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INFLUENCE OF TECHNOLOGICAL CASTING FACTORS ON THE PHYSICAL-MECHANICAL PROPERTIES OF HIGH-MANGANESE STEEL

Purpose. *Development of a rational technology of the casting process to improve the mechanical and operational properties of castings made of high-manganese steel 110G13L.*

Research methods. *Tensile tests were carried out on a URM-50 machine. Determination of the impact toughness of samples with a U-shaped notch was carried out on a pendulum impactor MK-30A according to DSTU ISO 148-1:2022. Brinell hardness was determined according to DSTU ISO 6506-1:2007. Samples of 110G13L steel for testing were made of two types: from cast bricks measuring 10×10×55 mm^3 (thin-walled sample) and cut from ingots measuring 80×80×200 mm^3 (thick-walled sample).*

Results. *It was established that the technological factor that increases the physical and mechanical properties of high-manganese steel 110G13L is the wall thickness of the casting and the cooling rate. A high strength index $\sigma_в$ is achieved on samples from castings with a small cross-section (brick) during accelerated cooling in a metal mold (chill). Thick-walled castings (ingots) leads to a decrease in the relative elongation and narrowing ϕ. The impact toughness of steel 110G13L decreases with increasing wall thickness of the casting.*

Scientific novelty. *High dynamic strength and toughness of steel 110G13L is provided by a single-phase austenitic structure. Slow cooling leads to the release of carbides (Fe, Mn)$_3$C outside the grain boundaries. The accumulation of carbides contributes to the propagation of cracks under impact loads, which reduces the impact toughness.*

Practical value. *Thick-walled castings (ingots) worsens the strength characteristics of steel compared to a thin-walled sample (brick). Casting thick-walled castings (ingots) leads to a decrease in the values of relative elongation and narrowing. The impact toughness of cast steel decreases with increasing wall thickness of the casting due to the formation of carbide precipitates. The maximum hardness of cast steel corresponds to a thick-walled casting (ingot) cast in a chill mold. The proposed recommendations will increase the reliability and durability of parts made of high-manganese steel 110G13L.*

Key words: *high-manganese steel, casting technology, austenite, carbides, strength, ductility, hardness.*

Introduction

High-manganese steel 110G13L (Hadfield steel) is the main structural material for the manufacture of replaceable parts of mining and metallurgical equipment, operated under wear conditions and heavy loads [1–3]. Steel 110G13L is widely used in applications where wear and tear is combined with high impacts: tank and excavator tracks, railroad crossings, crusher jaws, and mill linings. This steel's uniqueness lies in its exceptional ability to undergo strain hardening, where impact loads and high pressures dramatically increase the surface layer's strength and hardness [4–7]. Due to the ever-increasing volume of mineral extraction and processing, the demand for cast parts made from this steel is growing. Therefore, improving the performance of castings made from high-manganese steel grade 110G13L, within the existing production capabilities of metallurgical foundries, is relevant.

Analysis of research and publications

The influence of composition, smelting technology, modification, heat treatment and a number of other factors on the operational stability of high-manganese steels

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operating under conditions of mining and crushing of ores and minerals has been studied quite thoroughly [4, 6, 7]. The influence of carbon and manganese content on the physical and mechanical properties of high-manganese steels has been studied in [8, 9, 16], aluminum [10], chromium [11, 12], nickel [13]. An effective way to improve the properties of steel is heat treatment [14, 15]. Improvement of steel hardening modes is aimed at better dissolution of carbides and refinement of austenite grains [16]. After cooling in the mold, high-manganese steel castings have a structure consisting of austenite with inclusions of a carbide phase of variable composition $(Fe, Mn)_3C$. The phase, classified as carbide, is actually a conglomerate consisting of a thin strip of carbide and austenite decomposition products located along it. Deformation twins, intertwining of dislocations near small carbides, and martensitic transformations contribute to the formation of a new hard surface [17-19]. The precipitation of carbide, which contains a high proportion of manganese, causes depletion of manganese beyond the austenite interface. Upon subsequent cooling, the depleted austenite undergoes a transformation, creating troostite-sorbite structures. The quantity, shape, and nature of the arrangement of carbides depend primarily on the cooling conditions of the metal and its chemical composition, especially carbon and silicon. The slower the cooling rate of the steel and the higher the concentration of carbon and silicon, the more carbides are precipitated in the structure and the larger they are. In addition, the quantity and size of carbides in high-manganese steel are determined by other technological factors: the degree of steel overheating during pouring, the mass and wall thickness of the casting [20]. Depending on the factors listed, carbides in the structure of cast steel occur in the form of thin rims around individual austenite grains, small and large inclusions in grains, needle-shaped inclusions and wide continuous network. The purpose of subsequent heat treatment is to dissolve the carbides, equalize the chemical composition, and fix the austenitic structure. Ideally, high-manganese steel should have a purely austenitic structure after heat treatment. In fact, in addition to austenite, a certain amount of carbide phase is observed in the steel structure, most often at the grain boundaries [20].

