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Changes in Abrasive Wear Resistance During Miller Test of Cr-Ni Cast Steel with Ti Carbides Formed in the Alloy Matrix

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Abstract

Austenitic chromium-nickel cast steel is used for the production of machine parts and components operating under corrosive conditions combined with abrasive wear. One of the most popular grades is the GX2CrNi18-9 grade, which is used in many industries, and mainly in the chemical, food and mining industries for tanks, feeders, screws and pumps.

To improve the abrasion resistance of chromium-nickel cast steel, primary titanium carbides were produced in the metallurgical process by increasing the carbon content and adding titanium, which after alloy solidification yielded the test castings with the microstructure consisting of an austenitic matrix and primary carbides evenly distributed in this matrix.

The measured hardness of the samples in both as-cast conditions and after solution heat treatment was from 300 to 330HV0.02 and was higher by about 40-70 units compared to the reference GX2CrNi18-9 cast steel, which had the hardness of 258HV0.02.

The abrasive wear resistance of the tested chromium-nickel cast steel, measured in the Miller test, increased by at least 20% (with the content of 1.3 wt% Ti). Increasing the Ti content in the samples to 5.3 and 6.9 wt% reduced the wear 2.5 times compared to the common GX2CrNi18-9 cast steel.

Keywords: Chromium-nickel cast steel, Microstructure, Titanium carbides, Hardness, Abrasion

1. Introduction

Austenitic steels and chromium-nickel cast steels are used for the production of machine parts and components operating under corrosive conditions combined with abrasive wear. One of the most popular grades of stainless steel is X2CrNi18-9, successfully applied in many branches of the industry, but primarily in the chemical industry, food processing plants, pulp and paper industry and mining industry for heat exchangers, tanks, feeders, screws, as well as transmission pipelines and pumps. In these alloys, the addition of strong carbide-forming elements such as Ti is at the level of tenths of a percent (max. 0.7%) and is inherent in the technological process, e.g. 0.2% Ti acts as a modifier or is added to improve technological and operational properties such as weldability and corrosion resistance [1-10,14-16]. Table 1 gives examples of chemical compositions of austenitic corrosion-resistant steels. The chemical compositions of cast steel correspond to the chemical compositions of steel [10].

Table 1.
Sample chemical compositions of austenitic chromium-nickel steels [10]

Alloy designation	Chemical composition [wt%]								
	C	Mn	Si	P	S	Cr	Ni	Mo	Other
X2CrNi18-9	< 0.03	< 2.00	< 0.80	< 0.045	< 0.030	18.5	8.8	–	N < 0.11
X5CrNi18-10	< 0.07	<2.00	< 0.80	< 0.045	< 0.030	18.5	9.3	–	N < 0.11
X10CrNi18-8	0.1	< 2.00	<1.00	< 0.045	<0.030	17.5	7.8	< 0.8	N < 0.11
X6CrNiTi18-10	< 0.08	< 2.00	< 0.80	< 0.045	< 0.030	18.0	10.5	–	Ti=5xC÷0.7
X2CrNiMo17-12-2	<0.03	< 2.00	< 1.00	< 0.045	< 0.030	17.5	11.5	2.3	N < 0.11
X6CrNiMoTi17-12-2	< 0.08	< 2.00	< 1.00	<0.045	< 0.030	17.5	12.0	2.3	Ti=5xC÷0.7

The microstructure of this grade of cast steel should be austenitic (or austenitic-ferritic), free from chromium carbide precipitates at the grain boundaries, since their presence harms corrosion resistance. This type of structure is obtained by subjecting the alloy to a solution heat treatment. Apart from the austenitic matrix, a small amount of ferrite is also present in alloys containing the addition of Mo [1-9,14-16]. Figures 1 and 2 show the characteristic microstructures of austenitic-ferritic cast steel in as-cast conditions and after solution heat treatment.

Figure 3 compares the abrasive wear resistance of heat-treated austenitic Cr-Ni cast steel containing 0.1% C, 18.4% Cr, 8.3% Ni and 0.4% Mo with the abrasive wear resistance of steel of similar chemical composition. The cast steel is characterized by a significantly lower (nearly two times) degree of wear [own research].

