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The Yttrium Oxide Additives Influence On The AISI 304 Steel Structure and Characteristics Obtained By Centrifugal Casting

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Abstract:
The complex study of the possibility to obtain AISI 304 steel with increased resistance to radiation has been carried out. Yttrium thermodynamic interactions with AISI 304 steel liquid melt was studied. The possibility of introducing yttrium oxide into the liquid metal matrix is evaluated. Experiments were conducted to obtain AISI 304 corrosion-resistant steel prototypes with the yttrium oxide introduction into the liquid melt. The blanks were obtained by casting on the horizontal centrifugal casting machine. The micro hardness studies of samples showed that samples obtained with the yttrium oxide introduction have lower gradient of the cross-section hardness index. Microstructures are presented to reveal inclusions formed by yttrium oxide in the casting body.

Keywords*: yttrium oxide, centrifugal casting, microstructure, microhardness, hardening, casting, hollow billet, dispersed particles, chemical composition, structure.*

Introduction

In the emerging market, the industry is faced not only with challenges related to improving product quality, but also with cost cutting issues. The various products cost is inextricably linked to the cost of electricity. Nuclear power remains the most efficient way to generate electricity at the moment [1]. This industry includes many industrial processes that cannot be performed without the use of the materials with appropriate requirements [2]. Improving the functional characteristics in metal materials with increased radiation resistance, corrosion resistance, and structural uniformity is an important task for metallurgy and mechanical engineering [3-4]. One of the main problems with operating parts made from AISI 304 steel under the influence of radiation and high temperatures is the appearance of such defect as swelling [5].

The process of obtaining parts by casting is of the greatest interest due to its easy technological implementation. Casting production allows getting blanks close to the final product, which reduces the cost of parts' metal processing [6-7]. At the same time, new materials are being actively developed which will combine highly plastic metal matrices and high-strength refractory fillers. [8-11]. The combination of different phases makes it possible to increase the materials' main functional indicators such as wear resistance and resistance to abrasive wear [12]. The fillers introduction allows creating the reinforcing layer in the matrix body itself. In addition to expanding the resulting part load range, strengthening particles can be considered as the additional barrier to the radioactive radiation penetration, which increases the part's stability. The increase in radiation resistance occurs during braking by the reinforcing layer of active ions, which in turn leads to the decrease in the dislocations movement.

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The main mechanisms for strengthening steel and other metal materials are solution hardening, dislocation hardening, grain reduction, and phase transformation enhancement. [13]. Grinding grain is the only way to simultaneously improve the strength and resistance of the metal to ionizing effects. Secondary phase hardening can both improve the metal strength and reduce it. The reason is the formation of non-metallic inclusions that are voltage concentrators. However, fine particles of the secondary phase often have the grinding effect in the structure and strengthening the grain boundaries, which can increase the steel resistance to ionizing effects. Thus, in addition to grain grinding, dispersed hardening is the most preferred method.

The fundamentally new technology is needed to implement the grain grinding process and strengthening with the secondary phase. The secondary phase can be introduced into the steel matrix by mechanical alloying. The method of introducing fine particles into the steel matrix is a complex task, due to the introduced phase wettability related issues.

The refractory fillers introduction must be controlled by the process to ensure the reinforcing layer creation in the specific area of the workpiece. Combining such technologies as casting production and the hardening particles introduction when casting on the centrifugal casting machine will not only achieve the minimum cost of the final product, but also make the introducing particles process more or less controlled [14].

Dispersed particles introduction technology

Today, the problem can be solved only with the transition to the method of mechanical alloying (ML). The ML Technology was well described in the work [15]. This technology implies that powders mixture of different metals is subjected to the joint high-energy grinding with the prevailing friction mechanism. In the process of such grinding, the powder particles crushing (up to the nanocluster size) and the mutual solid-phase diffusion of metals into each other happen. In nanoclusters, the most thermodynamically advantageous compound is the solid solution, which is converted into metal compounds such as intermetallides, silicides and carbides [16]. When the compacted powders are subsequently heated, these compounds fall out of the solution as nanoscale particles (precipitates).

In the work [17], it was found that such thermodynamically strong oxide as Y_2O_3 can also be dissolved in solid metal, followed by the release of its nanocluster precipitates. At the same time, it is possible to enlarge (coalescence) nanoprecipitates as a result of the small particles dissolution and the growth of larger ones, which ultimately negates all the ML technology advantages.

At the same time, there is technology for improving the metal materials' mechanical properties by introducing dispersed particles into the liquid melt during casting using the centrifugal casting machine. This technology, with sufficient simplicity of its implementation, allows to receive stable results using dispersed particles of different densities to obtain gradient materials [18].