In addition to carbides, the properties of high-manganese steel are significantly influenced by the austenite grain size [9, 20], which forms during primary crystallization and remains unchanged after conventional heat treatment to dissolve carbides, i.e., quenching in water at a temperature of 1050–1100 °C. The formation of austenite grain size is primarily influenced by the cooling rate of the metal in the casting mold, which depends on many factors: the mold material, the thickness of the casting wall, the mass of the casting, and the duration of holding the casting in the mold before knocking out.

A method for special heat treatment of high-manganese steel is known, aimed at refining the austenite grain to improve its mechanical and operational properties [20]. This method involves annealing at 500-550 °C and subsequent quenching from a temperature of 1050 °C. Annealing leads to the formation of pearlite in the steel structure, and subsequent quenching leads to a refinement of the austenite grain. A pearlite content of 50 % is sufficient for refining the austenite grain. A similar amount of austenite decomposition products can also be achieved by slowly cooling thick-walled castings in a mold.

The influence of composition, melting, and heat treatment on the wear resistance of castings has been studied quite well, but the development of new technological solutions to improve the reliability of parts made from 110G13L steel remains in demand.

The purpose of the work

The objective of the presented research was to develop a set of measures to improve the mechanical and performance properties of high-manganese steel castings through the development of rational casting processes. This included investigating austenite decomposition processes depending on the cooling rate of castings in various molds (sand mold and chill mold) and the influence of casting wall thickness (thin-walled brick and thick-walled ingot) on the physical-mechanical properties of high-manganese steel 110G13L (Hadfield steel).

Research material and methodology

The object of the study was high-manganese steel 110G13L (Hadfield steel), which is used in the production of castings for mining and processing equipment [1]. Steel melting was carried out in an induction electric furnace with a basic lining. Casting was performed in a sand mold (slow cooling at a rate of 0,8 K/min.) and a chill mold (rapid cooling at a rate of 17 K/min.). The chemical composition of the studied steel samples (wt.%): 1,1 C; 13 Mn; 0,87 Si; 0,029 P. Samples of 110G13L steel for testing were made of two types: from cast bricks measuring 10x10x55 mm^3 (thin-walled sample) and cut from ingots measuring 80x80x200 mm^3 (thick-walled sample). Brick and ingots were quenched in water at a temperature of 1050 °C. Tensile and impact specimens were produced from the brick and the core of the ingots on metal-cutting machines. Tensile tests were performed on a URM-50 machine. To determine impact toughness, U-notch specimens were tested on an MK-30A pendulum impact tester in accordance with DSTU ISO 148-1:2022. Brinell hardness was determined in accordance with DSTU ISO 6506-1:2007. The following values were determined: yield strength $\sigma_{0.2}$, tensile strength $\sigma_в$, relative elongation δ and narroving ϕ, impact toughness KCU and hardness HB.

Research results and discussion

The dependence of the conditional yield strength $\sigma_{0.2}$ and the ultimate strength $\sigma_в$ of 110G13L steel on the casting wall thickness and the material of the casting mold is shown in Fig. 1.

