

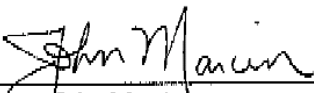
**A Comparison of the Ancient Metal Casting Materials and Processes to
Modern Metal Casting Materials and Processes**

by

Sarah Elizabeth Greer

A Masters Project Submitted to the Graduate Faculty of
Rensselaer Polytechnic Institute in Partial Fulfillment of the
Requirements for the Degree of
Masters of Mechanical Engineering

Approved:



Professor John Marcin
Project Adviser

Rensselaer Polytechnic Institute
Hartford, Connecticut

May, 2009

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ACKNOWLEDGMENT

The author gratefully acknowledges Professor John Marcin for his endless patience and expertise. She additionally wishes to thank her family and friends for their encouragement and motivation.

ABSTRACT

A comparison of ancient casting processes and materials to modern casting processes and materials is presented. A review of the history of castings relative to five ancient casting centers of excellence is presented, along with a discussion of how this history shaped the casting industry at these locations. The historical examination is limited from 3000 BC (earlier only if deemed significant) through 500 BC, and examines Mesopotamia, Egypt, China, Thailand, and India. Both material and process improvements are reviewed and discussed. The same metals cast during this time period are examined in the 21st century, including information on usage and popularity. The modern casting processes that can trace origin to the ancient ones are also discussed and linkages are analyzed.

1.0 INTRODUCTION

Everyday in the modern era, people interact with hundreds and thousands of objects that were created through casting. Casting is one of the most ubiquitous manufacturing processes in today's world. It is also one of the oldest manufacturing processes. People around the world have utilized casting as a manufacturing process since 3000 BC. However, while the casting processes used today are strikingly similar to those used in ancient times, we can now use them to cast a variety of materials, enabling castings to be used for simple objects to complex ones.

The ancient expertise in casting resided among several cultures – the Mesopotamians, the Egyptians, the Chinese, the Thai, and the Indians.

It's unusual to think that anything from a modern manufacturing process could be similar to an ancient process. The technological progress made by modern man is astounding – today, conveniences like electricity, indoor plumbing, even prepackaged groceries, are considered basic necessities. By contrast, ancient man is often portrayed today in pop culture as cave men, who grunt, are not intelligent, and surprised and suspicious of new ideas and concepts.

Despite these preconceived notions, the ancient men who invented metalcasting were intelligent, forward thinking, and discovered a process that is so basic and universal that it is recognizable as the process used in the modern world.

In today's world, three basic casting processes dominate that can trace their origins to the ancient times: sand casting, investment casting, and permanent mold casting. In the Near East, Mesopotamia and Egypt were the early leaders in the development of casting, while in the Far East, China, Thailand, and India dominated.

2.0 HISTORY OF ANCIENT METALWORKING

Ancient man began working with metal over 10,000 years ago. Table 1 below outlines an overview of the progression of metalworking through the first 9,000 years. The first metalworking was in the Mesopotamian area when man discovered native copper. Copper is soft enough to be fashioned into objects by hammering and shaping the material without heat.

Table 1: “Chronological list of developments in the use of materials” (Goodway)

Date	Development	Location
9000 B.C.	Earliest metal objects of wrought native copper	Near East
6500 B.C.	Earliest life-size statues, of plaster	Jordan
5000-3000 B.C.	Chalcolithic period: melting of copper; experimentation with smelting	Near East
3000-1500 B.C.	Bronze Age: arsenical copper and tin bronze alloys	Near East
3000-2500 B.C.	Lost wax casting of small objects	Near East
2500 B.C.	Granulation of gold and silver and their alloys	Near East
2400-2200 B.C.	Copper statue of Pharaoh Pepi I	Egypt
2000 B.C.	Bronze Age	Far East
1500 B.C.	Iron Age (wrought iron)	Near East
700-600 B.C.	Etruscan dust granulation	Italy
600 B.C.	Cast iron	China
224 B.C.	Colossus of Rhodes destroyed	Greece

From this first discovery of copper, man progressed to the Chalcolithic period, where heat was used to aid in working the copper. When copper is cold worked, it becomes harder. Using heat to work the copper gave man more options for its usage. Using heat with copper soon led to alloying copper with other materials and the onset of the Bronze Age in Mesopotamia.

2.1 MESOPOTAMIA

The Mesopotamians began working with metal in 9000 BC, per Table YY. Copper, gold, and silver were the first materials they noticed and worked. Their color likely made them stand out from other stones. Additionally, when these metals are hit, they behave differently than a stone would. Stone is a brittle material, and when hit it tends to splinter and break. Gold and silver are malleable, and when hit both will conform to the new shape. Copper will become harder when hammered or hit, though it will not break. The use of these materials progressed into heating copper and learning how to melt it during the Chalcolithic period, from 5000-3000 BC. The

Chalcolithic period led into the Bronze Age, which began in Mesopotamia about 3000 BC. In Mesopotamia and other areas in the Near East, the Bronze Age lasted about 1500 years. The Iron Age began in 1500 BC, but in this region iron was not cast for several thousand more years.

2.1.2 Material Development

Mesopotamia is generally accepted as the birthplace of castings. Mesopotamia is a region in the Middle East that stretches north from the Persian Gulf, between the Tigris and Euphrates rivers.



Figure 1: Map of Mesopotamia (MSN Encarta)

Its area has since been divided into modern-day Iraq, Turkey, and Syria. Due to its location, Mesopotamia had some unique advantages. Hunter-gatherer tribes decided to settle in this area and create a permanent home. This transformed the culture to one where husbandry and agriculture became vital to survival. This change helped drive additional needs into the people for tools. Instead of only requiring hunting tools, now man needed tools to grow food, build

permanent shelters, and establish a home. This settling additionally helped castings begin and flourish as an industry. Hunters-gatherers who travel constantly cannot create furnaces or large permanent tooling fixtures. Mining would be difficult, as well as creating foundries. In order for these steps to occur in the metal-casting industry, the founding society had to be stable and in a permanent location.

Man's first exposure to metalwork was with elemental ores such as gold, silver, and copper. Gold and silver were the first metals to be noticed and worked. These are malleable and flatten when hammered, which made it easy for ancient man to shape and use the materials. Gold and silver were valued, most likely for their colors, and used mostly as jewelry. However, neither was hard enough to be used for weaponry or tools.

Copper was a different story. Though it may have first been confused with gold due to its similar colors, man soon realized that this material became harder when hammered and worked. Civilizations in Egypt and the Middle East may have been first to discover this fact – at least, they seem to be the first who used it to their advantage. They used hardened copper to create tools, such as knives. While this was a big step, the copper was still not hard enough to be used as a weapon – it merely sufficed for agricultural uses and cutting game flesh. The next major copper discovery occurred between 4000 and 3000 BC. It is fabled that a prehistoric man banked his fire with copper sulfide ores, such as covellite or malachite. In the morning, the copper had melted out of the ore and was found in the fire bed. This led to the discovery that copper could be extracted from other materials, which meant people were not limited to using only those metals found naturally.

Covellite, an indigo blue mineral, has a wide-ranging copper and sulfur ratio – it can be anywhere from 1:2 to 2:1. Covellite is not a very abundant mineral today, though there is a natural occurrence in Lebanon. Lebanon is very close to the ancient site of Mesopotamia, making it very likely that this material was discovered and used by ancient man in the area. Malachite, on the other hand, is a green stone also known as copper carbonate. Its chemical formula is $\text{CuCO}_3\text{Cu}(\text{OH})_2$. This was also found and mined in the Middle East in ancient times. Copper mining has been occurring for years in the Timna Basi, on the Sinai Peninsula.

According to the Timna Copper Mines homepage, copper has been mined from this site since 4000 BC. Malachite is one of the most abundant materials in the area, along with chrysocolla ($\text{CuSiO}_3 \cdot 2\text{H}_2\text{O}$).



Figure 2: “The oldest known casting in existence, a cast copper from found in Mesopotamia, probably cast around 3200 B.C.” (Simpson 13)

Copper was the first metal to be cast. It has a low melting point, 1980 degrees Fahrenheit, so it was relatively easy to melt and shape the metal. Figure 2 shows the oldest known casting in existence. It was likely created using sand casting. Its complex shape and three dimensional characteristics would make this difficult to cast using a stone permanent mold. The Mesopotamians used copper castings to make horse harnesses, agricultural tools, domestic

wares, and some weapons. The need for these tools was driven by the creation of one of the world's first cities. The lifestyle of husbandry and architecture decided upon by the Mesopotamians drove the need for horse harnesses, agricultural tools, and domestic wares. It was also important for Mesopotamians to maintain their army, and their central location was visited by many other various groups of people.

As man created weapons and tools from copper, he learned that some coppers made better castings than others. This may have been largely based on the color of the metal. Certain "colors" or metal compositions formed more reliable, more consistent products. We now know these specific colors were bronze. The recognition and use of this alloy initiated the Bronze Age, around 3000 BC. The first alloys were most likely accidents. While casting copper, some lead, tin, or arsenic may have been in the ore. Man would have noticed the difference and begun to explore how this metal casting was different from others. Bronze castings are stronger and more sound than pure copper. Several different alloy compositions have been identified from this time period. The first variety was made with arsenical copper, and contained 4-12% arsenic. The artifacts made with this alloy tend to be silvery, and almost appear to be silver plated. Tin was also alloyed with copper, which had a number of positive impacts over the arsenic. Using 5-10% tin in the bronze alloy lowered its melting point, which deoxidized the melt, improved its strength, and produced an easily polished cast surface. Examining other artifacts has shown a composition of 87% copper, 10-11% tin, and small amounts of iron, nickel, lead, arsenic, and antimony.

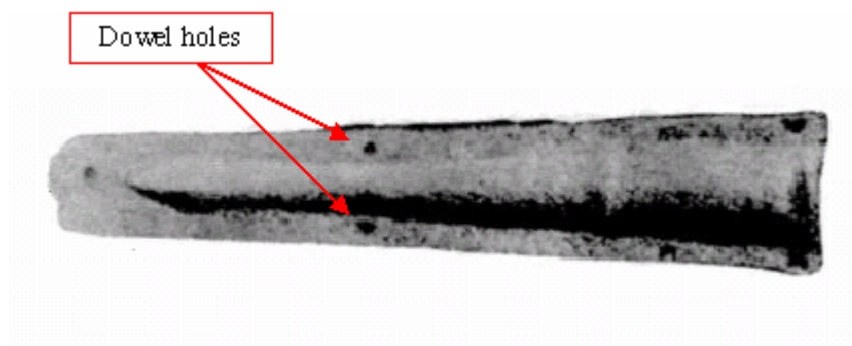
2.1.2 Casting Process

These early castings were created using open molds. Early molds even used sand as a base, but this was difficult as it was not easily repeatable. Stone, limestone, and sun-baked clay soon became the preferential mold material.



**Figure 3: “Open stone molds for the casting of implements and daggers, found at the site of ancient Troy”
(Simpson 8)**

Man quickly discovered that using closed molds produced more sound castings. Bivalve molds were very popular, and were often used to create symmetric objects. A bivalve mold is a mold with two symmetric halves. They are held closed together while molten metal is poured. Once the metal has cooled, the mold is broken apart to release the casting.



**Figure 4: “Photograph of an early two-part stone mold.” The drag, or bottom half of the mold is shown. Dowel holes are visible, indicating where the top half, or cope section, of the mold would be attached.
(Simpson 12)**

One side effect of closed mold casting was the discovery of flash. Flash is the excess metal that expands between the two halves of the mold. Flash occurred for various reasons. Metal molds were not precise, and the mating surfaces could be quite rough. Molten metal was able to seep through the spaces between the halves of the mold. To avoid having flash ruin or mar a cast item, molds were created such that flash occurred at edges which required finishing. Upon examination of artifacts, such as swords, metallurgists have observed the edges to be harder than the rest of the object, signifying the object had been work hardened in certain areas.

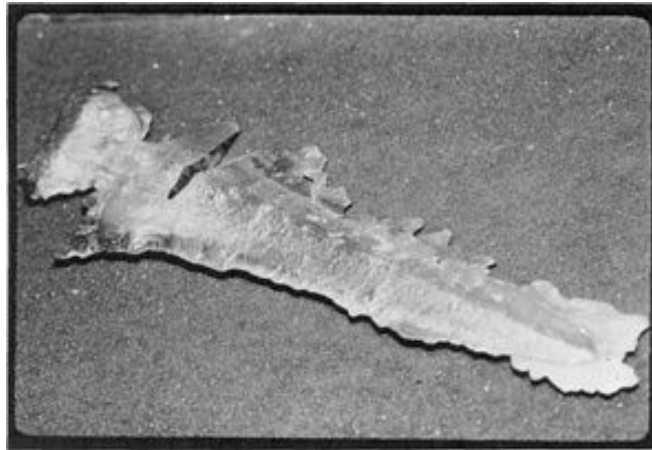


Figure 5: “A sword of typical Bronze Age design replicated...in arsenical copper using a bivalve mold. It has a silvery surface due to inverse segregation. The flash at the mold joint demonstrates the excellent fluidity of the alloy.” (Goodway)

Along with improvements to the mold materials and construction, improvements were being made to other aspects of the casting process. To speed production of cast goods, an assembly or production line approach was used. Molds were placed in an empty log, and molten metal was ladled in to fill the molds.