Centrifugal casting is the optimal method for producing blanks due to the high crystallization rate, which provides fine-grained structure. During the liquid metal first contact with the relatively cold substrate, fine-grained crust of solidified metal is formed. The hardening particles are fed as powder during the casting process almost immediately after the casting start into the casting sock to avoid settling in the casting bucket. The mill rotation makes the particles settle faster and distribute more evenly in the metal body during crystallization due to the Archimedean forces and centripetal forces influence. Crystallization follows standard pattern - from the periphery to the center, providing the fine-grained structure formation on the workpiece's surface. Figure 1 shows the particles distribution at the contact boundary between crystallized metal and the substrate. It is clearly visible that the outer crust has fine-grained structure and consists mainly of steel molecules. The workpiece's outer working layer is hidden under the crust, in which the carbides largest particles are concentrated. It can be noticed that carbides smaller particles are located between the larger particles, but they predominate in the peripheral zone relative to the "substrate-metal" interface, and their concentration gradually decreases as they move away from the phase interface to the workpiece center, forming a gradient texture [19].

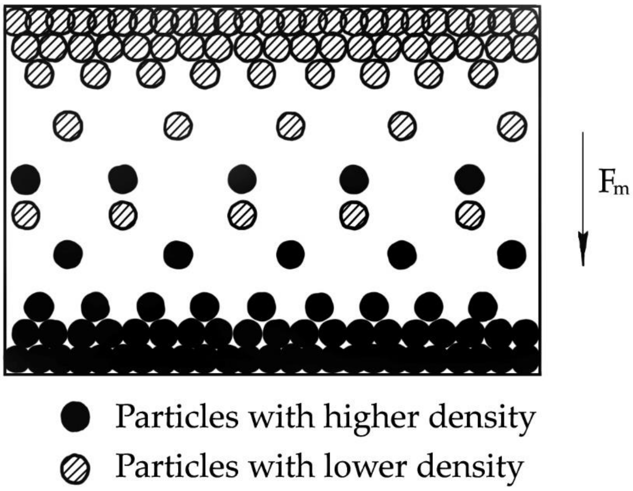

Figure 1. Distribution of reinforcing particles with different densities in steel matrix

To ensure a reliable molecular bond between carbides and the base metal, high interfacial adhesion is required, i.e. the carbide particles must have optimal wettability with liquid steel to form the reliable interfacial bond.

Determination of the materials' wettability mostly happens by empirical methods based on natural experiments. To predict the nature of the hardening particles distribution in the metal body, the formed layer thickness, the workpiece's possible physical characteristics, as well as to reduce the material costs for conducting natural tests, it was decided to create mathematical models for analysis in CAE systems.

Uneven introduction of strengthening particles leads to their uneven distribution in the crystallized melt body, which is expressed in the clusters appearance that can be detected during the castings analysis by the destructive method, despite the fact that during centrifugal casting, the strengthening particles are affected by the gravitational forces field, which accelerates the dispersed particles penetration deep into the crystallizing melt [20].

Because the casting process in centrifugal casting is pretty short-lived and lasts no longer than 30-60 seconds till complete crystallization of the steel castings weighing up to 10-20 kilograms, inaccurate dosing of the powder violates the dispersed particles required and specific concentration in unit volume of the melt jet. Consequently, there may be a situation of hardening particles complete absence in the workpiece's outer layers due to instantaneous crystallization in contact with the relatively cold mill or at some depth from the surface that exceeds the required tolerance during machining, resulting in the calculated diameter of the finished product completed or insufficient hardening, despite the centrifugal forces influence.

Similarly, different situation may arise. If the particles are introduced too early in the melt casting process, then all the hardening powder risks ending up in fine-grained crust which needs to be removed. In addition, this event will be stimulated by the gravitational field influence.

The information about the casting process and the ability to control the process itself with sufficient accuracy allows to minimize the risks of uneven hardening particles distribution, and also allows to perform rapid casting layers of one or more types of dispersed particles [21].

The diagram illustrating the casting process result with the dispersed particles of different densities introduction to strengthen the inner and outer annular billet surfaces is shown in figure 1. The half of the annular billet, in which light-weight particles tend to its rotation axis, is shown.

In this case, when using traditional methods of centrifugal casting without dosing and controlling the time of particles introduction, we are forced to use particles with different densities relative to the matrix melt. As mentioned earlier, powders made of rare or expensive materials may sometimes be used, such as TIC titanium carbides and WC tungsten carbides or yttrium Y_2O_3 oxide. In addition to this, there is another restriction related to the reinforcing material concentration. As the result, it will be necessary to reduce the product batch size, or inflate the products' final cost, or reduce the products' quality, which is expressed by reducing the hardening carbides concentration in the workpiece body per unit volume to maintain the minimum price of the product batch; F_m - the gravity direction caused by the high-speed mill's rotation.

Figure 2 shows optional puff casting, which involves controlling the powder and matrix melt dosage, as well as controlling the casting time with the certain time delay, which provides sufficient level of the first layer crystallization, filled with the lighter particles instead of the heavy ones.

