STAINLESS STEEL AND SPECIAL ALLOYS INGOTS. WHICH CASTING POWDER?

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Casting powders for ingot production have evolved from generic insulating materials to highly tailored products designed for specific steel and alloy families. Early powders, largely based on fly ash, provided basic thermal insulation and surface protection for ingot casting but offered limited control over melting behavior, viscosity, and steel–slag interactions.

The introduction of stainless steel ingot casting led to new powders, characterized by controlled CaO–SiO_2–Al_2O_3 chemistry, optimized basicity, and more stable viscosity. This marked a shift toward improved lubrication, heat transfer control, and surface quality suitable for stainless steels. Further refinement resulted in products specifically optimized for stainless steels and significantly enhanced the performance of Ti-stabilized grades by limiting titanium reactions and stabilizing mold flux behavior.

The need to cast increasingly complex materials drove the development of highly specialized powders. A new casting powder with a balanced free carbon content to ensure adequate lubrication, accommodate varying solidification behavior, and minimize surface defects has been formulated for martensitic steels with higher carbon and higher liquidus temperatures.

A product has been designed for special alloys with low melting temperatures, with characteristics that enable rapid slag formation and controlled heat extraction under extreme casting conditions.

Finally, a casting powder has been formulated for nickel-based alloys. It combines a very low melting range, high basicity, and excellent fluidity to ensure immediate slag melting and stable heat transfer under tightly controlled superheat conditions required for these highly reactive alloys.

Overall, the evolution of casting powders reflects a transition from universal solutions to alloy-specific formulations, enabling higher process stability, improved surface quality, and reliable casting of advanced stainless steels and special alloys.

KEYWORDS: MOLD FLUX – STAINLESS – SUPER ALLOYS – INGOT CASTING

INTRODUCTION

The evolution of stainless steel and superalloy ingot casting reflects a continuous pursuit of structural homogeneity, extreme cleanliness, and defect-free surfaces.[1], [2] Historically, the production of these highly alloyed systems has advanced significantly from turbulent top-poured static ingot casting to highly controlled uphill (bottom) teeming systems.[2] Because stainless steels and nickel- or iron-based superalloys are exceptionally sensitive to initial solidification kinetics, thermal stresses, re-oxidation, and surface crack formation, mold fluxes (or teeming powders) have transitioned from simple thermal insulators into highly engineered interfacial slags.[1], [4], [5] These fluxes play a governing role in stabilizing the rising meniscus, controlling horizontal heat transfer, absorbing harmful non-metallic inclusions, providing lubrication, and preventing atmospheric contamination.[1], [3],

Early manufacturing of stainless and special alloys relied heavily on conventional top-pouring into static iron molds where molten metal was poured directly from the ladle nozzle down into the top of the mold; this high-velocity stream caused severe metal splashing against the cold mold walls, leading to cold shuts, scabs, and surface laminations. Furthermore, the violent turbulence exposed the alloy to atmospheric oxygen, leading to severe re-oxidation and trapped macro-inclusions.[2]

Early insulating powders were rudimentary and based on purely insulating materials such as fly ashes; they acted primarily as a dry blanket to reduce heat loss from the top surface and prevent premature crusting (bridging) at the top of the ingot.[2], [5]

To overcome the limitations of top-pouring, ingot production shifted almost entirely to uphill teeming.[1]

Molten metal enters a central trumpet, travels through refractory runner bricks, and rises smoothly from the bottom of the ingot mold. This setup eliminates splashing and creates a calm, rising meniscus. It allows the liquid alloy to rise uniformly, dramatically reducing surface defects and improving the macrostructural uniformity of the ingot. [2], [4]

This tranquil rising meniscus created the ideal environment for teeming fluxes. These fluxes were originally developed in the late fifties by Hans J. Eitel by mixing fly ashes with sodium carbonate and coke to improve the melting behavior[5]. Placed at the bottom of the mold before casting or added in bags that rupture upon initial filling, these powders melt continuously to form a liquid slag layer covering the entire cross-section of the rising metal, providing insulation and lubrication. [1], [4]

The compositional design of ingot mold fluxes has advanced in lockstep with alloy complexity. Modern formulations are engineered to overcome specific thermophysical and chemical phenomena at the ingot-mold interface.

