ANALYSIS OF THERMAL DECOMPOSITION PROCESSES OF MOLDING MIXTURES IN CASTING PRODUCTION AND ITS IMPACT ON CASTING QUALITY

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Annotatsiya: *Ushbu maqolada quyma ishlab chiqarish jarayonida qoʻllaniladigan qolip aralashmalari tarkibidagi kvarts qumi, bentonit, koʻmir kukuni hamda fenol-formaldegid turidagi organik bogʻlovchilarning yuqori harorat taʼsirida (1400–1700°C) termik parchalanish jarayonlari tahlil qilingan. Termogravimetrik (TG/DTG) va gaz xromatografiyasi tahlillari asosida termik parchalanish jarayoni besh asosiy bosqichda kechishi aniqlangan. Erkin va adsorbsiyalangan namlikning ajralishi (25–200°C), gley suvsizlanishi va bogʻlovchining dastlabki parchalanishi (200–400°C), fenol-formaldegid smolasining intensiv destruksiyasi (400–700°C), karbonizatsiya (700–1000°C) hamda yuqori haroratli reaksiyalar (1000–1700°C). Parchalanish natijasida CO, CO2 , CH4 , H2 hamda uchuvchan organik birikmalar (VOCs) ajralib chiqishi qayd etilgan. Mazkur gazlarning qolip ichida bosimni oshirishi natijasida quyma metall tarkibida gazli gʻovaklik, mikroboʻshliqlar va sirt nuqsonlari hosil boʻlish mexanizmlari baholangan. Tadqiqot natijalari qolip aralashmalari tarkibini optimallashtirish va past gaz ajratuvchi bogʻlovchilarni qoʻllash orqali quyma sifatini oshirish imkoniyatini koʻrsatadi.*

Kalit soʻzlar: *Quyma jarayoni, qolip aralashmasi, termik parchalanish, gaz ajralishi, fenol-formaldegid smola, karbonizatsiya, gazli gʻovaklik, quyma nuqsonlari, TG/DTGtahlili.*

Аннотация: *В данной статье проанализированы процессы термического разложения формовочных смесей, используемых в процессе литья, под воздействием высоких температур (1400–1700°C). Исследование охватывало термическую стабильность компонентов формовочной смеси, таких как кварцевый песок, бентонит, угольная пыль и органические связующие на основе фенолформальдегидного. На основе методов ТГ/ДТГ и газовой хроматографии установлено, что термическое разложение происходит в пять основных этапов: удаление влаги (25–200°C), дегидратация глины (200–400°C), интенсивная деструкция смолы (400–700°C), карбонизация (700–1000°C) и высокотемпературные реакции (1000–1700°C). Зафиксировано выделение CO, CO2 , CH4 , H2 и летучих органических соединений (ЛОС). Оценено влияние этих газов на повышение давления внутри формы, что приводит к образованию газовой пористости, микропустот и поверхностей литья. Результаты показывают возможность повышения качества литья путем оптимизации состава смесей и использования низкогазообразующих связующих.*

Ключевые слова: *литейный процесс, формовочная смесь, термическое разложение, газовыделение, фенолформальдегидная смола, карбонизация, газовая пористость, литейные дефекты, ТГ/ДТГ анализ.*

Abstract*: This article analyzes the thermal decomposition processes of molding mixtures used in casting production under the influence of high temperatures (1400–1700°C). The study investigated the thermal stability of quartz sand, bentonite, coal powder, and phenol-formaldehyde organic binders included in the composition of molding mixtures. Based on TG/DTG and gas chromatography analyses, the decomposition process was determined to occur in five main stages: moisture removal (25–200°C), clay dehydration (200–400°C), intensive resin decomposition (400–700°C), carbonization (700–1000°C), and high-temperature reactions (1000–1700°C). The release of gaseous products such as CO, CO2 , CH4 , H2 , and volatile organic compounds (VOCs) was recorded. The mechanism by which these gases increase mold pressure, leading to gas porosity, microvoids, and surface defects in castings, was evaluated. The results demonstrate that casting quality can be significantly improved by optimizing molding mixture compositions and utilizing low gas-emission binders.*