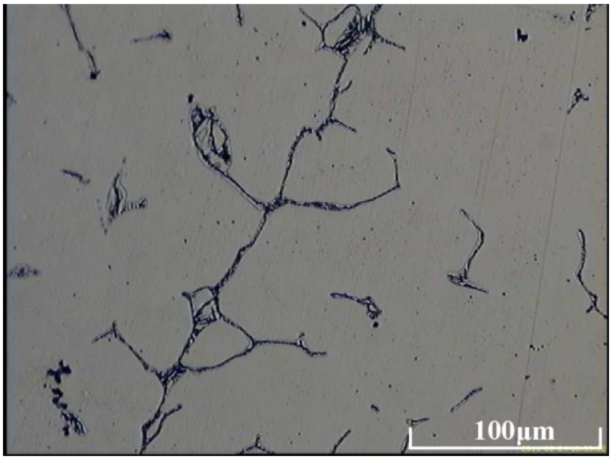

Fig. 1. Microstructure of GX10CrNiMo18-9 cast steel in as-cast condition; austenite with traces of ferrite and chromium carbides at the grain boundaries; etched with Mi16Fe [13]

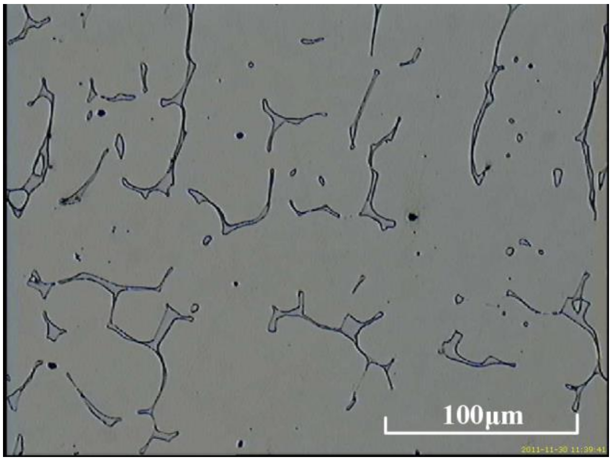

Fig. 2. Microstructure of GX10CrNiMo18-9 cast steel after solution heat treatment; austenite with traces of ferrite at the grain boundaries; etched with Mi16Fe [13]

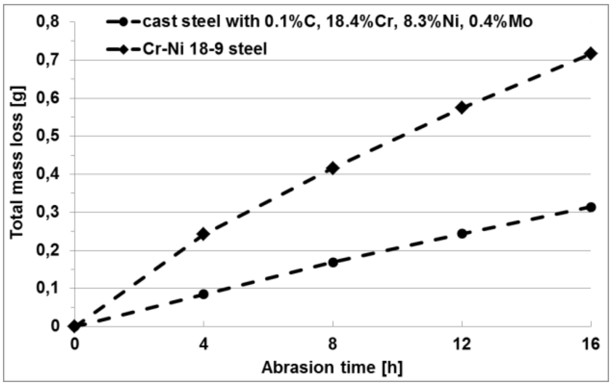

Fig. 3. Mass losses as a function of abrasion time in the Miller test compared for samples made of the Cr-Ni 18-9 steel and cast steel [13]

In previous research [11] on the properties of austenitic high-manganese cast steel with the addition of titanium, the author and his colleagues examined changes in the microstructure and abrasive wear resistance of Hadfield cast steel with the addition of Ti (0.4-2.5% Ti). The abrasive wear resistance was determined in the Miller test. In all tested samples after solution heat treatment, the structure obtained was composed of an austenitic matrix with primary titanium carbides evenly distributed in this matrix and cementite-free grain boundaries. Figure 4 shows an example of the microstructure of the tested alloy with 2.0% Ti content. In the Miller test of abrasion resistance, the obtained wear resistance was at least two times higher than in the classic Hadfield cast steel. Figure 5 compares the wear behaviour of Hadfield cast steel and high-manganese cast steel with the addition of Ti.

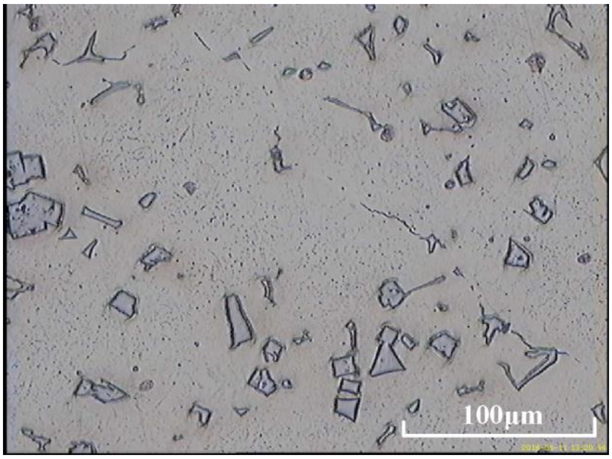

Fig. 4. Microstructure of cast steel with the addition of 2.0% Ti after solution heat treatment; austenitic matrix with primary titanium carbides evenly distributed in this matrix; etched with nital, [11]