Naturally, this scheme is almost an ideal outcome from the centrifugal casting process done by layers. However, it is possible that at the moment of hot melt contact, some of the fixed strengthening particles in the first layer will be moved to the second layer, thereby reducing the necessary concentration of strengthening particles in the outer layer

To obtain this result, it is necessary to accurately control temperatures in the first layer that has already undergone crystallization, as well as the melt's temperature. If the temperature difference is too low, there is a risk of the first layer complete crystallization in contact with the melt embedded to form the second layer. Therefore, all the particles fixed in the first layer can be displaced by the matrix melt, since in this case the reinforcing particles are light and less dense, relative to the steel melt.

The liquid melt temperature was determined using an immersion thermocouple; in other cases, an optical pyrometer was used. Here it is necessary to use mathematical apparatus, namely the crystallization thermodynamics laws of the steel melt, taking into account the embedded dispersed particles influence, air flows and the process of continuous centrifugal mill rotation.

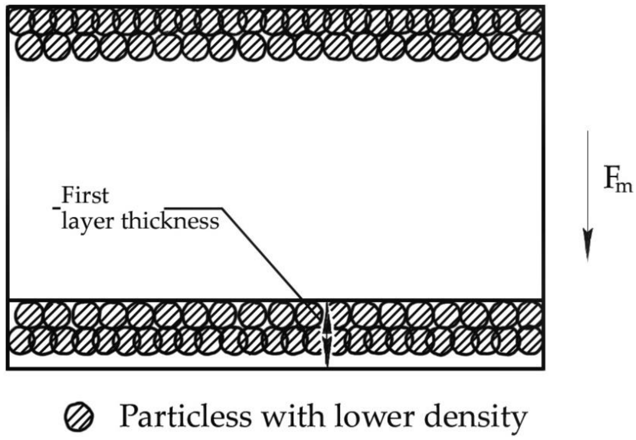

Figure 2. Casting using lower density particles with the layers' formation

The literature was analyzed in search for existing achievements and research results on the topic of refractory particles effects in the crystallizing metal body during centrifugal casting of blanks. To implement the technology based on the closest similarity, mathematical models presented in [22, 23] were adopted.

Yttrium oxide has density close to the density of metal materials based on iron 5.046 g/cm^3. Therefore, when implementing the technological scheme presented in the work, yttrium oxide must be located on the outer (working) side of the cylindrical casting. With a small wall thickness of the workpiece, it is possible to distribute it on the inner surface.

It is possible to increase the effect of dispersed particles introduction (higher values of mechanical properties, more than 300 MPa at 970 K, higher radiation resistance to neutron irradiation, higher resistance to corrosion in relation to heat carriers, at elevated temperatures) by using additional internal mechanical rolling, i.e. thermomechanical hardening.

Modeling the interaction of Y2O3 with the metal melt

Preliminary studies have shown that Y_2O_3 is the most stable thermodynamically non-metallic dispersed particle [24]. The yttrium oxide properties as compound are considered in work [25]. However, the work on the Y_2O_3 introduction into the pure

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metal phase did not give positive result. Creating reinforcing layer in the pure metal phase is not possible due to the poor wettability of this particles' type [26]. At the same time, the Y_2O_3 metal phase hardening is possible if the Nickel content in the main metal phase increases [27-29].

The development of the most effective technology for creating metal materials based on an iron matrix dispersed-strengthened with yttrium oxide, implies the creation of end-to-end technological schemes and innovative technologies, including both casting technologies with the strengthening phase introduction, and thermomechanical hardening. For this purpose, it is necessary to experimentally study the influence of various parameters (temperature, concentration, casting speed and furnace rotation, rolling forces, heat treatment modes, etc.) on the process and its results. For thermodynamic modeling of high – temperature processes occurring in the yttrium oxide-metal matrix (melt) system and recrystallization temperatures, it is advisable to use the FactSage software package [30]. The FactSage 7.0 software indicates possible directions in processes that occur during the implementation of technologies developed in the research course.

The composition used for the simulation was 0.1 % C, 1.5 % Mn, 0.5 % Si, 18.0 % Cr, 10.0 % Ni, 0.5 % Ti, 69.2 5% Fe. Additive Y_2O_3 – 1 g. per 100 g. mass of metal melt. The modeling results of the equilibrium phase compositions of metal with yttrium oxide according to temperature and modeling non-equilibrium crystallization (the Sheil-Gulliver model) of the metal with yttrium oxide are shown in figure 3. Calculations were made taking into account the possibility of the existence of phases with variable composition (solid and liquid solutions), and the deviation in such phases from the ideal.

In constructing the changes dependence in the alloy phase composition and non-equilibrium crystallization from temperature, the main emphasis was placed on the alloy's oxide phase. The simulation was performed for the temperatures at which the blanks centrifugal casting is usually performed, which allows to assume the phase composition of the studied alloy with greater or less accuracy. This circumstance allows to predict the dispersed oxides effects.

