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IMPACT ANALYSIS OF SURFACE ROUGHNESS OF THE PLATE-PLATE MEASURING SYSTEM ON RESISTANCE TORQUE IN INTERACTION WITH MR FLUID

ANALIZA WPŁYWU CHROPOWATOŚCI POWIERZCHNI UKŁADU POMIAROWEGO TYPU PŁYTKA–PŁYTKA NA MOMENT OPORU RUCHU W KONTAKCIE Z CIECZĄ MR

Key words: magnetorheological fluid, MRF, rheology, research methods, surface roughness, resistance torque.

Abstract: Magnetorheological (MR) fluids are complex suspensions of magnetic particles in a non-magnetic carrier fluid. They exhibit ‘smart’ properties that enable them to change their rheological parameters in response to a change in the external magnetic field applied. This behavior is used in some engineering solutions, e.g. MR clutches or brakes. For such systems to work correctly, the resistance torque achieved by contact with the MR fluid must be properly determined. This paper demonstrates how surface roughness of a contact surface between the solid and the MR fluid affects the resistance torque value. Measurements were made on a dedicated rotational rheometer using a shear mode fluid, most closely replicating the way MR clutches and brakes work. Plate-plate geometry was used, in standard design, and modified by pasting sandpaper with different grit levels. The tests have shown that the roughness of the mating surface affects the resistance torque results.

Słowa kluczowe: ciecz magnetoreologiczna, MRF, reologia, metody badawcze, chropowatość powierzchni, moment oporu.

Streszczenie: Ciecze magnetoreologiczne (MR) to złożone zawiesiny cząstek magnetycznych w niemagnetycznej cieczy nośnej. Wykazują one właściwości „inteligentne”, dzięki którym wraz ze zmianą oddziałującego pola magnetycznego mogą zmieniać swoje parametry reologiczne. Takie zachowanie jest wykorzystywane w niektórych rozwiązaniach inżynierskich, np. sprzęgłach lub hamulcach MR. W tych układach krytyczne dla ich poprawnej pracy jest właściwe określenie uzyskiwanego momentu oporu ruchu spowodowanego kontaktem z cieczą MR. W pracy zaprezentowano, jak chropowatość powierzchni ciała stałego w styku z cieczą MR wpływa na uzyskiwaną wartość momentu oporu ruchu. Pomiary przeprowadzono na reometrze rotacyjnym na cieczy dedykowanej do pracy w trybie ścinania, najlepiej odwzorowując sposób pracy sprzęgieł i hamulców MR. Wykorzystano geometrię płytka–płytka w standardowym wykonaniu oraz zmodyfikowanym poprzez naklejanie papierów ściernych o różniej gradacji. Przeprowadzone badania wykazały, że chropowatość powierzchni współpracującej ma wpływ na uzyskiwane wyniki momentu oporu ruchu.

INTRODUCTION

MR fluids are suspensions of magnetic particles in a nonmagnetic liquid. Under the influence of an external magnetic field, these particles organize themselves into chains, changing the internal structure of the liquid and, consequently, the viscosity of the suspension. This change is called the magnetorheological effect and is reversible when the magnetic field is removed **[L. 1]**. This effect has found application in some engineering structures with controllable operating parameters, i.e. vibration dampers, clutches, and brakes **[L. 2]**.

Although the rheological properties of MR fluids, as well as the description of their magnetic properties, are relatively well recognised

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[L. 3, 4], the phenomena occurring in the contact zone between the MR fluid and the solid surface still require a more detailed description. Due to the complex properties of MR fluids, nontrivial interaction mechanisms can be expected at the above-mentioned mating surface.

For shear mode MR fluid operation **(Fig. 1)**, in which fluid flow is induced by the movement of one of the mating surfaces, fluid-solid contact conditions play an important role. A crucial aspect that affects this contact is surface roughness. In the paper **[L. 5]**, the authors indicate that the interaction between magnetic particles and surface roughness is one of the reasons for underestimating the calculated flow point with respect to the experimentally obtained values. A similar effect of increased surface roughness was observed in the work of **[L. 6, 7]**. The influence of surface roughness on the behaviour of the MR fluid is not adequately described. Previous studies indicate that the stress values obtained in tests with a measuring plate with increased roughness are lower than for a smooth plate **[L. 8, 9]**. This dependence is atypical and indicates a completely different dependence of the effect of surface roughness in contact with a fluid with 'smart' properties.

