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TRIBOLOGICAL STUDY OF A PRESS-FIT ASSEMBLING PROCESS

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Abstract

A particular case of press-fitting of two metal parts is studied, with high fit interference inducing high contact pressures and plastic deformation of the bushing and collar. Furthermore, the female piece is polymer-coated by cataphoresis, and the coating evolution by damage and wear during sliding promotes significant changes of friction with sliding length. These particular frictional properties impact the structural mechanics behaviour of the system during assembling.

Keywords **:** press fitting ; friction measurement ; FEM modelling ; frictional energy

1 INTRODUCTION

The press-fit process is used to assemble pieces in several automotive sub-systems [1]. In the system studied, a cylindrical bushing (consisting in an external steel envelope connected to a central axis by a rubber layer) is press-fitted into a deep-drawn collar, made of a steel strip covered by a ca. 30 µm epoxy layer deposited by cataphoresis (Figure 1). The bushing envelope is covered by an electrodeposited zinc-nickel layer. The assembled joint must resist mechanical loadings all along the service life of the vehicle. It is therefore necessary to ensure a minimal level of joint mechanical resistance (disassembling force), which depends on force distributions to be undergone by the joint during its life. To be able to assess the quality of each joint, the purpose of the work is to establish reliable relations between this disassembling, joint resistance force and the press-fitting force which is systematically measured on the joint production line.

The press-fitting force as well as the disassembling force are basically friction forces. This relationship is therefore a tribological problem. This is a case where the highest possible friction between the pieces must be achieved at the end of the press-fitting stage; even galling is permitted, so far as the structural integrity of the pieces and of the joint is not endangered. The evolution of the interface and of friction during the time the piece remains assembled may be an important issue: friction generally increases with time, in particular when polymers are involved [2].

In the following, first, an elastic-plastic FEM mechanical study of the assembling process is performed (section 2) in order to understand the contact conditions. Secondly, optical and SEM examinations of press-fitted and cut joints show severe damage and wear of the epoxy and locally of its adhesion primer, so that by places, direct metal –

metal contact may occur. Wear may eliminate up to 10% of the pieces interference, and must therefore be taken into account when modelling the press-fitting process.

Based on the abovementioned results, a tribological test has been designed (section 3). It consists in a linear ball-on-plate rig where the materials of the joint are used. The epoxy layer is deposited either on the ball (the polymer is then in permanent contact) or on the plate (transient contact). The forces are measured and the damage of the materials is examined in details. The friction coefficient is related to the coating damage, and a relationship is established with the frictional energy spent.
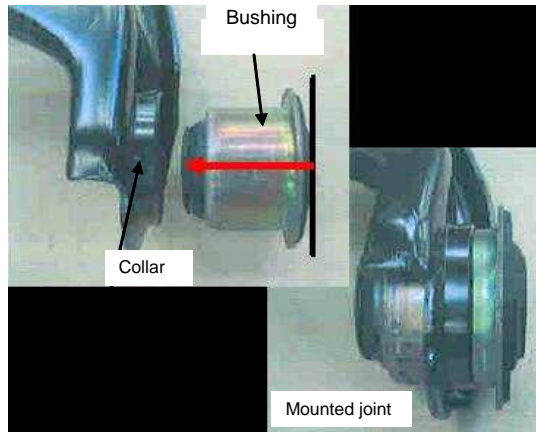

