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INVESTIGATION OF MICROSTRUCTURE OF HIGH-MANGANESE STEEL, MODIFIED BY ULTRA-DISPERSED POWDERS, ON THE BASE OF COMPOUNDS OF REFRACTORY METALS

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high-manganese steel, modification, titanium oxycarbonitride, cooling rate, crystal growth.

ABSTRACT

The paper presents the results of investigation of micro structural parameters of cast and quenched high-manganese steel depending on the amount of introduced titanium oxycarbonitride as well as on cast steel cooling rate. The main part of the work contains the experimental data in the effect of modification on average size and microhardness of austenite grain, on amount, average size and density of distribution of the excessive phase as well as its qualitative chemical composition. Generalization of the obtained experimental data allowed to reveal regularities of structure forming for high-manganese steel modified by titanium oxycarbonitride. The final part of the paper includes formulated conclusions as well as recommendations on the most rational amount of introducing modifier.

Introduction

High-manganese steels containing more than 9% of Mn are used in the industry as the alloys characterized by a row of unique properties, e.g. high wear resistance in combination with high ductility. It is possible due to the fact that steel structure consists of austenite able to deformation twinning under the effect of dynamic and/or static loads in wearing surface [1–11]. Hadfield steel manufactured in accordance with GOST 978-88 is considered as a classic wear-resistance high-manganese steel. Additional alloying of high-manganese steel by chromium, vanadium, boron, nitrogen and other elements is used to provide the high complex of operating properties, including abrasive wear without high contact loads. It allows to rise abrasive wear resistance with simultaneous keeping of impact abrasive resistance [12–18]. Essential influence of alloying appears in variation of austenite grain size and excessive phase. In addition, the alloying elements influence on morphology of the secondary phase that is extracting along the boundaries of austenite grains [19–23]. This is the base of suggestion that operating properties of the high-manganese steel can be effected by modification in the case when it will have influence like alloying has. This paper presents the results of investigations of the effect of titanium oxycarbonitride as powder modifier (TOPM) that is introduced in the melt in different amounts (from 0.14 to 0.68% of melt mass). The effect of melt cooling rate in the temperature range of crystal growth is also considered; it varies from 4.5 to 25 °C/s.

Examination of the effect of internal modification by ultra-dispersed powder on structure and phase composition of the Hadfield high-manganese steel is the aim of this work.

Material and technique of investigation

Experimental alloys for examination of their structure and properties have been melted in the IST-006 induction furnace with basic lining.

Heat treatment of the samples has been conducted in oxidized medium. Heat treatment procedure was based on water quenching from the temperature 1100 °C.

Hadfield steel modification has been done by titanium oxycarbonitride as powder modifier (TOPM).

Standard samples with dimensions 35×35×10 mm have been used for researches. The alloy has been cast in moulds of different types: dry and wet sand loam moulds as well as in metal mould, in order to realize different cooling rates. Each mould was used for obtaining of four experimental samples. Variation of metal temperature has been registered using molded tungsten-rhenium thermocouple, while the measurement results have been recorded via LA-50USB sensor with 50 Hz frequency for each channel.

Chemical composition of the samples has been determined by SPECTRMAXx spectrometer.

Grain size measurement and quantitative analysis of microstructure have been conducted through optical microscope Axio Observer, using the program Ticsomet Standard Pro in accordance with GOST 5639–82. Polished sections for microanalysis have been prepared according to the standard technique via pressing of samples in “Transoptic” resin at the automatic press Simplimet 1000 in the sample preparation line of Buechler company.

