doi: 10.32620/oikit.2025.105.05

UDK 669.15-196

O. G. Popova, V. V. Ostapchuk,
N. O. Lalazarova

Research of structural features of wear-resistant high-chromium alloys

National Aerospace University "Kharkiv Aviation Institute",
Kharkiv National Automobile and Highway University

The structure and distribution of alloying elements in wear-resistant high-chromium alloys with different chemical compositions were studied to ensure high hardness, strength and resistance to various types of wear. High-chromium cast irons are complex multicomponent alloys, so it is necessary to consider a number of features of alloying elements influence on the nature of phases formed in such alloys, as well as the processes occurring both during crystallization and during cooling of the casting in the solid state. In this regard, studies were conducted on the structure of high-chromium alloys with different chemical compositions. The structure of the high-chromium alloy was studied by X-ray spectral microanalysis, properties of the high-chromium alloys were determined by measuring hardness and microhardness. Heterogeneity of element distribution in the primary austenite grain was revealed. The chromium content varied from 4.7% in the region bordering the carbide to 14.9% in the grain center. The content of nickel, chromium, and manganese remained virtually unchanged across the specimen cross-section. Heterogeneity of silicon and molybdenum distribution across the specimen cross-section was revealed; their content is increased toward the center by 1.5–1.8 times. The carbide phase of the high-chromium alloys was represented by cementite-type carbides $(Fe, Cr)_3C$**,** special chromium carbides $(Cr, Fe)_7C_3$, and complex compounds based on Fe, Cr, Mo – $(Cr, Fe, Mo)_{23}C_6$. Research has established that increasing in the chromium content in the alloy leads to increasing in the level of microhardness of carbides. With increasing in the chromium content from 12.2 to 18.8%, the microhardness of carbides of the $(Fe, Cr)_3C$ type increases by 10 percent, and the microhardness of the special chromium carbides $(Cr, Fe)_7C_3$ increases by 5 percent.

***Keywords**:* high-chromium alloy; phase composition; carbides; microstructure; microhardness.

Introduction

The wear resistance of materials during abrasive wear is usually proportional to their hardness. During abrasive wear, the leading processes are multiple deformation of the surface by particles sliding along it and micro-cuts. The degree of development of these processes is largely determined by the ratio of the hardness of the material and abrasive particles. Since the hardness of abrasive particles is high, the greatest wear resistance is possessed by materials whose structure consists of a hard carbide phase and a high-strength matrix that binds them.

High wear resistance is typical for: white cast iron, steel, ceramics, aluminum oxide, zirconium oxide, etc. White cast iron has high hardness due to the presence of cementite, but it is quite brittle. High surface hardness provides good resistance to wear, especially abrasive wear. Due to different cooling rates across the section and obtaining different structures, casting has high internal stresses, which can lead to cracks. To relieve stress, castings are subjected to heat treatment.

High-chromium cast iron has high wear resistance. Chromium is the main alloying element of the group of white wear-resistant cast irons. Its content in such alloys can reach 35%. As a result of alloying with chromium, hardness, strength and resistance to various types of wear increase.

Mechanical properties of high-chromium cast irons depend primarily on the nature of the carbide phase being formed. Chromium is an element that promotes strong carbide formation. It can partially replace iron atoms in the carbide (Fe, Cr)$_3$C or form special chromium carbides in which some of its atoms are replaced by iron: (Cr, Fe)$_7$C$_3$ and (Cr, Fe)$_{23}$C$_6$.

At concentration of chromium up to 9.5%, the chromium carbide phase is represented by cementite. White cast irons of the Fe–C–Cr system with carbides (Fe, Cr)$_3$C crystallize with the formation of eutectic type ledeburite. However, cast irons with carbides of the Me$_3$C type have a greater tendency to brittle fracture.

Chromium–carbide eutectic is formed at chromium concentration of more than 10%. Microscopic pictures of solidification and morphology of structural components change which relates to appearance of new type of carbide phase. With increasing of chromium content in cast iron from 9.5 to 12%, ledeburite is gradually replaced by austenite chromium–carbide eutectics. Transition to carbides Me$_7$C$_3$, relates to crystallization of austenitic chromium–carbide eutectics providing advantages of cast irons with carbides of Me$_7$C$_3$ type over then cast iron Me$_3$C in strength and plasticity. The portion of carbides is determined mainly by the carbon content and the type of carbides by the chromium concentration. However, at the same carbon concentration, the quantity of carbides increases since the chromium concentration increases.

