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INFLUENCE OF THE SIZE OF SILICON CARBIDE NANOPARTICLES ON THE ABRASIVE WEAR OF ELECTROLESS NICKEL COATINGS. PART 2

M. KANDEVA[a,b*], YU. V. ROZHDESTVENSKY[b], P. SVOBODA[c], ZH. KALITCHIN[d], E. ZADOROZHNAYA[b]

[a]*Faculty of Industrial Engineering, Tribology Centre, Technical University – Sofia, 8 Kliment Ohridski Blvd., 1000 Sofia, Bulgaria*
E-mail: kandevam@gmail.com
[b]*South Ural State University, 76 Prospekt Lenina, Chelyabinsk, Russia*
[c]*Faculty of Mechanical Engineering, Brno University of Technology, 2 Technicka Street, 616 69 Brno, Czech Republic*
[d]*SciBulCom 2 Ltd., P.O. Box 249, 1113 Sofia, Bulgaria*

Abstract. The present work represents the results of an investigation on wear and wear resistance of electroless nickel coatings with SiC nanoparticles of different sizes – 10, 45, 100, 150 and 700 nm under conditions of dry friction along the surface of firmly attached abrasive particles. The investigations on silicon carbide (SiC) nanoparticles are presented in two parts. Part 1 presents the studies concerning the effect SiC nanoparticles size of 10, 45 and 100 nm, and in the current paper – Part 2 are presented results on the effect of 150 and 700 nm SiC nanoparticles. It has been established that the size of the SiC nanoparticles in combination with thermal treatment of the coatings exert substantial influence on the micro-hardness, on the character and the magnitude of linear wear, on the wear intensiveness and on the wear resistance of the coatings. The thermal treatment leads to increase in the micro-hardness of coatings without nanoparticles and coatings with nanoparticles. The highest wear resistance and micro-hardness is manifested by nickel coatings with the smallest size of the nanoparticles – 10 nm. Upon increasing the size of the SiC nanoparticles the wear resistance and micro-hardness become decreased. It has been found out that in case of 10 nm nanoparticle size the kinetic curve of the wearing off process has linear character and the stage of co-operation of the coating is missing, which indicates high energy effectiveness of these coatings. Upon increasing the size of the SiC nanoparticles the kinetic curve acquires wave-like character with well expressed stage of gradual cooperation.

Keywords: tribology, abrasive wear, electroless nickel coatings, nanoparticles, silicon carbide.

AIMS AND BACKGROUND

There are publications in the specialised literature discussing the incorporation of nanoparticles of different nature – silicon carbide, boron nitride, diamond and others, which leads to a significant change in the mechanical and tribological

* For correspondence.

properties of chemical nickel coatings[1–13]. The change in wear resistance depends on the heat treatment of the coatings, the nature, concentration and size of the nanoparticles, as well as the friction conditions[14–23].

This publication is a continuation of the work of the authors[1], which investigates the parameters of abrasive wear of chemical nickel coatings containing SiC nanoparticles with nanoparticles in the range of 10, 45 and 100 nm.

EXPERIMENTAL

This paper presents the results of a study of 6 types of nickel coatings – nanoparticles free and SiC nanoparticle coatings with an average size of 150 and 700 nm. The coatings were obtained at the same parameters of the technological regime by the method EFTTOM-NICKEL, developed at the Technical University in Sofia[24,25], in particular – the same concentration of nanoparticles from 5 to 7 vol.%. and heat treatment at 300°C for 6 h.

Table 1 represents the designation, the description, the thickness and microhardness of the tested coatings.

Table 1. Designation, thickness and microhardness of tested coatings

Sample	Designation	Description	Thickness (μm)	Microhardness ($HV_{0.5}$)
1	Ni	electroless Ni coating without nanoparticles and heat treatment	25.5	541
2	Ni^{HT}	electroless Ni coating without nanoparticles and with heat treatment	23.4	550
3	Ni-SiC150	electroless Ni coating with SiC nanoparticles of 150 nm size and without heat treatment	25.6	565
4	$Ni\text{-}SiC150^{HT}$	electroless Ni coating with SiC nanoparticles of 150 nm size and with heat treatment	24.4	645
5	Ni-SiC700	electroless Ni coating with SiC nanoparticles of 700 nm size and without heat treatment	27.6	640
6	$Ni\text{-}SiC700^{HT}$	electroless Ni coating with SiC nanoparticles of 700 nm size and with heat treatment	24.8	830

Note: in the designation of the samples the number after SiC shows the size of the nanoparticles, while the thermal treatment is denoted by the abbreviation HT.

