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DURABILITY INVESTIGATION OF A DISC-TYPE CLUTCH WITH ELECTRORHEOLOGICAL FLUID

BADANIE TRWAŁOŚCI SPRZĘGŁA WISKOTYCZNEGO TARCZOWEGO Z CIECZĄ ELEKTROREOLOGICZNĄ

Key words: durability, clutches and brakes with intelligent fluids, electrorheological fluids.

Abstract: The article concerns experimental research on the durability of a viscotic disc-type clutch with an electrorheological fluid. Viscotic clutches are currently used in the power transmission of multiple machines. The development of the viscotic clutch design is possible due to the use of working fluids with electrorheological properties, which renders it possible to control the drivetrain with the use of an electric current. The durability of the clutches with electrorheological fluid is important in determining the possibility of industrial use. On the basis of bench tests of a viscotic disc clutch, the article presents considerations regarding the operating factors of the clutch. These factors considerably impact the durability of the clutch and its components, including the working fluid.

Słowa kluczowe: trwałość, sprzęgła i hamulce z cieczami inteligentnymi, ciecze elektroreologiczne.

Streszczenie: Artykuł dotyczy badań eksperymentalnych trwałości wiskotycznego sprzęgła tarczowego z cieczą elektroreologiczną. Sprzęgła wiskotyczne są obecnie stosowane w układach przeniesienia napędu wielu maszyn. Rozwój konstrukcji sprzęgieł wiskotycznych jest możliwy w wyniku zastosowania jako cieczy roboczej cieczy elektroreologicznej, co umożliwia sterowanie napędem za pomocą prądu elektrycznego. Istotnym problemem, decydującym o możliwości aplikacji przemysłowej sprzęgieł z cieczą elektroreologiczną, jest ich trwałość. W artykule, na postawie badań stanowiskowych wiskotycznego sprzęgła tarczowego z cieczą elektroreologiczną, przedstawiono rozważania dotyczące czynników eksploatacyjnych, mających zasadniczy wpływ na trwałość sprzęgła wiskotycznego i jego elementów, w tym samej cieczy roboczej.

INTRODUCTION

Current research and development works on the power transmission of machines and devices focus on improving the component design, including viscotic clutches. The torque in a viscotic clutch is transmitted as a result of friction caused by shear stresses occurring in the working fluid within the gap between working elements (discs or cylinders) in the driving and driven parts. An important feature of viscotic clutches is the transmitted torque's dependence on the input shaft's angular velocity; this feature is most commonly used to control the torque. The torque can also be controlled by changing the working fluid's temperature, pressure or volume in the viscotic clutch.

In viscotic clutches, the effect of progress is the use of smart fluids as working fluids. Two types of smart fluids are electrorheological fluids (ER) activated by an electric field and

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magnetorheological fluids activated by a magnetic field. An advantage of the ER fluids is their reaction to an electrical field which can be easily generated by two electrodes connected to the poles of a high-voltage power supply. Using ER fluids as a working fluid in devices made it possible to increase their functionality and extend the application possibilities. Such devices include shock absorbers, viscotic brakes and clutches, hydrodynamic brakes and clutches, touch devices, etc. **[L. 1–4]**.

Electrorheological fluids do not occur; naturally, they are man-made products. Their composition and structure are selected individually, depending on the required properties and the intended use. By composition, ER fluids can be divided into two groups:
– single-phase fluids, i.e., homogenous fluids;
– two-phase fluids, i.e., heterogenous fluids **[L. 5–6]**.

The single-phase fluids are built as homogenous suspensions of:
– carbonic acids in mineral oil,
– glycerin and paraffin oil,
– or as multicomponent polymer mixtures and polymeric liquid crystals. **[L. 7–12]**.

The two-phase ER fluids are mixtures consisting of a liquid phase (base fluid), solid particles, additives, and surfactants. The components of an ER fluid significantly influence its rheological and electrical properties. The properties of the ER fluid are also influenced by the shape and size of solid particles, particle size distribution, density, properties of the liquid phase, additives and surfactants (e.g. anti-corrosives). Proper selection of the components of the ER fluid is highly important for new applications in power transmission components in order to ensure the desired durability. The most frequently selected components for the liquid phase are as follows:
– mineral oils,
– vegetable oils,
– chlorinated paraffins,
– kerosene.

The main task of the liquid phase is to isolate dispersed solid particles in order to facilitate their polarisation as much as possible. The electrorheological effect depends on the polarisation. Moreover, the liquid phase should be characterised by good temperature stability, oxidation resistance, good thermal conductivity, high flash point and low vapour pressure.

