INFLUENCE OF MOLD SURFACE COATINGS IN INJECTION MOLDING. APPLICATION TO THE EJECTION STAGE.

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Abstract
Mold surface coatings are used in thermoplastics injection molding to increase lifespan of the mold before maintenance. Development of coating processes such as PVD (Phase Vapor Deposit) and PACVD (Plasma Assisted Chemical Vapor Deposit) allowing thin coatings manufacturing gives access to new application fields. Investigated coatings were Chromium nitrium (CrN), Titane nitrium (TiN), Diamond like Carbon (DLC), glassy deposit (SiOx), Chromium and polished steel. This work intended to study the impact of those coatings on ejection stage in terms of unsticking the part from the mold surface and generation of scratches.
We studied coatings nature and their processings which influence their roughness. Injection campaign was led on an cube-shaped insert in an instrumented mold (with force sensors) on three polymers which differ in nature : an amorphous polymer (polycarbonate), a semi-crystalline one (polybutylene terephatalate) and a blend of copolymers (styrene acrylonitrile/ acrylonitrile butadiene styrene). We studied the evolution of these forces throughout the demolding stage. This allowed us to evaluate the work energy necessary to eject the part from the insert. We correlated those data to shrinkage of the polymer part, adhesion between polymer and mold surface and friction coefficient between those surfaces during the demolding stage. Surface energies of the polymers as well as those of the coatings were measured, and their evolutions with temperature were used to take into account this adhesion.
Study of demolding forces showed a role of the coatings depending on the polymer and its nature, and roughness of the coating. We noted that ejection consisted of two stages: unsticking of the part and dynamic friction. Amorphous polymers are mainly affected by the first step, related to the adhesion at polymer/mold interface. PBT, due to a higher shrinkage, is very sensitive to dynamic friction.

Keywords: Injection molding, coatings, ejection.

1 INTRODUCTION

Defects such as scratches are related to the ejection stage, especially the ejection forces exerted on the part. Therefore parameters influencing those forces were investigated by many authors. According to Kaminsky [1] originates in the interactions developped between the mold cavity geometry, the polymer used and process parameters, which implied a effective friction coefficient different from the theorical one. The mold cavity geometry is rela ted to the part geometry. For instance, Shen & al. [2] studied a cylinder geometry, with parts of various thickness, diameters and draft angles. It proved that an increase in diameter and thickness gave higher demolding forces whereas the increasing draft angle reduced them. Another cause which was considered was the influence of process parameters. Cooling time rise induced an increase of the forces ([3], [4], [5]). This was linked to the part surface temperature which tended to give lower forces when arisen, by lowering Young modulus and shrinkage of the part in the ejection stage. Menges & al. [6] also evocated the role of increasing the packing pressure, which reduced the shrinkage and therefore ejection forces. The same effects of packing pressure and demolding temperature (through variations in mold temperature) have been observed by Pontes & al. [7]. These authors proposed a model for tubular parts taking into account geometry of the part, shrinkage and ejection temperature as well as its influence on Young modulus [8]. They noticed that the ejection stage is divided in a static phase and a dynamic phase. Roughness was also quoted as an important factor for ejection forces ([4], [5], [6], [7], [8], [9], [10]). Ferreira & al. [9] studied its role on static and dynamic friction coefficient on polycarbonate and polypropylene. Sasaki & al.[10] evocated the idea of an optimal roughness below and above which ejection forces are increased. They also investigated several coatings and their impact on these demolding efforts.
For the ejection stage, ejection forces were evaluated, and the impact was then studied through ejection work and friction coefficient. These results were finally compared to adhesion energies occurring at the polymer/mold interface during the ejection.

We used thermoplastic polymers of various nature: two amorphous polymers (polycarbonate and SAN/ABS blend) and a semicrystalline polymer (polybutadiene terephtalate (PBT). This allowed us to take into account the specific action of a coating on a polymer depending on its nature.