Furnaces were another target to be quickly improved. Initially, metal was melted by being placed in a crucible over a fire. To get the fire hot enough to melt the metal, men would sit next to the fire and blow air on it. Often they used sticks of bamboo to direct the air into the fire. Using the fact that fire is hotter when air is around, man initially built furnaces on hillsides. This helped increase production through the furnaces, as the wind was more effective than using men blowing into bamboo sticks. It wasn't long before bellows were introduced. These allowed the

operator to control the furnace heat, and removed the dependency on the variable winds. Figure 6 shows an operator working a bellows furnace.

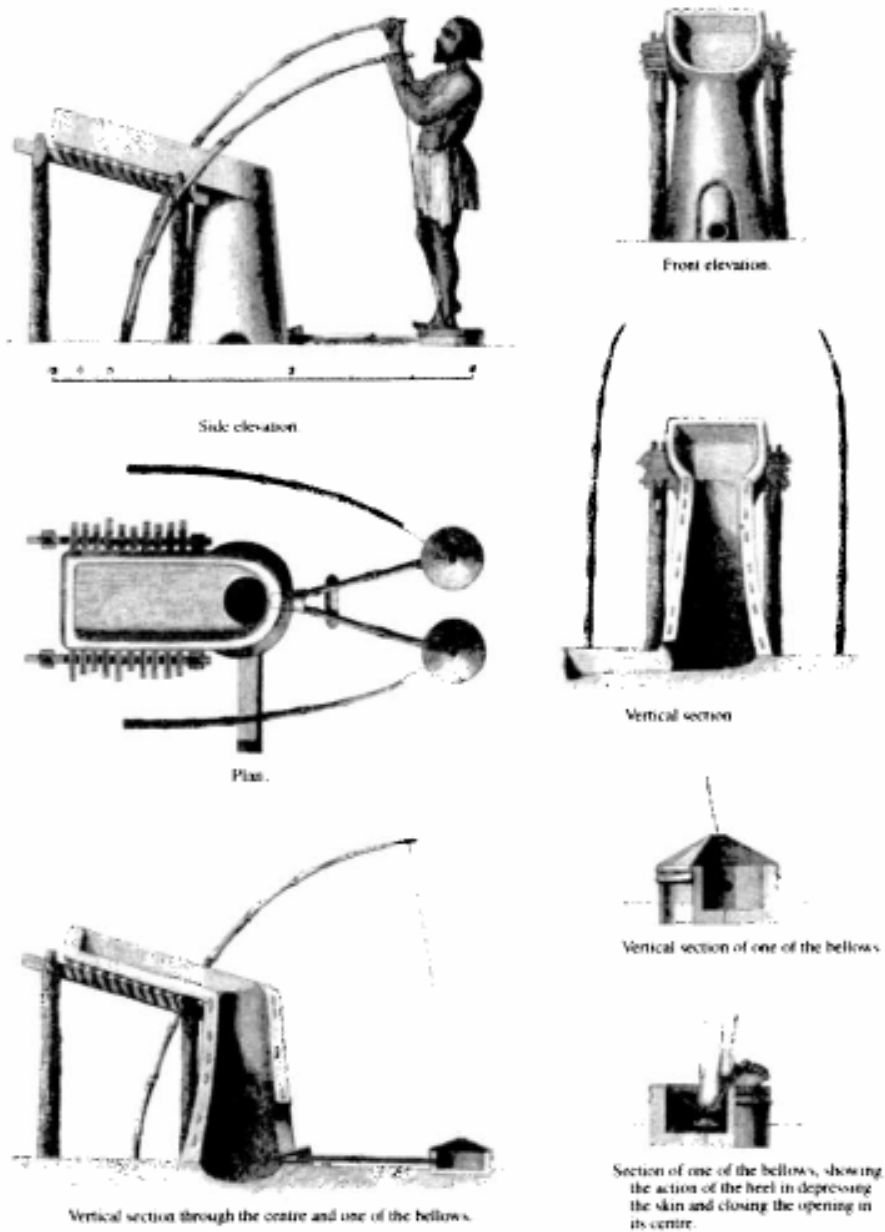


Figure 6: “Illustration of an early non-ferrous furnace. Ore was charged from the top of the furnace and blast applied through tuyeres of bamboo by means of foot-propelled bellows. Goatskin was the usual bellows material.” (Simpson)

The furnace set-up shown above is quite advanced. In order to operate this, the metal one wished to melt would be loaded into the top of the furnace. The chimney would be filled with wood and the wood would be set on fire. The operator stood behind on the foot bellows, and was able to step on them to blow air on the fire and increase its temperature. As the metal would melt, it dripped down the chimney and exited the hole on the side of the assembly, labeled "Exit" above. The molten metal could then be collected and poured into stone molds to create cast objects. This process enabled ancient man to melt a greater amount of metal, and to do so continuously with minimal effort.

Amid all this development in Mesopotamia, knowledge of metalworking and casting began to spread to other areas nearby. A team from the University of California-San Diego has been working a site where a copper foundry in present day Jordan was discovered. This foundry dates back to 2700 BC! The site was initially discovered in the 1970's, but a team was not able to excavate in earnest until 1999. This foundry is the largest found to date from that era. "The team has excavated thousands of artifacts from the site already, including...more than 1000 ceramic molds. By comparison, the largest copper production facility previously unearthed (in Hisarlik, Turkey) yielded fewer than 70 molds" (Univ. of California). Among the artifacts uncovered were copper tools, crucibles, ingots, and slag. UCSD Anthropologist, Thomas Levy, is extremely enthused about the prospects of this location. "'This is by far the largest evidence of copper production during this period,' said Levy" (Univ. of California).

2.2 EGYPT

Egypt, due to its close proximity and collaboration with Mesopotamia, was not far behind in casting metals. Egypt began working with bronze around 2800 BC, only a few hundred years after Mesopotamia first invented the process.



Figure 7: Map of Egypt (MSN Encarta)

2.2.1 Material Development

To understand the progression of material development in Egypt, it is critical to first understand its history. Ancient Egypt was divided both by dynasties and kingdoms. The first and second dynasties cover the earliest 400 years of ancient Egypt history, when the civilization was beginning to unite. They began developing a bureaucratic government. The Old Kingdom began in 2686 BC, and lasted approximately 500 years. It covered Dynasties IV through VI. The best known accomplishment of the Egyptians during this era was the building of the giant pyramids. The Old Kingdom is commonly known as the Pyramid Age. Between the Old Kingdom and Middle Kingdom were several dynasties with weak rulers.

The Middle Kingdom began in the last half of Dynasty XI, in 2000 BC and lasted through the end of Dynasty XIII, in 1650 BC. Dynasty XII was a turning point for the civilization. Egypt conquered Nubia, a kingdom immediately to its south. Also, they began trading with Syria and Palestine, in nearby southwest Asia. Finally, the arts flourished. However, the end of the 12th Dynasty brought about more weak rulers. This allowed a group of Asian settlers, known as the Hyksos, to enter Egypt and take control. This group introduced the Egyptians to new items, including horse-drawn chariots, improved bows, and other weapons. Up to this point, the Egyptians had not seen these tools, and this was a key introduction in the New Kingdom.

The New Kingdom began in 1554 BC in Dynasty XVIII, and lasted approximately 500 years to the end of Dynasty XX. During this period, Egypt kicked out the Hyksos forces, developed its own army, and grew itself into the world's strongest power. At the height of the Egyptian Empire, the Egyptians had conquered the eastern coast of the Mediterranean, and a large portion of surrounding land in Africa. Much of the required knowledge to develop the weapons to accomplish this feat was likely learned from the Hyksos. Additionally, the land they were conquering along the Mediterranean includes countries that also bordered Mesopotamia. This juxtaposition could have also helped pass new ideas about materials and processes between the civilizations. Finally, the lands conquered in Africa, Nubia and Kush, had valuable copper and gold mines. This would have provided the Egyptians a new source of materials.

As all this was occurring, the Egyptians continued to evolve and improve upon their existing tools and knowledge. Designing new and better tools was one of the early drivers for material development by the Egyptians. Wood was the first material used to make tools, but due to its softness it was limited in its uses. The Egyptians quickly found wood made better use as a handle for other materials. Stone was the next one incorporated as the base of the tool. Stone tools were generally used for pounding, cutting, and grinding various items. Stone tools could be used to grind grains, for example. Egyptians found this material to have an advantage over wood due to its higher specific weight and hardness, but had difficulty using it as a hammer due to its brittleness. When a stone hammer hit something else of substantial hardness, it could splinter off into pieces. The Egyptians spent time working with different stones to understand how to best utilize them as tools. They understand the material had promise, but just needed to understand

how to use it appropriately. This patience and effort would similarly reward them when they began working with metals and alloys. Copper was the first metal used and worked by the Egyptians. Unfortunately, it is too soft to be an effective tool on stones and other metals. Once bronze was introduced, it became very popular as a choice for tools.

The first bronze in Egypt can be dated to the Old Kingdom, during the 4th dynasty. Beyond learning that adding tin to copper would create bronze, the Egyptians examined adding tin to the bronze alloy. This created a harder alloy, which needed to be heated in order to be used. This harder material was used for tools and weapons, while softer bronzes were used to cast statues and vessels. The softer bronze allowed these art pieces to be engraved with decorations, hieroglyphics, or anything the ruling pharaoh desired. Around 2800 BC, the Egyptians were introduced to casting by the Mesopotamians. As both civilizations were close to each other, the Egyptians were easily able to learn what had been working for the Mesopotamians in regard to furnaces and processes. Thanks to their extensive background creating pottery, however, the Egyptians were able to expand upon this knowledge base and improve the existing casting processes. They invented lost wax casting, a derivative of investment casting, and also experimented with using other materials, such as stone, in a similar way.

Egyptians began working with iron around 2000 BC, but could not raise the temperature enough to melt and cast it. Instead they produced wrought and forged iron. By the 7th century BC, this material would come to replace bronze in tools. Once iron was able to be used in this manner, bronze became the material of choice for statues, cases, boxes, and other vessels. Iron is harder and a more effective tool than bronze.

2.2.2 Casting Processes

Their pottery background gave the Egyptians a head start when working with these new materials. They introduced the ancient world to cope, drag, and core molding – all of which are used today in casting processes. Additionally, the Egyptian potters are credited with inventing lost wax casting.

Cope and drag are fundamental steps in the casting process. Figure 8 below shows a simple diagram of a mold system.

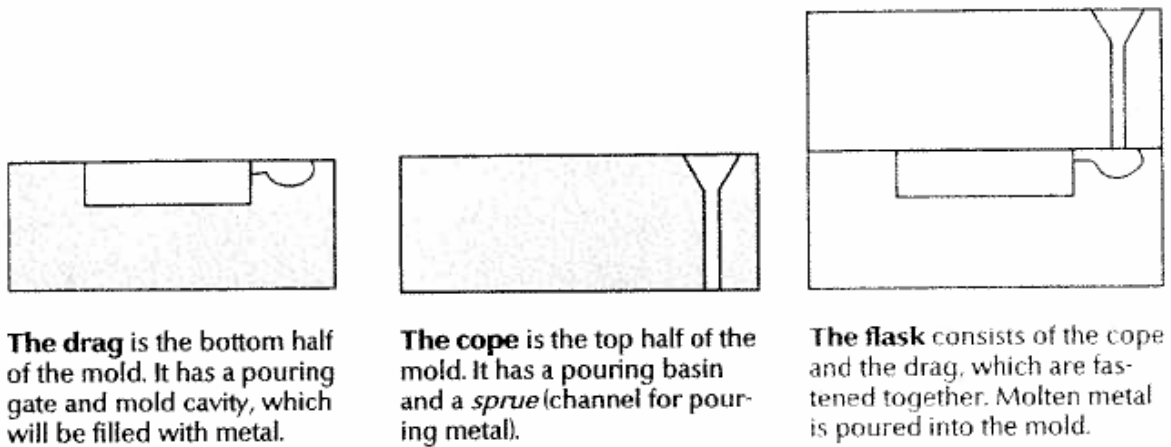


Figure 8: The Drag, the Cope, and the Flask (World Book 278)

The drag is the bottom section of the mold. It contains the mold cavity and a runner gate, where the molten metal will enter the mold cavity. The mold cavity should be in the shape of the finished product. The cope is the top half of the mold. This section contains the pouring cup and the sprue. The sprue is the passage through which molten metal flows to reach the mold cavity. Molten metal is poured into the pouring basin, and then travels through the sprue to the pouring gate. The sprue and pouring gate are considered part of the gating system. Once the casting is completed, these sections will also be cast in metal, and need to be removed from the final object.

Coring was another area where Egyptians broke new ground. A core is an object placed in a mold to create a cavity in the final casting. This can be used on objects such as cups, or a core can be included in a final cast object. This can make the object lighter and will require less material to be cast, which may result in a better finished product.

The figures below show an example of a finished casting that utilizes all the above concepts. The top photo shows a cast foot, with a sprue still attached to the heel. It is clear from this photo that the sprue fed directly into the mold cavity, rather than through a pouring gate. The bottom photo is a section of the cast foot. From this section, it is plainly visible that a core was used to

reduce the size of the casting required. This provides a second view on how the sprue attached to the mold.