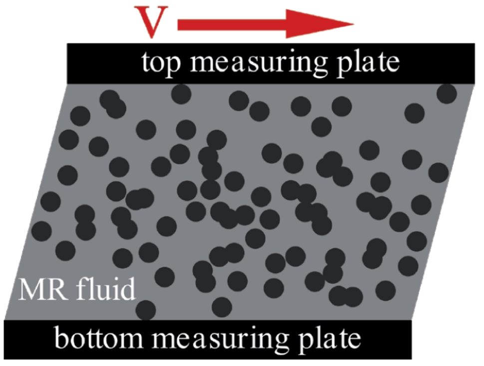

Fig. 1. MR fluid in shear mode
Rys. 1. Ciecz MR w trybie ścinania

The occurrence of slip is particularly important in applications such as clutches or brakes. Incorrect determination of the braking torque, caused by not considering the occurrence of slip at the interfacial boundary, can have a significant impact on the operation of the entire system **[L. 10]**.

The purpose of this study was to assess the impact of surface roughness of the parallel plate measuring system on resistance torque in contact with the MR fluid. The study involved modifying the roughness of the working surface of the moving measuring plate by pasting sandpaper with different grit levels, and then observing the resulting torque at different shear rates and magnetic field induction values.

EXPERIMENT

The tests were carried out on an MCR 301 rotational rheometer (Anton Paar) equipped with MRD-180/1T cell fluid analysis under exposure to a uniform, constant magnetic field. The magnetic field was controlled by adjusting the current of the electromagnetic coil. The values of magnetic field induction in the working area B = 0/50/90/180/360/670 mT were measured with a Hall probe for current values I = 0/0.25/0.5/1/2/4 A.

A parallel plate measuring geometry with a diameter of d = 20 mm was used. On the working surface, sandpapers with grit levels of 60/100/150/240/320/400 were pasted. The results obtained with the unmodified insert were labelled PP **(Fig. 2a)** and with modified plates – P60/P100/P150/P240/P320/P400 (**Fig. 2b**).

The height of the measuring gap between the plates was h = 0.6 mm, corresponding to a sample volume of v = 200 μl.

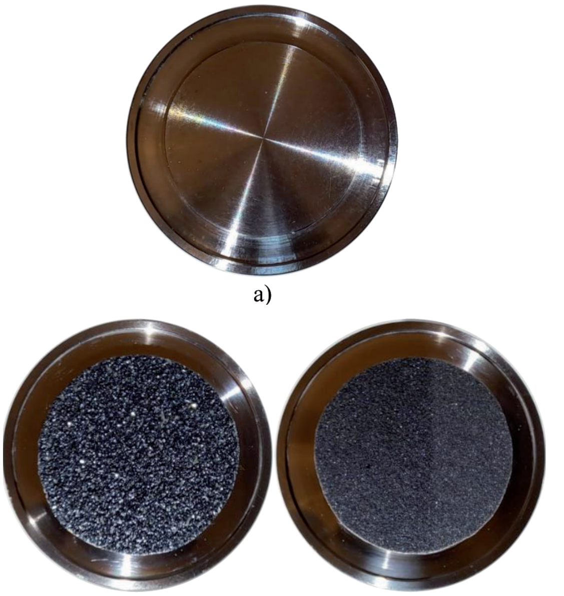

Fig. 2. Measuring plate in standard design (a) and modified by attaching sandpaper to the working surface – P100 and P400 (b)
Rys. 2. Płytka pomiarowa w standardowym wykonaniu (a) oraz zmodyfikowana poprzez naklejenie papieru ściernego na powierzchnię roboczą – P100 oraz P400 (b)

The surface roughness of the measuring plates was measured on a TOPO-01 contact profilometer manufactured by the Institute of Advanced Manufacturing Technology. Measurements were performed in accordance with PN-ISO 4288:1998 on 5 elementary sections. The results obtained are summarised in **Table 1** and **Fig. 3**, where Rz is the highest profile height, Rt the total profile height and Ra the arithmetic mean of the profile ordinates.

