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Analysis of Influencing Factors on the Performance of Precision Casting Wax

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Abstract: Precision casting wax is a key material in investment casting, and its performance determines the accuracy and surface quality of the castings. This study systematically investigates the effects of filler type, dosage, and component compatibility on the fluidity, mechanical properties, thermal stability, and dimensional accuracy of a paraffin-resin filled wax system. Results indicate that sebacic acid significantly enhances the comprehensive performance of the base wax. At a 30% dosage, the rotational viscosity reaches 504.2 mPa•s, flexural strength increases to 5.02 MPa, and linear shrinkage decreases to 0.67%. Sebacic acid regulates crystallization behavior through synergistic nucleation and volume effects, with X-ray diffraction and scanning electron microscopy confirming physical mixing and good compatibility among components. Thermal analysis reveals limited impact of filler addition on thermal stability. This research provides a theoretical foundation for the formulation design and process optimization of precision casting waxes.

Keywords: Precision casting wax; suberic acid; fluidity; flexural strength; linear shrinkage rate

Introduction

Precision casting is a crucial technology for producing complex and high-precision castings. As a key material for creating wax patterns, casting wax directly influences the accuracy and quality of castings. Ideal casting wax should possess moderate fluidity, sufficient flexural strength, and low linear shrinkage. Paraffin-resin blended systems are widely used, but traditional waxes often exhibit insufficient rotational viscosity (below 50 mPa • s in molten state) and low flexural strength, making them inadequate for complex thin-walled castings. Fillers are commonly added to modify these properties. Organic acid fillers have garnered attention due to their good compatibility and unique crystallization-regulating effects. Process parameters also significantly impact wax pattern quality. Systematically analyzing factors influencing casting wax performance and revealing filler modification mechanisms are essential for optimizing formulations and enhancing quality. This study conducts an analysis based on experimental data.

1. Composition and Performance Requirements of Casting Wax

1.1 Basic Composition of Precision Casting Wax

Precision casting wax typically consists of multiple components such as base wax, resin, filler, and plasticizer. The base wax formulation employed in this study includes paraffin wax, microcrystalline wax, stearic acid, terpene resin, and candelilla wax. Among these, paraffin wax and microcrystalline wax provide the fundamental melting characteristics and formability of the wax material. Terpene resin is used to enhance the surface hardness and toughness of the wax pattern, while stearic acid serves a dual function of adjusting hardness and improving compatibility. Candelilla wax further optimizes the toughness of the system. A rational proportion of each component is essential for achieving performance optimization.

1.2 Key Performance Indicators of Casting Wax

The performance requirements of precision casting wax are primarily reflected in the following aspects. Fluidity is a critical indicator for evaluating the wax's ability to fill molds, characterized by rotational viscosity. An appropriate viscosity range ensures complete filling while preventing splashing defects. Mechanical properties mainly include flexural strength, which determines the wax pattern's resistance to deformation during subsequent processes. Dimensional stability is assessed through linear shrinkage rate, where lower shrinkage rates result in higher dimensional accuracy of castings. Thermal stability influences the wax's behavior during the dewaxing process [1]. Additionally, crystallization behavior and microstructural homogeneity are also important factors affecting overall performance.

2. Effect of Fillers on the Properties of Casting Wax

2.1 Influence of Filler Type

Different types of fillers significantly influence the properties of wax systems due to variations in their physicochemical characteristics. This study compared three dicarboxylic acid fillers—succinic acid, adipic acid, and suberic acid—which differ in carbon chain length, melting point, and polarity, leading to distinct interactions with the wax matrix. Experimental results indicate that suberic acid most notably enhances the rotational viscosity of the base wax. The base wax exhibited a rotational viscosity below 50 mPa • s at 90°C. With the addition of suberic acid, viscosity increased continuously, reaching 504.2 mPa • s at a 30% loading. In contrast, succinic acid and adipic acid resulted in considerably lower viscosities at the same loading level. In terms of flexural strength, all organic acids improved the strength of the base wax, with suberic acid demonstrating the most pronounced enhancement. The base wax had a flexural strength of 3.33 MPa, which increased to 5.02 MPa at a 40% suberic acid loading—an improvement of over 50%. This is attributed to the formation of a rigid dispersed phase by suberic acid within the wax matrix, which hinders molecular chain slippage and enhances resistance to deformation. The influence of filler type on crystallization behavior is also noteworthy. X-ray diffraction analysis revealed characteristic diffraction peaks of the base wax at 2θ values of 21.49° and 23.84°, while suberic acid exhibited multiple sharp peaks at 9.98°, 20.21°, 24.85°, 26.03°, and 29.03°. The diffraction pattern of the blended wax showed the characteristic peaks of both components without any new peaks, confirming that the mixture is purely physical with no chemical reaction. Scanning electron microscopy observations showed that suberic acid, with a rod-like morphology measuring 20–40 μm in length and 5–10 μm in width, was uniformly dispersed in the cross-section of the blended wax. The fracture surface was smooth with no obvious phase separation, indicating good interfacial compatibility between suberic acid and the base wax.

