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CRITICAL REVIEW

# Coefficient of friction in the demoulding forces of the injection moulding process—a review

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**Abstract**
Ejection is the most critical phase in the injection moulding process and depends on several variables that can affect and difficult the demoulding process. Some phenomena in the mould, such as shrinkage, adhesion and friction, can lead to higher ejection forces. Friction, deformation and adhesion mechanisms are components of the coefficient of friction that occurs between the mould and the part surface. An increase in the coefficient of friction will result in higher ejection forces and consequently increase the energy consumption during the demoulding process. Mould and part material, mould surface roughness, coatings and ejection temperature are some of the variables that can affect the coefficient of friction in the injection moulding process. This review paper presents some considerations on the mechanisms, the process and material variables that can affect the coefficient of friction.

**Keywords** Injection moulding · Ejection phase · Coefficient of friction · Adhesion · Deformation

## 1 Introduction

Injection moulding of polymers is one of the processing techniques with most worldwide use. This processing technique allows the production of parts with simplest geometry to parts with high level of complexity and parts from the micro to the macro scale. The production of parts by injection moulding process involves the replication of the mould surface onto the surface of the part. Moreover, depending on the material being processed and the geometry of the part, it can be difficult to demould the part because the moulding tends to shrink around the mould surface, when a core is needed.

Further studies on the demoulding process requires an understanding of the tribological behaviour of materials. Tribology is the science and technology that allows the study of two interacting surfaces in relative motion and it comprises the fields of friction, wear and lubrication [1, 2]. Due to the highly complex surface interactions within the injection moulding process, tribological study requires knowledge of multidisciplinary areas including physics, chemistry, applied mathematics, solid mechanisms, fluid mechanisms, heat transfer, machine design, materials science, lubrication, performance and rheology [3]. Tribology is applied to problems with great economic significance, such as the reliability, maintenance and wear of technical equipment, from spacecraft to household appliances [3].

Injection moulding is divided into several phases: injection, packing, cooling and ejection of the part. In this process, the molten material is forced into a mould under pressure, then it is cooled and ejected. Due to economic and time-to-market reasons, the processing of the parts must occur in the lowest time possible and ejection can play a major role in part quality [4].

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The ejection phase is the most critical in the injection moulding process [5–7], because the part is mechanically forced to separate from the mould and it can cause several problems [5–9]. The part needs to achieve the right temperature to be removed from the mould, as soon as it has the required structural stability without being distorted or damaged by the ejector pins [10]. There are some effects that have influence on the ejection force, which are most pronounced on parts with deep cores [7, 11], such as shrinkage and the coefficient of friction, including its deformation and adhesion mechanisms.

This paper will focus on the coefficient of friction in the ejection phase, including the mechanisms that contribute to its development.

## 2 Coefficient of friction

One of the requirements for the optimisation of injection mould systems is the prediction and knowledge of the frictional behaviour during the ejection phase [7, 11].

Several authors, including Pouzada et al. [7], Blau et al. [9] and Popova et al. [12] referring to the literature, state that friction was first studied by da Vinci, followed by Amontons and Coulomb, centuries ago, where the concept of the coefficient of friction and the respective laws were developed. These models have been applied in several situations with good results, although their application in polymer moulding processes, such as injection moulding and thermoforming, leads to differences between the analytical models and the experimental results [7, 13]. These differences can be related with the factors that are considered in those models. Most of them did not consider the polymer thermal history with the increase of temperature to melt the polymer and consequent cooling, while others lack information regarding the real contacting area between the two surfaces or even other properties related with the material's chemical affinity.

According to Tabor [13, 14], there are three elements involved in the friction between two unlubricated solids, the real contact area, the type of bond formed at the interface between the two surfaces and the way how contact regions are broken during sliding. According to the three elements previously mentioned, it possible to say that roughness and injection temperature have an important effect on friction during the process of injection moulding and are associated with the two main mechanisms present in the coefficient of friction, namely adhesion and deformation.

The coefficient of friction ($\mu$) can be divided into two different phenomena, the static and the kinetic friction which corresponds to the resistance to movement in two different phases [15, 16]. The first corresponds to the frictional force needed to initiate the movement between two surfaces in contact and is defined as

$$\mu = \frac{F}{N} \tag{1}$$

where $F$ corresponds to the force required to start or maintain the movement and $N$ is the normal force that maintains the contact between two surfaces. And the second corresponds to the resistance to movement during the rest of the displacement between the two surfaces. Figure 1 presents a scheme with the friction force ($F_f$), the normal force (($F_N$) applied to promote contact between two bodies, as well as the pressure along the surfaces interface.

The factors that can influence the static and kinetic friction are different. While in the case of static coefficient of friction, Coulomb's model presents experimental evidence that it may depend on the contact aspects such as size and finishing, normal force, the nature of the materials in contact and the presence of lubricants between the surfaces. Dynamic friction, on the other hand, depends on sliding velocity, contact force and the dimensions of the surface asperities [15]. The Coulomb model does not consider the replication process that occurs during the injection moulding process and cannot be applied directly to predict the coefficient of friction in similar conditions to the injection moulding process, missing also the properties of the materials in contact.

There are also two different mechanisms associated with the coefficient of friction: deformation and adhesion. Both mechanisms increase the coefficient of friction between two contact surfaces. However, it is difficult to understand and determine the contribution of each mechanism to the tribological behaviour. The literature shows that adhesion and deformation depend on various factors, including sliding velocity, temperature, contact pressure, properties of the materials in contact and surface finishing [2, 9, 17–23]. These variables must be considered when a model for coefficient of friction is developed for the described system. The lack of knowledge in the behaviour at the interface between two contacting surfaces could lead to incorrect values of coefficient of friction that are then applied to calculation of movement resistance forces.

