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Cold-Resistant High-Strength Cast Iron and Its Application in Wind Turbine Structures

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Abstract: *Considerable deficit of electrical energy virtually in all countries of the Earth urges many countries to use all sources of its generation. Coal extraction accounts for a significant share among these sources, with coal being burnt by the operated thermal plants (TPP) which causes the global greenhouse gas emissions and polluting the Earth's atmosphere.*

Due to this fact, a need arose to abandon the use of coal and switch to clean alternative sources of power generation – wind turbines (WT), solar photoelectric power plants (SPPP) and other. This problem was highlighted at the World Climatic Summit COP26.

Due to intensive development of our planet's northern regions and the requirement for cold-resistant Arctic structural materials and cryogenic engineering, as well as

WT steel structures of Arctic and high-altitude version, the creation of a reliable and cheap cold-resistant structural material is of paramount importance that can be regarded as one of the world's main industrial problems.

The article describes advantages of cast sections made of unalloyed high high-strength cast iron (HSCI) with spheroidal graphite over cast steel and rolled steel sections; multi-zone applications of HSCI in the world's industry are described, and the problem of increasing HSCI cold resistance down to -100-150 °C is touched upon in order to further its extension of scope.

The results of a comprehensive study of the mechanical properties of cold-resistant HSCI (CRHSCI) in the temperature range of +20 to -150 °C are presented. Possible ways for increasing CRHSCI physical and mechanical properties by 30-40% and its cold-resistance down to -180—200 °C are determined.

Thus, the issue of creating a cold-resistant material that has no alternative – CRHSCI and its production technology, is solved. CRHSCI production shall be mastered and applied for production of casting by the world's industry that will ensure a considerable economic effect.

Key words*: cold-resistant high-strength cast iron, greenhouse gases, wind turbines, structures, Arctic version, materials, low temperatures, properties, casting process.*

Considerable deficit of electrical energy virtually in all countries of the Earth urges many countries to use all sources of its generation. Currently, coal extraction accounts for a significant share among these sources, with coal being burnt by the operated thermal plants (TPP). Coal burning causes the pollution of the Earth which is a great disadvantage of TPP operation in many countries.

The World Climatic Summit COP26 that that took place on October 26, 2021 in Glasgow, Scotland, ruled that in order to cut global emissions of the greenhouse gases in the nearest future (2030–2050) virtually all countries should abandon the use of coal and switch to large-scale introduction of next-generation green sources of power generation, that is, wind turbines (WT), solar photoelectric power plants (SPPP), hydroelectric power plants (HPP). Of all these power generation sources, WT will account for major part of

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power generation for a score of reasons. The results of power generation at existing HPPs indicate that their specific amount will significantly decrease due to a considerable reduction in river flows.

With respect to coal-based power generation, we can state that Portugal has already closed the last coal TPP. The use of coal for power generation was abandoned by three more European countries: Belgium, Austria and Sweden.

WT operated under critically extreme conditions for mechanical loads and temperature regimen – down to minus 50 °C. In this case, it should be noted that to prevent and avoid mechanical breakage, steel structures of plants' safety margin shall be 30—40% with respect to mechanical properties, and temperature strength margin of 30— 40 °C. The vibration of the plant structure, both under the influence of wind force and under the influence of the the plant operation shall be taken into account. With this regard, the issue of selecting the material for the plants structures is very important. The steel used as a material for plant structures is not reliable enough due to its limited cold resistance (down to -40 °C), as well as its lack of high damping capacity. High-carbon cast iron (HCCI) is undoubtedly the most efficient material having no alternative for plant structures. HCCI casts have a number of significant advantages over cast steel and rolled steel sections. HCCI has an obvious advantage over steel with respect to its casting properties, its lower cost (by 15–20%), better durability and antifrictionality, higher corrosive resistance and better machinability; HCCI lower density (by 8–10%) allows to reduce the parts weight when compared with steel parts weight; HCCI capacity to damp mechanical vibrations arising during operation, is higher than that of the steel. Currently, the production volume of gray iron castings is about 46.0%, while steel castings are about 9.0%, and HCCI castings account for more than 25.0% of the total world production of ferrous and non-ferrous alloys. These figures confirm the well-known advantages of HCCI casting over steel casting. The decrease in the production of steel castings is due to a further increase in HCCI castings production.

HCCI is widely used in nearly all industries: transport engineering, machine tool engineering, shipbuilding, road and energy engineering, as well as oil and gas processing and other industries.

But HCCI on the background of its well-known and undoubted advantages has a significant disadvantage – insufficient cold resistance of conventional HCCI grades which limits its application at negative temperatures below -50 C. Therefore, increase in cold resistance of HCCI is a very important problem.

– Due to the intensive development of northern regions and the need to manufacture the Arctic equipment, as well as parts for cryogenic engineering and wind turbines, the problem of increasing the cold-resistance of HCCI is very urgent and requires its solution.

– We have carried out a set of works related to the above development lines which resulted in in a scientific first internationally the development of technology for obtaining unalloyed cold-resistant cast iron with spheroidal graphite – CRHSCI down to -80 °C; -100 °C; -150 °C, and its introduction for mass production of castings that are operable down to minus 60 °C [1—6].

