Experimental Researches concerning the Rheology of Cutting Fluids

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Abstract. Cutting fluids are used to reduce the negative effects of the heat and friction on both tool and work piece. The cutting fluids produce three positive effects in the process: heat removal elimination, lubrication on the chip-tool interface and chip removal. This paper proposes to study the rheological properties of four different type of cutting fluids, as function of their chemical and physical characteristics. The tests were performed using a cone and plate Brookfield viscometer, by determining the rheological parameters and the variation of the apparent viscosity with the temperature. This approach has been used to quantify the performance of the tested products and to compare products in the marketplace.

1. Introduction

Improving machining processes includes high processing speeds and automated mechanical systems necessary for feeding and loading, correlated with operating flows. It also includes the use of various metallic materials for cutting tools, for different types of operations. All of these elements imply an important improving of cutting fluids for a wide range of machining processes and processing conditions [1], [2], [3]. Cutting fluids currently contain a wide variety of specialized chemical agents, designed to obtain the lubrication effect under different processing conditions, providing the stability of the physical, chemical and rheological characteristics, and also the antiwear protection [4].

The main functions of the cutting fluids are to remove the amount of heat released during the cutting process, to reduce the friction between the tool and the work piece, to increase the work life of the cutting tools by reducing the wear and to improve the quality of the surface for the work piece.

Depending on the specifics of the processing operations and the processed materials, cutting fluids are used in the following typological diversification [5], [6], [7]: water-immiscible oils, emulsifiable fluids such as oil/water, aqueous solutions of organic or inorganic compounds, suspensions or pastes of solid lubricants. The important rheological characteristics required of a cutting fluid for good operational performance are focused on sustaining a sufficiently large stress to maintain chips in suspension, particularly when fluid circulation is stopped. In the same time, cutting fluids need to have low enough viscosity in order to assure an efficient pumping. In steady shear flow, the cutting fluids have to be shear-thinning fluids, which means that the effective viscosity decreases by the increasing of the shear rate [8], [9].

The present paper proposes to study the rheological properties of four different type of cutting fluids, as function of their chemical and physical characteristics. The tests are performed using a cone and plate Brookfield viscometer, by determining the rheological parameters and the variation of the apparent viscosity with the temperature.
2. Experimental methodology

The cutting fluids used for the experimental tests are the following:

- **INSA Rezinol C-22**, which is a non-emulsifiable oil – cooling lubricant, used for lubrication and cooling of cutting tools in deep drilling of metals and alloys, in automatic lathe processing, highly alloyed steels, stainless steels and heat-resistant steels [10];

- **INSA Emulsol**, which is an emulsifiable lubricant – coolant, containing special emulsifiers, anti-corrosion inhibitors and bio-resistant components prepared using special technologies and refined mineral oil. It finds application in metalworking for high quality machining of cast iron, steel and other metals in operations - turning, milling, grinding, reaming, cutting [11];

- **Würth Cut & Cool, Cutting Oil**, which is used for drilling, thread cutting, thread moulding, lathing, countersinking, rubbing and sawing. It is ideally suited for stainless steel, but also for high-alloy steels, constructional steels, non-ferrous and precious metals. It can be also used as a preservative agent on semi-finished/finished parts and machine parts, and can be used as gun oil [12];

- **Rhenus RL 3 DW** is a thin corrosion preventive fluid with water displacing properties solved in hydrocarbons free of aromatics, which is free of heavy metals. It is universally used for grinding and machining operations of cast iron, steels and aluminium alloys [13].

The main physicochemical properties of these cutting fluids are presented in Table 1.

| Properties                      | INSA Rezinol C-22 | INSA Emulsol | Würth Cut & Cool, Cutting Oil | Rhenus RL 3 DW |
|---------------------------------|-------------------|--------------|------------------------------|---------------|
| Color                           | Light brown       | Light Brown  | Tan                          | Brown         |
| Physical state                  | Liquid            | Liquid       | Liquid                       | Liquid        |
| Odour                           | Characteristic    | Characteristic| Characteristic               | Characteristic|
| Kinematic viscosity at 40°C, mm²/s | 22                | 24           | -                            | 100           |
| Dynamic viscosity at 40°C, mPa.s | -                 | -            | 3.5                          | -             |
| Flash point /C.O.C./, °C        | 210               | 200          | -                            | -             |
| Pour point, °C                  | -15               | -15          | -                            | -             |
| Density at 20 °C, g/ml          | 0.860             | 0.855        | -                            | 0.78          |

Rheological tests were performed using a Brookfield viscometer CAP 2000+, with a cone and plate geometry. Three type of tests have been used:

- Determination of the soaking time, which represents the time necessary for the measurement to become stable and for the fluid to become homogeneous. Three „Time to stop” tests (variation of the apparent viscosity versus time) were performed for each type of fluid, with different rotation speeds: 100, 200 and 500 rpm.

- Determination of the rheological model, using a “velocity imposed gradient” test (variation of the shear stress versus shear rate), with the rotation speed range between 100 rpm and 1000 rpm, using cone geometry number 8.

