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Elastic Yarn Tensioner with a Noncontinuous Antiwear Nanocomposite Pattern

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Abstract
Continuous hard protective layers on soft substrates working under elastic deformation conditions are prone to uncontrolled cracking and detaching from the substrate during bending and straining. Implementation of a noncontinuous hard pattern deposited on the surface allows such an antiwear layer to freely deform with the substrate. The idea was demonstrated for patterns made of regularly spaced, micrometer range sized nanocomposite islands. The nanocomposite used consisted of an epoxy resin matrix and superhard silicon carbide nanoparticles as a reinforcing component. Good dispersion of nanoparticles in the matrix was verified by means of atomic force microscopy. The significant improvement in wear resistance was measured under an applied load in the millinewton range using a custom-made microtribometer, and in the newton range using ball-on-disk apparatus. Such a system can be applied in textile machines and elastic yarn tensioners for damping the longitudinal component of vibrations, largely influencing the quality of the fabric obtained.

Key words: *yarn tensioner, nanocomposite, nanoparticles, polymer substrate, silk prining, tribology tests.*

Introduction

The dynamics of yarn tension is a crucial factor in many textile processes, determining both the process efficiency and quality of fabrics. It influences the tendency of yarn to break, particularly at high yarn speeds. Yarn vibrations also result in fabric inhomogenities and thus in its lower quality.

Currently, textile machines do not provide effective solutions for dumping yarn vibrations. It has been demonstrated [1] that the best results can be obtained by simply running yarn between finger pads. Therefore, it has been proposed to build a dumping element, mimicking human finger pads. The idea of such an element, consisting of a non-Newtonian medium contained in an elastic bag, is illustrated in ***Figure 1***.

This elastic element would press yarn against the metal plate of a tensioner, providing the stable yarn tension desired. Taking into consideration the high yarn speeds and impurities present on its surface, the high wear resistance of the external bag wall surface is essential. The goal of the research presented in this paper is to design and test the idea of an antiwear protective layer for a soft, elastic bag, in the form of a thin nanocomposite layer, consisting of a hard epoxy resin matrix and superhard silicon carbide nanoparticles as reinforcing components. It is important to note, however, that during bending and straining, typical for target application conditions, such a hard continuous layer would easily produce multiple cracks and eventually detach from the elastic substrate.

We propose to address this issue by applying a well-defined noncontinuous hard pattern on the surface in the first place. Such a protective layer will be able to freely deform with the substrate and, if well adhering to the surface, should provide good resistance to detaching. The layer deposition technique chosen in this work is silk screen printing, a precise method for applying patterns to the surface. Another method of deposition was dip coating; the results obtained with this technique, less promising than the present ones, have been described in another work [2].

Experimental

Materials

Commercial epoxy paint for silk screen printing, a mixture of Apollo C63 lacquer and glossy hardener Apollo C, was used as the matrix material. This paint was chosen for its rheological properties, adequate for silk screen printing, good chemical resistance and surface adhesion. The nanofiller used was superhard spherical silicon carbide (SiC), with a purity of 97% and average size of 20 - 30 nm.

The idea of a noncontinuous protective layer was applied and tested on model substrates: single crystal silicon wafers and commercial polyester high temperature film.

Outline of the experimental procedure

Nanocomposites were obtained by dispersing SiC powder in paint before

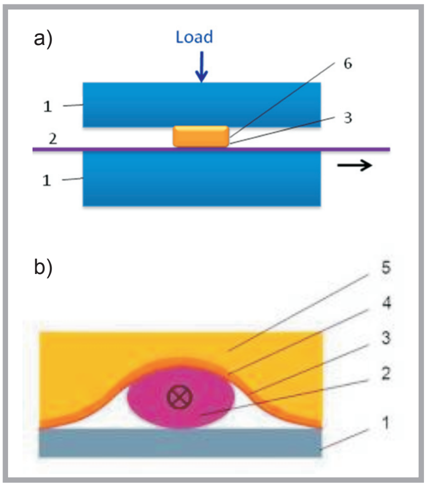

Figure 1. *Idea of the damping element in a yarn tensioner a) tensioner, b) blow-up of the friction point in a) cross-section: 1 – metal plates, 2 – yarn, 3 – protective, wear resistant layer, 4 – bag wall, 5 – damping medium, 6 – bag containing the non-Newtonian fluid.*

Celichowski G., Psarski M., Wiśniewski M.; Elastic Yarn Tensioner with a Noncontinuous Antiwear Nanocomposite Pattern.
FIBRES & TEXTILES in Eastern Europe, January/March 2009, Vol. 17, No. 1 (72) pp. 91-96.