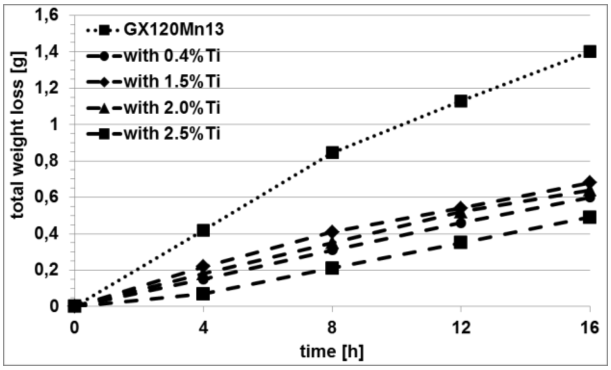

Fig. 5. Hadfield cast steel wear behaviour compared with that of high-manganese cast steel containing the addition of 0.4-2.5% Ti [11]

The satisfactory test results obtained so far for the high-manganese cast steel in terms of its microstructure and abrasion resistance determined in the Miller test prompted the author to research chromium-nickel cast steel with the addition of titanium.

2. Test materials and methods

The specimens were cut out from "Y" type test ingots with a wall thickness of 25 mm and a weight of about 0.8 kg. The test ingots were cast from the steel obtained by melting the 18-10 steel scrap with the required alloying additives and the addition of Fe-Ti70 in a laboratory vacuum induction furnace. To make the chemical composition complete, appropriate amounts of carburizer in the form of pig iron of known chemical composition, metallic chromium, electrolytic nickel and Fe-Ti70 were added to the 18-10 steel melt in the metallurgical process. The addition of titanium introduced at the final stage of the melting process caused the formation of primary titanium carbides in the liquid steel. After casting solidification, these carbides were evenly distributed in the alloy matrix.

The analysis of the chemical composition of the tested alloys was carried out under industrial conditions with a Foundry Master spectrometer. The industrial analysis was later completed with the laboratory analysis using an energy dispersive X-ray fluorescence spectrometer. Table 2 shows the chemical compositions of the tested alloys.

Based on the analysis of the chemical composition of the test ingots, it was found that in the melted cast steel the content of the basic elements, i.e. Cr and Ni, was comparable to the composition of the reference GX10CrNiMo18-9 cast steel. The carbon content in the test ingots ranged from 0.34 to 1.12%, while the silicon content increased from 0.45 to 1.28%, which was due to the adopted method of deoxidizing the steel melt with Fe-Ca-Si. The Ti content in the tested alloys ranged from 1.3 to 6.9% and was increasing along with the carbon content.

The specimens were subjected to the solution heat treatment at a temperature of 1050°C with cooling in water. The annealing time was 30 minutes.

The matrix hardness was measured with a Vickers hardness tester under a load of 20 g for samples both as-cast and after solution heat treatment.

The microstructures of the tested alloys were examined with a Neophot 32 light microscope equipped with a camera for digital image recording.

The analysis of the chemical composition of carbides in the tested alloys was performed with a JSM-7100F scanning microscope equipped with an EDS microanalyzer.

Phases detected in the tested samples were identified with a Kristalloflex 4H X-ray diffractometer made by Siemens, using the characteristic Cu radiation (Kα = 0.154 nm) at a step of 0.05 2theta/1s.

The abrasive wear resistance was determined in the Miller test, which is used to compare the abrasion resistance of various construction materials. The application of this method enabled the author to compare his results with the results obtained previously and with the results of research done by his colleagues [11-13]. The samples with dimensions of 25.4 x 12.7 mm and a thickness of 9 mm were placed in the holders of the device under a constant load of 22.2N and were subjected to abrasion in a mixture of water and silicon carbide in the ratio of 1: 1. The counter-sample was the rubber lining of the bottom of the trough where the abrasion process took place. Silicon carbide with a grain size of 53 - 73 µm was used. Sixteen-hour wear tests were performed in 4 cycles. Every four hours, the samples were weighed with an accuracy of 0.001g. Based on the obtained mass losses, the wear curves were plotted for the tested samples. The wear behaviour of the tested alloys was compared with the wear behaviour of a reference sample made of the corrosion-resistant austenitic cast steel containing 0.1% C, 18.4% Cr, 8.3% Ni and 0.4% Mo, subjected to standard solution heat treatment at a temperature of 1050°C. The average hardness of the reference sample was 258HV0.02.