Table 1. Measurement results of the roughness of the measuring plates
Tabela 1. Wyniki pomiaru chropowatości płytek pomiarowych

Parameter / Plate	Rz	Rt	Ra
	µm		
P60	214.691	338.213	60.582
P100	155.649	257.363	31.694
P150	118.883	168.925	27.832
P240	91.251	124.613	17.412
P320	84.512	115.677	16.883
P400	45.397	55.975	8.657
PP	0.266	0.343	0.051

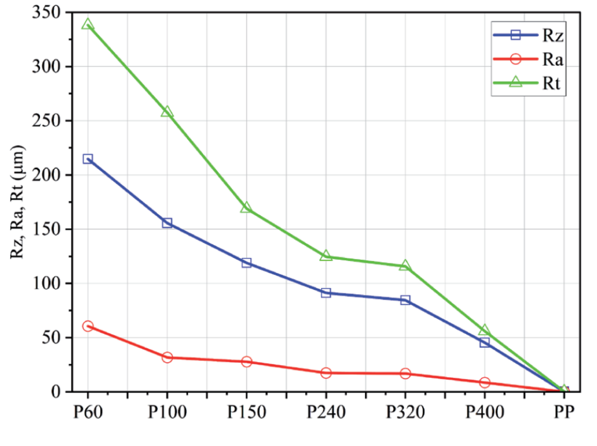

Fig. 3. The values of the roughness parameters of the sandpapers used in the tests
Rys. 3. Wartość parametrów chropowatości papierów ściernych wykorzystanych w badaniach

All tests were performed with a commercial MRF-122EG fluid manufactured by LORD Corp. The fluid parameters declared by the manufacturer are included in **Table 2**. The manufacturer indicates that it is a fluid dedicated for use in shear or valve mode.

The test involved placing the MR fluid in the working gap of the rheometer, setting a constant value for the magnetic field induction, and then increasing the shear rate in the range $\dot{\gamma}$ 0.01÷1000 s^{-1} in a logarithmic ramp. The measured quantity was the resistance torque occurring on a moving measuring plate with known surface roughness. The tests were conducted at ambient temperature (20°C); each measurement was performed on a new fluid sample, and a minimum of two repetitions of each test were performed.

Table 2. Physical properties of the tested fluid [L. 11]
Tabela 2. Właściwości fizyczne badanej cieczy **[L. 11]**

Property	Value	Unit
Density	2.28÷2.48	g/cm^3
Dynamic viscosity at 40°C	0.042÷0.2	Pa·s
Solid content	72	% by weight
	22	% by volume
Operating temperature	-40÷130	°C

RESULTS

Fig. 4 shows the results of torque measurements obtained for the analysed magnetic field induction and sandpapers with different grit levels used. In each case, the results obtained using the modified inserts are compared with those obtained with a standard measuring plate (PP). To show the variability of the recorded parameter in the low shear rate range, the graphs are presented in a semi-logarithmic system, focussing on the results obtained in the shear rate range up to approximately $\dot{\gamma}$ = 10 s^{-1}.

Under the absence of a magnetic field and at the lowest induction value (B = 50 mT), among the obtained curves, the result obtained for the P60 plate stands out, for which the lowest torque values were achieved. In this range of induction, no significant differences are observed between the results obtained using the remaining abrasive paper grades.

For the higher induction values (B = 90/180/360 mT) (**Fig. 4c, d, e**), a clear differentiation of torque values due to roughness is apparent. The torque obtained for P60 is the lowest, while the highest values were obtained for the PP plate. With increasing magnetic field induction, these differences become progressively greater. Note that the result obtained with the PP plate is the highest only in the range of lower shear rates: up to about $\dot{\gamma}$ = 1 s^{-1} for B = 90 mT, $\dot{\gamma}$ = 10 s^{-1} for B = 180 mT, and $\dot{\gamma}$ = 100 s^{-1} for B = 360 mT. At higher shear rates, the torque obtained for plates with higher roughness is higher than for the unmodified plate.