The matrix is much softer than the carbides, therefore, despite their high hardness, the matrix wears out due to chipping of carbides and scratching of the metal base material. Such wear is determined by the mechanical properties of the matrix material. If the base doesn’t have sufficient hardness, then carbides can chip off the surface, not realizing their high wear resistance. High wear resistance is a necessary but not sufficient condition for performance and reliability, therefore, when choosing the composition of cast iron, its strength and tendency to chipping should be considered.

The sizes of the structural components significantly affect the properties. With increasing of the degree of structure dispersion, the strength characteristics of cast irons increase significantly. By varying the cooling rate during crystallization, the direction of heat removal, etc., it is possible to change such important characteristics of the structure as the size and mutual arrangement of the carbide phase. In addition, it is possible to improve the properties of castings (reduce stress, increase plasticity and impact toughness, etc.) using heat treatment. The choice of heat treatment mode depends on the size, the original structure of the material, as well as on the requirements imposed on it [1-2].

Purpose and task statement

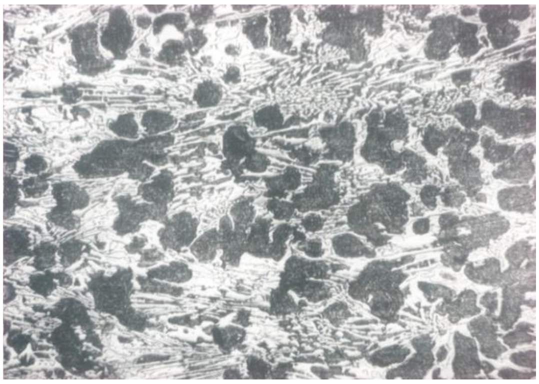
The purpose of the work is to research the structure and distribution of alloying elements in wear-resistant high-chromium alloys with different chemical compositions. In order to ensure the achievement of this goal, the following tasks were solved: the structure of the high-chromium alloys was studied by X-ray spectral microanalysis; properties of the high-chromium alloys were determined by measuring hardness and microhardness.

Analysis of research results

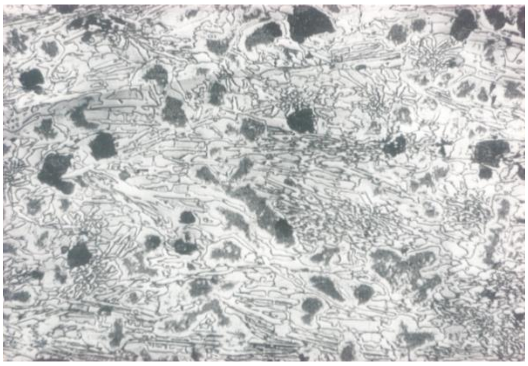
The initial structure of a high-chromium alloy is of decisive importance in the formation of its properties. High-chromium cast irons are complex multicomponent alloys. Therefore, it is necessary to consider a number of features of alloying elements influence on the nature of the phases formed in such alloys, as well as the processes occurring both during crystallization and during cooling of a casting in the solid state. In this regard, research was conducted on the structure of high-chromium cast irons with different chemical compositions.

Alloying the alloy with chromium, manganese, nickel and molybdenum leads to increasing the stability of austenite. Depending on the degree of alloying of an alloy, austenite acquires different ability to decompose, which in its turn, affects the phase composition of the alloy, the microstructure, and, consequently, its properties.

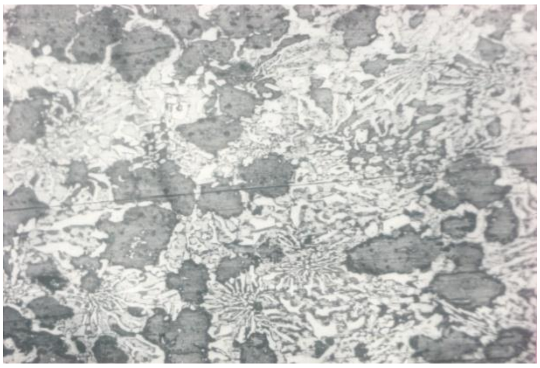
To assess the effect of chromium on the proportion of residual austenite and martensite, metallographic studies of alloys with a chromium content of 12.2–18.8% were carried out using a method for quantitatively assessing the phase composition (Fig. 1).



a



b



c

Fig. 1. Structure of high-chromium alloys with different chromium content:
a – 12.2% Cr; b – 16.6% Cr; c – 18.8% Cr, x100

Increasing of the carbon content in alloy leads to decreasing in the stability of austenite and increasing in the rate and degree of pearlite decomposition. Therefore, alloys with carbon content up to 2.80% were studied. Obtained dependencies are shown in Fig. 2.

