Chapter 2: Mold Making

2.1 Overview

2.1.1 Importance of Molds

2.1.2 Requirements for Molds

2.1.3 Process Flow of Mold Production

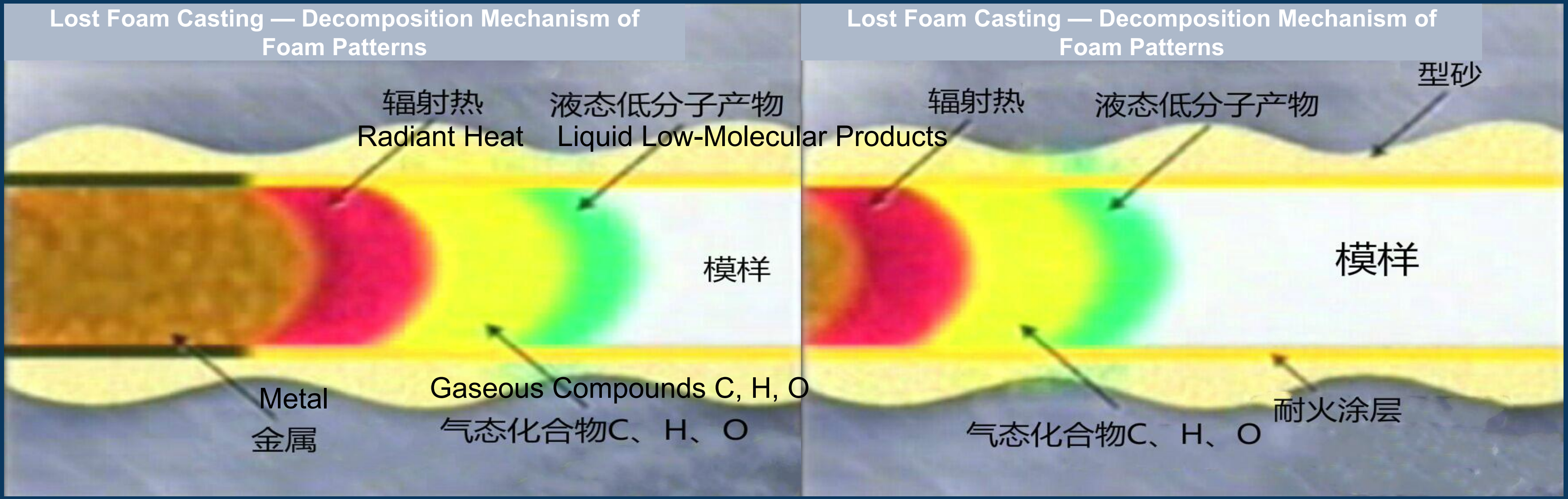
2.2 Mold Materials

2.2.1 Expandable Polystyrene (EPS)

2.2.2 Expandable Methyl Methacrylate (EPMMA) and Copolymer (STMMA)

2.1 Overview

In the lost foam casting process, the foam pattern is a unique modeling method specific to this technique. The disappearance of the foam pattern is a distinctive process in lost foam casting. The series of chemical and physical reactions triggered by this process introduce more uncertainties to the entire casting procedure. Therefore, the quality of the foam pattern directly affects the final casting quality. Two critical factors that influence the foam pattern quality are the choice of foam pattern material and the control of the pattern making process.



2.1.1 Importance of Molds

The pattern is an essential consumable in the lost foam casting process, with one pattern being consumed for each casting produced. The pattern not only defines the shape and dimensions of the lost foam casting but also participates in the physical and chemical reactions during the pouring process. Consequently, the pattern influences both the dimensional accuracy and the internal quality of the casting. Throughout the entire lost foam casting process, the pattern plays a pivotal role. Therefore, the pattern is a critical factor determining the success or failure of lost foam casting.

2.1.1 Importance of Molds

With the development of lost foam casting and increasing quality demands from customers, improving product qualification rates, enhancing product quality, and reducing production costs remain essential tasks for lost foam casting enterprises. The industry consensus worldwide is that "substandard white-area products equal substandard black-area products." The most fundamental constraint on the sound development of lost foam casting lies in the quality of the foam patterns used in the process.

a. High-quality foam patterns and casting products

b. Castings produced from inferior foam patterns

2.1.2 Requirements for Molds

The pattern is the critical factor determining the success or failure of lost foam casting. High-quality castings cannot be produced without high-quality patterns.