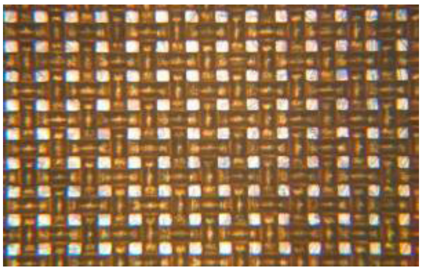

***Figure 2**. Silk screen printing with no pattern applied, used in this work for printing continuous layers.*

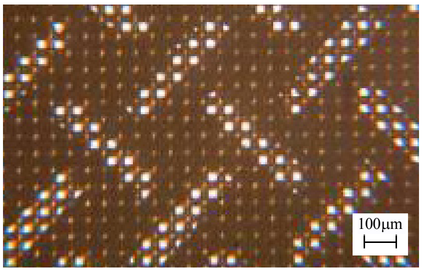

***Figure 3.** Pattern on the screen, made of uncovered mesh of the net, used in this work for printing noncontinuous layers.*

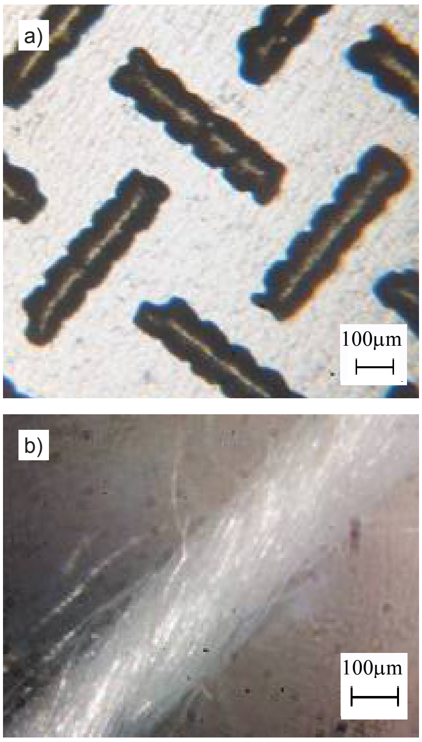

***Figure 4.** Comparison of sizes of the nanocomposite pattern and a typical yarn: a) 2% wt. SiC pattern, printed on polyester film, b) yarn shown at the same magnification.*

adding a hardener. Three experimental routes then followed: SiC investigation of the dispersion in the paint, composition optimisation and high load and 'real life' tests on the composite selected. In the first route, silicon wafers and polyester films were dip-coated with nanocomposite continuous layers to obtain samples for the investigation of the SiC dispersion in the matrix. In the second route, silk screen printing of nanocomposite continuous layers and patterns onto model substrates was performed to investigate and optimise the influence of the SiC concentration in the composite on its topography and wear properties in laboratory conditions. More severe wear tests corresponding to application conditions were performed on the optimised composite in the third step.

Preparation of SiC dispersions

For the initial evaluation of the dispersion, SiC nanopowder was manually mixed with the lacquer and hardener, with no additional dispersion enhancement, to obtain composites with an SiC content of 2% wt. For extended studies of the dispersion and for mechanical experiments, ultrasonification was applied to enhance the dispersion of SiC in the matrix. The SiC nanopowder was deagglomerated and distributed in tetrahydrofurane solution of the paint using a Hielscher UP200S high power density ultrasonic processor, operating at an acoustic power density of 80 W/cm^2. SiC deagglomeration was initially carried out in pure solvent with some detergent, then portions of the paint were subsequently added. The whole process took 30 minutes and 60 minutes in the case of samples prepared for dip coating and silk screen printing, respectively.

Adequate cooling of the mixture was provided during ultrasonification to avoid solvent boiling. After ultrasonification, tetrahydrofurane was evaporated in a rotary evaporator and the hardener was added to the mixture to obtain an appropriate viscosity for printing. The SiC concentration in the resulting composite was 3% wt. in samples prepared for dip coating. For silk screen printing, two batches of samples were prepared, with an SiC content of 1 - 3% wt. for preliminary wear and friction tests and 1.6 - 2.4% wt. for fine tuning the composites on the basis of wear and friction tests results

Dip coating

To facilitate investigation of SiC dispersion in paint, continuous nanocomposite layers were deposited on model substrates: silicon wafers and polyester films, by means of the dip coating procedure. Prior to use, the substrates were cleaned with methyl alcohol, after which low temperature RF plasma treatment was applied for 10 minutes to further clean the substrate surfaces. All nanocomposite layers were deposited under the same conditions, using a coating speed of 25 mm/min, at room temperature. Reference samples of pure paint were also prepared. To achieve full crosslinking of the matrix, the samples were heated to 60 °C and maintained at that temperature for 24 h.

