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WEAR AND FRICTION BEHAVIOUR OF A LUBRICATED THERMOSET-PAIRING ON A BALL-ON-THREE-PLATES-TEST

TRACK OR CATEGORY

Materials Tribology VI

AUTHORS AND INSTITUTIONS

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INTRODUCTION

In recent years plastics have become an increasingly important part in the development of new products. Thermosets, especially, have experienced a renaissance ensured by their high mechanical and thermal stability as well as good chemical resistance to many media [1, 2]. These properties are enhanced by a high percentage of glass or carbon fibers in the resin [3]. Plastics are used in tribological systems for a long time and thermosets are interesting for tribological systems, due to there properties [4]. Polymers, in particular thermoplastics, are often applied as bearing bushes for journal bearings, where they are usually paired with a counterbody made of steel. An example of such an application is a diesel high-pressure pump, where the bearing bushes are often made out of a thermoplastic [5].
For systems which are not exposed to such high loads like in a high-pressure pump, e.g. 2000 bar, pure plastic-pairings can be considered. For automotive applications this option offers a further weight reduction and thus a lower emission of environmentally harmful substances.
One possible usage of such a pure plastic-plastic pairing is the pump of sective catalytic reduction (SCR) systems which are used to reduce the nitrogen oxide emissions of diesel engines. In those systems the chemical resistance of the used materials against the reducing medium [6], an aqueous urea solution, is very important and can be provided by filled thermosets based on a phenolic Novolak resin [7].
The following investigations examine whether pure thermoset-pairings can be used for such a tribological system and how these react to different boundary conditions.

MATERIALS AND METHODS

The investigated phenolic resin materials consist of a Novolak resin with different filler types and filler ratios. The materials used in the test are listed in Table 1. The specimens are tested in two different states. One is the as-molded (am) state which means the samples don’t have any processing after molding. The second state is the post-cured state (pc). Curing is an additional production process which takes place after injection molding. For this purpose the specimen are slowly heated in a furnace following a defined cycle. Curing shifts the glass transition temperature of the material towards higher values, resulting in improved mechanical and thermal properties [8]. As a result of this additional process step, final chemical reactions take place, which ensure the material to be more cross-linked [9]. This is illustrated in Figure 1. The test specimens are sampled according to the specifications of the material manufacturer, half of the specimen are cured after injection molding.

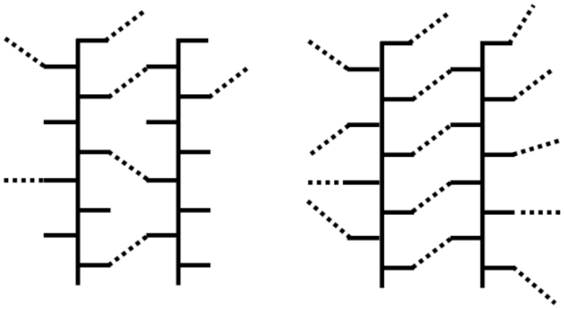

Figure 1: Cross-linking of thermosets at different stages of production. Left one shows the cross-linking of the thermoset after the molding-procedure. The cross-linking is not complete. The right one shows a thermoset after curing. The linking is completed [9].

Table 1: Tested phenolic Novolak materials.

Thermoset-Nr.	Material	Matrix	Filler
TS1	PF-(GF/GB/CD)55 wt%	Phenolic Novolak compound	**G**lass **F**iber, **G**lass **B**ead, **C**arbon **D**ust
TS2	PF-(GF/MD)80 wt%	Phenolic Novolak compound	**G**lass **F**iber, **M**ineral **D**ust

A ball-on-three-plate test rig is used for the tribological tests. The schematic test setup can be seen in Figure 2. The hemisphere (Ø12.7 mm) is always made out of TS2 and the plates (15 mm x 6 mm x 3 mm) are from TS1. All tests are carried out under lubricated conditions. A 32% urea-water solution is used as a lubricant.