Figure 1: Press-fit pieces

2   COUPLING BETWEEN STRUCTURAL AND TRIBOLOGICAL EFFECTS

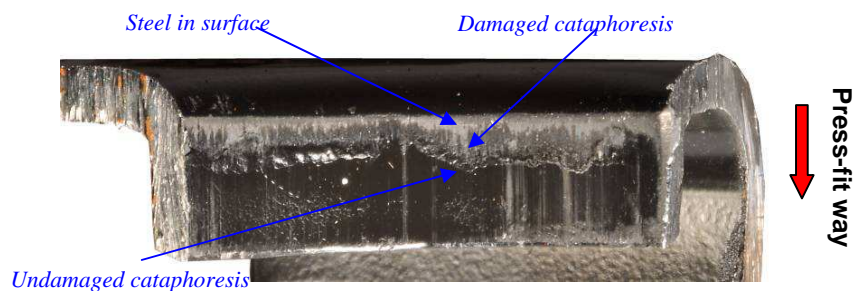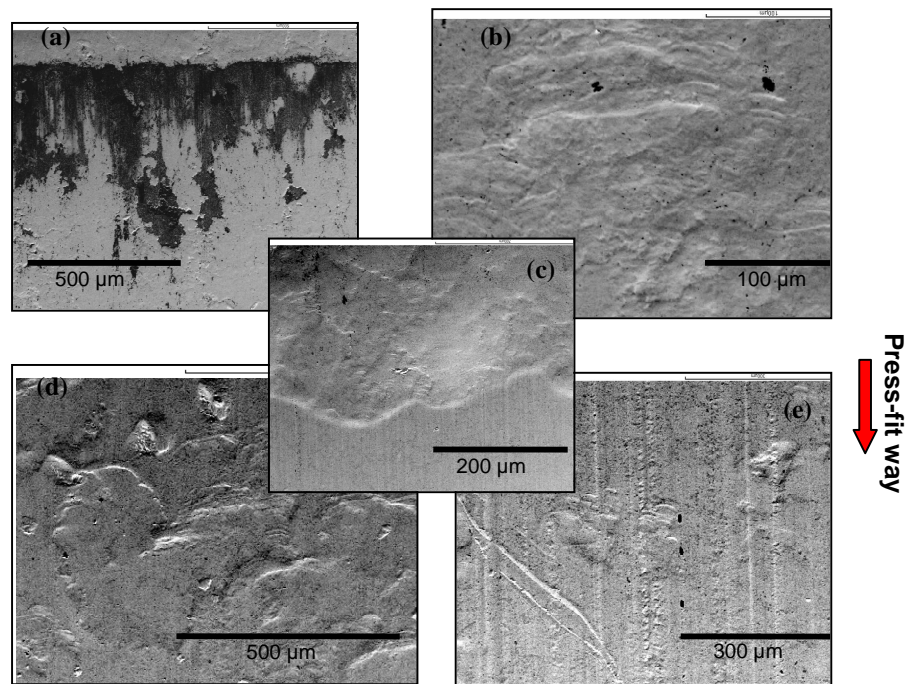### 2.1   SEM OBSERVATION OF PRESS-FIT SURFACES

Figure 2: Cutting of a "collar way" press-fitted lower arm – cataphoresis aspect

There are two ways of assembling a deep-drawn collar and a bushing : using the same direction for press-fitting ("collar way") as for deep-drawing, or using opposite directions ("counter-collar way"). They lead to different contact conditions, as will be shown.

Have a look at the "collar way" case. Figure 2 shows the range of damage undergone by epoxy during press-fitting and it gives information on the contact distribution between the two parts. Figure 3 shows SEM observation of the polymer coating, from the collar entry to its exit (i.e. along the press-fit way). At the top (figure 3a), epoxy is pushed down from the collar entry, forming an "epoxy roll" downstream (figure 3b,c). In some cases like in Figure 2, the epoxy layer is completely shaved off and the resultant surface is a patchwork of steel and phosphate layer (adhesion primer before cataphoresis) (Figure 3-a).

Figure 3 : SEM observation of rubbed polymer coating ; backscattered electron analysis, topographic mode – (a) :steel and phosphate show at surface of collar entry (complete wear of epoxy) – (b) : surface damage in the pushed-back epoxy area (before the "roll") – (c) : "epoxy roll" (transition between sheared and rubbed epoxy coating areas) – (d) : after the roll: epoxy damage by wrenching of particles – (e) : after the roll: epoxy light superficial damage mainly by scratching

Three mechanisms of cataphoresis coating damage during friction can be pointed out :

- epoxy particle wrenching is seen mainly in the pushed area (Figure 3-b) where the contact conditions are most severe.