All the coatings have been deposited upon the substrate of one and the same material – carbon steel St3kp (GOST 380-94) having chemical composition, shown in Table 2.

Table 2. Chemical composition (wt.%) of the coated material (substrate)

Element	C	Si	Mn	Ni	P	S	Cr	Fe
Percentage	0.40	0.20	0.55	0.30	0.45	0.045	0.30	Balance
Microhardness				235 $HV_{0.5}$				

The samples represent disks of diameter 100 mm and thickness of 2.5 mm with identical roughness, which has been measured by mechanical profile meter TESA Rugosurf 10-10G. The average roughness of the initial coatings, measured in two perpendicular directions, is $R_a = 0.089 \pm 0.05$ µm.

The thickness of the coatings has been measured by the device Pocket Leptoskop 2021 Fe, whereupon it is accepted to be the mean arithmetic value out of 8 measurements. The microhardness ($HV_{0.5}$) of the coatings has been measured by means of microhardness meter device Vickers under loading of 500 g.

All coatings are tested under the same dry surface friction modes with rigidly abrasive particles with the device and test methodology presented in our previous paper[1].

The relative wear resistance ($R_{i,j}$) is calculated as a ratio of reference sample wear resistance (I_j) and wear resistance of the analysed sample (I_i), where j and i denote the designation number of the sample – $R_{i,j} = I_i/I_j$. Relative wear resistance of the reference sample is always $R = 1$.

RESULTS AND DISCUSSION

The obtained results about the characteristics of the wearing off process – linear wear, wear intensiveness and wear resistance for different number of cycles N (friction path) are represented respectively in Tables 3, 4 and 5.

Figures 1, 2 и 3 represent graphically the plotted dependence of linear wear on the number of friction cycles for all the tested samples – nickel coatings without nanoparticles and those having dimensions 150 and 700 nm nanoparticles of SiC in the two cases – without thermal treatment and after thermal treatment, respectively.

Table 3. Linear wear of tested coatings

Sample	Coating designation	Number of cycles (N)							
		100	200	300	400	500	600	800	1000
		Sliding distance (m)							
		23.9	47.8	71.8	95.7	119.6	143.6	191.5	239.4
		Linear wear (µm)							
1	Ni	7.4	11.8	16.5	22.4	25.1	–	–	–
2	Ni^{HT}	4.5	6.0	7.2	9.7	10.8	12.4	16.1	23.0
3-	Ni-SiC150	8.4	9.2	10.6	14.6	18.5	22.2	23.6	25.0
4	$Ni\text{-}SiC150^{HT}$	6.1	6.8	7.1	9.4	11.2	13.1	17.3	20.6
5	Ni-SiC700	7.8	8.1	9.5	11.8	14.4	16.3	22.7	25.4
6	$Ni\text{-}SiC700^{HT}$	6.8	7.2	8.4	9.8	13.2	14.5	20.2	22.9

Table 4. Wear rate of tested coatings

Sample	Coating designation	Number of cycles (N)							
		100	200	300	400	500	600	800	1000
		Sliding distance (m)							
		23.9	47.8	71.8	95.7	119.6	143.6	191.5	239.4
		Wear rate (μm/m)							
1	Ni	0.31	0.25	0.23	0.23	0.21	–	–	–
2	Ni^{HT}	0.19	0.13	0.10	0.10	0.09	0.09	0.09	0.10
3	Ni-SiC150	0.35	0.19	0.15	0.15	0.15	0.15	0.12	0.10
4	Ni-SiC150^{HT}	0.25	0.14	0.10	0.10	0.09	0.09	0.09	0.09
5	Ni-SiC700	0.33	0.17	0.13	0.12	0.12	0.11	0.12	0.11
6	Ni-SiC700^{HT}	0.28	0.15	0.16	0.12	0.10	0.11	0.11	0.10