Figure 9: “Bronze foot cast in Egypt.” (Simpson)

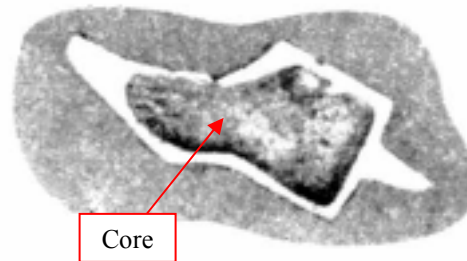


Figure 10: “Section of Egyptian bronze foot illustrated [above].” (Simpson)

The Egyptians are credited with the invention of a new casting process known as lost wax casting. The invention of this process is attributed to potters, according to Bruce Simpson. He theorizes that a potter, while creating a new piece on a ceramic wheel, realized the etching on the outer surface of the piece would look better if the piece were made in metal. The potter reduced the thickness of the outer wall of the piece of pottery, and then built it back up with wax. Desired shapes or characters could be carved in this wax, if desired. Once the design of the piece was completed, the worker would cover the assembly with layers of clay wrapped together. The clay needed to be applied carefully in order to preserve the integrity of the wax designs. To maintain internal cavities, as for a vase, the center would be filled with scrap clay and rubble. This assembly was then placed in a kiln and baked. The wax would be melted out of the mold during this step. Typically, it would be recovered to be reused in another application. At the end

of the kiln cycle, the mold would emerge and be ready to be used for metal. This mold had the desired decorative markings printed inversely on its inner surface, in the exact image the designer wanted. Molten metal would be poured into the mold. Once it cooled, the mold would be broken apart to reveal the finished casting.

The foot above in Figures 9 and 10 is a small, relatively simple casting. By contrast, the bronze cat pictured below in Figure 11 would be much more complicated to cast. This cat statue was originally cast with a core that was removed upon completion. The cat's facial features are well defined and distinct. An object this complex would have likely been cast using investment casting and the lost wax process to ensure the delicate features were maintained.



Figure 11: “Cast bronze cat...with core removed. Marks of core prints remain, indicating a considerable knowledge of foundry practice in early Egypt.” (Simpson)

This casting shows an example of advanced Egyptian investment casting with the use of lost wax to capture the details.

Lost wax casting was a large step forward in the metal casting industry. The Egyptians found ways to apply it to other materials as well. One of the more controversial topics surrounds its many stone columns and statues. Some claim these were castings by Egyptians, while Egyptologists maintain they were carved with copper and iron tools. This subject is discussed by Bill McNulty in his article “Casting Ancient Egyptian Statues”. He claims that “Ancient Egyptian artisans used an ingenious way to add hieroglyphics, figures and detail to their stone artworks. Beeswax or another temporary material was molded or cut into hieroglyphics, depictions of Gods and Goddesses, scenes of daily life, etc. These carved temporary hieroglyphics were placed on the inside of a casting form.” These casting forms were filled a mixture of natron and granite, diorite, schist, sandstone, or limestone. Water was then added to create the item desired, which included anything from stone statues, pyramid blocks, obelisks, columns, or stone artwork. Once the casting had cemented together, the mold would be broken apart, and the wax could either be melted off the finished object or pulled off by hand.

The process of casting these items also aids in explaining some of the damage that has been done to these objects. Without putting enough water into the mix, the statue might not form completely. These mistakes were not able to be corrected once the statue was complete. His evidence lies in a comparison of hieroglyphics carved into statues from usurping Pharaohs. When a Pharaoh would take power, he would commission people to carve new hieroglyphics into statues, etc, to make it appear that he had commissioned the object. The figures below compare cast hieroglyphics with carved symbols.



Figure 12: Example of cast and carved hieroglyphics (McNulty)



Figure 13: Example of cast and carved hieroglyphics (McNulty)

Figures 12 and 13 above show the contrast between cast hieroglyphics and carved hieroglyphics. “The usurping hieroglyphics are of inferior quality because it’s impossible to carve granite with copper or iron tools with any detail or depth.” (McNulty)

This theory is not supported by Egyptologists, but it is interesting to consider that materials other than metal could have been cast into objects during Ancient Egypt using the same processes as metal casting.

Another medium where the Egyptians excelled was in the casting of gold. Gold objects were cast in a similar manner as the Mesopotamian’s investment casting. Egyptian goldsmiths utilized crucibles to hold the metal over a fire, blowpipes and foot bellows to increase the heat of the fire.

Additionally, the painting below depicts two men pouring molten metal in the middle scene. The men are using two sticks to hold the hot ladle and control the pouring of molten metal.

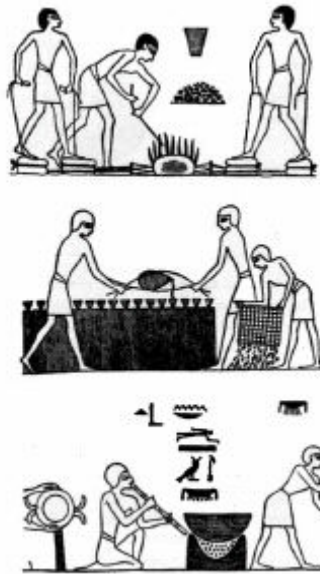


Figure 14: “Egyptian painting depicting ancient foundrymen melting gold. Note foot bellows, pouring the gold (ladle handled by means of sticks), blowpipe and crucible.” (Simpson 49)

Intricate pieces of gold jewelry were made using wax molding. Additionally, evidence has been found that gold jewelry was made using granulation. Granulation is a process where minute grains or tiny balls of gold are formed and attached to a surface. This process is only applicable with metals that, like gold, have a high surface tension. The smallest gold spheres were approximately 2 mm in diameter. Thousands of these could be joined to create a single object, most likely through soldering and sweating. Egypt’s neighbors across the Mediterranean, the Etruscans, were experts in this process:

“The finest work in granulation was done by the Etruscans in about the seventh century B.C. Its fineness has given it the name "dust granulation," the granules being less than 0.2 mm (0.008 in.) in diameter. Many thousands of granules were used to create the design on a single object. The Etruscan alloy was gold with about 30% Ag and a few percent of copper.” (Goodway)

Granulation required the use of soldering to decorate ornate gold pieces. The introduction of this process marks the beginning of welding – the process of joining two pieces of metal using heat.

2.3 CHINA

China got a comparatively late start in the development of casting. China's Bronze Age did not begin until 2000 BC. However, despite the late start, China quickly learned the processes being used by the Mesopotamians and Egyptians, and began inventing improvements.

2.3.1 Material Development

Meanwhile, the Middle East and Mediterranean regions were not the only areas utilizing casting of materials. The mid-East may have discovered the process of casting materials, but the Far East made it an art. The pottery/nonmetallic age ended around 2000 BC, and by 1500 BC the Bronze Age was thriving in China.

Chinese history is also important in understanding the evolution of material and casting development. The Shang dynasty ruled China from 1800 to 1045 BC. The Shang dynasty is credited with the creation of beautiful bronze vessels, horse-drawn chariots, and a system of writing. The earliest written records date from 1500 BC, and were carved into turtle shells and animal bones (collectively known as oracle bones). They were overthrown by the Zhou dynasty in 1045 BC. The Zhou ruled until 256 BC. They ruled largely in the western section of China, and divided the eastern section into semi-independent states, each with an individual ruler. The Zhou dynasty was weakened by invaders from the east, and when the semi-independent states began warring, it could not hold them off. Eventually, the Qin Dynasty won control. They ruled from 221 to 206 BC, and during this time established a strong centralized government. This was a large change from the independent states of the Zhou dynasty. Under the Qin Dynasty, the Great Wall of China was begun in an effort to keep out foreign invaders. Though this dynasty was strong, it used high taxes to support the building projects and military efforts and harshly enforced laws. Once the first Qin emperor, Shi Huangdi, died in 210 BC, a civil war broke out. The Han Dynasty seized power four years later in 206 BC. They continued to rule until AD 220. During this period, China became a dominant empire and used Confucianism as the philosophical basis of government.

The Chinese were very quick to progress along the metal development path of the Mesopotamians and Egyptians. Most likely, the foundations were passed from Mesopotamia and Egypt, perhaps through traders. Without written records, it is impossible to know for certain how this was accomplished. A sign that they were not starting from scratch is that the Chinese began working with bronze immediately. They did not begin with the soft metals, like copper or gold. Bronze casting began in China during the Shang dynasty, around 1800 BC. The earliest foundry known was located at Anyang in the Hwang Valley. The Shang Dynasty was centered in this valley as well, which located the foundry in a convenient area.



Figure 15: Map of Anyang, China (Courtesy MSN Encarta)

The castings created at Anyang include a variety of items, such as ritual vessels, dagger-axes, adzes, knives, arrowheads and spears. Many pieces from the Shang era were decorated with a pattern known as taotie. According to Peter Hessler in “China’s Bronze Age Recast”, the taotie

style “looks like a stylized animal face. The taotie’s meaning has long been debated, with the only consensus being that it carries a remarkable artistic power.” (79)



Figure 16: An example of a taotie design (Konstantin)

The earliest bronze used by the Chinese was leaded tin bronze. They had large natural stores of copper and tin, which provided plenty of material to alloy. Additionally, there is evidence they imported material from other locations. It may have been that the imported material contained various alloys that aided in the casting and creation. This material is very fluid when molten, which allows the Chinese to cast very thin walls. Unfortunately, the fluid material produced additional flash. To remedy, as the Mesopotamians and Egyptians did, it could either be trimmed off or incorporated into the design of the casting.

The Chinese had large natural stores of copper and tin, though there is evidence they also imported additional metals and ores from other areas. The Chinese had created guidelines for metal workings based on the purpose of the end casting. By experimenting with controlled quantities of metals, they were able to create a guideline for material ratios for various purposes. Bruce Simpson provides the following table in [History of the Metalcasting Industry](#):

Table 2: Copper/Tin Mixtures in Ancient China (Simpson 24)

Component	Copper	Tin
Bells and Kettles	5 parts	1 part
Axes	4 parts	1 part
Knives	3 parts	1 part
Spades and hoes	2 parts	1 part
Mirrors	1 part	1 part

These guidelines are approximate – with the available technology at the time, it would be near impossible to guarantee that no other materials were included in the alloy. It is not agreed upon that the Chinese control methods were precise enough to accurately control alloy content. Lisa Reiner asserts that while material control was attempted, it was not a concern for most cast items (vases, statues, other decorative pieces). Her research suggests the Chinese selected materials based upon the desired final color. “For example, a polished bronze surface could take on a light pink hue, a light yellow tone, various shades of grey, or a copper-red shade, just by varying the percentage of copper, tin, and lead.” (Reiner 40) This is similar to the way the Mesopotamians and Egyptians controlled alloy content. She goes on to admit that the variation in the alloy content with these three materials varies the material properties. Hardness is highly affected by the tin and lead content in the alloy, and Reiner does admit that this was realized by the Chinese. The Chinese had made a huge contribution with the determination that different alloys were suited for different purposes.

The main purpose of bronze castings was to create religious objects, tools, and weapons. A main component of this was the drinking vessels and food containers used in ancestor worship and state rituals. Use of these vessels was restricted to the king, royal family, and aristocracy. Different dynasties required different types of food and drink vessels. In the Shang dynasty, religious castings included many wine vessels. In the Chou dynasty, many ritual bells, musical rattles, and Chinese coins were cast. In the Zhou dynasty, religious containers were made that included new food cauldrons and containers. As feudal lords began ruling China, the type of castings shifted towards weaponry – more shields, bits, bridles, and chariot fittings were cast.

2.3.2 Casting Processes

The Chinese continued to utilize standard tools similar to those developed by the Middle East in order to cast bronze. Information on these similar processes likely passed verbally from Mesopotamia and Egypt, in the same way information about metallurgy and materials passed between these groups. They used a similar foot bellows furnace to the Mesopotamians and Egyptians. To create molds, they also used both stone and ceramics. The Chinese also used similar tricks to help create successful castings. They used coring, similar to the Egyptians, in order to reduce the amount of material needing to be cast.