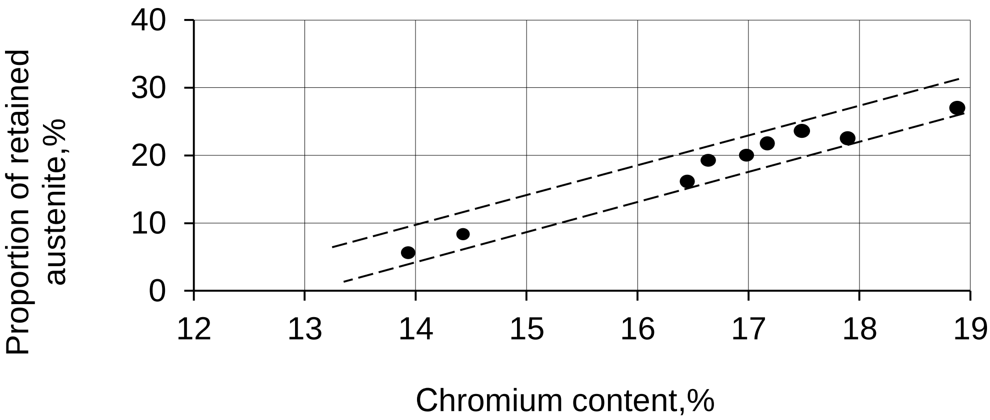


Fig. 2. Change in the proportion of residual austenite depending on the chromium content in alloys

The studies were conducted to determine the distribution of alloying elements in a high-chromium alloy using the X-ray spectral microanalysis method. The carbide phase of the alloy containing 17% Cr, 2.58% C, 0.74% Si, 1.10% Mn, 0.07% P, 0.04% S, 1.28% Ni, 0.98% Mo, 0.03% Mg in the cast state was studied using the X-ray spectral microanalysis method, which made it possible to study the content and distribution of alloying elements more precisely. The presence of carbides with chromium content of 10.6 – 13.2%, in which there was no molybdenum, the amount of manganese in them didn’t exceed 1.1% was revealed. Based on the literature data [1–4], it can be concluded that these carbides belong to cementite type. Carbides containing 34.6–39.9% chromium, 1% molybdenum, 0.56–0.8% manganese can be classified as special carbides of the $(Cr, Fe)_7C_3$ type. Carbides containing from 10.1 to 36.8% chromium and from 4.32 to 15.9% molybdenum were also identified in the structure. These carbides can be classified as the complex compounds of the $(Cr, Fe, Mo)_{23}C_6$ type [5–7].

Formation of carbides is accompanied by significant depletion of the alloying component of the solid solution boundary zones with them. Distribution of chromium and silicon in the primary austenite grain was estimated by X-ray spectral microanalysis. The measurement step was 5 μm. As studies have shown, the chromium content in the primary austenite grain varies from 4.7% in the boundary region with the carbide to 14.9% in the grain center. It was found that silicon is mainly concentrated in the matrix. Its content in the boundary region with the carbide is increased (1.8 – 2.2%) compared with the grain center, where its concentration doesn’t exceed 0.7 – 1.7%. The molybdenum content in the matrix varied from 0.6 to 5.2%, and nickel – from 0.4 to 2.8%. Zones without nickel and molybdenum were also revealed. Manganese is distributed uniformly and its amount in the carbide phase and matrix is almost equal.

The properties of high-chromium alloys are closely related to the type of phases formed and their ratio. The level of hardness and strength of high-chromium alloys is mainly determined by the type, size, distribution of the carbide phase and the structure of the metal matrix. The ratio of the matrix phases can be controlled by appropriate alloying and subsequent heat treatment. The number, shape, size and location of primary and eutectic carbides are predetermined by the crystallization process.

