

Static and kinetic friction of electroless Ni composite coatings

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ABSTRACT

Purpose: The aim of this study was to examine the static and kinetic friction of electroless Ni coatings of different surface roughening, in unlubricated contact with various counter-body materials. In particular, difference between static and kinetic coefficient of friction was analysed.

Design/methodology/approach: The Ni coatings deposition was done with electroless plating process. Samples of electroless Ni coatings without and with SiC nanoparticles were heat treated at 300°C for 6 hours. The microstructure of all samples was characterized by optical microscopy. Microhardness of samples and counter-bodies were also examined. The static and kinetic coefficient of friction was measured for each coating with initial and working surface roughness. Three typical materials used in industry were chosen as a counter-body material. The possibility of stick-slip occurrence was analysed through the static and kinetic coefficients of friction difference.

Findings: Obtained results show that coatings hardness has strong influence on coefficient of friction, and that slip-stick phenomenon is unlikely to occur, since the differences between static and kinetic coefficient of friction are small.

Research limitations/implications: The SiC nanoparticles were added to Ni coating in order to improve the abrasive wear resistance. In the same time, presence of SiC nanoparticles slightly increases the coefficient of friction in unlubricated conditions.

Originality/value: The SiC nanoparticles were added to standard electroless Ni coating, and their properties are investigated. Heat treatment was applied to achieve crystalline structure and to improve mechanical and tribological properties. Coefficient of friction testing was performed by simply and easy to operate test rig.

Keywords: Composites; Coatings; Friction; Stick-Slip

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MATERIALS

1. Introduction

An oscillation between static and kinetic levels of friction can occur in many tribological systems at low sliding speeds and high loads. This is known as “stick-slip”, a phenomenon where the instantaneous sliding speed of an object does not remain close to the average sliding speed. Instead, the sliding speed continuously varies between almost stationary periods and moments of very high speed [1]. Stick-slip is characterized by uniform motion (stick phase) followed by non-uniform motion (slip phase), and depends on the variation in the friction coefficient at low sliding speeds and on the vibrational characteristics of the system.

In many cases, stick-slip causes significant vibrations, which are undesirable in many tribological systems like machine tool slides, automatic transmissions, hydraulic driving systems, etc. These vibrations have negative effects on systems functionality and performance, as they can cause serious wear of the components, fatigue and positioning errors [2]. Precondition for occurrence of the slip-stick phenomenon is a considerable difference between the adhesion and the sliding coefficients, i.e. static and kinetic coefficient of friction. More generally, it occurs when there is non-linear friction-velocity dependence.

Distinctions between coefficients of static and kinetic friction have been mentioned in the friction literature for centuries, at least since the work of Euler, as described in [3]. In the same reference [3], a good historical review of the static and kinetic friction and stick-slip phenomenon could be found. The coefficient of static friction is usually greater than coefficient of kinetic friction of about 20 to 30% [4]. This is due to the fact that before the onset of motion, a large stress relaxation at the junctions may occur, which causes an increase in the real area of contact and allows the adhesive forces to fully develop. This is particularly important in the contact that are mostly plastic and when the sliding surfaces are without contaminants [4].

The deposition of nickel coating on steel with electroless plating process is applied in industry mainly to improve the corrosion and wear resistance, to build up worn or undersized parts, to modify magnetic properties, etc. [5]. The application of composite electroless Ni coatings with particles of different materials, sizes and amounts is very interesting, since this generally leads to the improvement of mechanical and tribological characteristics. Enhanced tribological characteristics were obtained by using the embedded micro- and nano-sized particles of silicon carbide [6-8], diamond [9], boron nitride [10], etc.

In this study, the static and kinetic friction of electroless Ni composite coatings, with and without SiC nanoparticles, with and without heat treatment, of different surface roughness preparation were analysed and compared. The investigation was in ambient air and unlubricated contact, with various counter-body materials.