In the case of the application of the inductions of the highest magnetic field analysed (B = 670 mT), a different variation in the observed torque compared to the other measurements is apparent. The characteristic inflection of the curves in the shear rate range around $\dot{\gamma}$ = 0.1 s^{-1} indicates the occurrence of structural yield stress, while the inflection around $\dot{\gamma}$ = 1 s^{-1} corresponds to the occurrence of full fluid flow (flow stress).

Analysing the influence of roughness on the obtained measurement results, while there is a clear trend of torque increasing with decreasing plate roughness (compare the results obtained for P60 to P240), the variation in the results obtained for the plates with the smallest gradations (P320 and P400) relative to the unmodified plate (PP) is more complex. In the shear rate range up to about $\dot{\gamma}$ = 0,1 s^{-1}, the highest moment values were obtained for P320 and P400. However, in the middle range of the curves presented in **Fig. 4e, f** and **Fig. 5e, f** the highest moment values were obtained for the PP plate, but at $\dot{\gamma}$ > 100 s^{-1}, the highest values were again obtained for P320 and P400 plates.

Fig. 5 presents analogous results to those in **Fig. 4**, with the difference that a linear scale of the coordinate axis was applied. This allows for highlighting the variability of the measured parameter in the range of medium and high shear rates.

In the range $\dot{\gamma}$ > 100 s^{-1}, the lowest torque is observed for the plate with the highest roughness (P60), while the highest torque is observed for the P320 and P400 plates. There is a clear trend towards an increase in measured torque with a decrease in the working surface roughness of the plate. For the unmodified insert, resistance torque values were obtained in a range between those obtained for P240 and P320. This result may indicate that in addition to the working surface itself, other factors, most likely related to the fluid-solid contact properties of the MR, may influence the value of the resistance torque due to the plate material used.

At the higher magnetic field inductions analysed (**Fig. 5d, e, f**), the torque values obtained for the unmodified plate (PP) and the plates with the lowest roughness (P320 and P400) are very similar, but there is a noticeable reduction in the measured torque obtained with the P240 plate. Therefore, increasing the roughness parameter Rz from a value of 84 μm to at least 91 μm, results in a significant change in the behaviour of the MR fluid in contact with the surface, and this change is increasingly evident as the magnetic field induction increases.

As the value of the observed torque depends on two parameters, i.e. the shear rate and the surface roughness of the measuring plate, to better illustrate the results, curves showing the dependence of torque on the parameter Rz were determined for arbitrarily selected five values of shear rate $\dot{\gamma}$ = 0.1/1/10/100/1,000 s^{-1}. The results are shown in **Fig. 6**. Furthermore, the data obtained were approximated with a linear model to determine how significant an effect on the reduction of torque values was exerted by changing the plate roughness.

Approximating the results obtained with a linear function provided a good agreement between the model and the experiment. The median of the coefficient of determination (Adj. R^2) is 0.91 and its mean is 0.88. Therefore, it can be stated with a good approximation that within the scope of the tests carried out, the variation of torque with increasing roughness (expressed by the parameter Rz) is linear. This is valid regardless of the value of the magnetic field induction and the shear rate.

As an indicator of the impact of roughness on the measured torque value, the slope of the linear function approximating the measurement data M = f(Rz) was adopted (**Fig. 6**). In each case, the value of this parameter is negative, which clearly indicates a decrease in the value of the recorded torque as the surface roughness increases. Meanwhile, the absolute value of the directional coefficient gives information on the strong effect of changing the roughness of the measuring plate on the value of the measured torque. A graph of the value of this parameter is shown in **Fig. 7**.