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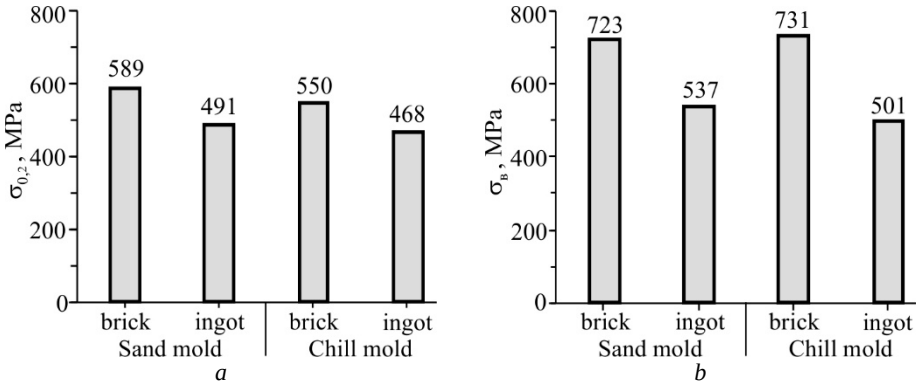


Figure 1. Dependence of the properties of 110G13L steel n the casting wall thickness (thin-walled brick and thick-walled ingot) and the material of the casting mold (sand and chill mold):
a – yield strength $\sigma_{0.2;}$ *b* – tensile strength $\sigma_в$

Analysis of the strain hardening reserve (the ratio of the yield strength to the ultimate strength $D = \sigma_{0.2}/\sigma_в$) showed that for a thin-walled sample (brick) $D \approx 0{,}75–0{,}81$ ($\sigma_в$ = 723–731 MPa is significantly higher than $\sigma_{0.2}$ = 550–589 MPa). For a thick-walled sample (ingot), this ratio increases to $D \approx 0{,}91–0{,}93$ ($\sigma_в$ = 501–537 MPa only slightly exceeds $\sigma_{0.2}$ = 468–491 MPa). This result can be explained as follows. In a thin-walled sample (brick), the austenitic matrix contains a smaller number of various inclusions and defects compared to a thick-walled sample (ingot), which allows steel to exhibit better ability to strain hardening under tension, increasing the gap between the onset of plastic flow ($\sigma_{0.2}$) and final failure ($\sigma_в$). In a thick-walled sample (ingot) $(Fe, Mn)_3C$ carbides at grain boundaries block plastic deformation, resulting in failure of the sample almost immediately after reaching the yield point, without even having time to engage the work hardening mechanism.

The influence of casting wall thickness (brick and ingot) is explained as follows. Enlarging the specimen cross-section (brick) during casting leads to a decrease in strength. The yield strength ($\sigma_{0.2}$) decreases by 15,0-16,6 % (a decrease of $\Delta\sigma_{0.2}$ = 83–99 MPa), while the tensile strength ($\sigma_в$) decreases more significantly, by 25,8–31,5 % (a decrease of $\Delta\sigma_{0.2}$ = 187–231 MPa). The yield strength ($\sigma_{0.2}$) correlates with the austenite grain size. Slow cooling of the ingot (thick-walled sample) stimulates the growth of coarse grains, which reduces resistance to microplastic deformation. The tensile strength ($\sigma_в$) decreases in the presence of carbides. Carbides act as internal notches, causing brittle intergranular fracture at relatively low tensile stresses.

The influence of the casting mold material (sand mold and chill mold) manifests itself differently on the yield strength and tensile strength. Sand mold casting increases the yield strength by $\Delta\sigma_{0.2}$ = 39 MPa for a brick and by $\Delta\sigma_{0.2}$ = 23 MPa for an ingot. This can be explained as follows. Casting in a metal chill mold (rapid cooling) creates a higher level of residual casting macrostresses in the structure. These stresses are added to the tensile force during testing, leading to an earlier onset of plastic flow. Chill mold casting of a thin-walled specimen (brick) slightly increases the tensile strength $\sigma_в$ = 731 MPa compared to sand mold casting $\sigma_в$ = 723 MPa due to the formation of a finer-grained structure. In a thick-walled sample (ingot), chill casting ($\sigma_в$ = 501 MPa), on the contrary, reduces the ultimate strength compared to a sample obtained by sand casting ($\sigma_в$ = 537 MPa).

