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EXPERIMENTAL STUDY OF SURFACE ROUGHNESS EFFECT ON THE RHEOLOGICAL BEHAVIOR OF MR FLUID

BADANIA WPŁYWU CHROPOWATOŚCI POWIERZCHNI NA WYNIKI BADAŃ REOLOGICZNYCH CIECZY MR

Key words: magnetorheological fluid, MRF, rheology, research methods, surface roughness, shear mode, high shear rate.

Abstract: Magnetorheological (MR) fluids are classified as smart materials. They are non-homogeneous substances of complex composition and are characterised by complex rheological properties. In addition, the characteristics of their behaviour can be actively affected by the magnetic field, both in terms of its value and spatial orientation. This paper presents the results of shear stress measurements of a commercial magnetorheological fluid using a plate-plate type geometry with a modified working surface. The purpose of the study was to determine the effect of changing the roughness of the measuring plate on the obtained shear stress results. Controlled shear rate tests and Magneto Sweep measurements were carried out for three MR fluid layer heights. The tests were carried out at magnetic field induction in the range of 0 to 680 mT. The study showed that the measurement system's geometric parameters significantly affect the MR fluid's behaviour under test. It was shown that increasing the surface roughness can increase or decrease the measured value of shear stress depending on the test parameters.

Słowa kluczowe: ciecz magnetoreologiczna, MRF, reologia, metody badawcze, chropowatość powierzchni, tryb ścinania, duże szybkości ścinania.

Streszczenie: Ciecze magnetoreologiczne (MR) zaliczane są do grona materiałów inteligentnych. Są to substancje niejednorodne o złożonym składzie i charakteryzują się złożonymi właściwościami reologicznymi. Ponadto charakterystyki ich zachowania mogą być aktywnie kształtowane przez pole magnetyczne, zarówno ze względu na jego wartość, jak i orientację przestrzenną. W pracy przedstawiono wyniki pomiarów naprężenia stycznego komercyjnej cieczy MR z wykorzystaniem geometrii pomiarowej typu płytka–płytka o modyfikowanej powierzchni roboczej. Celem badań było określenie wpływu zmiany chropowatości płytki pomiarowej na uzyskiwane wyniki naprężeń ścinających. Przeprowadzono badania z kontrolowaną szybkością ścinania oraz pomiary typu Magneto Sweep dla trzech wysokości warstwy cieczy MR. Badania przeprowadzono przy indukcji pola magnetycznego w zakresie 0 do 680 mT. Badania wykazały, że parametry geometryczne układu pomiarowego istotnie wpływają na zachowanie się badanej cieczy MR. Wykazano, że w zależności od parametrów badania zwiększenie chropowatości powierzchni może powodować zwiększenie lub zmniejszenie rejestrowanej wartości naprężeń stycznych.

INTRODUCTION

The analysis of near-wall phenomena in rheology and fluid mechanics is of specific relevance for the flow of liquids with complex rheological properties, i.e., polymer melts, emulsions, or highly concentrated suspensions. In such cases, slippage may occur at the interface between the fluid and the wall surface, and the slippage effect changes the spatial velocity distribution in the conduit with the flowing fluid. This has important implications in rheometry, as well as in all cases where fluid

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in the wall–fluid interference is relevant, such as fluid flow in narrow channels or processing using abrasive fluids.

The nature and scale of near-wall phenomena can be a function of flow conditions, surface geometry, material characteristics, and fluid properties. Furthermore, contact of the flowing fluid with the wall can cause a localised change in the properties of the flowing medium **[L. 1, 2, 3]**.

Fig. 1 shows the velocity distributions of the fluid schematically in a Couette flow between two surfaces separated by a distance of *h*. The condition of no-slip and partial slip were considered. The upper wall moves with a velocity of *u*, while the lower surface remains stationary. In the case of non-slip flow, the velocity of the fluid layer located directly adjacent to the stationary wall is 0, while that of the moving wall is equal to the velocity of the wall surface. This assumption is the basis for the vast majority of flow analyses and, in the case of homogeneous fluids, is fully justified.

The partial occurrence is associated with the presence of slip velocity, both on the moving and stationary walls. Neglecting this additional velocity leads to falsification of the results of rheological measurements and, in the case of machining fluids, to an incorrect determination of the nature of the fluid's behaviour in the near-wall zone.