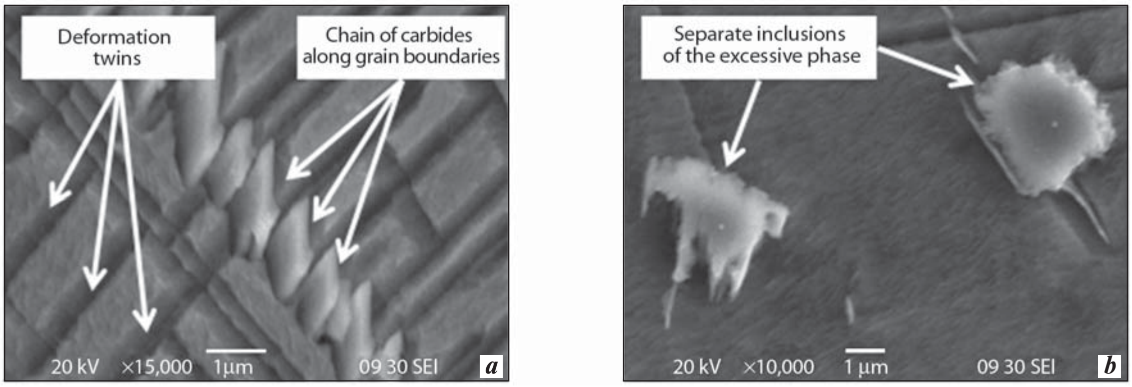


Fig. 1. Excessive phase of high-manganese steel modified by 0.41 % (mass.) of TOPM: along grain boundaries (*a*) and inside austenite grains (*b*)

Table 1. **Chemical composition of the basic alloy,%**

C	Si	Mn	S	P	Cr	Al
1,2	0,9	12,4	0,024	0,033	0,1	0,05

To examine microstructure, surface of polished sections has been subjected to pickling in the mixture of concentrated nitric and hydrochloric acids (HNO_3 — 65%, HCl — 35%) via dipping of polished surface in the bath with reagents. These investigations have been done by the Center of Collective Usage of the Scientific and Research Institute of Nanosteels at the Nosov Magnitogorsk State Technical University.

Microhardness has been determined by Buechler Mikromet hardness measuring device in accordance with GOST 9450-60 by the method of impression of a diamond pyramid having the angle 136° between the opposite planes for load loading duration equals to 1000 g and 10 s respectively.

Obtained results

The passed experiments included TOPM modification inside the mould. Cast billets having the same and permanent chemical composition (see **tab. 1**) were used as charge material. The amount of powder modifier introduced in the casting mould during experiments was varied in the range 0.14–0.68% of the mass of casting melt; finally it led to increase of titanium concentration in castings from 0.011 to 0.025%.

Microstructure of castings in cast state is presented by the grains of solid solution and excessive phase that was extracted along the boundaries of austenite grains as a carbide chain. Size of these grains does not exceed 0.5–2.0 μm that corresponds to the distance between strips of deformation twins of adjacent austenite grain (**fig.1, *a***). Excessive phase is also extracting uniformly inside austenite grains as round inclusions with diameter 2–10 μm (**fig. 1, *b***).

Qualitative X-ray microanalysis (see **fig. 2, *a*, *b***) displays that excessive phase is presented by manganese-alloyed cementite, as it was considered in previously mentioned works. However, it should be mentioned that carbides contain silicon (up to 1.0%). Such type of the excessive phase is extracted at any amount of introduced modifier.

In the case of low content of the introduced modifier (up to 0.3%, mass.), the structure of high-manganese steel is characterized by extraction of phosphide eutectics with size 2–8 μm (**fig. 2, *c, d***), in addition to manganese-alloyed cementite. If amount of introducing modifier exceeds 0.4% (mass.), several additional types of excessive phase, including carbides (**fig. 2, *e, f***) and carbonitrides (**fig. 2, *g, h***) are extracted together with cementite and phosphide eutectics. They contain (in addition to ferrum) also titanium, chromium, manganese.

Variation of the total amount, average diameter and density of distribution of excessive phases (amount of inclusions on 1 mm^2) from mass of introducing modifier is characterized by non-linear features.

Amount of excessive phase

Dependence between total amount of excessive phase and degree of modification (amount of introduced modifier) in cast samples has extremal features. Introduction of a modifier in the melt (up to 0.4%, mass.) leads to decrease of the amount of this phase from 5 to 3%, from 3.0 to 1.5% and from 2.5 to 1.3% at the cooling rate 4.5, 8.9 and 25 °C/s respectively. Additional increase of the amount of introducing modifier leads to enlargement of content of the excessive phase in the structure from 3 to 4%, from 1.5 to 3.0% and from 1.4 to 2.4% respectively for the cooling rates of alloys during crystallization equal to 4.5, 8.9 and 25 °C/s (see **fig. 3**).