Keywords: *casting process, molding mixture, thermal decomposition, gas evolution, phenol-formaldehyde resin, carbonization, gas porosity, casting defects, TG/DTG analysis.*

INTRODUCTION

The foundry industry is one of the important sectors of metallurgy and mechanical engineering, making it possible to produce complex-shaped metal parts in an economically efficient way. In sand-casting technologies, molding mixtures serve as the main technological material. Molding mixtures generally consist of quartz sand, bentonite, organic binders, coal powder, and various additives. When molten metal is poured into the mold, its temperature sharply reaches approximately 1400–1700◦C. Under the influence of such high temperatures, the components of the molding mixture undergo complex physical and chemical changes.

In particular, organic binders decompose thermally and form various gaseous products, including CO, CO2 , CH4 , H2 , and volatile organic compounds. The rapid accumulation of these gases inside the mold leads to a significant increase in internal backpressure. As a result, casting defects such as gas porosity, microvoids, cracks, and surface imperfections frequently occur in cast products. Therefore, studying the thermal stability of molding mixtures and analyzing their decomposition products are of great scientific and practical importance. Currently, the behavior of molding materials at high temperatures is widely investigated using thermogravimetric analysis (TGA), differential thermal analysis (DTA), gas chromatography, and spectral analysis methods. These methods make it possible to accurately determine the stages of decomposition, the kinetics of gas evolution, and the amount of emissions. In addition, increasing environmental safety requirements have made the reduction of harmful gases released from molding mixtures an urgent issue. For this reason, the development of low gas-emission binder materials is becoming increasingly important. The aim of this article is to analyze the multi-stage thermal decomposition products of molding mixtures during the casting process, study their formation mechanisms, and evaluate the effect of gas evolution on casting quality.

Literature Review

Modern scientific literature widely investigates the thermal decomposition processes of molding mixtures used in foundry production. Peter Beeley (2001) reported that binders based on phenol-formaldehyde resins undergo intensive decomposition within the temperature range of 200–600∘C, resulting in the formation of CO and CO2 gases. Studies conducted by John Campbell (2015) demonstrated that gases released from molding materials can form gas porosity inside castings, significantly reducing the quality of metal products. In addition, several studies have shown that bentonite and organic additives lose their structural stability at high temperatures, while microstructural changes occur on the surface of quartz sand particles.

According to the results of gas chromatography and TG/DTA analyses, the maximum mass loss occurs within the temperature range of 200–600∘C, where active evolution of carbon oxides and hydrocarbons is observed. The literature review indicates that optimization of molding mixture composition and the use of low gas-emission binders can significantly reduce casting defects.

Research Methodology During the research, the thermal decomposition processes of molding mixtures under high-temperature conditions were comprehensively investigated. A standard molding mixture formulated from 85 wt.% quartz sand (SiO2), 8 wt.%bentonite clay, and 7 wt.% phenol-formaldehyde resin binder was selected as the primary object of study. All prepared specimens were analyzed from ambient room temperature up to 1200∘C under a strictly controlled nitrogen (N2) atmosphere, applying a constant linear heating rate of 10∘C/min utilizing synchronized Thermogravimetric (TG) and Derivative Thermogravimetric (DTG) analytical instruments. Throughout the dynamic heating process, the initial evaporation of moisture followed by the subsequent pyrolysis and oxidation stages of the organic binders was monitored, whereby the evolution of gaseous products such as CO, CO2 , H2 , CH4 , and other volatile organic compounds was successfully detected. To systematically evaluate the mass loss kinetics and dynamics of the mixtures, synchronized TG and DTG analytical methods were deployed. Quantitative and qualitative identification of the evolved gas species was precisely executed using a gas chromatography system coupled with a Thermal Conductivity Detector (TCD). Furthermore, structural and phase alterations, including microcracking and structural phase transformations occurring on the surface of the quartz sand grains under high-temperature exposure, were recorded via microstructural analysis. Finally, the definitive correlation between these thermal degradation products and the final casting quality was thoroughly evaluated by calculating the absolute defect occurrence percentages within the actual experimental cast products.