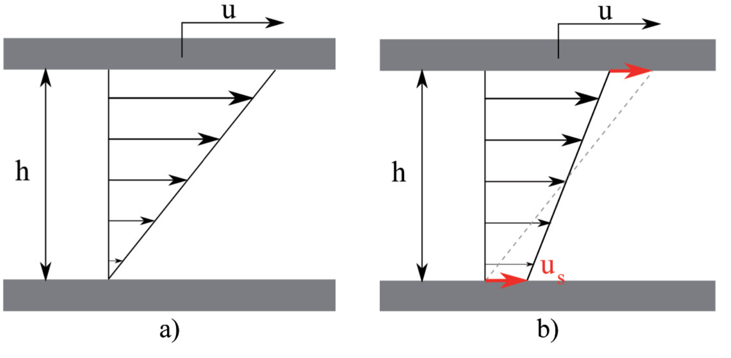


Fig. 1. Velocity profile in Couette flow: a) when there is no slip is present, b) under slip conditions
Rys. 1. Rozkład prędkości w przepływie wleczonym: a) gdy poślizg nie występuje, b) w warunkach poślizgu

The shear rate $\dot{\gamma}$ in the absence of slip can be written as the ratio of the moving wall velocity *u* to the gap height *h* (**Equation 1**). Under partial slip conditions, the shear rate $\dot{\gamma}_s$ also depends on the slip velocity u_s (**Equation 2**).

$$\dot{\gamma} = \frac{u}{h} \quad (1)$$

$$\dot{\gamma}_s = \frac{2u_s + u}{h} \quad (2)$$

Therefore, it can be seen that an important issue for rheological studies under slip conditions becomes the determination of the fluid's true (effective) shear rate, which involves the need to determine the velocity value u_s.

One method of determining the fluid wall's slip is the one proposed in **[L. 3]**. It is based on taking rheological measurements for different heights of the working gap h_1 and h_2. The flow curves obtained in this way can be used as a basis for determining slip phenomenon occurrence as well as for determining the slip velocity u_s. For this purpose, it is necessary to determine the shear rate $\dot{\gamma}_{s1}(\tau)$ and $\dot{\gamma}_{s2}(\tau)$, which correspond to the analogous stress value obtained from the measurements using each of the working gap heights. Slip velocity can be determined using **Equation 3**.

$$u_s = \frac{\dot{\gamma}_{s1}(\tau) - \dot{\gamma}_{s2}(\tau)}{2\left(\frac{1}{h_1} - \frac{1}{h_2}\right)} \quad (3)$$

The significant advantage of this method is the ease with which rheological tests can be conducted, particularly using parallel plate geometries. If the method of coaxial cylinders is used, it would be necessary to use at least two sets of geometries with different measuring gaps. However, attention should be paid to ensure that changing the gap height will not introduce a change in the properties and behaviour of the tested fluid.

As can be seen from **Equation 3**, the slip rate is the difference in the shear rate from two measurements taken at two different working gap heights. However, the values of these shear rates must be determined for the corresponding shear stress values in each of these measurements. This behaviour of the fluid under test can be interpreted as a local (near surface) reduction in fluid viscosity.

Alternatively, slip at the fluid-solid interface can be determined by comparative tests. For this purpose, the measuring system component with a modified working surface structure is used. The usual approach is to increase the roughness by cross-hatching, grooving, or sandblasting the working surface (**Fig. 2**).

Comparative tests are essential to determine the occurrence of slip on the interface surface and the conditions in which such a phenomenon

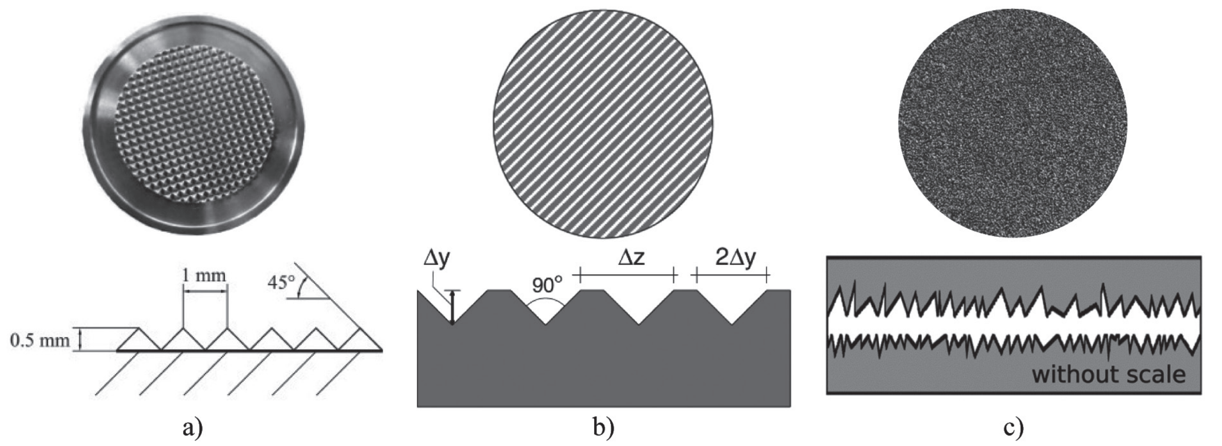


Fig. 2. Examples of work surface modifications of measuring elements: a) cross-hatched [L. 4, 5], b) grooved [L. 6], c) sandblasted **[L. 7]**

Rys. 2. Przykładowe modyfikacje powierzchni roboczej elementów pomiarowych poprzez: a) nacinanie **[L. 4, 5]**, b) rowkowanie **[L. 6]**, c) piaskowanie **[L. 7]**

may occur. A significant limitation of this type of method, especially using cross-hatched and grooved plates, is the difficulty in generalising the obtained results. Additionally, due to the size of the incisions or the high roughness of the work surface, it can be difficult to determine the precise volume of fluid required for the test. An additional aspect that affects the results is the directionality of the structure, especially in cross-hatched and grooved plates, where the working surface is strictly defined. Whereas in the case of sandblasted plates, this problem does not occur because of the random structure of the modified surface.