In this regard, the influence of the proportion of carbides and the matrix structure on the level of alloy properties was studied.

By increasing the proportion of residual austenite from 5 to 25% and martensite to 40% with a constant amount of carbide phase, it is possible to increase the hardness by 10 HS, which is 14.2% of its average level, while the coercive force increases by 30%. Increasing in the level of coercive force indicates a significant increasing in phase stresses, which can increase significantly during operation and contribute to crack formation. By reducing the proportion of carbide phase, it is possible to achieve decreasing in coercive force by 14.3%, while the hardness will decrease by 5 HS.

The level of properties of the carbide phase was assessed by microhardness. This method is the most sensitive to changes in its composition and condition.

The microhardness of the carbide phase was measured for alloys with different chemical compositions. Studies have shown that increasing in the chromium content in the alloy leads to increasing in the microhardness of the carbides (Table 1). With increasing of the chromium content from 12.2 to 18.8% (the coefficient K changes from 4.42 to 6.71), the microhardness of the carbides $(Fe, Cr)_3C$ increases from H_{50} = 856 to H_{50} = 936, and $(Cr, Fe)_7C_3$ from H_{50} = 1372 to H_{50} = 1436.

Table 1

Microhardness of carbide phases

Microhardness of carbides $(Cr, Fe)_7C_3$				Microhardness of carbides $(Fe, Cr)_3C$			
Content of elements, %		K = Cr / C	Average micro-hardness*	Content of elements, %		K = Cr / C	Average micro-hardness*
C	Cr			C	Cr		
2.86	13.9	4.86	1372	2.76	12.2	4.42	856
2.78	14.6	5.25	1381	2.86	13.9	4.86	876
2.77	15.3	5.52	1390	2.78	14.6	5.25	893
2.82	16.4	5.82	1400	2.77	15.3	5.52	900
2.94	16.8	5.71	1404	2.82	16.4	5.82	908
2.58	17.0	6.59	1408	2.94	16.8	5.71	914
2.70	17.5	6.48	1418	2.58	17.0	6.59	920
2.86	17.9	6.26	1427	2.70	17.5	6.48	931
2.80	18.8	6.71	1436	2.86	17.9	6.26	936

*Average results from 50 measurements

Thus, the microhardness of carbides of the type $(Fe, Cr)_3C$ is in the range of H_{50} = 856 – 936, and special chromium carbides $(Cr, Fe)_7C_3$ H_{50} = 1372 – 1436. Carbides with H_{50} = 1600 – 1900 were also identified, which apparently can be classified as complex compounds of the type $(Cr, Fe, Mo)_{23}C_6$. Research has established that increasing in the chromium content in the alloy leads to increasing in the level of microhardness of the carbides.

Conclusions

The properties of wear-resistant high-chromium alloy are most fully assessed by the level of hardness, strength and coercive force. The choice of the optimal chemical composition and technological parameters of casting allows providing the required level of properties.

The structure of the high-chromium alloy was studied by X-ray spectral microanalysis. Heterogeneity of element distribution in the primary austenite grain was revealed. The chromium content varied from 4.7% in the region bordering the carbide to 14.9% in the grain center. The content of nickel, chromium, and manganese remained virtually unchanged across the cross-section. Heterogeneity of silicon and molybdenum distribution across the cross-section was revealed; their content increased toward the center by 1.5–1.8 times. The carbide phase of the high-chromium alloy was represented by cementite-type carbides, $(Cr, Fe)_7C_3$, and complex compounds based on Fe, Cr, and Mo.

The microhardness of carbides of the $(Fe, Cr)_3C$ type is within the range of $H_{50} = 856 – 936$, and special chromium carbides $(Cr, Fe)_7C_3$ within the range of $H_{50} = 1372 – 1436$. Carbides with $H_{50} = 1600 – 1900$ were also identified, which can be classified as complex compounds of the $(Cr, Fe, Mo)_{23}C_6$ type. Research has shown that increasing in the chromium content in the alloy leads to increasing in the microhardness of the carbides. With increasing in the chromium content from 12.2 to 18.8%, the microhardness of carbides of $(Fe, Cr)_3C$ increases from $H_{50} = 856$ to $H_{50} = 936$, and $(Cr, Fe)_7C_3$ – from $H_{50} = 1372$ to $H_{50} = 1436$.