Heat treatment of samples leads to partial dissolution of the excessive phase, while its content in modified samples becomes appr. 1%, independently to cooling rate in the temperature range of crystallization.

Average size of the excessive phase

Cooling rate during crystallization has the substantial effect on the average size of the excessive phase. Low rate (4.5 °C/s) is characterized firstly by sharp increase of the average diameter from 3 to 5 μm (at introduction of 0.14% (mass.) of modifier), and then by decrease of the average diameter to 2.5 μm at rise of TOPM amount up to

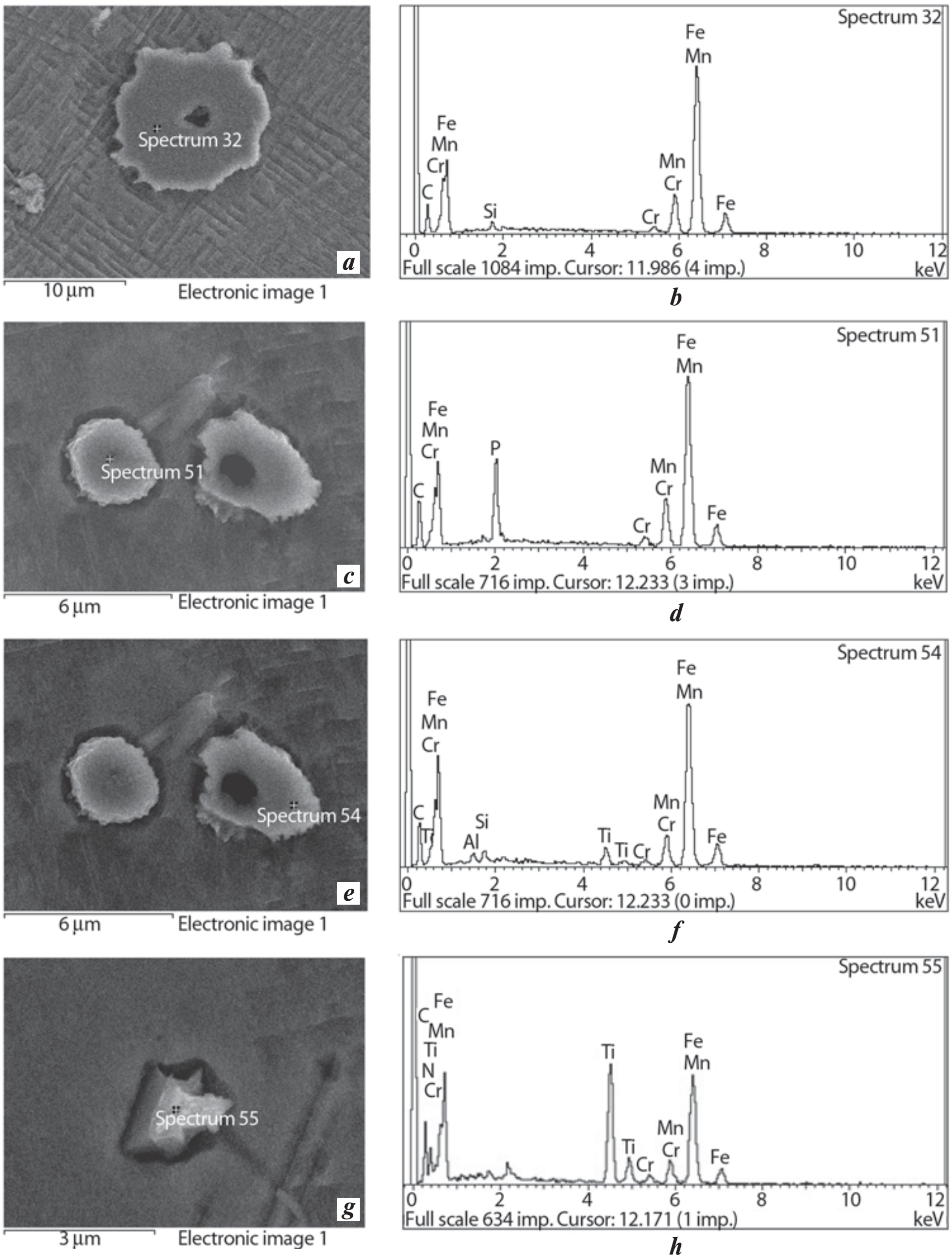


Fig. 2. The results of X-ray microanalysis of the excessive phase: image (*a, c, e, g*) and energy-dispersed spectrum (*b, d, f, h*)

0.4% (mass.). Additional increase of the amount of modifier leads to rise of the average diameter of particles to 3.0–3.3 µm.