- In Figure 3-d and to a lesser extent in Figure 3-b, there are steps in the profile, in the direction of press-fitting. Referring to the wave model of Challen and Oxley [3], this may be explained by local waves formed during sliding that degenerate into adhesive rolls (due to microscopic friction), which may eventually be detached by a crack at their basis. This mechanism is found mainly after the macroscopic "roll", but also in the pushed area.

- for lower friction conditions, i.e. locally after the epoxy roll, superficial scratches are noticed (Figure 3-e).

Another locally observed phenomenon, leading to overall epoxy removal, is blistering due to an interfacial decohesion during sliding. This is due to bad adherence of the coating on the collar and should be avoided.

The Zinc-Nickel coating on the bushing is much harder than epoxy (HV = 400 HV), and is in general not damaged.

2.2   PRESS-FIT FINITE ELEMENT SIMULATION

2.2.1   CONTACT DISTRIBUTION

The level of coating removal impacts the fit interference and the contact distribution. Therefore, it is important to take it properly into account in the model. It may neither be neglected, nor be assimilated to the collar steel. The coating is not part of the mesh, but is materialized in the mathematical contact condition as the maximum distance between the collar steel substrate and the bushing envelope for those to be considered in contact. The coating thickness loss during press-fitting, a function of contact conditions and friction properties of the two surfaces, is estimated through experimental measurements. This kind of "scalable contact" is handled with the Abaqus® contact subroutine UINTER.

Finite element simulations are carried out in a case of press-fitting with high interference, the same as for Figure 2, using a constant coefficient of friction (COF) μ = 0.3 . Contact pressure distribution is plotted in Figure 4. Apart from the "scalable contact" simulation, two other simulations are reported, with extreme cases of interference: considering the epoxy coating is off, and considering the coating as made out of the steel of the collar. For both cases, contact distribution is similar and is concentrated at collar entry with a high contact pressure. A secondary contact area is found at the other end of the joint, due to the plastic deformation of bushing external envelope. Press-fitting forces are 20.73 kN and 21.08 kN. Thus for this high interference case the 30 µm the additional interference fit effect due to cataphoresis do not change anything to efforts.

For the "scalable contact" simulation, both the contact pressure distribution and the remaining coating thickness are plotted along the collar in figure 4. It is obvious that contact pressure is more widely spread ; the coating is completely removed at the collar

entry (which is relevant, considering Figure 2). The press-fitting force is 25.09 kN, still with a constant $\mu = 0.3$. A constant COF is not necessarily realistic, considering the elimination of the coating at entry, but the goal is to uncouple tribological effects. Therefore the coating does not play just as an additional interference fit. Thanks to is elasticity, it tends to spread the contact and increase the integral contact pressure (hence, the disassembling force), all the more as interference is high.
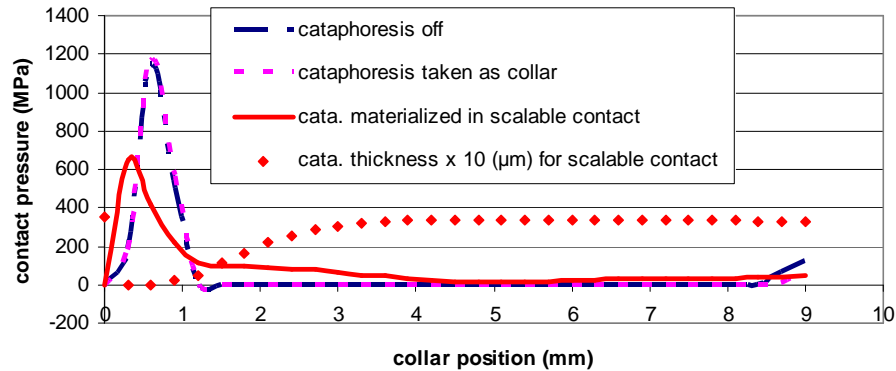

Figure 4 : press-fitting axisymmetric FEM simulation – contact pressure distribution along collar (position 0 = collar entry) at the end of press-fitting

Regardless of interference, the main result of simulation is that contact between the bushing and the collar does not occur uniformly on the whole nominal contact surface, but tends to be limited to short areas on the entry and exit sides, due to the elastic and plastic mechanical response of the collar and bushing to press-fitting forces. It is all the more concentrated at the entry as interference is high. This is consistent with optical observation of Figure 2.

