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The pull-off test of different materials using electroadhesive pads

***Abstract** The aim of the article was to investigate the phenomenon of electroadhesion in terms of the value of pull-off force for various materials. Application possibilities of electroadhesion, which is widely used in industry, are presented. A unique measuring and power-supplying system was designed and built. A dynamometer was used to test the pull-off force. The test was conducted for three materials: cellulose, silicone-modified cellulose and polyester. The measurements were presented on histograms, taking into account the average force used to pull off a given material.*

Streszczenie** Celem artykułu było zbadanie zjawiska elektroadhezji pod kątem wartości siły zrywu dla różnych materiałów. Przedstawiono możliwości zastosowania elektroadhezji, która jest szeroko stosowana w przemyśle. Zaprojektowano i zbudowano unikalny system pomiarowy i zasilający. Do badania siły zrywu użyto dynamometru. Badania przeprowadzono dla trzech materiałów: celulozy, celulozy modyfikowanej silikonem oraz poliestru. Pomiary zostały przedstawione na histogramach z uwzględnieniem średniej siły odciągania danego materiału. **Badanie siły zrywu matriałów używanych do prdukcji elektroadhezyjnych elementów

Keywords: electoradhesion, electroadhesive pad, pull-off, attracktion, electrostatic field, electroamagnetic field.
Słowa kluczowe: alektroadhezja, pad elektoadhezyjny, siła zrywu, elektrostatyka, pole elektromangrtyczne

Introduction

Electroadhesion is a phenomenon of adhesion and attraction, created as a result of the effect of high voltage on electrodes placed on an electroadhesive pad. The electroadhesive pad is a plate made of material with a very high dielectric constant, on which two copper electrodes are placed. The most popular material of which the electrodes are made is elastomer or polymer [1-3]. An electromagnetic field is produced between the copper electrodes located on the pad. After the power supply is disconnected, the electrostatic field remains on the electroadhesive pad. The material covering the pad should have insulating properties to avoid any breakdown between the copper electrodes. The thickness of the electrodes themselves and the distance between them also play an important role. The bigger distance between the electrodes, the lower the risk of breakdown and the formation of an electric arc. The bigger the distance between the electrodes, the lower the electroadhesive force. In research conducted on the phenomenon of electroadhesion, attention is also paid to the electrode shapes. The research [4] describes the impact of the electrode shape on the attractive force. The most popular shapes of electrodes include coils and combs.

The phenomenon of electroadhesion is widely used in industry. In some industrial branches, holders with electroadhesive pads – characterised by large surface area – are used. This enables the attraction of large sheets of textile materials with the pad and moving them to another place [5]. The materials of rough density are attracted with different force than smooth materials [6,7]. The article [8] explores how materials of different density are attracted. For this purpose, the surface of an aluminum plate was scratched and silicon carbide-based sandpaper was used. The result was more effective attraction by the pad because of air gaps between the scratches. The interfacial forces increased with the changing mean squared distance (Sq). The test was conducted by increasing the voltage from 2 kV to 6 kV. The high voltage caused an increase in the electroadhesive force.

Smart textiles used for reactive clothing are a new solution. The idea is to create a conductive, elastic dielectric material. The main purpose of this material is to have attraction properties, just like the electroadhesive pad. The material is made of elastomer and may be worn freely on the body. The textiles using electroadhesion have strong potential because they are comfortable and have multifunctional application in soft robotics [9].

In the tests, electroadhesion was used to penetrate such hard-to-reach areas as sewage pipes. For this purpose, a flexible actuator, similar to a robot arm, was produced. At its end, there is an electroadhesive pad and a camera. This allows to observe and attract a desired element with ease [10]. Electroadhesion is also applied in many devices for lifting objects by means of electrostatic force. These devices are able to operate under changing environmental conditions [11]. Temperature, pressure and humidity do not interfere with the operation of devices with electroadhesive pads. Therefore, they are increasingly used in machine diagnosis as well as diagnosis of other large devices [12-14]. Different concepts regarding climbing and flying robots are being designed [15]. Such robots are equipped with electroadhesive pads which enable attaching them to a flat surface. Furthermore, diagnostic cameras are placed on them. Climbing robots are able to penetrate high, hard-to-reach areas [16-19]. They are used for technical tests on large aeroplanes. Such concept is much more economic and accurate, and above all, it does not threaten human safety.

