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1 **Seals based on magnetic fluids for high precision spindles of**
2 **machine tools**

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9
10 **Abstract**

11 *The research work reported in this paper is focused on the use of magnetic fluids as*
12 *active elements in seals for improving sealing capacity and minimizing friction torque,*
13 *with application to the spindles of high precision machine tools. The prototype design*
14 *was optimized following numerical computation of the magnetic field in the rings of the*
15 *seal. Two magnetic fluids were analysed for their use in the seals: a ferrofluid and*
16 *magnetorheological fluid. The sealing capacity of the MRF based seals was higher than*
17 *45kPa per ring, but the friction of the seal in the bearing was 8 N·m, too large for the*
18 *use in precision spindles of machine tools. The ferrofluid seal achieved sealing capacity*
19 *around 9kPa per ring, good enough to be used in the spindles of machine tools, with a*
20 *friction 0.25 N·m. The feasibility of using ferrofluids for developing high performance*
21 *seals for high precision spindles and the validity of the simulation models has been*
22 *demonstrated experimentally.*

23 **Keywords**

24 Magnetic fluids, ferrofluids, magnetorheological fluids, magnetic fluid sealing,
25 machine tool spindle.

26 1. INTRODUCTION

27 The introduction is divided in three sections, 1) a brief introduction to classic seals
28 and labyrinths for high precision spindles in machine tools, 2) behavior of magnetic
29 fluids and their technological applications, and 3) seals for spindles and bearing houses
30 based on magnetic fluids.

31 *1.1. Seals and labyrinths for high precision machine tools*

32 High precision spindles of machine tools, as used in grinding machines, usually
33 implement hydrostatic bearings in their main shafts (wheelhead, workhead or tailstock)
34 in order to ensure the highest quality and accuracy of the grinded parts, since
35 hydrostatic lubrication provides best performance in terms of positioning resolution,
36 damping capacity and motion smoothness [1]. Hydrostatic lubrication requires handling
37 pressurized oil within the machine, fed through a manifold into the bearing and back
38 into the tank, and the sealing of the whole system is a critical issue in the reliability of
39 the bearings [2].

40 The sealing of the bearing housing must be ensured whether the shaft is at rest or
41 rotating at nominal velocity, avoiding the contamination of the lubricant oil with the
42 cutting fluid, chips from machining, abrasive micro grains from grinding, and any other
43 potential contaminant within the machine tool. A wide review of available sealing
44 technologies was given by Müller and Nau in their book about the principles and
45 applications of fluid sealings [3].

46 One of the most active fields in the study of fluid seals is turbomachinery and
47 rotordynamics, focused on energy applications [4]. CFD studies were carried out to
48 analyse the force perturbation in the system, key issue to ensure fluid stability [5], and

49 those forces were also studied from the tribology point of view, where the forces are
50 reduced with pattern based surface microtexturing [6].

51 In the particular case of hydrostatic journal bearings lubricated with low viscosity
52 fluids, as in the lubrication of very high speed bearings sealing (i.e. CBN grinding
53 applications), it is very important to avoid leakage in the spindle. An extreme case due
54 to very low viscosity is the water based hydrostatic lubrication, as presented in [7].

55 Therefore, high sealing capacity and low friction force are the main performance
56 criteria for bearing seals. A solution based on magnetic fluids is proposed in this work.

57 ***1.2. Magnetic fluids, behaviour and applications***

58 Magnetic fluids are materials whose physical properties can be tuned by external
59 magnetic fields. Two main groups can be distinguished: ferrofluids and
60 magnetorheological fluids, MRF hereinafter. All magnetic fluids are formed by: carrier
61 fluid, additives to improve fluid stability, and magnetic particles. The size of the
62 magnetic particles, nanometric or micrometric, categorize them as ferrofluids or MRF
63 respectively. Ferrofluids are composed by nanometric (5-12nm diameter) particles, and
64 due to their size and energy balance (gravity < particle's thermal energy) the colloidal
65 suspension is stable in time. These particles are usually formed by iron or cobalt oxides,
66 covered with surfactants (like oleic acid) to avoid aggregation and final settling of the
67 particles. The most relevant reference in ferrofluids behaviour is a book by Rosenweig
68 (Rosenweig 1985), while a wide overview of the synthesis, characterization and
69 application of ferrofluids is presented in the compilation book by Odenbach [8].

70 The MRF are similar to ferrofluids but the magnetic particles are in the range of
71 micrometres, within 1 to 10 μ m, mainly made of carbonyl iron powder (CIP). They are

72 strongly unstable, settling of the particles is inevitable, but to avoid agglomeration and
73 to have a quick restoration of homogeneous MRF, the fluids include several additives,
74 usually kept confidential by commercial manufacturers.

75 Engineering applications of magnetic fluids range from active dampers, bearings
76 lubrication, hydraulic actuators to sealing of spindles [9]. In this research paper the
77 application to spindle seals will be analysed.

78 ***1.3. Face sealing based on magnetic fluids for machine tool spindles***

79 Magnetic fluids based seals were presented in the early 1980's where the basic
80 design parameters were established [10], such as the gap, size and the distance between
81 the rings. Simulations of those seals with non-linear models to consider the real
82 magnetization curve were discussed [11]. Looking for a better response in the
83 ferrofluids based seals, the centrifugal force was analysed in the case of high speed
84 systems [12], computing Reynolds equations together with the magnetic pressure to
85 consider high speed effects in the fluid.

86 A theoretical study of the sealing capacity of large seals was presented , including
87 centrifugal, gravitational and magnetic effect [13]. The main parameters to be
88 considered in the design were identified: Width of the rings, distance between them and
89 the effect of the gap and magnetic fluid volume. Other papers went further in the
90 theoretical study and analysis of ferrofluids based seals with free surface consideration (
91 [14]–[16]) discussing the self-sealing capacity of ferrofluids for applications such as
92 bearings.

93 The use of MRFs for sealing applications was considered by Vardarajan [17], where
94 the pressurization and the wear generated in the rings by the magnetic fluids with
95 strong yield stress was studied.

96 Finally a deep theoretical and experimental study of ferrofluids based seal was
97 presented in [18], discussing the maximum pressure achieved by the rings and the
98 recovery pressure after the fluid seal was broken, once the maximum pressure was
99 overcome.

100 This research work was focused in the use of magnetic fluid seals for the application
101 of high precision spindles in machine tools. The work was based on the models
102 presented in the literature, two commercial magnetic fluids that were characterized
103 experimentally in the research, and a final construction of a prototype that was used to
104 validate the seal in close to industrial conditions. A section view of a magnetic fluid
105 based seal is described below following the numeration of Figure 1:

106 1 Semi-shaft: Rotating shaft. Sealing rings (part 2) is assembled in the semi-shaft.

107 2 Sealing rings: Ferromagnetic part filled with magnetic fluid. Sealing rings are
108 machined in this part, and magnetic fluid seals are formed in the edges. Different ring
109 edge shapes are studied in the research.

110 3 Magnetic poles: Steel made rings to conduct magnetic field from the magnets (part
111 4) to the seal rings (part 2).

112 4 Magnets: Strontium ferrite made permanent magnets

113 5 Seal body: Main structure of the seal made in aluminium. Air pressure is achieved
114 into the body, air inlet (orifice 7).

115 6 Assembly cover: Cover ring to assemble the sealing prototype.

116 7 Air inlet: Compressed air inlet to the main body. Interior volume of *seal body* (5) is
117 pressurized with compressed air, introduced by *air inlet* (7), with sealing capacity given
118 by *sealing rings* (2).