The most practical interest is the Central part of the graph, where straight line through the diagram passes the line it characterizes the mass of yttrium oxide in the system. The studied phase almost does not interact with the alloy components, does not dissociate, and does not undergo allotropic transformations

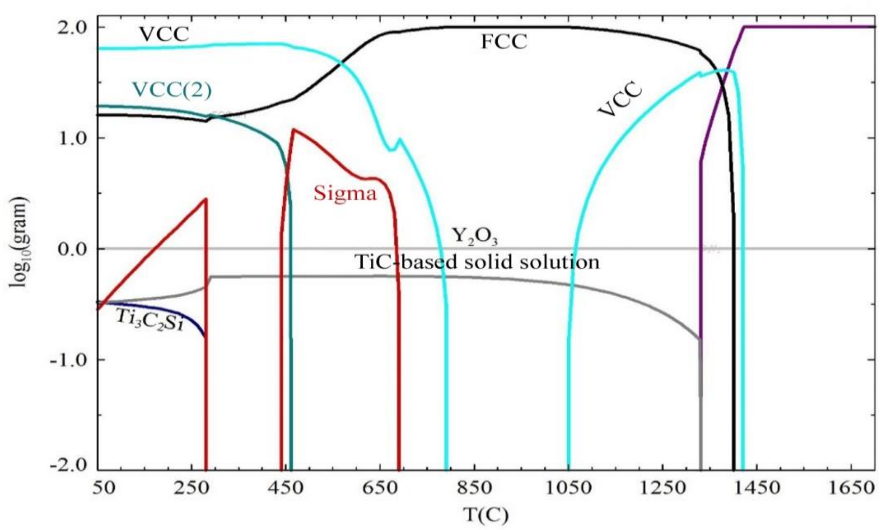

Figure 3. Modeling results of equilibrium phase metal compositions with yttrium oxide addition depending on temperature

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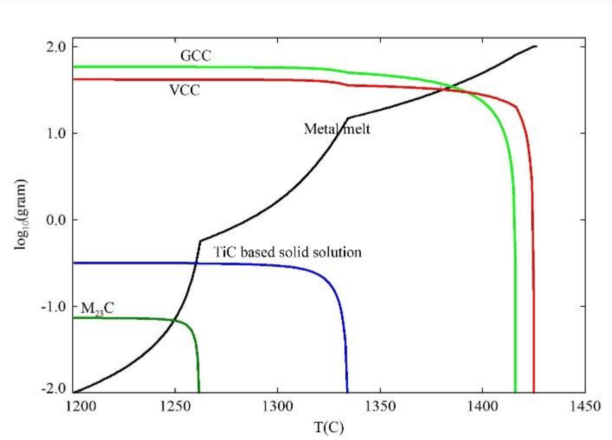
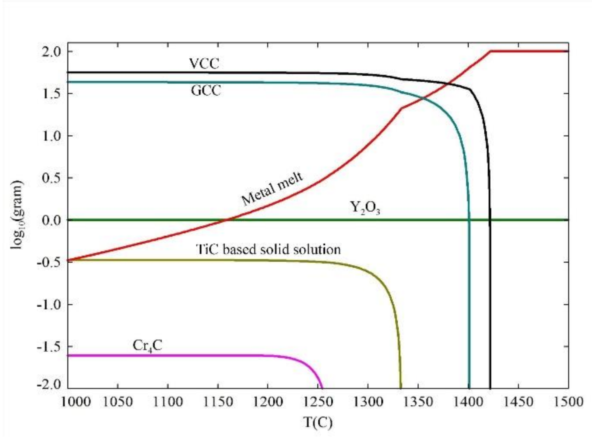
Figures 4a and 4b show the results of calculating the non-equilibrium crystallization model (the Sheil-Gulliver model) for the initial melt without yttrium oxide additives and with its reference composition. The line corresponding to particular phase, at the intersection with the temperature axis, marks the beginning point of phase crystallization.



a)



b)

Figure 4. Simulation results of non-equilibrium crystallization of the AISI 304 steel phase composition depending on the temperature (Sheil-Gulliver model): a - initial melt, b - metal with the yttrium oxide addition in the amount of 1 g. per 100 g.

The comparative analysis of figures 4a and 4b leads to the conclusion that yttrium oxide is present in the melt as crystalline phase. This increases the content of α-Fe (BCC phase) in comparison to the model for the melt without yttrium oxide additive.

Simulation data analysis showed that in the process of obtaining metal matrix materials done by centrifugal casting, there is no interaction of yttrium oxide with the metal melt. The compounds dissociation under the processes conditions is established. Thus, it can be concluded that it is advisable to conduct experiments on obtaining centrifugal castings with the use of yttrium oxide as the strengthening phase in order to possibly increase in radiation resistance.