Table 5. Wear resistance of tested coatings

Sample	Coating designation	Number of cycles (N)							
		100	200	300	400	500	600	800	1000
		Sliding distance (m)							
		23.9	47.8	71.8	95.7	119.6	143.6	191.5	239.4
		Wear resistance (m/μm)							
1	Ni	3.2	4.0	4.3	4.3	4.8	–	–	–
2	Ni^{HT}	5.3	7.7	10.0	10.0	11.1	11.1	11.1	10.0
3	Ni-SiC150	2.9	5.3	6.7	6.7	6.7	6.7	8.3	10.0
4	Ni-SiC150^{HT}	5.0	7.1	10.0	10.0	11.1	11.1	11.1	11.1
5	Ni-SiC700	3.0	5.9	7.7	8.3	8.3	9.1	8.3	9.1
6	Ni-SiC700^{HT}	3.6	6.7	6.3	8.3	10.0	9.1	9.1	10.0

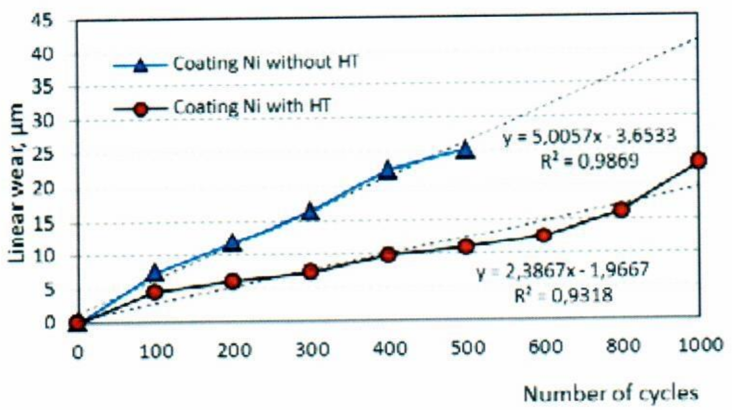

Fig. 1. Linear wear versus number of cycles for coatings without nanoparticles

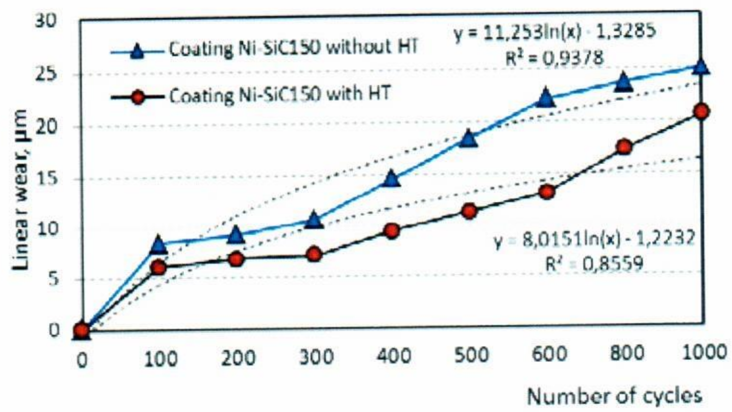

Fig. 2. Linear wear versus number of cycles for coatings with silicon carbide nanoparticles of 150 nm size

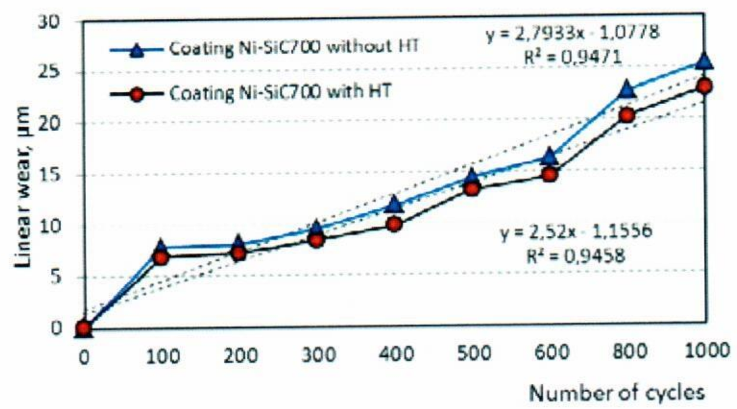

Fig. 3. Linear wear versus number of cycles for coatings with silicon carbide nanoparticles of 700 nm size