Список літератури

1. Вакуленко І. О. Структурний аналіз в матеріалознавстві / І. О. Вакуленко. – Дніпропетровськ, 2010. – 124 с.

2. Волчок И. П. Влияние легирования и термической обработки на распределение элементов и свойства высокохромистых чугунов / И. П. Волчок, В. В. Нетребко // Науч. вестн. Донбас. гос. машиностр. акад. : сб. науч. тр. –2015. – № 3 (18Е). – С. 52–59.

3. Нетребко В. В. К вопросу образования карбидов Fe3C и Fe7C3 в высокохромистых чугунах / В. В. Нетребко // Наука та прогрес транспорту. – 2016. – № 3 (63). – С. 138–147. doi: 10.15802/stp2016/74736.

4. Нетребко В. В. Особенности термической обработки высокохромистых чугунов легированных Mn и Ni / В. В. Нетребко, И. П. Волчок // Нові матеріали і технології в металургії та машинобудуванні. – 2016. – № 1. С. 53–57.

5. Чабак Ю. Г. Структурные изменения в комплекснолегированном белом чугуне при дестабилизирующем нагреве / Ю. Г. Чабак, В. Г. Ефременко, Р. Р. Станишевский // Вісн. Дніпропетр. нац. ун-ту залізн. трансп. ім. акад. В. Лазаряна. – 2011. – № 38. С. 229–232.

6. Kopyciński D. Analysis of the Structure and Abrasive Wear Resistance of White Cast Iron With Precipitates of Carbides / D. Kopyciński, M. Kawalec, A. Szczęsny, R. Gilewski, S. Piasny // Archives of Metallurgy and Materials / Institute of metallurgy and materials science of Polish academy of sciences. – 2013. – Vol. 58. Iss. 3. – P. 973–976. doi: 10.2478/amm-2013-0113.

7. Belikov S. Manganese influence on chromium distribution in high-chromium cast iron / S. Belikov, I. Volchok, V. Netrebko // Archives of Metallurgy and Materials / Institute of metallurgy and materials science of Polish academy of sciences. – 2013.

– Vol. 58. Iss. 3. – P. 895–897. doi: 10.2478/amm-2013-0095.

References

1. Vakulenko I. O. Strukturnij analiz v materialoznavstvi / I. O. Vakulenko. – Dnipropetrovs'k, 2010. – 124 s.

2. Volchok I. P. Vlijanie legirovanija i termicheskoj obrabotki na raspredelenie jelementov i svojstva vysokohromistyh chugunov / I. P. Volchok, V. V. Netrebko // Nauch. vestn. Donbas. gos. mashinostr. akad. : sb. nauch. tr. – 2015. – № 3 (18E). – S. 52–59.

3. Netrebko V. V. K voprosu obrazovanija karbidov Fe_3C i Fe_7C_3 v vysokohromistyh chugunah / V. V. Netrebko // Nauka ta progres transportu. – 2016. – № 3 (63). – S. 138–147. doi: 10.15802/stp2016/74736.

4. Netrebko V. V. Osobennosti termicheskoj obrabotki vysokohromistyh chugunov legirovannyh Mn i Ni / V. V. Netrebko, I. P. Volchok // Novi materiali i tehnologiï v metalurgiï ta mashinobuduvanni. – 2016. – № 1. – S. 53–57.

5. Chabak Ju. G. Strukturnye izmenenija v kompleksnolegirovannom belom chugune pri destabilizirujushhem nagreve / Ju. G. Chabak, V. G. Efremenko, R. R. Stanishevskij // Visn. Dnipropetr. nac. un-tu zalizn. transp. im. akad. V. Lazarjana. – 2011. – № 38. – S. 229–232.

6. Kopyciński D. Analysis of the Structure and Abrasive Wear Resistance of White Cast Iron With Precipitates of Carbides / D. Kopyciński, M. Kawalec, A. Szczęsny, R. Gilewski, S. Piasny // Archives of Metallurgy and Materials / Institute of metallurgy and materials science of Polish academy of sciences. – 2013. – Vol. 58. Iss. 3. – P. 973–976. doi: 10.2478/amm-2013-0113.