Quality requirements for premium patterns:

1.Superior pattern material:

Appropriate selection of expandable beads for lost foam casting based on the casting material, performance requirements, and process specifications.

2.Uniform density distribution:

Density gradient across the pattern should be controlled within ±1g/L, with a pattern-to-casting mass ratio of approximately 1:300.

3.High internal bead fusion density:

Internal bead fusion rate ≥95%. No beads should detach when the cross-section is manually rubbed after fracturing the pattern.

4.Smooth surface and dense bead fusion:

Surface gaps between beads <0.2 mm.

5.Volatile content control:

Residual volatile content in patterns before pouring must be <3%.

6.Moisture content control:

Moisture content in patterns before pouring must be <1% (≤0.5% for steel castings).

7.Dimensional stability control:

STMMA copolymer patterns: Shrinkage <0.3%

Conventional patterns (EPS/FD): Shrinkage <0.6%

2.1.3 Process Flow of Mold Production

01 02 03 04 05 06

Foam Bead Selection

Select the appropriate expandable beads for lost foam casting based on the material, performance requirements, and process specifications of the casting.

Bead Pre-expansion

Perform pre-expansion of beads according to the selected bead specifications and casting process requirements.Control the quality of pre-expanded beads during this step.

Bead Aging

Age and dry the pre-expanded foam beads to stabilize them.
Control the moisture and volatile content of the beads during aging, and measure and observe changes in density.

Mold Formation

Place the aged and dried beads into a mold to form the desired shape.Pay attention to the quality of the beads and the precision of the mold during formation.

Pattern aging treatment

The formed foam pattern is aged at room temperature to stabilize its shrinkage, and then placed in a drying chamber for forced drying.

Bonding and assembly

The dried mold segments and gating system are assembled and bonded using cold glue or hot melt adhesive to form a complete cluster of molds.

2.2 Mold Materials

- **Analysis of Pattern Materials Used by Lost Foam Casting Enterprises Domestically and Internationally:**

High-quality pattern materials are the prerequisite for producing high-quality patterns. Globally, foam bead materials suitable for lost foam casting processes can be categorized into three types:

The first type is ****Expandable Polystyrene (EPS)****, a polystyrene product containing a blowing agent, typically low-boiling-point pentane. EPS appears as colorless, transparent bead-like particles. Representative products for lost foam casting include EPS produced by Canada's Styrochem Chemicals (e.g., T170, T180, T175A, T185F). Among these, T175A and T185F contain bromides and are suitable for lost foam casting of aluminum alloy castings, while T170 and T180 are suitable for gray iron castings.

It is widely known that China currently does not produce EPS beads specifically designed for lost foam casting. Domestic lost foam casting enterprises use EPS beads intended for packaging or construction. These EPS beads often come from mixed sources, sometimes blending materials of different properties, leading to frequent defects in castings and increased production costs.

2.2 Mold Materials

- **Analysis of Pattern Materials Used by Lost Foam Casting Enterprises Domestically and Internationally:**

The second category is ****Expandable Styrene-Methyl Methacrylate Copolymer (STMMA)****, a copolymer of methyl methacrylate and styrene polymerized in a specific ratio (currently, the optimal ratio is recognized as 70:30). It appears as milky white, opaque bead-like particles, with a low-boiling-point pentane as the blowing agent. This type of foam bead is currently the most widely used pattern material in lost foam casting enterprises globally. Representative manufacturers of such foam beads include Japan's JSP Corporation, which produces the CL300–CL600 series, and Zhejiang KST New Materials Co., Ltd., which offers the STMMA series, including STMMA and STMMA-FD expandable copolymer resins.

STMMA beads are not only suitable for gray iron and carbon steel castings but are also particularly well-suited for ductile iron, low-carbon steel, alloy steel, copper alloy, and stainless steel castings. STMMA-FD beads are primarily used as a substitute for EPS beads and are applied in the production of lost foam castings for mid-to-low-end materials such as gray iron, carbon steel, and certain ductile iron castings.

