sand, and clay or bentonite is used as the binder. The proper mixing ratio of raw sand and bentonite is about 100:4 and is kneaded with a little water [144]. The quality of the bell core can be improved by choosing high-quality zircon sand or other ceramics with excellent fire resistance [145,146].

The relationship between the moisture content of the molding sand (the breathability) and the strength of the molding sand was investigated in previous study [144]. The breathability was optimal at a 2~3% moisture content, and the strength of the mold increased up to a 10~20% moisture content, and it tended to decrease when it exceeded the moisture content. Considering the air permeability, the authors suggested that mold strength and workability was optimal at a moisture content of 6~8% [144].

4.2.3. Major Applications of Rotomolding

Rotomolding processes are cost-effective compared to other casting methods due to their lightweight, flexible, and corrosion resistance properties, etc. [147–149]. However, there are certain limitations of rotomolding such as its low strength and stability [150–154]. Certain additives have been used to improve the rotocast strength [155–160]. Therefore, rotomolding is often used to fabricate hollow, multilayered seam-free products. This technique has attracted enough attention in the past few decades and produces stress-free products with heat [161–164]. Rotomolding molds are less expensive than other cast molds and material wastage is minimized [165,166]. Rotomolding has been commonly used in tanks, medical instruments, fuel storage tanks, toys, traffic signs, toys, furniture, toolbox, etc. [167,168]. Other miscellaneous applications include light laundry mats, kayaks, vehicle crash bars, oxygen mask lids, vending and display items, aquarium accessories, drug dispensers, contact lenses, etc. [169]. As early as the 1970s, cross-linkable and modified polyethylene-grade polymers were present in the rotomolding market. These new polymers again fueled new market areas, especially the production of large tanks.

4.3. Pep-Set Casting Method

4.3.1. Pep-Set System

Pep-set is a highly reactive process used to make sand cores and molds in a foundry using the no-bake process. This process requires a pep-set system, which needs a relatively long time for polymerization and simultaneous fast curing and provides higher productivity [170]. The cast product strength is very high and there is no need for the further addition of a binder with the pep-set system, which in turn minimizes contamination and the emission of impurities during molding. The standard concentration of a pep-set system is less than 0.6% per part. The curing speed depends on the ambient temperature and can be controlled by the quantity and/or quality of catalyst used in the ratio (1:0.5–5.0% per part).

The pep-set system is a potential casting process, where the binders rely on the polymerization reaction of phenolic resin with an isocyanate additive. The process involves a three-part binder system (binder, hardener, and liquid catalyst). The hardening proceeds without any formation of by-products such H$_2$O or HCHO [170].

4.3.2. Background of Pep-Set Casting

The pep-set casting method and the LWC method are modern casting techniques that began to be used in the 1980s. The pep-set process was developed mostly in Europe and
later introduced into Korea in the 1980s [171]. Pep-set binders are primarily a product of polymerized phenolic resin and an isocyanate component. The process involves the three steps of a binder, hardener, and liquid catalyst [172]. The pep-set method is more productive than the conventional rotary method but also results in a better quality of the product. The pep-set process, one of the self-hardening mold casting methods, is a modern casting method developed in Europe and introduced into Korea in the 1980s through Japan. It was used for the casting of automobile engines and precision machine parts but started to be used to case sculptures such as bells and statues in 1986. Even though there was resistance in the main industry at the time, it was an opportunity to raise the quality of Korean bells. More than 10 years later, in 1997, the traditional method of beeswax casting was restored by Won Kwang-Sik, which is an important cultural asset [173].

A limited number of studies exists on the casting of Buddhist temple bells. A few notable works were summarized by Y.H. Yeom in around 1991–1995 [11,149]. There are a lack of studies that have been carried out on the use of the pep-set method for temple bells. In 2006, a new beeswax casting method was used for large Buddhist bells for the first time in the world [174,175]. However, due to the low yield, the beeswax casting method fell into hibernation at the industrial level, but it was later improved and is being used today.