2 EXPERIMENTAL AND RESULTS FOR EJECTION STAGE

2.1 Experimental

The aim of this study is to evaluate forces that are necessary to eject a polymer from a mold and its demolding temperature. The apparatus developped for this purpose is shown in figure 1. Forces measurement system is independant from the ejection system (cf. Fig.2) to allow a direct measure of the forces transmitted from the part (A) when ejected by the demolding platen (B). The core (C) transmits forces to the cylinder (D) and then to the support disc (E). Another platen (F) is there to ensure that no infiltration of polymer in the ejection system is possible in the filling and cooling stages of the process. It is removed at the end of cooling stage, before demolding. The support disc applies ejection force on three force sensors (G) located at 120° around the axis. Temperature is measured at the end of the opening of the mold with an infrared camera located above the mold, vertically to the part.

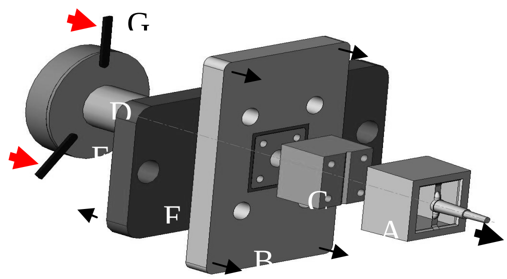

Figure 1: Ejection system – movements on the demolding stage ans transfer of forces on force sensors.

2.2 Results and discussion

We observed very classical evolutions of these forces through time for polymers, that is to say, a quick reach to a peak force which is said to correspond to the rupture of adhesion between core and part, and then a slower decrease, with a change of slope after a few hundreds of milliseconds. The decrease corresponded to the dynamic friction occurring between the mold surface and the polymer which is the second step of ejection stage. All coatings were found to decrease ejection forces for PBT compared to polished steel, whereas their presence increased them for SAN/ABS. For PC, the coatings had a small influence even though their presence tended to decrease those forces.

We estimated the cumulative ejection taking into account the displacement of the ejection plate using the expression:

$$W = \int_0^t F(t).dl(t)$$

We also tried to evaluate the apparent friction coefficient μ at the mold/polymer interface considering the forces occurring at this position. It led us to the following expression:

$$\mu(t) = \frac{F(t)}{4l.m(t).\sigma_T.\cos\beta + \tan\beta.(\sin\beta.4l.m(t).\sigma_T - F)}$$

where F(t) is the measured force at time t

l and m(t) are the width and height of the part in contact with the mold at time t, β the draft angle

σ_T is the product of the Young Modulus of the polymer considered at the demolding temperature and the shrinkage of the part.

It appeared that, for both amorphous polymers, the first step of the ejection stage, the unsticking, which corresponded to the rupture of adherence between the part and the core was the leading phenomena to be taken into account as can be seen in figure 2 for the case of SAN/ABS. In fact, the end of this step corresponded to a brutal change of slope in the evolution of ejection work. This step was very quick and the friction step had almost nor role in the ejection of the part. The comparison with the information given by the model of friction confirmed that no apparent friction coefficient existed after the end of unsticking, as can be seen in figure 3.