Suh et al. [24] studied the frictional force in a kinetic system with sliding and rotating movements on unlubricated surfaces. They considered that friction has contributions of the two deformation mechanisms, namely elastic deformation and plastic deformation, as well as a third mechanism, the adhesion. Furthermore, it was proposed that these contributions are contingent upon the local friction conditions at the interface between the two contacting surfaces, as well as the factors that need to be considered in the calculation of

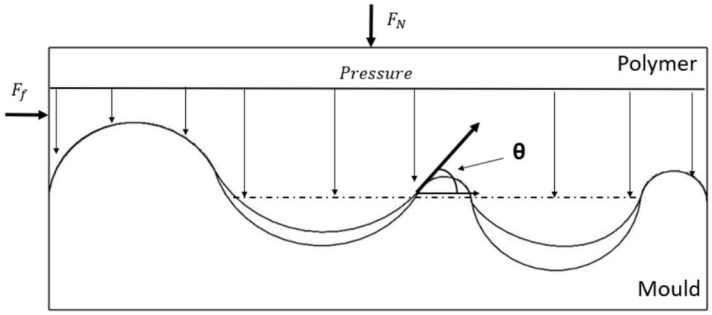


**Fig. 1** Scheme of the forces present at the interface between two materials

the coefficient of friction. The coefficient of friction is given by the sum of the three contributions:

$$\mu = f_d\mu_d + f_a\mu_a + f_p\mu_p \tag{2}$$

Correia [5, 25] in his work considers that the coefficient of friction has the contribution of two types of deformation, the elastic and the plastic deformation. In his work, two different methods were used to measure the coefficient of friction, the Mouldfriction prototype developed by Pouzada et al. [7] and the mould developed by Berger et al. [26]. Both systems were developed to measure the coefficient of friction between two contacting surfaces, although they differ in their operation method of function, and values of coefficient of friction measured by the two systems. However, the values of coefficients of friction show similar tendencies using both systems. In his study, it was also concluded with the numerical simulations that at lower values of roughness, the ploughing contribution is negligible. This could be explained by the asperity's presence, since with lower roughness, the asperities height should be lower leading to a smoother surface.

Other factor that needs to be considered is the replication of the mould surface on the polymer part. Even with dry conditions, this will play a significant role in the development of the coefficient of friction. Since during the injection moulding process, the molten polymer will reproduce the roughness of the mould surface with varying degrees of accuracy, depending on the material, mould temperature and holding pressure. The contribution to each coefficient of friction mechanism is presented in Fig. 2.

The literature above shows that the friction between a polymer and a mould is an extremely complex process, influenced by many factors, which affect the friction forces and consequently the coefficient of friction [21]. To develop a prediction model, it is important to carefully select these factors, whether a lubricant or a frictionless coating (see Sect. 3.3.2) is present or not. It also requires knowing the polymer heating and cooling story, as shrinkage of the material, correct surface characterisation, among other factors.

## 2.1 Deformation

Deformation occurs when the surface of the part moves over the asperities of the mould surface. The contribution is assumed to correspond to the energy responsible for the material movement through a surface when asperities are present [30] at the surface. These asperities can cause scratches on the part surface. The difference between the elastic and plastic deformation lands on the roughness magnitude. In the first case, the yield stress of the softer material is lower than the maximum stress, and the material recovers to its initial shape. On the other hand, if plastic deformation occurs and the yield

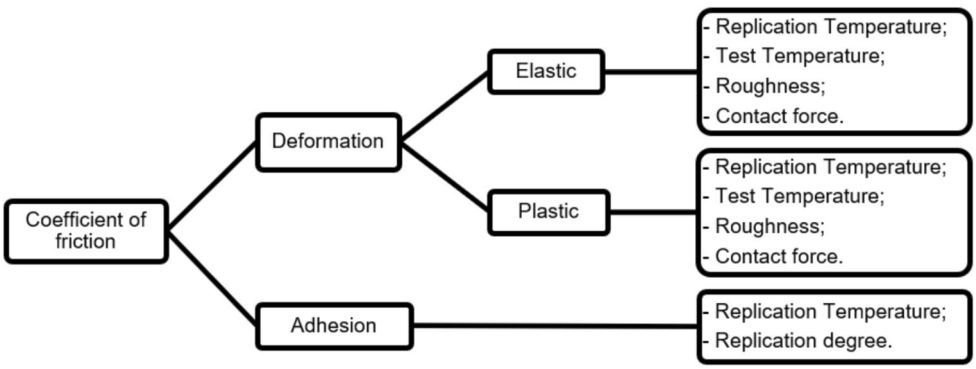


**Fig. 2** Factors with major contribution in the different coefficient of friction mechanism in similar conditions to the injection moulding process [27–29]

stress of the material was exceeded, the surface will be permanently scratched. Thus, the elastic deformation and the plastic deformation of the material will always be dependent on the surface roughness, as well as the pair of contacting materials.

The elastic deformation is related to the elastic and viscoelastic properties of the polymer, the ejection velocity and the pressure distribution over the contacting surfaces (see Fig. 1).

The plastic deformation is called by several authors as ploughing or plowing. This term is associated with the conical asperities that are present on the harder surface [1]. This phenomenon was studied by Tabor [14], where the contact area is determined by the surface topography and material deformation properties. The asperities present in the topography are also subjected to elastic and plastic deformation upon contact with another surface. The coefficient of friction that results from ploughing mechanisms (described in Eq. 2) can be estimated for conical asperities with a semi-angle of $\theta$ (as shown in Fig. 3) using Eq. 3.

$$\mu = \frac{F}{W} = \frac{A1}{A2} = \frac{2}{\pi} cot\theta \tag{3}$$

The slopes of the asperities have angles between 5 and 10 degrees, which is equivalent to a value of $\theta$ between 85 and 80 degrees. The calculated value of $\mu_p$ is typically between 0.07 and 0.14, although it is often neglected due to its small size.

Ploughing occurs when there is plastic deformation in the contact between two surfaces. It has been considered a coefficient of friction mechanism by several researchers, and it could be the most accurate explanation since it still affects the coefficient of friction even with a low value. Neglecting it could lead to values to inaccurate measurements.

Greenwood and Williamson (GW) [31] developed a theory on elastic contacts. They showed the influence of surface roughness on contact deformations and presented a method to distinguish between elastic or plastic deformation. The authors claimed that, in the contact of two flat metal surfaces, the real area of contact is determined by the highest peaks of roughness that lead to plastic deformation. The theory assumes an approximation of the surface topography and only considers the peaks of the highest asperities, leaving out the lower asperities of the surfaces. This approach may lead to issues in determining the roughness influence on contact deformations. Ciavarella et al. [32] conducted a study using the Greenwood and Williamson model with some differences. The study describes the basic features of the GW model and removes assumptions that do not have significant computational costs. In this case, the accuracy of the model depends on the assumption of the asperity's geometry with a limited form of interaction using a 3D model for the asperities. In fact, Ciavarella [33] already performed a study with a 2D model and concluded that the definition of asperities in the GW model is better than the 2D model. So, it was expected to solve the 2D limitations implementing a 3D model. Regarding the results of the 3D theory, the differences are the existence of a finite size in the specimen, whereas the GW model assumes an infinitely long size specimen. The results from the Ciavarella model are consistent with those from the GW theory.