The most frequently selected solid particles are:
– inorganic materials (metal oxides, silica, zeolites, glass),
– natural organic materials (starch, cellulose, resins, rubber),
– artificial (polyaniline, polyphenylene, polypyrrole, polythiophene).

Solid particles should be characterised by high chemical purity, as well as homogeneity and spherical shape, which significantly influences the agglomerate formations of the particles and the time of returning to the dispersed phase after the electric field is switched off. Additionally, the solid particles must resist abrasion and mechanical damage. The dimensions of the solid particles range from 0.1μm to 100 μm. The third important component of ER fluids is different additives which support the electrorheological effect and surfactants. These additives are water, acids, inorganic salts, alcohols, esters and substances which prevent sedimentation, corrosion and solid phase separation. The surfactants accelerate and facilitate the formation of dipoles in fragmented liquid particles. Additionally, they reduce the particles' tendency to coagulate, enable faster re-dispersion, and maintain an appropriate fluid pH. The exact composition and the types of additives and protective substances are kept secret by the manufacturer and are not disclosed to users of the ER fluid.

The physicochemical phenomena which describe the electrorheological effect (i.e., the behaviour of the ER fluid under the influence of an electric field) are not fully explained. They are characterised by high randomness of events and largely depend on the operating conditions of the device in which the ER fluid is used. The electrorheological effect occurring in ER fluids is a highly complicated phenomenon, which is the reason for creating models of interactions occurring in the ER fluid placed in an electric field. In accordance with one of these models **[L. 3]**, the solid particles of the ER fluid are freely dispersed in the base fluid in the absence of an electric field. The associated electrostatic charges are distributed randomly. When the electric field is switched on, the particles are polarised, forming electric dipoles and aligning along the force lines of the electrostatic field. **Fig. 1** shows the transfer of the solid particles of the ER fluid placed in the gap between the clutch discs under the influence of the electric field.

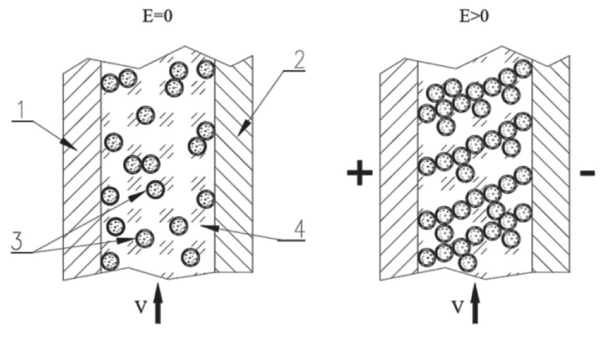


Fig. 1. ER fluid in the clutch channel: a) with the voltage off; b) with the voltage on: 1, 2 – clutch discs, 3 – solid particles, 4 – liquid phase

Rys. 1. Ciecz ER w kanale sprzęgła: a) bez włączonego napięcia; b) przy włączonym napięciu: 1, 2 – tarcze sprzęgła, 3 – cząstki stałe, 4 – faza ciekła

In the next phase, the solid particles form chains along the force lines of the electrostatic field, perpendicular to the direction of the ER fluid's flow. As a result of the flow, the chains are shifted or broken, and then they reconnect. The hindered flow of the ER fluid between the clutch discs is the effect of the formation of spatial structures in the ER fluid under the influence of the electric field. This causes an increase in shear stresses within the ER fluid. As a result, the torque transmitted by the clutch is increased. After the electric field disappears, the ER fluid returns to particle and charge dispersion state. The entire process takes place continuously over a period of several milliseconds. In practice, in the presence of an electric field, a current of very low intensity flows through the ER fluid; it is called the leakage current. The detailed course of the phenomena occurring in the ER fluid depends on the electric field strength value. When the electric field values are low, the interconnected particles are broken apart and rotate within the liquid. Individual particles do not maintain the polarisation accordant to the lines of the electric field's force. As the value of the electric field strength increases, the chains break, but the dipoles maintain their polarisation in accordance with the field's force lines. Inside an electric field of high intensity, the chains do not break down completely, but there occurs a deviation from the course of the field force lines. The mechanical wear of ER fluid's solid particles is related to the particle flow between the discs of the viscotic clutch. The discs rotate, and as a result, the particles move in the direction of the ER fluid's flow; then, as they come into contact with other particles and clutch elements, they are destroyed. In order to learn the intensity of these phenomena, it is necessary to conduct bench tests of prototypical devices with ER fluids **[L. 5–6]**.