2.2.2   COUPLING BETWEEN STRUCTURAL AND TRIBOLOGICAL EFFECTS

From what precedes, it may be concluded that contact conditions are severe at collar entry and the coefficient of friction must depend on the damage level. Also note the influence of the global mechanical behaviour of the collar / bushing system on tribology.

Inversely, Boissonnet et al. [4] mention the effect of the COF on press-fitting and disassembling forces. They show that the higher the coefficient of friction, the higher the tangential forces that tend to "open" the collar (make it divergent) during press-fitting and "close" it (make it convergent) during disassembling ; hence, the higher the ratio of the disassembling force to the press-fitting force. Thus, in turn, friction influences the structural mechanics of press-fitting.

Tribological and structural aspects are coupled because the COF is a function of coating damage. This calls for a systemic approach, with finite element simulations of press-fitting including coating wear and COF evolution, in order to get good prediction of press-fitting and disassembling efforts. Tribological, mechanical and damage properties of the epoxy coating must therefore be determined. The contact in press-fitting is

conformal, involves large sliding length (several mm), a kinematics in which a given point of the coating remains in contact throughout, partly under high pressure (> 500 MPa) et entry and partly under low pressure (a few MPa) everywhere else. Several tests have been designed to examine all these characteristics. Measurement of the normal and tangential force allows the frictional energy to be determined (in the macroscopic sense, including plastic dissipation in the polymer coating) ; correlation with COF is attempted to confirm that frictional energy may be used as a state variable for the evolution of coating thickness and local friction in the numerical simulations.

3 TRIBOLOGICAL BEHAVIOR OF THE COUPLE EPOXY – ZN-NI COATING

3.1   MECHANICAL CHARACTERISATION OF THE EPOXY COATING

3.1.1.   NANO-INDENTATION TESTS

Nano-indentation tests were carried out to get basic mechanical properties of the epoxy coating using a Triboscope Hysitron apparatus with a Berkovich indenter. Indentation is interesting because of the compressive state similar to press-fitting. Moreover, it proved impossible to obtain and test bulk epoxy or free-standing epoxy film by cataphoresis. Finally, the thickness (30 µm) is such that substrate effects are not to fear. From a loading – unloading cycle, hardness was found using the Oliver and Pharr technique [5], giving $H = 350\,MPa$, which corresponds, according to Tabor's relationship, to a yield stress $\sigma_0(\varepsilon = 7\%) = 150\,MPa$. The elastic modulus is $E^* = 10\,GPa$.

3.1.2.   CYLINDER ON BUSHING SLIDING TEST

A tribological test has been designed to study, under conditions close to press-fitting, both mechanical behavior of the epoxy coating and tribological behaviour. The former is dealt with here, the latter is detailed in section 3.2. It consists in a steel cylinder of diameter 14 mm covered by a 30 µm epoxy layer sliding linearly on a bushing: cylinder and bushing axes are perpendicular and sliding is along the bushing axis. This is a case of maintained contact for the polymer coating ; hence, even if this is point contact with high pressure at the beginning, the non-confined polymer flows, the contact area increases and contact pressure is quickly decreasing . The goal here is to analyse epoxy shear deformation, and not the consequences of surface damage. Therefore sliding tests were performed on a short sliding length (0,5 mm) to examine incipient shear, with a normal force of 150 N at a speed of 0,1 mm/s. The apparent COF is measured anyway, at the end of the test it has reached a stable value of 0.32. A "roll" (bulge) is formed, with maximum height 15 µm ; the area after deformation is about 1,1x0,7 mm². This gives an average contact pressure of 250 MPa, which is moderate and an average frictional stress of 80 MPa. Figure 5-a shows the mark on the polymer coating, showing large-scale, through-thickness shear, superficial tearing and the induced roughness; no sign of delamination has been found. This suggests that perfect adhesion may be assumed for moderate contact pressure, and that internal shear and high rate of polymer wear are responsible for the disappearance of the coating, rather than a weak interface.