Kim and Suh [34] state that the friction force results from asperity deformation, adhesion and wear particles. The study concludes that large asperities and soft solids (smooth surfaces) increase the mechanical interactions at the solid

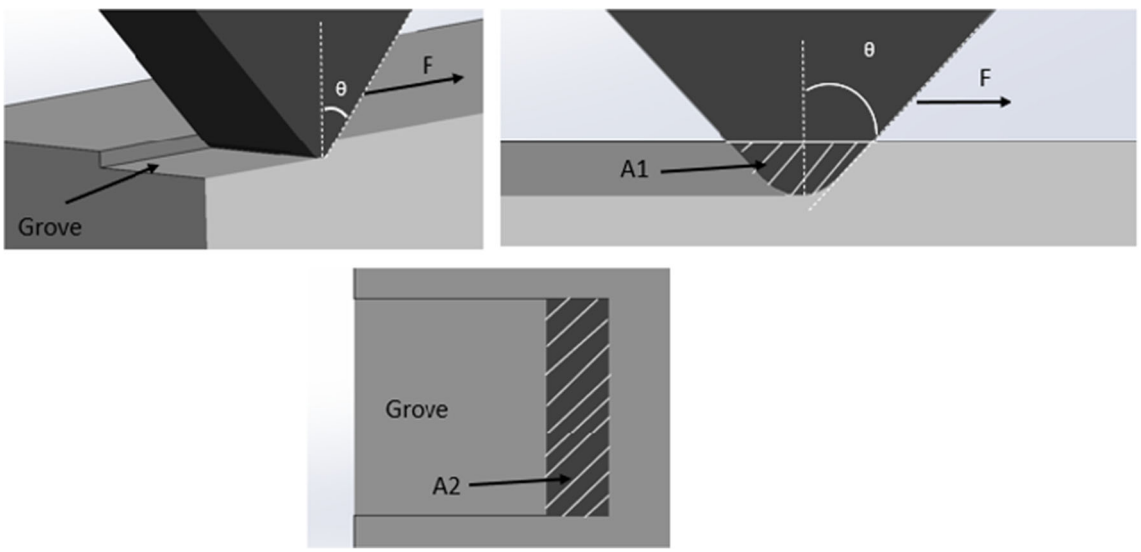


**Fig. 3** Ploughing component on a soft material due to an asperity

interface, leading to high values of friction. The presence of wear particles can also increase the coefficient of friction, as they promote plastic deformation on the soft material. The wear of the soft material or of the high asperities present on a surface can get loose at the interface between the two materials, leading to an increase of the coefficient of friction since there will be more resistance to the movement (see Fig. 4). In the case of the injection moulding process, it could occur in continuous processing cycles where there is not cleaning of the mould surface between cycles, and the presence of those particles may increase the friction between the part and the mould walls.

Deformation was also studied by other several authors, including Greenwood and Williamson [31], Archard [35], Meine [36] and Onions and Archard [37]. However, it is difficult to accurately apply the existing deformation models, both elastic and plastic, to the coefficient of friction during the ejection stage of the injection moulding process. This difficulty may be due to several factors, including the replication of the mould surface onto the polymer surface and its degree, the roughness of the mould surface and the temperatures of injection and ejection stages, as well as the height of asperities responsible for plastic and elastic deformation. As mentioned before, there is an asperity height that is responsible for elastic deformation, and above that value of high the deformation will be plastic. That value is dependent on the softer material (polymer). It is required to evaluate all the two types of deformation along the total contact between the two surfaces to correctly access their contribution to the coefficient of friction.

## 2.2 Adhesion

The other mechanism of friction that can occur during the injection moulding between the mould and part surface is the adhesion. Adhesion is highly influenced by the mould and the part material [25, 38–41], as well as surface tension [3, 42–44]. The friction force includes an adhesion component when interatomic interactions are present due to proximity of surface asperities [45]. The adhesion mechanism is observed when two surfaces come into contact due to an applied normal force or a combination of normal and shear forces. In order to separate these surfaces, a tensile force must be applied [45]. The coefficient of adhesion ($\mu'$) is calculated using Eq. 4, where $W'$ is the tensile force required to separate the surfaces and $W$ corresponds to the compressive force initially applied. Figure 5 illustrates the load force ($W$) applied to maintain the two surfaces in contact prior to the application of a pull-off force.

$$\mu' = \frac{W'}{W} \tag{4}$$

In the case of polymer processing, specifically injection moulding, adhesion forces can occur between the mould and part surface. This implies a force application to separate the two surfaces in contact [46]. Adhesion is highly dependent on the material of the mould and the part [25, 35, 39–41] as well as the surface tension [3].

The friction force contributes to adhesion when interatomic interactions caused by the proximity of the asperities in the surface [45]. Adhesion contribution in the coefficient of friction depends on several factors related with the materials in contact and with the interface conditions, including the solubility of the materials one into another, surface cleaning, temperature, normal force, contact duration, surface roughness, material hardness, elasticity modulus, ductility and real area of contact [45, 46].

In relation to its contribution to the friction process, adhesion mechanism has a specific nature that results from the bonds formed during the mechanical interaction of the surfaces in contact [47]. This interaction causes a significant variation in the potential energy of the surface and the contiguous layers. Quantitatively, it is difficult to determine the strength and other factors that contribute to the adhesion mechanism. The adhesion bonds break when a release force is applied, causing complete or partial distortion of the deformed section's shape on the surface. Adhesion can result from various interaction types and have different natures. The literature presents different theories regarding the nature of adhesion interactions, including mechanical, adsorption,

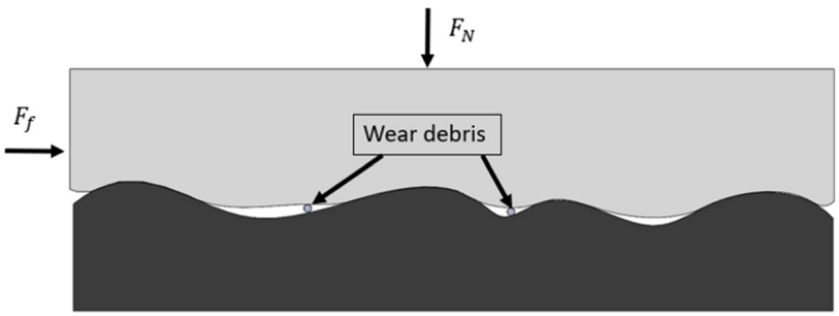


**Fig. 4** Presence of wear debris between the two surfaces

electrical, diffusion and chemical [43, 47]. Although aspects cannot be related to the coefficient of friction in the demoulding process.