The experiment

AISI 304 is used as the liquid metal melt. This steel grade is widely used for the parts' production in the nuclear industry. The Nickel content of 9-11 % should ensure hardening particles wettability by the liquid phase and the strengthening layer creation. To obtain batch of prototypes, the SELT furnace was used-001-40/12-T, the casting was carried out in the centrifugal casting machine (figure 5). The mill's rotation speed was 650 rpm. The liquid melt was released into the preheated furnace up to 600 °C. Particles injection feeding to the metal jet was carried out during the entire casting period. After the experiment, three complete blanks with the satisfactory surface quality were obtained. The blanks had the outer diameter of 156 mm, the length of 180 mm and the wall thickness of 30 mm. The blanks had the satisfactory surface quality. The first billet was obtained without the dispersed particles introduction. The number of particles in the second billets was 30 g. (sample no. 1) and 39 g. (sample no. 2). After receiving the blanks, samples were taken for research, the cutting scheme is shown in Fig. 6

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Figure 5. Workpieces ‘s machine for centrifugal casting

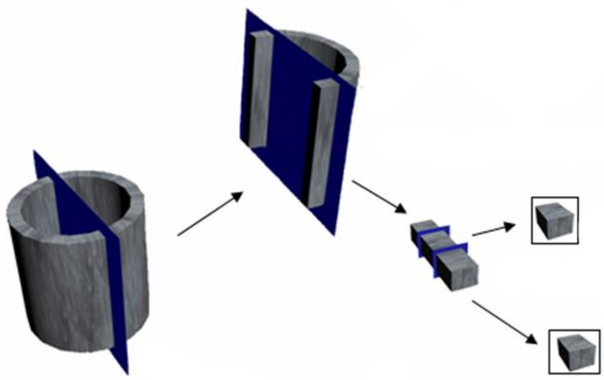
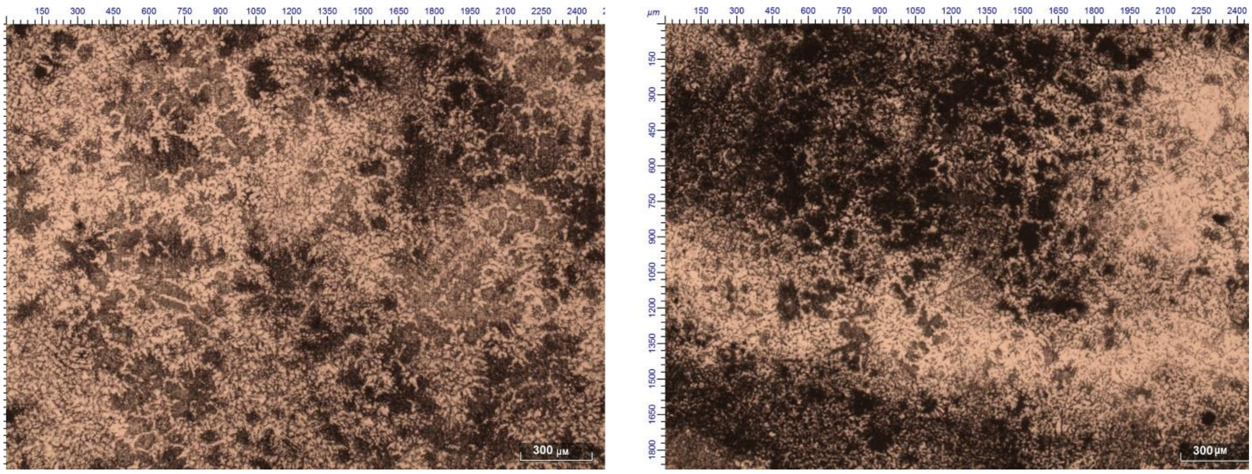


Figure 6. The obtained samples cutting scheme

Results

For centrifugal casting molds, this casting is characterized by distinct layer-by-layer crystallization in the direction from the outside of the casting to the central (internal) part. The castings are dense, without pores, cracks and any other defects of shrinkable character. The studied castings microstructure is represented by cast alpha-Fe dendritic crystals. The crystals growth has clear orientation to the casting center. Etching revealed internal dendritic liquation, which is the logical consequence of the metal phase complex chemical composition. Photos of etched samples are shown in figure 7. Microstructures are shown in figures 8a and 8b.

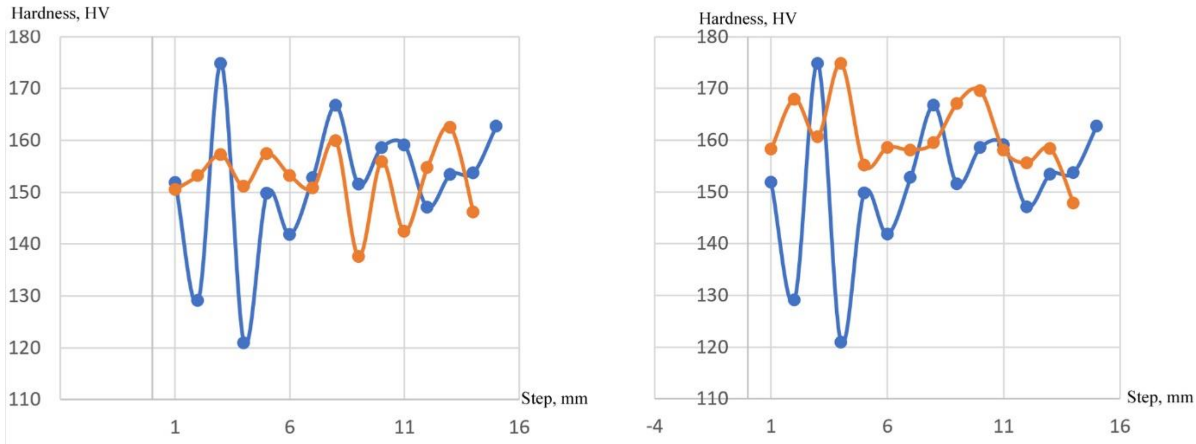
Figure 7. The appearance of etched samples: at the top there is a sample obtained with the introduction of 30 g. of Y_2O_3, bottom sample obtained with the introduction of 39 g. of Y_2O_3