- Determination of the variation of apparent viscosity with temperature, using a “velocity imposed gradient” test, with the rotation speed 500 rpm and temperature range between 20°C and 75°C.
The experimental results corresponding to the determination of the rheological parameters were numerically treated assuming the validity of power law rheological model:

\[ \tau = m \left( \frac{\delta u}{\delta y} \right)^n \] (1),

where: 
- \( \tau \) – shear stress
- \( m \) – consistency index
- \( n \) – flow index
- \( \frac{\delta u}{\delta y} \) – shear rate

Regarding the variation of the apparent viscosity versus temperature, the Reynolds model was used:

\[ \mu = \mu_{50} e^{m(t - 50)} \] (2),

where:
- \( \mu \) – apparent viscosity
- \( \mu_{50} \) – viscosity at 50 °C
- \( m \) – temperature parameter
- \( t \) – temperature

3. Results

The experimental results corresponding to the determination of the soaking time, for all four fluids, are presented in Figures 1, 2, 3 and 4.

Figure 1. Variation of the apparent viscosity versus time for INSA Rezinol C-22
**Figure 2.** Variation of the apparent viscosity versus time for INSA Emulsol

![Graph showing variation of apparent viscosity versus time for INSA Emulsol](image)

**Figure 3.** Variation of the apparent viscosity versus time for Würth Cut & Cool, Cutting Oil

![Graph showing variation of apparent viscosity versus time for Würth Cut & Cool](image)

**Figure 4.** Variation of the apparent viscosity versus time for Rhenus RL 3 DW

![Graph showing variation of apparent viscosity versus time for Rhenus RL 3 DW](image)

Table 2 presents the effective values of the soaking time for each one of four fluids. These values are necessary for the second type of test – determination of the rheological model, because they serve as input parameters for test designing.

| INSA Rezinol C-22 | INSA Emulsol | Würth Cut & Cool, Cutting Oil | Rhenus RL 3 DW |
|-------------------|--------------|-------------------------------|----------------|
| Soaking time, sec.| 40           | 50                            | 30             | 30             |

The experimental test regarding the determination of the rheological parameters consists of a load from the 200 s\(^{-1}\) to 2000 s\(^{-1}\) shear rate gradient, followed by an unload in order to highlight the thixotropy of the lubricant - "shear memory". The test is repeated three times for each cutting fluid, at a temperature of 20 °C, and the duration of homogenization (soaking time) of the sample at a certain shear rate was given by the values from Table 2. The comparative rheograms (Figure 5) are obtained by plotting shear stress as a function of the shear rate, as an average of three points, using the software Capcalc 32 specific for the viscometer.
The results regarding the variation of the apparent viscosity with temperature, using a “velocity imposed gradient” test, are presented in Figure 6.

### Figure 6. Variation of the apparent viscosity versus temperature for all four cutting fluids, at a constant shear rate gradient of 1000 s⁻¹

4. Discussions

The experimental results concerning the determination of the rheological parameters, obtained in the hypothesis of validity of power law model (eq. 1), are presented in Table 3. These results are also synthesized in Figures 7 and 8.

### Table 3. Rheological parameters according to power law model, for all four cutting fluids

| Cutting fluid                  | Consistency index, Pa·sⁿ | Flow index | Correlation coefficient, % |
|-------------------------------|---------------------------|------------|-----------------------------|
| INSA Rezinol C-22             | 1.393                     | 0.461      | 72.1                        |
| INSA Emulsol                  | 0.344                     | 0.703      | 92.4                        |
| Würth Cut & Cool, Cutting Oil | 0.278                     | 0.815      | 96.3                        |
| Rhenus RL 3 DW                | 0.313                     | 0.842      | 98.7                        |
Figure 7. Variation of the consistency index, for all cutting fluids

Figure 8. Variation of the flow index, for all cutting fluids

Analysing the rheological results (Figure 5), it can observe that INSA Rezinol C-22 and INSA Emulsol cutting fluids have a pronounced thixotropic behaviour, which is due to the inhomogeneity of the internal structure. For the other two cutting fluids, Würth Cut & Cool, Cutting Oil and Rhenus RL 3 DW, the thixotropic behaviour is almost absent, which denotes a very stable and homogeneous structure.

Regarding the rheological model, from Table 3 results that power law model is very appropriate for INSA Emulsol, Würth Cut & Cool, Cutting Oil and Rhenus RL 3 DW cutting fluids, because for these three fluids the correlation coefficient is very high, over 92%. For INSA Rezinol C-22 cutting fluid the correlation coefficient is very reduced, due to the pronounced thixotropy of the fluid, so the power law model cannot be considered.

From the point of view of the consistency index, it can be observed that there is approximate no difference between cutting fluids INSA Emulsol, Würth Cut & Cool, Cutting Oil and Rhenus RL 3 DW. Regarding the flow index, this parameter has different values according to the type of cutting fluid, in the range of 0.45 … 0.85.