As complex substances (including suspensions) are primarily susceptible to the occurrence of slip, the possibility of this phenomenon in magnetorheological fluids (MR) can be expected. MR fluids are non-colloidal suspensions of micrometre-sized particles with ferromagnetic properties in a carrier fluid, usually oil, paraffin, or water. Additionally, MR fluids may contain additives and stabilisers **[L. 8]**. Thus, because of the composition and complexity of the structure of MR fluids, it is essential to take a closer look at their behaviour and properties near the fluid-wall contact region. This is significant for engineering applications of MR fluids, i.e., brakes and clutches.

As presented in the work **[L. 9]**, increasing the roughness of the brake walls results in an increase in braking force by reducing the slip effect. The slip phenomenon also substantially impacts the abrasive finishing technology; when there is slippage in the contact between the machining fluid and the workpiece, the abrasive grain may not have enough energy to cut the material **[L. 10]**.

The slip phenomenon has a major impact on the ability to determine the rheological quantities that characterise MR fluids. In the work **[L. 11]**, it was shown that using a smooth plate can lead to a systematic underestimation of the fluid's viscosity, yield stress, and dynamic properties. This paper presented results for MR fluids with a relatively high magnetic particle content (50% vol.). The high concentration of particles increased the slip effect so that it could be observed more easily. The tests were carried out based on the comparison of the measurement results obtained for plates with the smooth and cross-hatched surface. It should be noted that the largest discrepancies related to the occurrence of slip were observed in the absence of a magnetic field. This research was further developed in the work **[L. 12]**, determining that the main reason for the underestimation of the yield stress is particle aggregation related to both colloidal interactions (e.g. the presence of van der Waals forces) and also related to the presence of a magnetic field.

Similar tests were carried out with a top measuring plate on which sandpaper was taped **[L. 9]** for three different volume fractions of carbonyl iron particles: 25, 30 and 35%. The dependencies obtained in the work **[L. 11]** were confirmed. In addition, it was indicated that the slip phenomenon in the absence of a magnetic field most influences the value of zero viscosity and the value of the material's yield stress in its presence. Stefan Odenbach's research team **[L. 7]** carried out tests with a foamed porous material in addition to tests with sandpaper. The stress values obtained for the modified plates differed significantly from those obtained on the smooth test plate. The paper concludes by emphasising that the problem is very complex due to a number of yet unexplored factors, i.e., the influence of the roughness of the measuring geometry on the gap height or the relationship of the gap height to the formation of magnetorheological structures. They also pointed out that further research on the occurrence of slip in MR fluids should be carried out at high shear rates, where chains of magnetic particles will be broken.

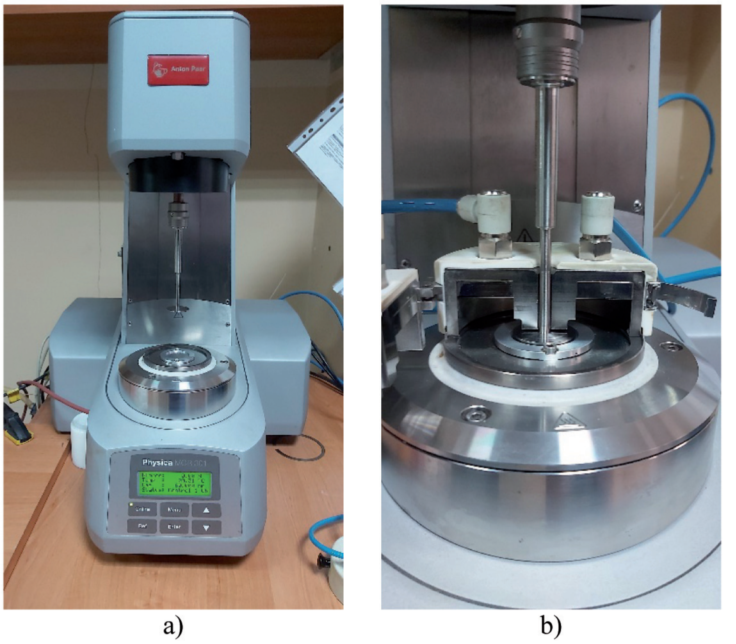
The purpose of the study was to determine the possibility of observing the slip of the MR fluid as a result of comparative tests. The tests included changing the working gap's height and using a measuring plate with increased roughness. The testing was carried out at low and high shear rates.