2.2 Mold Materials

➢ **Analysis of Pattern Materials Used by Lost Foam Casting Enterprises Domestically and Internationally:**

The third category is **Expandable Polymethyl Methacrylate (EPMMA)**, a polymer formed solely through the polymerization of methyl methacrylate. Previously, this type of foam bead required exceptionally high steam pressure during pre-expansion and foam molding, demanding advanced equipment for pattern production. Additionally, the high gas generation during subsequent pouring made it difficult for lost foam casting enterprises to control the process when using these beads. As a result, Dow Chemical Company in the United States has discontinued the production of EPMMA products.

After more than three years of dedicated research,Castchem Company has successfully developed a new type of EPMMA resin specifically designed for lost foam casting. This innovation has undergone experimental testing and practical application, demonstrating significant breakthroughs in performance and effectiveness. The new EPMMA resin is tailored for the production of foam patterns for low-carbon steel and stainless steel castings. It effectively reduces carbon pickup, minimizes or eliminates carbon-related defects, and expands the process window for lost foam casting of low-carbon steel and stainless steel. It has already been tested in Castchem's steel casting experimental base.

2.2 Mold Materials

➢ **Analysis of Pattern Materials Used by Lost Foam Casting Enterprises Domestically and Internationally:**

EPS

1. Domestic General-Purpose EPS
2. Styrochem Chemicals' EPS for Lost Foam Casting of Aluminum Alloys (Canada)

STMMA

1.STMMA copolymer resin
2.STMMA-FD resin

EPMMA

1. EPMMA by Dow Chemical Company (USA)
2. EPMMA by Nippon Synthetic Chemical Industry Co., Ltd. (Japan)
3. Advanced EPMMA by Zhejiang Castchem New Material Co., Ltd (China)

2.2 Mold Materials

- **Requirements for Foam Beads in Lost Foam Casting Process:**

Lost foam casting is a method that uses foam patterns to replace traditional molds (e.g., wooden molds, metal molds) for producing castings. Unlike other casting processes, the factors influencing casting quality are unique. Since foam patterns are essential consumables in the lost foam casting process—each casting requires one foam pattern—the quality of the foam pattern is critical to the success of lost foam casting. Without high-quality foam patterns, it is impossible to produce high-quality castings.

Foam patterns not only define the shape and dimensions of the lost foam castings but also participate in the physical and chemical reactions during the pouring process. As a result, foam patterns influence both the dimensional accuracy and the internal quality of the castings. To produce superior castings, the material used for foam patterns in lost foam casting is of utmost importance.

Although there are numerous types of foam pattern materials, those used in lost foam casting must meet the following requirements:

2.2 Mold Materials

➢ **Requirements for Foam Beads in Lost Foam Casting Process:**

There is a wide variety of foam pattern materials, but those used in lost foam casting must meet the following requirements:

1. **Low Carbon Content in Foam Beads**:
   The foam beads must have a low carbon content to minimize carbon-related defects in the castings.

2. **Low Gasification Temperature and Gas Evolution**:
   The foam patterns should gasify at a low temperature and produce minimal gas during the casting process.

3. **Rapid and Complete Decomposition and Gasification with Minimal Residue**:
   The patterns should decompose and gasify quickly and completely, leaving behind little to no residue.

4. **Long Shelf Life and Moderate Cost of Foam Beads**:
   The foam beads should have a long storage life and be reasonably priced.

5. **Low Density, High Strength, and Good Surface Rigidity of the Patterns**:
   The produced foam patterns should have low density, high strength, and excellent surface rigidity.

6. **Comprehensive Range of Bead Types and Specifications**:
   The foam beads should be available in a variety of types and specifications to meet the molding needs of different materials and casting structures.

2.2 Mold Materials

➢ Impact of Foam Pattern Decomposition Products on Casting Quality:

Foam patterns are a unique modeling method in the lost foam casting process. The decomposition of foam patterns is a distinctive feature of lost foam casting, introducing a series of chemical reactions that add uncertainties to the casting process. Corresponding process measures are required to eliminate potential quality risks.