2. Experimental details

2.1. Materials

The Ni coatings were fabricated by electroless plating process with addition of 5-7 vol% SiC nanoparticles (150 nm in diameter). The substrate material was a carbon steel Cт3кп (GOST 380-94) in disk shape of 100mm diameter and 3mm thickness, with following chemical composition: Fe-0.4C-0.045S-0.55Mn-0.45P-0.20Si-0.30Cr-0.30Ni (wt.%). Hardness of the substrate was 135 HV0.05. Average coatings thickness was 17µm, measured in 10 points on each coating surface. Heat treatment (heating at 300 °C during 6 hours) was applied to some of the samples to improve its mechanical properties and adhesion in the substrate-coating interface.

Three different samples with electroless Ni coatings were investigated: 1) Ni coating without SiC nanoparticles and with heat treatment; 2) Ni coating with SiC nanoparticles and without heat treatment; 3) Ni coating with SiC nanoparticles and with heat treatment. Each of these samples was tested with two surface roughness: 1) Initial roughness (after coating deposition without machining); 2) Working roughness (after purposely roughening of the samples; purposely roughening of the samples was done in order to simulate working, i.e. in-service conditions on Taber Abraser with abrading wheel Calibrase® CS-10 and equal load, speed and abrading time). All together three counter-body materials were used for tests: 1) Bronze; 2) Polymer; 3) Steel (1.0402: EN 10083-2). This makes in total 18 different contact pairs. These coatings were previously tested on abrasion wear and it is showed that the addition of SiC nanoparticles, as well as, heat treatment improved wear resistance [6,8]. The counter-body materials were chosen to represent three different situations frequently appearing in the tribological systems. Designation of tested samples and contact pairs are shown in Table 1.

Table 1.
Designation of tested samples and contact pairs

Contact pair No.	Sample coating (designation)	Sample surface roughness condition	Counter-body material
1	Electroless Ni coating with heat treatment (Ni^{HT})	Initial	Bronze
2		Working	
3		Initial	Polymer
4		Working	
5		Initial	Steel
6		Working	
7	Electroless Ni coating with SiC nanoparticles (Ni-SiC)	Initial	Bronze
8		Working	
9		Initial	Polymer
10		Working	
11		Initial	Steel
12		Working	
13	Electroless Ni coating with SiC nanoparticles and heat treatment ($\text{Ni-SiC}^{\text{HT}}$)	Initial	Bronze
14		Working	
15		Initial	Polymer
16		Working	
17		Initial	Steel
18		Working	

2.2. Microstructure, microhardness and surface roughness characterization

Microstructural characterization of coatings was investigated by optical microscopy (OM). Particle size of SiC nanopowders were analysed using scanning electron microscopy (SEM).

Measurements of surface microhardness (HV0.05) were carried out using Vickers microhardness tester under the load of 50g and dwell time of 15s. At least five measurements were made for each sample in order to eliminate possible segregation effects and to obtain a representative value of the material microhardness.

The roughness of the samples was examined with mechanical profilometer, according to the ISO 4287 and ISO 4288. The test parameters were the same for all samples, i.e. diamond tip radius: 5 μm ; pick-up measuring range: $\pm 20\mu\text{m}$; cut-off length (single measured length): 0.25mm; evaluation length (total measured length): 5x cut-off length=1.25mm; digital filter: Gaussian. Measurement was performed in at least five points, in radial direction, on the surface of coatings and the average value is presented.

2.3. Coefficients of friction testing

The coefficient of friction testing was performed on the test rig presented in Figure 1. The sample (2) is mounted in the bed of the foundation and fixed. The counter-body (1) is in contact with the test sample (2), fixed in the holder (3) and connected through the non-elastic string with the dynamometer (6). The normal force (F_n) is set by means of the weights (4). Tangential force (T) is loaded to the counter-body near the contact surface through the very slow rotation of the micrometric screw (5) and displayed on the dynamometer (6).