From Figs 2 and 3 it can be seen that the coatings with dimensions of 150 and 700 nm dependence is highly non-linear and has a wavy character.This is to be seen more clearly in the graphical dependences showing the changes in the wear intensiveness on the number of cycles, illustrated by Figs 4 and 5.

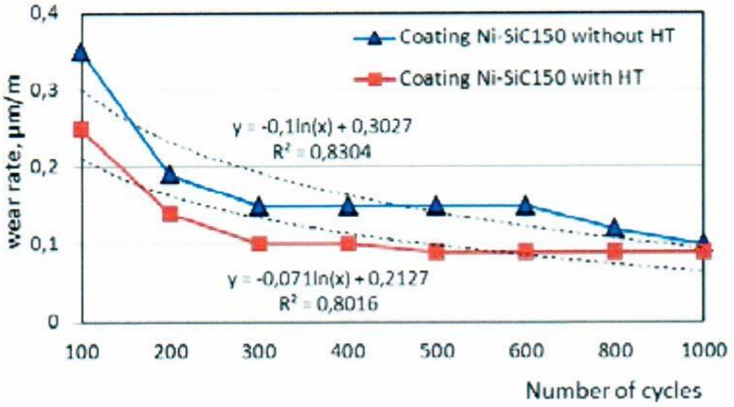

Fig. 4. Wear rate versus number of cycles for coatings with silicon carbide nanoparticles of 150 nm size

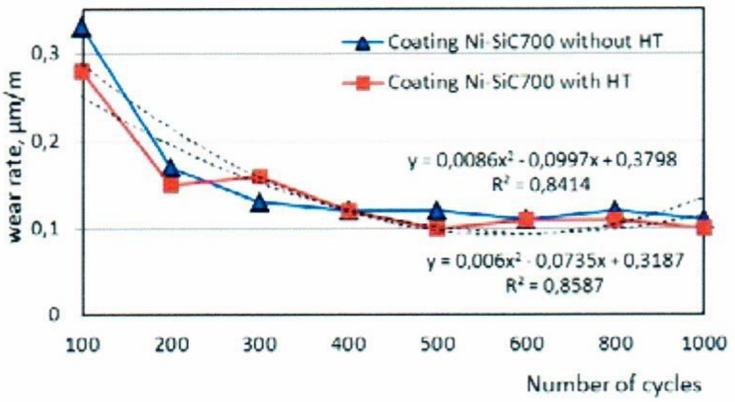

Fig. 5. Wear rate versus number of cycles for coatings with silicon carbide nanoparticles of 700 nm size

It becomes clear from the represented results that the thermal treatment and SiC nanoparticle size exert substantial influence on the characteristics of the wearing off process and on the wear resistance of the nickel coatings.

Figures 6 and 7 illustrate the dependence of the wear intensiveness on the SiC particles sizes for coatings without and with thermal treatment in both cases of friction – after 500 and after 1000 cycles. At a friction path of 500 cycles (Fig. 6), the coatings without heat treatment with increasing nanoparticle size from 150 to 700 nm decrease the wear rate gradually but remain higher than the coatings with heat treatment. In heat treated coatings, the wear rate remains constant and almost equal to that of nanoparticle coatings. With a friction path of 1000 cycles (Fig. 7) with increasing nanoparticle size, the SiC wear rate increases linearly and reaches values higher than those for nanoparticle coatings[1], the presence of such particles has the opposite effect – reducing the life of the coating.