As the liquid metal rises during uphill teeming, the molten flux at the meniscus is pushed toward the perimeter, infiltrating the narrow gap between the expanding ingot shell and the cast-iron mold wall. [1], [3]

Stainless steels and superalloys are highly susceptible to thermal cracking. Early glassy fluxes often resulted in uneven heat extraction[3], while modern ingot fluxes are formulated to precipitate specific crystalline phases (such as cuspidine, $3CaO{\cdot}2SiO_2{\cdot}CaF_2$) during cooling.[3], [5] This solid crystalline slag film increases the interfacial thermal resistance, providing a "mild" and uniform heat extraction rate that prevents longitudinal and transverse surface cracking.

The liquid portion of the slag film provides continuous lubrication, preventing the solidifying alloy shell from sticking to the ingot mold and ensuring a smooth, defect-free macro-surface.[1], [4]

The high concentration of reactive alloying elements in stainless steels (e.g., chromium, titanium) and superalloys (e.g., aluminum, titanium) poses a severe challenge to slag stability.

The interaction between molten metal and mold flux during uphill ingot teeming directly dictates the occurrence of surface, subsurface, and structural defects. Because stainless steels and superalloys possess highly distinct solidification behaviors and reactive chemistries, the specific criticalities influenced by the mold flux vary significantly by alloy class.

CASTING POWDER DEVELOPMENT

As described in the previous section, the original product for carbon steel casting was based on a mixture of fly ashes, sodium carbonate, and coke, and its aim was primarily to insulate the liquid metal bath and provide minimal lubrication to the forming metal skin. Its composition is reported in table 1.

Tab. 1 – product A

Analyte	**$\%_{w/w}$**
SiO_2	34.0 – 37.0
Fe_2O3	5.0 – 7.0
$Al2O3$	18.0 – 20.0
CaO	3.0 – 6.0
MgO	<2.0
Na_2O+K_2O	6.0 – 9.0
CO_2	4.0 – 7.0
C_{free}	17.0 – 20.0

Austenitic grades solidify entirely or primarily as austenite, which has a high thermal expansion coefficient and low high-temperature mechanical strength, leading to longitudinal cracking and surface depressions.[1], [2]
These grades are highly sensitive to thermal stress. If a mold flux forms a purely glassy film, the horizontal heat transfer rate is too rapid and uneven.
The product developed (product B in table 2) for these grades was more similar to a continuous casting powder. The addition of CaO and CaF_2 led to a higher crystallization temperature and favored the formation of a crystalline phase—specifically cuspidine ($3CaO{\cdot}2SiO_2{\cdot}CaF_2$).[3] The crystalline layer scatters infrared radiation and introduces an interfacial thermal resistance, ensuring "mild" and uniform cooling that prevents cracking. Basicity below one, combined with calibrated viscosity, ensured good lubrication, while the low amount of free carbon in the mold flux reduced carbon pickup issues.
Ferritic stainless steels exhibit rapid initial shell growth and a narrow solidification range. If the flux viscosity is too high, it fails to infiltrate this gap, leading to localized shell sticking, severe surface ripples, or even transverse tearing. [4],[6]

Tab. 2 – product B

Analyte	**$\%_{w/w}$**
SiO_2	34.5 – 36.5
Fe_2O3	5.0 – 7.0
$Al2O3$	11.0 – 13.0
CaO	30.0 - 32.0
MgO	<1.5
Na_2O+K_2O	1.0 – 3.0
F^-	2.5 – 4.5
CO_2	6.0 – 9.0
C_{free}	1.5 – 2.5

Furthermore, product B has been given a granular shape through the spray-drying process, leading to improved spreadability over the steel bath, as shown in figure 1.

Fig.1 – Powder A behavior (left) compared to powder B (right) during casting.

The presence of reducing elements, particularly titanium, in the alloys added a further complication due to the

interaction with the oxidant in the casting powder. The oxidation of titanium and its dissolution in the slag could increase the powder's solidification temperature, leading to poor lubrication and increased slag entrapment in the ingot skin.
To reduce this issue, product C (table 3) was developed by removing iron (III) oxide from the mold flux composition.

Tab. 3 – Product C

Analyte	**$\%_{w/w}$**
SiO_2	37.5 – 39.5
Fe_2O3	<1.5
Al2O3	10.5 – 12.5
CaO	32.5 - 34.5
MgO	0.5 – 2.5
Na_2O+K_2O	1.5 – 3.5
F^-	3.0 – 5.0
CO_2	4.5 – 7.5
C_{free}	1.0 – 3.0

Figure 2 shows the surface of a Ti-stabilized austenitic ingot cast with powder C.