7. ‘Belikov S. Manganese influence on chromium distribution in high-chromium cast iron / S. Belikov, I. Volchok, V. Netrebko // Archives of Metallurgy and Materials / Institute of metallurgy and materials science of Polish academy of sciences. – 2013. – Vol. 58. Iss. 3. – P. 895–897. doi: 10.2478/amm-2013-0095.

Надійшла до редакції 18.08.2025, розглянута на редколегії 18.08.2025

Дослідження особливостей структури зностійких високохромистих сплавів

Досліджено структуру та розподіл легуючих елементів у зносостійких високохромистих сплавах з різним хімічним складом для забезпечення високої твердості, міцності та опору різним видам зносу. Високохромисті чавуни є складними багатокомпонентними сплавами, тому необхідно враховувати цілий ряд особливостей впливу легуючих елементів на природу фаз, що утворюються в таких сплавах, а також процеси, що протікають як при кристалізації, так і при охолодженні виливки в твердому стані. У зв'язку з цим були проведені дослідження структури високохромистих сплавів з різним хімічним складом. Структуру високохромистого сплаву вивчали методом рентгеноспектрального мікроаналізу, властивості високохромистих сплавів визначали шляхом вимірювання твердості та мікротвердості. Виявлено неоднорідність розподілу елементів у зерні первинного аустеніту. Вміст хрому варіювався від 4,7% в області, що межує з карбідом, до 14,9% у центрі зерна. Вміст нікелю, хрому та марганцю практично не змінювався по поперечному перерізу. Виявлено неоднорідність розподілу кремнію та молібдену по поперечному перерізу; їх вміст збільшувався до центру в 1,5–1,8 рази. Карбідна фаза високохромистих сплавів була представлена карбідами цементитного типу (Fe, Cr)$_3$C; спеціальними карбідами хрому (Cr, Fe)$_7$C$_3$ та комплексними сполуками на основі Fe, Cr, Mo – (Cr, Fe, Mo)$_{23}$C$_6$. Дослідженнями встановлено, що збільшення вмісту хрому у сплаві призводить до підвищення рівня мікротвердості карбідів. Зі збільшенням вмісту хрому від 12,2 до 18,8% мікротвердість карбідів типу (Fe, Cr)$_3$C збільшується на 10 відсотків, а мікротвердість спеціальних карбідів хрому (Cr, Fe)$_7$C$_3$ – на 5 відсотків.

Ключові слова: високохромистий сплав; фазовий склад; карбіди; мікроструктура; мікротвердість.

Відомості про авторів:

Попова Олена Георгіївна – к.т.н., доцент кафедри композиційних конструкцій і авіаційного матеріалознавства (№ 403), тел. (+38) 067-570-12-17, e-mail: o.popova@khai.edu, Національний аерокосмічний університет «Харківський авіаційний інститут», м. Харків, Україна, ORCID: 0009-0003-3599-2273.

Остапчук Валентина Віталіївна – старший викладач кафедри композиційних конструкцій і авіаційного матеріалознавства (№ 403), тел. (+38) 093-574-99-67, e-mail: v.ostapchuk@khai.edu, Національний аерокосмічний університет «Харківський авіаційний інститут», м. Харків, Україна, ORCID: 0000-0002-1584-6960.

Лалазарова Наталія Олексіївна – к.т.н., доцент кафедри технології металів та матеріалознавства, тел. (+38) 095-390-38-16, e-mail: lalaz1932@gmail.com. Харківський національний автомобільно-дорожній університет, м. Харків, Україна, ORCID: 0000-0002-2138-9081.

About the Autors:

Popova Olena – PhD, Associate Professor, Department of Composite Structures and Aviation Materials, (+38)067-570-12-17, e-mail: o.popova@khai.edu, National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine, ORCID: 0009-0003-3599-2273.

Ostapchuk Valentyna – Senior Lecturer, Department of Composite Structures and Aviation Materials, (+38) 093-574-99-67, e-mail: v.ostapchuk@khai.edu, National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine, ORCID: 0000-0002-1584-6960.

Lalazarova Nataliia – PhD, Associate Professor, Department of Technology of Metals and Materials Science, tel. (+38) 095-390-38-16, e-mail: lalaz1932@gmail.com, Kharkiv National Automobile and Highway University, Kharkiv, Ukraine, ORCID: 0000-0002-2138-9081.