The decomposition of foam patterns occurs simultaneously with the pouring process, producing carbon compounds, carbon, carbon dioxide, and water. Carbon dioxide and water are gases and, if promptly expelled, do not adversely affect casting quality. Carbon in the form of graphite is partially absorbed by the coating or expelled, while another portion is absorbed by the molten metal, resulting in carbon pickup. Carbon that is neither absorbed nor expelled, if dispersed on the casting surface, does not negatively impact internal or external quality. However, if concentrated due to the impact of molten metal, it can form macroscopic defects known as carbon defects.

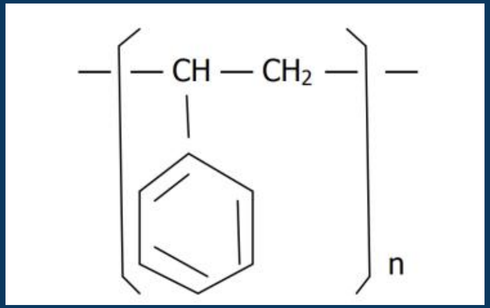
Carbon compounds are large particles that cannot be absorbed or expelled and inevitably manifest as carbon defects in various shapes and sizes. Carbon defects are among the most challenging issues to overcome in lost foam casting, significantly limiting the expansion of product categories. Under identical process conditions, enhancing the gasification efficiency of foam pattern decomposition and reducing solid residues are the most effective ways to minimize or eliminate carbon defects. Therefore, selecting qualified beads and preparing qualified foam patterns are prerequisites for successful lost foam casting.

2.2.1 Expandable Polystyrene (EPS)

Expandable Polystyrene (EPS) beads are produced by polymerizing styrene and then impregnating it with a blowing agent.

Chemical Formula: $(C_8H_8)_n$

Molecular Structure: (Refer to the attached diagram.)



Each ethylene molecule combines with one benzene molecule, forming a styrene molecule with a benzene ring. The benzene ring is resistant to addition reactions and oxidation, making the carbon ring exceptionally stable.

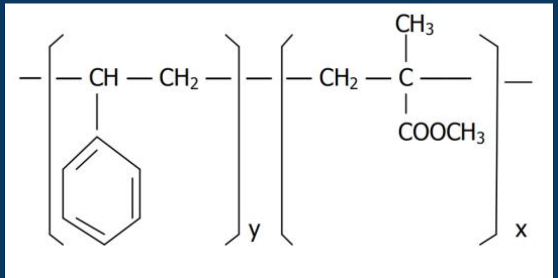
Each styrene molecule consists of 8 carbon atoms and 8 hydrogen atoms, with a carbon content of 92%. For foam beads used in lost foam casting, the ideal decomposition products are carbon dioxide and water, i.e., complete gasification. The degree of gasification is the standard for evaluating the decomposition level of the beads. In polystyrene, the stable benzene ring accounts for a high proportion, resulting in poor gasification capability of EPS beads. According to the law of conservation of energy, this leads to a significant amount of solid residues during decomposition, causing numerous carbon defects. If stable or flame-retardant components are used during polymerization, the amount of solid residues will increase further, posing substantial risks to casting quality.

2.2.2 Expandable Methyl Methacrylate (EPMMA) and Copolymer (STMMA)

Styrene and methyl methacrylate (PMMA) are polymerized in varying ratios, and a blowing agent is introduced during the polymerization process to produce expandable copolymer resin.

Chemical Formula: $[(C_5H_8O_2)_x(C_8H_8)_y]_m$

Molecular Structure: (Refer to the attached diagram.)



Methyl methacrylate (PMMA) belongs to a molecular chain structure that is easily decomposed, without the presence of benzene rings, and exhibits strong gasification capability. When styrene and methyl methacrylate are copolymerized, the proportion of benzene rings in the copolymer molecular chain is reduced. Additionally, the rapid decomposition of methyl methacrylate catalyzes the decomposition of benzene rings. As a result, STMMA series copolymer resins decompose more completely, achieve a higher degree of gasification, and produce fewer solid residues, thereby reducing carbon defects formed during the pouring process.

The greater the amount of methyl methacrylate involved in the copolymerization, the more complete the decomposition of the foam pattern and the higher the degree of gasification.