Results and Discussion The synchronized TG/DTG and gas evolution profiles demonstrated that the thermal decomposition of the quartz-bentonite-resin molding mixture is a highly complex, multi-stage mechanism governed by temperature-dependent physical and chemical kinetic paths. Based on the gathered empirical data, the continuous thermal degradation spectrum was systematically categorized into five distinct operational stages: 1. Stage 1: Moisture Removal (25–200◦C) During the initial thermal phase, a minor mass loss of approximately 2.3% was documented. This explicit stage is predominantly characterized by the thermodynamic evaporation of free, unbound moisture and physically adsorbed water molecules trapped within the interstitial spaces of the bentonite clay matrix. As the thermal boundary reaches 100–200◦C, the moisture transitions into water vapor ($H_2O(g)$), inducing early-stage physical alterations within the clay structure, whereas the cross-linked synthetic resin matrix remains completely unaffected at this temperature range.

2. Stage 2: Clay Dehydration and Initial Binder Decomposition (200–400◦C) When the temperature advances into this specific interval, the bentonite clay undergoes an irreversible dehydroxylation process via the loss of its chemically bound structural (crystalline) water molecules. This permanent transition collapses the characteristic layered lattice of the clay, severely reducing its inherent binding and swelling capacities. Simultaneously, the input thermal energy begins to rupture the peripheral, lower-energy aliphatic chains of the organic binder, where initial pyrolytic cracking results in the evolution of minor traces of water vapor, light organic fractions, CO, and CO_2 .

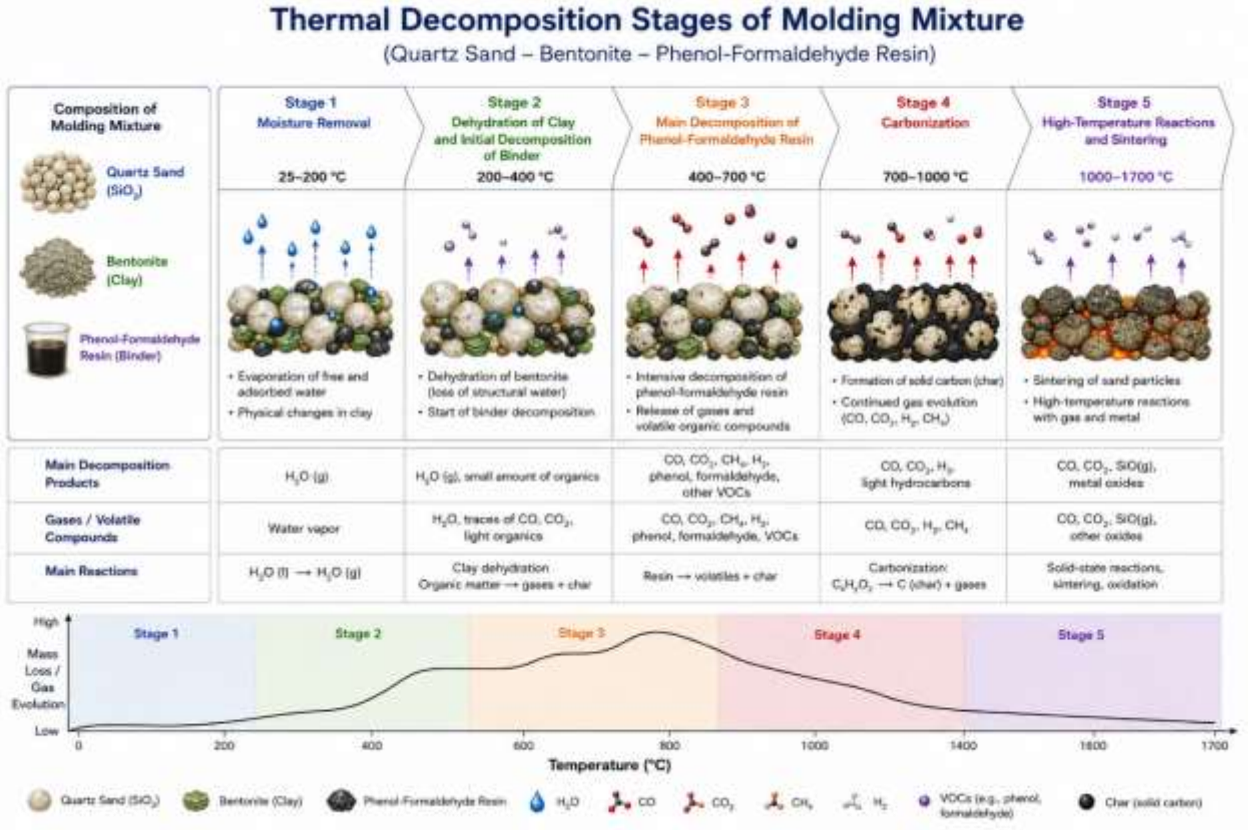
3. Stage 3: Main Decomposition of Phenol-Formaldehyde Resin (400–700◦C) This stage represents the most volatile, reactive, and critical zone of the entire metallurgical simulation. The intensive pyrolytic destruction of the organic binders is primarily concentrated within the broader 200–600◦C range, where the corresponding DTG curve exhibits a sharp, dominant endothermic peak representing a substantial mass loss of 57.6%. At this thermodynamic threshold, the core aromatic ring structures and methylene bridges ($-CH_2-$) comprising the resin network undergo severe macromolecular cleavage, rapidly breaking down into high-velocity gaseous phases. The highly active evolution of methane (CH_4), carbon monoxide (CO), carbon dioxide (CO_2), molecular hydrogen (H_2), and complex volatile organic compounds (VOCs), alongside free phenol and formaldehyde monomers, was clearly confirmed within this temperature zone.