Thus, slow cooling of thick-walled castings (ingots) degrades the strength properties of 110G13L steel in the as-cast condition, reducing the tensile strength $\sigma_в$ by ≈ 26 %. A sand mold is preferable for massive ingots, as it reduces residual stresses and eliminates the risk of shrinkage cracks, maintaining a higher tensile strength $\sigma_в$. The strength of a cast ingot, $\sigma_в$ = 501–537 MPa, is insufficient for the operation of components under high loads. The maximum strength $\sigma_в$ = 731 MPa is achieved on specimens with a small cross-section (brick) with accelerated cooling in a metal mold (chill mold).

Fig. 2 shows the values of the plasticity parameters (relative elongation δ and relative narroving ϕ) of 110G13L steel melts depending on the wall thickness of the casting (thin-walled brick and thick-walled ingot) and the material of the casting mold (sand and chill mold).

We note the relationship $\delta \geq \phi$, which is typical for Hadfield steel and can be explained as follows. The austenite of 110G13L steel has a low stacking fault energy (SFE ≈ 0,02–0,03 J/m^2). A low SFE hinders the transverse slip of dislocations, and under mechanical stress, the process of strain-induced twinning and high-density dislocation structures (phase hardening) actively develops in the austenite. As soon as local deformation begins in a certain section of the specimen, this area immediately hardensand becomes stronger than its neighbors. Therefore, the deformation is transferred to adjacent, as yet undeformed sections of the specimen.

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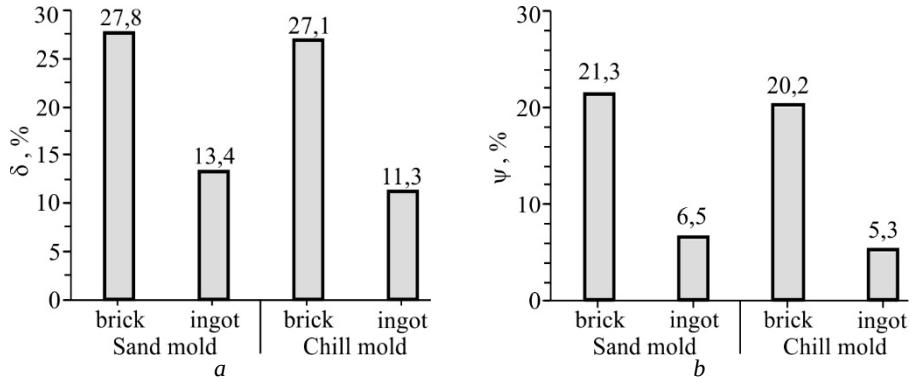


Figure 2. Dependence of the properties of 110G13L steel on the casting wall thickness (thin-walled brick and thick-walled ingot) and the material of the casting mold (sand and chill mold):
a – relative elongation δ; *b* – relative narroving ϕ

As a result, the specimen stretches uniformly along its entire calculated length without the formation of a pronounced "neck". The narrowing ϕ remains relatively small (≈ 5–20%), and the elongation δ due to uniform deformation reaches higher values (≈ 20–28 %).

Data analysis shows that the casting wall thickness significantly affects the ductility of the sample. The transition from a thin-walled brick to a thick-walled ingot leads to a significant decrease in both parameters: Relative elongation δ decreases by more than 2 times (from 27,0–27,8 % to 11,3–13,4 %). Relative narroving of area ϕ decreases by more than 3.3–3.8 times (from 20,2–21,3 % to 5,3–6,5 %). This change is explained as follows. In a slowly cooling ingot, the carbide phase $(Fe, Mn)_3C$ precipitates along the boundaries of austenite grains. Carbides block the possibility of sliding and twin formation. As a result, the steel loses its ability to undergo strain hardening and fails along the grain boundaries with a minimum value of relative narroving (ϕ ≈ 5–6 %).

