Transient rheology of a magnetorheological fluid under shearing

Ilari Jönkkäri[1] and Seppo Syrjälä[1]

[1] Tampere University of Technology, Tampere, Finland.

ABSTRACT

Transient behaviour of a magneto-rheological (MR) fluid under constant long lasting shearing is studied using Anton Paar MCR 301 rheometer and MRD180/1T magneto-cell. Effect of the shear rate, magnetic flux density and surface material and texture of the plate-plate measuring geometry are investigated by a series of time sweep measurements. In addition to the original titanium Anton Paar rotor two custom made aluminum rotors with different plate surface textures are used. It is found that the shear stress of MR fluid typically has either a steadily decreasing or increasing trend as a function of time depending about measuring parameters, mostly shear rate. The results also show that the rotor plate texture and material can have a significant effect to the measurement.

INTRODUCTION

MR fluids are suspensions of magnetizable particles in a non-magnetic Newtonian liquid. Particles are typically spherical and composed of a ferromagnetic material such as carbonyl iron. MR fluids may also include substances to decrease particle sedimentation and wear of hydraulic systems. The magnetorheological effect is seen as a rise in the suspension viscosity and appearance of the yield stress upon application of a magnetic field. The effect is caused by formation of particle structures that hinder fluid flow. Structures are columnar at static no-flow conditions and become lamellae under shearing[1]. The intensity of the MR effect is influenced by several variables, such as composition of the MR fluid, magnetic flux density, shear rate, temperature and time.

Long term stability of the MR effect under shearing is important in certain applications such as clutches and breaks. Transient rheological response may also play a significant role in rheological measurements where a transient change can cause misinterpretation of the results.

Transient rheology of suspensions in a shear flow is well studied by a number of authors[2,3,4]. Changes of rheological properties in steady shear are usually caused by migration of particles due to hydrodynamic interactions. Particles can migrate towards the centre or edges of the plate causing decrease or increase in apparent viscosity and shear stress. Inward migration is often viewed as shear-induced and outward migration as curvature-induced. Inward migration of particles is generally explained by a shear stress gradient of the plate-plate geometry where the shear stress decreases towards the centre of the plate. Particles tend to migrate to lower stress regions[2]. The origin of outward migration lies in the shape of the plate-plate geometry that results in the curvature of streamlines, thus influencing particle motion[3]. Merhi et. Al[4] were the first who presented experimental evidence of an outward migration of particles submitted to flow between parallel plates.

The same mechanisms of particle migration are valid for MR suspensions as with any suspensions. However under magnetic field hydrodynamic interactions of particles are added with field-induced forces[1]. Radial gradients in magnetic flux density can severely increase migration[5]. Few researchers have studied transient response of MR fluids over long time periods.

Ciocanel et al.[6] studied MR fluids transient behavior with parallel plate rheometer. Fluid was under constant shear rates over periods of two hours. A number of different magnetic flux densities and shear rates were used. Overall decrease in shear stress in time was observed. Decrease became more significant at higher shear rates and flux densities. Authors proposed that the reason behind the decrease could be a combination of slippage at the plate surfaces and separation of liquid and particle phases. It was suggested that roughening of the plate surfaces could reduce the intensity of the slippage and improve stability of the fluid.

Ulicny et al.[7] studied the transient response of MR fluids with custom-made Couette type rheometer. Fluids were subjected to step changes in applied magnetic field strength at fixed shear rate. Application of the magnetic field lasted for 60 seconds. At small field strengths the shear stress increased rapidly to a steady value. Above critical field strength, the rapid initial increase in shear stress was followed by a slow, transient increase.

Laun et al.[5] studied the effect of a radial magnetic flux density gradient to particle migration in MR fluid. They showed that carbonyl iron particles migrate towards maximum of the flux density at the edge of the parallel plate geometry. This can be seen as a rise in apparent shear stress over time. Migration could be avoided by redesigning the MR rheometer so that it produces flatter magnetic flux density profile.

In this study the time dependency of the MR fluid structure is evaluated with time sweep measurements. Shear rate, magnetic flux density and surface material and texture of the plates are varied and the effect to the transient behaviour of the MR fluid is evaluated.

EXPERIMENTAL

Measurements were performed with an Anton Paar Physica MCR301 rotational rheometer equipped with a MRD180/1T magneto-cell. Schematic of the magneto-cell is given in Figure 1.

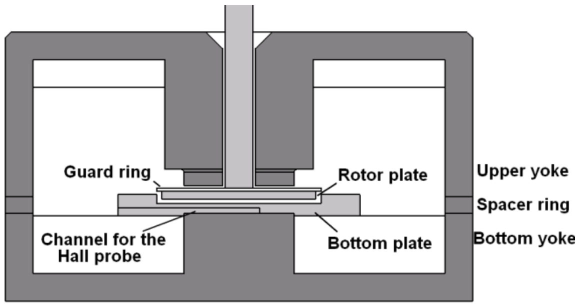

Figure 1. Schematic of the MRD180/1T magneto-cell.