In a viscotic clutch with the ER fluid, a change in the transmitted torque is obtained as a result of changing shear stresses caused by changes in the electric field. An increase in the shear stresses in the ER fluid causes an increase in the torque transmitted by the viscotic clutch. The electric field is changed by changing the high voltage with the use of electronically controlled electric power supplies. In order to supply the power to the electrodes connected to rotary parts of viscotic clutches, slip rings, brushes and electric wires are used. Using an ER fluid as a working fluid demand introducing design changes in the viscotic clutches. The changes mainly concern supplying power to the electrodes and using insulation materials. So far, clutches with ER fluids have not been widely employed in drive systems of machines. This is due to numerous factors, one of which is the durability of the elements of the clutches and ER fluids. The durability is described as the device's ability to maintain the required functionality over a time period in predetermined operating conditions **[L. 3, 12–20]**. Therefore, the device's durability significantly influences its operational reliability, which is important in industrial applications. The professional literature also discusses the issue of durability of clutches and brakes with ER liquids. This type of research can be divided into two groups:

– testing the properties of ER fluids using various special and laboratory devices **[L. 40–44]**;
– testing of prototypes in terms of the impact of various working conditions on the durability of ER liquids (performed at specialised test benches) **[L. 15–21]**.

So far, the literature does not provide broader studies on the research concerning the durability of viscotic disc clutches with ER fluids.

The state of advancement in the design and research concerning the clutches with ER fluids indicates a high Technology Readiness Level (TRL). On the basis of the literature analysis, it can be concluded to be level 5, which includes technological validation of the developed prototype in an environment similar to the real one **[L. 21–39]**. The next level includes testing in real-life conditions. In order to achieve this level, it is necessary to improve the durability of the clutches and the ER fluids used as working fluids.

The purpose of the research on the durability of the disc clutch with the ER fluid, as shown in this article, is to determine the factors affecting the deterioration of the clutch components' functionality and to determine the properties of the ER fluids by determining the causes of destruction of the fluid and its components.

THE TEST OBJECT

The tested disc viscotic clutch with the ER fluid consists of a driving part, a driven part and a casing. The discs are the working elements of the clutch. The discs located in the driving part are connected to the input shaft, and the discs located in the driven part are connected to the output shaft. The discs of the driving part and the driven part are placed alternately inside the clutch's casing while maintaining the working gap filled with the ER fluid. The test object is shown in **Fig. 2**.

The "+" pole of the high-voltage power supply is connected to the slip ring with the use of electric wires and a brush. The "-" pole of the high-voltage power supply is connected to the grounded clutch casing with the use of electric wires. The components of the examined clutch are made in accordance with the guidelines included in the article **[L. 45],** using grade X5CrNi18-10 chromium-nickel steel, whose composition is presented in **Table 1**.

a) b)

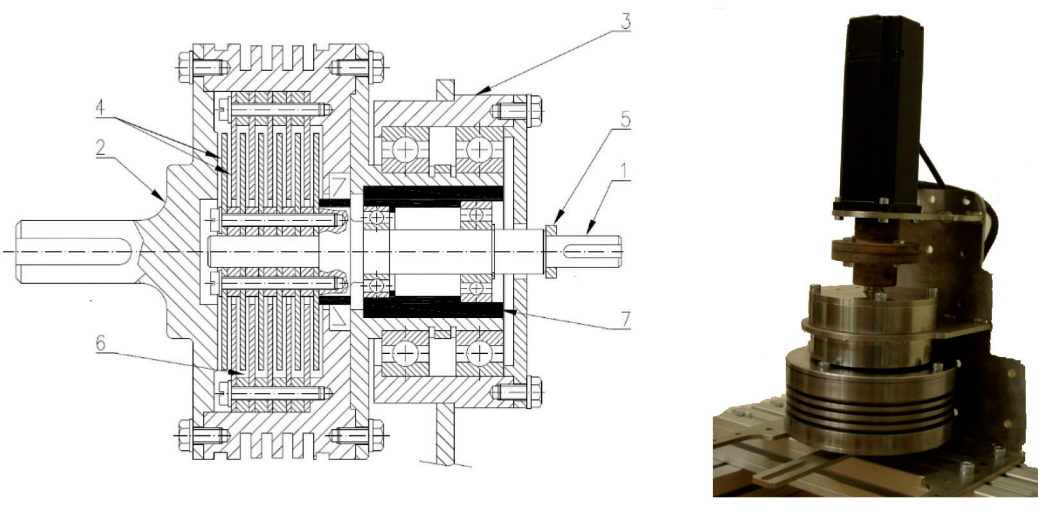


Fig. 2. The tested viscotic disc clutch with the ER fluid: a) design scheme, b) view of the clutch mounted on the test bench: 1 – input shaft, 2 – output shaft connecting element, 3 – casing of the bearings, 4 – clutch discs, 5 – slip ring, 6 – ER fluid, 7 – insulator