A sand mold provides higher δ and ϕ values compared to a chill mold. In a thin-walled sample (brick), the change is minimal: Δδ = 0,7 %, Δϕ = 1,1 %. In a thick-walled sample (ingot), the advantage of sand casting becomes more noticeable (Δδ = 2,1 %, Δϕ = 1,2 %). Thus, the wall thickness of the casting significantly affects the ductility of the steel sample. In a thick-walled sample, compared to a thin-walled sample (brick), a decrease in elongation δ is observed by 2–3 times, and narroving of area ϕ is observed by almost 3–4 times.

The dependence of the impact toughness KCU of high-manganese steel 110G13L on the wall thickness of the casting (thin-walled brick and thick-walled ingot) and the material of the casting mold (sand mold and chill mold) is shown in Fig. 3. As in the case of plasticity characteristics (δ and ϕ), the wall thickness of the casting has a significant effect on impact toughness: When casting in a sand mold, the impact toughness of a thick-walled sample (ingot) decreases by 3,9 times (KCU = 0,49 MJ/m^2), compared to a thin-walled (brick) sample (KCU = 1,87 MJ/m^2).

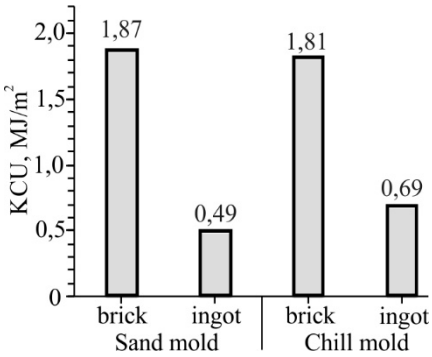


Figure 3. Dependence of the impact toughness KCU of 110G13L steel melts on the casting wall thickness (thin-walled brick and thick-walled ingot) and the material of the casting mold (sand and chill mold)

During chill casting, the transition from a brick to an ingot reduces toughness by a factor of 2,6 (from 1,81 to 0,69 MJ/m^2). The unique properties of 110G13L steel, namely its high dynamic strength and toughness, are due to its single-phase austenitic structure. In a massive ingot, the rate of solidification and subsequent cooling in the carbide precipitation temperature range is significantly lower than in a thin brick. Slow cooling leads to diffusional decomposition of the supersaturated solid solution and the precipitation of manganese/iron carbides $(Fe, Mn)_3C$ along grain boundaries. The accumulation of carbides serves as an ideal pathway for rapid crack propagation under impact loads, critically reducing impact toughness. The influence of the casting mold material (sand mold or chill mold) is characterized by an interesting anomaly that distinguishes the dependence of impact toughness from the previously discussed ductility indices. For a thin-walled specimen (brick), sand casting yields slightly better impact toughness (1,87 MJ/m^2) than chill mold casting (1,81 MJ/m^2). This is due to the lower level of residual casting stresses in the thin section. For a thick-walled specimen (ingot), chill mold casting provides significantly higher impact toughness (0,69 MJ/m^2) than sand casting (0,49 MJ/m^2), i.e., an

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increase of over 40 %. For an ingot prone to prolonged cooling, a chill mold (possessing high thermal conductivity) significantly accelerates heat removal during the solidification stage and subsequent cooling compared to a heat-insulating sand mold. Due to accelerated cooling in the chill mold, the growth of critically large austenite grains is suppressed (a finer-grained structure is formed). The overall number and thickness of carbide precipitates at grain boundaries are reduced. Despite the presence of internal stresses in the chill casting, grain refinement and suppression of carbide formation within the bulk of the ingot have a decisive positive effect on dynamic strength (impact toughness KCU).