The mechanical theory (Fig. 5 a) relates to the capability of the soft material to penetrate the features present on the surface of the contacting body, forming adhesion bonds due to unilateral or mutual impregnation of the surfaces [47]. In the context of friction, this theory can be applied to surface roughness and the presence of defects, such as scratches on the mould surface. These defects can cause the polymer material stick, making the demoulding process difficult. This can result in the replication of these elements on the moulding surface. This theory may also be applied to surfaces with varying degrees of roughness and topography. Heise and Popov conducted a study on the adhesive contribution of rough surfaces to the coefficient of friction [48]. They found that the adhesive contribution of the friction force is proportional to the root mean square (RMS) multiplied by a factor that depends only on the ratio of the critical distance of separation of the asperities to the average roughness. They found that the adhesive contribution of the friction force is proportional to the RMS multiplied by a factor that depends only on the ratio of the critical distance of separation of the asperities to the average roughness. In fact, there is a divergence between most of the existent models that does not consider the replication process. Those models assume that roughness is higher for smooth surfaces and the contact area is higher in this case than for rougher surfaces. Although it could not occur when the softer material replicates the harder material due to temperature. In these cases, the real area of contact can increase significantly due to the roughness magnitude.

The adsorption theory (Fig. 5 b) suggests that molecular bonds, also known as Van der Waals forces [43], are formed between the surfaces of two bodies in contact. Under certain conditions of proximity, the surfaces experience an increase in the attractive forces [47]. The nature of the bonds between the interacting elements involved determines the type of contact. The type of the bonds includes orientation, dispersion, induction, ionic, intermolecular and hydrogen bonds [47]. However, it is difficult to use this theory to accurately explain the relationship between adhesion and deformation rate and the differences between calculated and experimental bond values. These differences may be attributed to basic surface defects.

The diffusion theory can be applied when studying contact between two surfaces made from identical polymers to explain the adhesion of polymers, also known as autohesion (direct-bonding or self-bonding) [47]. This theory determines the strength of adhesion bonds based on intermolecular interactions. However, we cannot explain adhesion between polymers and metals, glass or related materials. Additionally, this theory cannot be applied when studying the ejection phase of the injection moulding process.

The chemical theory explains adhesion phenomenon through the existence of strong chemical bonds at the points of contact between two surfaces, mainly of covalent or ionic types [47], which are considered stronger than intermolecular bonds [46]. It is important to distinguish between adhesion and cohesion. The first occurs when two materials create an interface boundary between the two surfaces in contact. While cohesion is related to the atomic boundary forces of materials, which link atoms from different surfaces in contact [45]. Several studies have shown the existence of chemical bonds in the adhesion process between polymers and metals and polymers, as well as between polymers, which may explain the frequently observed experimental values for adhesion being higher than their cohesive strength [47]. Although the adhesion component has a lower contribution, it exhibits many features of cohesive properties. The strength of a polymer-metal contact depends on various factors, including time-temperature [44], molecular weight [49] and variations in the shaping and utilisation process.

Lucchetta et al. [50] conducted a study on the correlation between surface roughness of aluminium sheets and adhesion in metal hybrid overmoulding. The study concluded that the adhesion between the two materials increases with the temperature of the aluminium sheet. This occurs due to the capability of the polymer to replicate the aluminium surface more accurately at higher temperatures. If replication occurs, it will be different if the counter body is produced by steel or

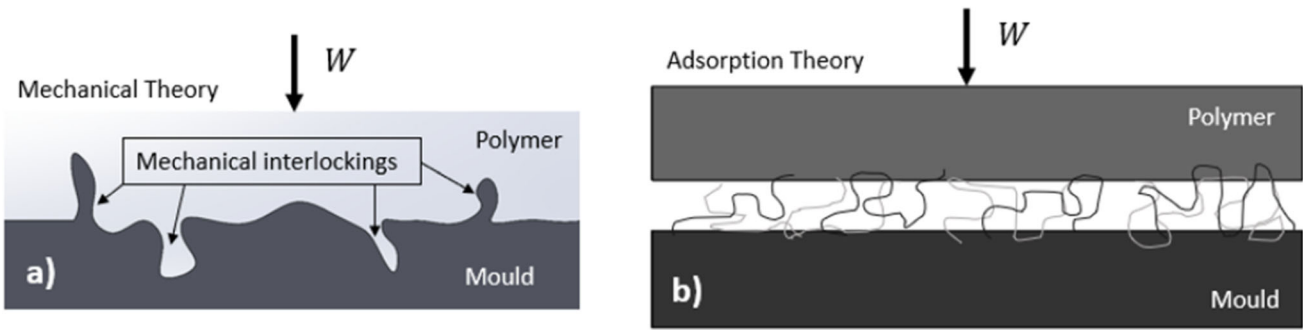


**Fig. 5** Adhesive bonding types. **a** Mechanical and **b** adsorption/diffusion theories of adhesion

by aluminium. In the aluminium case, it will require less temperature to fully replicate its surface on a polymer surface, due to the higher aluminium heating capacity.

Reid and Schey [51] performed a study on material hardness in friction development. They analysed the adhesion force using the friction force divided by the normal force (coefficient of friction), the damage of one of the samples and the metal transfer to the harder specimen. It is important to note that this method does not allow for the quantification of the adhesion contribution, as it only evaluates the metal transfer from one surface to the other and the surface damage.

Regarding the adhesion contribution to the coefficient of friction in the injection moulding process, it appears that the mechanical and adsorption theories are the most suitable for explaining it. Nevertheless, if the mould material is a metal, the chemical affinity between the part and the mould material is unlikely to occur. Consequently, the chemical theory should not be considered unless the mould material is from a different group to metals.