For the test the normal force (**F**$_N$), the sliding speed (**v**) and the medium temperature (**T**) are varied, while the sliding distance (**s**) remains constant at 360m. Furthermore the medium temperature is kept at 25°C unless otherwise stated. The experiments carried out in this first investigation are listed in Table 2. Each of the listed tests was carried out at least three times for better statistics.

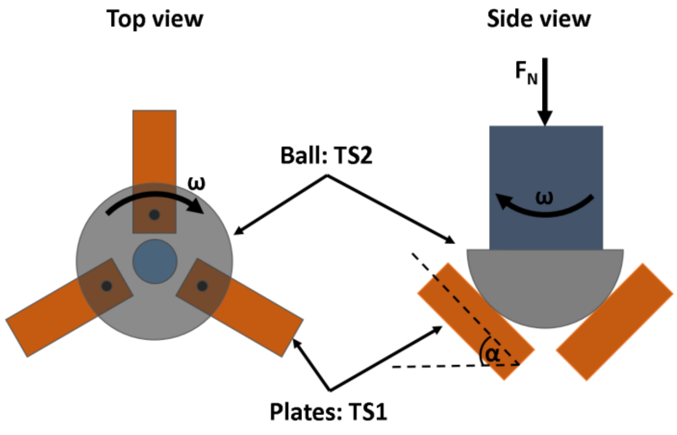

Figure 2: Schematic view of the Ball-on-three-plates-tester (BOTP), inspired by [10].

Table 2: Test parameter for am- and pc-pairing

Test	F_N [N]	v [mm/s]	T [°C]
1	10	50	25
2	20	50	25
3	40	50	25
4	10	25	25
5	10	100	25
6	10	50	-5
7	10	50	70

RESULTS AND DISCUSSION

Figure 3-5 show the mean values and the range of the wear volume (**W_V**) as well as the stationary coefficient of friction (**COF**). The stationary coefficient of friction is calculated from the second half of the test, when the running-in can be considered to be finished. Therefor the mean-value of the COF is calculated for each test.

Figure 3 shows the influence of normal force on W_V and COF. As can be seen from the figure for both manufacturing states (am and pc) the COF decreases with an increasing normal force. This behavior can be attributed to the effect of the reinforcing fillers [11]. The COF and W_V for the as-molded paring are significantly higher than the values of the post-cured pairing. For the am-pairing a linear dependency between wear volume and normal force can be seen. For the pc-pairing however COF and W_V don't respond to changes in the normal force in the same way as the am-pairing does.

With sliding speed changes, another behavior can be seen (Figure 4). As the speed increases, wear and friction initially decrease then rise again when the speed increases more. This behavior is the same for both pairings. The lower W_V and COF at higher speeds can be explained due to hydrodynamic effects. The higher wear at v = 100mm/s results from a higher input of energy into the surface during startup. As seen for at a changing normal force, when changing the sliding speed am- and pc-pairings show different behaviors.

Since SCR-systems have to operate in a wide temperature range, high and low media temperatures are investigated, too. Therefore the temperature is set and held for five minutes prior test start to ensure the parts, as well as the medium, are properly heated up/cooled down. Here the am-pairing and pc-pairing behave differently. For the am-pairing W_V and COF increase with higher temperatures, while for the pc-pairing both decrease, as seen in Figure 5. The behavior of the am-pairing can be explained by the change in viscosity of the medium. The viscosity increases with lower temperatures and is twice as high at -5°C as at 25°C. This results in a better lubrication film which separates the parts from each other. The pc-pairing acts in a different way. COF decreases with temperature increase, while W_V is similar at all temperatures.

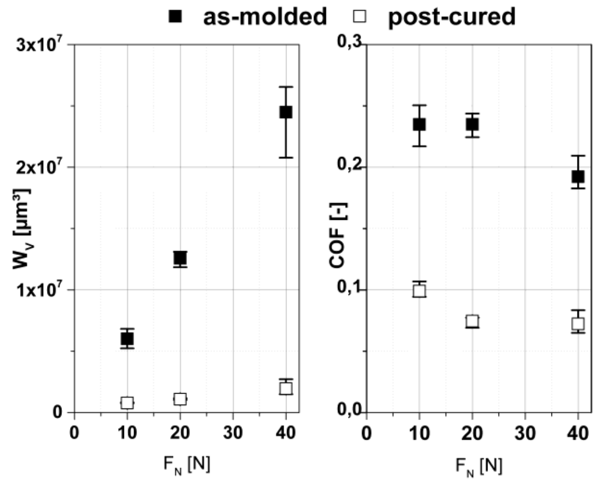

Figure 3: W_V (left graph) and COF (right graph) as a function of normal force F_N.