4. Stage 4: Carbonization (700–1000◦C) Within the higher temperature landscape of 700–1000◦C, a definitive mass loss of 12.8% was recorded. At this juncture, the majority of the low-molecular-weight volatile fractions have completely escaped the matrix, causing the remaining carbon-rich organic residue to undergo deep carbonization, thereby transforming into a highly stable, solid carbonaceous skeleton known as coke char. Although the overall rate of mass loss slows down considerably compared to Stage 3, the continuous thermal cracking of the residual char ensures a steady, prolonged release of CO, CO_2 , H_2 , and light short-chain hydrocarbons.

5. Stage 5: High-Temperature Reactions and Sintering (1000–1700◦C) The final extreme thermal boundary induces a localized mass loss of 2.1%, bringing the cumulative total mass loss of the reactive components to 74.8%. In this extreme zone, the organic components are entirely spent.

The inorganic quartz sand grains experience immense thermal stress, leading to prominent surface microcracking and solid-state phase transformations, such as the conversion of quartz into cristobalite.

Concurrently, partial sintering of the ultra-fine sand particles is triggered. At the immediate metal-mold interface, high-temperature chemical redox reactions between the liquid metal and the mold atmosphere provoke the distinct evolution of gaseous silicon monoxide (SiO(g)) and various metal oxide vapors.



Thermal Decomposition Stages of Molding Mixture

(Quartz Sand – Bentonite – Phenol-Formaldehyde Resin)