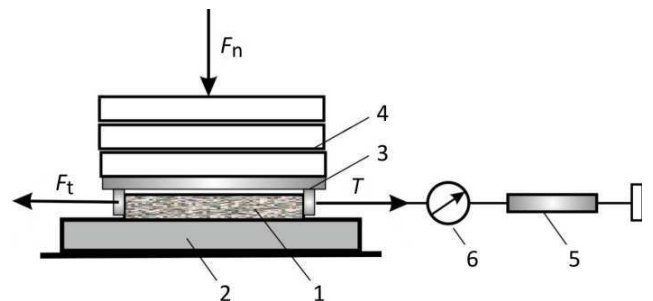


Fig. 1. Schematic diagram of the coefficients of friction testing

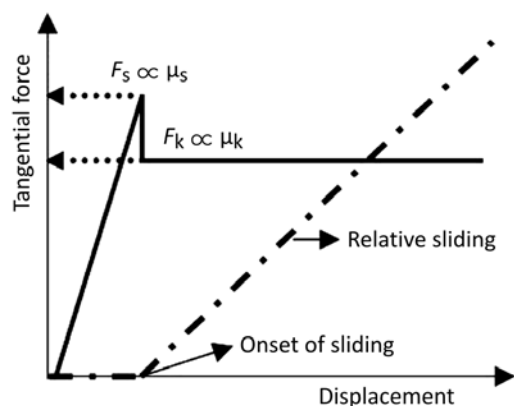


Fig. 2. Variation of the friction force and coefficient of friction with displacement

Test parameters were as follows: normal load of 4.6kg (45.1N); dry contact condition, in ambient air at room temperature ($\approx 25^\circ\text{C}$) and relative humidity of 40–45%. Test sample was in the shape of disk of 100 mm diameter and 3mm thickness, and the counter-body was in the shape of cylinder having 16.5mm diameter and 20mm length. This gives the geometrical contact area of approximately 214mm^2 . Taking into account this contact area, the specific load was approximately 0.21MPa. The resting time (time for the possible stress relaxation at the junctions) was 30s for each contact pair.

The test rig shown in Figure 1 enables determination of the two values, i.e. static and kinetic coefficient of friction. The hypothetical static (F_s) to kinetic (F_k) friction transition diagram is shown in Figure 2. Both values are read from the same dynamometer (position 6 in Fig. 1). For each of the 18 tested contact pairs, four to five identical measurements were performed, and the average values are calculated and presented.

3. Results and discussion

3.1. Microstructure and microhardness

Microstructural analysis of Ni coatings presented in Figure 3 have shown bulging and cauliflower like structure. This structure is characteristic for electroless Ni coating. It is assumed that sample with SiC nanoparticles and without heat treatment (Fig. 3b) has amorphous structure and that the heat treated samples (Figs. 3a and c) have crystalline structure. According to literature [11, 12] heat treatment provides sustainably crystallinity with presence of small crystallites, which enable good mechanical properties and is in consistency with obtained microhardness values. Figure 4 shows SiC nanoparticles obtained by SEM analysis and discussed elsewhere [13].

The obtained microhardness values of Ni coatings indicate that heat treated samples have higher values than non-treated. The values of microhardness are shown in Table 2. Increase of microhardness is due to the presence of crystalline, fine-grained structure [14].

Table 2.
Microhardness (HV 0.05) of tested materials

Sample coating		
Ni ^{HT}	Ni-SiC	Ni-SiC ^{HT}
841.4	607.3	691.4
Counter-body		
Bronze	Polymer	Steel
264.4	71.5	415.4