The tribological properties of surfaces have been extensively studied with regards to the adhesion contribution. Various theories and tests have been used to experimentally determine this contribution. However, due to the complex nature of adhesion forces, it is challenging to apply this knowledge to predict the friction coefficient and consequently assess the ejection forces in the injection moulding process [16]. This difficulty is specifically due to the absence of effects such as plasticity, adhesion, friction and surface chemistry in the models used to assess the tribological behaviour at the interface between two materials [52].

#### 2.2.1 Adhesion models

Some models have been developed to predict the adhesion behaviour between two surfaces in contact. The most well-known models and basis for several other studies are the DMT (Derjaguin-Muller-Toporov) [53, 54] and JKR (Johnson-Kendall-Roberts) [54, 55]. The DMT model was originally developed for bodies with nanometre sizes and metal properties [54, 56], while the JKR model is applied to bodies with polymer properties and micrometre or higher sizes [54, 56]. It is not possible to rely on a single model to predict adhesion during the injection moulding process, as both polymers and metals are typically present. Additionally, both models only consider certain surface factors, such as contact size and some material properties, while ignoring other important factors that are implicated in the replication of one surface onto another as a consequence of heating processes.

The JKR model assumes that surface interactions occur only within the contact area. The elastic contact is analysed with respect to the van der Waals forces between the two surfaces and the applied load [54]. This model obtains the equations for the main contact parameters by combining the Hertzian pressure distribution for loading and the Boussinesq distribution for unloading. This results in an infinite tensile stress at the boundaries of contact, while the compression is concentrated in the central region. The equation used to calculate the adhesion force, or pull-off force, without any deformation in this study is as it is presented in Eq. 5, where $\Upsilon$ corresponds to the energy per unit contact area and $R$ to the sphere radius [54, 57].

$$P_{pull-off} = -\frac{3}{2}\pi R\Upsilon \tag{5}$$

This theory is useful for studying soft elastic materials as it can explain the adhesion between two surfaces in terms of surface energy using the area of contact [55]. Although this technique was originally developed to study the adhesion between a sphere and a plane, it has also been applied to other types of shapes [58].

The DMT theory assumes that non-contact forces are molecular attraction forces acting across the gap between two bodies. It also assumes that these forces do not change the particle shape [53, 57]. Similar to the JKR model, it assumes the contact of a sphere with a plane surface, using the contact radius according to the Hertz theory and assuming that van der Waals forces act in the contacting area. If there is no deformation, adhesion force reaches its maximum value at the contact point and can be calculated as follows:

$$F_{DMT} = 2\pi R\Delta\Upsilon \tag{6}$$

In both cases, there are methods to calculate and determine the deformation caused by the adhesion force [53, 55, 57].

To distinguish between the JKR and DMT models, a parameter known as Tabors' parameter, $\mu_T$ [57], is often used. This parameter is related to the height of the "neck" present in the profile described by the JKR model [55], where adhesion should vary between $1.5\pi R\Delta\Upsilon$ and $2\pi R\Delta\Upsilon$. When $\mu_T \geq 1$ and the "neck" has high values, non-contact attraction force can be disregarded, and adhesion is equal to $1.5\pi R\Delta\Upsilon$. If the non-contact forces cannot be ignored due to low values of the "neck," adhesion force can be calculated using $2\pi R\Delta\Upsilon$ [59]. It is not possible to use Tabor's parameter directly when studying rough surface contacts [58]. However, it can be applied directly when studying the contact of a sphere with a surface.

Over the years, several studies have been conducted using the JKR, DMT, and Hertz models [57]. It has been concluded that the JKR model is suitable for "soft" materials, while the last two are more appropriate for "hard" materials. The studied materials were spheres rather than entire surfaces. The studies describe a gap in the adhesion map for a sphere that is not covered by any of the three models for sphere contact with a surface mentioned earlier. This gap corresponds to

intermediate values of the Tabor parameter [58]. To address this issue, Maugis developed a new model, known as the Maugis-Dugdale model, that stands in the transition between the JKR and DMT models [58, 60]. In the context of the injection moulding process, the coefficient of friction is crucial due to the replication of the polymer onto the mould walls. Therefore, it is necessary to extend the contact analysis to encompass the entire surface, rather than limiting it to the asperities of the harder surface.

Fuller and Tabor [61], as well as Greenwood and Williamson [31], conducted studies regarding the modelling of rough surfaces covered with spherical asperities with a determined radius $R$ where the peaks size respect the Gaussian distribution [58]. There is a possibility of error when using this type of distribution, since in the case of injection moulds, it could not be verified due to the techniques used in their production and the materials of this tool acquiring a different height distribution to those promoted by the Gaussian distribution. The production techniques available for mould development lead to several differences in the surface topography that can be heterogeneous or homogeneous.

Other authors have attempted to achieve the correct determination of the adhesion between two surfaces by introducing different models that use rough surfaces. Person [62] proposed a model that considers both complete and partial contacts. The model accounts for an increment of roughness that corresponds to the increment of magnification, but it may present errors. To address this, a correcting factor was introduced [63] to calculate the elastic energy at the interface, resulting in more accurate predictions of the contact area. Despite the alterations implemented, the results regarding the relationship between the area of contact and the load of the bodies differ from the multi-asperity contact theories and the calculated values [64–67].

Recent studies on flat rough surfaces have focused on using a Gaussian isotropic 2D roughness, the Power Spectral Density (PSD) [58], to characterise surfaces and improve surface roughness accuracy. Ciavarella et al. [68] and Afferrante [69] used the Weierstrass function to describe a linear contact problem between an elastic half-plane and a rigid fractally rough surface, employing the Archard model. The first study [68] demonstrates that none of the applied pressure is sufficient to promote complete contact between the surfaces. However, a group of fractal characters exists for all geometry values of the load parameters, indicating that the real area of contact will always depend on the applied load. In the second study [69], the contact problem of adhesion between two rough surfaces using the JKR regime is examined. The study concluded that the results are dependent on load redistribution, as per the Archard model and their assumption of the JKR model.