Composition of Molding Mixture	Stage 1 Moisture Removal 25–200 °C	Stage 2 Dehydration of Clay and Initial Decomposition of Binder 200–400 °C	Stage 3 Main Decomposition of Phenol-Formaldehyde Resin 400–700 °C	Stage 4 Carbonization 700–1000 °C	Stage 5 High-Temperature Reactions and Sintering 1000–1700 °C
Quartz Sand (SiO_2) Bentonite (Clay) Phenol-Formaldehyde Resin (Binder)	• Evaporation of free and adsorbed water • Physical changes in clay	• Dehydration of bentonite (loss of structural water) • Start of binder decomposition	• Intensive decomposition of phenol-formaldehyde resin • Release of gases and volatile organic compounds	• Formation of solid carbon (char) • Continued gas evolution (CO, CO_2, H_2, CH_4)	• Sintering of sand particles • High-temperature reactions with gas and metal
Main Decomposition Products	H_2O (g)	H_2O (g), small amount of organics	CO, CO_2, CH_4, H_2, phenol, formaldehyde, other VOCs	CO, CO_2, H_2, light hydrocarbons	CO, CO_2, SiO(g), metal oxides
Gases / Volatile Compounds	Water vapor	H_2O, traces of CO, CO_2, light organics	CO, CO_2, CH_4, H_2; phenol, formaldehyde, VOCs	CO, CO_2, H_2, CH_4	CO, CO_2, SiO(g), other oxides
Main Reactions	H_2O (l) → H_2O (g)	Clay dehydration Organic matter → gases + char	Resin → volatiles + char	Carbonization: $C_xH_yO_z$ → C (char) + gases	Solid-state reactions, sintering, oxidation

Gas chromatographic analysis utilizing a Thermal Conductivity Detector (TCD) provided precise quantification of the total gas volume released during the process: Carbon Dioxide (CO2): 35.6%

Carbon Monoxide (CO): 25.4%

Methane (CH4): 15.8%

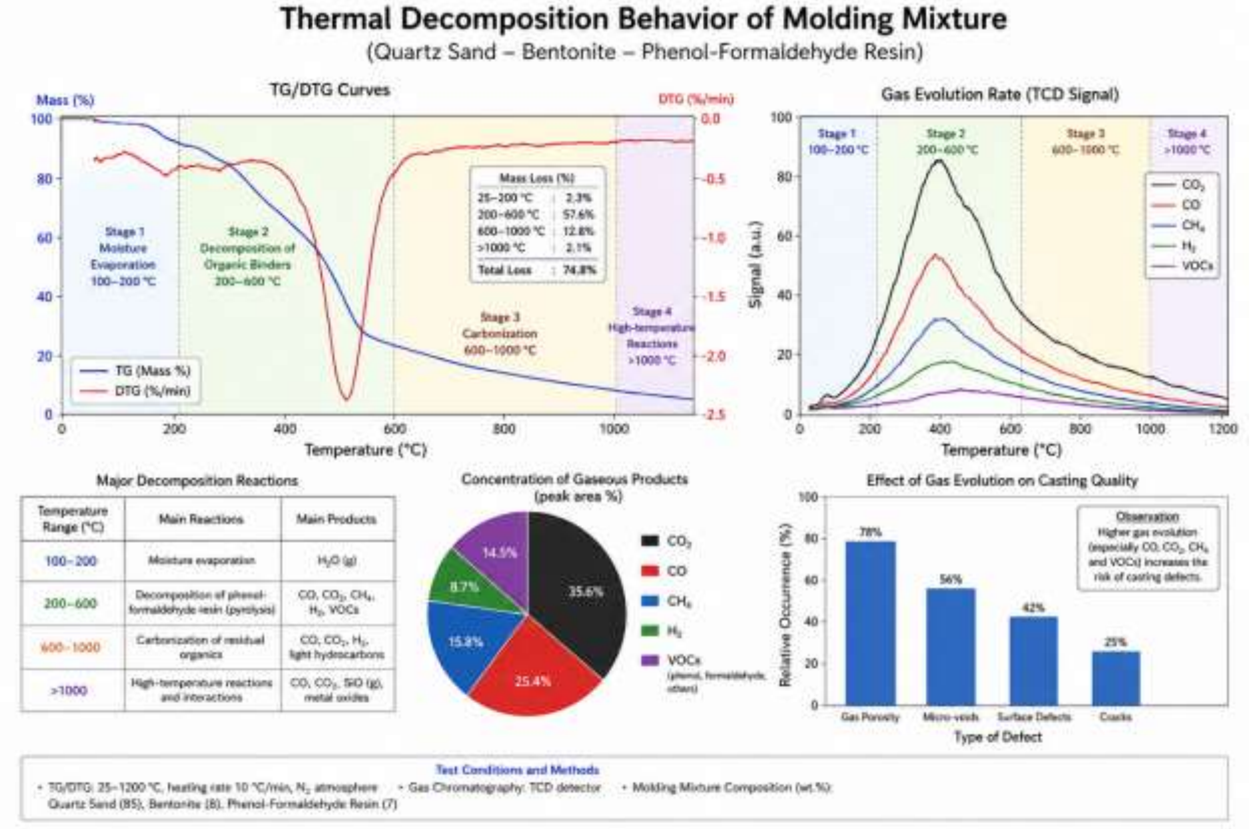
Volatile Organic Compounds (VOCs): 14.5%