Based on the copolymerization content of methyl methacrylate (PMMA), the casting-specific STMMA series copolymer resins are divided into two categories: STMMA and STMMA-FD.

2.2.2 Expandable Methyl Methacrylate (EPMMA) and Copolymer (STMMA)

STMMA-FD beads are a type of copolymer resin composed of methyl methacrylate and styrene in varying proportions. The amount of methyl methacrylate involved in the polymerization of STMMA-FD is moderate, resulting in a carbon content of 82% in the beads. These beads decompose relatively thoroughly, exhibit a high degree of gasification, and produce minimal solid residues. They can be understood as a modified version of EPS.

The physical and chemical performance indicators of STMMA-FD are listed in the table (based on the draft standard for the machinery industry association).

ITEM	Specifications			
	size range.，d，mm	Expansion ratio.，（120℃，10min）	Volatile content.，wt. %	Bulk density.，g/mL
STMMA-FD Special	0.90≤d＜1.25	≥ 40.0	≥4.50	0.500~0.650
STMMA-FD大1#	0.71≤d＜0.90			
STMMA-FD小1#	0.60≤d＜0.80			
STMMA-FD2#	0.40≤d＜0.65			
STMMA-FD3#	0.35≤d＜0.45			
STMMA-FD4#	0.25≤d＜0.35			
Note: The weight percentage of beads within the specified particle size range exceeds 90%.				

2.2.2 Expandable Methyl Methacrylate-Styrene Copolymer Resin (STMMA-FD)

The physical and chemical performance indicators of STMMA-FD are listed in the table (based on the draft standard for the machinery industry association).

ITEM	Specifications			
	Size range，d，mm	Expansion ratio，（120℃，10min）	Volatile content，wt. %	Bulk density，g/mL
STMMA-FD Special	0.90≤d＜1.25	≥ 40.0	≥4.50	0.500~0.650
STMMA-FD大1#	0.71≤d＜0.90			
STMMA-FD小1#	0.60≤d＜0.80			
STMMA-FD2#	0.40≤d＜0.65			
STMMA-FD3#	0.35≤d＜0.45			
STMMA-FD4#	0.25≤d＜0.35			

Note: The weight percentage of beads within the specified particle size range exceeds 90%.

2.2.2 Expandable Methyl Methacrylate (EPMMA) and Copolymer (STMMA)

STMMA copolymer resin is a type of expandable copolymer resin produced through suspension polymerization, using methyl methacrylate (MMA), styrene, and low-boiling-point hydrocarbon blowing agents as the main raw materials, and peroxides as initiators. STMMA contains a higher proportion of methyl methacrylate in its polymerization, resulting in a carbon content of 63%. It decomposes thoroughly, exhibits a high degree of gasification, and produces minimal solid residues.

The physical and chemical performance indicators of STMMA copolymer resin are listed in the table (based on the JB/T 11846 standard for the machinery industry).

ITEM	Specifications			
	size range，d，mm	expansion ratio，（120℃，10min）	Volatile content，wt. %	Bulk density，g/mL
STMMA-1#	0.85≤d＜0.90	≥ 50.0	7.0~12.0	0.530~0.600
STMMA-2#	0.65≤d＜0.85	≥ 50.0	7.0~12.0	
STMMA-3A	0.50≤d＜0.65	≥ 45.0	7.0~12.0	
STMMA-3#	0.35≤d＜0.50	≥ 45.0	7.0~12.0	
STMMA-4#	0.25≤d＜0.35	≥ 40.0	7.0~12.0	
Note: The weight percentage of beads within the specified particle size range exceeds 90%.				

2.2.2 Expandable Methyl Methacrylate (EPMMA) and Copolymer (STMMA)

The physical and chemical performance indicators of STMMA copolymer beads are listed in the table (based on the JB/T 11846 standard for the machinery industry).

ITEM	Specifications			
	size range，d，mm	expansion ratio，（120℃，10min）	Volatile content，wt. %	Bulk density，g/mL
STMMA-1#	0.85≤d＜0.90	≥ 50.0	7.0~12.0	0.530~0.600
STMMA-2#	0.65≤d＜0.85	≥ 50.0	7.0~12.0	
STMMA-3A	0.50≤d＜0.65	≥ 45.0	7.0~12.0	
STMMA-3#	0.35≤d＜0.50	≥ 45.0	7.0~12.0	
STMMA-4#	0.25≤d＜0.35	≥ 40.0	7.0~12.0	

Note: The weight percentage of beads within the specified particle size range exceeds 90%.