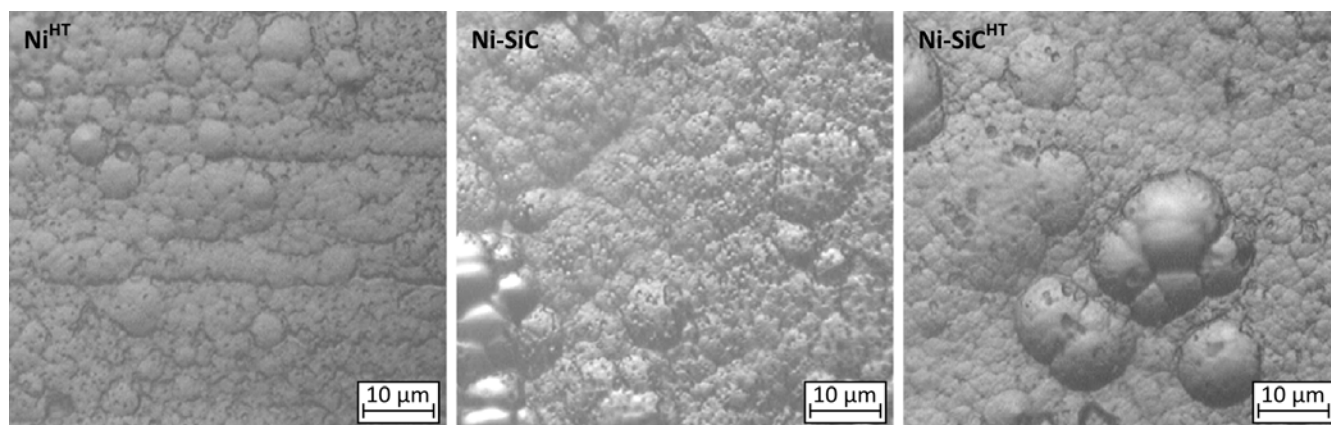


Fig. 3. Microstructure of the coatings surface conditions (top side): coating Ni^{HT} (left), coating Ni-SiC (middle) and coating Ni-SiC^{HT} (right)

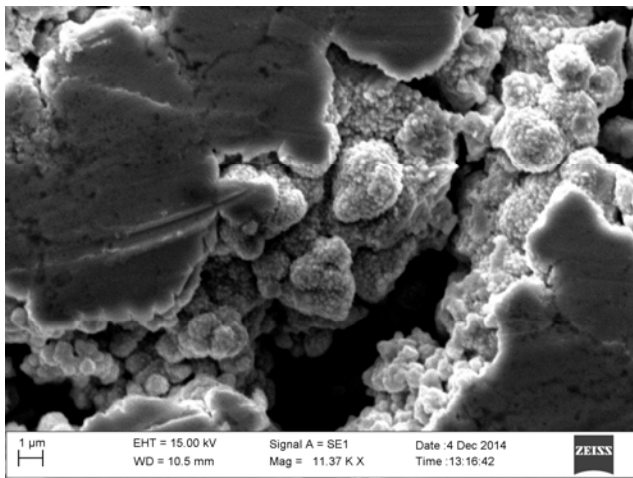


Fig. 4. SEM image of the SiC nanoparticles

3.2. Surface roughness

If the hardness of solids in contact are not the same, the more important is the roughness of the harder material because asperities of the harder surface plough the surface of the softer body [15]. Surface roughness of the coatings samples, measured before the friction test, is presented through the root mean square deviation of the assessed profile (R_q) and mean width of the profile elements (R_{Sm}) values in Figure 5.

These two parameters were chosen as a representative of amplitude parameters (R_q) and spacing parameters (R_{Sm}) of the surface texture. The root means square deviation of the assessed profile (R_q) is used since it is more sensitive to deviations from the mean line than the arithmetic mean deviation of the assessed profile (R_a), i.e. the R_a value is directly related to the area enclosed by the surface profile about the mean line, and any redistribution of material has no effect on its value [1].

The obtained values of the surface roughness are very similar for the initial and working conditions. This is unexpected, since the visual inspection (Fig. 6) shows obvious differences between the working (darker circular track) and initial texture (rest of the disk). One of the reasons is that initial texture was as it is, i.e. without machining. Other than that, a relatively high hardness of the tested coatings (Table 2) means that they are not easy to wear and consequently change the surface texture. In addition, profile roughness parameters reduce all of the information to a single number, and even small changes in how the raw profile data is filtered, how the mean line is calculated, and the physics of the measurement can greatly affect the calculated parameter. In some cases different curves like material ratio curve of the profile (Abbott Firestone curve) or 3D roughness parameters could be useful, but in practice 2D parameters are mostly used. There were also attempts to introduce some parameters that will combine amplitude parameters with other parameters these two influences [16] but they are not standardised yet.