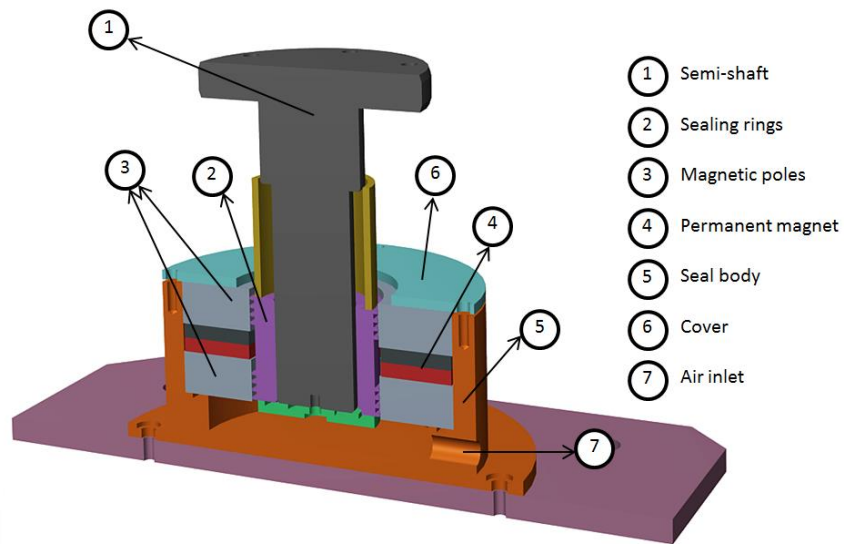


Figure 1 Magnetic fluids sealing, section view with parts description.

119 In Section 2, the experimental characterization of the magnetic fluids used in the
120 research is performed; Section 3 deals with the modelling of the seals; Section 4
121 presents the test bench and the prototype for experimental validation; Section 5
122 summarizes the results and finally in Section 6 the main conclusions are outlined.

123

124 2. CHARACTERIZATION OF FERROFLUIDS AND 125 MAGNETORHEOLOGICAL FLUIDS

126 Most magnetic fluid based seals found in the literature use ferrofluids, but there are
127 also some solutions based on MRF. In order to analyse both alternatives, the following
128 commercial magnetic fluids were used in this research work: a ferrofluid from
129 FERROTEC® APG s10n and a magnetorheological fluid from LORD® Corp. model
130 MRF 122-2ED. Data given by manufacturers are usually approximate values, both for
131 magnetic and rheological behaviour, and therefore a detailed characterization of these
132 fluids was performed, looking at the magnetic response and the rheological properties
133 under the magnetic field and the temperature. The characterization of those fluids was
134 essential to have an accurate computation of fluids magnetization and sealing capacity
135 of the rings, as it is presented in section 3.

136 The magnetic characterization was performed with a Magnet-Physik Permagraph L
137 magnetometer and the electromagnet EP-3, from which the magnetic field strength, flux
138 density (Figure 2), and magnetic fluid permeability were obtained (Figure 3). The
139 magnetorheological characterization was carried out with a Thermo HAAKE
140 RheoStress RS150, with a magnetic module and a thermally controlled plate.

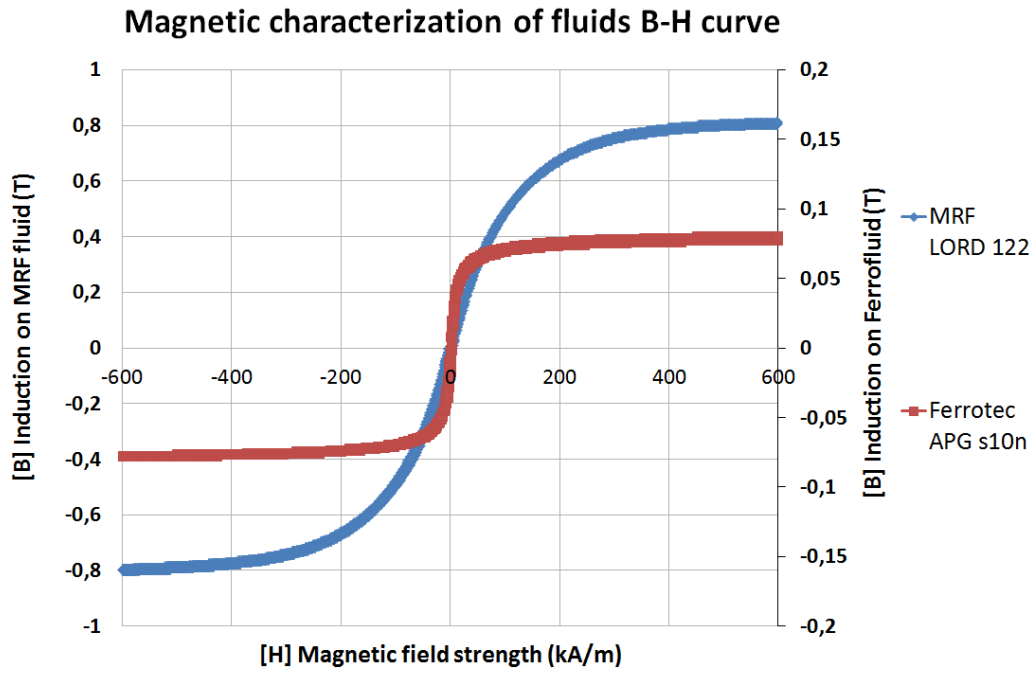


Figure 2 Magnetic characterization of the magnetic fluids: flux density and magnetic field strength.

141

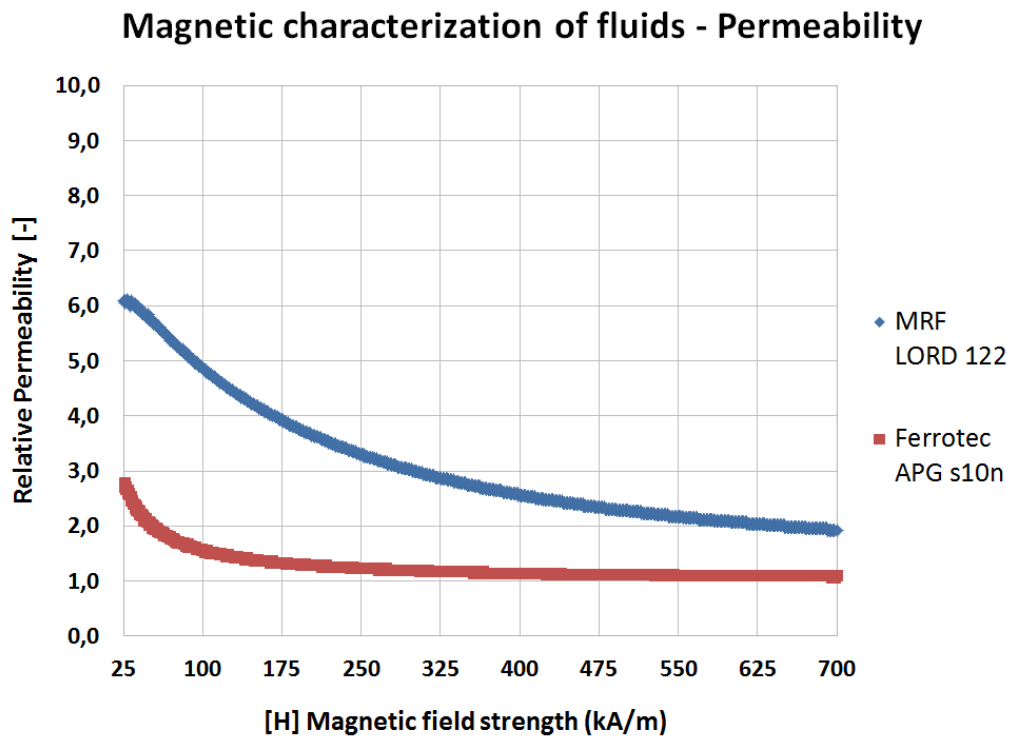


Figure 3 Magnetic characterization of the magnetic fluids: relative permeability.