As the contact pressure is quite similar to nano-indentation tests, the elastic-plastic properties determined in section 3.1.1 have been selected to perform a numerical simulation of the test using Abaqus® Explicit. Epoxy and the underlying steel are supposed perfectly adherent and are both meshed, whereas the bushing is considered rigid. Moreover the Coulomb COF is set to 0,35 and the friction stress is limited to 80 MPa (corresponding to a limitation by a friction factor of m=0,9). The simulated contact area is increasing only over the first 50 µm sliding, with polymer distortion. It can therefore be considered that contact pressure is moderate (250 MPa) over the whole test. The result at the end of the simulation is shown in Figure 5-b : the shape of the contact surface is correct, but its area of 0,65x0,8 mm² and the bulge height of 6 µm are lower than experimental values. One hypothesis is that the yield stress may be lower than 150 MPa in this case, which raises the question of a possible hydrostatic pressure dependence (pressure is higher in indentation, overestimating the yield stress). This should be checked in future investigations.
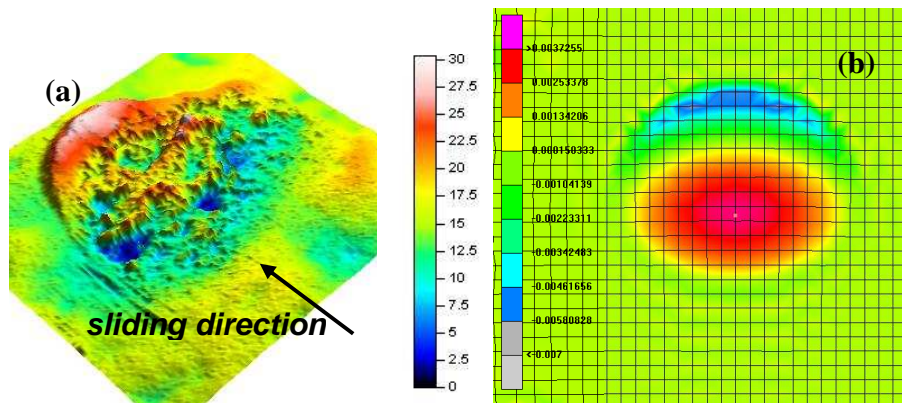

Figure 5 : Sliding of an epoxy-coated. cylinder on a bushing, Fn=150 N (a) 3D roughness mapping of sliding track (b) : FEM simulation of the test, normal displacement of the coating surface.

3.1.3. BALL-ON-PLATE LINEAR SLIDING TEST

Then sliding tests were carried out at higher contact pressure on a longer sliding distance, similar to what occurs at entry in press-fitting using another point contact configuration, namely a steel ball of diameter 20 mm covered with a 10 µm Zn-Ni passivated layer and sliding linearly on a HE400M steel plate covered with a 30 µm epoxy layer. Higher contact pressures are expected because the epoxy coating is more confined, and coating fracture is possible.

Two successive runs on the same track were carried out under a normal force of 500 N. The 3D roughness mapping is reported in Figure 6. The first run leads to a small ploughed groove (lateral bulge, no coating removal): the groove width is 2a=0,6 mm, the bulge height is between 2 and 8 µm, and the measured apparent COF is 0,16.