2.2 Mold Material

- **Comparison of Key Indicators of Commonly Used Beads in Lost Foam Casting:**
- **(1) Comparison of Physical, Chemical, and Application Indicators for EPMMA, STMMA, FD, and EPS (Refer to the Table):**

ITEM	Physical, Chemical, and Application Indicators.			
	EPMMA	STMMA	STMMA-FD	EPS
Size range，mm	0.25~0.85	0.25~0.85	0.35~1.25	0.35~1.8
Expansion ratio, times.（120℃，10min）	40~65	65~75	50~70	50~70
Volatile content， %（150℃/1h）	10.50`11.50	9.00~10.00	6.50~7.50	4.50~6.50
Bulk density，g/mL	0.550~0.560	0.530~0.600	0.500~0.650	0.590~0.600
Carbon content，%	45	63	82	92
Gas evolution volume.（1000 ℃），mL/g	900	800	700	600

2.2 Mold Material

➢ **Comparison of Key Indicators of Commonly Used Beads in Lost Foam Casting:**
(2) Comparison of Pre-Expansion Parameters for Various Beads (Refer to the Table):

ITEM	EPMMA	STMMA	STMMA-FD	EPS
Pre-expansion temperature.（℃）	95~105	95~105	90~95	90~95
Pre-expansion pressure.（Mpa）	0.03~0.05	0.03~0.05	Atmospheric pressure	Atmospheric pressure
Pre-expansion time.（s）	40~60	40~60	15~25	15~25
Curing time.（h）	24~48	24~48	8~24	8~24

2.2 Mold Material

How to Choose Specialized Beads for Lost Foam Casting:

(1) Gray Iron Characteristics and Bead Selection:

Carbon Equivalent: Typically ranges from 3.7% to 4.1%.
Initial Crystallization Temperature: Relatively low, around 1200° C to 1230° C.
Pouring Temperature: Can be significantly increased since normal gray iron does not contain low-melting-point or easily burned alloy elements.

Advantages of Gray Iron for Lost Foam Casting:

High Pouring Temperature: Promotes more complete decomposition and gasification of the foam pattern.
Low Initial Crystallization Temperature: Allows for a superheat temperature exceeding 300° C, providing ample time for the foam pattern to decompose and gasify from the start of pouring to initial crystallization.
Directional Solidification and Good Fluidity: Carbon and carbides entrapped in the molten iron during pouring have a higher chance of floating to the surface during solidification.

Implications for Bead Selection:

Under the same bead and process conditions, gray iron is more conducive to reducing carbon defects and mitigating their impact on the internal quality of castings.

Recommended Bead for Gray Iron Castings:

For gray iron products such as gearbox housings, clutch housings, engine blocks, motor housings, valve bodies, and pump bodies, STMMA-FD beads are recommended to replace non-casting-specific EPS. This substitution can significantly reduce carbon defects and greatly improve product qualification rates.

2.2 Mold Material

How to Choose Specialized Beads for Lost Foam Casting:

(2) High-Quality Gray Iron Castings:
For high-grade safety components, high-pressure-resistant parts, and other gray iron products with extremely high internal quality requirements, such as those with a high proportion of machined surfaces, strict assembly requirements, and high sensitivity to casting defects, copolymer beads (STMMA) should be directly selected. Copolymer beads decompose more thoroughly and exhibit better gasification effects. Under the same pouring temperature and process conditions, they result in the fewest carbon defects.

(3) Ductile Iron Characteristics and Bead Selection:
Carbon Equivalent: Typically ranges from 4.1% to 4.7%.
Initial Crystallization Temperature: Relatively high, around 1250° C to 1270° C.
Pouring Temperature: To minimize magnesium loss during and after the nodularization process, extend nodularization effectiveness, and ensure nodularization quality, the pouring temperature should not be too high. The upper limit is generally controlled at 1450° C.