142

143 Rheological analysis of magnetorheological fluid has been carried out following
144 Bingham model, Equation (1). Total shear stress of the fluid (τ) is the sum of yield
145 stress (τ_0), which is in function of magnetic field (H), and the product of base viscosity
146 of the fluid (K) and shear rate ($\dot{\gamma}$). Experimental values for MRF characterization are
147 shown in Figure 4:

$$\tau = \tau_0(H) + K \cdot |\dot{\gamma}| \quad (1)$$

148

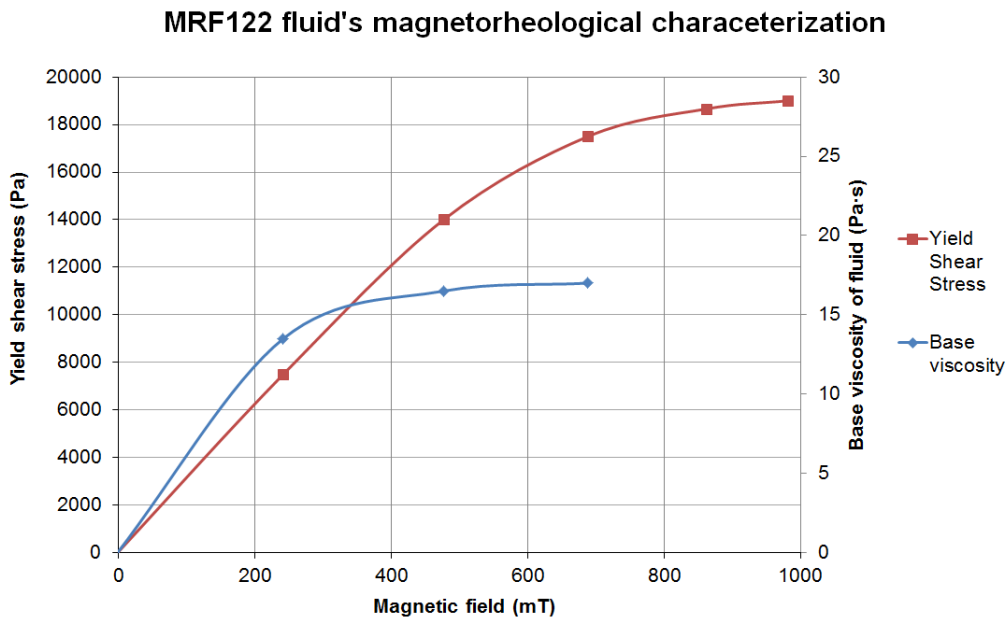


Figure 4 Rheological characterization of MRF: shear stress and base viscosity.

149 Ferrofluids rheology was characterized following tuneable Newtonian fluid (2),
150 where fluid dynamic viscosity (η) it is in function of temperature (T) and applied
151 magnetic field (H).

$$\eta = \eta_m(H, T) \quad (2)$$

152 The values for ferrofluids characterization are shown in Figure 5, where magnetic
153 tests were done at room temperature and ferrofluid temperature characterization without
154 magnetic field:

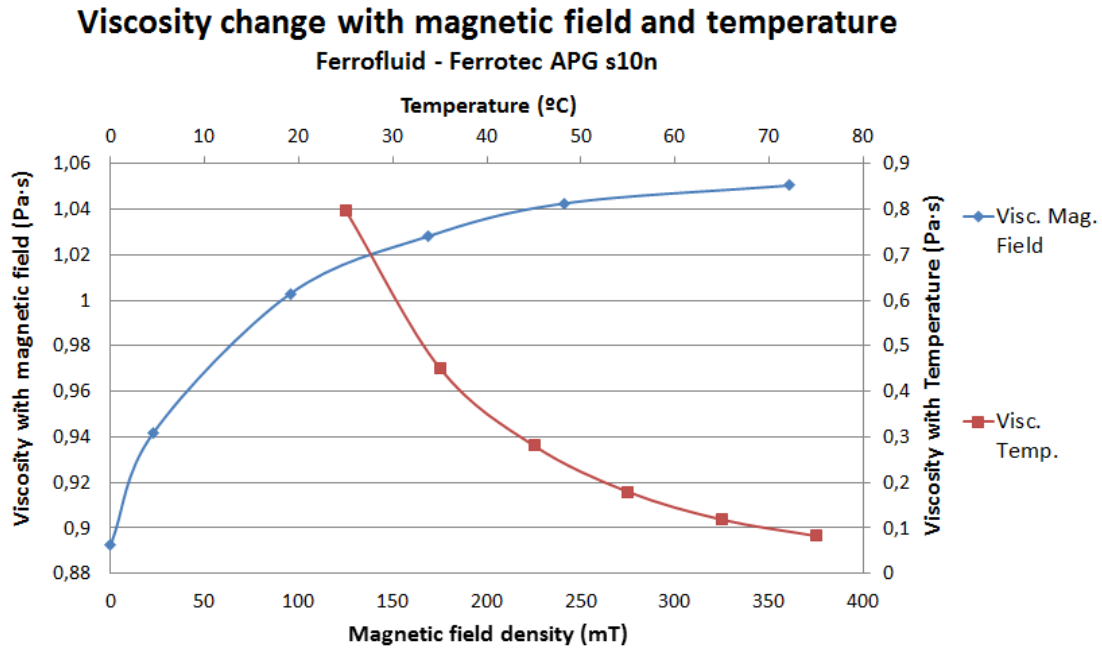


Figure 5 Rheological characterization of ferrofluid: viscosity and temperature.

155

156 3. DESIGN AND MODELLING OF SEALING WITH MAGNETIC FLUIDS

157 A model of the magnetic fluid based seal was developed to support the prototype
158 design process (see Section 4), and they were later validated with the experimental
159 evaluation (see Section 5). The model considers the magnetic field in the seal and the
160 pressure in the fluid.

161 Magnetic simulations were performed to determine the magnetic field strength and
162 flux density with the FEMM finite element software. Then, fluid pressure was simulated
163 based on the model presented by Park, Kim, Hahn and Lee, [11], solved by integration

164 in in-house software. Those results are based on the experimental values of magnetic
165 fluids characterization, section 2.

166 *3.1. Design of seals with magnetic fluids*

167 The ring of magnetic fluids based seal, as presented in Figure 1 (part 2), is
168 manufactured by different groves and edges. In this section the shape of these ring
169 edges was discussed and designed. Four different designs were studied for the ring,
170 which are presented in Fig.6: a) plain seal, b) square rings, c) saw shape and d)
171 triangular shape. In all those cases the gap, overall geometry and magnet were the same,
172 so only the effect of rings shape was analysed.

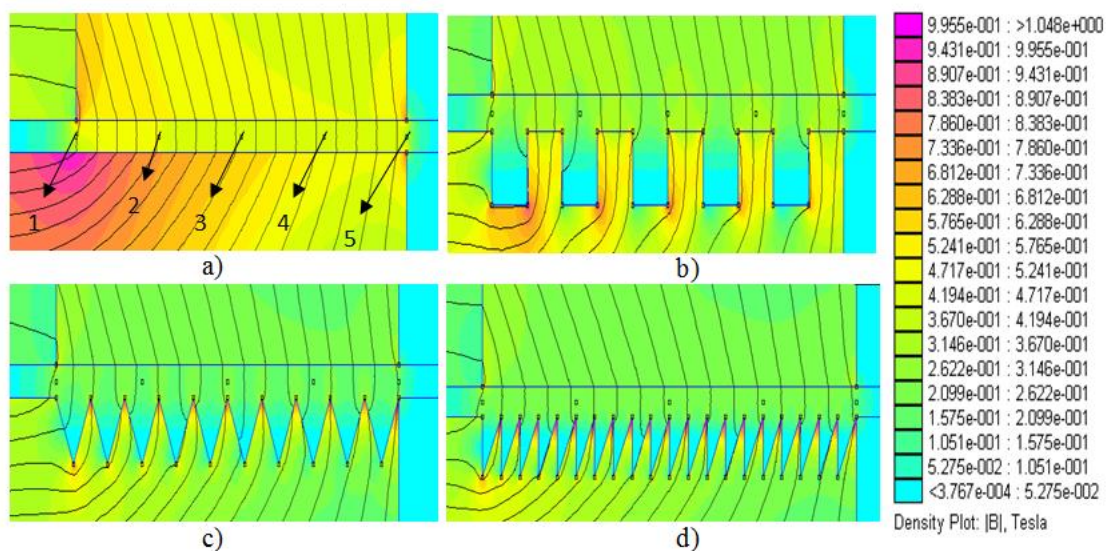


Figure 6 Magnetic field distribution for different rings shape studied in the paper : a) plain seal, b) square rings, c) saw shape and d) triangular rings.