CRHSCI possesses a unique combination of physical and process properties, that is: high strength and ductility, high cold-resistance (down to 100—150 °C), very high damping capacity (a very important property for WT parts), high corrosive resistance, machinability of castings during their manufacture, and low cost price compared with other structural materials. It is this cast iron that is an ideal structural material for critical high-load parts of WT made in Arctic and high-altitude versions.

In order to develop and verify the effectiveness of CRHSCI production technology, numerous tests were conducted to check CRHSCI metal mechanical properties for strength and ductibility at normal and negative temperatures. This allowed to obtain valuable definite regularities which are described in numerous publications on this subject [1–5].

Below are the results of one of the numerous studies of unalloyed CRHSCI mechanical properties at normal and negative temperatures (down to – 150 °C). The process for obtaining the CRHSCI sampling metal for mechanical tests is described in [5]. CRHSCI chemical composition in %: 3.47 C; 1.91 Si; 0.37 Mn; 0.06 Mg; 0.051 P; 0.019 S; 0.041 Cr; 0.031 Ti. Two modes were used for thermal treatment (TT): mode 1 — heating up to 760 °C, exposure interval 3.5 h, cooling with oven down to 620 °C, exposure interval 0.5 h, which is followed by cooling at the open air; mode 2 – heating up to 760 °C, exposure 5.5 h, which is followed by TT in mode 1.

metallic substrate after TT in mode 1 – 80...90% ferrite, the rest is perlit, and after TT in mode 2 – 90...97% ferrite, the rest is perlite. 10 x 10 x 55 mm samples were subjected to Impact strength testing without cutting on impact testing machine, while the tensile strength test was performed on standard tensile samples.

The results of CRHSCI mechanical properties comprehensive study are presented in the table.

The analysis of the data provided in this table, allows us to arrive to the following conclusions:

– strength characteristics σ_B and $\sigma_{0.2}$ CRHSCI 1, CRHSCI 2 and CRHSCI3 are high level characteristics, but when temperature decreases from +20 °C to -150 °C, these indicators rise by 1.2—1.3 times.

– for thermally treated CRHSCI 2 and CRHSCI3 insignificant, but regular increase in δ, % is characteristic when temperature decreases from +20 °C to —60 °C, and when temperature is decreased further,
from -60 °C to -150 °C δ, % decreases, in this case, CRHSCI3 decreases to the least extent (from 18.5 to 12.1%);

– indicator Ψ %, decreases insignificantly within the temperature interval under study; in this case, CRHSCI3 has the highest indicators;

Condition of cold-resistant nodular iron	Test temperature, °C	$\sigma_в$, MPa	$\sigma_{0,2,}$ MPa	δ,%	ψ,%	KCU, J/cm^2
Cast CRHSC1	+20	504	310	14.0	8.2	42
	-60	599	382	13.0	8.0	20
	-80	-	-	—	—	10
	-100	607	398	10.1	7.6	5
	-150	621	457	7.2	7.6	—
TT – mode 1 CRHSCI2	+20	396	308	14.5	10.5	113
	-60	493	352	16.0	11.0	114
	-80	-	-	—	-	25
	-100	483	367	10.0	9.8	30
	-150	486	373	9.0	10.0	7
TT – mode 2 CRHSCI3	+20	415	277	18.5	13.5	130
	-60	490	335	20.0	14.5	120
	-80	—	—	—	—	128
	-100	470	339	12.5	12.9	52
	-150	506	365	12,1	12.0	11

— Kc indicator, J/cm of CRHSCI3 virtually does not decrease (from 130 to 128 J/cm2) when temperature drops from +20 °C to -80 °C), but when temperature drops further to 150 °C, it decreases significantly.

In general, when temperature decreases from +20 °C to –150 °C, the changes in strength and ductile indicators of cast and thermally treated CRHSCI are subjected to the same regularities. In this case, CRHSCI3 is the most efficient cast iron.

The damping capacity, crack resistance and corrosion resistance are important operational characteristics of metal for the operating conditions of wind turbines metal structures. The structure of HCCI metal, consisting of a metal matrix and spherical graphite inclusions, has a very high damping capacity, which allows to effectively dampen the vibrations of HCCI structures during their operation, unlike steel structures whose metal has a solid metal matrix.

Taking into account extreme operating conditions of wind turbines, it should be maintained that the metal structures of wind turbines shall possess a mandatory combination of the following basic performance characteristics at normal and negative temperatures:

— High strength and ductile properties;

— High damping capacity;

— High cracking resistance and corrosive resistance.

Only CRHSCI complies with these requirements. Thus, the developed technology of CRHSCI production ensures their operability down to negative temperature of -150 °C and allows us to consider the beginning of CRHSCI application as a material for high-loaded metal structures of wind turbines, and for parts of Arctic equipment and cryogenic engineering.

Summing up, the following should be noted:

1. The technology provides for the use of individual know-how elements that precondition effective production and gaining competitive advantages;
2. Perfection of cast iron melting and optimization of its chemical composition and structure will ensure increased indicators of CRHSCI ductility and viscosity by 30-40% and increase in its cold resistance down to 180-200 °C. To achieve the above indicators, relevant facilities and resources and the customer's concern are required;
3. To ensure successful and efficient application of CRHSCI for WT steel structures, it is reasonable to develop new models of these structures with respect to CRHSCI metal properties, and to provide WT operation in favorable and adverse conditions (high-altitude, Arctic and other);
4. The obtained results allow us to consider the fact of breakthrough in casting technology that ensures the new era in production and application of cold resistant high-strength cast iron.

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