

Comparative Analysis of Mechanical Properties and Cold Resistance of Metal of Steel Castings from the Special Alloyed Steel

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Abstract. In this paper, the experimental observation of influence of casting conditions on steel alloy quality is presented. We studied the casted steel samples obtained with the following methods: sand casting mold (as a reference sample), thin-wall mold with height-adjusted ceramic layer and forced water-air mixture cooling, same as above but with micro-cooling channels used during liquid steel casting. We showed that the steel density as well as typical distribution of non-metallic inclusions and mechanical properties are dependent on casting technology been used. We present the figures of impact toughness, crack growth energy and filamentation ratio with respect to the test temperature. We observed that the impact toughness of the samples is higher than for the reference one within the entire test temperature range. In particular, the impact toughness exhibits a smooth dependence versus temperature as opposed to its abrupt decrease for a reference sample. We showed, that the samples obtained according to the new technology are less fragile and have better cold resistance, similar results were obtained after crack filamentation ratio analysis.

1. Introduction

Increasing the reliability and performance of critical products operating at sub-zero temperatures, which are typical for the most of Russia, is a very topical and important problem [1-5].

The creation of materials for these structures involves a number of engineering challenges associated with the extreme conditions of their operation [6-12]. The studies [13-14] describe experience of developing cast cold-resistant and wear-resistant steels for specific operation conditions.

The purpose of this paper is to investigate the standard mechanical properties, density and cold resistance of metal of shaped castings of special alloyed Cr-Ni-Mo-V steel. During the investigation, test castings were prepared with an external (variant 1) and complex action (variant 2) on their crystallization and solidification. The external action was that the castings were produced in thin-walled metal shell molds with external forced cooling of the surface and a height-differentiated refractory layer. In the complex action, the castings were produced under the same conditions, while simultaneously injecting dispersed solid particles into the molten metal jet, i. e. the suspension pouring was performed. For comparison, the same castings were produced conventionally using bulk liquid-glass molds, i.e. without any action on the forming cast (variant 3– the reference metal).

The following is a prerequisite for choosing the experimental technologies. High-intensity cooling of the molten metal of a casting in a metal shell mold promotes progressive crystallization, increases



the density and improves the mechanical properties of the metal. In the case of suspension pouring, solid powder particles (microchills, inoculators, dispersed particles) injected into the molten metal are uniformly distributed in the volume of the metal being poured and have a double effect on the molten metal: thermophysical – intensereduction of overheating and volumetric shrinkage of the metal, and modifying – by being additional crystallization centers both during pouring and subsequent solidification of the casting in the mold [14-15]. Iron powder PZhV 1.450.26 (GOST 9849-86) in the amount of 2 percent of the mass of steel poured with the addition of 0.1% silicocalcium was used as the microchills. The microchills were added as per known flow sheet from the measuring hopper mounted on the ladle through a special sprue extension [15 - 20].

2. Methods of research

For the purpose of research, castings were produced from complex alloyed steel using three above-mentioned technologies. First, the templates were cut from the castings to make specimens and then determine the mechanical properties and cold resistance. The templates were cut from sub-risers of the castings, the specimens – from the central upper zones of the templates.

Mechanical properties (strength, ductility and toughness) were determined using standard procedures.

The brittle fracture susceptibility was found using the serial curves $KCU = f(T)$ and $KSV = f(T)$ on impact bending test specimens as per GOST 9454-78 by method of A.P. Gulyaev and the nature of a fracture (%F– percentage of fibering). In the first case, the criterion for ductile-brittle transition or the brittle temperature (T_k) was $KCU = 0.6 \text{ MJ/m}^2$, in the second case - $T_k^B = 70\%$, the fracture was evaluated based on the calculation of the areas of crystalline or ductile fracture of the impact bending test specimens.

3. Results of research and their analysis

Fig. 1 shows the fracture of the specimens of investigated as-cast steel (before heat treatment).

The casting produced in the metal shell mold has a shining crystalline fracture (Fig. 1a). The casting produced in the metal shell mold with using microchills is fibered with a coarse dendritic pattern (Fig. 1b). The fracture of the casting produced in the bulk mold is mixed (Fig. 1c).