2.2 Effect of Filler Addition Amount

Filler content is a critical factor in regulating the properties of casting wax. As the suberic acid content increases from 0% to 40%, the rotational viscosity of the wax system continuously rises, demonstrating a typical filler reinforcement effect. The linear shrinkage rate exhibits a non-monotonic trend: it gradually increases within the 5%–20% additive range, peaking at 20%; beyond 20%, the linear shrinkage rate begins to decline, reaching a minimum of 0.67% at 35%. This phenomenon reflects the competitive relationship between nucleation and volume effects. At low additive levels, suberic acid particles act as nucleating agents, promoting wax crystallization and leading to increased volume shrinkage. At high additive levels, suberic acid remains in solid form throughout the preparation process, reducing the volume difference between the molten and solidified states of the wax, thereby decreasing the linear shrinkage rate. In terms of thermal properties, differential scanning calorimetry

(DSC) results show that the onset melting temperature of the base wax is 37.49°C. After adding suberic acid, the onset melting temperature of the blended wax decreases to approximately 33°C and remains stable within the 15%–40% additive range, indicating a saturation effect of suberic acid on melting behavior. The melting enthalpy decreases with increasing additive content, dropping from 105.5 J/g for the base wax to 61.28 J/g at 40% additive content, a reduction of 40%, reflecting a decrease in the proportion of meltable components in the system. Thermogravimetric analysis (TGA) reveals that the onset decomposition temperature of the base wax is 243.2°C. After adding 20% and 40% suberic acid, it decreases to 223.2°C and 234.2°C, respectively. Although thermal stability slightly declines, it still meets the requirements for precision casting processes [2].

2.3 Influence of Fillers on Crystallization Behavior and Microstructure

X-ray diffraction analysis revealed the mechanism by which suberic acid affects the crystallization behavior of the base wax. The crystallinity of the base wax was 20.38%, which increased significantly to 40%–55% after the addition of suberic acid. When the addition amount was in the range of 15%–35%, the crystallinity remained stable between 40% and 50%. When the addition amount reached 40%, the crystallinity further increased to 55.14%. This pattern indicates that at low addition levels, the number of nucleation sites provided by the filler is limited, and crystallinity rises rapidly with increasing filler content. After reaching saturation, sufficient nucleation sites are available for wax crystallization, and further increases in filler content have a diminishing effect on crystallinity. The additional contribution of the filler's own crystallization to the total crystallinity leads to another significant increase in crystallinity at high addition levels. Scanning electron microscopy observations showed that the cross-section of the base wax exhibited a scaly morphology with a rough surface and no obvious delamination, indicating good compatibility among the components. After the addition of suberic acid, the cross-section of the blended wax still displayed a scaly structure but with a smoother surface, and almost no independent suberic acid particles were observed, confirming uniform mixing of the two. This excellent compatibility is attributed to the amphiphilic structure of stearic acid: its nonpolar alkyl end is compatible with paraffin wax, while its polar carboxyl end interacts with suberic acid, acting as a bridge that reduces incompatibility caused by polarity differences.

3. The Effect of Component Compatibility on Wax Properties

Component compatibility is crucial for determining the uniformity and stability of precision casting waxes. Good compatibility ensures that all components form a homogeneous system during melt blending, maintaining microstructural stability after cooling and avoiding phase separation or precipitation. Systems with poor compatibility are prone to issues such as filler aggregation and interfacial debonding, which compromise wax pattern quality. This study employed scanning electron microscopy (SEM) and X-ray diffraction (XRD) for characterization. SEM images revealed that the fracture surface of the base wax exhibited a scaly morphology with a rough texture and no distinct layering, indicating excellent component compatibility. After adding suberic acid, the fracture surface of the blended wax retained its scaly structure but became smoother, with virtually no independent suberic acid particles observed, demonstrating uniform mixing. This high compatibility is attributed to the amphiphilic structure of stearic acid, whose nonpolar alkyl end is compatible with paraffin wax, while its polar carboxyl end interacts with suberic acid, acting as a bridging agent [3]. XRD analysis confirmed the presence of characteristic peaks from both the base wax and suberic acid in the blended wax pattern, with no new peaks formed, indicating that the mixing was purely physical without chemical reactions. This physical blending state helps preserve the inherent performance advantages of each component while enabling performance optimization through synergistic effects. It also ensures the system's stability over multiple melting-cooling cycles, which is vital for the reuse of casting waxes and process stability.