Thus, it can be stated that the casting wall thickness has a negative effect on the viscosity value. The impact toughness of cast high-manganese steel decreases several times with an increase in casting thickness due to the formation of intercrystalline carbide precipitates. The advantage of a chill mold for large castings is the following. In contrast to the relative elongation, where the chill mold is inferior to the sand mold, the impact toughness of a massive ingot during chill casting increases (from 0,49 to 0,69 MJ/m^2) due to the refinement of the structure and the accelerated overcoming of the dangerous temperature range of carbide formation. It should be noted that the properties can be improved by using complex heat treatment [20]. KCU values at the level of 0,49–0,69 MJ/m^2 for ingots are considered unsatisfactory for industrial operation under high impact loads.

Fig. 4 shows the hardness values of high-manganese steel 110G13L in the cast state depending on the wall thickness of the casting (thin-walled bar and thick-walled ingot) and the material of the casting mold (sand and chill mold).

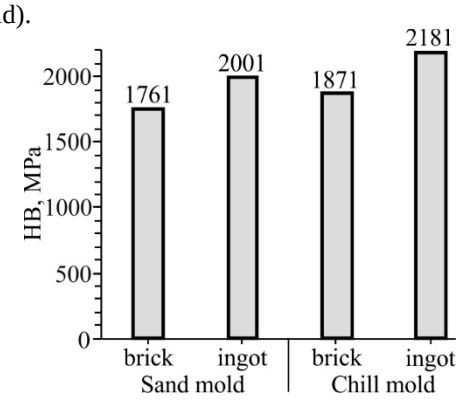


Figure 4. Dependence of the hardness of 110G13L steel melts on the thickness of the casting wall (thin-walled brick and thick-walled ingot) and the material of the casting mold (sand and chill mold)

The Brinell hardness (HB) values of the studied melts of high-manganese steel 110G13L vary in the range from 1761 MPa to 2181 MPa, which fully corresponds to the standard condition of cast Hadfield steel.

The hardness of 110G13L steel exhibits a dependence pattern directly opposite to the previously discussed parameters of ductility (δ, ϕ) and impact toughness (KCU). The factors that reduced toughness, in this case, lead to an increase in hardness. The effect of casting wall thickness on steel hardness is as follows. The transition from a thin-walled sample (brick) to a thick-walled sample (ingot) leads to an increase in steel hardness by 13,6–16,6%. During sand casting, the hardness increases from 1761 to 2001 MPa. During chill casting, the hardness increases from 1871 to 2181 MPa. In a slowly cooling massive thick-walled sample (ingot), diffusional decomposition of supersaturated austenite occurs with the precipitation of excess manganese and iron carbides of the $(Fe, Mn)_3C$ type along the grain boundaries. These carbides themselves possess extremely high hardness. Despite the steel becoming brittle (impact toughness decreases), under standard Brinell ball indentation, the presence of the hard carbide phase and the lattice distortions around it resist plastic deformation, thereby increasing the integral hardness of the alloy. Cooling in a metal mold (chill mold) increases hardness by 6,2–9,0 % compared to a sand mold for both casting geometries. The increase in hardness in the chill mold is due to grain refinement processes (the modifying effect of cooling rate): Rapid heat removal by the chill mold promotes a high rate of crystal nucleation, forming a finer-grained austenitic structure. According to the Hall-Petch law, decreasing grain size increases the yield strength and, consequently, the hardness of the material. Accelerated cooling in the chill mold "freezes" high internal stresses in the austenite crystal lattice, further hindering dislocation slip during mechanical indentation. Thus, the influence of casting conditions on the hardness behavior of steel is inversely proportional to its viscosity and ductility. The maximum hardness of 2181 MPa is achieved under conditions that ensure the greatest structural rigidity and carbide formation susceptibility in a massive ingot cast in a chill mold. It should be noted that increasing the cross-section (ingot) and accelerating cooling (chill mold) leads to increased hardness in high-manganese steel.

The initial hardness (before equipment operation) of 110G13L steel in the as-cast state is relatively low (1801–2201 MPa). Increased hardness due to carbide precipitation in a slowly cooled ingot is undesirable, as it makes the steel brittle. High wear resistance of Hadfield steel should be achieved not by carbides, but by dynamic work hardening (phase hardening and strain hardening of austenite) directly during operation under impact and abrasion loads. This significantly increases the hardness of the working surface (the hardness of jaw crusher plates as a result of work hardening reaches 5000–6000 MPa) while preserving the austenite phase in the casting core.