173 The magnetic flux density was simulated in the fluid for these four different shapes,
174 where the field is generated by a permanent magnet. The simulations were carried out
175 considering axis-symmetry assumption (cylindrical structure like shown in the section
176 view of Figure 1), and magnetic model of the seal is depicted in Figure 7:

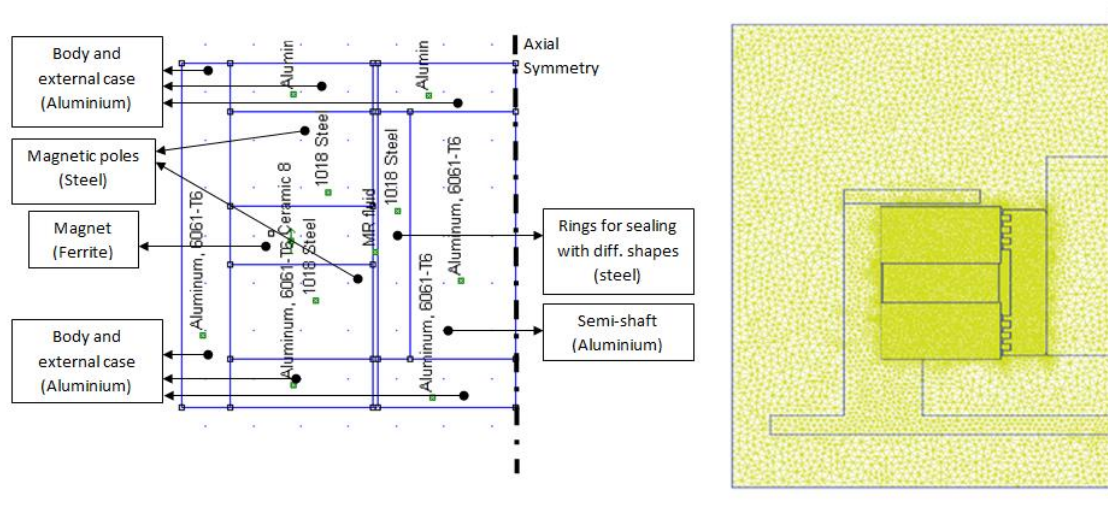


Figure 7 Magnetic fluid seal magnetic model with parts description and detail of mesh.

177 Magnetic field simulations were carried out with the open source software FEMM
 178 (<http://www.femm.info>). The minimum, maximum and average values of the magnetic
 179 field and the magnetization in the fluid for different rings shape (a, b, c and d), and in
 180 five control points (shown in Figure 6-a) are summarized in Table 1.

Table 1 Magnetic flux density (B -Tesla) values in the fluid.

<i>Control points in the model</i>						B_{\min}	B_{\max}	B_{ave}
<i>Shape</i>	1	2	3	4	5			
Plain	0.4167	0.4719	0.4661	0.4620	0.3443	0.3433	0.4760	0.4167
Square	0.4481	0.3770	0.4641	0.5026	0.3832	0.3591	0.5105	0.4398
Saw	0.4885	0.4206	0.4603	0.4127	0.3534	0.3534	0.4939	0.4236
Triang.	0.4620	0.4508	0.4459	0.4424	0.3486	0.3486	0.4729	0.4107

181 Considering the higher magnetic flux density achieved (from 0.359T to 0.510T),
 182 square rings were selected for the development of a magnetic fluid seal prototype.

183 **3.2. Sealing capacity of magnetic fluid**

184 The final step in the modelling of magnetic fluids seals was to determine the sealing
185 capacity (pressure difference withstood by the rings) that they could achieve. In the case
186 of MRF based seals, the sealing capacity is defined by the yield stress (function of
187 magnetic field), which was experimentally described in Section 2 by Equation (1) and
188 experimental results summarized in Figure 4.

189 For ferrofluids, the pressure achievable by each ring of the seal was determined
190 following Equation (4),[18].

$$p_m = \max \left[\int_{H_1}^{H_2} \mu_0 M dH \right] \quad (3)$$

$$p_m \approx \max [\mu_0 M_s (H_2 - H_1)] \quad (4)$$

191 Where (p_m) is the pressure in the fluid due to the magnetic field, (μ_0) is the
192 permeability in the vacuum, (M_s) the saturation magnetization of the fluid and (H) the
193 magnetic field intensity, H_1 and H_2 are the values of the magnetic field intensity on both
194 free ferrofluid surfaces within one sealing stage.

195 In Equation (3), M is function of H , as shown in Figure 8. If the variation of
196 magnetization with field is neglected at high fields within the bearing seal, and the
197 magnetization is put equal to saturation magnetization (M_s), than one can use Equation
198 (4). The maximum pressure corresponds to the maximal difference of fields H_1 and H_2
199 and is calculated imposing a certain volume of the ferrofluid ring and displacing this
200 volume along the shaft direction by small steps.

201 The model was fed by the magnetic characterization of the ferrofluid (section 2) and
202 the magnetic field simulation carried out in section 3.1. Finally, the sealing capacity is

203 determined calculating the integral in Eq. (3) as presented graphically in Figure 8, and
 204 finding its maximum for a given volume of the ferrofluid contained in one sealing stage:

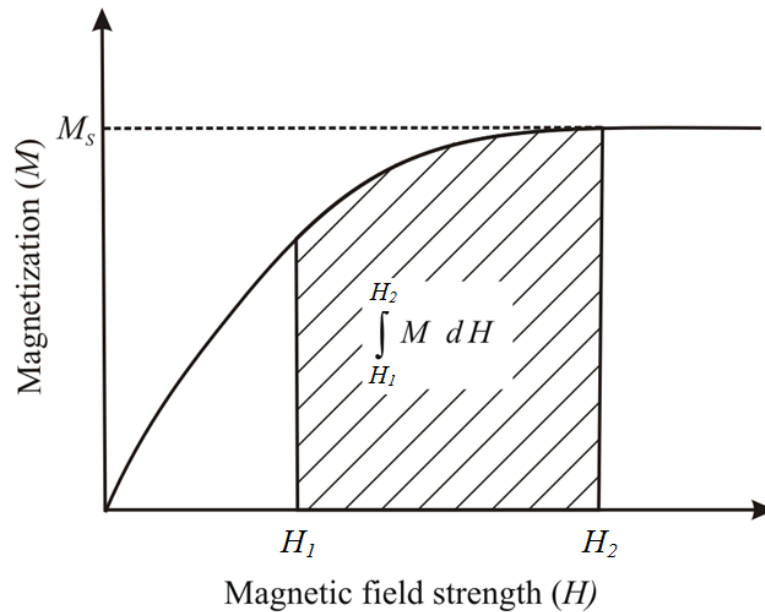


Figure 8 Fluid magnetization and magnetic field strength, pressure computation (Equation (3)).

205 The nature and therefore the response of MRF are different from ferrofluids so the
 206 calculations were based on the yield stress in the rings and the average pressure
 207 achievable by the seal.

208 Once the yield stress was obtained (from magnetic simulations and fluids
 209 experimental analysis), the pressure in the ring was achieved with the computation of
 210 Equation (5):

$$F_m = 2\pi \left(R_i \int \tau_0(H_i) dz + R_e \int \tau_0(H_e) dz \right) \quad (5)$$

211 Where R_i and R_e are the shaft radius and the internal radius of the magnetic poles; H_i
 212 and H_e – the magnetic field intensity on the shaft and magnetic pole surfaces. If the field
 213 H does not change significantly across the gap of the seal ($H_i \approx H_e \approx H$), Equation (6) is
 214 applied:

$$F_m = 2\pi(R_i + R_e) \int \tau_0(H) dz \quad (6)$$

215 Finally, the fluid magnetic force (F_m) was divided by the annular area (A_r) of the ring
 216 and gap to get the sealing pressure (p_m), or sealing capacity, as presented in Equation (7).

$$p_m = F_m / A_r \quad (7)$$

217 4. DESING OF SEAL PROTOTYPE AND TEST BENCH

218 The experimental analysis was carried on a test bench (see Figure 9) where the
 219 prototype of magnetic fluid seal was analysed under variable operating conditions
 220 (rotational speed and pressurized air).