To clarify the contact conditions in this test, numerical simulation has been carried out. The results show that substrate displacement in the normal direction is only 2 µm and the contact can be supposed on a whole disc (contact area $\pi.a^2$ and contact length in the sliding direction 2.a) with an average contact pressure reaching 2000 MPa. The mapping of the groove after the second run shows local coating wrenching at the bottom. There is still epoxy at the surface, which means that fracture happened within the coating, near the phosphate primer ; between 5 and 10 µm of epoxy remain, based on the groove depth. An estimate of the frictional dissipated energy per unit area for one run is

$$w_f = \mu_{app} \cdot \overline{p} \cdot 2a \approx 200 \, mJ / mm^2 \cdot$$

For the second run, the apparent COF increases to 0.3 , so the energy necessary to generate fracture in the coating seems to be comprised between 200 and 600 mJ/mm².

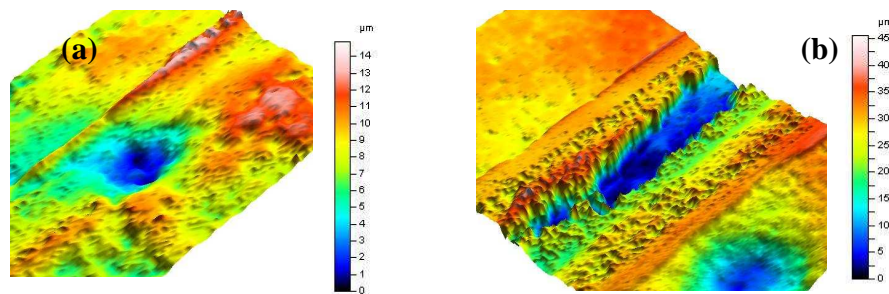*Figure 6 : Sliding of a Zn-Ni-coated ball on an epoxy-coated steel plate; 3D roughness mapping of the groove for Fn=250 N (a) after one run – (b) : after two runs.*

To better estimate this energy, we have carried out tests with linearly increasing normal force. This does not increase the contact pressure because it is limited by the steel plate plastic deformation, but it increases the contact width. Epoxy wrenching happens during the first run when the normal force exceeds 6000 N. The apparent COF is 0.18 and the groove width is 2a=2,2 mm. From numerical simulation, the contact area is 2.5 mm², hence an average contact pressure of 2400 MPa and an average contact length of about 1,5 mm. The frictional dissipated energy is 650 mJ/mm². This estimate is higher than at 500 N, but at such high loads, steel deforms plastically, dissipating part of this energy. The conclusion is that at high contact pressure, when the frictional shear stress $\mu \cdot P_{contact}$ reaches the order of magnitude of the coating shear yield stress $\sigma_0 / \sqrt{3}$, epoxy is sheared through its whole thickness, sometimes wrenched near the interface with the primer, when frictional dissipated energy per unit area reaches around 600 mJ/mm².

3.2   FRICTION MEASUREMENT

Now, returning to the cylinder on bushing layout exposed in 3.1.2, the focus is on the COF study in case of moderate contact pressure on contact length of several mm, similar to press-fitting. The same epoxy coating damage types are found as in press-fitting. They are combined and by increasing shear stress, scratching then cracking of adhesive "epoxy rolls", then particle wrenching occur.

Figure 7 shows a large evolution of the measured apparent (macroscopic) COF as a function of sliding length for F_n=150 N (dashed curve). This is similar to the previous section, where the apparent COF was shown to increase from 0.16 at the first run to 0.3 for the second. This is due to the epoxy coating being sheared and damaged by the frictional energy, so that the contact area increases and the pressure decreases; since under high pressure, the contact is in the limiting shear stress regime, the apparent COF decreases.