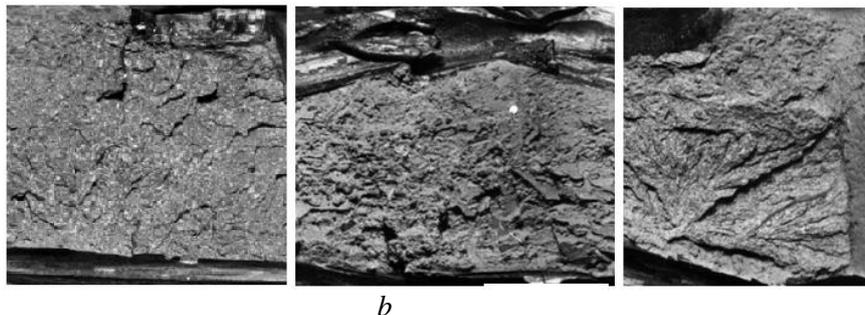


Figure 1. Macrobends of castings in a cast state: a - metal shell form with forced cooling; b - same with input of microrefrigerators; c – volume form.

The investigation has shown that the macrofracture of the cast specimen for all three variants is crystalline. The unsatisfactory appearance of the fracture is associated with the structural features of as-cast steel. A significant improvement in the fracture structure, as well as a better combination of mechanical properties, is achieved by heat treatment, performed according to the following regimen: step-by-step diffusion annealing and quenching with high tempering. In this case, the macrofracture of the castings (Fig. 2) was ductile in all three variants.

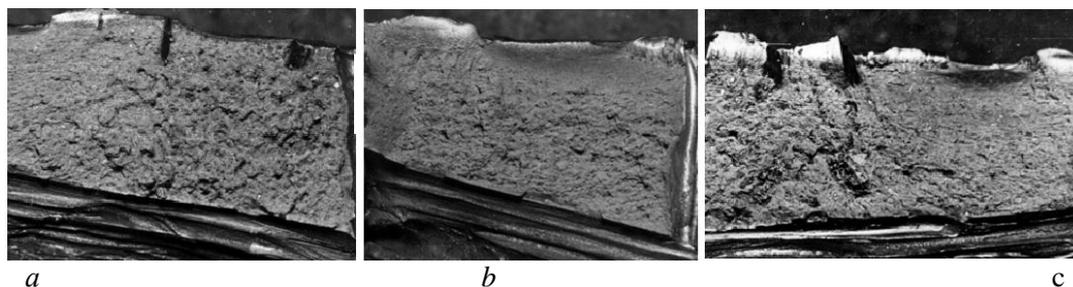


Figure 2. Macrobreaks of castings after heat treatment filling options: a - metalshell form with forced cooling; b - same with input of microrefrigerators; c – volume form

The results given in Table. 1 indicate that the highest combination of strength, ductility and toughness were obtained in the casting produced by the complex action on the solidifying metal.

Table 1. Table 1. Mechanical properties steel

Filling option	σ_T , MPa	σ_B , MPa	δ , %	Ψ , %	KCU, MJ/m ²
Volume form	635,2	690,2	10,5	41,3	1,15
Metalshell form with forced cooling	740,5	775,5	17,2	64,5	1,58
Same with input of microrefrigerators	715,7	765,5	17,7	66,2	1,75

The table shows that the mechanical properties of the specimens cut from the test castings are much better than those of the reference metal. The improvement of the mechanical properties of the test castings can be explained by accelerated crystallization, structure refinement, a better distribution of non-metallic inclusions, and a higher metal density.

Non-metallic inclusions in cast steel were investigated by metallographic method, which allows to determine the quantity, shape and size of inclusions as per GOST 1778-70. The metallographic analysis was carried out on polished specimens cut along the cross section of the casting. The analysis results are provided in Fig. 3. Fig. 3 shows the characteristic distribution of non-metallic inclusions, depending on the casting technology. As a result of the investigation, it was found that the amount and the distribution pattern of sulfides increase from the periphery to the center of the casting, with the maximum increase in the casting produced in the bulk mold, in the central parts they are arranged as films along the grain boundaries. With forced cooling they are located more evenly throughout the entire section and look like thinner and more intermittent films. In complex action, oxysulfides are formed, located mainly within the grain as a compact form.

