
RESOURCE
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Technology of Melting an Invar in an Induction Furnace

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Abstract—A process of melting a 32NKD superinvar alloy from industrial wastes in a 1100-kg FS (core-free) induction furnace is developed. The preparation of a charge, namely, fraction composition, oxidation, the content of harmful impurities, and a method of charging, is considered in detail to ensure the maximum resistance of a crucible and to optimize melting. The methods of decreasing the height of the meniscus that forms on the melt surface because of the specific features of induction heating and the related features of slag formation are analyzed.

Keywords: induction heating, technology of melting, remelting of industrial wastes, inductor, crucible

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INTRODUCTION

A 32NKD precision alloy, which is a superinvar with a linear thermal expansion coefficient (LTEC) of $1.0 \times 10^{-6} \text{ K}^{-1}$, is used to produce high-precision device elements, which must have constant sizes in the climatic temperature range from -60 to 100°C . Moreover, this alloy is used to produce high-precision shaped sections, precision-alloy strips with a given LTEC, and rods 100–150 mm in diameter. The chemical composition of the 32NKD alloy (GOST 10994–74) is as follows (wt %): $\leq 0.05 \text{ C}$, $\leq 0.2 \text{ Si}$, $\leq 0.4 \text{ Mn}$, $31.5\text{--}33.0 \text{ Ni}$, $\leq 0.015 \text{ S}$, $\leq 0.015 \text{ P}$, $3.2\text{--}4.2 \text{ Co}$, $0.6\text{--}0.8 \text{ Cu}$, and Fe for balance.

The melting temperature of the 32NKD alloy is 1450°C .

The recommended heat treatment of articles made of this alloy is water quenching from $830\text{--}850^\circ\text{C}$, tempering at $305\text{--}325^\circ\text{C}$ for 1 h, and slow furnace cooling.

To improve the strength characteristics, metallurgists subject 32NKD alloy articles to cold plastic deformation and subsequent low-temperature treatment. After this treatment, the article surfaces are polished and the material acquires resistance to atmospheric corrosion. The articles made of this alloy and intended for operation in aggressive media are coated with a protective layer [1, 2].

The 32NKD invar is mainly produced by remelting industrial wastes in induction furnaces. The following materials are usually used for its production: N-0 electrolytic nickel; armco iron with at most 0.0005% lead, 0.005% tin, a total oxygen and nitrogen content of 0.004%, and the minimum sulfur and phosphorus contents; ferrosilicium with at least 65% silicon and

crystalline silicon (at least 90% Si); nickel–magnesium master alloy; ferromolybdenum with at most 0.01% lead, metallic molybdenum or its wastes, and nickel–magnesium master alloy; metallic chromium and ferrochromium better than Kh-98 and FKh010, respectively; K-2 cobalt; A-7 aluminum; MR-2 metallic manganese; cathode copper or nickel–copper master alloy; ferrotitanium, metallic titanium, or its wastes; silicocalcium or metallic calcium; and ferroboron and boron-containing master alloy.

The physical and magnetic properties of the 32NKD alloy are as follows [3]:

| | |
|---|-------------------|
| Electrical resistivity ρ , $\Omega \text{ m}$ | 0.80 |
| Elastic modulus E , 10^{-1} N/mm^2 | 15000 |
| Thermal conductivity λ , 10^{-2} W/(m K) | 0.125 ± 0.017 |
| Coercive force H_c , A/m | 12.73 |
| Magnetic susceptibility m , mH/m | 0.78 |
| Maximum magnetic susceptibility m_{max} , mH/m | 5.52 |
| Remanent magnetization B_0 , 10^{-4} T | 4700 |
| Induction in a field of 8 Oe $B_{8\text{Oe}}$, 10^{-4} T | 3700 |

To make high-quality steels by remelting industrial wastes, metallurgists usually apply induction crucible furnaces without a core. Such a furnace consists of a cylindrical melting crucible made of a refractory material and placed in the cavity of an inductor connected to an ac power supply. A metallic charge is loaded into the crucible, absorbs electric power, and melts. The primary winding of the furnace is the inductor through

Table 1. Recommendations for the use of a refractory dry mass for the lining of a crucible for melting various metals

| Type of melt | Base of lining mass | | | | |
|------------------------------|---------------------|--------------------------------|---|--------------------------------------|-----|
| | SiO ₂ | Al ₂ O ₃ | Al ₂ O ₃ , SiO ₂ | Al ₂ O ₃ · MgO | MgO |
| Cast iron | × | — | — | — | — |
| Cast steel | × | — | — | — | — |
| Steel and high-quality steel | — | — | — | × | × |
| Ferroalloys (FeMn; FeCr) | — | — | — | × | × |
| Nickel and nickel alloys | — | × | — | × | — |
| Copper and copper alloys | — | — | × | — | — |
| Aluminum and aluminum alloys | — | × | × | — | — |

which an alternating current passes, and the secondary winding is the metal to be melted in the crucible.