Silk screen printing

In the silk screen printing procedure, a pattern created on a screen is reproduced on a surface by pressing paint with a squeegee through the screen against a substrate [3]. The screen is made of a net stretched on a frame, and the pattern is applied by photochemically covering selected parts of the screen. The screens used in this research are shown in ***Figure 2***. Such screens with no pattern applied were used in this research to print continuous layers for wear and friction tests in the millinewton scale. The pattern designed for the screens consisted of regularly spaced rectangles of 100 × 400 µm, as seen in ***Figure 3***.

As stated above, two batches of composites were used for silk screen printing: 1 - 3% wt. and 1.6 - 2.4% wt. The pattern was very precisely reproduced on substrate layers by painting nanocomposite cuboids of 100 × 400 × 10 µm, as can be seen in ***Figure 4.a.***

The pattern spacing was dense enough to ensure the smooth transport of yarn on top of the layer (***Figure 4.b.***), at the same time providing enough room for layer deformation.

Wear and friction tests in microscale

Investigating the antiwear properties of the nanocomposite materials developed, frictional tests in the millinewton scale were performed with continuous layers printed on model substrates, as described above. The principal goal of these experiments was to evaluate the properties of nanocomposite material itself but not the pattern, therefore continuous layers were used instead of patterns to eliminate any geometrical effects that might interfere with the friction force readout. The samples were frictionally tested on a reciprocating ball-on-flat machine, developed by the Department of Chemical Technology and Environmental Protection, University of Lodz and the Tribology Department of the Institute for Tero-

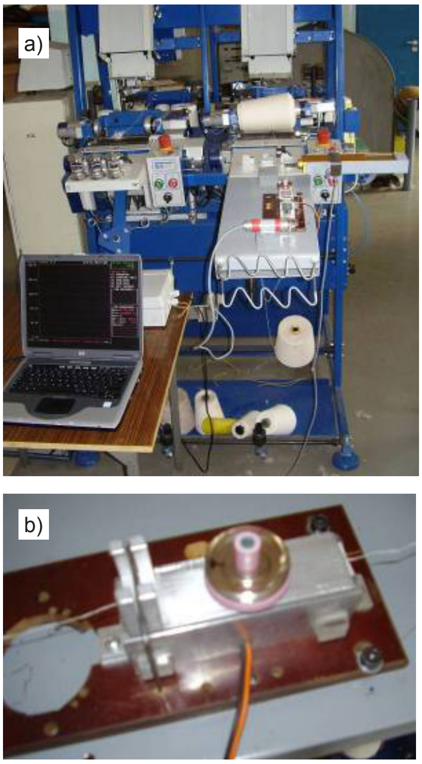

Figure 5. *Yarn winding testing rig: a) overall view, b) yarn tensioner with new elastic damping system.*

technology, Radom, Poland [4, 5]. The device consists of a control and a testing block. The control block is a computer-based unit, with four channels of data acquisition, computerized motor controllers for motion in the x and y-directions, and a system of normal load application. The microtribometer can provide linear motion with a speed ranging from 2 to 2000 μm/s. A normal load, which can be applied during frictional tests, covers the range of 1 – 1000 mN.

Tests were run under a load of 450 mN, at room temperature. The counterpart used was a steel ball with a diameter of 10 mm, moving up and down in 100 cycles at a velocity of 2 mm/s, for a distance of 7 mm. At least three runs were performed for each SiC concentration investigated.

High load and 'real life' tests on the selected composite

Wear and friction tests in the newton scale

Wear tests of continuous layers and patterns in the Newton range of loads were performed using a ball-on-disk tribometer (model T-11) [4], made by the Institute for Terotechnology, Radom, Poland. Measurements were carried out during frictional contact created by a rotating disk with a sample on it, and a ball pressing against it. The samples were taped to the disk. The disk and ball were made of steel. Tests were run under loads of 1 N, 2 N and 5 N, at room temperature; test times were 60 s, 600 s, 1800 s and 3600 s. The sliding speed was 0.01m/s. Before and after each test, the ball and the disk were washed with chloroform to remove any wear products. After the tests, the samples were collected for evaluation of wear traces.