If we introduce the corresponding amount of modifier in the alloy and if the metal is subjected then to crystallization with the rate 8.9 °C/s, we can observe the following relationship: increase of the average size of inclusions to 3.3 µm, its lowering to 1.8 µm after introduction of TOPM amount equals to 0.4% (mass.) in the melt and its consequent rise to 3–4 µm. In this case the authors observed less distinct oscillating features of variation of the average size of the secondary phase- in comparison with the actual castings with the cooling rate 4.5 °C/s in the temperature range of crystallization.

Increase of the melt cooling rate during crystallization up to 25 °C/s equalizes the effect of the amount of added modifier on the average diameter of the excessive phase practically completely. It leaves on the level 3.0–2.7 µm (**fig. 4**).

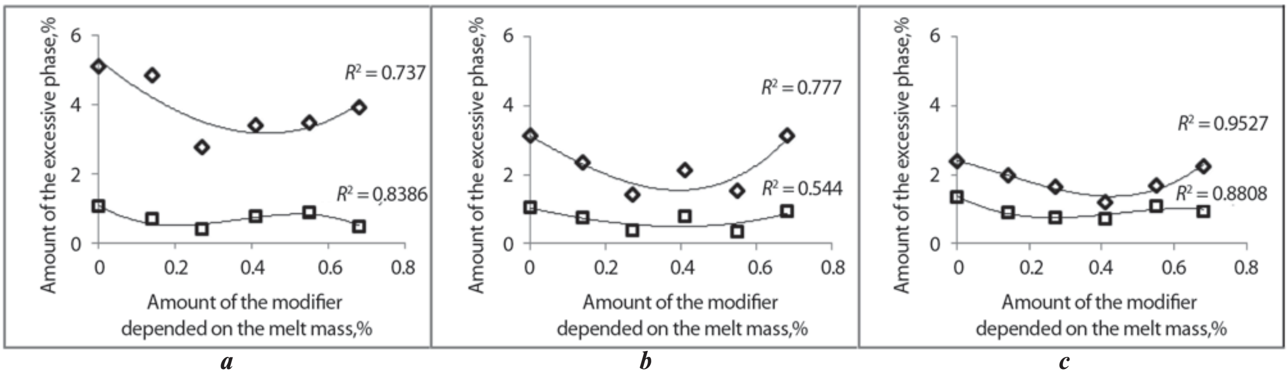


Fig. 3. Dependence between the amount of excessive phase and the amount of introducing modifier at the cooling rate in the temperature range of crystallization equal to 4.5 °C/s (*a*), 8.9 °C/s (*b*) and 25 °C/s (*c*), ◊ — in cast condition; □ — in heat treated condition