Table 2.
Chemical compositions of the tested Cr-Ni-Ti cast steel

Alloy designation	Chemical composition [wt%]									
	C	Mn	Si	P	S	Cr	Ni	Mo	V	**Ti**
Cr-Ni-Ti-3	0.34	1.41	0.45	0.031	0.014	18.7	8.5	0.4	0.1	**1.3**
Cr-Ni-Ti-2	0.57	0.99	0.64	0.033	0.019	18.5	9.5	0.4	0.2	**3.1**
Cr-Ni-Ti-4	0.88	1.06	0.60	0.046	0.016	16.6	9.3	0.3	0.2	**5.3**
Cr-Ni-Ti-1	1.12	0.90	1.28	0.003	0.009	19.0	8.9	0.3	0.3	**6.9**

3. Test results

Table 3 gives heat treatment parameters applied to the tested samples and measured hardness values. Compared to the samples in as-cast condition, the solution heat treatment from 1050°C with cooling in the water had no significant effect on the obtained values of hardness. In both cases, the hardness was from 300 to 330HV0.02 and was 40-70 units higher compared to the reference cast steel (258HV0.02). The scatter of the measured hardness values proves the homogeneity of the tested alloys and is due to the presence of carbide precipitates in the matrix. This is also the reason why the average hardness values are not given in Table 3.

Table 3.
Heat treatment of the tested alloys and their hardness

Alloy designation	Heat treatment	Hardness [HV0.02]
Cr-Ni-Ti-1	As-cast	307, 318, 296
Cr-Ni-Ti-2		301, 307, 312
Cr-Ni-Ti-3		307, 324, 312
Cr-Ni-Ti-4		330, 330, 324
Cr-Ni-Ti-1	1050°C/0.5h/water	357, 343, 343
Cr-Ni-Ti-2		318, 307, 318
Cr-Ni-Ti-3		318, 307, 330
Cr-Ni-Ti-4		330, 343, 330
GX2CrNi18-9	1050°C/0.5h/water	258, 258, 258

Based on the observations carried out by the light microscopy (Figs. 6-9) and scanning microscopy (Fig. 10), analysis of the chemical composition of the visible precipitates (Fig. 11 and Table 4) and X-ray examinations of the phases (Fig. 12), it was found that the microstructure of all tested cast steels after solution heat treatment consisted of an austenitic matrix and primary titanium carbides evenly distributed in this matrix. At the same time, TiC carbides (Fig. 10, Table 4, spot 9) are the crystallization nuclei for complex (Ti, Mo, Cr, Nb)$_x$C$_y$ carbides (Fig. 10, Table 4, spot 10). The results of X-ray examinations (Fig. 12) have indicated traces of ferrite in the matrix which were not revealed by metallographic examinations. Higher content of carbon (0.88 and 1.12%) and titanium (5.3 and 6.9%) makes carbides prone to the formation of clusters (Figs. 6-9).

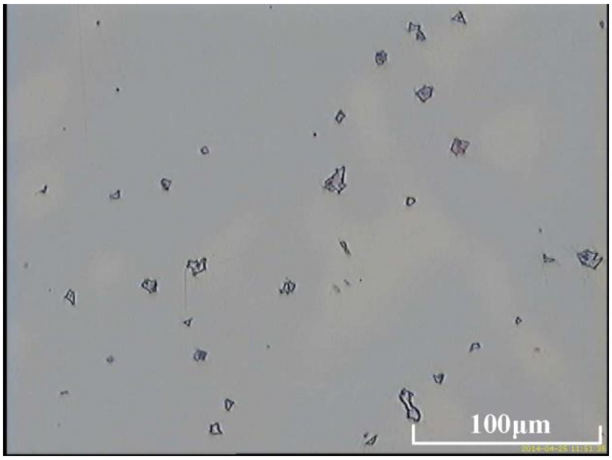

Fig. 6. Microstructure of cast steel with the addition of 1.3% Ti after solution heat treatment; austenitic matrix with primary titanium carbides; etched with Mi16Fe