Rys. 2. Badane sprzęgło wiskotyczne tarczowe z cieczą ER: a) schemat budowy, b) widok sprzęgła zamontowanego na stanowisku badawczym: 1 – wał wejściowy, 2 – element przyłączeniowy wału wyjściowego, 3 – obudowa łożysk, 4 – tarcze sprzęgła, 5 – pierścień ślizgowy, 6 – ciecz ER, 7 – izolator

Table 1. Chemical composition of X5CrNi18-10 steel

Tabela 1. Skład chemiczny stali X5CrNi18-10

PN-EN 10088designation	**Elemental content [%]**						
	C	**Si**	**Cr**	**Ni**	**Mo**	**Mn**	**N**
X5CrNi18-10	≤0.07	≤1.00	17.5–19.5	8.0–10.5	–	≤2.0	≤0.11

The insulating components are made of textolite due to their good strength and mechanical properties, also at elevated operating temperatures.

In the tested viscous clutch, the employed ER fluid is ERF#6. This fluid has been developed and produced as part of work on new ER fluids at the Department of Inorganic Chemistry and Solid State Technology, Faculty of Chemistry, Warsaw University of Technology. The fluid is a two-phase mixture of silicon oil and solid particles with a diameter of 10 μm. The solid particles are made of sulfonated styrene-divinylbenzene resin with sodium cation. The silicone oil is annealed in a vacuum in order to remove low fractions, which increases its viscosity and causes water evaporation. The ERF#6 fluid also contains small amounts of additives preventing sedimentation and improving the fluid's electrorheological properties. **Table 2** shows the basic parameters of the ERF#6 fluid.

Table 2. Basic data concerning the ERF#6 fluid
Tabela 2. Podstawowe dane dotyczące cieczy ERF#6

Parameter	**Designation**	**Value**	**Unit**
Dynamic viscosity coefficient in 25°C	μ	60	mPa·s
Kinetic viscosity in 25°C	μ	56	mm²/s
ERF#6 fluid density	ρ	1.074	g/cm³
Dynamic viscosity coefficient of a liquid phase	μ_c	16 ÷ 18	mPa·s
Density of the liquid phase	ρ_c	0.98	g/cm³
Solid phase density	ρ_s	1.21	g/cm³
Solids fraction by weight	ϕ_w	40	%
Solid phase share by volume	ϕ_o	35	%
Flash-point	–	> 250	°C
Solidification temperature	–	< – 20	°C

DURABILITY TESTS OF A VISCOTIC DISC CLUTCH WITH ER FLUID

Durability tests of the viscotic disc clutch with ER fluid are performed at a test bench consisting of mechanical and electro-measuring parts. **Fig. 3** shows the mechanical part of the test bench.

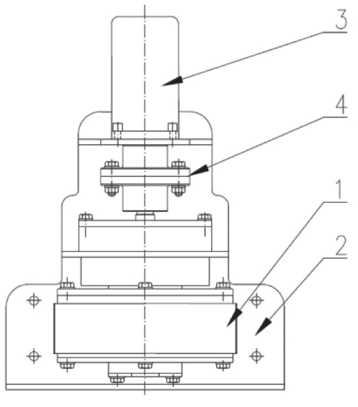


Fig. 3. Mechanical part of the test bench: 1 – viscotic clutch with ER fluid, 2 – test bench frame, 3 – DC electric motor, 4 – clutch
Rys. 3. Część mechaniczna stanowiska badawczego: 1 – sprzęgło wiskotyczne z cieczą ER, 2 – rama stanowiska, 3 – silnik elektryczny prądu stałego, 4 – sprzęgło

A DC electric motor is mounted on the frame of the test bench. A clutch connects the motor's output shaft to the driving part of the viscotic clutch with ER fluid. The connecting clutch is made of a non-conductive material to isolate the test bench elements. The bearing body of the viscotic clutch is attached to the frame. The driven part of the clutch is connected to a bearing-mounted rotating lever whose task is to apply pressure to the force sensor. A strain gauge sensor enables continuous measurement to measure the pressure force. The ER fluid temperature sensor is installed in the casing of the viscotic clutch. The relative air humidity was measured with a humidity converter placed near the clutch. The rotational speed was read using an encoder.