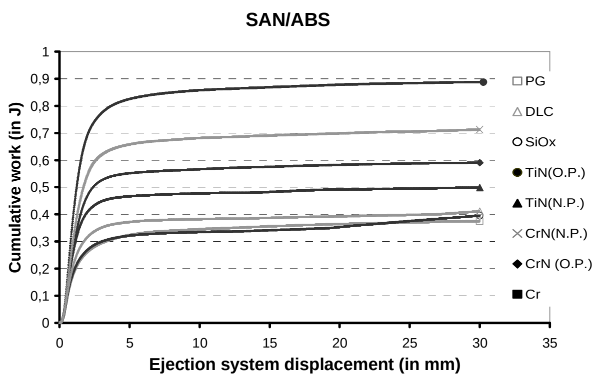

Figure 2: Evolution of cumulative ejection work for SAN/ABS

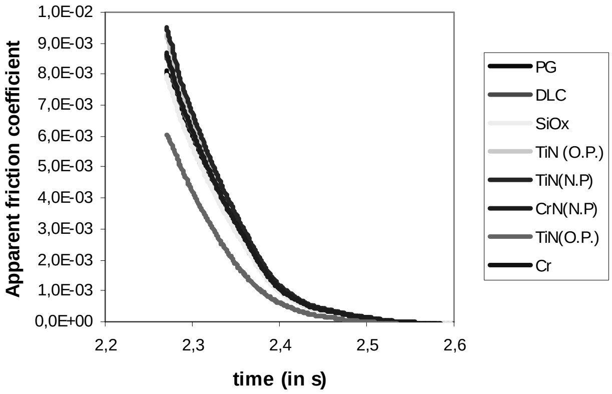

Figure 3: Evolution of friction coefficient for SAN/ABS

The same results were observed for polycarbonate. Both amorphous polymers were found to be sensitive to the unsticking step only, therefore the ejection work value at the end of unsticking gave us a classification of the influence of the different coatings for these materials which depended on the polymer considered. The unsticking energies, corresponding to the values of work at the change of slope were compared to the adhesion energies for a given polymer/system. These last ones were determined by sessile drop method on both solid polymer and coating surfaces, as well their evolution with the temperature. Then, taking into account the contact surface existing in our geometry between those surfaces, it was possible to determine the adhesion occurring at the interface at the demolding temperature. Unsticking and adhesion energies proved to be within the same order of magnitude, and the differences between those two values could be explained by a contact in the ejection which was not perfect due to the roughness. This clearly proved that for amorphous polymers the main influence of coatings in the ejection stage was related to a modification of the adhesion at the interface which was also affected by the topography of the coating surface. Furthermore, no effect of dynamic friction between polymer and mold surface was noticed.

The semicrystalline polymer showed a completely different behaviour due to its higher shrinkage. First of all, the transition between unsticking and dynamic friction steps was not visible in the evolution of ejection work (cf. Fig. 4). The ejection work was likely to be expressed as:

$$W(t) = K_0\left(1-e^{\frac{-t}{t_c}}\right)$$

where W(t) is the cumulative ejection work at a given time, K_0 is the total ejection work and t_c a characteristic time for our geometry depending on the nature of the coating.

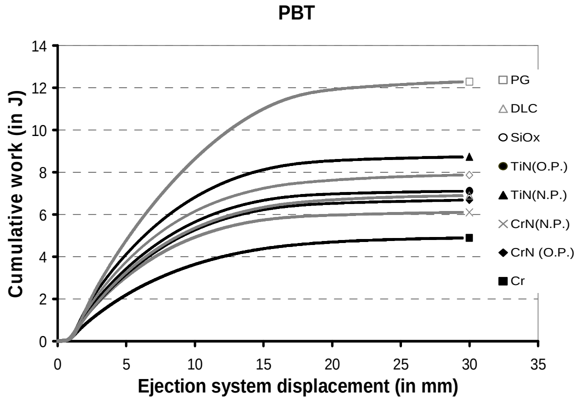

Figure 4: Evolution of cumulative ejection work for PBT

The friction model results were also different from the amorphous polymers ones for PBT (cf. Fig. 5). It showed the unsticking step ended at the same time at for PC and SAN/ABS, but for the second step, a friction between part and mold surface occurred, which induced an apparent friction coefficient decreasing almost linearly with time after a brutal change of slope corresponding to the end of unsticking. Indeed, the contribution of dynamic friction step appeared to have a major role in the ejection stage. The impact of the coatings was then to be taken into account both on unsticking and dynamic friction steps for this polymer.
The model of friction gave us the time at which the first step ended, which allowed us to determine from the measured values of work which was the contribution of each step. Results are indicated in figure 6, and compared to the average value of apparent friction coefficient in the dynamic step and values of adhesion obtained by the same method as amorphous polymers. The first remark to be made is that the values of unsticking energies are greater than the values of adhesion, indicating that the unsticking for PBT is widely affected by the roughness which created a mechanical anchor at mold/polymer interface, increasing the static friction coefficient corresponding to this step. This phenomenon was induced by the higher shrinkage of the semicrystalline material. It also appeared that the contribution of the dynamic friction step was the main one to be considered in the ejection stage, whereas unsticking due to adhesion was the main one for both amorphous polymers. Finally, we found a good correlation between measured values of friction work and the apparent friction coefficient given by the model for the various coatings considered.