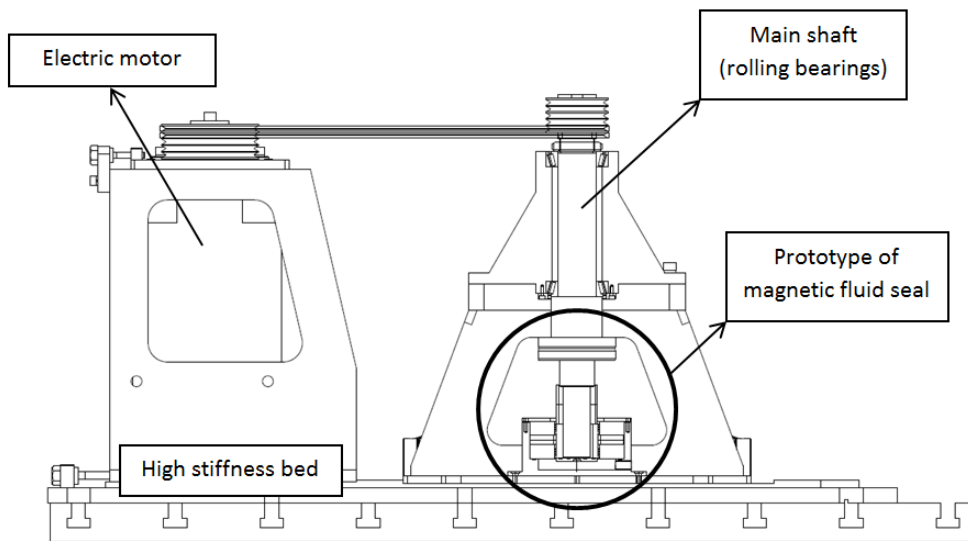


Figure 9 Test bench with the prototype of magnetic fluid based seal.

221 The magnetic fluid based seal prototype was located in the semi-shaft, which can
 222 rotate up to 3000 rpm with a run-out below 5 μ m. The pressurization of the rings, tested
 223 with an air inlet in the body, was evaluated in function of the rotational speed.

224 Based on the results from magnetic calculations, a prototype of magnetic fluid seal
 225 was designed. This prototype is analysed in the test bench presented in Figure 9,
 226 assembled in the area marked with a circle. In Figure 10 a section view of the prototype
 227 with main dimensions is presented.

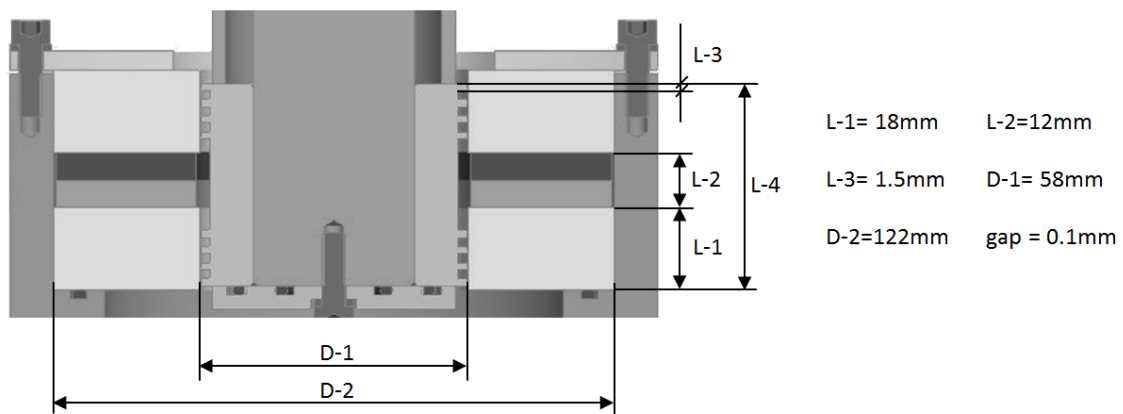


Figure 10 Magnetic fluids sealing, main dimensions

228 The magnetic field was created with a strontium ferrite permanent magnet located in
 229 the sealing body and having an axial polarization (120mm external diameter, 60mm
 230 internal diameter and 12mm thickness). The average magnetic field strength of the
 231 magnet (given by manufacturer) was around 260kA/m, when flux density achieved is
 232 around 0.4T. This magnetic field was guided with two annular poles towards the rings
 233 of the sealing, 8 rings in this case as shown in Figure 10. The magnetic field in the rings
 234 and a photo of a disassembled seal are shown in Figure 11.

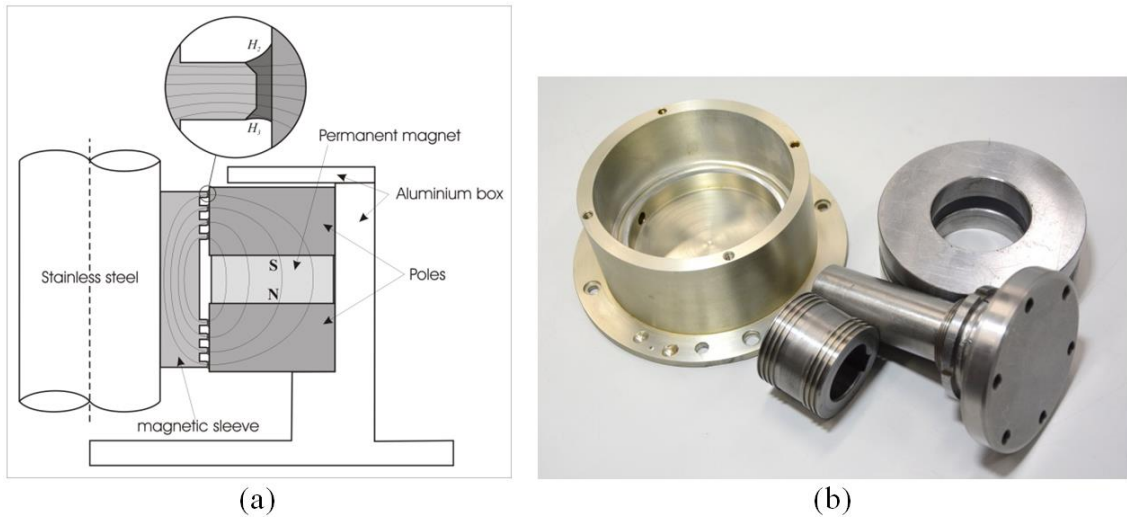


Figure 11 Magnetic fluids sealing, working principle (a) and manufactured set-up (b)

235

236 5. RESULTS AND DISCUSSION

237 The experimental tests to analyse the behaviour of magnetic fluids based seals are
 238 presented in this section. The section is structured in three parts: Analysis of the friction
 239 torque, sealing capacity of MRF and sealing capacity of ferrofluids.

240 5.1. Friction torque analyse

241 Friction torque was evaluated for two different magnetic fluids, FERROTEC APG
 242 s10n and LORD MRF122. In addition, two other magnetic fluids were tested: a dilution
 243 of 30% and 50% of MRF 122. Finally, a lubricant oil fluid (viscosity ISO-VG 46) and
 244 the torque without any fluid were also tested to determine friction of the kinematic
 245 chain. Results are shown in Figure 12 . The friction torque with MRF fluids, even under
 246 diluted concentration, is very high, between 2 and 8 N·m at 100rpm, too large to be
 247 used as sealing for spindles of machine tools. The torque with ferrofluid in the seal was

248 slightly higher than base friction, around 0.25N·m, at the same rotation speed of the
249 shaft eligible to be used in machine tool applications.