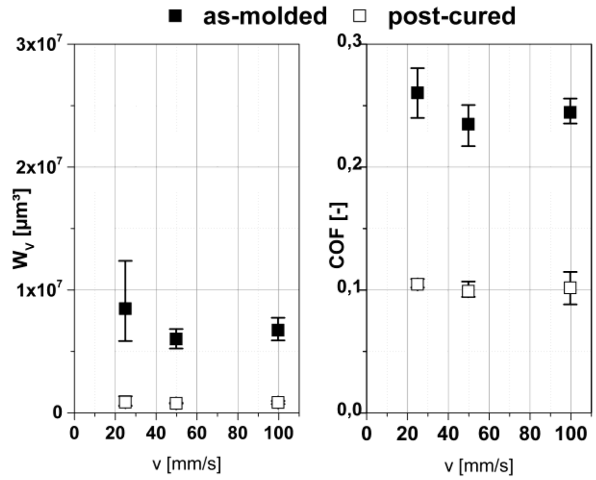

Figure 4: W_V (left graph) and COF (right graph) as a function of v.

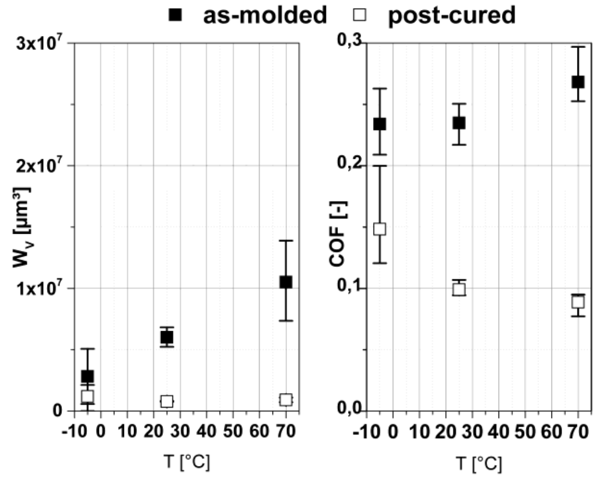

Figure 5: W_V (left graph) and COF (right graph) as a function of T.

The difference in the tribological behavior results mainly from the different manufacturing states. Therefore the development of COF and W_V was observed (Figure 6). The curves show a big difference for COF and W_V.