Most of the models mentioned in this paper refer to the contact between a surface and a sphere with a known radius. Although, these models cannot be applied directly to predict the adhesion force between two surfaces with known roughness. The presented models that assume multi-asperity contact do not account for the melting of the softer material and the replication of the harder one, resulting in missing information for predicting the adhesion force between the two surfaces. Additionally, deformation must be considered in the adhesion prediction as it constitutes a significant factor.

### 2.2.2 Adhesion studies

Correia [25] investigated the contribution of the adhesion mechanism and concluded that it is not possible to predict the contribution of this mechanism on the friction force based solely on the mould surface roughness and the mechanical properties of the materials. The adhesion contribution was not fully understood and therefore could not be incorporated into the developed model. The study highlights the importance of considering all major factors when developing a coefficient of friction prediction model.

Gonçalves et al. [41] studied the tribological properties between the polymer used for the part and moulds obtained by stereolithography. They concluded that there was chemical adhesion between the resin from the mould block and the material of the moulding.

Chen and Hwang [38] developed an adhesion force tester for the injection moulding process to test resins with high adhesion issues, such as PMMA, PC, and TPU. The instrumented three-plate mould includes a piezoelectric force sensor for measuring adhesion force. The test outcomes indicate that the mould can accurately measure the adhesion force between the mould and the surface of the part. This demonstrates that it is feasible to acquire the adhesion contribution to the coefficient of friction by using the appropriate tools and considering the relevant factors.

During the demoulding process in injection moulding, the adhesion mechanism is most pronounced at the beginning. Berger et al. [26] measured the ejection force using their apparatus and found that the horizontal force as a function of demoulding length shows a peak that is dependent on the adhesion mechanism, followed by a constant force.

Chen and Hwang [39] studied the adhesion phenomena in thermoplastic polyurethane during injection moulding. The authors used different values of surface roughness and coatings applied on the instrumented mould surface. According to the authors, the adhesion force can be measured uniformly.

However, it is unclear whether the existing tests performed for measuring the adhesion force represent the actual values for the adhesion component in the coefficient of friction. Further studies are needed to clarify this. This requirement is associated to the development of a coefficient of friction prediction model that takes into account both deformation and adhesion contributions. The predicted values derived from

the model should closely match the results measured during the tests conducted under similar conditions to the ejection phase of the injection moulding process. Although at this moment it seems that in the developed models to predict the adhesion forces is steel missing the presence of contributions of the temperature change in the injection moulding process and the behaviour of polymers in the heating and cooling process.

### 2.3 Friction and adhesion force measurement devices

Friction tester devices are for measuring the friction between two surfaces in contact. They typically follow accepted standards from the International Organisation for Standardisation (ISO) and the American Society for Testing and Materials (ASTM). Although these standards are generally effective, they may not be suitable for measuring the coefficient of friction in similar conditions to the ejection phase of the injection moulding process. Furthermore, there are differences in the testing methods used to measure this coefficient. To simulate the ejection phase of the process, it is necessary to heat and cool the interface between the two materials in order to replicate the mould surface onto the polymer surface. One issue with ASTM D1894 is that it requires the use of a second equipment to promote sliding between surfaces and measure the friction force. It appears that none of the existing standards can be directly applied or followed for this particular problem.

Another issue is that most devices used to measure the coefficient of friction do not provide information about its different components. Studies have been conducted to measure both static and dynamic friction under similar conditions to injection moulding [7, 70, 71]. The tribometer developed by Kashani et al. [70] allows the identification of static and dynamic friction in short-term experiments and wear rate of samples in long-term experiments. Despite the coefficient of friction measurement, the aforementioned equipment is unable to isolate the contribution of the adhesion and deformation mechanisms.

The equipment described by Pouzada et al. [7] allows the measurement of the coefficient of friction under similar conditions to those of the injection moulding process. Figure 6 shows the equipment, which allows the variation of conditions to verify their influence on the coefficient of friction.

Delaney et al. [71] have developed an equipment that aims to measure friction under similar replication conditions. The equipment is similar to that described by Pouzada et al.[7], which heats the tool insert above the glass transition temperature of the polymer and then replicates the insert surface onto the polymer surface. After replication, the insert is cooled down to perform the friction test using a universal testing machine. This equipment was also used to perform studies by Rodrigues et al. [72–74] and Pontes et al. [75]. Berger et al. [26] also studied the coefficient of friction using an instrumented mould for measuring the ejection forces and coefficient of friction.

There are some devices used to measure the coefficient of friction between two surfaces in similar conditions to the injection moulding process. However, they are not able to isolate the different contributions to friction, such as deformation and adhesion. The inaccurate values for the coef-

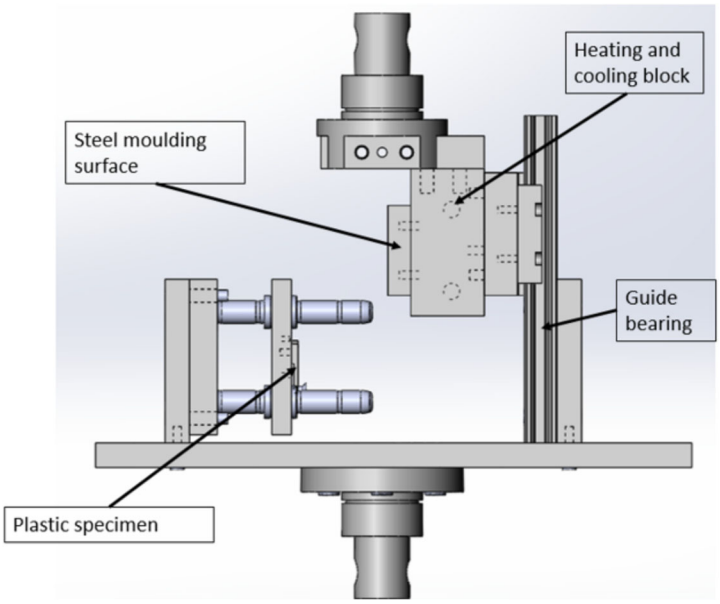


**Fig. 6** Schematic view of the friction test equipment developed by Pouzada et al. [7]

ficient of friction lead to differences between the predicted and measured values when applied to ejection force prediction models.

Moreover, measuring the coefficient of friction is recognised as complex, prompting several researchers to develop specialized equipment to determine this value. Therefore, beyond the developed equipment, it is crucial to have a model that reliably interprets the values obtained under these specific tribological conditions.