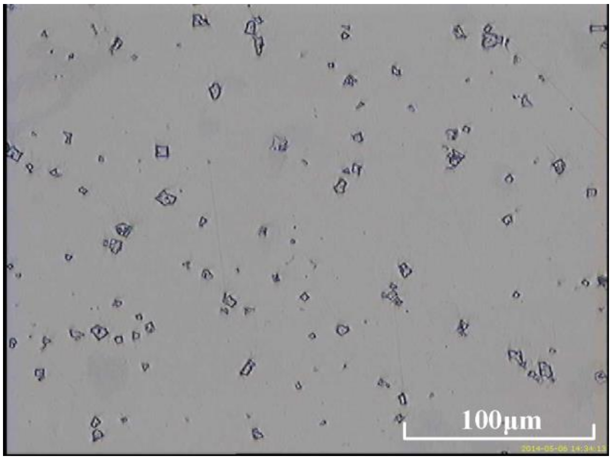

Fig. 7. Microstructure of cast steel with the addition of 3.1% Ti after solution heat treatment; austenitic matrix with primary titanium carbides; etched with Mi16Fe

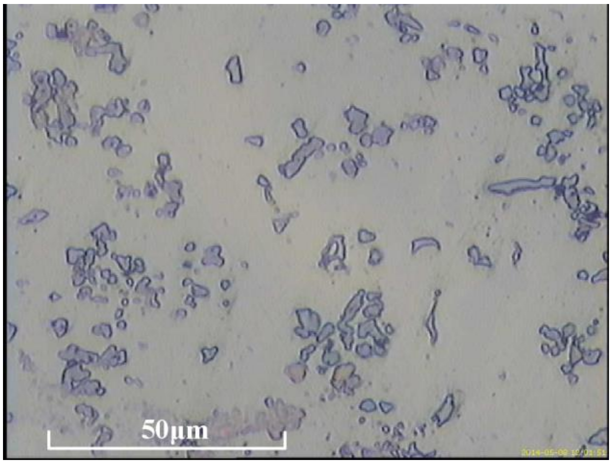

Fig. 8. Microstructure of cast steel with the addition of 5.3% Ti after solution heat treatment; austenitic matrix with primary titanium carbides; etched with Mi16Fe

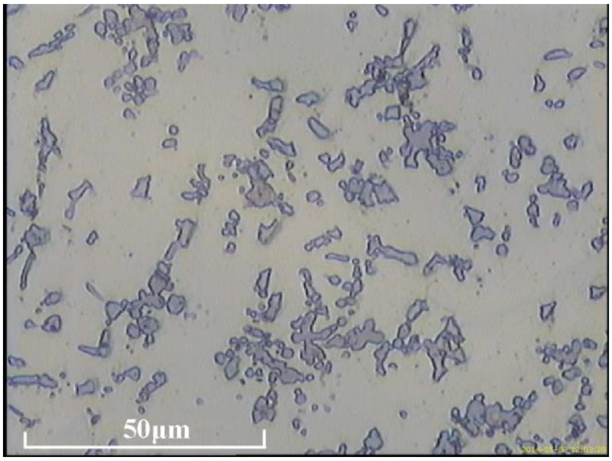

Fig.9. Microstructure of cast steel with the addition of 6.9% Ti after solution heat treatment; austenitic matrix with primary titanium carbides; etched with Mi16Fe

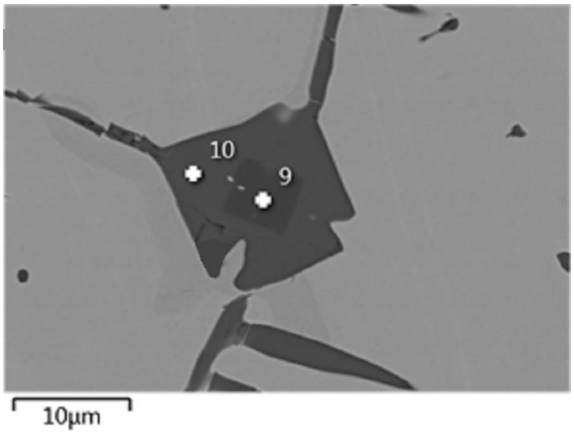

Fig.10. Scanning image of the alloy containing 1.3% Ti with marked spots of analysis

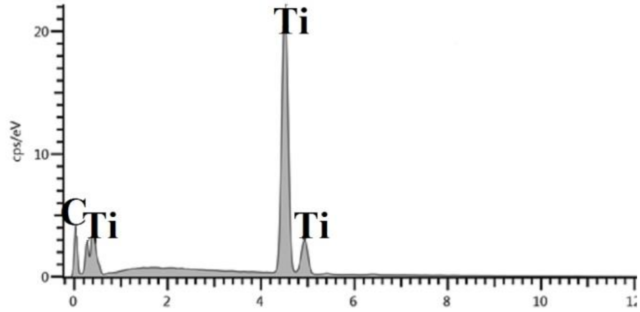

Fig. 11. EDS energy spectrum of the visible titanium carbide precipitates

Table 4.
Chemical composition of the alloy in areas at spots 9 and 10 in Figure 10