Another example of the application of electroadhesion is connecting different components together, e.g. connecting polymer wafers. This is a widely applied process of manufacturing microflow devices. Previous solutions of polymer connections did not allow to obtain enough strength. That is why, the model of electroadhesive force was set for improved bonding characteristics for the most of polymers [20]. Electroroadhesion is used for adaptation to strength as well as for tuning and strengthening mechanical structural elements. With the use of electric fields of various intensities, on copper-polyamide laminates, the procedure of mechanical performance tests is conducted [21]. As in the case of the robotic arm [10], the design of the flexible actuator [22,23] was optimised by means of dry adhesives. They improve adhesion to smooth surfaces thanks to elastic hybrid adhesives [24]. These gecko-inspired adhesives are very elastic. Thanks to these properties they can stick to any surface [25].

The measuring system

The measuring system was designed to conduct the tests. The equivalent diagram of the system is presented in Figure 1. The test system comprises two parts: power-

supplying part and measuring part. The power-supplying part consists of 12V power supply, mains-operated by voltage of 230V. It has been powered with DC of approx. 0.2 A. Then a high-voltage converter and a high-voltage rectifier with an electronic filter were connected to it. A polarisation adjustment system was connected to the system at the outputs of the high-voltage rectifier. It is equipped with a button enabling discharging of the whole system and a switch for adjusting the polarization.
The second part of the system is the measuring part. It consists of a digital dynamometer from which the results were read with accuracy of 0.5 N. An electroadhesive pad of 5 cm x 10 cm, was attached to the dynamometer. Similar dimensions had the materials with which the pull-off force tests were carried out. The output voltage on the electrodes of the electroadhesive pad was 4,2 kV. In the room, where the measurements were performed, there were standard conditions: temperature: 20.5°C, humidity approx. 45% and pressure: 1012 hPa..

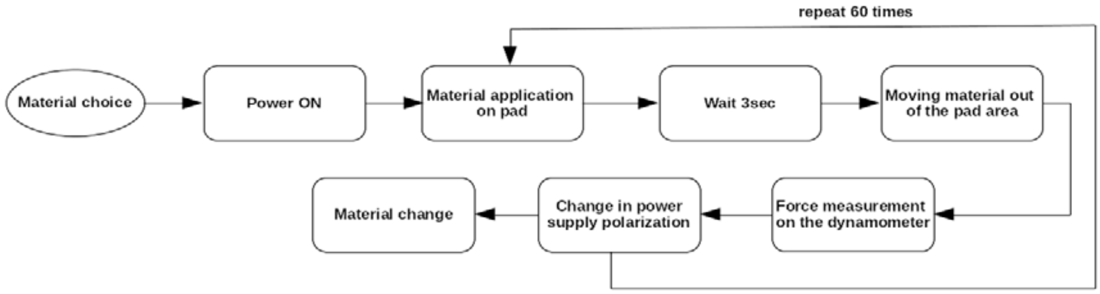

Fig. 1. Diagram of the measuring system.