The methods used to obtain the friction forces between two surfaces in contact should also enable the variation of several factors that affect friction and its mechanisms.

## 3 Factors which affect the coefficient of friction

The coefficient of friction in the injection moulding process can be affected by several factors, including mould material, part material, ejection temperature, mould roughness and coatings applied to the mould surface.

The factors that influence the coefficient of friction during the demoulding phase of the injection moulding process can be divided into four main groups: the material being processed, the part design, the injection mould and processing conditions.

The factors present in those main groups can be related to each other. For instance, certain process conditions can affect polymers properties, such as viscosity, which may vary depending on the melt and mould surface temperature. To accurately analyse the coefficient of friction between two surfaces, it is necessary to understand the factors that can increase or decrease its value. Although there are various parameters that could influence the coefficient of friction, roughness and contact pressure appear to be the most significant. When considering injection moulding, coefficient of friction is dependent on both the processing temperature and the ability of the molten polymer to replicate the mould surface.

The following paragraphs explain how these factors influence the coefficient of friction and discuss related studies.

### 3.1 Part material

The material used to produce the parts by injection moulding affects the coefficient of friction and, therefore, the ejection forces. The coefficient of friction can be reduced or increased depending on weather the material is semi-crystalline or amorphous. The presence of reinforcements or additives also affects the coefficient of friction. Some studies have been conducted to evaluate the impact of reinforcements and additives in the material used for mouldings, for example the addition of carbon fibres typically leads to a decrease in the coefficient of friction [1]. This reduction is attributed to the decrease in wear and, consequently, the reduction of wear particles that tend to increase the coefficient of friction at the interface between the two materials in contact. Increasing the percentage of reinforcements, particularly the glass fibre reinforcements, leads to an increase in the coefficient of friction due to the increase in the mechanical modulus of the material [76]. The use of reinforcements can either increase or decrease the coefficient of friction, which may be related to the development of wear and wear particles between the two contacting surfaces. Materials such as PMMA and PC are known for their high adhesion [27, 38] which results in a higher coefficient of friction compared to materials such as PP. This difference in the coefficient of friction may be attributed to the morphological nature of the materials, whether they are amorphous or semi-crystalline.

Pontes et al. [77] have studied the effect of processing conditions on ejection forces in tubular injection mouldings of PP, PC and PS. The temperature of the core surface has influence on the ejection force. The authors observed a decrease in the ejection forces when the mould temperature increased. The increase in the material temperature at the demoulding phase could lead to a decrease in the shrinkage and the elastic modulus of the material, which decreases the coefficient of friction.

The viscosity of the material can influence the adhesion forces between the mould and the part. Chen and Hwang [38] identify it as one of the main factors that can change the adhesion force value. The use of materials with lower viscosity allows a better replication of the mould walls into the polymer sample, which implies a better replication of the mould surface and a higher area of contact at the interface mould/moulding part.

When dealing with semi-crystalline materials or polymer blends, it is crucial to have a good understanding of their mechanical properties, particularly the elasticity modulus and the ultimate compression stress. These are highly dependent on temperature, specifically within the range of the ejection temperature [25]. According to Shen and Jiang [78], the ejection force is also strongly influenced by thermal contraction strain, Poisson's ratio and Young's modulus.

Most of the factors and studies described are related to the ejection force, although these same factors also influence the coefficient of friction.

### 3.2 Part design

As previously mentioned, the design of the part has a great influence on the coefficient of friction. Mouldings with intricate details, microstructured surfaces and deep cores can increase the force required to eject the part from the mould, as this will increase the coefficient of friction between the mould and the moulded part surfaces.

The thickness of the moulding and the presence of microstructures or textures in the mould surface greatly influence the coefficient of friction during the injection moulding process. In a study performed by Su and Gilchrist [79], the effect of micron-sized features on ejection forces was analysed. The authors concluded that the ejection forces of the micro ridges result from the combination of adhesion and friction forces between the elements and the corresponding microcavities. Differences in shrinkage and the micro ridges cause variations in adhesion and friction forces. This study emphasises the significance of the contact area surface in the interface of both materials, as well as the existence of different elements in the mould surface that needs to be replicated in the part surface that usually tends to increase the friction and the adhesion forces in the system.

Santhapuram and Nair [80] performed a study using molecular dynamics simulations to investigate the frictional and mechanical response of a surface with cylindrical and spherical asperities. They compared the results with those of a surface without asperities and analysed the effect of nanoindentation and scratch processes on the coefficient of friction. This study concludes that the average coefficient of friction is equal to or lower when surface asperities are present in comparison to a smooth surface. This suggests that surfaces with lower coefficients of friction can be produced by using the appropriate value for surface asperities. The coefficient of friction evaluation depends on the test used. In this study, an indenter test was used, which does not represent the effect on the replication processes, such as injection moulding process. Replicating the mould surface into a polymer specimen could lead to different results.

The impact of deep cores of the moulding on the ejection force was studied by Masato et al. [81] in the micro-injection moulding process. They produced a mould for a part with four holes, each 800 μm in diameter and without draft angles using micro-milling. The study concluded that improving the tool processing can reduce ejection forces. They also conclude that there are other factors contributing to the ejection forces. If the optimum processing conditions are achieved, the forces required to eject the part can be reduced. It is expected that reducing the coefficient of friction between the mould and the part surfaces will result in a reduction of ejection forces.

To accurately evaluate the contact conditions at the interface between the two materials, it is it is necessary to identify the different zones of the mould and the various friction mechanisms. For example, if a flat surface is present in the demoulding direction, the friction mechanisms will differ from those of a wall that is almost perpendicular to the ejection movement; the contribution of the friction mechanism will be different for both cases. In both cases, the contribution of adhesion and deformation mechanisms will be different. This raises several questions about how to study the development of the coefficient of friction in the injection moulding process and whether it is appropriate to use a general value or calculate the contributions of each wall to its development.

## 3.3 Injection mould

### 3.3.1 Material

The material applied to the moulding tool is another factor that can affect the coefficient of friction. Nowadays, the use of rapid tooling in mould design is common due to the rapid changes in the innovation of polymer products. The use of cheaper and easier methods of processing materials for tooling is constantly increasing. However, the use of rapid tooling materials results in tools that are more susceptible to wear, which can affect the coefficient of friction.