The ESPTs-6 arc-furnace plant has an induction unit with two 5.5 t/h FS (core-free) crucible furnaces to make high-quality alloys R9, Kh9K15M, 32NKD, 20NG, and 45N from wastes. The technical characteristics of the FS furnace are given below. The furnace capacity is 1100 kg. An aspiration plant is mounted above each furnace to remove furnace gases. The induction coil is made of copper and equipped with a water-cooling system. The coil is surrounded by cast iron stacks, which create a directional magnetic field and absorb the energy induced by the thermal expansion of the induction turns.

The plant is equipped with a hydraulic furnace inclination system for metal tapping. The in-plane furnace sizes are 4840 × 3600 mm and the height is 5570 mm.

Technical characteristics of the FS induction crucible furnace

| | |
|---|---------|
| Maximum furnace capacity, kg | 1100 |
| Voltage, V | |
| supply main | 600 |
| generator circuit | 1500 |
| contour circuit | 2000 |
| Inductor current frequency, Hz | 250 |
| Average melting time (1030-kg charge), min | 37.9 |
| Specific electric power consumption, kWh/t | 590–600 |
| Maximum output, t/h | 1.7 |
| Metal tapping temperature, °C | 1650 |
| Heating rate for overheating by 100°C and maximum charge of crucible, K/min | 46.1 |

| | |
|---|------|
| Heat losses of furnace at closed cover, kW | 52 |
| Heat losses of open melt surface, kW | 167 |
| Crucible diameter, mm | 535 |
| Average charge depth in crucible, mm | 676 |
| Total crucible depth, mm | 875 |
| Nominal crucible wall thickness (ceramic plus insulation), mm | 90.0 |
| Static frequency converter power, kW | 1000 |
| Installed transformer power, kW | 500 |

The lining of the crucible in melting a 32NKD alloy was based on Al₂O₃ · MgO, 500 kg of which was used to line one crucible. The lifetime of the crucible depends on the periodicity of operation of the induction unit and is at least 120 heats. Recommendations for using the lining material for induction furnace crucibles are given in Table 1.

Isolation materials in the form of plates are formed according to the furnace crucible radius and sizes.

The developed process of making a 32NKD alloy in FS furnaces includes the following periods (melting cycle is relatively short, since oxidation and reduction periods, which are characteristic of steelmaking in electric arc furnaces, are absent).

CHARGE PREPARATION

A charge for a furnace should be composed with allowance for its fraction composition, i.e., the piece sizes for rational charging into a crucible. It should be noted that insufficient specific power is generated in small charge pieces, which leads to an increase in the melting time and the electric power consumption. It is known that the lower the current the frequency, the larger the penetration depth and the lower the power consumption.

A charge should not be strongly oxidized, since the electric contact between individual pieces is poor and eddy currents are closed in every piece, which increases the melting time and the specific electric power consumption. The melting time substantially depends on the quality of charge packing: the denser the charge packing, the faster the melting of charge and the lower the consumed energy.

CHARGING AND MELTING

Before charging, a crucible is brought into a working state. A fine charge is placed on the crucible bottom to weaken the impacts of large pieces, and a small amount of a slag, ferromanganese, and ferrosilicium is loaded to prevent a metal from oxidation. Refractory ferroalloys, the melting temperatures of which are higher than those reached in the crucible, are also placed at the bottom. In this packing, these ferroalloys begin to dissolve right after the appearance of the first portions of a melt.

The largest charge pieces should be placed at the crucible walls at the two-thirds of the inductor height for the magnetic lines of force to intersect the maximum cross-sectional area of a piece. The remaining part of the charge should be loaded at the maximum possible packing density up to the two-thirds of the height at the center of the crucible and at a lower density above this point. The crucible should not be filled above the inductor level, since the pieces lying above the upper inductor level are not intersected by the lines of force and are mainly heated via heat conduction from lower pieces and hinder the motion of the charge down in melting.