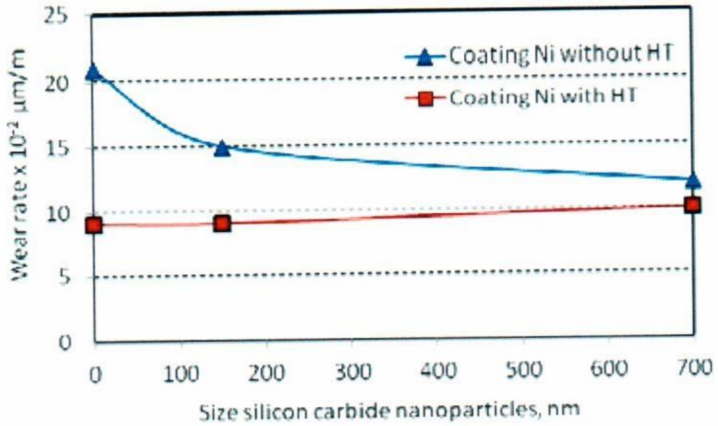

Fig. 6. Wear rate versus size of silicon carbide nanoparticles for tested coatings (500 cycles)

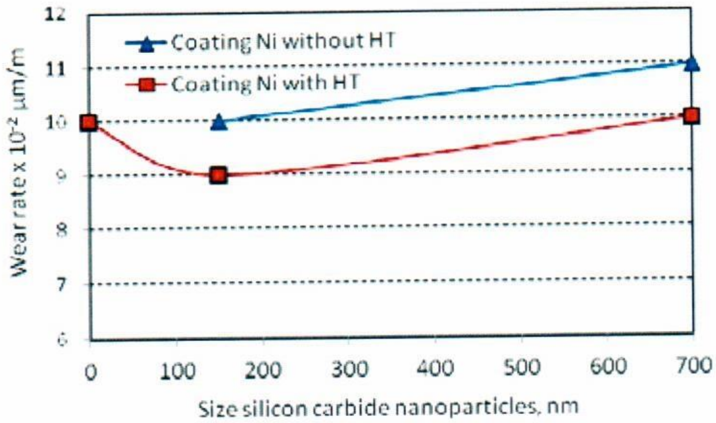

Fig. 7. Wear rate versus size of silicon carbide nanoparticles for tested coatings (1000 cycles)

The influence of heat treatment, nanoparticle size and their joint influence on all tested nanoparticle coatings of 10, 40, 100, 150 and 700 nm in Ref. 1 and in the present work is estimated with the relative wear resistance parameter (R_{ii}, $j = I_i/I_j$). The values of the relative wear resistance for a friction path of 500 cycles are presented in Table 6. For the sake of clarity, the results are presented through the diagrams in Figs 8, 9 and 10.

Table 6. Relative wear resistance and the influences of heat treatment and addition silicon carbide nanoparticles on the increase of wear resistance of tested coatings

Sam-ple	Coatings	Wear resistance (m/μm) (500 cycles)	Relative wear resistance (R)		
			influence of heat treatment	influence of particles addi-tion	both influence
1	Ni	4.8	$R_{1,1} = 1$	$R_{1,1} = 1$	$R_{1,1} = 1$
2	Ni^{HT}	11.1	$R_{2,1} = 2.3$	$R_{2,2} = 1$	$R_{2,1} = 2.3$
3	Ni-SiC10	8.3	$R_{3,3} = 1$	$R_{3,1} = 1.7$	$R_{3,1} = 1.7$
4	Ni- $SiC10^{HT}$	14.1	$R_{4,3} = 1.7$	$R_{4,2} = 1.3$	$R_{4,1} = 2.9$
5	Ni- SiC45	7.7	$R_{5,5} = 1$	$R_{5,1} = 1.6$	$R_{5,1} = 1.6$
6	Ni- $SiC45^{HT}$	12.5	$R_{6,5} = 1.6$	$R_{6,2} = 1.1$	$R_{6,1} = 2.6$
7	Ni- SiC100	6.7	$R_{7,7} = 1$	$R_{7,1} = 1.4$	$R_{7,1} = 1.4$
8	Ni- $SiC100^{HT}$	8.3	$R_{8,7} = 1.2$	$R_{8,2} = 0.7$	$R_{8,1} = 1.7$
9	Ni- SiC150	6.7	$R_{9,9} = 1$	$R_{9,1} = 1.4$	$R_{9,1} = 1.4$
10	Ni- $SiC150^{HT}$	11.1	$R_{10,9} = 1.7$	$R_{10,2} = 1$	$R_{10,1} = 2.3$
11	Ni- SiC700	8.3	$R_{11,11} = 1$	$R_{11,1} = 1.7$	$R_{11,1} = 1.7$
12	Ni- $SiC700^{HT}$	10.0	$R_{12,11} = 1.2$	$R_{12,2} = 0.9$	$R_{12,1} = 2.1$