A new trick the Chinese invented was to cast larger, more intricate objects in pieces. They would cast the pieces of a final assembly separately, and then place them in the mold of the larger casting. “The technique enabled the production of larger vessels and also facilitated the sculpting of many animated appendages.” (Reiner, 40)

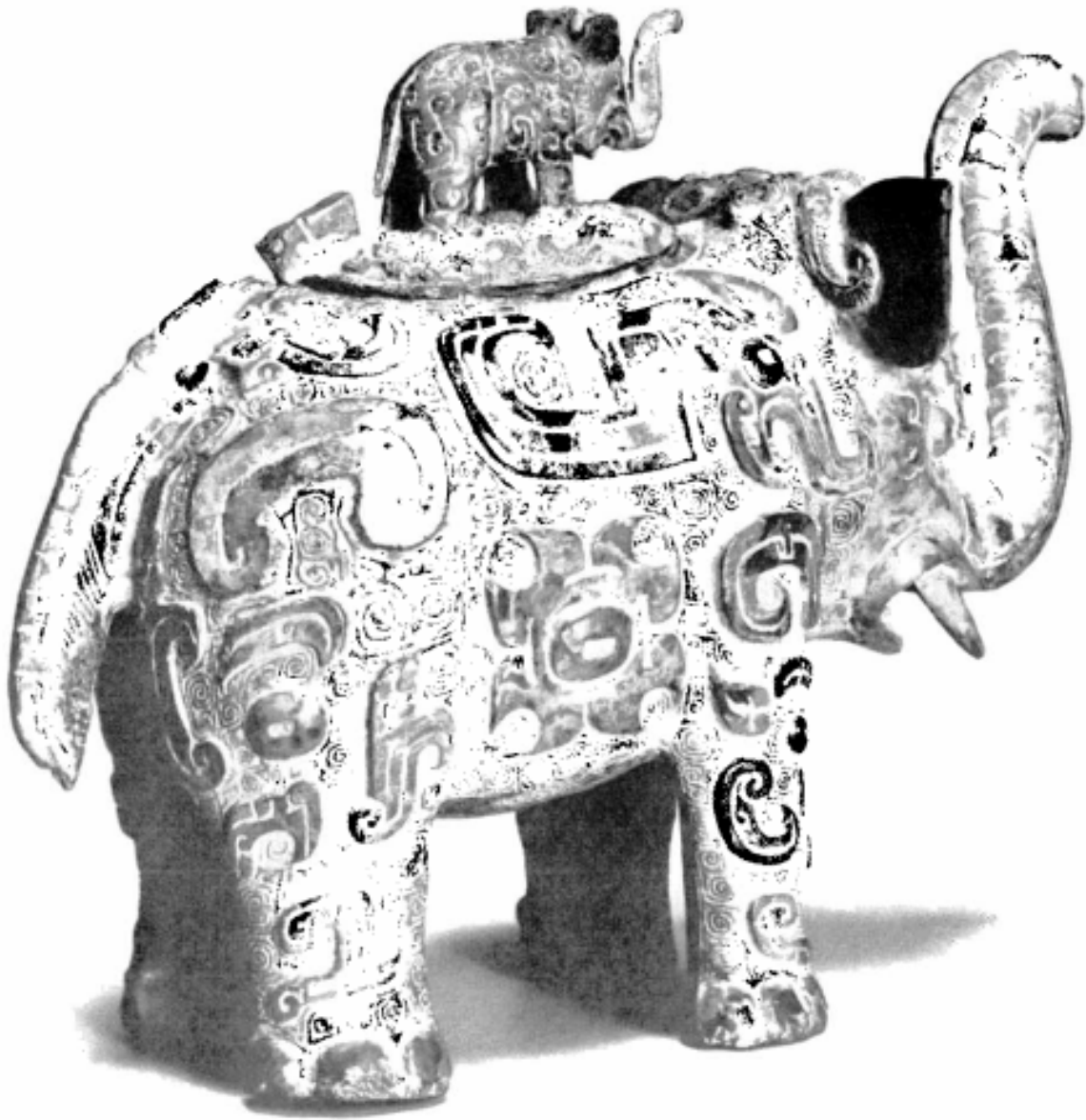


Figure 17: “Bronze ceremonial elephant cast in two parts and joined, depicting the workmanship and patience of the early Chinese foundrymen. From the Chou dynasty (1122 to 255 BC) or earlier.” (Simpson 26)

In order to create pieces like Figure 17, handles, legs, and appendages would be cast first. These were then placed into the empty mold. The molten metal would then be poured into the mold, and when the casting cooled, the appendages would be attached to the larger body. This process allowed for very intricate details to be cast into designs, and careful planning was needed to

ensure flawless execution. With skill in the welding process, it was possible to incorporate the weld joints into the artistic design of the casting.

Using carefully controlled processes allowed the Chinese to cast objects of incredible size. The biggest vessel found from Anyang, Si Mu Wu fang ding, weighs over 1900 lbs!



Figure 18: Si Mu Wu fang ding (Ikepu)

The Si Mu Wu fang ding was a cooking vessel from the late Shang dynasty. It measures 3.61 feet long, 4.36 feet tall, and 2.59 feet wide. “But size wasn’t the critical characteristic for the Shang, whose artistic style set the tone for centuries of Chinese art.” (Hessler, 79) Even a vessel of this size was covered with intricate designs. The Si Mu Wu fang ding is decorated on the legs, the borders around each face, and on the handles. It is a true testament to the Chinese philosophy that cast is art that even on a 1900 lb casting, the appearance was valued and considered.

The Chinese were the first to produce cast iron products. The oldest cast iron objects are from 800-700 BC, and the first sand mold has been traced to 645 BC. Two key advances made the casting of iron possible: an advanced knowledge of materials, and new superior tools. Iron castings were used to create both tools and for statues or decorations. Donald Wagner, in “The Earliest Use of Iron in China” alleges that the first cast iron would have been a poor material to work with. “It would have been very low in silicon, and therefore be what is called *white* cast iron, which is difficult to cast and also very hard and brittle.” (Wagner) Therefore, the Chinese needed to be inventive in order to find a way to utilize the material to their advantage.

As discussed above, the Chinese had very stringent material controls. Thus, they understood that different alloy content in metals reacted differently. The melting point of pure iron is 1530 C, and this could not be achieved in the small furnaces. However, if iron is held at high heat while in contact with carbon, it will absorb the carbon. This drops the melting point to 1170 C. Additionally, by using iron oxide with high phosphorous content and adding high-phosphorous coal, the melting point could be lowered to 980 C. Additionally, high phosphorous and sulfur increased the fluidity of the cast iron, which allowed the Chinese to cast products with similar thin walls as the bronze castings. There were some downsides to the addition of carbon into iron, however. The high carbon content made the final product more brittle.

The Chinese also improved the tooling used previously to create the bronze castings in order to produce solid iron castings. One major improvement in furnace design was the Chinese developed a superior form of bellows capable of delivering a continuous stream of air into the furnace. This furnace was commonly known as the “box bellows” furnace, and is still in use in China today. Meng His Pi Tan described the methods and Bruce Simpson provided the following translation in History of the Metalcasting Industry:

“Iron ores are smelted with charcoal in a shaft furnace. The blast is obtained from a box-blowing engine of wooden construction. A piston is moved backward or forward by human or animal power. The air enters openings provided with valves in the side of the box, and passes out to the furnace through a passage formed by placing in the box a perpendicular parting wall connected with the piston chamber by valves at both ends. From this passage the air passes through a tuyere into the furnace.

From the furnace the metal produced flows to a reservoir and from there it is ladled out into molds for castings. The furnace for the manufacture of iron is made of clay mixed with salt. A hollow in a mountain is sometimes lined with clay, or a large wooden mold is used and the furnace is allowed to dry for a considerable length of

time. Such a furnace holds two or three tons of ore.” (Simpson 28-30)

An accompanying drawing of this process is shown below.

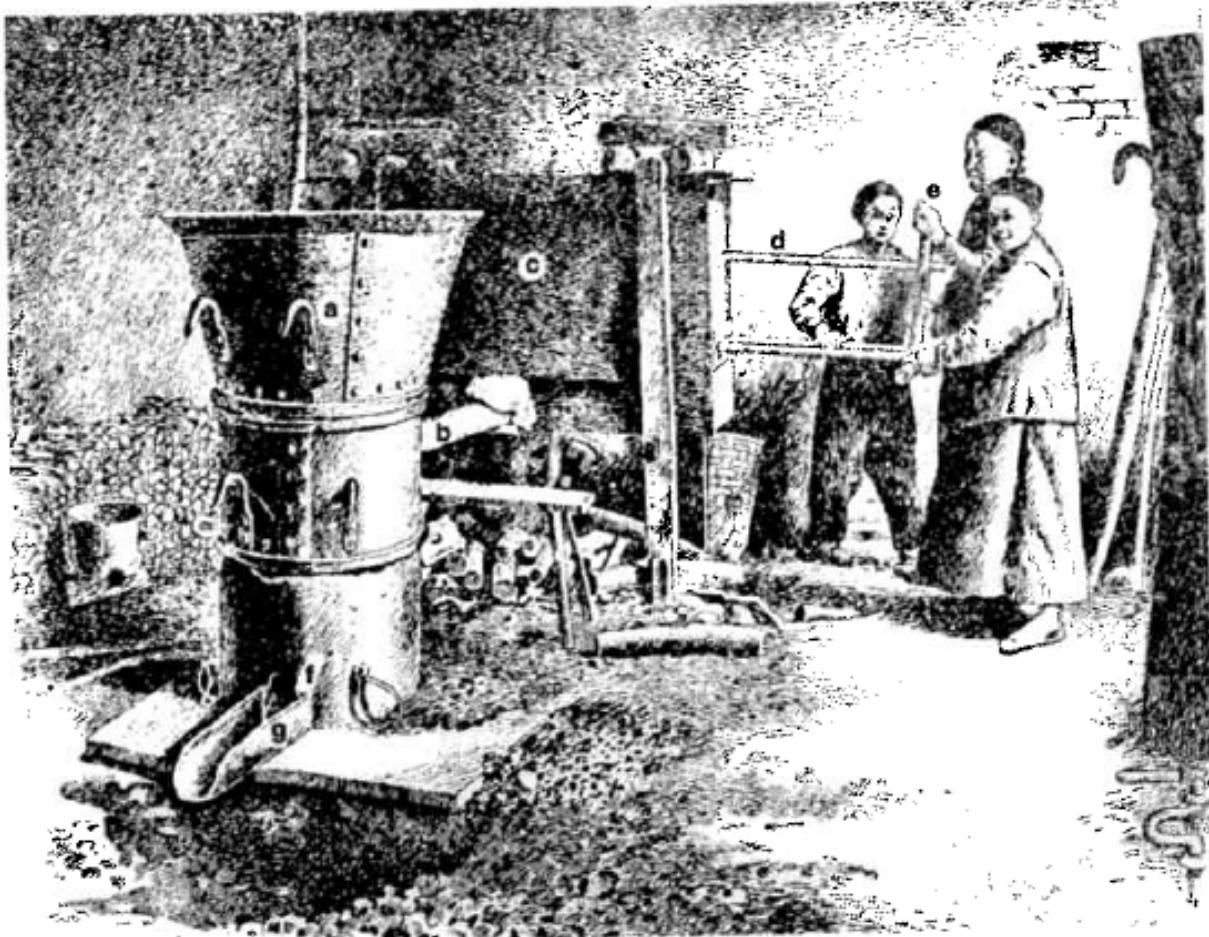


Figure 19: “Drawing of a Chinese cupola which...depicts the improved bellows box.” (Simpson 30)

The western world did not have the ability to cast iron for about 1500 years after the Chinese. This technologically advanced furnace allowed the Chinese to heat iron enough to melt it (rather than smelting), and could be used in a variety of locations. While they took advantage of hollowing a mountain or hillside, a wooden mold could also be used to create the outer shell of the furnace. The process was not dependent upon a natural feature.

The Chinese government did strictly control the casting of iron – a special bureau was created to monitor and control the iron casting business. If people were caught casting iron without the proper accreditation, they were punished. This control coincided with the rise of the Qin

Dynasty. As mentioned previously, the Qin Dynasty's greatest feat was the creation of a strong centralized government and iron casting was one of the fields that fell under its governance. The Han dynasty continued with these policies, and the some of the oldest known iron castings in tact are their legacy.

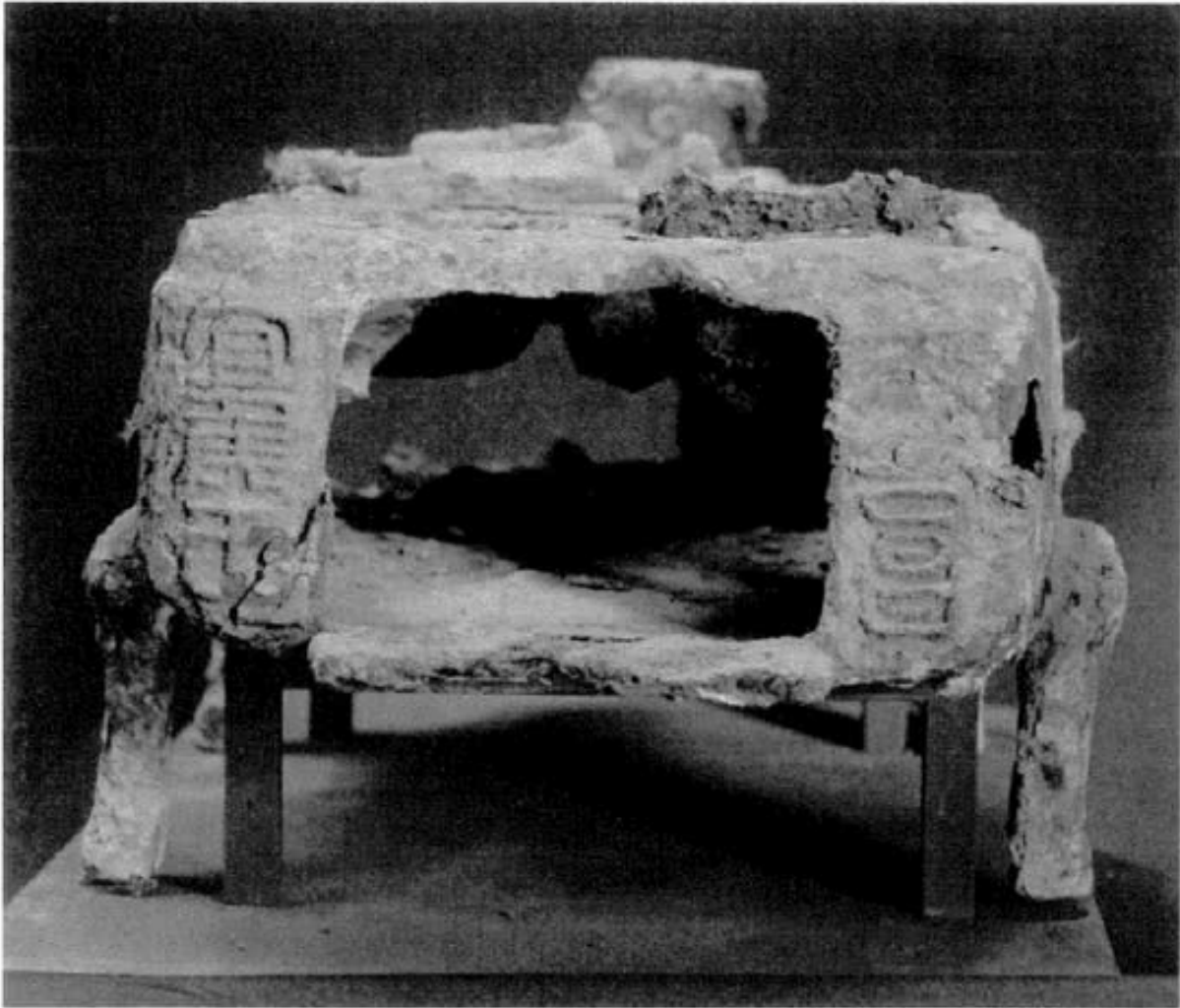


Figure 20: “Front view of oldest known Cast iron stove of the Han dynasty (206 BC to AD 22), the last of China’s great dynasties. Inscription reads ‘May it please your lords’.” (Simpson 31)

The Chinese created many beautiful and useful castings that continue to awe and inspire people today.

