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Issue VI, 22 November 2023
e-ISSN 2707-9481
ISBN 978-601-323-356-7
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https://doi.org/10.31643/2023.20

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On the feasibility of producing locally modified metallic materials with controlled gradient of properties

Abstract: Metallurgy and engineering endeavours to develop and implement advanced technologies to save metal and create new metallic materials with improved characteristics. These scientific and technological activities include improvements to existing materials as well as the development of new materials by various methods. One such method is the creation of iron-based materials with a gradient of properties along the cross-section, obtained by locally modifying a given volume of the formed billet by filling the structure with heat-resistant, high-strength, dispersed phases. This paper describes the course and results of a number of experiments on the formation of a gradient of properties in steel castings of various compositions, and analyses the results of experiments on the creation of such materials.
Keywords: metal melts; dispersed particles; centrifugal casting; dispersed hardening; microstructure; properties.

Cite this article as: Chumanov I., Anikeev A., Sedukhin V. (2023). On the feasibility of producing locally modified metallic materials with controlled gradient of properties. *Challenges of Science*. Issue VI, 2023, pp. 176-179. https://doi.org/10.31643/2023.20

Introduction

Traditionally, the increase of mechanical properties of used steels and alloys in ferrous metallurgy is achieved by introducing a significant amount of alloying elements into the composition of the metal (base - iron) or alloy. At present, the existing grade compositions are more than sufficient to solve most of the current industrial problems. At the same time, the analysis of the cost market for alloying elements has shown that the prices are increasing every year. For this reason, one of the main objectives of the study is to develop a theoretical and practical basis for the development of technology for obtaining metals that meet the specific requirements of the existing industry, and at the same time having a relatively low cost. The solution to this problem is the rational design of steels by providing the necessary properties only to those amounts of metal that are subjected to specific effects, which is achieved by using a small amount of properly selected ultradisperse powders (Brown, 2014; Camagu, 2020; Parashivamurthy, 2014; Sobula, 2017; Zhang, 2015), and their location in specified volumes - on the working surface or in other volumes of the product that need specific properties. In other words, this can be characterised as the creation of materials with a controlled gradient of properties (Fernandes, 2017; El-Hadad, 2011; Kiviö, 2016; Watanabe, 2009, 2017).

At present, heterogeneity of properties in the volume of metals is achieved in several ways:

- by assembling different grades of steel into a single "package" and rolling, forging or explosion welding it;

- forming cavities in steel and filling them with other material;

- creating "frames" that hold materials with different properties in one product;

- suspension exogenous or endogenous casting.

All these methods have significant disadvantages:

- there is no physical-chemical interaction between dissimilar materials. Even in the case of rolling a "package" (or explosive welding) in an inert atmosphere or vacuum, delamination is observed due to the presence of oxide films. The lack of interaction between dissimilar materials increases the likelihood of failure at the interface, making them less suitable for use in structures, machines and mechanisms. In addition, these materials do not fulfil the requirements for the properties of structural materials, i.e. it is difficult to join separate parts by welding (due to their different weldability);

- production is not technological: firstly, separate layers of materials are formed and only then joined together. The joining requires specific expensive equipment: it is difficult to create a vacuum in the rolling mill to deform the "package"; explosion welding requires separate special chambers, the use of explosives and highly qualified, trained personnel with the appropriate tolerances;

- if the mechanical "frames" holding materials with different properties in one product are destroyed, the whole product is destroyed;

- the application of existing methods of exogenous or endogenous suspension moulding is impossible because there are no mechanisms for controlling the distribution of introduced or formed particles. As a consequence, it is impossible to achieve accurate prediction of the resulting properties in different volumes, which is especially important in materials where layers must have different properties (e.g., alternating viscous and solid layers).

In the present paper, the authors present variants of the method of suspension exogenous casting during metal casting on a centrifugal casting machine in order to obtain locally modified metallic materials with a controlled gradient of properties.

Research Method

In the absence of mechanisms to control the distribution of introduced or generated particles, the authors propose to utilize the density difference between the metal to be hardened and the dispersed particles to be introduced. In a static, stationary melt (for example, in an ingot or in a ladle), due to the difference in density, particles whose density is greater than that of the metal to be hardened move downwards (under the action of gravity), and particles with lower density - move in the direction opposite to gravity - to the top of the ingot or melt.

To control the distribution of particles in the volume it is proposed to apply centrifugal force, which can be used when using a centrifugal casting machine for casting melt and obtaining cylindrical billets. If the density of the dispersed particles in the melt is different from the density of the melt itself, a force will act on the particle that does not balance its centrifugal force and gravity. This creates conditions for the particle to move in or out of the workpiece. When the particle comes in contact with the forming crystallization front, it may be anchored there or continue to move, depending on the forces acting on it.

This method involves the interaction of dispersed carbide particles with metal melts, and the variety of particles and steels makes it possible to obtain an almost infinite number of combinations of variations in material properties.