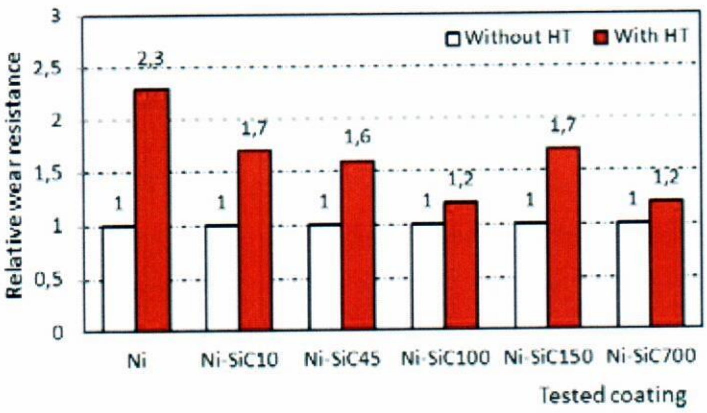

Fig. 8. Influence of heat treatment (HT) on the wear resistance of tested coatings

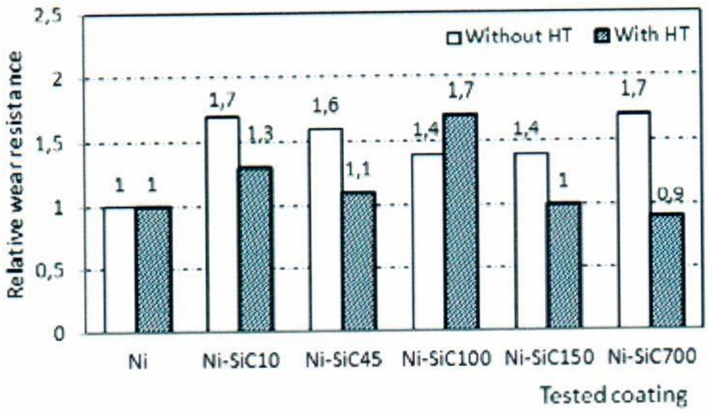

Fig. 9. Influence of nanoparticles addition on the wear resistance of tested coatings

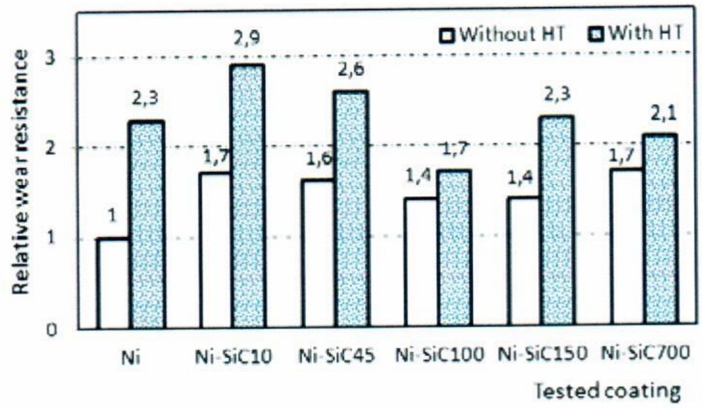

Fig. 10. Influence of heat treatment (HT) and nanoparticles addition on the abrasive wear resistance of tested coatings