Yarn tensioner

Laboratory tests conditions are far from those present in the application environment of textile machines – the counterpart is steel not yarn, the magnitude and dynamics of the load are also significantly different. Additional tests were, therefore, conducted on selected nanocomposites, utilising a real yarn tensioner setup [6, 7], enhanced with several control and acquisition features allowing to precisely monitor yarn tension dynamics. The yarn winding testing apparatus, shown in ***Figure 5***, was developed at the Institute for Terotechnology, Radom, Poland.

The composite prints on the polyester film substrate were glued to an elastomeric bag filled with a non-Newtonian fluid and placed in the tensioner. The tests were conducted under the following conditions: a yarn tension of 60 cN, a yarn travel velocity of 1000m/min, and a test time of 5 min. After the tests, the samples were collected for evaluation of wear traces.

Microscopy

Dispersion SiC particles in the paint matrix were evaluated by means of atomic force microscopy (AFM), with a NT-MDT Solver system, operating in the tapping mode, using the Si/SiO$_2$ tips. Plasma etching was applied for 5 minutes before the measurements to expose SiC particles near the surface.

Wear traces on the surfaces of the samples after the wear and friction tests were investigated using an optical microscope.

Results

Investigation of dispersion

SiC dispersion in continuous nanocomposite layers

The deposition of continuous layers on model substrates using the dip coating technique allowed to obtain flat, smooth layer surfaces, suitable for atomic force microscopy. AFM was used for investigation of SiC dispersion in the matrix. The effectiveness of the ultrasonification procedure applied was thus evaluated in comparison with composite preparation with no dispersion enhancement. As shown in ***Figure 6***, high power density ultrasonification proved to be very efficient in deagglomerating and dispersing SiC in the paint. Separate nanoparticles can be seen homogeneously distributed, their height being of about 10 nm.

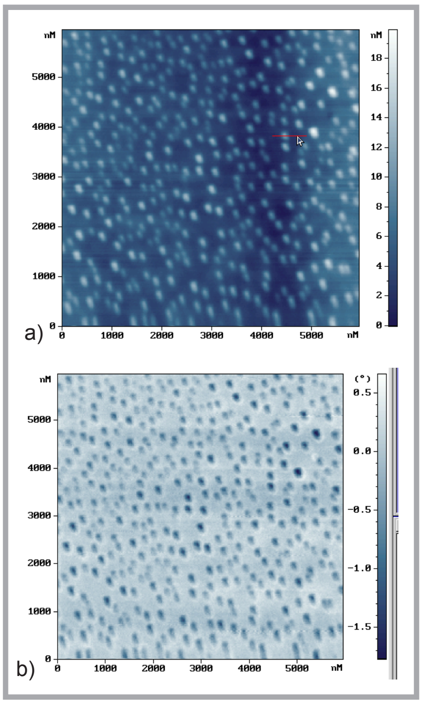

Figure 6. *SiC nanoparticles in continuous layers containing 3% wt. SiC, dip coated on polyester films: a) topography, b) phase contrast.*

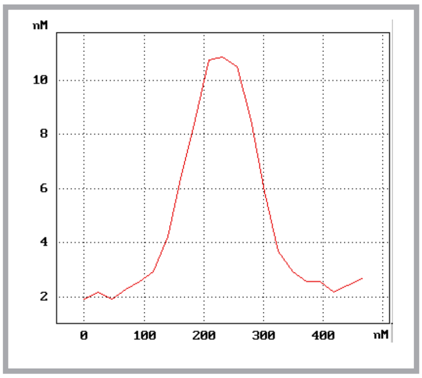

Figure 7. *Distribution of nanoparticles in the cross-section.*

Topography of printed continuous layers

To evaluate the influence of the printing process on SiC dispersion, continuous nanocomposite layers were also prepared using the silk screen printing method,

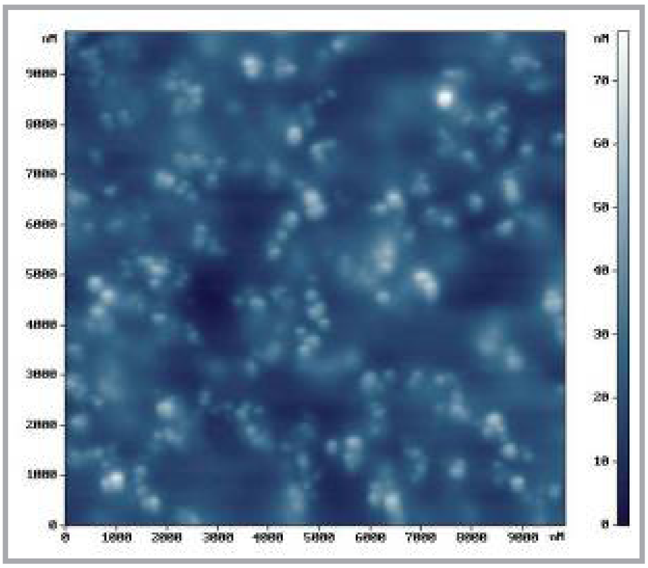

Figure 8. Topography (AFM) of the printed continuous layers with 2% wt. SiC.