Therefore, a small normal force of 14 N is chosen, so that no plastic distortion of the coating occurs. In this simple case, the contact properties can be estimated through an elastic foundation hypothesis: area 0,21x0,62 mm² and maximum contact pressure 271 MPa at the beginning, without considering wear. Indeed, with sliding, the epoxy film is removed from the cylinder by abrasive wear and the contact area increases.
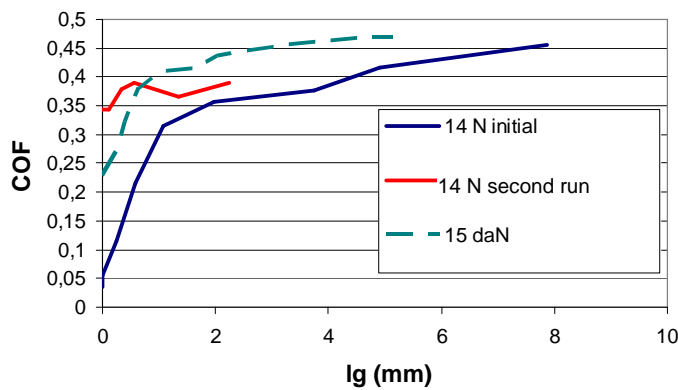

Figure 7: Apparent coefficient of friction vs sliding length – epoxy-coated cylinder on bushing layout.

There is still an increase of the COF with sliding length : from below 0,1 to 0,45 after 8 mm of sliding. Considering that this is linked to the frictional dissipated energy, it is important to realize that in this case, the coating is sheared only in its topmost layer, not in the whole thickness. The reason of such an increase could be strain hardening of the polymer, or maybe roughness increase (remember that in this configuration, the same coating area is in contact throughout with a constantly renewed bushing surface).

For confirmation, we performed a second run, with as far as possible the same rubbed epoxy surface sliding on the same part of the bushing. The result is a COF of 0,35 at the beginning of the test. This is smaller than the final 0,45 of the first run, which would be expected if friction depends only on a single state variable, frictional energy; the difference can be explained by a slightly different contact area. Nevertheless, the increase during the first mm of sliding is very small compared to the first run, which is reminiscent of the quasi-stable COF of the end of the first test. In a first approximation, it confirms the link established between friction and surface energy dissipation.

The beginning of sliding is critical to the press-fitting process where most of the epoxy coating undergoes only weak frictional interaction. The measurement of the COF must be refined in the first mm of sliding.

4 CONCLUSIONS

Several aspects of the press-fitting of a steel bushing in an epoxy-coated deep-drawn steel collar have been addressed. From the observation of polymer damage and FEM press-fitting simulations, we found that contact pressure distribution is highly non uniform due to plastic deformation of the metallic parts occurring during the process (structural effect). The high contact pressure met locally (at entry) leads to epoxy plastic flow, damage and wear, it may even be torn off.

We have shown that epoxy coating surface damage has a significant effect on the tribological behaviour. The numerical simulation is able to take this into account based on an internal variable, frictional energy, provided we input adequate mechanical properties, including perhaps the effect of the hydrostatic pressure on the polymer yield stress.

5 REFERENCES

[1]   D. Croccolo, R. Cuppini, N. Vincenzi : *"Friction Coefficient definition in compression-fit couplings applying the DOE method"*. Strain 44 (2008) pp.170–179

[2]   G. Luengo, J.M. Pan, M. Heuberger, J.N. Israelachvili: *"Temperature and time effects on the adhesion dynamics of poly(butyl methacrylate) (PBMA) surfaces"*. LANGMUIR 14, 14 (1998) pp.3873-3881

[3]   J.M. Challen, L.J. Mc Lean, P.L.B. Oxley : *"Plastic deformation of a metal surface in sliding contact with hard wedge : its relation to friction and wear"*. Proc. Royal Soc. Lond. A394 (1984) pp.161–181

[4]   L. Boissonnet, P. Montmitonnet, F. Lehoux *: « Etude tribologique de l'emmanchement en force dans des tôles embouties »* Proc. CD-ROM Congrès Français de Mécanique 2009 (Marseille, 24-28 August 2009).

[5]   Oliver W C and Pharr G M : *"An improved technique for determining hardness and elastic modulus using load and displacement sensing indentation experiments"*. J. Mater. Res. 7(6) (1992) pp.1564-1583.