Three different plate-plate measuring geometries were used; one was original Anton Paar geometry with titanium rotor and others were custom-made with aluminum rotors. Custom-made rotors consist of aluminum plate part and stainless steel adapter as illustrated in Figure 2. Rotor plates were similar to Anton Paar model with 20 mm plate diameter. One aluminum plate had a smooth surface and the other was roughened. Rough surface is less vulnerable to wall slip that can affect measurements[6]. Original Anton Paar bottom plate was used with smooth rotors. With rough rotor the bottom plate was also roughened. Gap height of 0.5 mm was employed in all measurements. Temperature of the magneto-cell was held at 30 °C with a circulating bath.

Figure 2. Different geometries used in measurements. Anton Paar geometry left, custom made geometries with and without adapter.

The MR fluid was prepared by mixing carbonyl iron particles into a carrier fluid. Mixing was done in an ultrasonic mixer for half an hour. MR fluid was remixed prior to each measurement for 5 minutes. The particle was BASF HQ with average diameter of 2.0 µm and the carrier fluid was Dow Corning® 200/50cS silicone oil. Particle concentration of the fluid was 80 w-%. MR fluid was dosed into the measuring gap with a syringe.

Long term stability of the MR fluid under shearing was evaluated by time sweep measurements. During a measurement the shear rate and the magnetic flux density were held constant and the shear stress was monitored as a function of time. Fluid was sheared at 0.1 and 10 1/s for 2000 seconds.

In some measurements with 10 1/s the MR fluid would climb from the gap between the plates to the space above the rotor plate giving a strong increase in shear stress. This was prevented by mounting a 0.5 mm thick PVC guard ring above the plate as previously described by Laun et al.[8]. Additional vertical space for the guard ring was obtained by raising the upper yoke of the magneto-cell 0.5 mm by machining a thicker ferromagnetic spacer ring between yokes. Increase in the distance between yokes changes the rather flat magnetic flux density profile to slightly more uneven as seen in Figure 3. This can affect particle migrations by increasing field-induced forces. Magnetic flux density profile was measured from the top of the bottom yoke with F.W.Bell Model 5180 Tesla meter and Hall probe STD18-0404 by moving the probe with 0.5 mm segments from the middle of the plate towards the rim. Custom-made actuator was used to ensure precise movement of the probe.

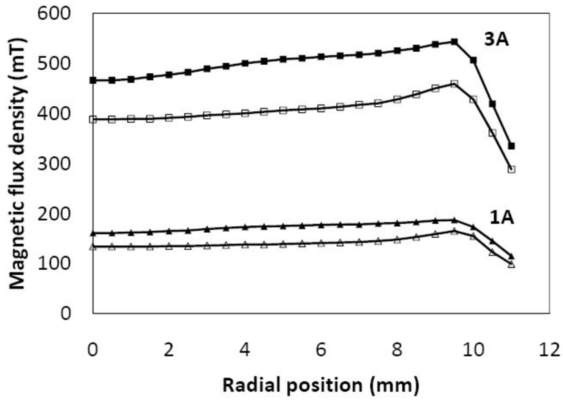

Figure 3. Magnetic flux density profiles for 1 (triangles) and 3A (cubes) coil currents with original (filled symbols) and modified (empty symbols) magneto-cell setup.

RESULTS AND DISCUSSION

Results of the time sweep measurements are illustrated in Figures 5, 6 and 7. Shear stresses and rates are given at the rim of plates. Shear stresses show a strong increase at the beginning of the measurements with 152 mT flux density and 0.1 1/s shear rate as illustrated in Figure 5. Reason for the increase is that with small shear strains most of the particle chains in MR fluid are deforming elastically and the ones that are breaking are able to form new structures with adjacent chains. After peaking at about 100 seconds shear stresses begin to decrease. At this point more and more particle structures begin to break and the deformation mechanism changes. The decrease levels out over time and after 400 seconds there are no major changes excluding some fluctuation observed with both smooth surfaces. The decrease rate is considerably slower with rough surface but the overall decrease is at the same level with others. There is a distinct difference in shear stresses between measuring geometries. The rough geometry gives the highest readings and the smooth geometry the lowest. This indicates that there is some slippage at smooth plate surfaces affecting transmittable shear stress.