Hydrogen (H2): 8.7%

When evaluating the correlation between the distribution of these evolved gases and the final casting imperfections, it was confirmed that the rate of gas generation acts as the primary driver for metallurgical failure. The rapid accumulation of gases within the mold cavity generates a critical internal backpressure gradient, forcing these volatile phases directly into the liquid metal matrix before solidification.

This physical entrapment directly accounts for the high relative occurrence rates of specific casting defects recorded during the experimental trial operations: Gas Porosity (78%), Micro-voids (56%), Surface Defects (42%), and Hot Cracks (25%).

Consequently, it is established that optimizing the molding mixture composition, implementing thermally stable binders, and utilizing high-permeability materials can drastically suppress internal backpressure and minimize defect rates.



Thermal Decomposition Behavior of Molding Mixture

(Quartz Sand – Bentonite – Phenol-Formaldehyde Resin)

TG/DTG Curves

Mass Loss (%)	
25–200 °C	2.3%
200–600 °C	57.6%
600–1000 °C	12.8%
>1000 °C	2.1%
Total Loss	74.8%

Gas Evolution Rate (TCD Signal)

Major Decomposition Reactions

Temperature Range (°C)	Main Reactions	Main Products
100–200	Moisture evaporation	H_2O (g)
200–600	Decomposition of phenol-formaldehyde resin (pyrolysis)	CO, CO_2, CH_4, H_2, VOCs
600–1000	Carbonization of residual organics	CO, CO_2, H_2, light hydrocarbons
>1000	High-temperature reactions and interactions	CO, CO_2, SiO (g), metal oxides

Concentration of Gaseous Products (peak area %)

Effect of Gas Evolution on Casting Quality

Observation
Higher gas evolution (especially CO, CO_2, CH_4 and VOCs) increases the risk of casting defects.

Test Conditions and Methods

- TG/DTG: 25–1200 °C, heating rate 10 °C/min, N_2 atmosphere
- Gas Chromatography: TCD detector
- Molding Mixture Composition (wt.%): Quartz Sand (85), Bentonite (8), Phenol-Formaldehyde Resin (7)

Conclusion

The conducted research demonstrated that molding mixtures undergo highly complex, multi-stage thermal decomposition processes under the influence of extreme casting temperatures.

The primary and most significant mass loss (57.6%) is concentrated within the temperature range of 200–600◦C, driven directly by the pyrolytic destruction of the phenol-formaldehyde organic binder, which leads to the dense evolution of carbon dioxide (CO2), carbon monoxide (CO), and methane (CH4) gases.

It was confirmed that the physical entrapment of these high-volume gases inside the mold cavity generates a critical internal backpressure gradient, ultimately triggering structural casting defects such as gas porosity (78% occurrence rate), microvoids (56%), and various surface imperfections.

Furthermore, exposure to thermal boundaries exceeding 1000◦C was found to induce severe microcracking and permanent solid-state phase transformations within the quartz sand grains, which severely impairs the dimensional and structural stability of the mold shell.

Based on the obtained empirical results, it is established that both the metallurgical quality of the final cast components and the overall environmental safety of the foundry ecosystem can be significantly enhanced through the systematic optimization of the molding mixture composition, the integration of alternative low gas-emission binders, and the deployment of high-thermal-stability materials.

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