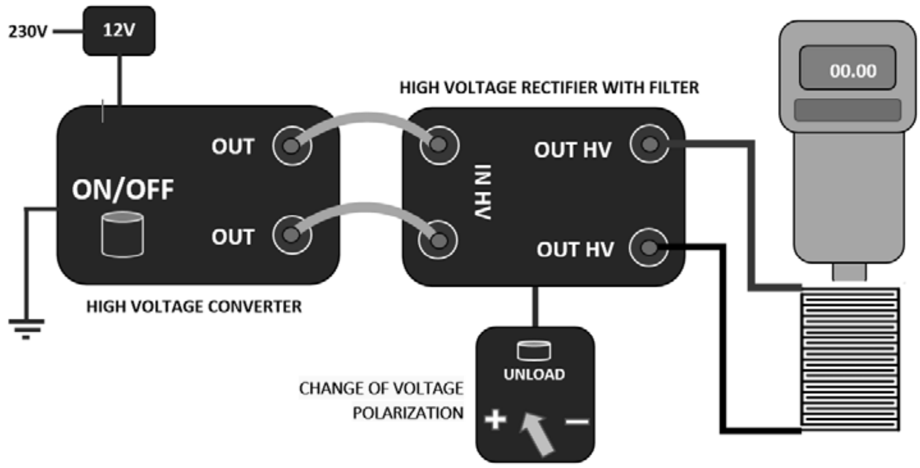

Fig. 2. Block diagram of pull-off force measurements.

Research methodology

In the article [26], a digital scale was used to test the force with which the electroadhesive pad attracts materials. Small pieces of cellulose were placed on it, and above them – the electroadhesive pad. After powering the pad, the high voltage was gradually increased. With a voltage of approx. 5kV, the electroadhesive pad began to attract the cellulose placed on the scale. As part of the test, it was possible to record a shift in the digital scale reading. This is one of the test methods analysing the attractive force between materials and the electroadhesive pad.

Jianglong Guo et. al. analysed many ways of generating this force as well as the concept of electrode shapes on electroadhesive pads [23].

The electroadhesive force was tested both in theory and practice – with the use of adhesives [23]. Different electrode shapes used on the pads were designed and computer simulation was performed using Comsol [4]. In this way, the distribution and electroadhesive force were modelled. The measurements were repeated on physical pads using the same electrode shapes and identical parameters as in the simulation. In many cases, the results coincided with the simulation ones performed in Comsol

After turning the power supply on, the material was applied to the pad for one second. After that time, the material was gently moved outside the pad area. Noticeable resistance between the material and the pad could be recorded. When the material was completely pulled off from the pad, the reading of the dynamometer indicated the highest force achieved. For more accurate results, the system was discharged and the power supply polarity was changed after each measurement.

Results and discussion

The tests were conducted for three types of materials: cellulose, polyester and silicone-modified cellulose. The latter material was selected because of its composition, as cellulose coated with silicone is applied in gastronomy to avoid food sticking during baking. Such silicones are synthetic organosilicon polymers (they contain silicon atoms – Si – and carbon ones – C). A series of 60 measurements was taken on each of the three materials. The test results are presented in the form of histograms. The pull-off force was presented in newtons on the x-axis, whereas the number of measurements – on the y-axis.

Cellulose was the first material tested. The results are shown in Figure 3. The measurement was repeated 60 times; after each measurement the polarisation was changed. The results ranged from 4N to 8N. The average recorded force with which the cellulose was pulled off from the electroadhesive pad constituted 5.5 N. The highest pull-off force obtained was 8 N.

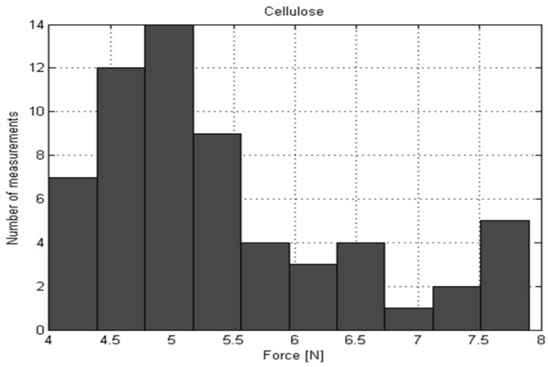

Fig. 3. Histogram showing the measurements of the cellulose pull-off force.