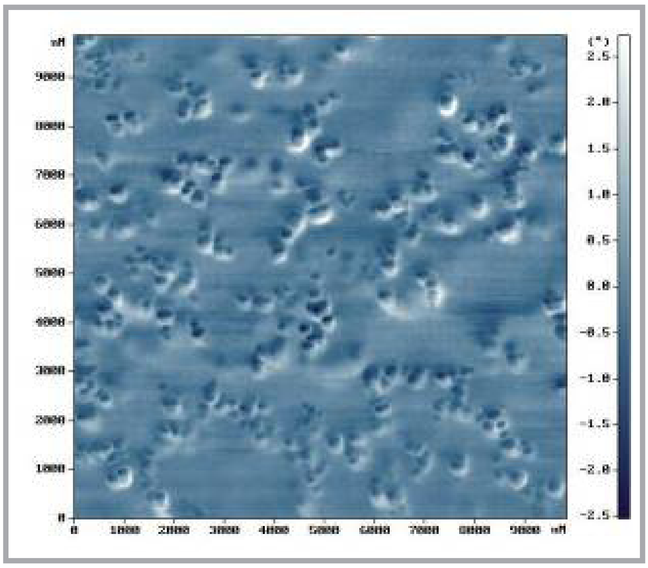

Figure 9. Phase contrast image of the printed continuous layers with 2% wt. SiC.

wherein the screen with no pattern was used, as described in the subchapter 'Silk screen printing' Nanocomposites containing SiC particles in the range of 1 - 3% wt. were printed on silicon wafers and polyester films. The film surfaces were investigated using an optical microscope and AFM. Compared to dip coated layers, some more particle aggregation occurs in the printed layers, as can be seen in ***Figures 8*** and ***9***. This can be attributed to shear forces resulting from pressing the composite through the screen mesh during printing. Nevertheless, the dispersion is still extremely satisfactory in these composites.

Composite optimisation

A series of laboratory scale wear and friction tests under loads in the millinewton scale were performed to relate the wear properties of the composites to their composition and to select a composite with the best wear resistance – for further, more severe, application related testing. Most tests were performed on printed continuous layers. In the case of printed patterns, the results were more difficult to interpret due to the layer discontinuity interfering with the friction force readout. The tests were performed primarily to investigate wear trace topography.

In the experiment, the friction force versus time and sample displacement was acquired. Experimental records were statistically elaborated, excluding extreme data, to calculate the friction coefficients for each up and down cycle. Plots of the friction coefficient versus the overall test time, equivalent to the number of cycles, are shown in ***Figure 10***, for the different SiC contents. For comparison, plots for unfilled paint prints are also shown. As the wear of the sample surface progresses, more debris is produced, manifested by the increase in the friction coefficient. The important feature on these plots is that the time of reaching a plateau indicates the wear resistance of the sample.

The wear resistance of the paint is not affected by the addition of up to 1.5% wt. of SiC nanoparticles, but it significantly increases at 2.0% wt.; however, it decreases again with a further increase in the SiC content. A separate plot for the composition with the best antiwear properties is provided in ***Figure 11*** for clarity.

In order to precisely determine the composition for which the best wear resistance is achieved, a series of tests were performed on composites with a narrowed SiC content range of 1.6-2.4% wt. The friction coefficient versus time plots

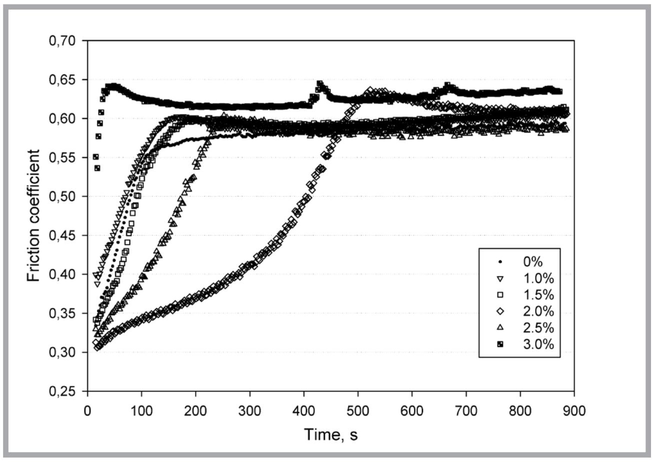

Figure 10. Friction coefficient of continuous layers vs. test time, 1 - 3% wt. SiC