A number of experiments with different particles and steels have been carried out by a team of authors:

1. particles carbide of tungsten and silicon in various amounts into steel 1020 and steel 1030 (Anikeev, 2016);
2. particles carbide of tungsten and boron in various amounts into nickel and chromium alloyed steel 20 (up to 5 %);
3. particles carbide of tungsten and titanium, yttrium oxide into steel 1020 (Anikeev, 2016);
4. particles carbide of tungsten and titanium in steel AISI 420 (Chumanov, 2017);
5. particles carbide of tungsten and titanium in steel AISI 321 (Chumanov, 2022).

Each series of experiments resulted in cylindrical castings containing different amounts of particles individually and in combinations. For the uniformity of the study, a research methodology was developed, including the study of changes in the structures and properties of multifunctional composite materials. All the obtained blanks were investigated according to the following standards:

- the macrostructure of the samples was examined for voids, friability, shrinkage, air bubbles, delaminations, cracks and other defects using the naked eye and a magnifying glass. To assess the size change of different crystalline regions, the samples were scanned with high resolution on an Epson scanner after etching. The obtained panoramic images of the crystal structure were downloaded into a computer and processed using the image analysis software "Thixomet", version "Pro". During the analysis, the panoramic images were compiled into a single image of the surface of the entire sample, after which the length of the macrostructure zones was measured using the built-in tool;
- microstructure of the obtained samples is examined for changes in the size of dendritic cells by measuring the length of chords on the outer and inner volumes of the blanks, as well as in the centre (½ of the radius). The uniformity of distribution of ultradisperse particles in the structure is also evaluated by counting the number per unit area in accordance with GOST 5639, as well as changes in the chemical and morphological composition of inclusions;
- tests of mechanical properties included tensile tests according to GOST 1497-84, Charpy tests (GOST 9454-84), hardness was measured by Rockwell method according to ISO 6508-86, DIN 50103 and ASTM E18-74 standards, GOST 9013-059. Tests of all mechanical properties are also carried out from three horizons of the billet (from the outside, ½ of the billet radius, inner edge).

Results and Conclusions

1. Titanium and boron carbide, yttrium oxide has low wettability indices with carbonaceous melts and almost do not interact with melts: individual particles are in the structure of castings, but their concentration is residually low. This is confirmed by a slight increase in the concentration of titanium and boron in the castings (traces). When titanium is added to steel, the wettability of titanium carbide increases, probably due to a decrease in surface tension.
2. Changing the chemical composition of the studied steels (within the limits of the experiments) in order to reduce the values of surface tension, practically did not affect the change of wettability of boron carbide and yttrium oxide.
3. Dispersed particles of tungsten carbide, regardless of the chemical composition of steel, affect the macro - and microstructure of the obtained blanks. When examining the macrostructure, the alignment of the structure along the cross-section, the elimination of clear boundaries of crystallization zones, and a decrease in the length of the dendritic crystals zone are observed. The greatest influence on the structure is exerted by tungsten carbide particles fed in the amount of more than 3%.
4. The study of microstructure of samples with tungsten carbide shows that the size of dendritic cells in carbon steels decreases as the amount of introduced dispersed particles increases. In the samples without particles, the cell size ranges from 156 to 48 micrometers (in the inner and outer layers of the billets, respectively). The addition of tungsten carbide above 2.4% in the sample mass leads to a decrease in cell size from 25.5 to 15.5 micrometers (in the inner and outer layers of the billets, respectively).
5. When adding dispersed particles of tungsten carbide up to 0.5%, no significant changes in the macro- and microstructure of the samples are observed, changes occur only in the outer areas of the blanks, where the size of dendritic cells decreases by 15-20% compared to the samples without particles.
6. When introducing dispersed particles in a volume exceeding 2.4% of the mass of the investigated sample, it is observed that there is no increase in the concentration of particles in the surface volumes. Instead, there is an expansion of the zone with high concentration of carbides from the outer part of the sample to its inner part.
7. The concentration of 4-6 ultradisperse particles per square micrometre in the metal structure allows to increase (in comparison with comparison samples without particles) the strength of various steel grades in the range from 20 to 38 %, impact toughness - from 15 to 26 %, hardness - from 15 to 35 % and abrasive wear resistance - from 25 to 36 %. This concentration corresponds to the introduction of 2.4 % of ultrafine particles from the weight of the billet.

8. Due to the high cost of carbides (especially tungsten) it is reasonable to use the method of disperse hardening in centrifugal casting to obtain workpieces weighing more than 20 kg. This allows saving significantly on alloying elements, forming the required properties only on the outer surface layers of the formed billet. When the mass (and, accordingly, dimensions) of the workpiece to be hardened increases, the feasibility of the method will increase due to the scale factor.

Acknowledgement

This work was supported by the Ministry of Science and Higher Education of the Russian Federation (grant FENU-2023-0013).

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