Challenges for Ductile Iron in Lost Foam Casting:
Low Pouring Temperature: Hinders the complete combustion and decomposition of the foam pattern.
Low Superheat Temperature: Below 200° C, providing insufficient time for the foam pattern to burn and decompose from the start of pouring to initial crystallization.
Simultaneous Solidification and Poor Fluidity: Carbon and carbides entrapped in the molten iron during pouring have difficulty floating to the surface during solidification.

2.2 Mold Material

How to Choose Specialized Beads for Lost Foam Casting:

Implications for Bead Selection:

Compared to gray iron under the same foam pattern material and process conditions, ductile iron is more prone to carbon defects. Therefore, copolymer beads (STMMA) with excellent gasification effects and minimal residue must be used to maximize the reduction of solid residues and effectively lower the probability of carbon defects.

For ductile iron castings, STMMA copolymer beads are essential to achieve high-quality results with minimal defects.

(4) Carbon Steel Castings:

Carbon Content: Typically below 0.5%.
Initial Crystallization Temperature: Around 1500° C.
Fluidity: Extremely poor.
Fluidity: Extremely poor.

Challenges for Carbon Steel in Lost Foam Casting:

High Pouring Temperature: To ensure casting quality, the pouring temperature generally exceeds 1620° C, sometimes approaching 1700° C.
Severe Oxidation: Higher melting and pouring temperatures lead to increased oxidation, potentially causing issues such as "overheating," "burning," and coarse grain structure.
Superheat Temperature Limit: The superheat temperature should ideally not exceed 200° C.
Poor Casting Properties: High initial crystallization temperature, low superheat temperature, early crystallization, rapid solidification, and extremely poor fluidity leave insufficient time for the foam pattern to decompose. Carbon and carbides entrapped in the molten steel have difficulty floating to the surface.

2.2 Mold Material

How to Choose Specialized Beads for Lost Foam Casting:

Bead Selection:
Due to the poor casting properties of carbon steel, copolymer beads (STMMA) or EPMMA products with superior performance must be selected to effectively reduce and eliminate carbon defects.

(5) High-Furnace Cooling Plates and High-Manganese Wear-Resistant Products:
Carbon Defect Tolerance: These products are less sensitive to carbon defects.
Appearance Repair Costs: Using ordinary EPS materials can result in large-area carbon defects, leading to high appearance repair costs.

Coating Requirements: Even for counterweight castings with coating requirements, defects must be repaired before coating.

Bead Selection:
To reduce carbon defects, improve surface quality, and lower overall production costs, casting-specific foam materials should be used.

Conclusion:
For carbon steel castings, STMMA or EPMMA beads are recommended to minimize defects.
For high-furnace cooling plates and high-manganese wear-resistant products, casting-specific foam materials are advised to enhance quality and reduce costs.

2.2 Mold Material

How to Choose Specialized Beads for Lost Foam Casting:

(6) Specialized Applications: Machine Tool Beds, Large Bases, and Automotive Cover Molds:
For certain products such as machine tool beds, large bases, and automotive cover molds, which are characterized by small batches and multiple specifications, foam patterns are typically unsuitable for mold forming. Instead, they are often created by bonding or carving **foam boards**.

****Key Considerations**:**
1. **Ordinary EPS Boards**: These are not casting-specific materials and inevitably produce a large number of carbon defects.
2. **Casting-Specific Boards**: Zhejiang Kaiste New Materials Co., Ltd. has successfully developed casting-specific **STMMA boards** and **STMMA-FD boards**, which have demonstrated excellent performance in practical applications.

****Comparison of Foam Boards**:**
- **Ordinary EPS Boards**:
 - Made from pre-expanded beads larger than 0.9mm.
 - Each bead forms a relatively deep indentation after cutting, resulting in a "pockmarked" surface appearance.
 - Increasing the board density does not significantly improve the surface quality.

- **Casting-Specific Boards (STMMA and STMMA-FD)**:
 - Made from pre-expanded beads smaller than 0.9mm.
 - Each bead forms a minimal indentation after cutting, resulting in a smooth and high-quality surface.
- Superior carving performance compared to EPS boards.
- Significantly higher strength than EPS boards, reducing carbon defects, improving surface quality, and effectively preventing product deformation.