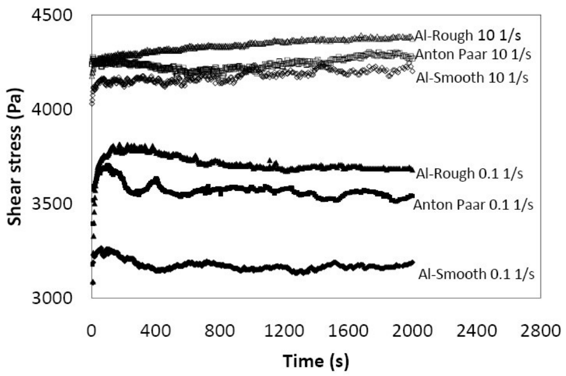

Figure 5. Time sweep measurements with 152 mT flux density and 0.1 (filled symbols) and 10 1/s (open symbols) shear rates.

Shear stresses rise as expected when the shear rate is increased to 10 1/s. Strong peaking of stresses at the beginning of the measurement is no longer observed because particle structures reach breaking strain faster and the sampling time is too large to capture the sudden changes. As the shear rate is increased the overall trend in shear stress changes from steady decrease to increase. Likely reason for this is that the directions of particle movement changes from inward to outward migration as curvature-induced forces become stronger. The difference in shear stresses between measuring geometries has become smaller suggesting that the amount of wall slip with smooth geometries has reduced.

Particle structures become substantially stronger as the magnetic flux density is increased to 450 mT. This is seen as an increase in shear stresses as illustrated in Figure 6 for 0.1 and 10 1/s shear rates.

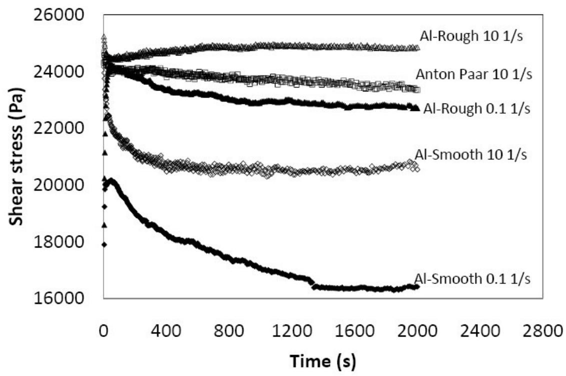

Figure 6. Time sweep measurement for Anton Paar geometry with 450 mT flux density and 0.1 1/s shear rate.

With 0.1 1/s the overall transient behavior for both aluminum geometries is quite the same as with lower flux density. The maxima of the shear stress are now reached sooner and the decrease is stronger than before. Anton Paar geometry however shows major differences to previous as illustrated in Figure 7.

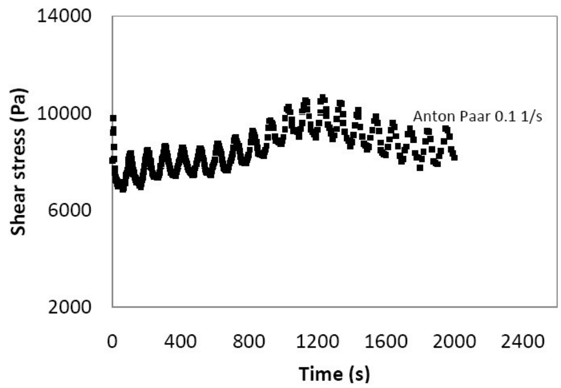

Figure 7. Time sweep measurement for Anton Paar geometry with 450 mT flux density and 0.1 1/s shear rate.

Shear stresses are distinctly lower than with other geometries and show oscillation. Behavior is likely caused by substantial amount of wall slip that is varying. Phenomenon disappears when the shear rate is increased to 10 1/s. Shear stresses rise back to same level with other showing a decreasing trend over time. With 10 1/s both aluminum geometries show a strong decrease in shear stress at the beginning of the measurement. The decrease is likely preceded by a peaking of shear stress as with lower shear rate but the sampling time is too large to capture this. With rough geometry the decrease turns quickly to a steady increase that levels out after about 600 seconds. The smooth geometry does not show similar increase. It is worth noticing that with 10 1/s there is almost no difference in shear stresses between measuring geometries at the beginning. However at the end of the measurements the difference has increased substantially. This clearly indicates that the material and surface texture of plates has an effect on MR fluids transient behavior.

CONCLUSIONS

Transient behavior of a MR fluid was studied at various shear rates and magnetic flux densities using the rotational rheometer with a magnetic field generator and three plate-plate geometries. In addition to the original titanium Anton Paar geometry two custom-made aluminum geometries with different plate surface textures were used. The time sweep measurements indicated that the shear stress of MR fluid typically has either a steadily decreasing or increasing trend as function of time depending about measuring parameters, mostly shear rate. The results also show that the plate material and surface texture can have an effect on transmittable shear stress and on how the shear stress changes over time.

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