The experimental results concerning the variation of the apparent viscosity versus temperature, according to the Reynolds model (eq. 2), are presented in Table 4 and Figures 9 and 10.
Table 4. Rheological parameters for Reynolds model

| Cutting fluid                  | $\mu_{50}$, Pa·s | $m$, °C$^{-1}$ | Correlation coefficient, % |
|-------------------------------|------------------|----------------|-----------------------------|
| INSA Rezinol C-22             | 0.005            | -0.0715        | 89.2                        |
| INSA Emulsol                  | 0.012            | -0.0571        | 97.4                        |
| Würth Cut & Cool, Cutting Oil | 0.031            | -0.0253        | 95.0                        |
| Rhenus RL 3 DW                | 0.018            | -0.0634        | 98.6                        |

Figure 9. Variation of the apparent viscosity at 50 °C, for all cutting fluids

Figure 10. Variation of the temperature parameter, for all cutting fluids

Analysing the thermal results (Figure 6 and Table 4), it can observe that Würth Cut & Cool, Cutting Oil and Rhenus RL 3 DW cutting fluids are more stable on the whole range of temperatures than INSA Rezinol C-22 and INSA Emulsol cutting fluids. The apparent viscosity of Rhenus RL 3 DW is greater than for Würth Cut & Cool, Cutting Oil for temperatures between 20 °C and 32 °C. If the temperature is greater than 32 °C, Würth Cut & Cool, Cutting Oil has a greater apparent viscosity than Rhenus RL 3 DW.
Another interesting observation is the fact that the variation of the apparent viscosity for Würth Cut & Cool, Cutting Oil is less affected by the increasing of the temperature than for Rhenus RL 3 DW. This means that the viscosity index of Würth Cut & Cool, Cutting Oil is greater than that of Rhenus RL 3 DW, which is an important quality of a cutting fluid.

5. Conclusions
In this paper was performed the study of the rheological properties on a range of temperatures for four different cutting fluids: INSA Rezinol C-22, INSA Emulsol, Würth Cut & Cool, Cutting Oil and Rhenus RL 3 DW. It results that INSA Rezinol C-22 and INSA Emulsol cutting fluids show very important thixotropic behavior, which means that they have reduced stability during functioning and they are less homogeneous compared to Würth Cut & Cool, Cutting Oil and Rhenus RL 3 DW. Also, the apparent viscosity of INSA Rezinol C-22 and INSA Emulsol cutting fluids is very small, so from rheological point of view, it is recommended to use them in common cutting processes, without intense cutting regimes.

Würth Cut & Cool, Cutting Oil and Rhenus RL 3 DW cutting fluids are much more stable and homogeneous and have almost no hysteresis or thixotropy. They are recommended, from rheological point of view, to be used for intensive cutting processes, with high surface quality requirements. If the local temperature during the cutting process is low (20 °C … 40 °C), Rhenus RL 3 DW cutting fluid is recommended, because it has a greater viscosity than Würth Cut & Cool, Cutting Oil. In the case when the local temperature during the cutting process has important variation, from the ambient temperature to high values, Würth Cut & Cool, Cutting Oil cutting fluid is recommended, because its apparent viscosity decrease less with temperature and it is more stable than that of the other studied fluids.

6. References
[1] S Kalpakjian, K S Vijai Sekar and S R Schmid 2014 Manufacturing engineering and technology Pearson
[2] W Grzesik 2008 Advanced machining processes of metallic materials: theory, modelling and applications Elsevier
[3] N Gopikrishna, M S Chander and M Srikiiran 2016 Determining the Influence of Cutting Fluid on Surface Roughness during Machining of EN24 and EN8 steel by using CNC Milling Machine Journal for Research| Volume 1(11)
[4] E Kuram, B Ozelik, E Demirbas and E Sik 2010 Effects of the cutting fluid types and cutting parameters on surface roughness and thrust force Proceedings of the World Congress on Engineering 2 pp 978-988
[5] S Boran and A Tamas 2014 Rheological behavior of castor oil mixed with different pyromellitic esters Journal of the Serbian Chemical Society 79(2) pp 241-251
[6] D R Brewer, J M Franco and L A Garcia-Zapateiro 2016 Rheological properties of oil-in-water emulsions prepared with oil and protein isolates from sesame (Sesamum indicum) Food Science and Technology 36(1) pp 64-69
[7] E D S Santos, A P D P Camargo, E A D Faria, F A F D Oliveira Junior, S M Alves and E L D Barros Neto 2017 The Lubricity Analysis of Cutting Fluid Emulsions Materials Research 20 pp 644-650
[8] N J Alderman, D Ram Babu, T L Hughes and G C Maitland 1988 The rheological properties of water-based drilling fluids Proceedings of the Xth International Congress on Rheology, Sydney 1 pp 140-142
[9] D Dichev, H Koev, D Diakov, N Panchev, R Miteva and H Nikolova 2017 Automated System for Calibrating Instruments Measuring Parameters of Moving Objects Proceedings of 59th International Symposium ELMAR pp 219-224
[10] *** http://insa-motoroils.bg/INSA_RESINOL_C22_18L
[11] *** http://insa-motoroils.bg/other-products/EMULSOL/INSA_EMULSOL_10_L
[12] *** http://pim.wurth.ca/Technical/SDS_893.050004.PDF
[13] *** http://www.pingyiao.com/en/rhenus/rh8/r.rhenus%20RL%203%20DW.htm