EXPERIMENTAL

Test stand

Measurements were performed on an Anton Paar Physica MCR 301 rotational rheometer (**Fig. 3a**) with an MRD180/1T magnetorheological test accessory (**Fig. 3b**).

A parallel plate geometry with a diameter of d = 20 mm was used in two variants: standard design with a smooth surface (**Fig. 4a**) and modified by sandblasting (**Fig. 4b**). For the purpose of this study, the labels PP (Plate-Plate) were assigned to the unmodified plate and PPS (Plate-Plate Sandblasted) to the sandblasted plate.



a) b)

Fig. 3. Test stand
Rys. 3. Stanowisko badawcze

Fig. 4. Working surface of the upper plate of the plate-plate system: a) standard (PP), b) sandblasted (PPS)
Rys. 4. Powierzchnia robocza górnej płytki układu płytka-płytka: a) standardowa (PP), b) piaskowana (PPS)

Parameters characterising the surfaces of the condition of the plates were measured. Roughness measurements were made with a TOPO-01 contact profilometer manufactured by the Institute of Advanced Manufacturing Technology. Measurements were carried out according to PN-ISO 4288:1998 on five elementary distances. The values obtained are summarised in **Table 1**. An approximately 35-fold increase in the Ra and Rz parameters was observed for the sandblasted plate. Due to the sandblasting technology used, the working surface had an isotropic, undirected geometrical structure.

Table 1. Comparison of the roughness parameters of the working surfaces of the upper measuring plate
Tabela 1. Porównanie parametrów chropowatości powierzchni roboczych górnej płytki pomiarowej

Parameter / Geometry	Rz [µm]	Rt [µm]	Ra [µm]	Rz [µm]
	Maximum height	**Total height**	**Mean**	**Height according to 10 points**
Standard (PP)	0.266 ± 0.048	0.343 ± 0.063	0.051 ± 0.011	0.313 ± 0.043
Sandblasted (PPS)	9.274 ± 1.942	9.274 ± 1.942	1.794 ± 0.519	11.547 ± 1.319

The MR fluid used in tests

LORD's commercial MRF-122EG fluid was selected for the study. The fluid parameters declared by the manufacturer are included in **Table 2**. The used MR fluid is dedicated for use in valve mode and shear mode applications **[L. 13]**.

Table 2. Physical properties of MRF-122EG [L. 13, 14]
Tabela 2. Właściwości fizyczne MRF-122EG **[L. 13, 14]**

Property	Value
Density	2.28-2.48 g/cm^3
Dynamic viscosity at 40°C	0.042±0.02 Pa·s
Solid content	72% wt. 22% vol.
Flash point	> 150°C
Operating temperature	-40÷130°C

Comparing the data for the roughness parameter Rz from **Table 1** and the magnetic particle size of the MR fluid (**Fig. 5**), it can be noted that for the smooth plate, the magnetic particles are about five times larger than the surface roughness, and for the sandblasted plate about eight times smaller.

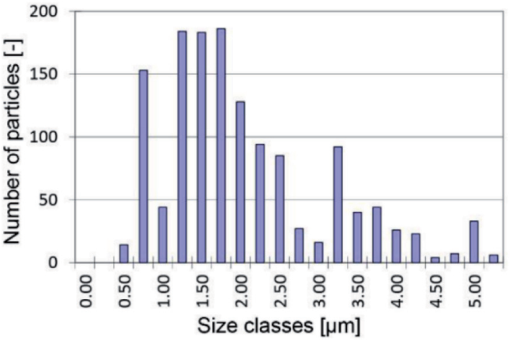


Fig. 5. MRF-122EG fluid particle size distribution [L. 14]
Rys. 5. Rozkład wielkości cząstek cieczy MRF-122EG **[L. 14]**

Test method

Two types of tests were performed: the Magneto Sweep and typical rotational tests dedicated to obtaining flow curves, both with controlled shear rates.

Magneto Sweep tests consist of observing the change in rheological parameters caused by the continuous increase in magnetic field induction in the working gap in the range B = 0 – 680 mT. Measurements were carried out for three shear rates $\dot{\gamma}$ = 1/10/100 s^{-1} and three working gap heights h = 0.1/0.2/0.6 mm corresponding to the volumes of applied fluid v = 50/75/200 µl.

In rotational tests, the shear rate was continuously changed in the range $\dot{\gamma}$ = 0.01 – 1000 s^{-1}. Measurements were carried out for zero magnetic field conditions and five different magnetic inductions B = 0/40/75/150/300/560 mT and three different working gap heights, as in the previous type of test.

Each measurement was repeated a minimum of three times, and the average of the measurement results was taken for further analysis.