a) b)

Figure 8. Microstructure of samples: a - with the introduction of 30 g. Y_2O_3; b - with the introduction of 39 g. Y_2O_3, ×65

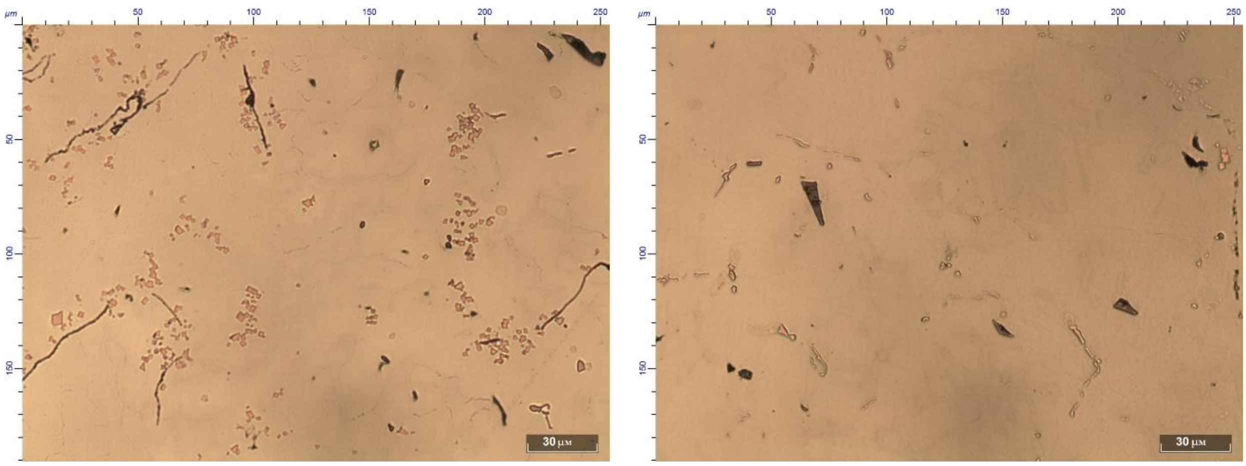
Microhardness was measured in the obtained samples. Measurements were made from the outer to the inner area of the formed billet. The workpiece hardness values with the introduction of Y_2O_3 in the amount of 30 g. decreased relatively to the standard, in turn, the workpiece obtained with the introduction of 39 g. has higher hardness values. It is worth noting that both Y_2O_3-hardened blanks have lower gradient of this indicator. This indicates that the particles acted as micro-coolers, this factor caused the structure crushing. The results are shown in figures 9a-9b. The blue lines represent the hardness values of the reference sample, and the orange lines represent the values of samples with the hardening particles introduction.



a b

Figure 9. Microhardness values from the edge to the center of the sample cross section, the blue line shows the values of the reference sample: a - with the entered number of particles equal to 30 g.; b - the sample with the entered number of particles equal to 39 g.

The non-metallic phase of castings is represented by titanium nitrides, sulfides, aluminosilicates, which are common for AISI 304 and special inclusions of Y_2O_3. The non-metallic phase is actively represented by titanium nitrides (figure 10a). Aluminum nitrides and titanium carbonitrides are also observed in the structure (figure 10b).



a) b)

Figure 10. Photos of microstructures: a - titanium nitrides; b - aluminum nitrides and titanium carbonitrides, ×130

The presence of this inclusions type is confirmed by studies done with electron microscope. In figures 11a-11b the spectrograms of the non-metallic phase for certain chemical elements are presented. Inclusions based on Y are represented. The chemical composition of the detected inclusions is shown in table 1.

Taking into account the thermodynamic stability of the Y_2O_3 compound, it can be assumed that this type of inclusions is the introduced refractory dispersed Y_2O_3 particles. The introduced oxides acted as substrate for the aluminosilicate and nitride inclusions crystallization, forming solid ceramic inclusions.