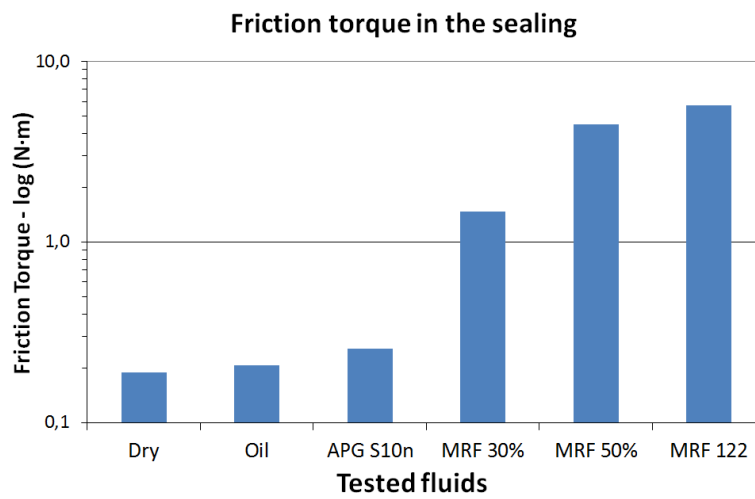


Figure 12 Friction torque in the sealing with different magnetic fluids at 100rpm.

250 5.2. MRF based sealing results

251 Tests were carried out to determine the sealing capacity of the system, evaluated as
252 the pressure difference that it can sustain. The experimental procedure was the same for
253 both magnetic fluids, MRF and ferrofluids (section 5.3), and it was the following the
254 scheme shown in the Figure 13: the sealing body was filled gradually with compressed
255 air, controlling the inlet air with a flow valve. The flow rate and pressure were measured
256 with a flowmeter and a pressure gauge, respectively. This set-up was used for the
257 experimental validation of the magnetic seals, and the characterization of sealing
258 capacity of the tested magnetic fluids.

259

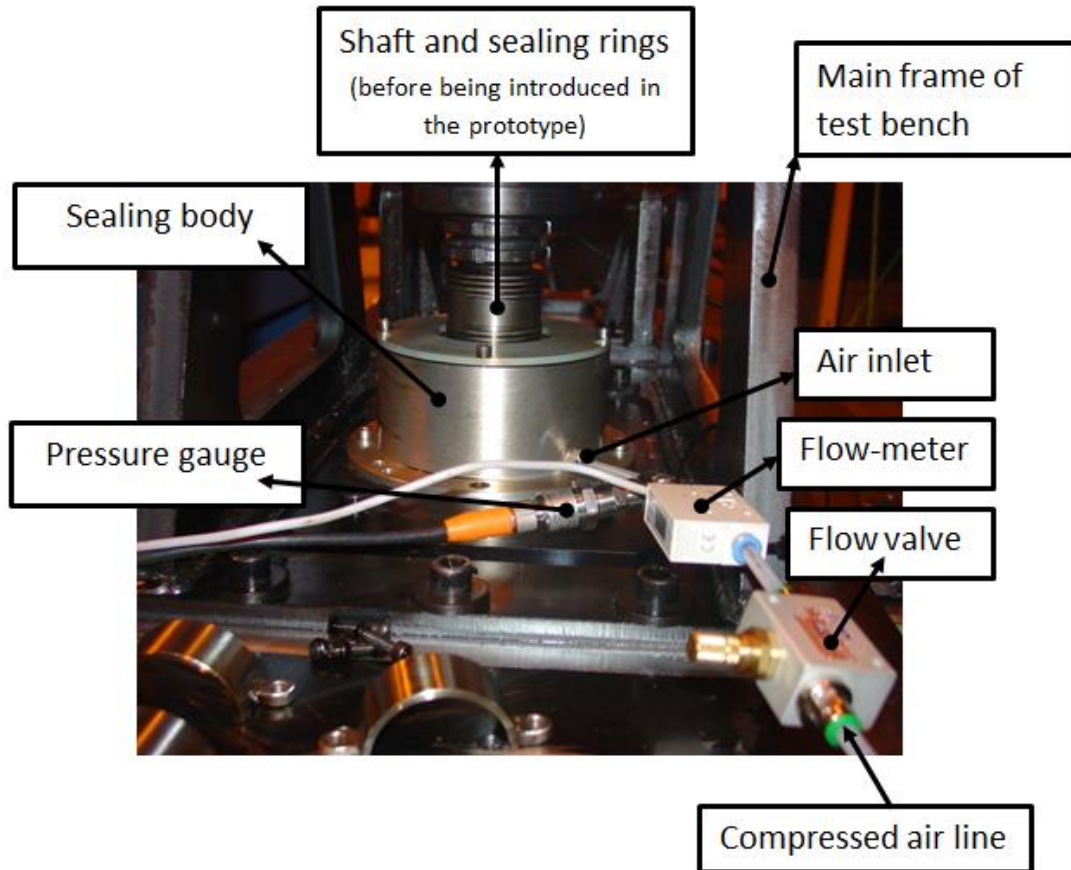


Figure 13 Friction torque in the sealing with different magnetic fluids.

260 Once the maximum pressure was reached two behaviours were shown: In the case of
 261 MRF the pressure stayed constant, and with the ferrofluids the magnetic seals broke
 262 (falling down the pressure) and the flowrate increased instantaneously. After a recovery
 263 time the seal was formed again and the air pressure increased again till the previous
 264 limit (maximum pressure) periodically.

265 The prototype was composed of eight sealing rings, therefore the sealing capacity of
 266 each ring, evaluated with the integration of equation (4) for ferrofluids and Equation
 267 **Erreur ! Source du renvoi introuvable.** and **Erreur ! Source du renvoi introuvable.**
 268 for MRF, it was multiplied by eight. The results from model and the experimental tests
 269 are summarized and compared in Table 2:

Table 2 MRF based seal, sealing capacity (Pa).

Sealing capacity (kPa)		MRF 122 (dilution 30%)		MRF 122	
		per ring	Seal	per ring	Seal
Calculated sealing capacity	Min	12.36	98.88	41.2	336.8
	Max	15.75	126.0	52.5	420.0
Experimental value in the seal (shaft at rest)		----	130.0	----	320.0

270 In the case of MRF the pressure for each ring goes from 41.2kPa to 52.5kPa in
 271 function of the magnetic field in the fluid, which as shown in Figure 6, is not constant
 272 over the ring. For the case of 30% dilution, assuming a proportional reduction of yield
 273 stress, and therefore the sealing capacity, the theoretical values go from 12.36kPa to
 274 15.75kPa. Summarizing, the theoretical sealing capacity of MRF for all system with
 275 eight rings was: 336.8Pa (3.3bar) to 420kPa (4.2bar), and for 30% diluted MRF:
 276 98.9kPa (0.99bar) and 126kPa (1.26bar).