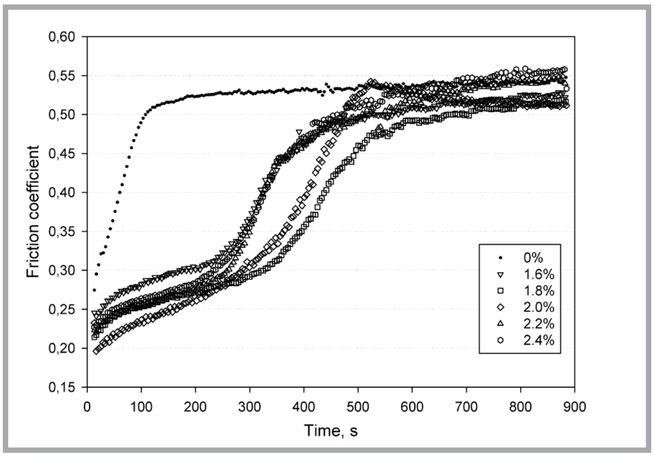

Figure 12. Friction coefficient of continuous layers vs. test time, 1.6 - 2.4 % wt. SiC.

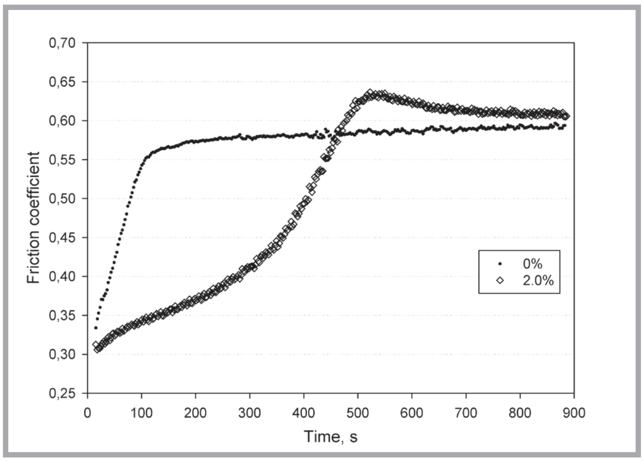

***Figure 11.** Friction coefficient of a 2.0% wt. SiC continuous layer, printed on silicon wafer, versus the test time.*

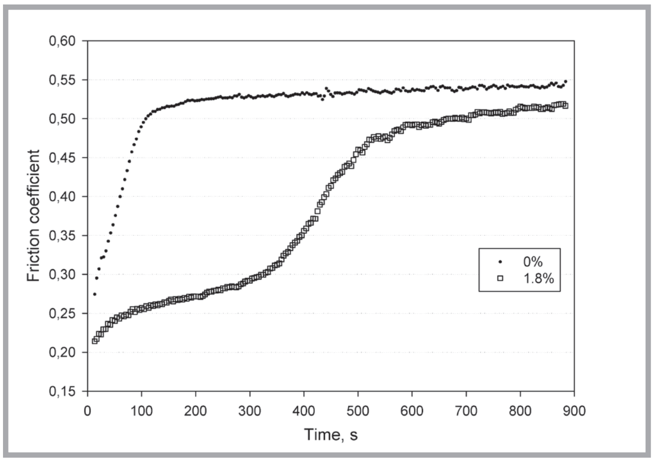

***Figure 13.** Friction coefficient of a 1.8% wt. SiC continuous layer, printed on silicon wafer, versus the test time.*

obtained in these tests are shown in ***Figure 12***. The longest time to reach a plateau was obtained for the 1.8 % wt. SiC composition, shown separately in ***Figure 13***, which composition was chosen for further, high load testing involving the Ball-on-Disk tribometer and experiments in application conditions, using the yarn tensioner.

Topography of wear traces after microtribometer tests

To further evaluate the wear of nanocomposite layers, the topography of wear traces was investigated using optical and atomic force microscopy. In ***Figure 14***, the wear trace in a 1.8% wt. SiC printed continuous layer after a microtribometer test is shown. The total layer thickness is approx. 10 µm, as measured with optical microscopy. ***Figure 14.a*** shows that although the outmost layer was removed during the test, the continuity of the layer is preserved. In other words, even though some wear occurs during the test, the layer fully maintains its protective ability.