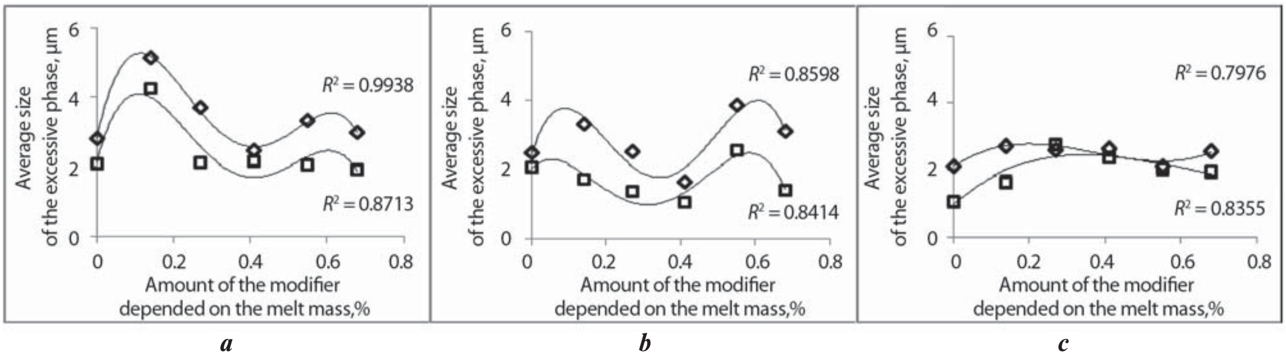


Fig. 4. Dependence between the average size of excessive phase and the amount of introducing modifier at the cooling rate in the temperature range of crystallization equal to 4.5 ˚C/s (*a*), 8.9 ˚C/s (*b*) and 25 ˚C/s (*c*), ◊ — in cast condition; □ — in heat treated condition

Heat treatment leads to decrease of the average size of the excessive phase, while intensification of this process is in inverse proportion to the alloy cooling rate during crystallization. Maximal decrease of grain size was observed in the samples where temperature reduces during crystallization with the rate 4.5 ˚C/s. As for the samples cast in a metal mould, and containing more than 0.3% (mass.) of modifier, their size does not decrease.

Density of distribution of the secondary phase

Variation of the density of distribution of excessive phase depending on the amount of introduced modifier and cooling rate during crystallization is also characterized by complicated features.

Introduction of modifier in the alloy, with the amount less than 0.3% of cast mass, decreases density of distribution of particles. It decreases from 4,000 to 1,700 or to 2,000, or to 2,500 units/mm² in the case of alloy cooling during crystallization with rate 4.5, 8.9 or 25 ˚C/s respectively.

Additional increase of the amount of introduced modifier leads to rise of density up to 4,000–4,200 units/mm², depending on cooling rate in the temperature range of crystallization. The higher is rate, the larger is content of modifier required to achieve maximal density of distribution of inclusions: so, maximal density of distribution of the particles of modifier was obtained during its introduction in the melt in the amount 0.4, 0.5 and 0.6% (mass.) for cooling rate values 4.5, 8.9 and 25 ˚C/s respectively.

Austenite grain size

Extremal features of variation of austenite grain size depending on the amount of introduced modifier was observed independently of cooling rate during crystallization as well as state of casting (as-cast or heat treated) (**fig. 5**).

Decrease of the average austenite grain size from 580–600 to 180–220 µm occurs just at introduction of 0.14% (mass.) of TOPM, depending on cooling rate of the alloy during its crystallization. Minimal grain size was observed in castings made of the alloy that was modified by ultra-dispersed powder in the amount 0.3–0.4% (mass.). In this case the average austenite grain size makes 150–210 µm. Rise of modifier content in the metal above 0.4% leads to increase of austenite grain size in the cast high-manganese steel. Intensity of this growth is the larger, the lower is the alloy cooling rate in the temperature range of crystallization. Thereby, introduction of 0.68% (mass.) of TOPM in the samples cooled during crystallization at low cooling rate (4.5 ˚C/s) is characterized by correspondence between austenite grain size and grain size in the samples without modifier; it makes appr. 600 µm. Increase of the melt cooling rate during crystallization to 25 ˚C/s helps to reserve fine-grained structure in castings modified by pulverized modifier in the amount 0.5–0.6% (mass.). If the amount of modifier is more than