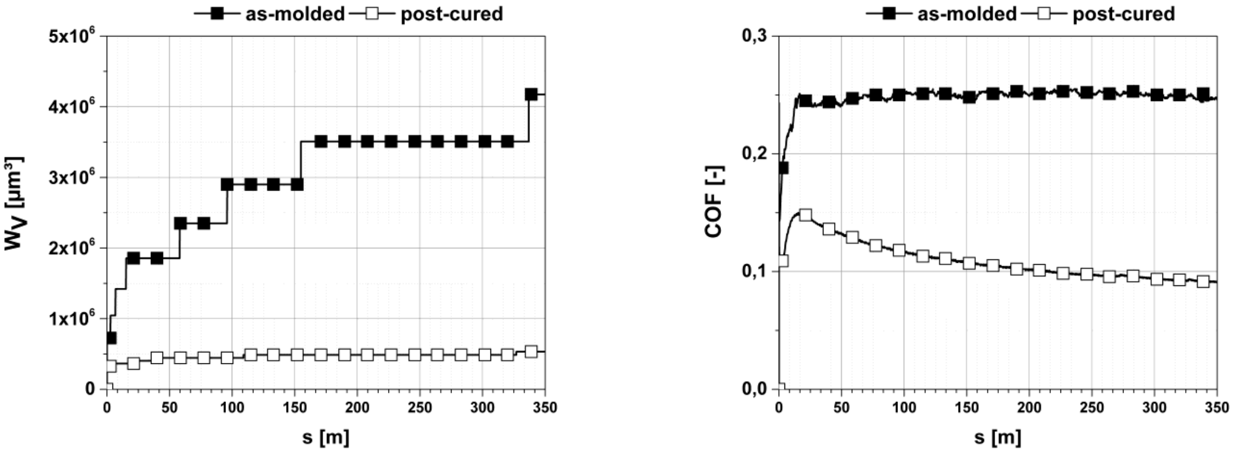

Figure 6: Development of W_V (left graph) and COF (right Graph) during an experiment. Test parameters: $F_N = 10N$, $v = 50mm/s$, $T = 25°C$.

While COF for the am-pairing rises and reaches a steady-state after 10m sliding distance, wear continues to increases steadily. The COF for the pc-pairing rises initially but decreases, after reaching a maximum. Wear increases slightly after COF has passed its maximum. The results of the experiments lead to the assumption that the wear process itself differs from am and pc. This can also be seen from the SEM images in Figure 7. The wear on the am-pairing is dominated by heavy abrasion, whereas the pc-pairing only shows mild abrasion. Also the am-specimen shows that the fibers and fillers are removed in the same manner as the matrix. The pc-pairing shows a very smooth surface and no big changes in wear during the test. On the am-pairing it can be seen that the matrix seems to get damaged more and more, the longer the sliding distance is. This suggests that for the pc-specimens, when the injection molded surface is removed (after running-in), a “wear-resistant” layer is formed from exposed fibers as it is known for other material combinations in a tribological contact [12, 13]. To proof this assumption random specimen were scanned with an AFM imaging technique. The results show that, differently than assumed, that the fibers of the pc-specimen are not exposed from the matrix, but the matrix is exposed from the fibers (Figure 8).

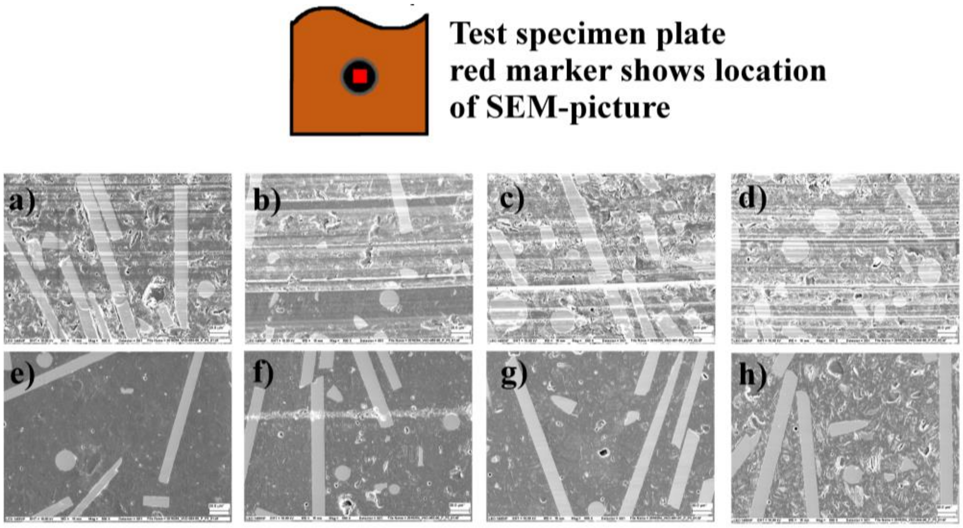

Figure 7: SEM images of the middle of the wear scar on the plate at different manufacturing states and different times on the test rig. Upper row shows the am-pairing after a) 1m, b) 10m, c) 360m and d) 720m sliding distance. Lower row shows the same for the pc-pairing. e) 1m, f) 10m, g) 360m, h) 720m.