Spot of analysis	[wt%]							
	C	Si	Ti	Cr	Fe	Nb	Mo	Total
Spot 9	10.5	–	89.5	–	–	–	–	100.0
Spot 10	21.3	0.2	73.3	1.2	0.8	1.1	2.1	100.0

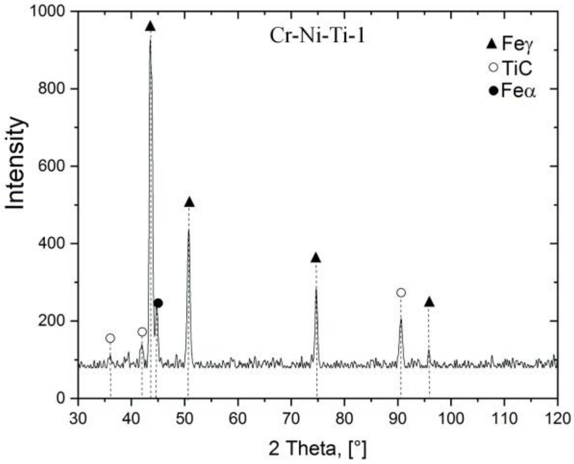

Fig.12. X-ray diffraction pattern of alloy with the addition of 6.9% Ti

Based on the results of the abrasion test, the total mass loss of the samples was calculated and was used to plot the total mass loss of the tested alloys as a function of abrasion time (Fig. 13).

Based on the obtained results, it was found that the abrasive wear resistance of the tested chromium-nickel cast steel increases with the content of titanium added. Even at 1.3% Ti, the wear decreases from 0.314 g/16h for the reference cast steel to 0.244 g/16h, while increasing the Ti content to 3.1% reduces the wear to 0.224 g/16h, which gives the values of 22 and 29%, respectively. For higher Ti content (5.3 and 6.9%), the wear is the lowest and amounts to 0.128 and 0.123 g/16h, respectively. This value is about 2.5 times lower than the value obtained for the reference Cr-Ni alloy.

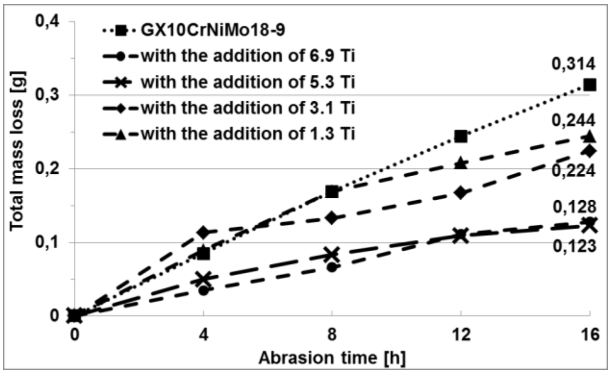

Fig. 13. Total mass loss of the tested alloys as a function of abrasion time

Improving one of the chromium-nickel cast steel properties, which is its resistance to abrasive wear, is the main research challenge related to the use of this material in the industry. The introduction of strong carbide-forming additives such as Ti allows increasing the abrasion resistance owing to the formation of primary carbides in the alloy matrix. The quoted data shows, however, that in all cases the carbides are in the form of polyhedrons and plates with sharp edges (Fig. 10). This morphology of carbides may increase the tendency of castings to crack formation due to the presence of high stresses at the carbide-alloy matrix boundary. Therefore, it would be desirable to develop a cast steel melting technology such that would produce oval or spherical carbides in the casting after its solidification.

4. Conclusions

From the research carried out, the following conclusions can be drawn:

1. The microstructure of the tested cast steel after solution heat treatment consists of a chromium-nickel austenitic matrix with primary titanium carbides evenly distributed in this matrix.
2. Higher carbon and titanium content makes carbides prone to cluster formation.
3. The addition of titanium increases the matrix hardness to 330 HV0.02, which makes it by 40-70 units higher than the hardness of the GX2CrNi18-9 cast steel.
4. The increase in titanium content has little effect on the hardness of the tested samples after solution heat treatment.
5. The presence of titanium carbides in the structure increases the abrasive wear resistance even 2.5 times.

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