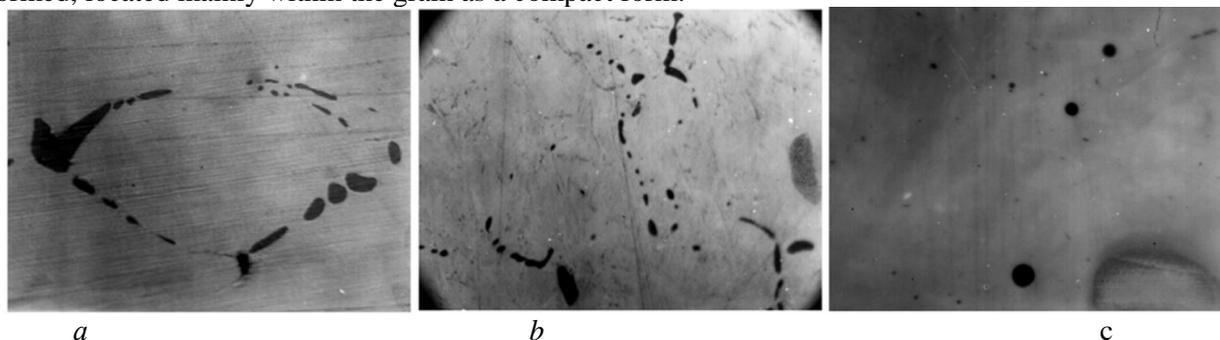


Figure 3. Characteristic distribution of nonmetallic inclusions: a - volume form; b – metalshell form with forced cooling; c - same with input of microrefrigerators

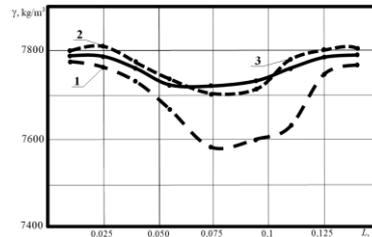


Figure 4. Distribution of density on the section of castings:

1 – volume form; 2 – metalobolochkovy form; 3 – same with input of microrefrigerators

Despite the increase in the number of oxide inclusions, addition of microchills makes them to bond into rounded oxysulfides.

The amount of silicate inclusions and their size do not almost vary in the cross section of the casting and do not depend on the crystallization rate.

The above results indicate that an increase in the crystallization rate of the test castings due to external cooling of thin-walled molds, as well as using of microchills, influences the total amount and the distribution pattern of non-metallic inclusions.

The change in the density along the section of the specimens cut from the upper zones of the castings is shown in Fig. 4. It can be seen that the density of the metal in the center of the reference casting is noticeably reduced in comparison with the periphery and the metal of the reference castings. External cooling and complex action contribute to homogenization and increasing the density uniformity. Similar results were obtained in the investigation of the density along the height of the casting.

Since toughness is an integral characteristic, and the operation conditions of the product at the stages of initiation and propagation of a crack are significantly different, it is therefore quite natural to investigate the ductility of the metal before the crack initiation and in the presence of a crack. Considering that the material always contains stress risers in the form of defects (microcracks, non-metallic inclusions, etc.), the structure reliability is mainly determined by the material resistance to the crack propagation.

In our paper, we constructed serial curves based on the results of impact testing of the specimens with both U- and V-notches. Figure 5 shows the serial curves of the change in toughness of the specimens with U ($R = 1.0$ mm) and V ($r = 0.25$ mm) notches, depending on the casting technology. It can be seen that toughness of the test metal at sub-zero temperatures is higher both for specimens with U- and V-notches, compared with the reference metal. The toughness curves with the decreasing temperature in the test castings are more smooth, while in the reference casting there is a sharper decline in toughness from the temperature of 20°C . Throughout the investigated range of test temperatures, the toughness values are on average $0.2\text{--}0.3$ MJ/m² higher in the test castings than in the reference castings.

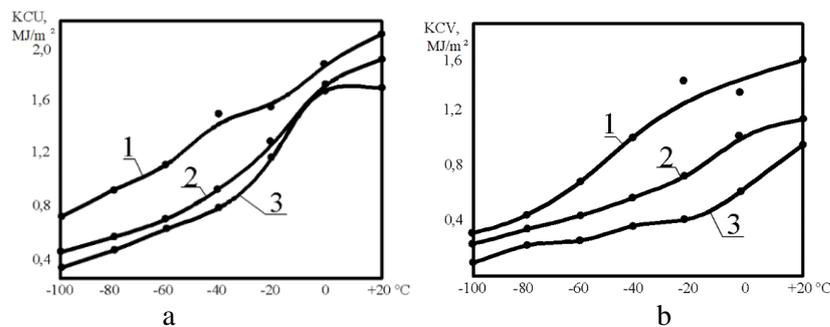


Figure 5. Serial curves of impact strength of samples with a radius of a cut of $R=1,0$ of mm (a) and $r=0,25$ of mm: 1 – metalshell form with forced cooling and input of microrefrigerators; 2 – metalshell form with forced cooling; 3 – volume form