The mechanical part of the test bench is connected to the electrical and measuring part, which contains the following components:

– servo drive (driver 6SL3210-5FB10-4UF1, DC motor1FL6034-2AF21-1AA1);
– control cabinet (ProfibusSlavefor PLC from series S DVPPF02-SL, PLC from series SA2DVP12SA211T, distributor RS-485 ASD-CNIE0B06);
– analogue input module for ET200S 6ES7134-4GB01-0AB0;
– high voltage power supply (HCP 350-3500);
– humidity transducer AR250/I;
– force sensor KMB19-K-100N-0000-D;

– temperature sensor Heraeus M222;
– temperature sensor;
– computer set.

The scheme of the electrical and measuring part and the mechanical part of the test bench is shown in **Fig. 4**.

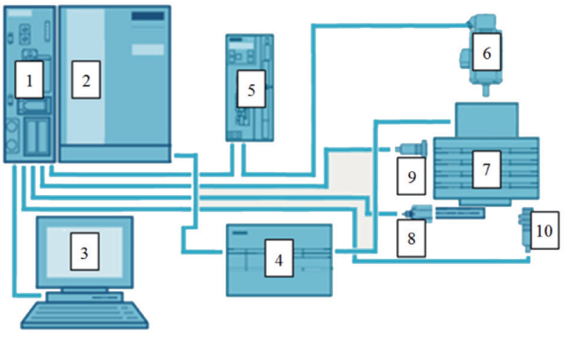


Fig. 4. Scheme of the test bench: 1 – PLC driver, 2 – control cabinet, 3 – computer set with software, 4 – high voltage power supply, 5 – driver with analogue input module, 6 – DC motor, 7 – viscotic clutch with ER fluid, 8 – force sensor, 9 – humidity transducer, 10 – temperature sensor

Rys. 4. Schemat stanowiska badawczego: 1 – sterownik PLC, 2 – szafa sterownicza, 3 – zestaw komputerowy z oprogramowaniem, 4 – zasilacz wysokiego napięcia, 5 – sterownik z modułem wejść analogowych, 6 – silnik prądu stałego, 7 – sprzęgło wiskotyczne z cieczą ER, 8 – czujnik siły, 9 – przetwornik wilgotności, 10 – czujnik temperatury

The control of the motor rotational speed within the range from 0 rev/min to 800 rev/min is achieved using a touch panel installed on the front door of the control cabinet. The value of the electric voltage was applied directly from the high-voltage power supply connected to the examined clutch. The following values were recorded during the tests: pressure force, working fluid temperature, and relative air humidity. The computer measuring system recorded the measured values. Operation of the control system and the measurement system is carried out by using an application created in the visualisation program. The operating parameters of the clutch with the ER fluid during the durability tests are shown in **Table 3**.

After the durability tests of the viscotic disc clutch with the ER fluid, samples of the processed ERF# fluid are collected, and the clutch is disassembled.

WEAR OF THE COMPONENTS OF THE VISCOTIC DISC CLUTCH WITH THE ER FLUID

During the inspection of individual components of the viscotic clutch, a leak was noticed at the edge between the clutch body and the bottom cover, **Fig. 5**.

Table 3. Operating parameters of the clutch with the ER fluid ERF#6

Tabela 3. Parametry pracy sprzęgła z cieczą ERF#6

Parameter	**Designation**	**Value**	**Unit**
Rotational speed	n	800	rev/min
Average torque	M_o	0.29	Nm
Voltage	U	1	kV
Electric field strength	E	0.7	kV/mm
Working fluid temperature range	T	22 ÷ 24	°C
Average relative humidity	w	30	%
Clutch volume	V	80	cm³
Clutch operation time	t	200	h

Fig. 5. View of the working fluid leakage

Rys. 5. Widok wycieku cieczy roboczej

After disassembling the lower part of the clutch from the bearing sleeve, it was found that the working fluid leakage also occurred in the place where the sealing ring was set, between the clutch body and the insulating sleeve of the drive shaft, **Fig. 6**.