For B = 0 mT and B 360 mT (compare **Fig. 6a-e**), the variation trend of the slope has a similar course, and throughout the entire range, the absolute value of this parameter increases in value with the shear rate. Therefore, as the shear rate increases, the effect of the roughness on the value of the measured torque becomes more significant.

In contrast, a trend reversal is apparent for B = 670 mT. For low shear rates ($\dot{\gamma}$ = 0.1 s^{-1}) the strongest effect of roughness on the value of the resistance torque emerges, stabilising at higher shear rates at a constant level (about -0.07). It is likely that this behaviour is related to a change in the properties (or structure of the MR fluid) when transitioning from a stable, shaped fluid structure, which occurs at low shear rates, to a cyclically deformed MR fluid structure at higher shear rates.

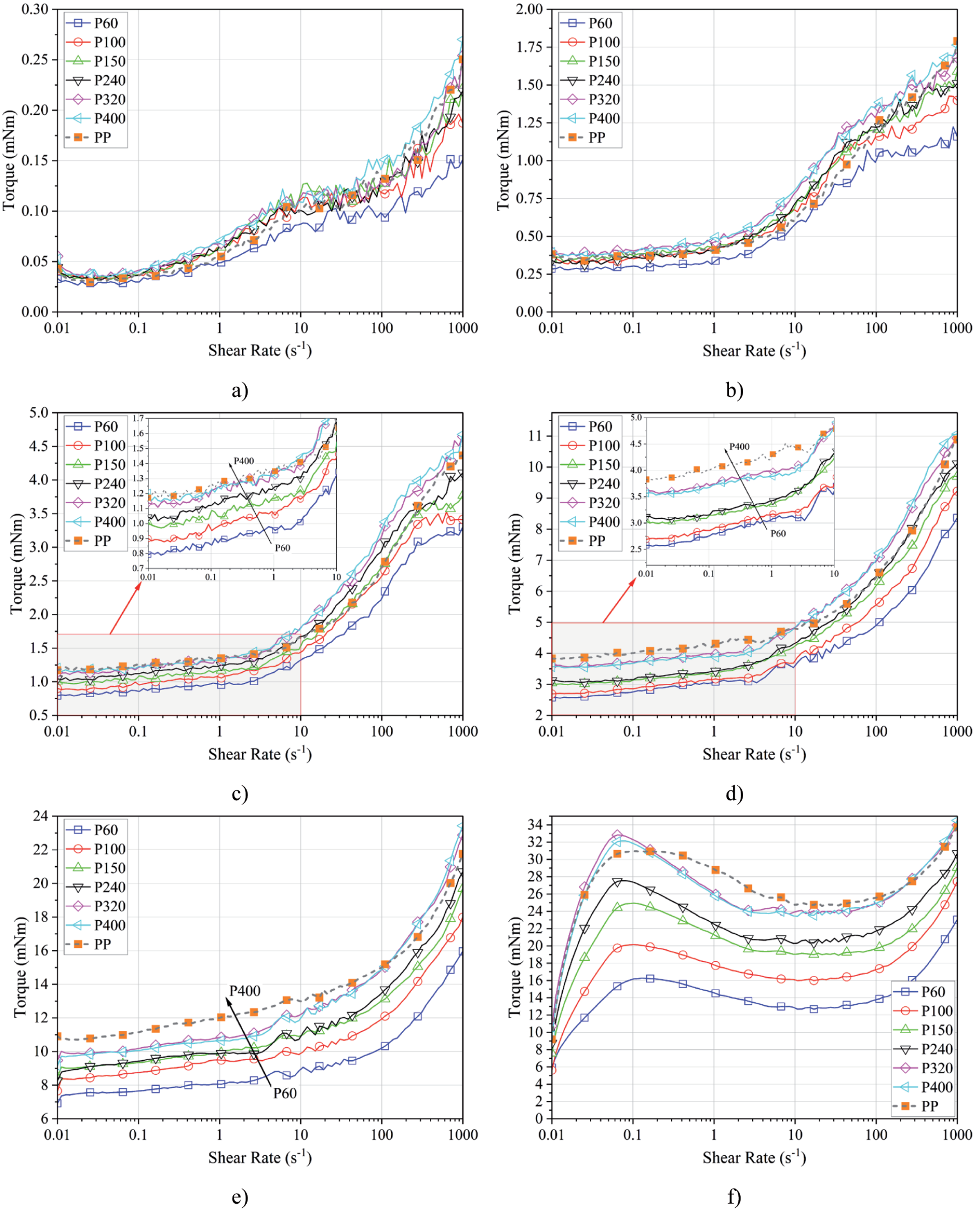

Fig. 4. Measurement result of resistance torque in the low shear rate range: a) B = 0, b) B = 50, c) B = 90, d) B = 180, e) B = 360, f) B = 670 mT

Rys. 4. Wynik pomiaru momentu oporu w zakresie niskich szybkości ścinania: a) B = 0, b) B = 50, c) B = 90, d) B = 180, e) B = 360, f) B = 670 mT