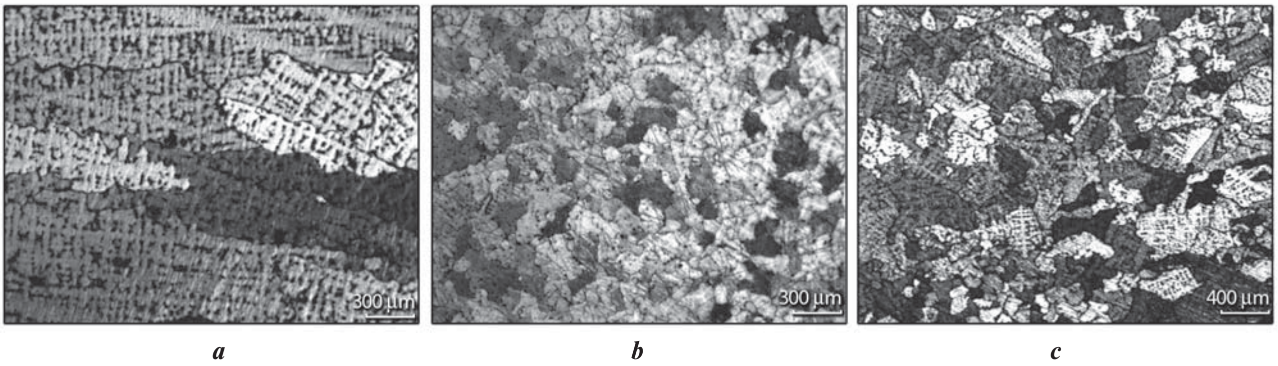
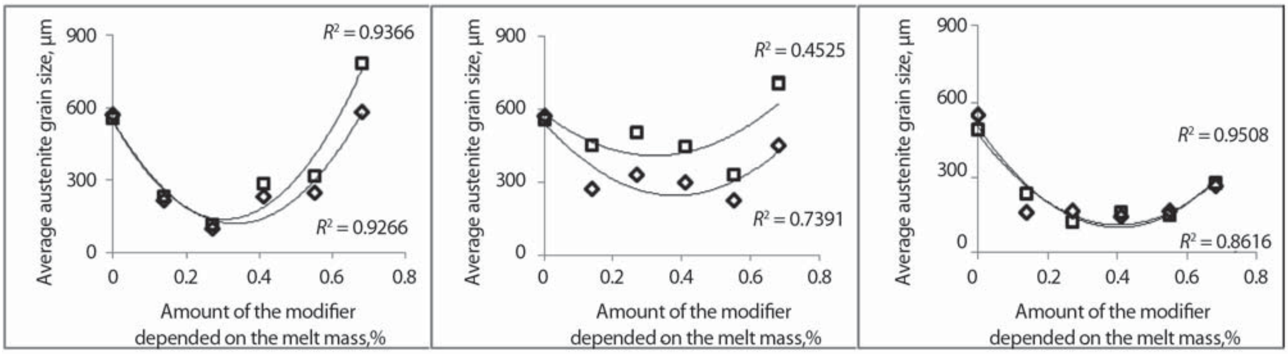


Fig. 5. Microstructure of the high-manganese steel cooled in the temperature range of crystallization with the cooling rate 4.5 ˚C/s, ×50:

a — without modification; *b* — modified by 0.41% (mass.) of TOPM; *c* — modified by 0.68% (mass.) of TOPM



a *b* *c*

Fig. 6. Dependence between the average austenite grain size density and the amount of introducing modifier at the cooling rate in the temperature range of crystallization equal to 4.5 °C/s (*a*), 8.9 °C/s (*b*) and 25 °C/s (*c*), ◊ — in cast condition; □ — in heat treated condition

0.68% (mass.) and the alloy cooling rate is the same, more coarse grain structure with the average grain size equals to appr. 220 µm is forming. Alloy cooling during crystallization with intermediate cooling rate 8.9 °C/s finalizes in obtaining of "intermediate" results: grain size during modification increases up to 410 µm and the range of fine-grained structure is restricted by modifier content as high as 0.5% (mass.) (**fig. 6**).

Increase of austenite grain size is observed during heat treatment. Extremal relationship between the grain size of solid solution and the amount of introduced modifier is saving in the quenched state: the minimal grain size was observed during introduction of pulverized modifier in the melt in the amount of 0.3–0.4% of TOPM.

Initial state of the alloy, depending on the cooling rate in the temperature range of crystallization, has the effect on the quantitative evaluation of this growth. Low rates of the alloy cooling (4.5 °C/s) and introduction of modifier in the amount 0.14–0.68% (mass.) accompany with increase of grain size after quenching from 6 to 25% respectively. At high cooling rates in the temperature range of crystallization, the opposite relationship is observed: increase of austenite grain size during heating before quenching varies from 45 to 4% respectively for the same content of introduced modifier. In the case if intermediate melt cooling rate (8.9 °C/s) is realized, the extremal relationship is observed; it is characterized by variation of increase of austenite grain size from 65 to 45% for rise of TOPM amount from 0.14 to 0.3–0.4% (mass.) and its further rise by 55% at modifier amount equals to 0.68% (mass.).