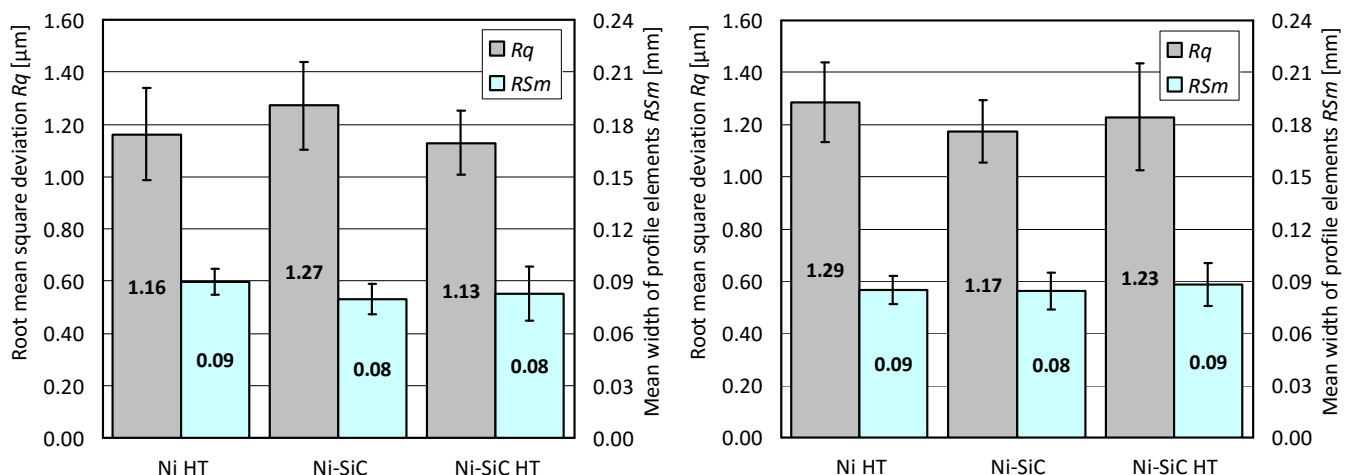


Fig. 5. Surface roughness of tested coatings measured before the friction test: initial roughness (left) and working roughness (right); Error bars represent standard deviation values



Fig. 6. Optical image of the initial and working texture on the tested coated discs (coating Ni-SiC^{HT})

3.3. Static and kinetic coefficient of friction

It is known that the sliding coefficient of friction, both static and kinetic, between solids under the influence of a nonzero normal load is a function of several factors whose relative contributions vary on a case-by-case basis: composition of the materials; surface roughness of each solid; nature of the surrounding environment; load holding the solids in contact; relative velocity of sliding; nature of the sliding (unidirectional, back and forth, steady, variable, etc.); nature of the contact (conformal or nonconformal); contact temperature; prior sliding history of the surfaces; characteristics of the machine and fixtures in which the materials are affixed [17].

The obtained values of the coefficients of friction are presented in Figure 8. Values of both coefficients of friction (0.11 to 0.17 for metal-polymer contact and 0.13 to 0.27 for metal-metal contact) correspond to the experimental values for materials under dry sliding conditions [17]. During the experiments, it was noticed that there was very small difference in the obtained values of the coefficient of friction, when the resting time (time with loaded contact, before the start of the test) is greater than 10s. Therefore, before each test the loaded contact was resting for 30s, so the real contact area can be established.

The first feature that can be noticed in Figure 8 is that the coefficient of friction is the lowest when the test samples were in contact with polymer counter-body material. This is valid for all coatings and for both initial and working roughness. Mean value of coefficient of friction for polymer in contact with coatings was 0.130. Copper gave 0.187, and steel 0.209. This is in accordance with the hardness of the counter-body materials (Table 2)

and with the fact that polymers have low modulus of elasticity. Lower hardness of the softer body in contact usually gives lower shear stress, which cause lower coefficient of friction [18].