4.3.3. Molding in Pep-Set

This method requires a high initial cost due to the various sizes of the molds and their usage. The mold used in the pep-set casting method is manufactured by a method that is completely different from the method used in the rotary or other casting methods. First, the rotary plate is made with POP, which is the same shape as the bell, and then a pattern engraved on POP is inserted to make a bell model out of POP (Figure 13a,b). FRP (fiber-reinforced plastic) is again applied to the POP model, and the process of hardening is repeated to make a \( \text{ROUND} \)-shaped FRP model by removing the plaster inside when the appropriate thickness is reached. If FRP is applied to the inside of this \( \text{ROUND} \)-shaped FRP model and separated again, a \( \text{LONG} \)-shaped FRP model is made, which is used as a mold (Figure 13c). At this moment, the mold is divided into three to four parts so that it can be separated from the formwork after molding.

![Figure 13. The fabrication process of a bell form. (a) A POP bell form, (b) an engraved plaster bell form, (c) an intaglio FRP bell form, and (d) a completed bell form.](image-url)

The molding operation is carried out by putting a mold that is large enough to be filled with the molding sand on the outside of the vertical mold made of FRP, mixing resin (pep-set) and molding sand with a kneader, and filling the space between the mold and mold walls.

Artificial silica sand is mainly used with casting sand, mixed in a ratio of 50:50. The smaller the particle size of the molding sand, the more delicate the surface obtained. Since it is impossible to obtain a sound casting, it is important to select a particle size that is suitable for the casting. When the molding sand is hardened, the FRP mold inside is disassembled and removed, and a ZnCO\(_3\)-based coating agent is applied to the mold surface engraved with the pattern (Figure 13d).
According to historical records, casting technology dates to 5000 BCE and originated in the Middle East and later entered Asian countries such as China, Korea, Japan, and India. The earliest records of casting technology are preserved in the writings of the monk Theophilus Presbyter in his book *Schedula Diversarum Atrium* in 12th century BCE [176]. According to Theophilus Presbyter, the operational sequence of bell-making consists of several steps, such as building and shaping the clay core with a horizontal lathe, removing the lath spindle, and closing the hole with plastic clay to support the U-bent iron staple hanging on the clapper. After that, the upper part of the mold is added to the core, and four pole guides are used as a sink. The casting pit is prepared with Roman tiles plastered with clay. Heat is provided from both the upper and lower part of the square outer furnace. After firing, the pit is quickly emptied, and the mold is slowly lifted out and detached to recover the bell and the iron hoops [177].

In the late 1950s, a detailed operational sequence for casting neck collars of the Early and Middle Bronze Age was created by Hans Drescher [178]. Later, in the 1980s, Rønne added an important knowledge base regarding stamping and spiral techniques [179,180]. In summary, these developments led to the assumption that these decorated artifacts (such as neck collars, belt discs, and tutuli) were crafted via the wax model into their final forms [178]. Secondary decorative components such as rims and geometrical elements were either stamped [180] or added to the wax.

With the advancement of modern casting technology, computational tools have enabled foundrymen to bridge the gap between design and manufacturing. New computational approaches should be used to identify defects (hot tear, shrinkage pore, cold shut, etc.), determine the casting time, guide the morphology, and optimize the entire process.

5. Advanced Rapid Prototyping Techniques in Investment Casting

As already discussed, conventional wax casting technology is expensive for low-volume manufacturing such as customized or prototype component casting. As such, the process is highly time-consuming and spans weeks to months depending on the machine shop’s capacity and schedule. Design errors and iterations add up and impact the final manufacturing cost. In these situations, rapid prototyping (RP) techniques are receiving increasing attraction for casting objects with freedom from design constraints. LWC has been integrated with RP techniques to improve the yield and flexibility of manufacturing in various applications [181,182].

Advanced computer-aided manufacturing (CAD) design has helped to achieve the best RP techniques. The CAD model of a 3D object is sliced into several sequential layers that can be joined to consequent layers in a layerwise fashion. The different RP techniques’ process flow is shown in Figure 14a. The diversity in the materials and processes used for binding the layers in sequence constitutes the different RP processes. The existing RP techniques are classified into four major classes: liquid, powder, sheet, and gas-based platforms (Figure 14b). The first RP technique, stereolithography (SLA), was discovered in the late 1980s. After, several improvements of the RP techniques were performed. According to Liu et al. [177], other commercial RP techniques include fused deposition modeling (FDM), laminated object manufacturing (LOM), selective laser melting (SLM), and 3D printing.
According to these technological advances, this classification will allow 3D manufacturers to choose a suitable RP technique with increased accuracy, performance, and durability. Cheah et al. [181] reviewed the diverse applications of RP techniques to several LWC processes ranging from jewelry casting, sports goods, biomedical implants, injection molded parts, and die casting to the automotive/aircraft industries. The integration of RP techniques with LWC has potential merit for rapid and cost-effective production of high-precision castings.