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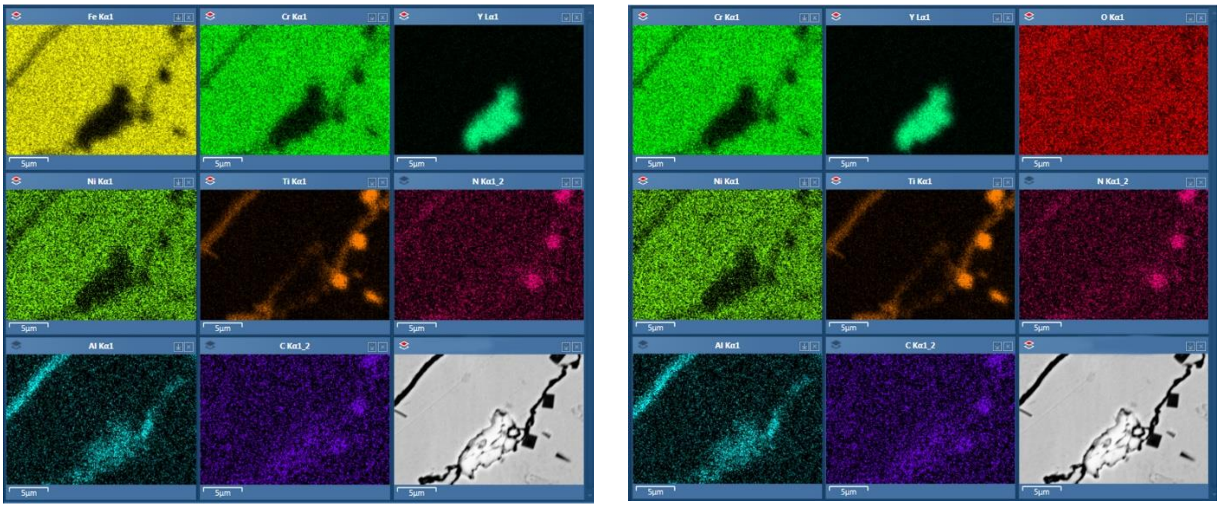

a) b)

Figure 11. Microstructures of hardened materials samples with an electron microscope: a - in a light field, b - in a dark field

Table 1. Chemical composition of the inclusion

Al	Si	Ti	Cr	Mn	Fe	Ni	Cu	Y	W
1.43	0.89	4.00	16.25	0.64	60.15	9.10	0.13	7.33	0.08

Conclusion

Evaluating the Y_2O_3 injection effect on the structure of AISI 304 castings, the following conclusions can be drawn. It is technologically possible to assimilate Y_2O_3 during workpieces centrifugal casting. However, the thermodynamic stability of Y_2O_3 did not cause the change in the phase state of the melt. Based on the results obtained, it can be assumed that it is more appropriate to introduce yttrium oxide in AISI 904L steel with high concentration of nickel in the composition.

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References

1. Nuclear energy of the future: what research for which objectives. Paris, CEA Saclay and Groupe Moniteur, 2006.
2. Kinev, E.A., Pastukhov, V.I., Shikhalev, V.S. (2016). Physicochemical Interaction of EK-164 Steel with Uranium Dioxide During High-Temperature Irradiation. *Atomic Energy*, 120(3): 199-204.
3. Doan, P.H.L., Duquesnoy, T., Devezeaux de Lavergne, J-G. (2017). Economic appraisal of deployment schedules for high-level radioactive waste repositories. *EPJ NuclearSciences&Technologies*, 3, 13 pp.
4. Bergström, U. International perspective on repositories for low level waste / U. Bergström, K. Pers, Y. Almén. – Stockholm: SKB Report R-11-16, 2011. – 72 pp.
5. Lidskog, R. The management of radioactive waste. A description of ten