By comparing of the surface roughness (Fig. 5) and coefficient of friction differences between tested contact pairs, it seems that surface roughness did not have major influence on both static and kinetic coefficient of friction, i.e. although the roughness of initial and working texture are similar, working roughness had higher values of the coefficient of friction by 13 % for static and 16 % for kinetic friction. This is not in accordance with the accepted theory, which claims that contact surface roughness has direct influence on the static friction coefficient, and coefficient of friction value increases if contact surfaces have bigger roughness parameters [15]. Nevertheless, materials distribution in the surface layer, which is very important for tribological processes, and many other parameters also have influence [15,17]. It is possible that the working texture had better distribution of the material in the surface layer (higher bearing area), giving higher real area of contact. Higher real area of contact increase adhesion component of friction, and it is known that in most cases adhesion component of friction is much higher than the ploughing component [18].

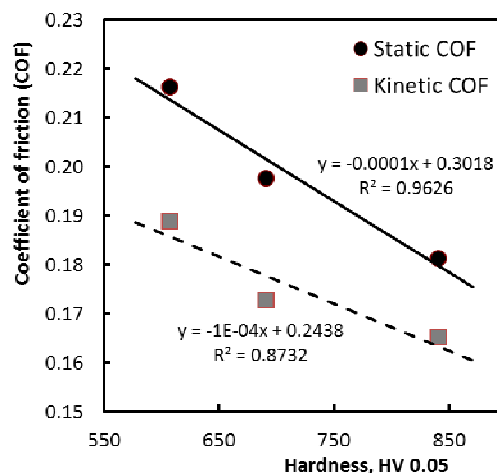


Fig. 7. Coefficient of friction vs. hardness of tested coatings

Higher hardness of both bodies in contact induces lower real area of contact, i.e. decrease the adhesion component of friction. That is why coating with the highest hardness (Ni^{HT}) had the lowest average coefficient of friction (0.181 for static and 0.165 for kinetic friction), while coating with the lowest hardness (Ni-SiC) had the highest average coefficient of friction (0.216 for static and 0.189 for kinetic friction). Average coefficients of friction for the third coating (Ni-

SiC^{HT}) were 0.198 for static and 0.173 for kinetic friction. The relationship between static and kinetic coefficients of friction and hardness of the coatings is shown in Figure 7.

The average decrease of kinetic comparing to static coefficient of friction was 0.016 (8.8 %) for Ni^{HT} coating, 0.027 (13.1 %) for Ni-SiC coating and 0.025 (12.8 %) for Ni-SiC^{HT} coating. The obtained difference between static and kinetic coefficient of friction is generally acceptable for all coating, concerning the occurrence of stick-slip phenomenon, i.e. they were lower than the usual differences

of 20 to 30 % [4,14]. Although the Ni^{HT} coating showed the best friction properties (the lowest coefficient of friction and the lowest difference between static and kinetic coefficient of friction), the other two coatings (with addition of SiC nanoparticles) also had acceptable friction properties. Having this in mind and knowing the fact that the addition of SiC nanoparticles improved abrasive wear resistance [6,8], it can be concluded that the addition of SiC nanoparticles in general have favourable influence on the tribological properties of Ni coating.