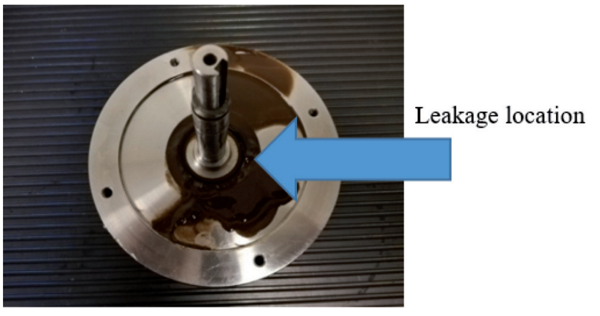


Fig. 6. View of the working fluid leakage in the place where the sealing sleeve is located
Rys. 6. Widok wycieku cieczy roboczej w miejscu osadzenia tulejki uszczelniającej

It should be assumed that due to the centrifugal forces caused by the occurrence of high rotational speeds, the fluid leaks through the gap between the sealing ring and the sealing sleeve of the drive shaft. Moreover, it is possible that the sealing ring does not operate properly due to the fact that the permissible relative speed of the peripheral surface of the shaft journal is exceeded.

During the disassembly of the clutch, wear of the copper brush supplying voltage to the clutch shaft is observed. As a result, there is an accumulation of metal filings on the upper part of the clutch body, **Fig. 7**.

Fig. 7. View of the accumulated metal filings on the upper part of the clutch body
Rys. 7. Widok nagromadzonych opiłków metalu na górnej części korpusu sprzęgła

The inspection of the location of the drive shaft bearing inside the textolite insulating sleeve shows that the textolite used as an insulating material is partially burned as a result of exposure to high voltage. The effects of electric breakdowns are also observed. The local loss of the insulating properties of the textolite is probably caused by moisture. **Fig. 8** shows a view of the clutch sleeve in the places where the driveshaft bearings are located. The burned-out surface of the sleeve is visible at the point of contact with the shaft bearing.

After inspection of the remaining elements of the clutch, no other mechanical damages are found.

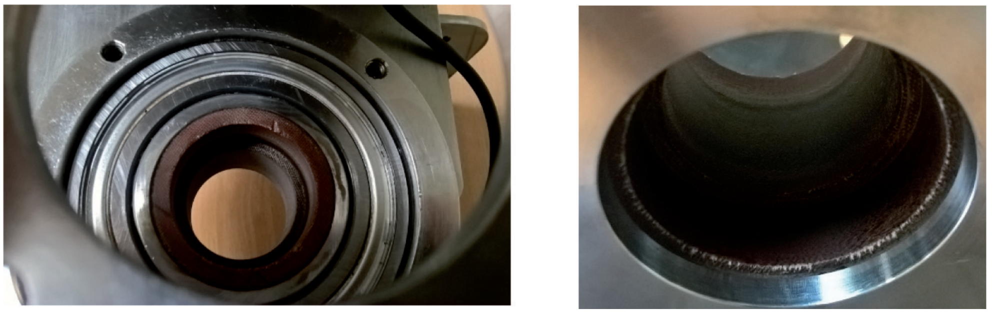


Fig. 8. View of the textolite burn at the bearing seat
Rys. 8. Widok przypalenia tekstolitu w miejscu osadzenia łożyska

WEAR OF THE ERF#6 FLUID

The degradation degree of the ER fluid operating in a viscotic disc clutch is estimated on the basis of the change in the value of the leakage current and the change in the chemical composition and shape of solid particles in the ER fluid. The operation of the ER fluid causes the changes as a working fluid for a specified period of time.

The changes in leakage current found during the measurements are caused by the high-water content in the tested fluid sample ERF#6. During measurements at voltages exceeding 2.5 kV, the leakage current density is higher than 8 mA/cm^2, which resulted in an overload of the high-voltage power supply. This resulted in lowering the high voltage of the power supply control system. The production technology of the ER fluids ensures that right after production, solid particles and silicone oil are water-free as a result of heating. For this reason, untreated ERF#6 fluid has a water content close to zero. It can be assumed that the water absorption occurred as a result of the contact of ERF#6 fluid with humid air during the fluid's operation in the clutch.

Subsequently, the processed and non-processed fluid is subjected to detailed tests in order to assess the changes occurring in the fluid's composition and shape. The mass content of elements in solid particles of ERF#6 fluid is determined using the Varian 720ES emission spectrometer with inductively coupled plasma. The methodology of preparing samples for testing, i.e., samples of the processed liquid and the sample of the non-processed liquid, is identical. In order to separate solid particles from silicone oil, the ER fluid is centrifuged in a laboratory centrifuge, then filtered using filter paper, and then washed with deionised water. The obtained precipitate is then dried in a laboratory dryer at 60°C for 24 hours. Sample weights from the dried residue are then dissolved in a closed microwave system SPD 80 using 9 mL HNO_3 + 3mL HCL. The elemental composition obtained from the tests for both samples is presented in **Table 4**.