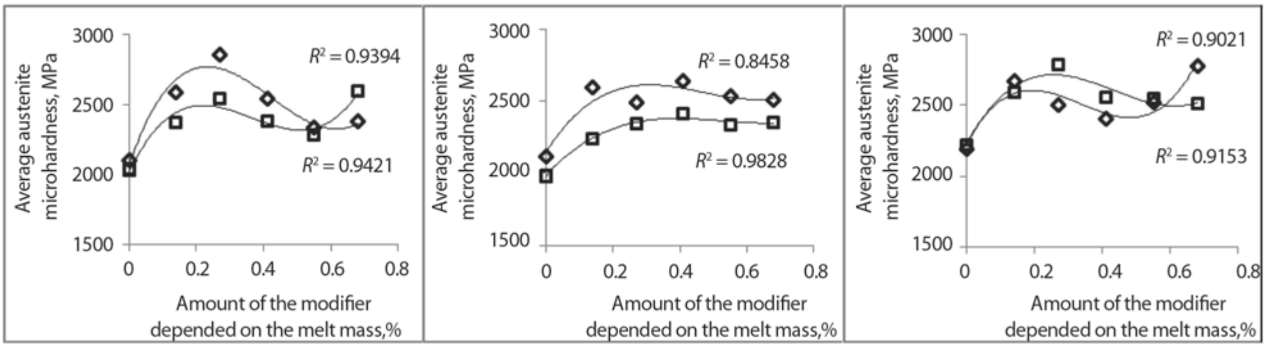
Micro-hardness

Average micro-hardness of the samples made of high-manganese TOPM-modified steel is also characterized by extremal relationship independently of the alloy cooling rate during crystallization (see **fig. 7**).

Modification of the high-manganese steel by TOPM in the amount 0.14–0.41% (mass.) leads to increase of austenite micro-hardness from 2,000 to 2,500–2,700 MPa depending on the alloy cooling rate during crystallization and its state (cast or heat-treated). Introduction of modifier in the amount exceeding 0.41% (mass.) in the melt leads to lowering of its average micro-hardness to 2,400 MPa.

Discussion of the results

Introduction of the modifier in the alloy leads to elimination of phosphide eutectics in the structure — both along the grain boundaries and as the separate in-



a *b* *c*

Fig. 7. Relationship between the average austenite microhardness and the amount of introduced modifier at the cooling rate in the temperature range of crystallization:
a — 4.5 °C/s; *b* — 8.9 °C/s; *c* — 25 °C/s (◊ — in cast state; □ — in heat treated state)

clusions. Additionally, titanium oxycarbonitride, being a center of heterogeneous origination, provides forming fine grain of austenite and creates the conditions for forming of equiaxial grains, in comparison with the basic (without modification) composition of the researched steel. This speculation is true for modifier concentrations 0.3–0.4% (mass.). In this case the structure of cast high-manganese steel is characterized by minimal amount of the excessive phase; in its turn, this phase has minimal average size and distribution density achieves the maximal value. Decrease of the amount of the excessive phase in the structure leads to rise of alloying degree of austenite, what is reflected in increase of its average micro-hardness.

Introduction of modifier in the amount less than o.3% (mass.) in the melt causes partial reservation of phosphide eutectics in microstructure, and the less is modifier amount, the more is the area of this eutectics. Total amount of the excessive phase increases in the structure, as well as its average size; in this case distribution density lowers.

Introduction of modifier in the amount exceeding 0.4% (mass.) in the melt leads to extraction of titanium-alloyed cementite as well as separate titanium carbonitrides; thereby we can conclude that such addition has alloying features. In this case, the average size of austenite grain of the high-manganese steel increases together with simultaneous increase of the amount of the excessive phase.

Cooling rate in the temperature range of the alloy crystallization has no effect on the average size of austenite grain and its micro-hardness; however, it has influence on the amount of the excessive phase: increase of the cooling rate finalizes in decrease of its amount in cast state.