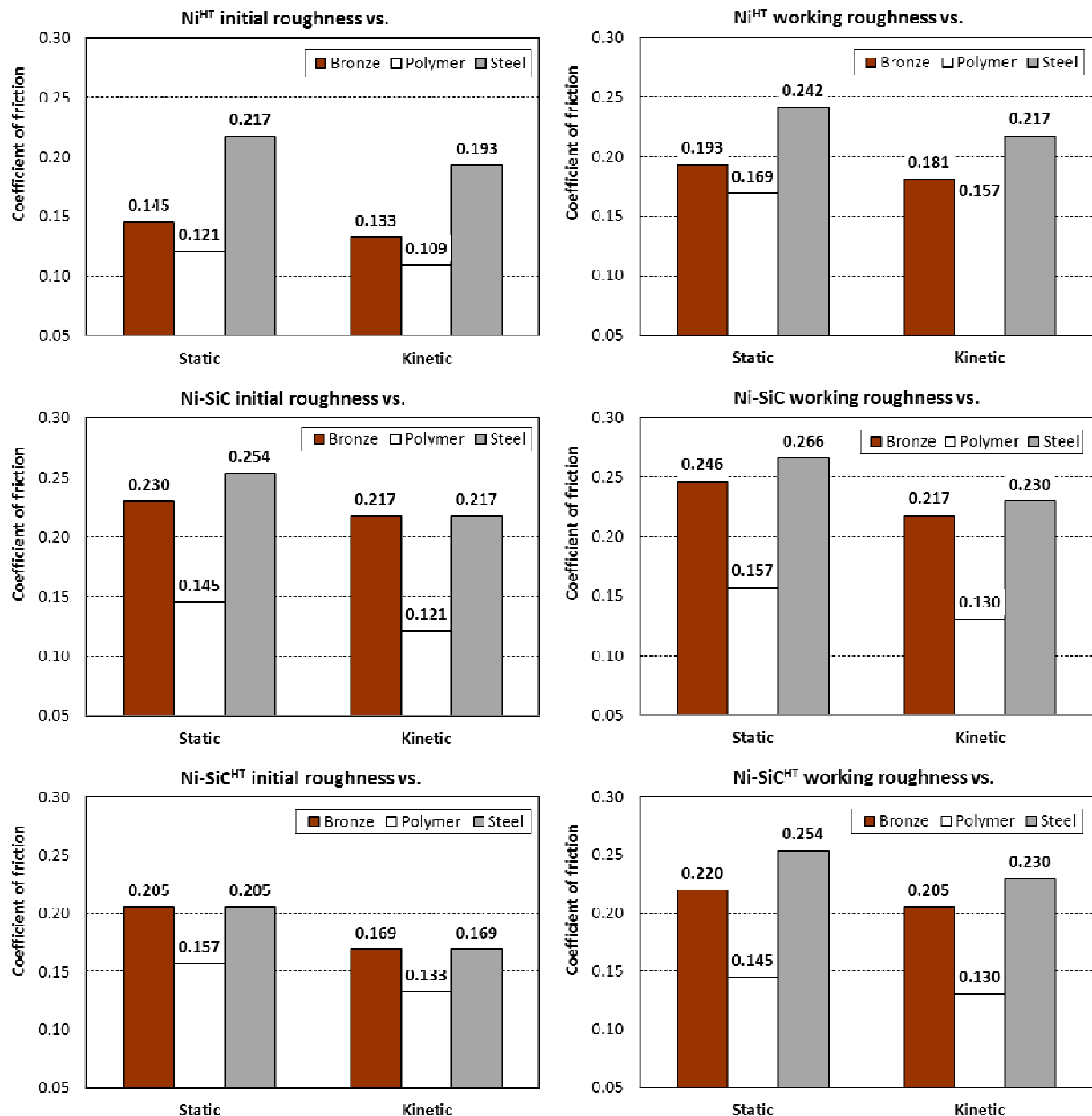


Fig. 8. Coefficient of static and kinetic frictions of tested coatings: initial roughness (left) working roughness (right)

4. Conclusions

Influence of SiC nanoparticles presence and application of heat treatment on electroless Ni coatings were investigated. Therefore, characterization of microstructure, microhardness and surface roughness and determination of static and kinetic coefficient of friction was done. Based on performed analysis and obtained results following conclusions can be derived:

- The proposed experimental procedure and used test rig has proved to be adequate for measurements of the static and kinetic coefficient of friction.
- Obtained results showed that surface roughness does not have major influence on the coefficient of friction of tested coatings, and that coatings hardness is more influential.
- Although the SiC nanoparticles were added to Ni coating in order to improve the abrasive wear resistance, they also slightly increase the coefficient of friction in unlubricated conditions.
- Due to small difference between static and kinetic coefficient of friction, for all tested contact pairs, the slip-stick phenomenon is unlikely to occur in practice, which is favourable.

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