4. Influence of Process Conditions on Wax Pattern Quality

Precision casting wax is a pseudoplastic fluid, with viscosity sensitive to temperature and shear rate. The wax injection temperature is a critical process parameter; increasing temperature intensifies molecular chain movement, reduces viscosity, and enhances fluidity. Appropriately raising the temperature can improve filling capability. However, excessively high temperature leads to overly low viscosity, which may cause splashing and flow marks, while also increasing linear shrinkage rate and affecting dimensional accuracy. Studies indicate that lower wax injection temperatures facilitate rapid solidification of the wax material, reducing volumetric shrinkage. Therefore, wax injection temperature must be balanced between fluidity and dimensional stability, and optimized based on the wax formulation and casting structure. Injection pressure and shear rate directly influence filling effectiveness. Increasing injection pressure enhances flow velocity, helping to overcome flow resistance, which is particularly beneficial for thin-walled and complex structures. However, excessive pressure can easily cause splashing and residual stress, increasing the risk of deformation. Precision casting wax exhibits shear-thinning characteristics, where viscosity decreases with increasing shear rate. Numerical simulations show that when viscosity is high, merely increasing temperature is insufficient for complete filling, and it is necessary to combine it with higher injection rates. However, excessively high rates may lead to defects such as porosity [4]. In actual production, the coupling relationship between pressure, rate, and viscosity must be comprehensively considered, and high-quality wax patterns should be achieved through optimization of process parameters.

5. Performance Optimization Collaborative Mechanism

The performance optimization of precision casting wax results from the synergistic effects of multiple factors, including filler type, additive amount, component compatibility, and process conditions. Organic acid fillers regulate crystallization behavior through nucleation and volume effects, thereby influencing linear shrinkage and mechanical properties. With its moderate carbon chain length and high melting point, suberic acid not only functions as a nucleating agent but also reduces volumetric shrinkage by existing as solid particles, thereby enhancing dimensional stability. Within the 5%–20% addition range, the nucleation effect predominates, leading to increased linear shrinkage. Beyond 20%, the volume effect becomes dominant, reducing linear shrinkage to a minimum of 0.67% at 35% addition. Component compatibility is essential for maximizing filler effectiveness. The incorporation of surfactant components such as stearic acid significantly improves compatibility between components with large polarity differences, promoting uniform dispersion and preventing filler aggregation. This uniformity in microstructure directly translates to stability in macroscopic properties, ensuring consistent performance of the wax material during repeated processing and use.

Table 1 Synergistic Mechanism of Suberic Acid-Modified Paraffin-Resin Composite Wax

Action Type	Mode of Action	Impact on performance
Nucleation effect	Sebacic acid particles act as heterogeneous nucleating agents, providing numerous crystal nuclei.	Improve crystallinity and enhance flexural strength
Volume effect	Azelaic acid has a high melting point and remains solid throughout the wax preparation and molding process.	Reduce the volume difference between the molten and solidified states, and decrease the linear shrinkage rate.
Capacity expansion	Amphiphilic structure of stearic acid bridges polar and non-polar components	Improve the dispersion uniformity of fillers to prevent phase separation.
Physical Enhancement	Rigid filler particles dispersed in a wax matrix	Hinder the sliding of molecular chains and enhance mechanical properties.

Overall, the optimal precision casting wax should exhibit the following characteristics: appropriate viscosity in the molten state to ensure filling capability while preventing splashing; sufficient flexural strength at room temperature to prevent wax pattern deformation; low linear shrinkage rate to guarantee dimensional accuracy of castings; thermal stability meeting dewaxing process requirements; and good compatibility among components with uniform and stable microstructure [5]. Current experimental research indicates that when the suberic acid addition reaches 30%, the paraffin-resin filled wax achieves an optimal balance in these performance metrics, demonstrating promising application prospects.

Conclusion

The performance of precision casting wax is influenced by the coupled effects of multiple factors, including fillers, component compatibility, and crystallization behavior. With an appropriate molecular chain length and polarity, suberic acid forms strong physical interactions with the paraffin-resin matrix, establishing a stable network structure that regulates flow and mechanical properties. Its nucleation effect enhances crystallinity and flexural strength, while its volumetric effect reduces linear shrinkage. The synergistic interaction results in nonlinear changes in performance, with the minimum linear shrinkage of 0.67% achieved at a 35% addition level. Stearic acid improves compatibility and promotes filler dispersion, with X-ray diffraction confirming excellent component compatibility. Although thermal performance slightly decreases, it still meets process requirements. Comprehensive evaluation indicates that a 30% addition of suberic acid yields the optimal results.

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