RESULTS

Magneto Sweep

The variation of all shear stress curves obtained from the Magneto Sweep test was similar; therefore, **Fig. 6** shows only the result of a series of measurements for the lowest of the analysed gaps (h = 0.1 mm) performed at three shear rates ($\dot{\gamma}$ = 1/10/100 s^{-1}). The colours of the lines correspond to the individual shear rates, while the solid line refers to the result obtained from the PP measuring plate, and the dashed line shows the results obtained for the sandblasted plate (PPS).

Under analogous measurement conditions, differences in the stresses obtained depending on the surface condition of the measuring plate are observed. In **Fig. 6**, there is a noticeable trend towards increasing this difference, above all at low shear rates, as the magnetic field induction increases.

The results of all Magneto Sweep measurements are shown in **Fig. 7** in the form of absolute differences in the result of the shear stress measurements obtained with a plate with a smooth surface (PP) and with increased roughness (PPS). Since $\Delta\tau = \tau_{PP} - \tau_{PPS}$, so a positive value on the graph means that a higher stress value was recorded with the smooth plate (PP).

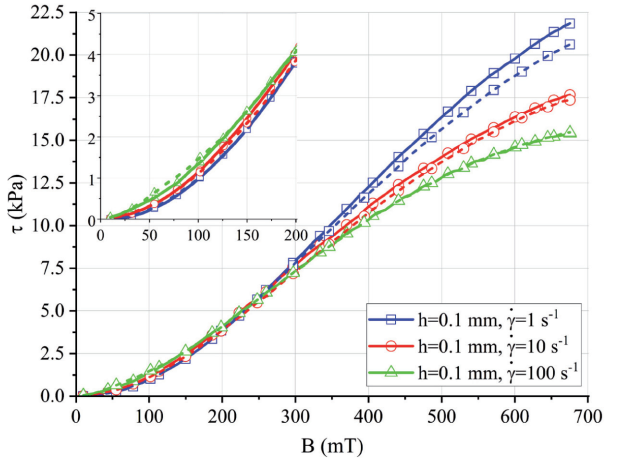


Fig. 6. Sample Magneto Sweep sample measurement result

Rys. 6. Przykładowy wynik pomiaru Magneto Sweep

For the smallest measurement gap (h = 0.1 mm, **Fig. 7a**), only for the lowest shear rates analysed is a significant increase in the difference in shear stresses. It should be noted that for each measurement, lower stress values were obtained using a plate with higher surface roughness (PPS).

The results obtained for h = 0.2 mm (**Fig. 7b**) have a similar pattern. In the low induction range, the absolute difference in the measurement results is relatively low and increases with increasing magnetic field induction. For narrower gaps, initially, higher values were obtained for the PP plate, whereas for the largest gap, higher stress values were registered for the PPS plate over almost the entire range.

For the widest measuring gap (h = 0.6 mm) (**Fig. 7c**), only at the lowest shear rate and in a narrow induction range (in the middle range of magnetic induction) are positive values observed. For the other measurements, the use of a plate with a higher roughness (PPS) led to higher shear stress values compared to an unmodified plate.

A similar trend is recognisable in all measurement results; higher stress values are obtained for the non-modified plate (PP) when there were narrow gaps (h = 0.1 and 0.2 mm), but for h = 0.6 mm, the use of the sandblasted plate (PPS) resulted in higher stress values.

In order to illustrate the differences in measurement results more clearly, the relative differences in measured stresses are shown in **Fig. 8**.