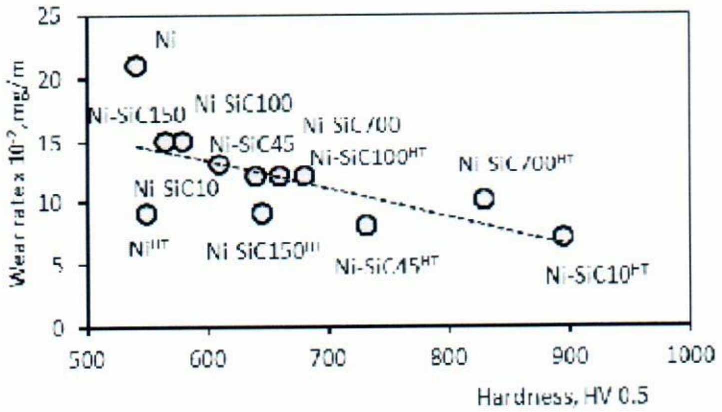

Fig. 11. Wear rate versus hardness of tested coatings

The influence of the thermal treatment on the coatings is most strongly expressed in the case of nickel coating without nanoparticles with thermal treatment – Ni^{HT}, whereupon the relative wear resistance is $R = 2.3$, while in presence of nanoparticles – it is observed for the coatings Ni-SiC10^{HT} and Ni-SiC150^{HT}, in which cases $R = 1.7$ (Fig. 8). The effect of the sizes of the nanoparticles is the greatest with three types of coatings: coatings without thermal treatment – Ni-SiC10 and Ni-SiC100 and coating with thermal treatment Ni-SiC100^{HT}, in which cases the relative wear resistance has identical value $R = 1.7$ (Fig. 9).

The combined influence of the thermal treatment and the sizes of the particles upon the wear resistance is clearly expressed in the case of thermally treated coating with dimension of the nanoparticles 10 nm – Ni-SiC10^{HT}. The relative wear resistance has the highest value compared to those values for all the tested coatings $R = 2.9$ (Fig. 10).

The high wear resistance of the coating Ni-SiC10^{HT} at this stage of the investigation could be explained by the high microhardness of the coating (Figs 11 and 12), which is the result of the crystalline structure of the composite coating[1].

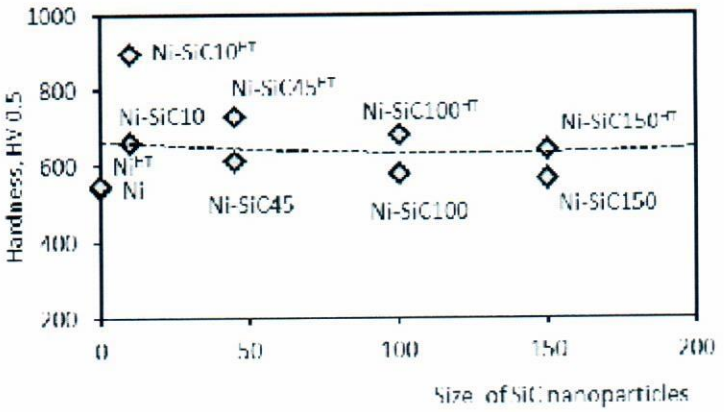

Fig. 12. Hardness versus size of silicon carbide nanoparticles of tested coatings

CONCLUSIONS

The obtained results show the ambiguity of effects and interconnected influence of the thermal treatment and the size of the nanoparticles of SiC upon the linear wear, the wear intensiveness and wear resistance.

The main results of the comparative study of the chemical composition coating nanoparticles SiC with dimensions of 10, 45, 100, 150 and 700 nm, disclosed in the present work and in Ref. 1 can be summarised as the following conclusions:

– The thermal treatment leads to increase in the microhardness of the coatings without nanoparticles and coatings with nanoparticles. The highest microhardness is shown by coating with thermal treatment having nanoparticle size of 10 nm – 895 HV, while the lowest micro-hardness is shown by coating with nanoparticles and without thermal treatment – 541 HV.

– Upon increasing the size of the nanoparticles, the wear resistance is reduced.

– The sizes of the SiC nanoparticles in combination with thermal treatment exert substantial influence upon the micro-hardness of nickel coatings. The greatest microhardness is manifested by coatings having small size of the nanoparticles – 10 nm. Upon increasing the size of the nanoparticles, the microhardness is reduced.

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