The refractory components are arranged in the hottest crucible zone, namely, along the periphery of its lower third. Large charge pieces are placed to the top of the crucible. If additional charging should be performed, less refractory materials are to be used for it. After the end of charging, the furnace should be closed by a cover (roof) and be turned on to reach the maximum power (1000 W) and, hence, the maximum melting rate.

Short circuits, which cause voltage jumps in the inductor circuit, can appear between charge pieces at the beginning of melting; therefore, melting should be started at a slightly lower source power. The power supply can be switched on the maximum power after voltage jumps terminate.

The charge begins to melt at half the inductor height near the crucible walls and then propagates gradually throughout the volume. The motion of the charge down to the melt is hindered by the bridging of charge lumps, which can result in local melt overheating, the loss of alloying elements, melt splashes, and a

damage of the crucible lining. To eliminate bridging, the charge should be periodically moved in melting.

The following standard slag mixture is used to build up slag during melting and refining: 65% ground lime, 20% magnesite powder, and 15% ground fluorspar. Fluorspar or spent fluxes after ESR are used to dilute slag, and a mixture of lime and a magnesite powder is used to thicken slag if necessary.

When the charge melts and a melt forms, slag-forming materials are added to the crucible in the amount that ensures complete covering of the metal by slag. Partial opening of the melt surface is allowed but not recommended in melting the charge. After complete melting of the charge and heating of the metal to 1500–1520°C, the slag is poured off and a new slag is made from a standard mixture. As follows from the results of experimental heats, the average time of melting the charge was at most 38 min.

Induction melting is characterized by electrodynamic circulation of a metal, which causes the formation of a convex meniscus on the melt surface; as a result, the slag flows to the edges of the crucible and opens its surface. When the meniscus height increases, the amount of slag should be increased to cover the metal. The slag temperature decreases under these conditions, since slag is only heated via contact heat transfer from the metal during induction melting. In turn, a decrease in the slag temperature decelerates chemical reactions and, hence, increases the melting time. In addition, a cold and viscous slag does not create conditions for the removal of sulfur and phosphorus from a melt, and a high amount of slag and a high metal velocity cause rapid wear of the crucible lining. The meniscus height can be decreased by decreasing the introduced power, which increases the melting time. The most widely used method for decreasing the meniscus height is to locate the upper edge of the inductor slightly below the bath surface. In this design of the plant, the metal surface can be almost flat. To achieve a flat melt surface, the inductor is to be sectioned and its upper section is to be turned off after melting the charge. In furnaces with a low location of an inductor, melting is performed when a charge is thoroughly moved down for a meniscus not to form and the meniscus height to be as small as possible.

REFINING

The time of pouring the slag is taken to be the beginning of refining. In this period, silicon, manganese, and phosphorus are oxidized and pass to the slag. This slag should be removed to avoid the reduction of phosphorus to the melt. A new slag is then formed, and its deoxidation is performed by powdered or fragmented silicocalcium and 75% ferrosilicium. The formation of a new slag promotes more complete removal of excess carbon, phosphorus, and sulfur

from the melt and decreases the heat losses from the metal surface. For combined deoxidation, 4–6 kg/t brocalc (mixture of aluminum oxides and lime) should be placed on slag and powdered silicon-containing deoxidizers should be introduced after the burning of brocalc. The assimilation of silicon by a metal is about 50%.

Manganese and ferrosilicium were introduced after slag clarification (8–10 min after the introduction of powdered deoxidizers into the melt). The metal was deoxidized by a nickel–magnesium master alloy and silicocalcium 5–8 min before tapping. Pouring into ingots was performed from above. The average chemical composition of the 32NKD invar made according to the developed technology is as follows (wt %): 0.02 C; 0.17 Si; 0.36 Mn; 0.006 S; 0.003 P; 0.02 W; 0.06 Cr; 32.27 Ni; 0.02 Mo; 0.7 Cu; 0.01 Nb; 3.71 Co; 62.6 Fe; and traces of V, Ti, and Al.

CONCLUSIONS

The following results were obtained after pilot heats of a 32NKD invar alloy according to the developed technology and proper labor organization: the capacity of the furnace at 1030 kg charge was 1.7–1.85 t/h at a specific power consumption of 670–680 kWh/t.

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