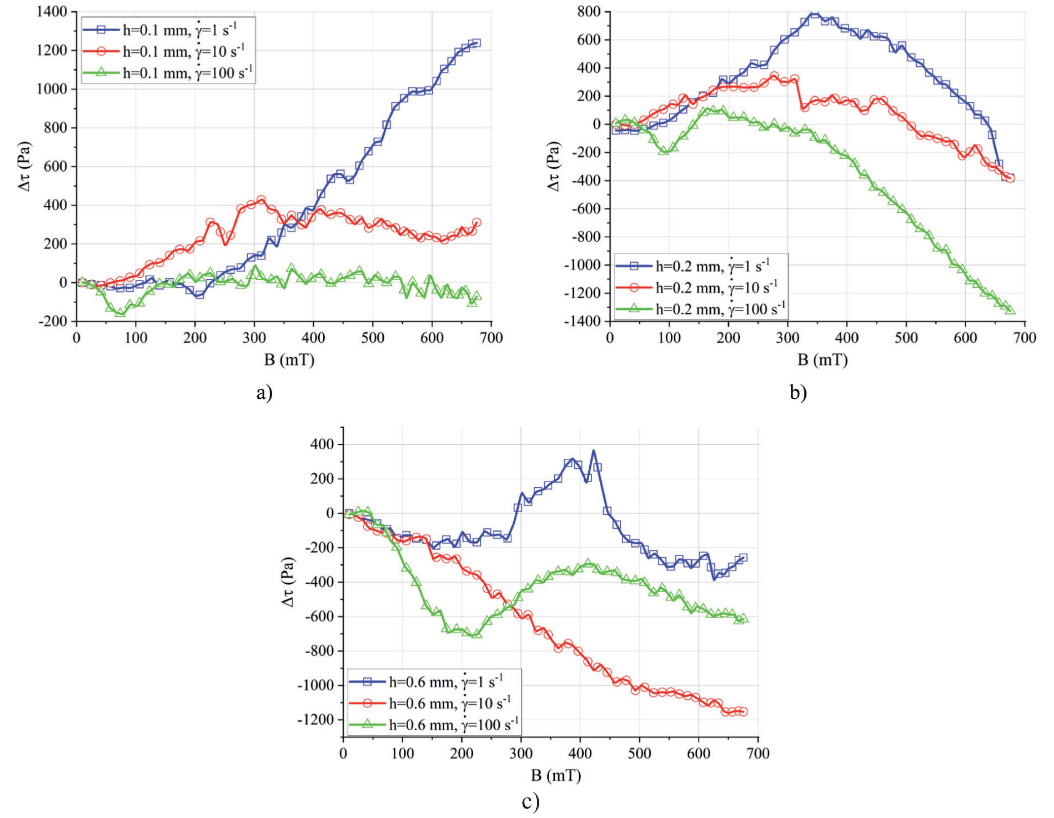


Fig. 7. The difference between the PP and PPS measurement (Magneto Sweep)
Rys. 7. Różnica pomiaru PP i PPS (Magneto Sweep)

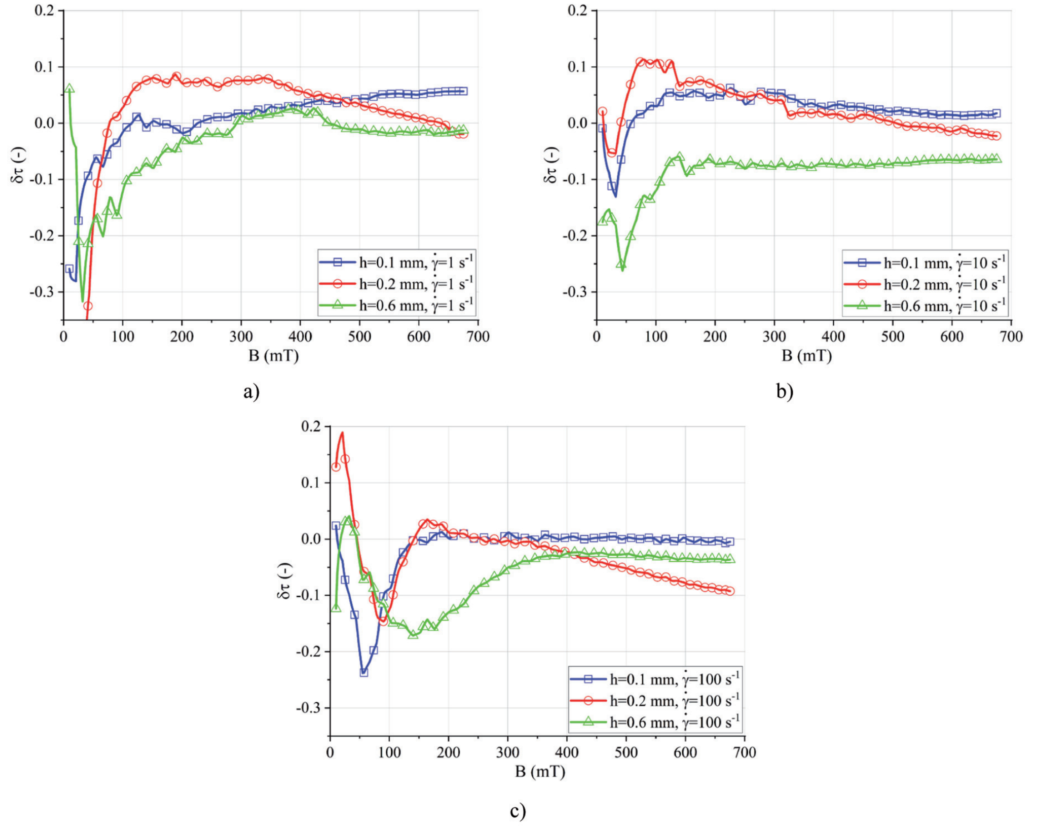


Fig. 8. The relative difference between PP and PPS measurement (Magneto Sweep)
Rys. 8. Różnica względna pomiaru PP i PPS (Magneto Sweep)

Considerably high relative differences seen for lower magnetic field induction values result from low-stress values and do not indicate the possibility of significant slip. For this reason, only the values obtained for higher magnetic field induction (B ≥ 150 mT) were analysed. In this range, for all cases, the relative difference between the results of the PP and PPS plates measurements stabilises at a fixed level and is less than ±10%, with greater differences for smaller gaps, which have positive values and therefore indicate the appearance of greater slippage when using the PPS plate.