The data in Fig. 5 showed that T_k , determined from the serial curves, depends on the casting conditions and the notch acuity. In the test metal, T_k is shifted to a region of lower temperatures by 30-40 degrees, depending on the casting technology. The critical temperature for the U-notched specimens is a more constant, since this value is 1.5-2.0 times lower than for the U-notched specimens.

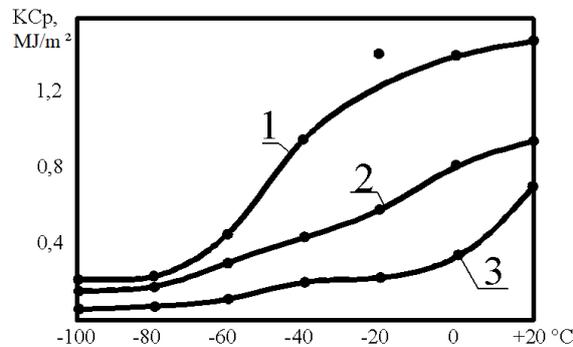


Figure 6. Serial curve works of development of a crack: 1 – a metal shell form with forced cooling and input of microrefrigerators; 2 – a metal shell form with forced cooling; 3 – volume form

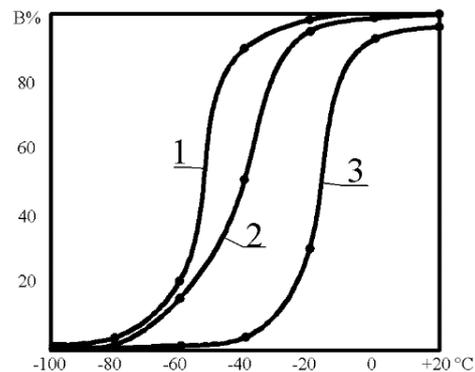


Figure 7. Change of a share of a fibrous component in a break: 1 – metal shell form with forced cooling and input of microrefrigerators; 2 – metal shell form with forced cooling; 3 – volume form

Figure 6 shows a change in the crack development, depending on the casting solidification conditions. The serial curves show that the test metal has a greater resistance to crack development or a lesser brittle fracture susceptibility in the investigated temperature range, and therefore greater cold resistance at sub-zero temperatures.

Figure 7 shows the change in the proportion of the ductile component in the fracture (B %), depending on the test temperature. The above results showed that there is a smaller brittle fracture susceptibility of steel in the test metal. Throughout the critical range of the brittle transition (100 to 0% B), the fibrous component in the fracture is larger for the metal produced by the complex action. The fracture of the reference metal showed a smaller percentage of fibering in, the best values are demonstrated by the metal poured into metal shell molds with forced cooling and addition of microchills.

4. Summary

Forced cooling of metal-shell molds and using of microchills strongly affect the number and the distribution pattern of non-metallic inclusions. The test castings have a higher density and better mechanical properties of the metal. An improvement of the mechanical properties of the test castings with accelerated cooling is associated with structure refinement, decreased porosity, transfer of the sulphides to a metastable solution, and increased homogeneity of the metal.

Comparison of the serial curves clearly reveal the order of three investigated variants, if arranged by the increasing value of cold resistance: the bulk mold, the metal-shell mold with forced cooling, and the complex action on the solidifying casting.

An external, much less complex, action increases the resistance of the metal to the crack development. With an increase in the notch acuity, the conditional cold brittleness threshold ($T_k^{B=70}$ and $T_k^{KCU=0,6}$) shifts toward above-zero temperatures.

Thus, by influencing the process of forming the solidifying casting, it is possible to increase the reliability of the products by increasing the level of ductile and viscous properties, as well as the cold resistance of steel at sub-zero temperatures.

As a result of the investigations conducted, it was established that external action (a thin-walled metal-shell mold with forced cooling) and complex action (suspension pouring into the same molds) allow to control crystallization and solidification of castings in order to improve the metal quality.

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