On the basis of the obtained results of the research on the mass content of elements in the samples, it can be concluded that the solid particles of the liquid attached some elements, e.g., Cr, Ni, as a result of friction against the metal parts of the clutch within the working gap. This phenomenon also occurs in the case of Fe and Cu. An increase in Fe and Cu content may indicate the leaching of metallic contaminants (adhering to the solid particles of the fluid) from seals, copper rings and other clutch components.

In the next stage of the ER liquid research, the solid particle size distribution is determined using the Mastersizer 3000 analyser with a wet dispersing attachment (Hydro EV). The Hydro EV attachment circulates the liquid mixture containing the solids through the measuring cell of the analyser. The selected model for milled or crushed materials is suitable for irregularly shaped or uneven particles.

Table 4. Mass content of elements in solid particles of samples of ERF#6 fluid

Tabela 4. Zawartości masowe pierwiastków w cząstkach stałych próbek cieczy ERF#6

Element	Value		Unit
	Non-processed fluid sample	Processed fluid sample	
Al	18.9	19.1	mg per kg of dry weight
Ca	358	399	
Cr	28.9	31.3	
Cu	3.57	5.59	
Fe	239	295	
K	198	202	
Mg	60.0	54.6	
Na	6.4	6.6	
Ni	3.6	10.8	
Zn	4.8	10.8	
Mn	1.9	2.2	
Co	2270	2975	

The charts of the solid particle size distribution of the non-processed and processed ERF#6 fluid are shown in **Fig. 9**.

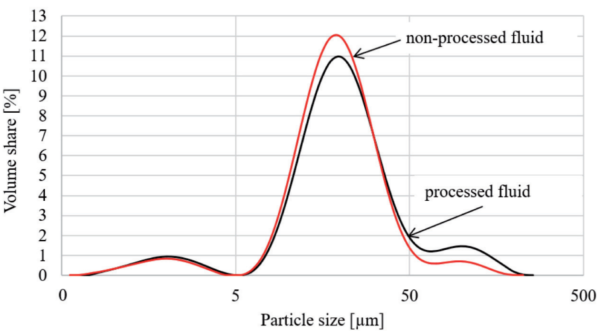


Fig. 9. Particle size distribution of the ERF#6 fluid's solid phase

Rys. 9. Rozkład wielkości cząstek fazy stałej cieczy ERF#6

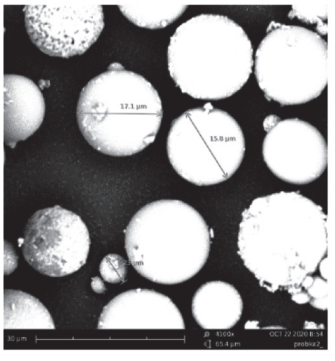
Table 5 shows the standard percentages read from the particle size analysis of the non-processed and processed fluids.

Table 5 shows the symbols Dv (10), Dv(50) and Dv(90), which mean that, respectively, 10%, 50% and 90% of the solid particles are smaller than the size specified in micrometres. The shape of the solid particles is determined on the basis of microscopic photos taken under different magnifications. Photos of particles of the solid phase of the non-processed and processed fluids are shown in **Fig. 10**.

Table 5. Percentages read from the particle size analysis
Tabela 5. Udziały procentowe odczytane z analizy wielkości cząstek

Designation	Value		Unit
	Non-processed fluid sample	Processed fluid sample	
Dv (10)	9.30	9.25	µm
Dv (50)	18.8	20.0	µm
Dv (90)	37.0	51.8	µm

a)



b)

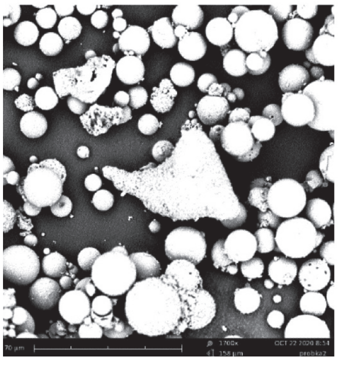


Fig. 10. Photos of solid phase particles of the fluid after processing in magnification: a) x 4100; b) x 1700
Rys. 10. Zdjęcia cząstek fazy stałej cieczy po pracy w powiększeniu: a) 4100 x; b) 1700 x