Although RP techniques are highly productive and flexible, the application of these techniques to temple bells is new due to the expenses incurred over the raw materials. The printing of bronze bells requires the integration of wax 3D printing and LWC technologies. Wax 3D printing uses the SLA technique to create the wax pattern from a wax-like resin. For additional support to stand the wax pattern, support structures are also printed together with the wax model. The support structures are removed manually after the printing process followed by cleaning of the wax pattern for casting.

Initially, one or more wax sprues can be joined to the pattern. Next, these sprues can be attached to a wax ‘tree’ together with other wax patterns. This wax tree is then placed in a flask and covered with a fine POP. As soon as the POP solidifies, a mold is formed for bronze casting. The POP mold is then fired or oven heated to burn all the wax. The liquid bronze is then poured to fill the cavities left by the wax followed by cooling, solidification, and breaking off the mold to obtain the cast model.

The process of employing RP techniques together with the fabrication of wax patterns is referred to as rapid investment casting (RIC). The advantages of RIC include its cost effectiveness, high manufacturing ability, freedom in the design of parts that were initially difficult or impossible to make via machining, feasibility of design iterations or tool modification, and ability to facilitate parametric optimization effectively. However, RIC patterns are not economical and are limited to mass production due to the expensive RP materials involved. For a high production volume, rapid tooling (RT) can effectively manufacture tens to millions of wax patterns in an economical way.

6. Conclusions

In this paper, the history, materials, and casting methods used to produce bells were overviewed. Primitive bells were manufactured using casting and bell-making technology such that even a complex bell material composition was well-designed. Korea’s bell-making technology has been steadily developing, breaking away from the traditional method due to the development of new bell materials and processes. Owing to a lack of metallurgical knowledge of compositions in earlier bells, the alloys used in the Middle Ages were significantly different from the current bell metals. A study of earlier bells through
Metallography revealed substantial differences in the microstructure and compositions through modified melting and casting approaches. During the post-independence era, Korea steadily innovated different rotational methods, pep-set casting, and LWC methods, becoming a world leader in cast bell technology. Future research should be carried out with other low-cost wax and additives to improve the castability of bells. Nowadays, the use of pure elements and progressed melting practices has decreased contamination levels due to the addition of P and S, which makes bells more robust and less sensitive to cracking when hit by a hammer or wooden block. However, limited attempts have been carried out to cast a temple bell to replace conventional metal casting techniques. Future research should be directed towards RP techniques to fabricate wax patterns directly from the CAD file by layerwise deposition of wax droplets. Though these RP techniques are more advanced, conventional LWC techniques are still being used today for different metal casting and temple bell fabrication because of the obstacles of the high cost of materials and experimentation so that small- and medium-sized industries are unable to procure them. Therefore, further amendments of the current methodologies that reduce tooling costs are desired. Technological developments of RP techniques are expected to bring the cost down and lead to a better casting quality, temple bells, and acoustics, resulting in a longer service life to mankind.

Author Contributions: Conceptualization, C.-S.W. and J.P.J.; methodology, C.-S.W.; formal analysis, K.-S.W.; investigation, K.-S.W.; resources, A.S.; writing—original draft preparation, C.-S.W. and A.S.; writing—review and editing, C.-S.W. and K.-S.W.; project administration, A.S.; funding acquisition, A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References
4. Isogawa, S. Casting sites of bronze bell and iron kettle in ancient and medieval Japan. ISIJ Int. 2014, 54, 1123–1130. [CrossRef]


97. Regert, M.; Colinart, S.; Degrand, L.; Decavallas, O. Chemical alteration and use of beeswax through time: Accelerated ageing tests and analysis of archaeological samples from various environmental contexts. *Archaeometry* **2001**, *43*, 549–569. [CrossRef]


113. Craig, R.G.; Eick, J.D.; Peyton, F.A. Strength properties of waxes at various temperatures and their practical application. *J. Dental Res.* **1967**, *46*, 300–305. [CrossRef] [PubMed]