Heat treatment of the high-manganese steel modified by titanium oxycarbonitride leads to a small growth of austenite grain (up to 20%) in the case of forming primary cast structure at low (4.5 °C/s) and high (25 °C/s) cooling rates of the alloy during its crystallization and in the case of introduction of modifier (0.3–0.4% (mass.)). Increase or decrease of TOPM content relating to the above-mentioned amount leads to enlargement of the average austenite grain size up to 30–40% at low and high alloy cooling rates respectively. Cooling of the alloy during crystallization with the rate 8.9 °C/s promotes larger growth of austenite grain during heat treatment from 50 to 65%, depending on the amount of introduced modifier. However, the minimal enlargement is achieved during introduction of 0.3–0.4% of TOPM from the melt mass cast in a mould.

Any distinct influence of heat treatment on the average austenite micro-hardness was not revealed. The cooling rate of a casting in the temperature range of crystallization and the amount of introduced modifier don't effect on the total amount of the excessive phase equals to 0.8–1.0%.

Conclusions

Titanium oxycarbonitride has a modifying effect on the high-manganese steel, varying such microstructural parameters as average size of austenite grain, average austenite micro-hardness, quantitative and qualitative parameters of the excessive phase.

The most rational amount of introduced modifier is in the range 0.3–0.4% (mass.). In tis case the maximal decrease of the average size of austenite grain and the amount of the excessive phase can be achieved, with simultaneous decrease of its average size and increase of distribution density in microstructure of manufactured castings. Austenite micro-hardness is also maximal at such amount of introduced modifier.

Introduction of pulverized modifier (in the amount of less than 0.3% of the alloy mass) in the melt of high-manganese steel does not lead to essential variation of microstructural parameters. It makes such consumption of modifier inexpedient, while increase of modifier amount above 0.4% does not help to form complex carbides, i.e. provides alloying of the excessive phase.

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PHYSICAL MODELING OF CAST IRON RADIATOR NIPPLE OPPOSITELY DIRECTED THREAD TURN MILLING

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Key words:

thread turn milling, simulation, lathe, single cutter, thread, eccentric workpiece fixing.

ABSTRACT

The paper covers a single cutter lathe thread turn milling simulation that significantly reduces physical testing costs. The turn milling process involves a synchronized tool (helical mill), and workpiece rotation with a radial oncoming feed through a mill and workpiece relative movement. The cutting rate occurs by the mill teeth movement over the workpiece. The machining depth in each pass varies from zero to the max value, a common milling process feature. The proposed approach simulates the process parameters through thread turning or incomplete circular groove turning of workpieces attached off-center to a lathe tooling. The proposed turn milling simulation method has reduced the number of machined referenced parts by 710 times. Accordingly, the experimental research period and cost have also been reduced. The research has revealed that the VK6M hard alloy tool life in turn milling with coolant is 50 times longer than the R6M5 HSS tool life while the useful tool life (measured as the number of parts machined within the tool life) for VK6M tools in turn milling with coolant is 50 times higher than that of R6M5 HSS tools.

Introduction

Cast iron sectioned radiators are extensively used for heating of residential and industrial high-rise buildings. The heat transfer fluid temperature in such buildings is up to 130 °C (i.e. in steam heating systems), the operating manometric pressure is up to 1.2 MPa. To ensure structural strength, the minimal test pressure for the radiators is 1.8 MPa.

Cast iron radiators were introduced over a hundred years ago. Initially they were used in steam heating, and then in centralized water heating systems. The classic MS-140 Soviet-design cast iron radiators are installed in many Russian buildings.

The cast iron radiator benefits are high reliability and long service life (over 50 years). A radiator consists of several sections made of high quality foundry iron. Radiator sections are made from high-quality cast iron and connected with nipples from malleable cast iron. Due to a large throat diameter, cast iron radiators are tolerant to poor heat fluid quality. They are suitable for contaminated water commonly used in Russian centralized heating systems. Their hydraulic resistance is low for the same reason. Thick walls and cast iron's chemical properties make the radiators corrosion-resistant. It is a huge benefit