Conclusions

A study of the mechanical properties of high-manganese steel grade 110G13L with a fixed chemical

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composition but produced under different casting conditions (casting wall thickness and cooling rate) led to the following conclusions:

1. Casting thick-walled castings (ingots) reduces the strength characteristics of 110G13L steel compared to thin-walled specimens (brick). Sand casting (slow cooling) reduces the ultimate strength $\sigma_в$ by ~26% (from 723 MPa to 537 MPa). The maximum strength $\sigma_в$ = 731 MPa is achieved for specimens with a small cross-section (brick) with accelerated cooling in a metal mold (chill mold).

2. The casting wall thickness significantly affects the ductility of 110G13L steel. Casting Thick-walled castings (ingots) results in a 2-3-fold decrease in relative elongation δ, and a nearly 3-4-fold decrease in narroving ϕ.

3. The impact toughness of cast 110G13L steel decreases (from 1,81-1,87 MJ/m^2 to 0,49-0,69 MJ/m^2) with increasing casting wall thickness due to the formation of intergranular carbide precipitates.

4. The maximum hardness (2181 MPa) of cast 110G13L steel corresponds to a thick-walled casting (ingot) cast in a chill mold.

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ВПЛИВ ТЕХНОЛОГІЧНИХ ФАКТОРІВ ЛИТТЯ НА ФІЗИКО-МЕХАНІЧНІ ВЛАСТИВОСТІ ВИСОКОМАРГАНЦЕВОЇ СТАЛІ

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Мета роботи. *Розробка раціональної технології процесу лиття для підвищення механічних та експлуатаційних властивостей виливків із високомарганцевої сталі 110Г13Л.*

Методи дослідження. *Випробування на розрив проводили на машині УРМ-50. Визначення ударної в'язкості зразків з U-подібним надрізом проводили на маятниковому копрі МК-30А згідно ДСТУ ISO 148-1:2022. Твердість за Брінеллем визначали згідно ДСТУ ISO 6506-1:2007. Зразки сталі 110Г13Л для випробувань виготовлялися двох видів: з литих брусків розміром 10×10×55 мм³ (тонкостінний зразок) та вирізаних зі зливків розміром 80×80×200 мм³ (товстостінний зразок).*

Отримані результати. *Встановлено, що технологічним фактором, який підвищує фізико-механічні властивості високомарганцевої сталі 110Г13Л, є товщина стінки виливка та швидкість охолодження. Високий показник міцності $\sigma_в$ досягається на зразках із виливків з малим перетином (брусок) при прискореному охолодженні у металевій формі (кокілі). Лиття товстостінних виливків (зливків) призводить до зменшення відносного подовження та звуження ϕ. Ударна в'язкість сталі 110Г13Л зменшується зі збільшенням товщини стінки виливки.*

Наукова новизна. *Висока динамічна міцність та в'язкість сталі 110Г13Л забезпечується однофазною аустенітною структурою. Повільне охолодження призводить до виділення карбідів $(Fe, Mn)_3C$ за межами зерен. Накопичення карбідів сприяє поширенню тріщин при ударних навантаженнях, що знижує ударну в'язкість.*

Практична цінність. *Лиття товстостінних виливків (зливків) погіршує характеристики міцності сталі в порівнянні з тонкостінним зразком (бруском). Лиття товстостінних виливків (зливків) призводить до зменшення величин відносного подовження та звуження. Ударна в'язкість литої сталі зменшується зі збільшенням товщини стінки виливка через утворення карбідних виділень. Максимальна твердість литої сталі відповідає товстостінному виливку (зливку), відлитому в кокіль. Запропоновані рекомендації дозволять підвищити надійність та довговічність деталей із високомарганцевої сталі 110Г13Л.*

Ключові слова: *високомарганцева сталь, технологія лиття, аустеніт, карбіди, міцність, пластичність, твердість.*

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