Fig.2 – Austenitic ingot cast with powder C.

For larger ingots of standard austenitic steel and for martensitic steels, where carbon pickup was less of an issue and the liquidus temperature is higher, product D (Table 4), an evolution of product C with a higher content of free carbon, was created to improve thermal insulation and reduce the rate of liquid slag formation.

Tab. 4 – Product D

Analyte	**$\%_{w/w}$**
SiO_2	36.0 – 39.0
Fe_2O3	<1.5
Al2O3	10.5 – 12.5

CaO	31.0 - 34.0
MgO	0.5 – 2.5
Na_2O+K_2O	1.5 – 3.5
F^-	3.0 – 5.0
CO_2	4.5 – 7.5
C_{free}	3.0 – 5.0

Ferritic grades have very low carbon solubility. Even a small carbon increase can form chromium carbides ($Cr_{23}C_6$), reducing chromium available for corrosion resistance and toughness.
Stabilized grades (439, 444 with Ti/Nb additions) are particularly sensitive, as they are designed around very low carbon levels.
Carbon pickup during melting, refining, or casting can consume stabilizing elements and degrade performance.[9]
Meanwhile, austenitic low-carbon grades and duplex stainless steels are specified with C ≤ 0.03%
Carbon pickup may lead to a series of issues such as increased carbide precipitation, reduced intergranular corrosion resistance, and lower pitting and stress-corrosion performance.
Because these grades often have strict ultra-low carbon specifications, product E (Table 5), another evolution of product C, was developed without any free carbon in the formulation.

Tab. 5 – Product E

Analyte	**$\%_{w/w}$**
SiO_2	37.5 – 39.5
Fe2O3	<1.5
Al2O3	10.5 – 12.5
CaO	32.5 - 34.5
MgO	0.5 – 2.5
Na_2O+K_2O	1.5 – 3.5
F^-	3.0 – 5.0
CO_2	4.5 – 7.5
C_{free}	<1.0

Superalloys contain high concentrations of highly reactive elements like titanium (Ti) and aluminum (Al) to form strengthening phases.[7], [8]
These elements can cause chemical degradation of the flux, scum formation, and macrostructural segregation. The rapid accumulation of Al_2O_3 and TiO_2 into the slag layer causes a catastrophic shift in its thermophysical properties. The slag's viscosity surges, its melting point climbs, and it forms a thick, crusty "scum" at the meniscus. This completely destroys lubrication, leading to severe ingot surface tearing, deep slag patches, and altered alloy chemistry at the ingot rim.
A completely different product (product F, table 6) was developed for these alloys. The mold flux basicity is significantly increased, typically exceeding 1.15, which decreases the activity of silica in the slag and reduces its reactivity with the reducing elements.
Furthermore, the low viscosity and melting temperature ensure improved lubrication even for alloys with a low liquidus temperature, improving surface quality.
The very low free carbon in the composition finally avoids carbon pickup and recarburization issues.

Tab. 6 – Product F

Analyte	$\%_{w/w}$
SiO_2	28.0 – 31.0
Fe_2O3	<1.0
Al2O3	7.0 – 9.0
CaO	35.0 - 37.0
MgO	<1.5
Na_2O+K_2O	6.5 – 8.5
F^-	6.0 – 8.5
CO_2	9.5 – 12.5
C_{free}	0.5 – 1.5

Figure 3 shows examples of the different surfaces for these ingots cast with powders E and F.

Fig.3 – Surface of superalloys ingots cast with powder E (left) compared to powder F (right).

CONCLUSIONS

The development of mold fluxes for ingot casting has closely followed the increasing complexity of the steels and alloys produced. Materials that were initially intended primarily for thermal insulation have progressively evolved into engineered products designed to balance heat transfer, lubrication, and slag stability.
As the range of cast grades expanded, the requirements imposed on casting powders became increasingly specific. Differences in alloy chemistry, solidification behavior, susceptibility to cracking, and sensitivity to contamination have made tailored flux formulations essential for achieving consistent ingot quality.
The continued development of advanced stainless steels and special alloys is expected to increase the importance of specialized mold fluxes further. Close collaboration between steel producers and flux manufacturers therefore remains a key factor for supporting product quality.

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