The test results represent only a preliminary qualitative evaluation of the observed phenomenon. Typical rheological tests with a controlled shear rate were performed for a quantitative assessment.

ROTATIONAL TESTS

The next stage of the study consisted of flow curves at fixed six values of magnetic field induction (B = 0/40/75/150/300/560 mT) and increasing shear rate ($\dot{\gamma}$ = 0.001 – 1000 s^{-1}). **Fig. 9a** summarises all results in the typical form of this type of curve ($\tau = f(\dot{\gamma})$). As before, dashed lines represent the results of measurements obtained with the PPS plate.

To determine the conditions of the potential slip occurring, the curves from **Fig. 9a**, are shown in **Fig. 9b** in the modified axis reference system ($\dot{\gamma} = f(\tau)$). Since, for typical substances, the slip rate depends only on the shear stress, a benchmark of slip occurrence can be the value of the difference in the shear rate occurring at a given stress (see **Equation 3**).

Fig. 10 shows the results of the absolute shear rate difference $\Delta\dot{\gamma}(\tau) = \dot{\gamma}_{PP}(\tau) - \dot{\gamma}_{PPS}(\tau)$. Positive values in the graphs indicates the possibility of slip on the PP plate, while negative values indicate the possibility of slip on the PPS plate.

In each of the cases, in the lower stress range, the value of $\Delta\dot{\gamma}$ is close to zero. This confirms the assumption quoted earlier that slip is primarily a function of shear stress, and at sufficiently low values of the stress, there is no slip, or its intensity is relatively low.

In all analysed cases, except for the test carried out without a magnetic field (**Fig. 10a**), a clear division in the character of the variability of the discussed curves is observed. The curves obtained for narrower gaps (h = 0.1 mm and h = 0.2 mm) have a similar pattern compared to the measurement results for the measurement gap h = 0.6 mm. For narrower gaps, already at relatively low values of

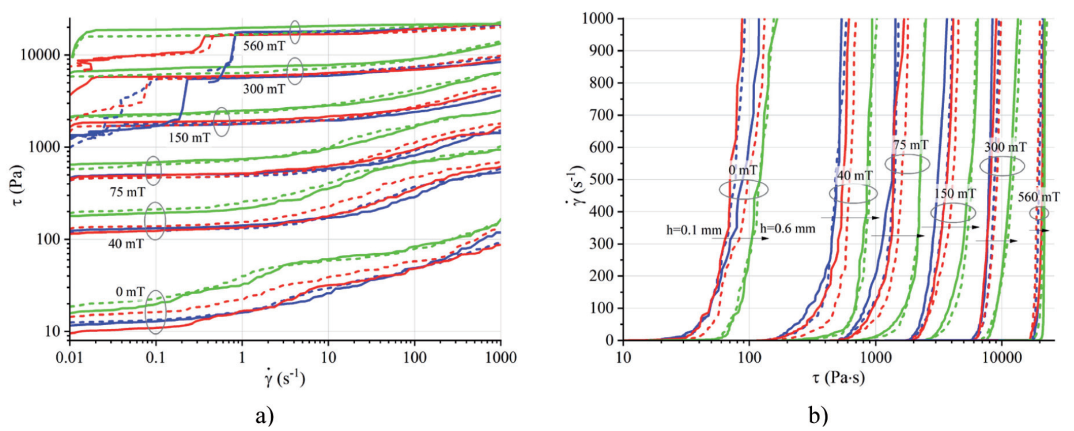


Fig. 9. Summary of flow curves: a) $\tau = f(\dot{\gamma})$, b) $\dot{\gamma} = f(\tau)$
Rys. 9. Zbiorcze zestawienie krzywych płynięcia: a) $\tau = f(\dot{\gamma})$, b) $\dot{\gamma} = f(\tau)$

the magnetic field induction, an increase in the difference in shear rate in the positive direction is observed, so it can be expected that in these cases, slippage occurs when a PP plate is used.

On the other hand, for a gap h = 0.6 mm, the slip occurs at significantly higher shear stress values. A lower intensity characterises this slip, and as the magnetic field induction increases, there is a tendency for increased slip on the sandblasted plate (PPS).