July-August 2020
ISSN: 0193-4120 Page No. 3553 - 3564

countries / R. Lidskog, A. C. Andersson. – Stockholm: SKB Report, 2002. – 107 pp.
6. Dong H. Technological progresses of research activities on steel products. China Metallurgy, 2008, 18(10): 1-1.Liu Y C, Liu C X, Sommer F, et al. Martensite formation kinetics of substitutional Fe–0.7at.% Al alloy under uniaxial compressive stress. Acta Materialia, 2015, 98: 164-174.
7. Liu Y C, Wang D J, Sommer F, et al. Isothermal austenite–ferrite transformation of Fe–0.04 at.% C alloy: dilatometric measurement and kinetic analysis. Acta Materialia, 2008, 56(15): 3833-3842.
8. Zhang H J, Li C, Guo Q Y, et al. Improving creep resistance of nickel-based superalloy Inconel 718 by tailoring gamma double prime variants. ScriptaMaterialia, 2019, 164: 66–70.
9. B. Al-Mangour, D. Grzesiak, J.-M. Yang, In-situ formation of novel TiC-particle-reinforced 316L stainless steel bulk-form composites by selective laser melting, Journal of Alloys and Compounds, 706, 2017, 409-418.
10. S. Singla, J.S. Grewal, A.S. Kang, Wear behavior of weld overlays on excavator bucket teeth, Procedia Materials Science, 5, 2014, 256-266.D.Alexandrov, Nonlinear dynamics of polydisperse assemblages of particles evolving in metastable media, European Physical Journal: Special Topics, 229 (2-3), 2020, 383-404.
11. L.N. Belyanchikov, Rational process of production of corrosion-resistant ferritic steel with nanocluster oxide hardening for atomic power engineering, Russian Metallurgy (Metally), 2012, 2012, 461-467.
12. Rekha, M. Novel amorphous precursor densification to transparent Nd:Y2O3 Ceramics / Mann Rekha, LaishramKiranmala, Ashfaq Sheikh, Malhan Neelam // Ceramics International. – 2012. – 38. – P.4131–4135.
13. Harris, I. R. Grain boundaries: Their Character, Characterisation and Influence on Properties / I. R. Harris, A. J. Williams. – London: IOM Communications Ltd., 2001. – 328 p.
14. Al-Mangour, B. In-situ formation of novel TiC-particle-reinforced 316L stainless steel bulk-form composites by selective laser melting / B. Al-Mangour, D. Grzesiak, J.-M. Yang // Journal of Alloys and Compounds. – 2017. – Vol. 706. – P. 409-418.
15. Harris, I. R. Grain boundaries: Their Character, Characterisation and Influence on Properties / I. R. Harris, A. J. Williams. – London: IOM Communications Ltd., 2001. – 328 p.
16. Suzuki T, Inoue J, Koseki T. Solidification of iron and steel on single-crystal oxide. ISIJ International, 2007, 47(6): 847.
17. Han X, Zhang Z P, Hou J Y, et al. Tribological behavior of shot peened/austempered AISI 5160 steel. Tribology International, 2020, 145: 106197.
18. Microstructure and Hardness of a Dispersion-Reinforced Casting / Anikeev, A.N., Chumanov, I.V. / 2018, Russian Metallurgy (Metally), Vol. 2018(12), p. 1161-1164
19. Experiments on obtaining nanostructured metallic materials and their investigation / Anikeev, A.N., Sergeev, D.V., Chumanov, I.V. / 2016, Materials Science Forum, Vol. 843, p. 139-144
20. Fabrication of functionally graded materials by introducing wolframium carbide dispersed particles during centrifugal casting and examination of

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ISSN: 0193-4120 Page No. 3553 - 3564

FGM's structure / Chumanov, I.V., Anikeev, A.N., Chumanov, V.I. / 2015, Procedia Engineering, Vol. 129, p. 816-820

21. Studying the effect of fine particles of tungsten carbide on the macro-structure, hardness and microhardness of gradient steel billets / Anikeev, A.N., Chumanov, I.V., Sedukhin, V. / 2020, Materials Science Forum, Vol. 986 MSF, p. 3-8
22. Catalina, A. A Dynamic Model for Interaction between a Solid Particle and an Advancing Solid/Liquid Interface / A. Catalina, S. Mukherjee, D. Stefanescu // Metallurgical and materials transactions A. – 2000. – V. 31A. – P. 2559 – 2568.
23. Han, Q. Particle pushing: critical flow rate required to put particles into motion / Q. Han, J. Hunt // Journal of Crystal Growth. – 1995. – V. 152. – P. 221-227.
24. Singla, S. Wear behavior of weld overlays on excavator bucket teeth / S. Singla, J. S. Grewal, A. S. Kang // Procedia Materials Science. – 2014. – Vol. 5. – P. 256-266.
25. Huang Y. Synthesis of mono-dispersed spherical Nd: Y2O3 powder for transparent ceramics / Y. Huang, D. Jiang, J. Zhang, Q. Lin, Z. Huang // Ceramics International. – 2011. – 37. – P.3523 - 3529.
26. V.D. Katolikov, I.A. Logachev, L.E. Shchukina et. al., Thermodynamics of nitrogen solubility in nickel-based alloys at plasma-arc remelting, Izvestiya. Ferrous Metallurgy, 63(3-4), 2020, 231-237.
27. Benjamin, J. S. Dispersion strengthened superalloys mechanical alloying / J. S. Benjamin, P. D. Mercer // Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science. – 1970. – Vol. 1. – № 10. – P. 2943-2951.
28. Badmos, A. V. The Evolution of Solutions: Thermodynamic Analysis of Mechanical Alloying / A. V. Badmos, H. K. D. H. Bhadeshia // Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science. – 1997. – Vol. 28A. – P. 2189-2194.
29. Olier, P. Structural and Chemical Characterisations of ODS Ferritic Steels Produced by Mechanical Extrusion / P. Olier, J. Mabaplate, M. H. Mathon and al. // Proceedings Powder Metallurgy World Congress and Exhibition, 10-14 October 2010, Florence, Italia. – 2010. – P. 151-158.
30. A.M. Mikhailov, K.A. Zubarev, G.I. Kotel’nikov et. al., Model of evaporation of the components at the nickel alloys smelting in a vacuum induction furnace. Izvestiya. Ferrous Metallurgy, 59(1), 2016, 35-38.