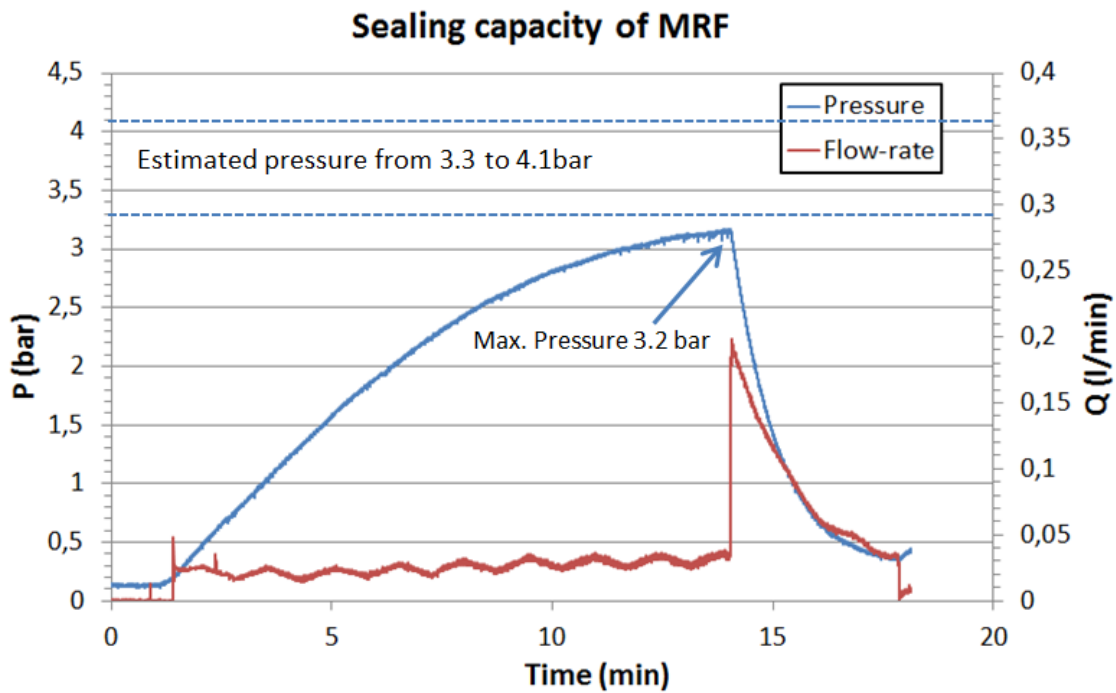


Figure 14 Seal capacity of the system with MRF.

277 As shown in the Figure 14, the pressure achieved within the tests was around 3.2bar
 278 slightly lower than the expected values, which go from 3.3 to 4.1bar following the
 279 simulations and calculations described above. Due to the high friction torque of MRF, a
 280 diluted fluid at 30% was analysed, where the results are shown in Figure 15. In this case
 281 the experimental value matches with expected pressure, from 0.99 to 0.126bar.

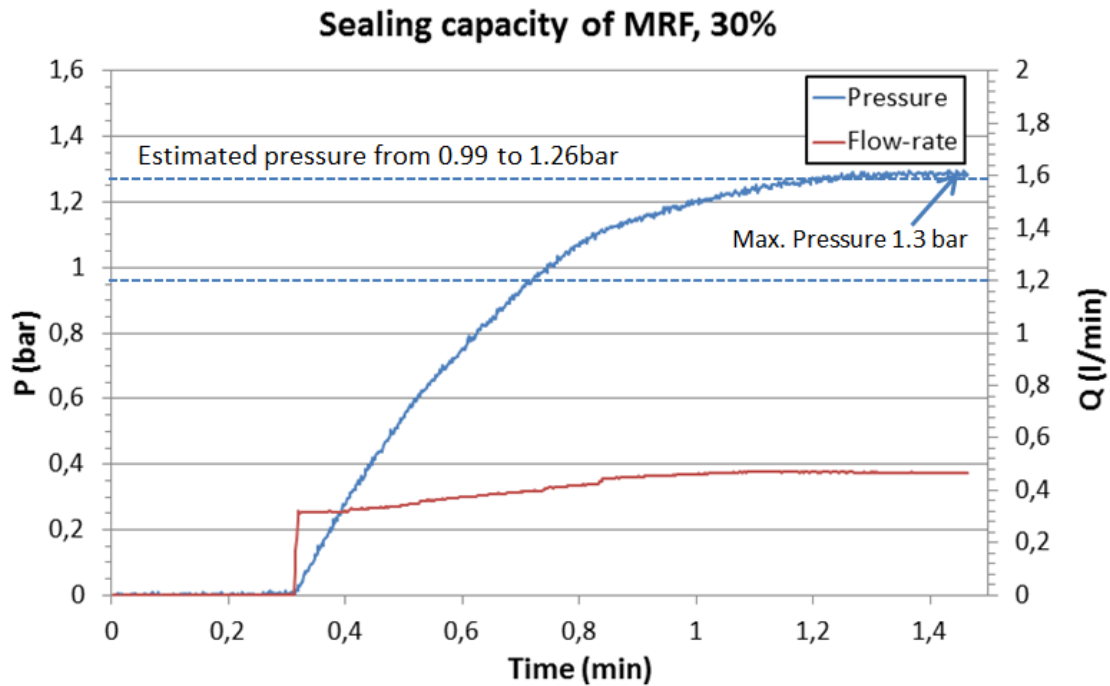


Figure 15 Seal capacity of the rings with MRF at 30% dilution.

282 Those results were obtained at rest because the pressure in the rings was the same for
 283 analysed rotational speed, up to 100rpm. Rupture and recovery pressure were not
 284 detected as in ferrofluid based seals, (see section 5.3).

285 MRF based seals have high sealing capacity, but the friction torque presented in the
 286 system is not compatible with machine tool spindle application.

287 **5.3. Ferrofluid based seals results**

288 In Figure 16 the pressure value estimated in each one of the ring filled with
 289 ferrofluids is shown, where as calculated the average pressure value was around 9kPa,
 290 which means a total pressure capacity (by eight), around 72kPa (0.72bar) in the
 291 prototype. The summary of results is presented in Table 3:

Table 3 Ferrofluid based seal, sealing capacity (Pa).

<i>Sealing capacity (kPa)</i>		Ferrofluid	
		<i>per ring</i>	<i>Seal</i>
Calculated sealing capacity		9	72
Experimental (at rest)	Max	----	70
	Recovery	----	48
Experimental (50r/min)	Max	----	68
	Recovery	----	58
Experimental (100r/min)	Max	----	60
	Recovery	----	58

292

293 *Recovery pressure*, as shown in Figure 17, was the pressure where the magnetic seals
 294 (after rupture at maximum pressure) got again pressurization, recovering sealing
 295 capacity. These values are a very good pressurization capacity to be used in machine
 296 tool's spindles, which together with the low friction torque in the shaft it could be
 297 considered as a good candidate for industrial application.

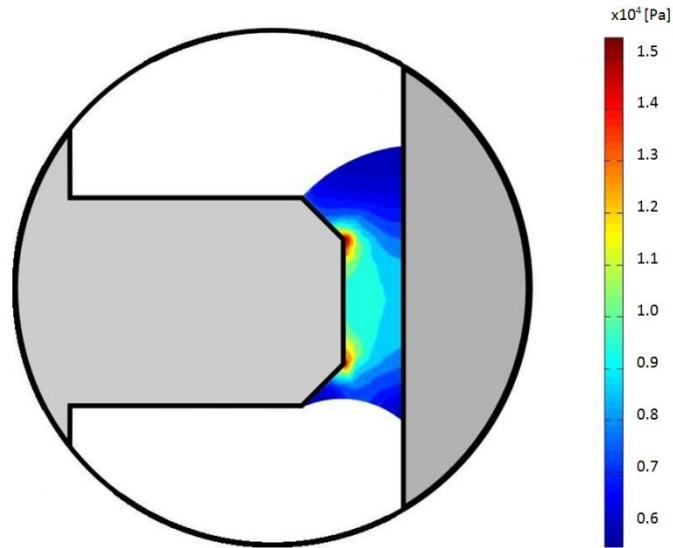


Figure 16 Sealing capacity of each ring with ferrofluid FERROTEC APG s10n.

298 In Figure 17, Figure 18 and Figure 19 the evolution of air pressure and flow rate for
 299 0 rpm, 50rpm and 100rpm respectively are shown.