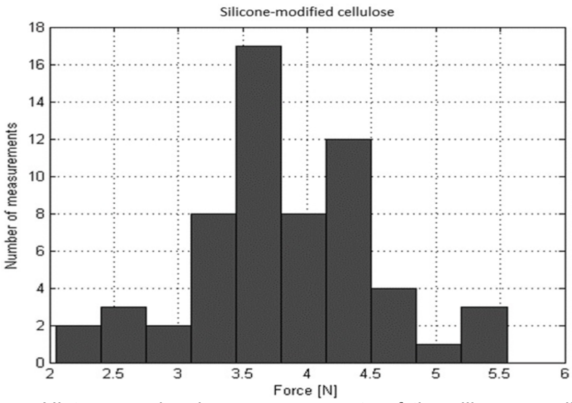

Fig. 4. Histogram showing measurements of the silicone-modified cellulose pull-off force

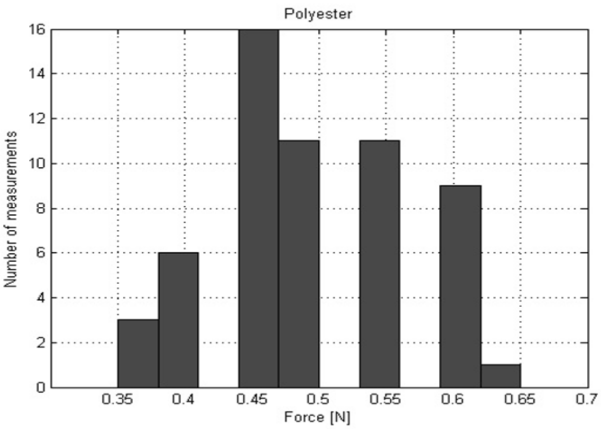

Fig. 5. Histogram showing the measurements of the polyester pull-off force.

The next material tested was silicone-modified cellulose. The values obtained were slightly lower than those obtained when testing cellulose. The highest recorded value was 6 N. The lower limit of the obtained pull-off force was 2 N. The average silicone-modified cellulose pull-off force was approx. 3.8 N. A histogram with the measurements of silicone-modified cellulose is shown in Figure 4.

The last material tested was polyester. The results of force measurements were considerably lower than those for the results obtained for cellulose and silicone-modified cellulose. The measurements presented in the histogram (Figure. 5) show that the polyester pull-off force was the lowest and constituted 0.65 N.

Summary

The article describes the phenomenon of electroadhesion and its attraction properties. Electroadhesive pads, i.e. plates with copper electrodes connected to high voltage (5 kV), are used to obtain electroadhesion. After powering the system, an electrostatic force is generated on the pad, which lasts for some time after disconnecting the power supply. Thanks to this, the electroadhesive pad has attraction and adhesion properties.

The paper describes the current possible applications of electroadhesion. This phenomenon is widely used in industry to attract and grab various elements [5]. It constitutes additional equipment for flexible actuators [22,23] and robotic arms, allowing to attract objects from hard-to-reach areas [9,10]. Thanks to electroadhesive pads, robots climbing on smooth surfaces can be used. It is great convenience for the tests of large industrial machines and aeroplanes. In addition, flexible electroadhesive pads are used as an element which enables various components to connect together [20].

The course of research was presented in the form of a block diagram shown in Figure 2. In order to test the pull-off force, an experiment was carried out on several materials, out of which three ones with the best results were selected. The first material was cellulose. The results obtained were the highest when compared to other materials tested. The pull-off force of the cellulose from the electroadhesive pad was 8 N. However, the results were not repeatable, as they ranged from 4 N to 8 N. The next material tested was silicone-modified cellulose. The results were slightly lower than the previous ones. The highest pull-off force of silicone-modified cellulose was 6 N. Polyester proved to be the weakest material – its maximum pull-off force was only 0.65 N. The results obtained showed that the electroadhesive pad attracted materials with different forces, depending on their chemical composition [6.8].

Other articles will concern research related to the selection of electroadhesive materials that are used for covering electroadhesive pads. The aim of these papers is to select the material with the highest possible puncture resistance. Furthermore, the research will involve the minimisation of the negative impact of a pad's electroadhesive layer on the value of the recorded pull-off force and on its thickness selection

The main aim of this article was to conduct electroroadhesion testing for pull-off force. For this purpose, a unique power-supplying and measuring system was designed and built. The power-supplying part included a high-voltage converter and a rectifier. An additional device was a system allowing to discharge the system and adjust the polarisation at the outputs from the high-voltage rectifier. In the measuring system part there was a digital dynamometer with an attached electroadhesive pad. The dynamometer was applied to record results with accuracy of 0.05 N.

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