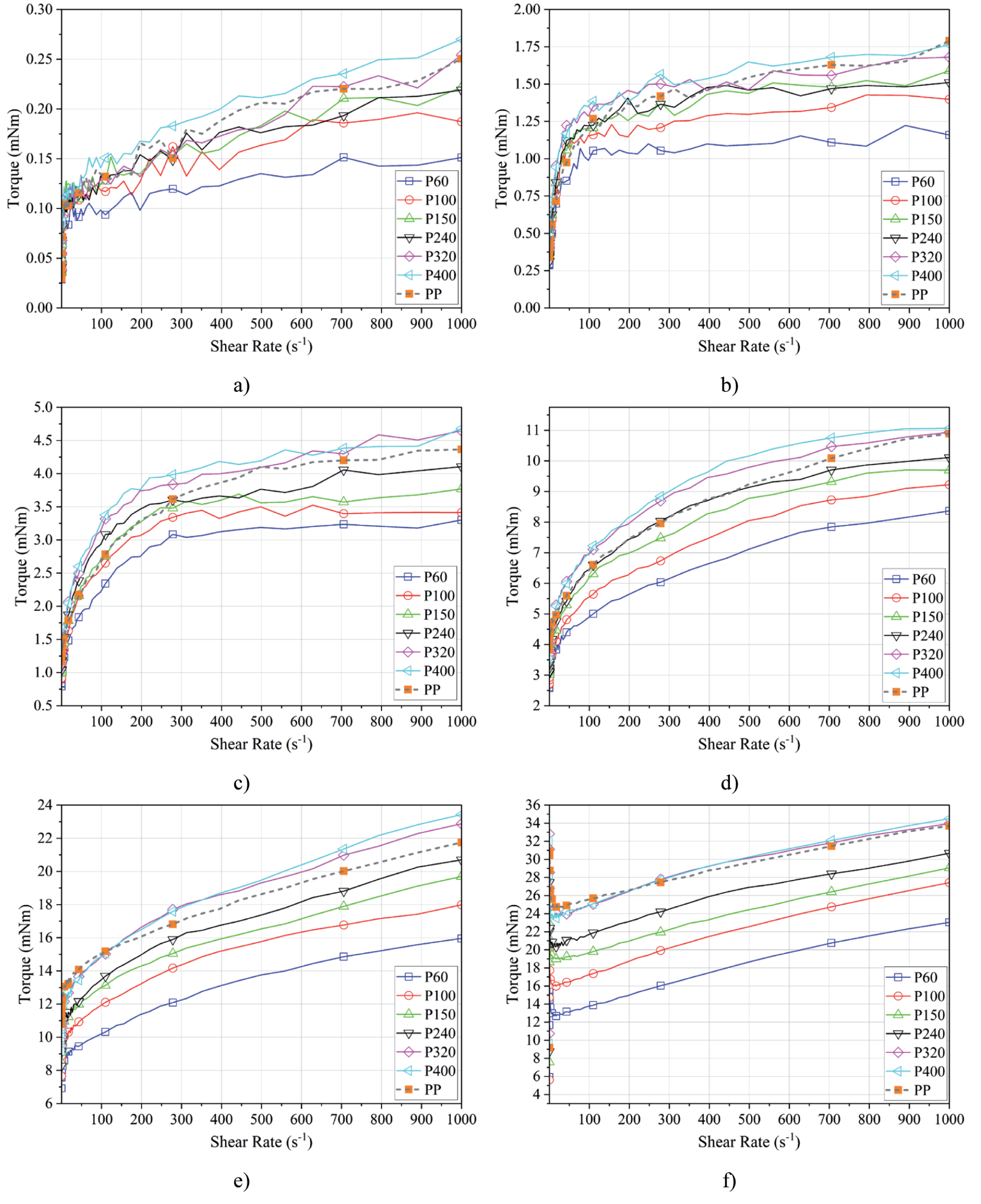

Fig. 5. Measurement result of torque in the medium and high shear rate range: a) B = 0, b) B = 50, c) B = 90, d) B = 180, e) B = 360, f) B = 670 mT

Rys. 5. Wynik pomiaru momentu oporu w zakresie średnich i wysokich szybkości ścinania: a) B = 0, b) B = 50, c) B = 90, d) B = 180, e) B = 360, f) B = 670 mT