2.4 INDIA/THAILAND

While China's metal casting industry made many notable contributions to the process of casting, there were several other centers of casting in the Far East. Both Thailand and India had early roles in the development of the casting industry.

2.4.1 Thailand

Perhaps the greatest insight into the history of casting in Thailand stems from the discovery of Ban Chiang. Dr. Elizabeth Hamilton, of the University of Pennsylvania Museum of Archaeology and Anthropology has spent a considerable amount of time researching the metallurgy of Thailand. Along with several colleagues, she spent several years analyzing samples of metals from this area. The samples were dated from approximately 1800 BC to AD 300. The artifacts found at the site included bracelets, rings, anklets, wires, rods, spearheads, axes, adzes, bells, blades, and hooks. A sample of items found is shown in Figure 21.



Figure 21: Bronze spearheads or spearhead sockets. The first is from Ban Tong; the others were found in Ban Chiang. (Hamilton)

These appear to be cast using permanent molds, which would have been made from stone. From the analysis, it was possible to understand what processing had been done to the object. Figure 22 shows the structure of a bronze that was cast, but not processed any further.

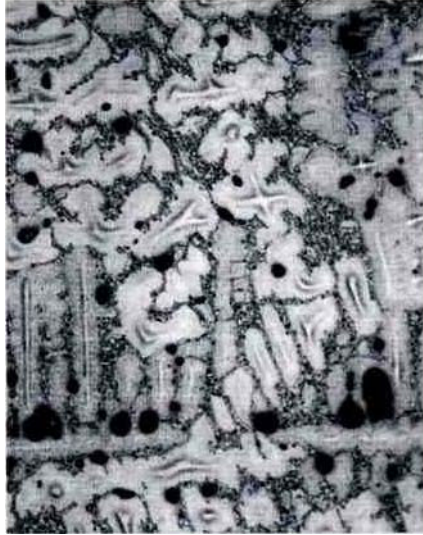


Figure 22: A metallurgical sample of bronze from Ban Chiang. (Hamilton)

“[If] the artifact has been cast of bronze with no further working, we can see dendrites, or long thin arms of copper-rich metal. With a cast artifact that has been allowed to cool slowly, the dendrites are replaced by grains; and if the artifact has been reshaped by a hammer afterward, the grains will be flattened and streaked with strain lines.” (Hamilton)

Further processing of these samples included performing a Vickers hardness test on 37 of the samples. The Vickers test consists of pushing a diamond tip into a material sample, and measuring the size of the resulting indentation. Smaller indentations correspond to harder materials. Additionally, samples were sent to the University of Delaware’s Bartol Research Institute to be analyzed for alloy content. Only 4 of the 44 analyzed samples were copper, showing the Thai had a clear preference for bronze. However, “our hardness tests show that the bronze used in the Ban Chiang area was not much harder than the copper. This is true even of the spearheads and axes/adzes.” (Hamilton) Dr. Hamilton further hypothesizes that the Thai put the effort into creating bronze instead of just using copper was because they valued the color. This is consistent with philosophy used by other cultures in the era. The Egyptians and Mesopotamians both used color to judge approximate alloy content. The Chinese had better material controls, though they also used the color to help experiment and determine what material alloys were best suited for various situations.

2.4.2 India

Meanwhile, excavations in India show that by 3000 BC, people were casting copper tools and weapons in closed molds. These molds would most likely have been made of clay. They used a variety of metals, including gold, copper, tin, silver, and lead. These were smelted in brick furnaces (similar to pottery furnaces) then were remelted in crucibles for casting. The Indians worked with iron early on, but did not cast it until around 200 AD.

The Indus Valley Civilization is also known as the Harrapan Culture. This group settled in an area rich in resources, and were able to create an agricultural civilization, similar to the beginning of Mesopotamia. Copper was native to India, mined from the Khetri region of Rajasthan beginning in the 3rd-2nd millennium BC. Evidence exists that there were 16 copper furnaces in the Indus Valley. As manpower is required to work these furnaces, metallurgists in ancient India became dependent upon the farmers and agriculturists to produce enough food to sustain them. This was the start of a formalized community – different people worked different jobs so the community as a whole could prosper.

There is further evidence that the Indians used lost wax to create figurines with delicate features. “Amongst the earliest bronze castings in the world is the well executed statue of a dancing girl from Mohenjodaro from the Indus Valley”. (Srinivasan) “Dancing girl” has been dated to circa 2500 BC. (Muley) This girl today dances in the National Museum in New Delhi.



Figure 23: The dancing girl from Mohenja-Daro (Muley)

The dancing girl has delicate facial features, and is wearing jewelry. Lost wax casting would have been required to capture these details on such a small scale – the dancing girl stands only about 10 cm tall. No evidence exists that the lost wax process used to create Dancing Girl was any different than the lost wax processes used elsewhere in the ancient world. News of this process could have traveled from either China or the Middle East.

Unfortunately, poor recordkeeping and lack of archaeological evidence still leaves many questions open about this society. It is clear the Indians were developing metal casting just as the Mesopotamians, Egyptians, Chinese and Thai. “[Their] accomplishments are shrouded in the mysteries of the cults and sects which controlled the shaping and casting of metal and greatly influenced the growth of the industry.” (Simpson 40) While questions may exist about their early accomplishments, later ones are widely acclaimed. In AD 500, the Indians would become the first civilization to cast steel. They were known for many years for their iron and steel casting abilities, most famously for their Damascus steel swords. In the future hopefully more will be revealed about this culture and its contributions to the metalcasting industry.

2.5 CONCLUSIONS FROM ANCIENT DISCUSSIONS

By 500 BC, the ancient civilizations led by the Mesopotamians, Egyptians, Chinese, Thai, and Indians had made significant discoveries in the cast metal process. They utilized a number of methods that would be used in years to come, including investment casting, sand casting, and permanent mold. They had developed lost wax casting, a derivative of investment casting, and were able to use it both to create practical objects and to create art work.

Shortly after this time of flourish, the progress in the development of castings would slow. In China, new political leadership prevented the development of new technologies, and in fact forced the progress backwards at times. Meanwhile, in the Middle East and Europe, casting technology continued to prosper throughout the Roman Empire, but stalled once the Dark Ages began. Despite these temporary setbacks the casting industry has survived and numerous process and material improvements have made it one of the most popular manufacturing techniques in the modern world in the 21st century.

3.0 MODERN MATERIAL DEVELOPMENTS

Over the past few years, global casting production has continually increased. According to a staff report titled “42nd Census of World Casting Production – 2007” in Engineered Casting Solutions’ (ECS) January/February 2009 edition, in 2007 95 million tons of material was cast. The amount produced in 2007 gained only 4.3% 2006’s production volumes. The top 10 list includes China at position 1, and India at position 4. Both countries have seen large growth over the past year, and are predicted to continue growing. China has been the top producer since 2002, and has experienced 92% growth since then. It alone produces 31.3 million tons of material, which comprises a third of the world’s total production. India, while not as big a producer as China, produced 7.8 million tons in 2007. Since 2002, it has grown 136%, the largest growth by a major casting producer in that time frame.

While not on the Top 10 list yet, Turkey gets an honorable mention in the article. It has experienced 42% growth since 2002 to reach 1.3 million tons in 2007. The Turks have been handling this growth productively – their metalcasting facilities are operating at greater than 90% capacity. Thailand is included in census report, but only produced 304 thousand tons of material in 2007 – not enough to have a heavy impact on the world markets. Egypt, meanwhile, does not appear in the report. Its metalcasting industry has not yet reclaimed its former prosperity.

Below is an excerpt from the “42nd Census of World Casting Production – 2007” to compare the various countries with the breakdown of their casting industry.

Census of World Casting Production—2007 (metric tons)										
Country	Gray Iron	Ductile Iron	Malleable Iron	Steel	Copper-Base	Aluminum	Mag.	Zinc	Other Nonferrous	TOTAL
China	15,460,176	7,698,396	535,316	4,047,505	571,279	2,740,075		216,883		31,269,630
India	5,332,000	802,000	65,100	964,000		608,000				7,771,100
Thailand ^a	70,000	30,000	30,000	28,600	28,600	100,000		16,900		304,100
Turkey	623,000	394,000	6,500	144,000	19,000	112,150		18,000		1,316,650
United States	3,889,000	3,890,000	67,000	1,248,000	283,000	1,847,000	110,000	298,000	54,000	11,819,000 ^p
TOTALS	44,917,143	22,877,201	1,101,222	10,183,295	1,596,834	12,727,106	278,496	939,394	165,294	94,919,007

^a2005 tonnage ^b2006 tonnage ^c2004 tonnage ^dIncludes 133,000 tons of investment castings ^e2002 tonnage

Figure 24: Modified table to show countries of interest. Totals are global, not specific to countries shown in table. ("42nd Census...")

While in ancient times bronze was one of the most used materials, iron, steel, and aluminum have overtaken it. Iron, in its three main variations, is the most cast material throughout the world by tonnage at nearly 70 million tons. This is over 40 times the world total production of copper-based alloys.

Another way to assess the vitality of each country’s metalcasting industry is to review its growth. Russia, Turkey, and India were among the top 6 growing metalcasting countries.

Shakeups

While total global casting production increased a mild 4%, a few individual countries saw drastic gains and losses in 2007.



Image by Andrea Presazzi, Dreamstime.com

Moving Up

Countries with production of close to 1 million metric tons or more are included in this roundup.

Russia (since 2005)	+13%—7 million tons
China	+11%—31.3 million tons
Poland	+11%—900,000 tons
Turkey	+9%—1.3 million tons
India	+8%—7.8 million tons
Spain	+8%—1.4 million tons

On the Slide

Fewer countries saw significant losses, but the ones who did are well known.

Great Britain	-34%—700,000 tons
Japan	-12%—7 million tons
U.S.	-5%—11.8 million tons

Figure 25: Change in Casting Production in 2007 (“42nd Census...”)

While these countries may have been set back due to politics, the Dark Ages, and other societal challenges, they have been making a big comeback to rank among the top casting producers in the world.

Despite the recent growth of these areas, the worldwide casting industry expects to see a drop in production to 90 million tons by 2010. Global economic challenges offer a new challenge to the casting industry, and have impacted many industries. People have been scaling back their spending, causing companies to produce fewer products, while drives the metalcasting industry to reduce their output as well. (Kirgins)

3.1 Copper and Copper Alloys

Copper and its alloys continue to have an important role in modern society. Copper in its pure form has excellent electrical and thermal conductivities. Other important properties are copper's corrosion resistance, ease of fabrication, and high strength and fatigue resistance (Tyler). Cast copper items, specifically, are used as electrical and thermal conductors.

Bronze, as a copper alloy, has many of the same properties. Tin bronzes, in particular, are closest to the bronze materials used in ancient times. Cast tin bronzes are used in more structural applications than cast copper. Examples include bearings, bushings, pump impellers, piston rings, and gears. (Tyler) The majority of these items are used in the automotive industry.

In modern times, the variety of copper alloys has expanded far beyond bronze to include brass, copper nickels, and nickel silvers. When considering usage between all these various alloys, a number of industries are impacted. Below is a table of the industries utilizing copper and copper alloys, that illustrates its change from 1980-1989.

Table 3: Major end-use applications for copper and copper alloys in the United States in 1989 (Tyler)

Application	% of total	
	1989	1980
Building wiring	16.9	10.7
Plumbing and heating	14.9	13.4
Autos, trucks, and buses	9.8	8.7
Telecommunications	8.1	13.1
Power utilities	7.7	7.4
Air conditioning and commercial refrigeration	7.1	6.3
In-Plant equipment	7.1	8.4
Electronics	5.7	4.2
Industrial valves and fittings	3.4	3.5
Appliances and extension cords	2.7	2.9
Coinage	0.9	2.7
Other	15.7	18.7
Total	100.0	100.0

Source: Copper Development Association Inc.

3.2 Iron

Iron is also a popular choice in today's industry. While in ancient times, most metalworkers were restricted to using iron they could melt (high levels of carbon and phosphorous), today there are many variations of iron that are useable. Each has a unique set of properties and applications.