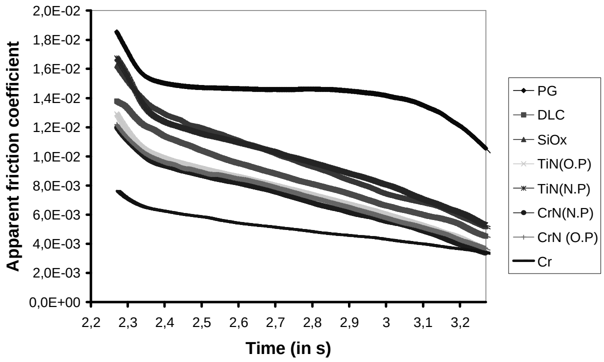

Figure 5: Evolution of friction coefficient for PBT

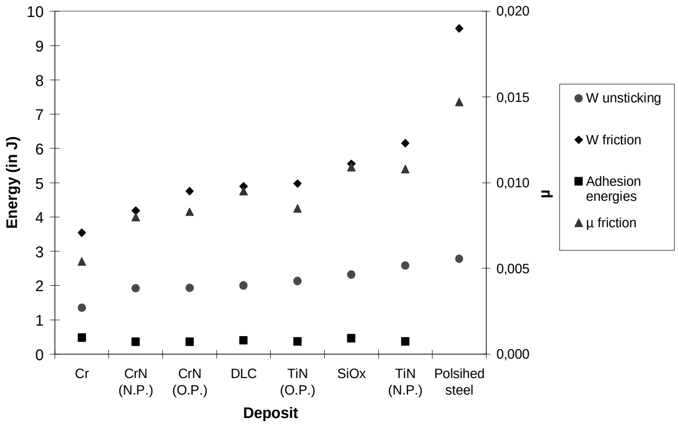

Figure 6: Comparison of the different contributions of work towards adhesion energies and friction coefficient for PBT

The combination of the measurement of ejection work and the friction model allowed us to completely characterize the impact of the coatings for PBT.

4 CONCLUSION

A study was led to investigate the effect of coatings on the mold surface in order to reduce the occurrence of weldlines in polymer parts. It appeared that their influence was related to thermal properties of the coatings (even for very thin coatings), roughness and physical adhesion of the polymer on the surface, whose influences are summed up in the contact thermal resistance associated to the coating. This impact occurs mainly in the filling stage of the process, and it proved that coatings can be an interesting way to reduce weldlines but that their influence was polymer dependent. It implies that we need a better understanding of the interactions between physical adhesion, tribology of polymer/mold contact, and thermal properties of the coatings and their impact on solidification of the polymer.

Another study led on ejection forces showed a strong influence of the coatings in the ejection stage. It proved that their impact was polymer dependent, their use tending to increase those forces for SAN/ABS and decreasing them for PBT for instance. The results were interpreted in terms of ejection work correlated to a friction model. It appeared that for amorphous polymers, the ejection work, and therefore forces, was mainly related to the adhesion occurring at the coating/polymer interface during the static friction or unsticking step. On the contrary, for PBT, this step was affected also by the roughness inducing a mechanical anchor of the part. Furthermore, the main contribution for work was attributed to the dynamic friction step. It implies that, considering the physicochemical nature of the polymer, completely different impacts of the coatings could be found.

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