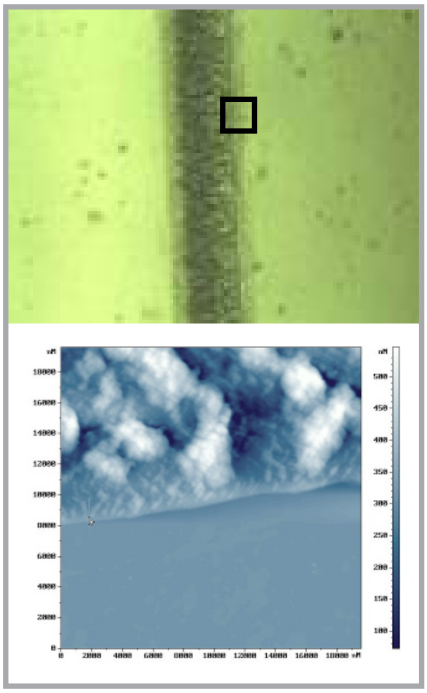

***Figure 14.** Topography of the wear trace in a1.8 % wt. SiC printed continuous layer, after a microtribometer test, a) optical microscopy, b) AFM, blow-up of the area selected in a).*

Partial wear is also shown in ***Figure 15*** (for 1.8% SiC wt. nanoc omposite printed patterns). It can be seen that the nanocomposite "islands" undergo some plastic deformation but remain attached to the substrate, which demonstrates their good adhesion to the substrate.

Topography of wear traces in 1.8% SiC composites after ball-on-disk tests

Ball-on-disk tests were performed on printed patterns of the 1.8% SiC composites to evaluate their wear behaviour and topography of wear traces after wear tests in the newton scale. A comparison was also made between composites prepared using high power ultrasonification and those prepared without dispersion enhancement. Increasing loads and test times were employed until layer disruption was seen in the topography examination, except for samples which did not reach that point under reasonable test conditions.

Prints of unmodified paint on polyester film, shown in ***Figure 16***, survive under a load of 2 N for up to 30 minutes. The addition of 1.8% wt. SiC with no dispersion enhancement does not significantly change the layer wear resistance (***Figure 17.a***).

The application of high power density ultrasonification, however, changes the situation significantly – the print remains intact for 60min under a load of 2N (not shown here). The first wear traces are only visible after 10 min under a load of 5N, and even after 30min under such a load the pattern is still present on the substrate surface (***Figure 17.a and 17.b***).

It is important to note that the loads applied in these tests far exceed loads that will act on bag walls in yarn tensioner applications. Therefore, tests employing

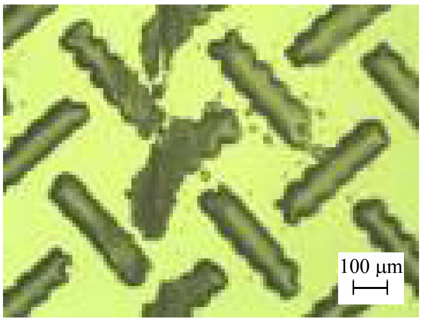

***Figure 15.** Topography of a 1.8 % wt. SiC printed pattern, after a microtribometer test.*

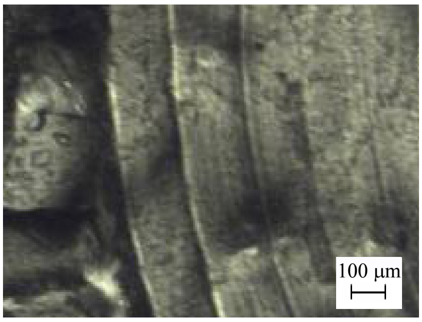

***Figure 16.** Topography of a paint print on polyester film after the ball-on-disk test, after 30min under a load of 2N.*