Ductile iron is one of the most useful variations of cast iron. With ductile iron, graphite is present as spheres instead of flakes. This makes ductile iron much stronger and tougher than other cast irons.

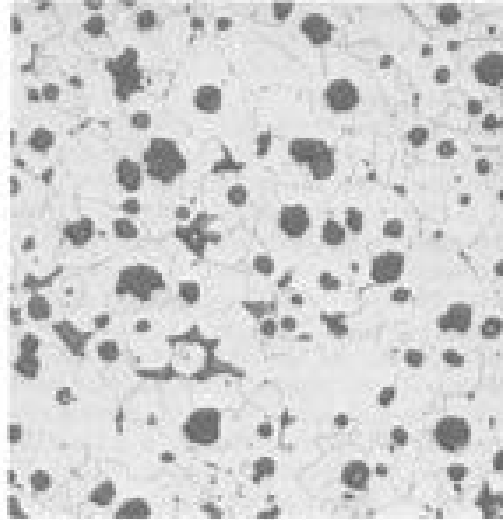


Figure 26: Microstructure of as-cast ferritic ductile iron. (Jenkins)

Figure 26 clearly shows the spheres of graphite in the material. The structural advantages of this material stem from the inclusion of graphical spheres. With flakes of graphite, as in gray iron or malleable iron, there is potential for stress to occur along the borders (or grains) of the flakes, potentially leading to cracks and destruction of the material. This is not the case with the spheres of graphite. The shape of the sphere does a better job of dispersing stresses amongst the material and does not provide an easy starting point for cracks to grow.

Ductile iron is used in many applications, including gears, wear-resistant parts, high-fatigue strength applications, high-impact strength applications, automotive crankshafts, chain sprockets, refrigeration compressor crankshafts, universal crank shafts, chain links, and dolly wheels. (Jenkins) The automotive industry is one of the biggest users of ductile iron, along with the agricultural industry and cast iron pipe industry.

Cast iron is most commonly melted by way of blast furnace, similar to the one used by the Chinese. The furnace itself is now constructed out of a steel stack, instead of a mountain, and is lined with refractory brick. The iron ore and other materials are dumped into the top of the furnace, and hot air is blown in through the bottom via mechanized process. Automating the machine is a large improvement as no one will need to stand with the foot bellows to operate the furnace going forward.

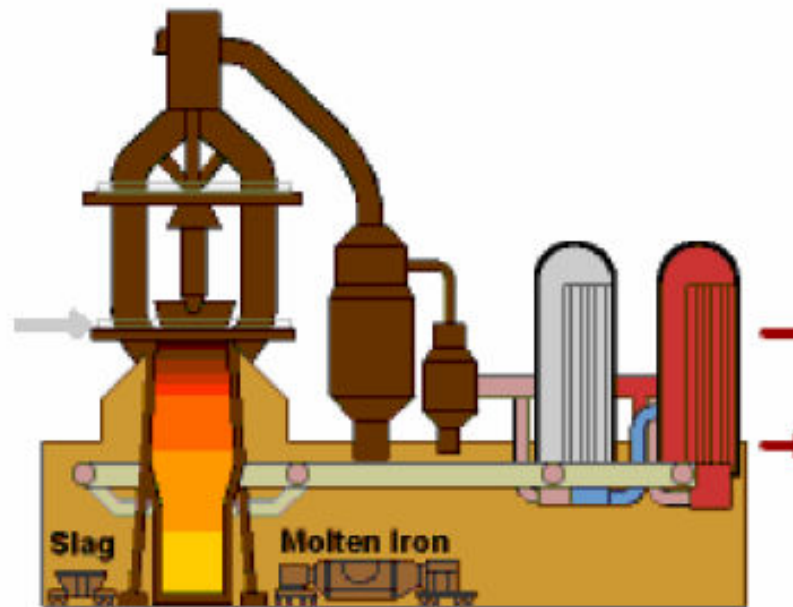


Figure 27: Blast Furnace (Ricketts)

It can take up to 8 hours for the raw materials to reach the bottom of the furnace, while the hot air reaches the top in 8 seconds. Once the materials reach the bottom of the furnace, they will comprise a mixture of liquid iron and liquid slag. The two products are drained through separate channels at predetermined intervals. Once this process is started, it can run for up to ten years, only needing to stop to perform maintenance on the system. (Ricketts)

4.0 DISCUSSION OF MODERN CASTING PROCESSES

While there are many varieties casting processes today, most fall into one of four categories: Investment Casting, Sand Casting, Permanent Mold Casting, and Die Casting. Each one will now be explored to understand their beginnings in the ancient world.

4.1 INVESTMENT CASTING

Investment casting is a precision casting process that is able to maintain highly accurate dimensions, tight tolerances, and smooth surface finishes. Additionally, it can cast complex parts easily, helping to reduce both material costs and machining costs. Investment casting can be used to create products weighing only a few grams, such as dental alloys, to larger products weighing up to 300 kg, such as a stainless steel fan exit case, as shown below.

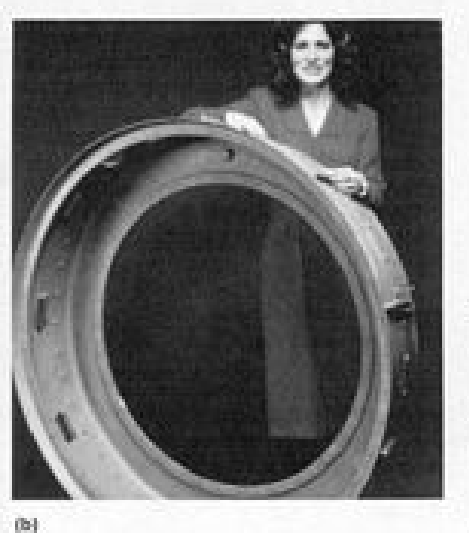


Figure 28: 17-4PH stainless steel fan exit case; weight: 96 kg (212 lb). Courtesy of Precision Castparts Corporation. (Horton)

Investment casting can produce parts with smooth as-cast surfaces and hold close dimensional tolerances.

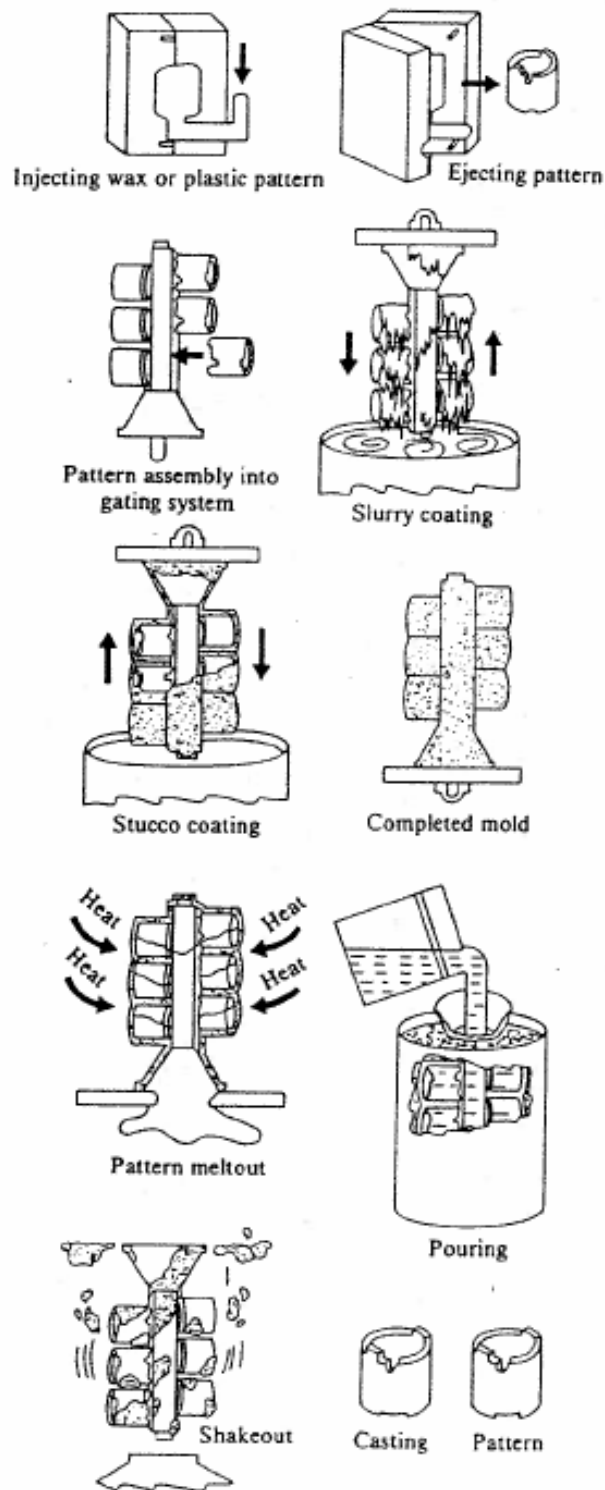


Fig. 4.1 Investment Casting Process

Figure 29: Modern Investment Casting process steps. (Bradley 68)

The basic steps of the process are similar to the ancient investment casting steps, though the execution of this process has greatly increased its capability. First, a die is created that will be used to form the wax mold. This die is injected with wax, and the mold of the part is created. This wax mold needs to include the gating system (pouring cup, sprue, runners, and ingates) in order to facilitate the molten metal flowing into the mold. Next, the mold is either dipped into a slurry coating and then covered in stucco or covered in a ceramic material. This creates a shell around the wax mold. In order to solidify the shell, the assembly needs to be fired. During this process, the heat melts the wax and causes it to run out the bottom of the assembly. The casting mold is now empty and ready to receive the molten metal. The metal is poured in and allowed to cool. Once the metal has solidified, the shell is broken off the casting. Any parts of the gating system that remain on the casting are removed, and the part is finished as necessary. Finally, it is ready to be inspected to ensure there are no quality defects and it is ready for use.

The pattern die used to begin the investment casting process is typically manufactured from aluminum or steel, and is produced by machining. This die can be used numerous times to create wax or plastic molds. “Most waxes are a blend of synthetic, animal, and vegetable waxes, with various resin and rosin additives.” (Bradley, 69) To allow complex parts to be cast with this process, ceramic cores are inserted into the mold prior to injecting the pattern wax. Once the wax has set in the shape of the final cast object, these cores can either be removed or dissolved, depending on the material. This process step allows internal cavities to be cast.

The molds are designed to have a built in gating system to facilitate casting the mold. “The gating system, also made of wax, merely involves features that are necessary to get the molten metal from a ladle to the mold cavity.” (Bradley, 69) The process behind incorporating these features takes serious consideration of how the mold will fill with metal and cool. They are located to ensure the cast component has filled and solidified as soundly as possible. “As the metal cools, the parts, gates, sprue and pouring cup become one solid casting. After the casting has cooled, the ceramic shell is broken off and the parts are cut from the sprue using a high-speed friction saw.”(Pasqualoni 34)

There are several variations of the investment casting process. A common one is known as investment shell casting, or ceramic mold casting. This method involves dipping the pattern into a ceramic slurry mixture and stuccoing with fine sand or zircon several times in order to build up the outer shell. (“Investment Casting Review”) Investment casting in the purest sense involves only one invested coating, also known as a monolithic mold.

Investment casting is also known as lost wax casting. It traces back to the Egyptians and Chinese previously discussed that used this method to create pieces of jewelry and delicate features of other castings. It was not recognized as a production process until recently (circa 1930’s), but ancient man realized its potential for creating well defined shapes and intricate details.

One main difference between ancient lost wax castings and modern lost wax castings is the intent of using the lost wax. The ancient people of Egypt and China used lost wax casting in order to create intricate designs on the exterior of objects. This was either used for artwork or to imprint a meaning on the objects (notably in the case of hieroglyphics).

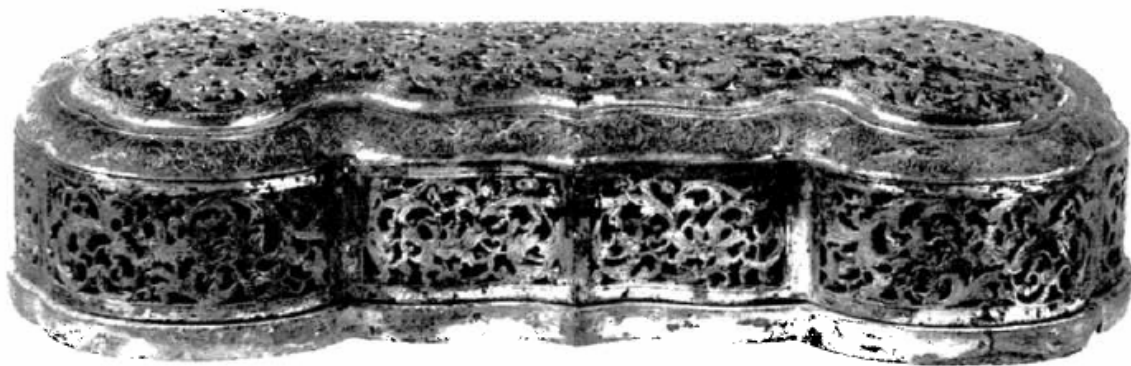


Figure 30: “A beautiful cast bronze box dating from China’s Shang dynasty (1766 to 1122 B.C.). The delicate filigree was achieved by the lost-wax process of casting, still used today in casting many of the finest art bronzes.” (Simpson 24)

In the modern world, lost wax casting is often used to create complicated inner passages, in order to fabricate high performance objects. One common example is a turbine airfoil, from a jet engine. These parts have critical structural requirements, internal passages for cooling, and precision tolerance requirements. A blade that develops a crack could destroy an engine, and

potentially cause an airplane to crash. The investment shell casting process is used to create these components, and can do so economically. Modern lost wax process allows designers the ability to choose the desired microstructure for a component. For turbine blades, for example, casting the component with a single crystal structure is desired. In other cases, directionally solidified crystals (long grains that grow in the same direction) or equiaxed crystals (many small round grains) may provide the desired structural properties.