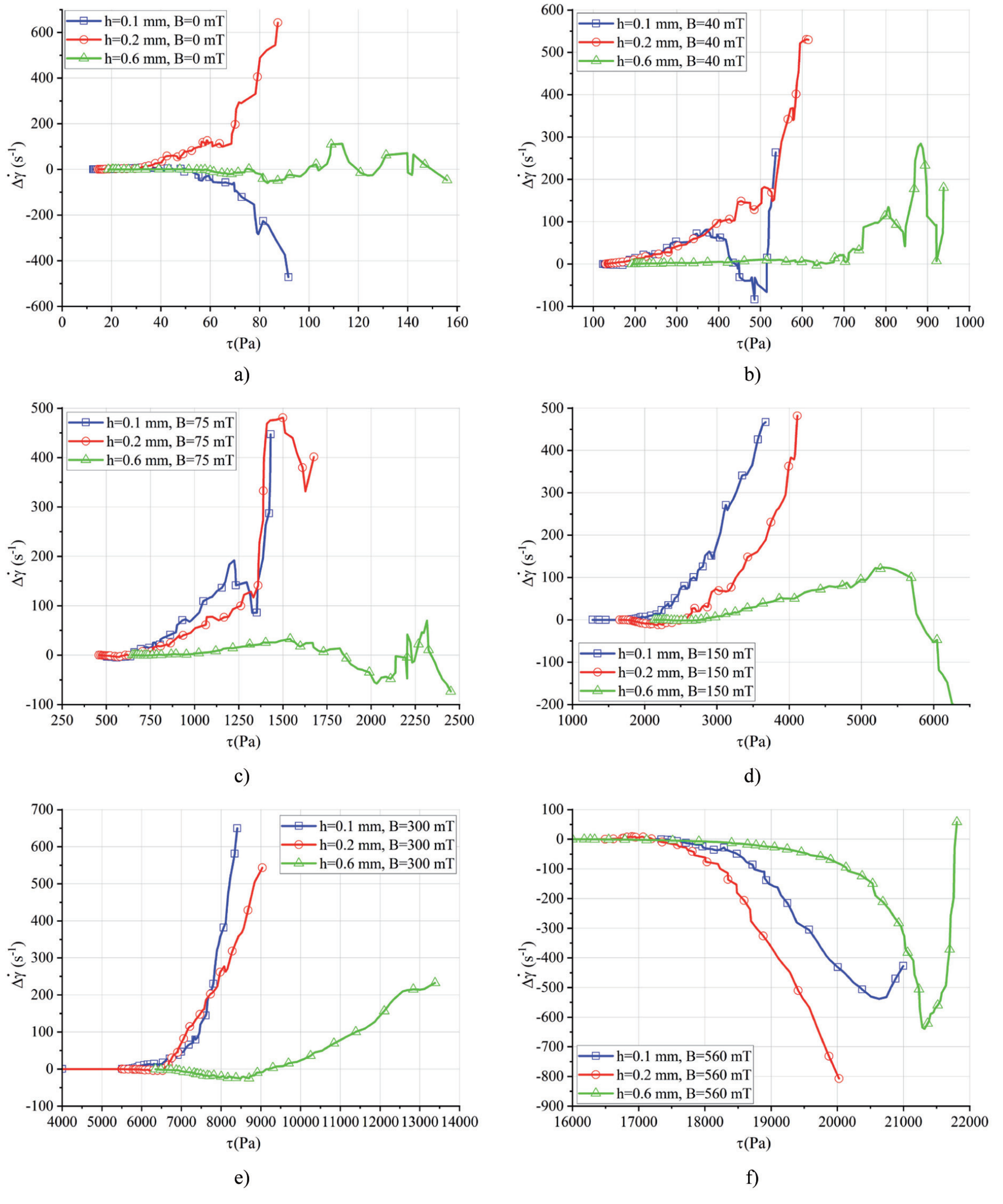


Fig. 10. Measurement data $\dot{\gamma} = f(\tau)$
Rys. 10. Dane pomiarowe $\dot{\gamma} = f(\tau)$

CONCLUSIONS

The paper presents the results of comparative rheological studies using a typical (smooth) gauge plate and a system with increased surface roughness. The study aimed to determine the effect of changing the measurement plate surface roughness on the values obtained shear stresses in the context of the possible occurrence of slip at the MR fluid-measuring plate interface. The main conclusions of the research can be identified as follows:

A significant part of the results obtained from the Magneto Sweep tests indicates that higher stress values are obtained with an unmodified (PP) plate. It should be noted that this is not an expected result and indicates an increase in a slip at the interface between the MR fluid and the plate may occur in geometry with increased roughness.

The pattern of variation in the relative stress difference indicates that it is correct to assume that fluid slip is proportional to shear stress. This is demonstrated by the absence of variation in the curves shown in **Fig. 8** with an increase in the stress difference shown in **Fig. 7**. Furthermore, this is evidence that slip is constant under constant operating conditions. Thus, for the MR fluid, too, it depends only on the shear stress.

It was demonstrated that there is a different character of the measurement results depending on the height of the measurement gap. For narrow gaps (h = 0.1 mm and h = 0.2 mm), similar results were obtained. On the contrary, the results for h = 0.6 mm are significantly different both qualitatively and quantitatively. At this research stage, it is unknown whether this is due to a change in the distribution of magnetic field induction in the gap or to a change in the deformation mechanism of the MR fluid when it is operated at an increased height of the measuring gap. This aspect of the results requires further research.

The results indicate that there may be two different slippage mechanisms in MR fluids, depending on the surface roughness with which the fluid interacts.

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