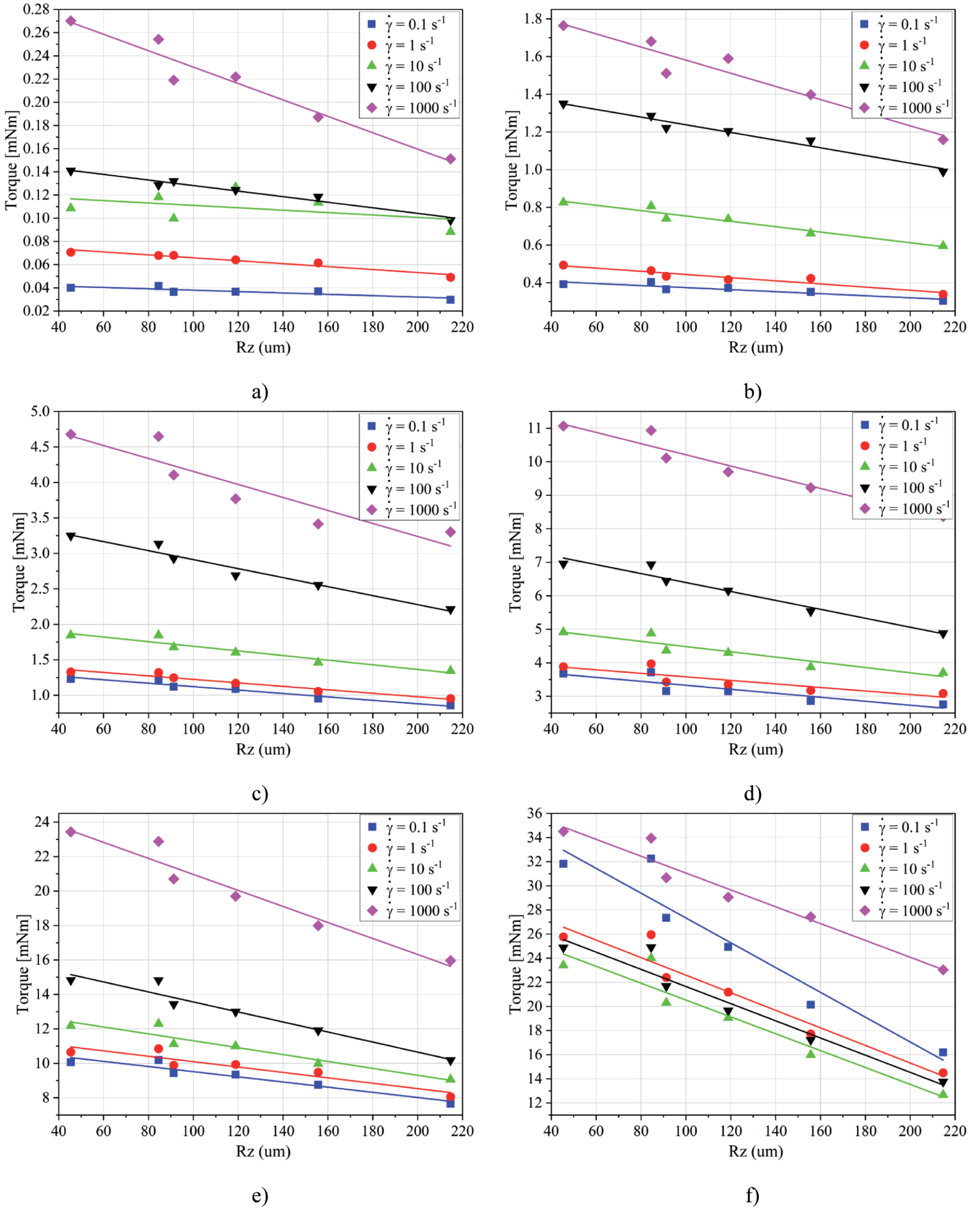

Fig. 6. Measurement result of resistance torque as a function of the roughness parameter Rz: a) B = 0, b) B = 50, c) B = 90, d) B = 180, e) B = 360, f) B = 670 mT

Rys. 6. Wynik pomiaru momentu oporu w funkcji parametru chropowatości Rz: a) B = 0, b) B = 50, c) B = 90, d) B = 180, e) B = 360, f) B = 670 mT

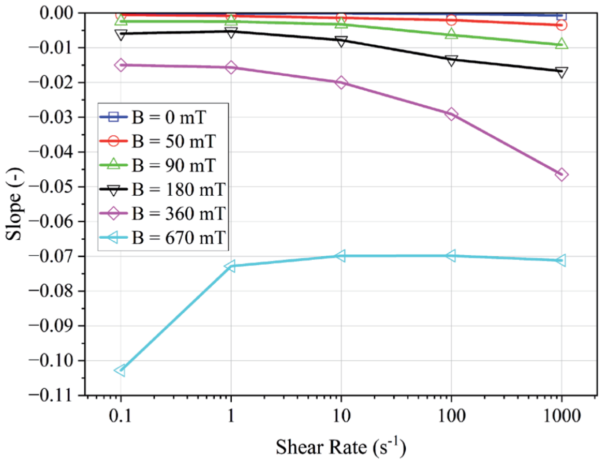

Fig. 7. Variation in the directional coefficient of the approximating function of the M = f (Rz) formula

Rys. 7. Wykres zmiany współczynnika kierunkowego funkcji aproksymującej zależność M = f (Rz)

CONCLUSIONS

This paper presents the results of torque measurements obtained when a rotating plate with modified surface roughness interacts with MR fluid. The tests were performed at different values of magnetic field induction and over a wide range of shear rates. The results obtained allow for the conclusion that:

- The surface roughness has a significant impact on the obtained values of torque, and this dependence is multifactorial, influenced by both the shear rate and the magnetic field induction value.
- Within the scope of the tests carried out, the relationship between a decrease in the value of the recorded torque and an increase in the roughness, described by the parameter Rz, can be expressed by a linear function.
- In the range of low shear rates ($\dot{\gamma} < 0.1\ s^{-1}$) and B = 50/90/180/360 mT, the highest torque values were obtained for the unmodified plate (PP), which has the lowest roughness. This behavior indicates favorable contact conditions for the examined MR fluid in contact with a relatively smooth surface.
- In addition to the surface roughness value, other factors may have an impact on the torque, possibly related to fluid-solid contact properties due to the plate material used.
- At high shear rates and high magnetic field induction, there is a significant torque jump in the roughness range Rz = 84÷91 µm. It is likely that there is a change in the MR fluid-measuring plate contact mechanism. This issue requires additional, more detailed research.
- The nature of the relationship between the torque and the surface roughness of the measuring plates changes when the magnetic field induction is increased above about B = 360 mT. This behaviour may also be related to a change in the nature of the deformation of the internal structure of the MR fluid at high magnetic field values.

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