The studies of the solid phase under the microscope show that the size of the solid particles of ERF#6 liquid changed slightly. The particle size in the processed fluid has increased. This is caused by forming agglomerates of solid particles, as shown in **Fig. 10b**. As a result of friction against the working elements of the clutch (caused by the flow of the fluid in the clutch channels), the outer surfaces of the particles wear out. This is important because substances on the surface of the particles prevent the particles from sticking together and sedimenting the fluid. The particles become deformed and crumbled, thus losing their spherical shape. This facilitates the particle agglomeration, sticking and adhesion of elements from the metal elements of the clutch. Changes in the size of solid particles and the presence of impurities negatively affect the properties of the ER fluid.

DISCUSSION OF THE RESEARCH RESULTS

The research results show that an important factor influencing the durability of the tested viscotic clutch is the method of sealing the bearings and working space of the clutch. As a result of inadequate sealing of the clutch, the ER fluid comes into contact with atmospheric air, and leakages occur. Contact of ER fluid with atmospheric air causes an increase in the fluid's humidity, thus changing the fluid's electrorheological properties. The leaking fluid contains more base oil because the solid particles are centrifuged due to rotations of the clutch components. Therefore, as a result of leakages, not only does the amount of the ER fluid in the clutch change; the fluid's weight, composition and, thus, rheological properties change. The type of solid particle material of the ER fluid is also important for sealing. Particles made of soft materials are more easily crushed due to friction against each other and the clutch elements. The fragmented solid particles of the ER fluid pass between the lip of the sealing ring and the shaft surface, breaking the oil film. This is the direct cause of the wear of the sealing lip surface.

Ensuring a long and correct operation of the clutch requires the use of appropriate construction and insulating materials. Due to the several per cent increases in the mass content of elements in the solid particles of the used fluid sample related to the adhesion process, it is necessary to use construction materials which are resistant to abrasion by solid particles. The test results show that stainless steels are best used for structural and working elements of clutches with ER fluids. Stainless steels are corrosion-resistant and conduct electricity well; however, not every material can be used in viscotic clutches with ER fluids. The textolite used in the prototype clutch for insulating sleeves was burned locally under the influence of the flowing electric current and electric breakdowns, thus losing its insulating properties. The probable cause of this phenomenon was the dampness of the textolite surface.

The durability of the viscotic disc clutch with the ER fluid depends on the durability of the ER fluid. The observed degradation of the solid particles of the ERF#6 fluid is mostly related to the particle movement inside the clutch working space. As the particles move between the discs of the viscotic clutch, they hit and rub against the walls and each other, thus losing the outer protective surface. Flattening and sticking of solid particles indicate the plastic properties of the material from which they are made. Water penetrating from the environment into the ER fluid causes the fluid's degradation due to electrolysis. The ER fluid's oil base's durability is better than the solid particles' durability. The formation of contaminants in the ER fluids occurs due to the following factors: adhesion of particles of materials from which the clutch is made, mechanical wear of sealing rings, and corrosion of metal parts.

CONCLUSIONS

On the basis of the experimental research concerning the durability of the viscotic disc clutch with the ER fluid, the following conclusions are formulated:

1. The main factors influencing the durability are the manner of sealing the bearings and the working space, materials used for the construction of the clutch, and the type of the working fluid.
2. In order to seal the bearings, it is advised to use sealing rings which are suitable for work with mixtures containing solid particles and resistant to chemical components contained in the ER fluid.
3. The materials used to construct the clutch should have sufficient wear resistance so that they are not affected by intensive abrasion as a result of contact with solid particles of ER fluids. Moreover, ensuring the clutch's long and correct operation requires using appropriate insulating materials.
4. The ER fluid's durability depends mainly on its solid particles, which are subjected to wear due to impact and friction. Due to that, during the selection of the ER fluid for a clutch, special attention should be paid to the mechanical and physicochemical properties of solid particles.
5. The research was performed in predetermined working conditions. Therefore, its results do not provide a complete answer to the questions concerning the wear mechanisms of the clutch components and the selected ER fluid. Therefore, further experimental research on the durability of clutches with intelligent fluids is necessary.
6. Durability tests of clutches with ER fluids are a valuable source of information for designers because they enable the verification of design solutions as well as the selection of materials and ER fluids. The obtained research results can facilitate the development of guidelines for designing viscotic clutches with ER fluids, including selecting appropriate construction materials.

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