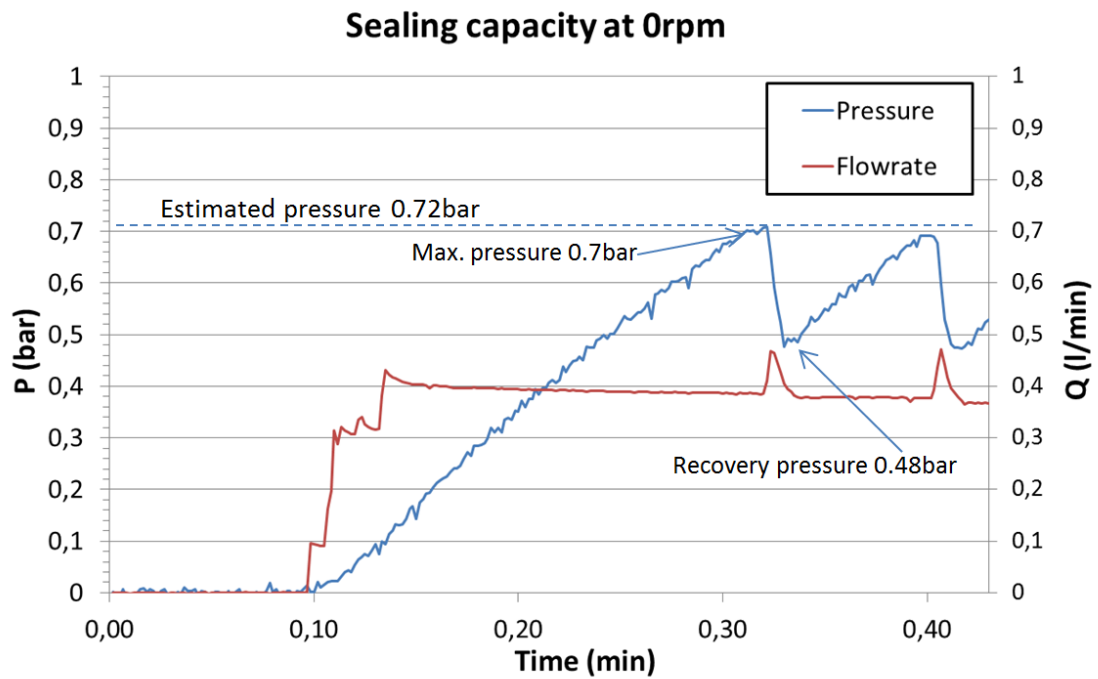


Figure 17 Sealing capacity at rest with FERROTEC APG s10n

Sealing capacity at 50rpm

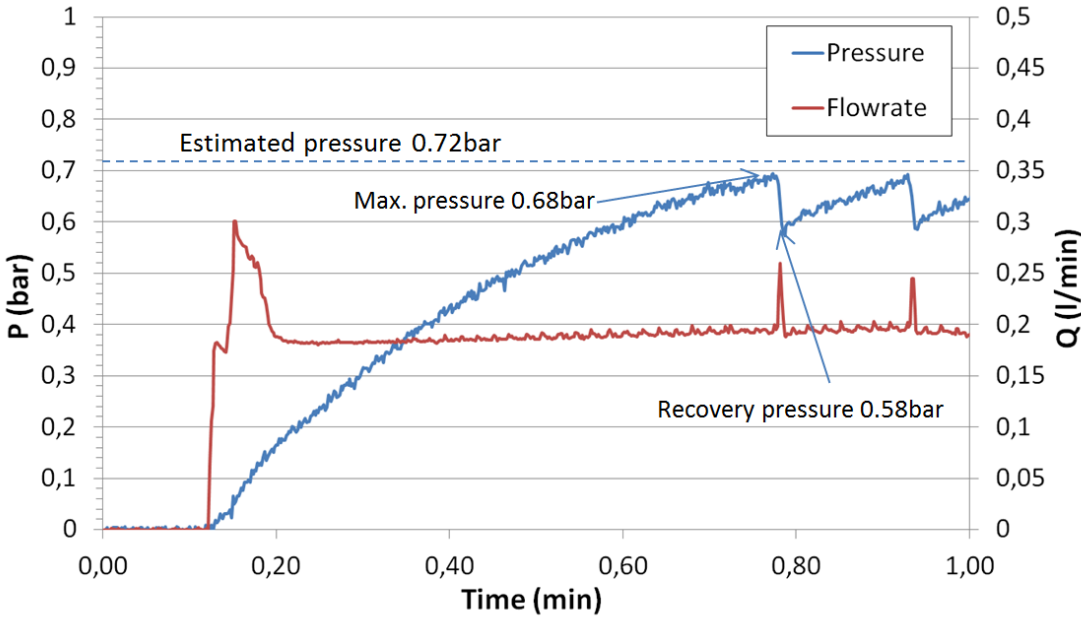


Figure 18 Sealing capacity at rest with FERROTEC APG s10n

Sealing capacity at 100rpm

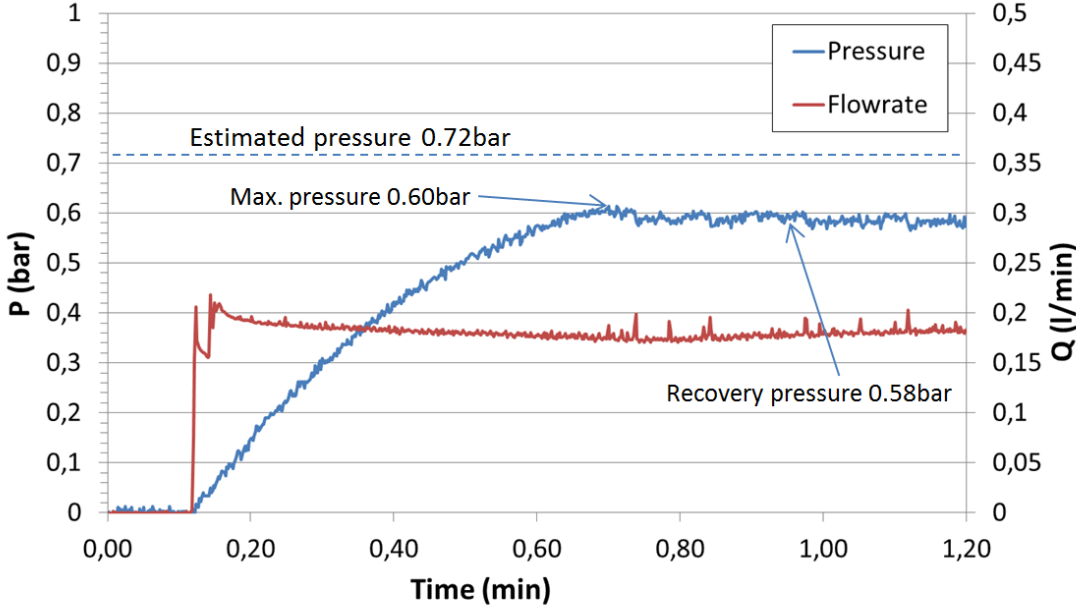


Figure 19 Sealing capacity measured in the test bench with FERROTEC APG s10n.

300 As shown in Figure 17, the maximum pressure of the sealing matched quite well
301 with the estimated value, around 72000Pa. When the shaft was rotating (see Figure 18),
302 the difference between maximum pressure and recovery pressure was reduced, and at
303 100r/min (see Figure 19), both pressures were almost equal, converging at a value
304 around 0.6bar. Above this rotational speed it was not noted variations in the results.

305 **6. CONCLUSIONS**

306 The use of magnetic fluids as active elements in seals was analysed in this research
307 work. A close to industrial application prototype has been developed, and the validity of
308 the simulation models and the final performance of the systems were demonstrated
309 experimentally.

- 310 • Two magnetic fluids (a ferrofluid and a MRF) were experimentally analysed,
311 obtaining deeper information about their behaviour than that offered by the
312 manufacturers. Such a detailed experimental characterization is highly
313 recommended for any studies in the field of magnetic fluids.
- 314 • MRF and ferrofluid based seal models were developed, simulating the
315 magnetic field and the sealing capacity measured in pressure per ring.
- 316 • The seal based on MRF showed very good sealing performance (over 3 bar)
317 but with an excessive friction torque (8Nm). Even diluted at 30%, sealing
318 was still good but the torque was too high for machine tool applications.
- 319 • The seal based on ferrofluids demonstrated a good enough sealing capacity
320 (0.9bar) and with a friction torque slightly higher than without the seal.
- 321 • The seal based on ferrofluids showed thus true potential for industrialization
322 in machine tool spindles.

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