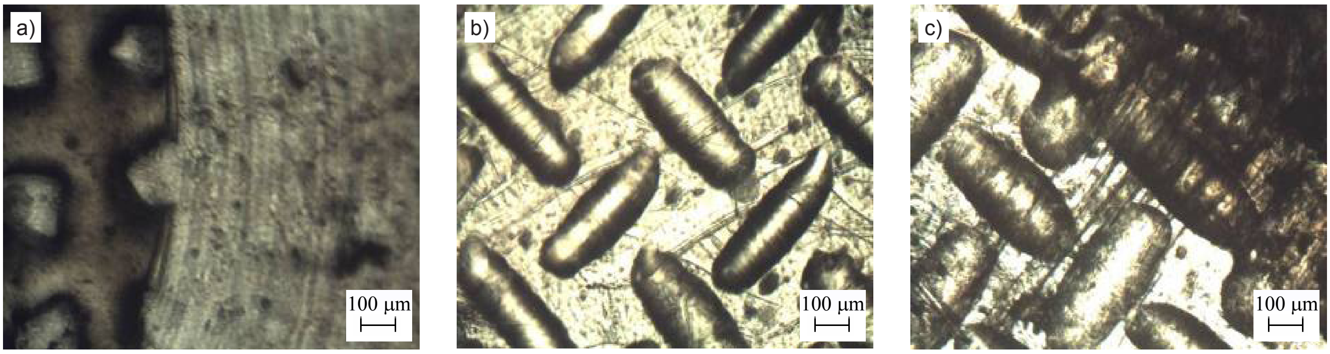

Figure 17. *Topography of prints of 1.8% SiC composites on polyester film, a) unultrasonicated print after 30 min under a load of 2 N, b) ultrasonicated print after 10 min under 5 N, c) ultrasonicated print after 30 min under 5 N.*

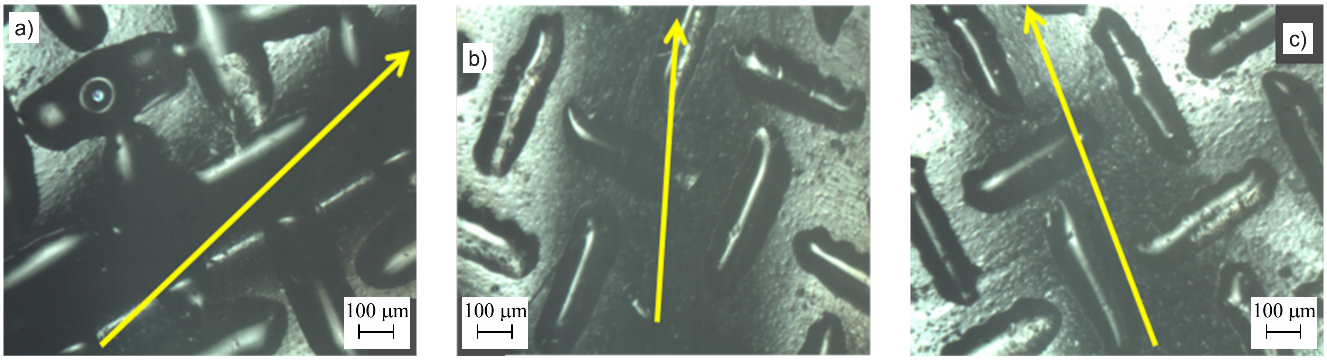

Figure 18. *Topography of prints (arrows indicate yarn travel direction) on polyester film made of: a) paint, b) 1.8% SiC unultrasonicated composites, c) 1.8% SiC ultrasonicated composites.*

longer times and higher loads were not performed. The friction force was stable in these tests, thus no significant wear phenomena occurred. As in microtribometer tests, only minor layer destruction occurs during tests of these compositions, which does not impair their protective function.

Topography of wear traces after yarn tensioner tests

Topography of prints on polyester film after yarn tensioner tests is shown in ***Figure 18.***

The wear trace is visible in the form of a dark stripe along the yarn travel direction and is most pronounced on the unmodified paint print. The addition of SiC without dispersion enhancement results in a somewhat less distinct trace, and almost no visible destruction is seen in prints with ultrasonificated SiC nanoparticles.

It should be also noted that pyrometric measurements carried out during the tests indicated no temperature increase at the friction point. The yarn temperature was 18 °C, either before or after the friction point. The sample surface temperature also remained constant. Given that in real yarn tensioners yarn is forced into transversal movements on the bag surface, this allows to expect that the temperature increase may be well within the layer heat resistance limit in these applications.

Summary and conclusions

A novel antiwear protective layer has been designed in the form of a discontinuous pattern of regularly spaced epoxy nanocomposite islands of micrometer range size. Very effective nanofiller dispersion in paint was achieved by applying high power density ultrasonification using the solvent procedure. The addition of SiC nanofiller, in concentrations ranging from 1.0% wt. to 3% wt. strongly influences wear properties of the nanocomposite layers investigated. Effective antiwear protection of model substrates by these nanocomposites was demonstrated under laboratory test conditions. The best antiwear properties were observed for the 1.8% wt. SiC share, which was further confirmed in the high load experiments and in a real working environment.

Editorial note

Extended version of communication at the 16th International Colloquium Tribology, Technische Akademie Esslingen, Ostfildern, Germany, 2008

Acknowledgment

This research was funded by the Polish Ministry of Science and Higher Education, Grant # 3 T08E 024 29.

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Received 29.02.2008 Reviewed 12.11.2008