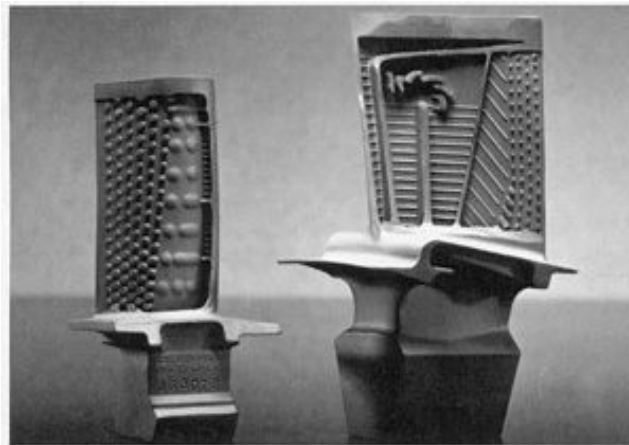


Figure 31: Single-crystal turbine blades investment cast using complex ceramic cores. Courtesy of Pratt and Whitney Aircraft. (Horton)

With modern casting processes, lost wax and permanent mold casting has become a better production process. In ancient times, casting an object using the lost wax method required designing a component, replacing part of the clay with wax, creating the mold, melting the wax and baking the mold, then casting the piece in the new mold. All this effort could only produce one part at a time. With modern processes, as shown above in Figure 30, a number of parts can be cast simultaneously. In modern casting processes, many objects can be structured to an assembly, or tree. This entire assembly is created in wax, and undergoes the process outlined above of getting covered in stucco, having the wax melted out, and getting cast. Once the casting is completed, the individual components are broken off of the tree. This allows the lost wax process to be used for complicated components with high demand and production values.

Another large difference between ancient and modern casting processes is the way in which metal is melted. In ancient times, man would place a crucible over a fire and blow on the fire through a bamboo stick. The Chinese were advanced enough to create a box bellows furnace.

The box bellows furnace was able to melt iron, the most challenging metal of the time. In modern casting processes, a popular melting process is induction melting. There are two types of induction furnaces: channel and coreless. A channel furnace, shown in Figure 32, can have a capacity over 180 Mg or 200 tons. In this application, the copper coil surrounds the inductor of the unit. The channel induction furnace “must be started with a supply of molten metal, and a metal heel must be continuously maintained in the furnace. The furnace must not be shut down even for holidays or for other extended periods as the metal will freeze and considerable refractory damage will be incurred.” (Perkul) The channel furnace is best used for superheating, duplexing, and holding.

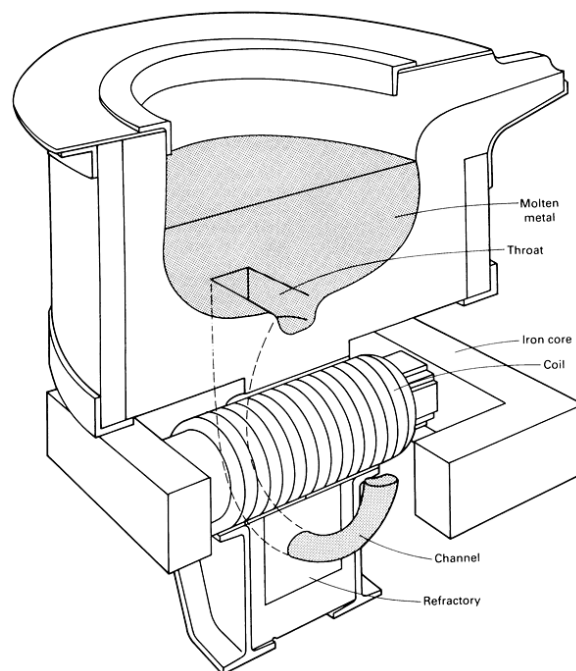


Figure 32: "A cross section of a channel-type induction furnace" (Perkul)

Meanwhile, the coreless furnace does not have the same start-up requirements, making it an easier process to utilize. The coreless furnace is shown in Figure 33. It has a refractory-lined crucible which “is completely surrounded by a water-cooled copper coil.” (Perkul) It has a capacity up to 68 Mg or 75 tons. The coreless furnace can be easily started and stopped, which makes it convenient to change alloys or to accommodate factory shutdowns. It is best used for melting and superheating.

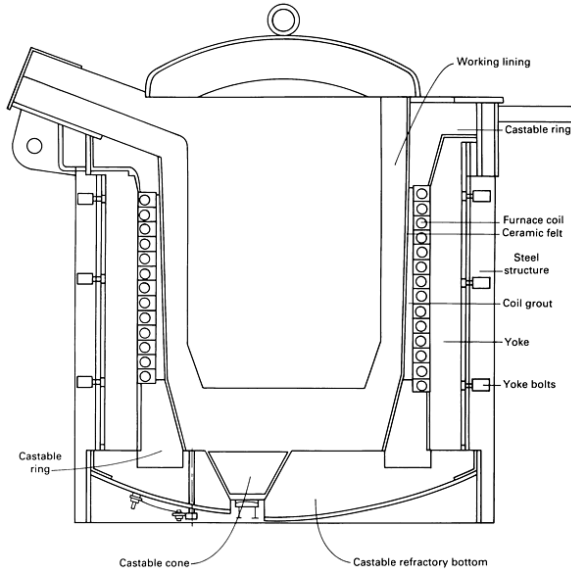


Figure 33: "A cross section of a coreless-type induction furnace" (Perkul)

Using these new furnace technologies, it is possible to melt nickel-based superalloys at 3000 degrees Fahrenheit. This allows for the use of new and improved materials in the casting process and extends the capability of the process.

4.2 SAND CASTING

Sand casting, notably green sand casting “is the most widely used molding method for small-to-medium size castings.” (Bradley, 95) Green sand molding is used to produce components for use in a variety of industries, including automotive, farm equipment, and railroad. “In fact, about 90% of castings produced annually in the United States are made in green sand molds.” (Bradley, 95) Green sand molding is very low cost and flexible in its capabilities. Molds require no conditioning treatment or pre-heating before the molten metal is poured. The process, from sand preparation to finished product, has a short cycle time. Using automated machinery helps keep this continuous.

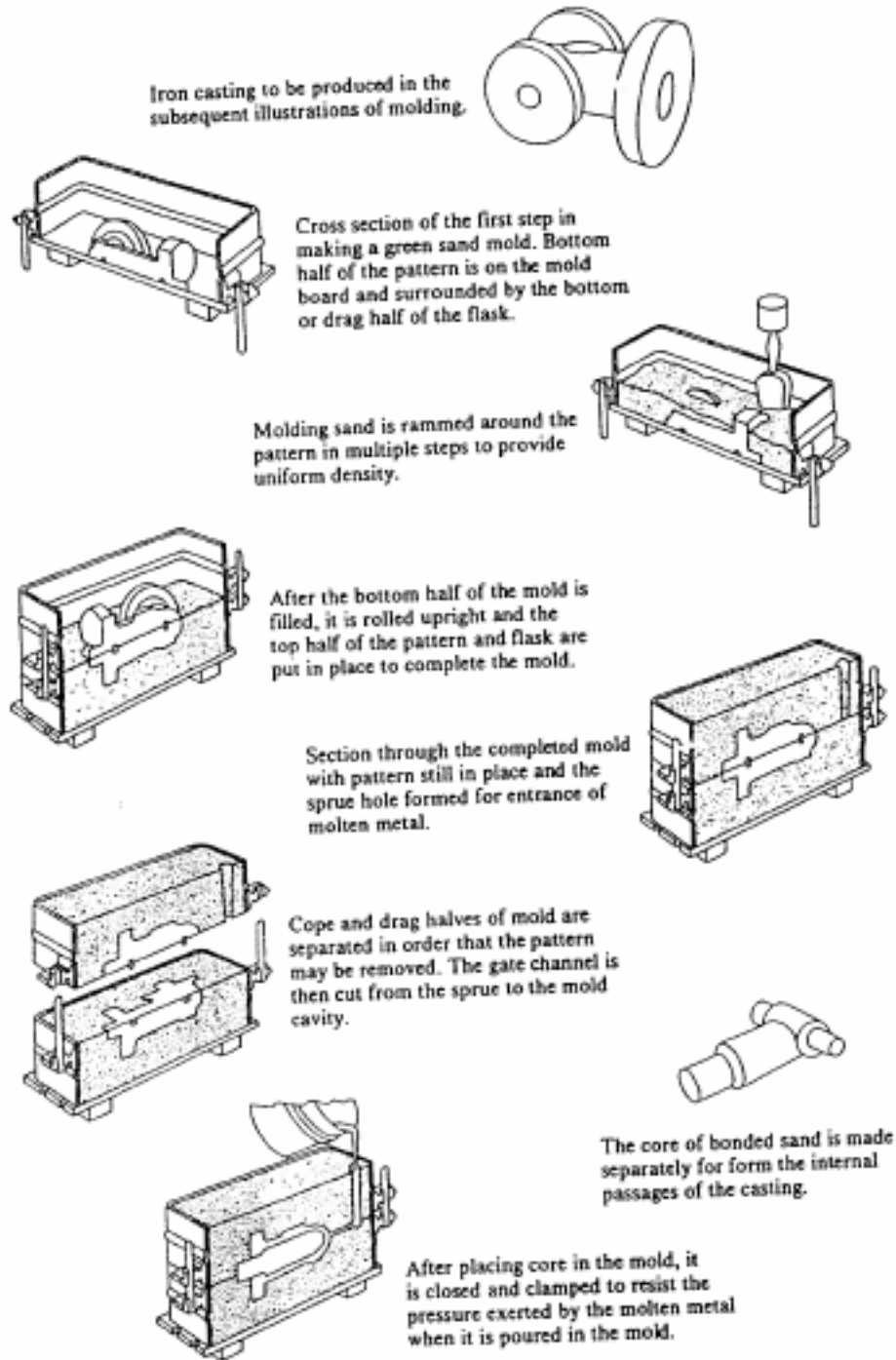


Figure 34: “Sequence of operations for making a green sand mold.” (Bradley, 97)

Another variation of sand molding is known as the dry sand method. This is modified from green sand molding by baking the mold in either a large mold oven or by using large heaters. The dry sand method is more effective on large or medium sized castings, such as engine cylinders, frames, and large gears. While it is more expensive than its green sand counterpart,

dry sand molding can produce stronger castings with more precise dimensions and improved surface finish.

The first step in the sand molding process is to create the pattern. Patterns can be made of wood, plastic, or metal. Cores are also used in this process to define inner compartments. The choice of mold material depended upon the application. Softwood patterns could be used in a limited manner before replacement. Hardwood patterns could last longer than softwood patters; aluminum could outlast hardwood, and cast iron generally has the longest pattern life. Depending on the structure of the pattern, areas that are subject to wear could be either made of metal or faced with metal to extend the life of the pattern.

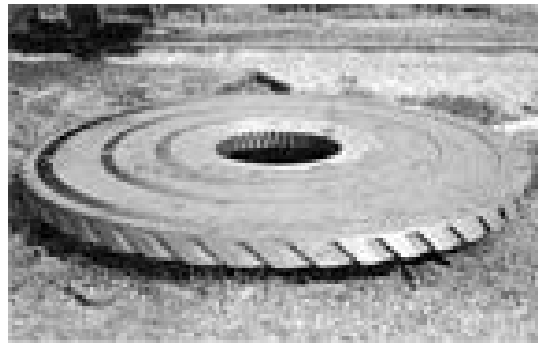


Figure 35: “Casting produced by loam molding.” (O’Meara)

Sand casting is one of the oldest methods used in ancient times. The Mesopotamians used sand to create some of the earliest molds. This was a convenient material to make a mold from, as sand was readily available in the natural environment. However, this did not make repeatable molds, which added to the degree of difficulty. In modern sand casting, binders are used with both green sand and dry sand casting to hold the mold together. Ancient man would have had to use available materials to create a binder. Unfortunately, sand molds have the capability to be broken down and reshaped, so no sand molds have survived. Possible binders could have been as simple as clay and water. The Egyptians similarly had vast experience with clay, sand, and straw. They may have used straw as a binder in addition to the clay and water.

Sun-baked clay was used by both the Mesopotamians and the Egyptians. This material would have had similar benefits to the sand molding – it is a flexible material that can be shaped to

create a precise mold shape. Given that the Mesopotamians baked the clay in the sun, this process corresponds well with the modern dry sand molding process.

4.3 PERMANENT MOLD CASTING

The fourth key process of the modern world is permanent mold casting, or the gravity die casting process. Molds with this process can be used repeatedly, and are designed to separate and release the casting once it has set. Metal molds are used in this process, and they help cool the casting quicker than a sand mold. This improves room temperature strength of the casting. Additionally, the process creates uniform castings with better dimensional accuracy over sand molds.