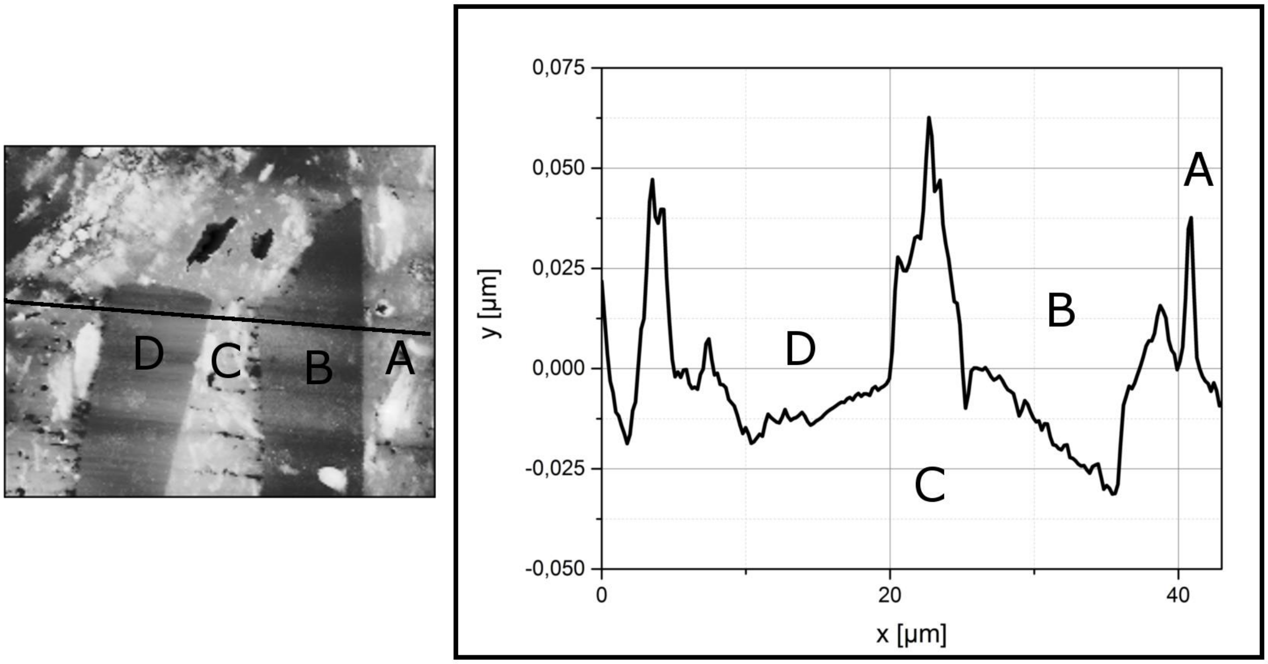

Figure 8: AFM image of a PC-specimen after test. The height profile on the right shows the difference between matrix (A, C) and the fibers (B, D).

This behavior is not fully understand yet and has to be investigated in ongoing tests.
The reason for the dramatic difference in wear results from the change of mechanical properties when the material is cured after injection molding. E.g. the tensile strength rises after curing [8]. Also the hardness, an indicator for wear resistance, increases due to the curing process. For the investigated materials the hardness increases about 10% for TS1 and about 30% for TS2. The curing process ensures that chemical reactions in the resin are completed and a better three-dimensional cross-linking takes places. As a result the molecular mobility of the phenolic Novolak resin is reduced, leading to greater mechanical stability and therefor to a better wear resistance [14]

OUTLOOK

The experiments have shown that the tribological behavior of pure thermoset-pairings is significantly influenced by the manufacturing state. The post-cured specimen showed a good and stable performance during all tests. This is based on the wear mechanism and the formation of a "wear-resistant" layer but also from the experimental setup. While wear is generated the contact pressure is reduced and the applied force might not be big enough to create more wear after running-in. The results from this investigation can directly be used to increase the lifetime of thermoset products used in a tribological contact, as well as in the engineering process of new products.

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KEYWORDS

Materials:: Polymer (solid), Surfaces: Running-In, Wear: Wear Mechanisms