There are some disadvantages associated with the permanent mold process, however. Tooling is very expensive, and the process can be used only for small to medium sized parts. A typical permanent mold casting weighs up to 20 lbs. It is possible to produce castings between 250-500 lbs, but will be very costly. As the tooling is permanent, it can be difficult to change the mold design. Additionally, it can be difficult to cast thin sections using permanent mold.

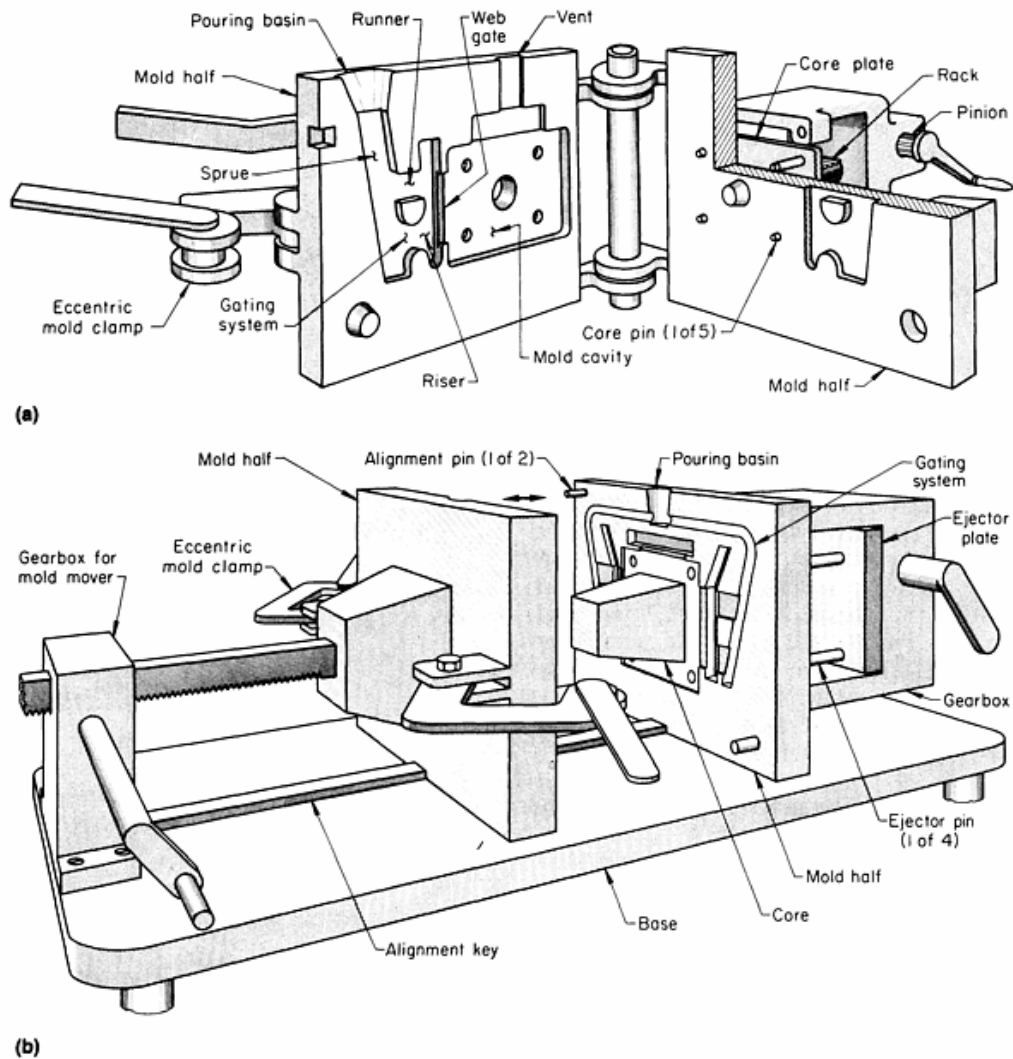


Figure 36: Two examples of manually operated permanent mold casting machines. The top machine would be used for a component with a shallow cavity. The bottom machine would be used for a casting with a deep cavity. (West)

Many molds in this process are made from cast iron. It has an ideal heat transfer rate to cast aluminum, and the use of free carbon helps give the cast iron resistance to erosion from the molten metal. Additionally, it has a higher melting point than many other alloys. Carbon and alloy steel can also be used to create the molds. Graphite has been used for its erosion resistance, but is fragile and easily damaged. The mold material limits the alloys that can be cast with this process. The cast alloy must have a lower melting temperature than the mold material. Aluminum is the most popular material to cast, but copper, lead, magnesium, tin, and zinc are

other options. For many of these materials, investment casting is a lucrative option – the determination of what casting process to utilize typically falls to the economics. If a large production number is planned to be created, permanent mold casting would be the method of choice.

Permanent mold casting clearly has its roots in ancient casting. In ancient Egypt, Mesopotamia, Thailand, China, and India, metal workers would use piece of molds repeatedly. Archaeological digs have shown evidence of molds at all these locations. These molds were typically bivalve molds carved out of a rock. This could be accomplished by using a harder rock as a tool. Some of the comments from ancient times indicate that this was not the most ideal process. Piece molds often resulted in flash, which could be dealt with but was not the intended result.

A key variation of the piece mold process today includes the introduction of permanent mold die casting. “In the die casting process, the molten metal is introduced under pressure into a metal mold.” (Bradley, 101) This process is limited to smaller parts. The costs of the zinc-alloy molds used with this method can be very expensive, and often increase in cost with size of finished part. However, it is possible to producing castings at a very high rate – up to one every couple of seconds – using the die casting process.

The process is simple. Molten metal is forced into a mold by a pressure piston. The pressure of this injection helps to cool the metal, and the entire casting takes only a few seconds to produce. Once the casting has solidified, the mold opens and ejects the casting. The mold is now ready to create another object. There are two basic machines used for this process: a cold chamber and a hot chamber. The cold chamber machine is used for alloys with a higher melting point than zinc. This process uses a high injection pressure that allows the molten metal temperature to be lower. The hot chamber is used for casting zinc-based alloys. A reservoir of molten metal is maintained at very hot temperature, and is forced into the mold by an air-pressure operated plunger. The lower pressure of this plunger requires the metal to be hotter.

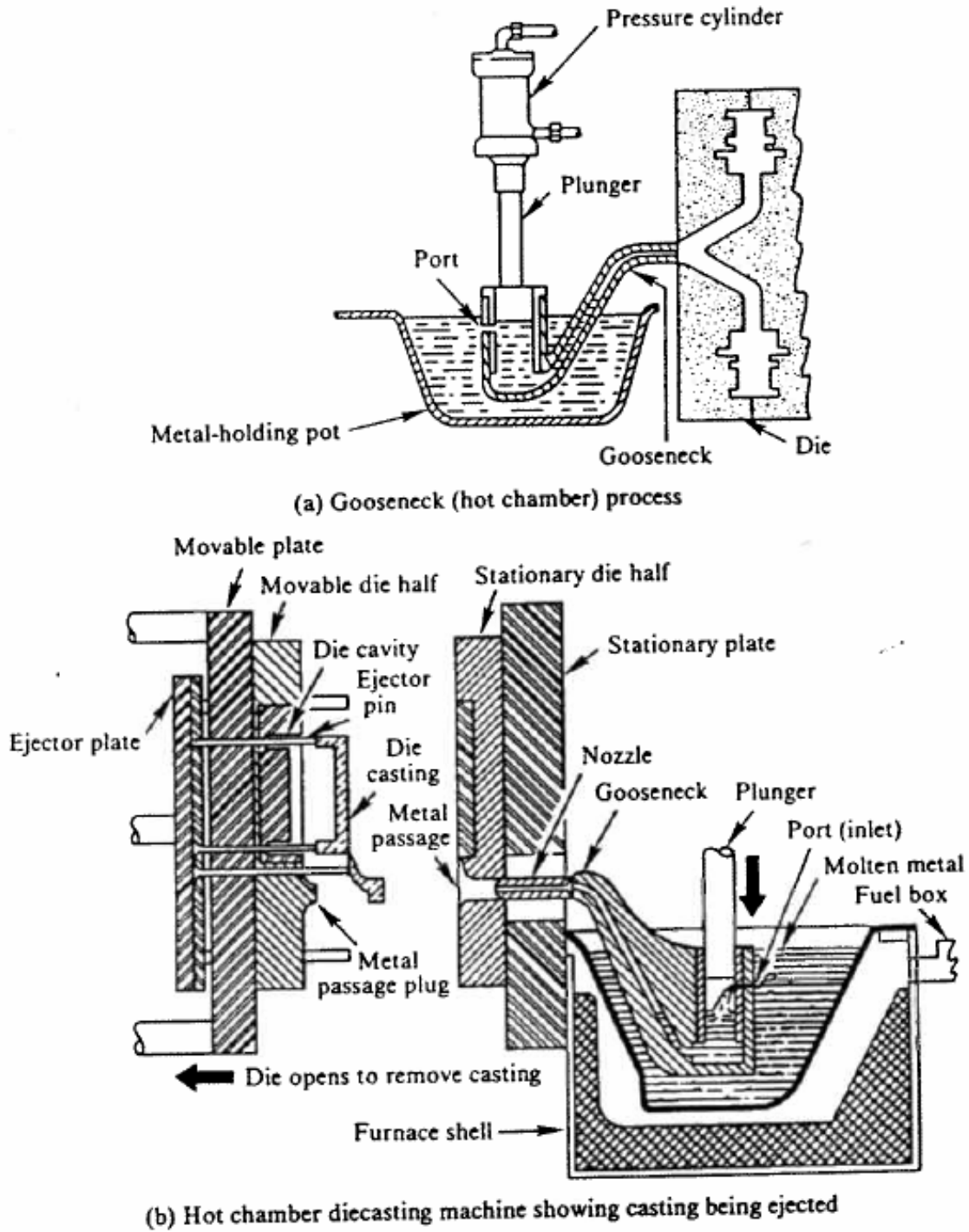


Figure 37: Hot chamber diecasting process and machining. (Bradley, 100)

There is no evidence of ancient man using pressure to cast components in this method, but the basics of permanent mold casting they developed continue to hold.

5.0 CONCLUSIONS

Casting, as a process, has a unique history that sets it apart from other modern processes. Though it can seem a simple process – melting metal and forming it into shapes – has countless variations and intricacies. It is clear that the three basic casting processes used today have their roots in the ancient world, and similar processes were developed and used from 3000-500 BC. The following table highlights some of the information presented throughout the paper.

Table 4: Summary table of ancient casting locations and their capability compared to modern casting process capability

		Metals Cast	Tooling	Wax Materials	Mold Materials		
Ancient	Mesopotamia	Sand Casting	Copper, Bronze	Wood and clay used as patterns		Sand, Clay	
		Investment Casting		Clay molds		Clay	
		Permanent Mold		Logs hollowed and used as a production line, stone hammers, bellows furnace		Stone, Limestone, Sun-baked clay	
	Egypt	Sand Casting	Copper, Bronze, Gold	Wood, stone, copper, bronze, and wrought iron used as tools. Furnace equipment uses crucibles, blowpipes, and foot bellows. Cores were used with sand and investment casting.		Sand	
		Investment Casting				Bees wax	Clay/Ceramic
		Permanent Mold					Stone
	China	Sand Casting	Iron	Foot bellows were used, created the box bellows furnace, wooden molds used for sand casting.		Sand	
		Investment Casting	Bronze, Iron			Bees wax	Clay/Ceramic
		Permanent Mold	Bronze, Iron				Stone, Ceramic
	Thailand	Sand Casting					
		Investment Casting					
		Permanent Mold	Bronze	Stone hammers		Stone	
India	Sand Casting						
	Investment Casting	Gold, Copper, Tin, Silver, Lead	Brick furnaces, Crucibles	Bees wax	Clay/Ceramic		
	Permanent Mold				Clay		
Modern	Sand Casting		Copper, Aluminum, Bronze, Iron, Nickel-Based Superalloys	Patterns made from hard/soft wood, aluminum, and iron.		Sand, resin binders	
	Investment Casting		Copper, Aluminum, Bronze, Iron, Nickel-Based Superalloys	Patterns, vats to hold slurry/collect stucco, casting chambers, saws to separate pieces from assembly.	Bees Wax, Plastic, Synthetic Wax	Ceramics, Slurry/Stucco mix	
	Permanent Mold		Copper, Aluminum, Lead, Magnesium, Tin, Zinc	Machine to press molten metal, die casting machines require pressure plungers		Zinc-alloys, Carbon Alloy Steel	

Modern man has been able to take the basic casting processes invented and developed by ancient man and apply them to meet the needs of the 21st century. Sand casting, permanent mold casting, and investment casting have now extended their reach to include a variety of materials and applications. While variations of all three are used today, the demands of the modern world dictate how and when each should be applied. The options when designing a new component are no longer “what is available and easy” but look at the resulting microstructure of the materials, account for the anticipated production demand, and also the stability of the component design.

New demand has arisen for automotive components, plumbing needs, and engine parts that was not required or even dreamed of when these processes were invented. The fact that the processes used today on these components can be directly linked to those used thousands of years ago is a true testament to the fundamental capability of the casting process. It has proven that it deserves to be a key process as man continues to evolve for the next several thousand years.

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