Hopkinson and Dickens [82] carried out a study to compare the ejection forces between aluminium and tools produced by stereolithography (SL) and concluded that aluminium moulds must be smooth on the surface to reduce the ejection forces. In this case, this could be explained by the possible presence of wear particles of aluminium leading to a higher surface roughness. Finishing SL inserts to give a smooth surface can reduce the ejection forces. However, depending on the chemical affinity between the moulding and mould materials, it is possible that adhesion may occur and lead to higher ejection forces due to the coefficient of friction present in the system.

The chemical affinity between the mould and the part material has been studied by Gonçalves et al. [41]. It was concluded that knowledge of the mechanical and chemical properties of stereolithography is essential to achieve the best mould performance, especially for low-crosslinking resins. It is therefore necessary to know in advance what the material to be moulded in order to correctly select the correct SL resin to ensure that chemical adhesion between the mould and the part is negligible. The performance of stereolithography has also been studied by Westphal et al. [83]. Different materials for the moulding were tested, and it was concluded that moulding materials with similar solubility parameters to the SL resin can cause wear in the mould due to the chemical affinity between the two materials. Martinho and Pouzada [84] arrived to the same conclusion when SL resins were used and observed adhesion between the mould material and the moulded material (PP) due to their similar value of factor of solubility (Hildebrand parameter). From those studies, it is possible to verify that selecting the mould material, when produced for low production series, is important to reduce the adhesion at the interface between the materials. Materials that have chemical affinity between them will increase the adhesion mechanism of coefficient of friction.

The performance of hybrid moulds was studied by Pontes [85] in terms of mould integrity during the injection moulding process. If hybrid moulds are used, there is a risk of

destroying mould details during the ejection phase due to adhesion at the interface. This phenomenon may occur due to the material's chemical affinity.

Benabdallah [86] conducted a study to measure the static coefficient of friction between certain polymers against steel or aluminium. The study concluded that static friction increased under lubrication compared to dry conditions, indicating that surface chemistry has a significant impact on the measured value of static friction.

Dorin et al. [21] investigated the quantitative correlation between the coefficient of friction and steel surface wear with glass fibre-reinforced polymers. The researchers concluded that the hardness of the mould material affects the coefficient of friction values as expected. The production of injection moulding products with reinforced polymers leads to a higher wear in the mould walls, and wear debris promotes an increase in the coefficient of friction at the interface especially in continuous production cycles.

The study Sabino Netto et al. [87] aims to develop an epoxy resin composite reinforced with short steel fibres. Additionally, they found that increasing the amount of steel reinforcements reduces the coefficient of friction between the mould and the moulding. It was concluded that these types of moulds are useful for small-scale productions, as their surfaces wear out earlier than those made of steel, resulting in a higher coefficient of friction due to the wear particles.

Correia et al. [88] studied the strength and frictional behaviour of mould inserts produced using rapid prototyping tooling techniques. It was concluded that mould inserts produced by different RTP techniques resulted in different shrinkage and consequently different ejection forces due to the increase in coefficient of friction.

#### 3.3.2 Mould surface

The mould surface and its topography depend on the material, the interactions between the surface and the surroundings and the method used to prepare the mould surface [72, 73, 89, 90]. Surface properties are important for surface interactions, as they affect the real area of contact and tribological aspects such as friction, adhesion and wear [89–91]. Even the smoothest surface has irregularities, as there is no machining process capable of producing a molecular flat surface in commonly used materials [89].

Surface topography can consist of a repetitive or random structure [89], including micro and nanoroughness, waviness, lay and flaws, which can affect the performance of a surface in tribological contact [91]. Surface roughness can be characterised by different parameters divided into three groups: average roughness parameters, statistical analyses and fractal characterisation [89]. When characterising a mould surface, it is common to use the $R_a$ parameter, which measures the vertical heights in relation to a centre line (see Fig. 7). However, for a more precise prediction of the coefficient of friction and ejection forces, other parameters such as spacing parameters that characterise a surface in the horizontal direction can also be included. It is a well-established fact that surfaces with the same $R_a$ value can have different topographies and asperity distributions, which can result in variations in tribological behaviour between two surfaces [89, 92, 93]. Therefore, it is advisable to use other types of parameters for better characterisation.

A surface is usually characterised by two statistical height descriptors $R_a$ (also known as CLA (centre-line average) or AA (arithmetic average)) and $R_q$ (also known as $\sigma$ (standard variation or variance) or RMS (root mean square)) [89, 90, 94]. However, $R_t$ (maximum peak to valley height, $R_y$ or Rmax), $R_p$ (maximum peak height), $R_v$ (maximum valley depth), $R_z$ (average peak to valley height) and Rpm (average peak to mean height) can be used to characterise a surface in terms its topography.

The influence of surface roughness on the coefficient of friction has been studied by several authors [5, 6, 25, 27–29, 34, 36, 72–74, 81, 91, 95, 96], and all of them agree that the coefficient of friction increases with the increase in surface roughness, and the same occurs at lower values of roughness. Thus, it is well known that there is an optimum value of roughness that results in a lower coefficient of friction [91, 97]. Above this value, the mechanisms responsible for the coefficient of friction are deformation and ploughing, leading to a higher coefficient of friction [5, 25, 36, 95]. As the roughness value decreases and polished surfaces are used, the mechanism with a higher contribution is adhesion [25, 26, 36]. This is usually true for dry contacts, where the real contact area increases with lower surface roughness. However, it is difficult to confirm that this also occurs when replicating one surface into another, as at higher roughness the material will melt and mimic the roughness of the harder surface, which is likely to result in higher contact areas.

Masato et al. [81] studied the micro-injection moulding process using three inserts with different topographies which were produced by optimising tool manufacturing, in this case micro-milling. With the different strategies, the value of $R_a$ was reduced by 39% from insert 1 to insert 2 and by 62% from insert 1 to insert 3. As expected, this leads to a decrease in the demoulding forces resulting from the reduction of the coefficient of friction. Although, as would be expected at low roughness, an increase in mould surface replication is observed with the increase in packing pressure, leading to an increase in the coefficient of friction between the two surfaces, probably favoured by the increase in adhesion forces.

In their study, Lucchetta et al. [50] found that a surface with higher roughness and higher temperatures results in better replication of the aluminium surface. This promotes higher contact areas between the two materials at the interface, leading to increased adhesion between them.

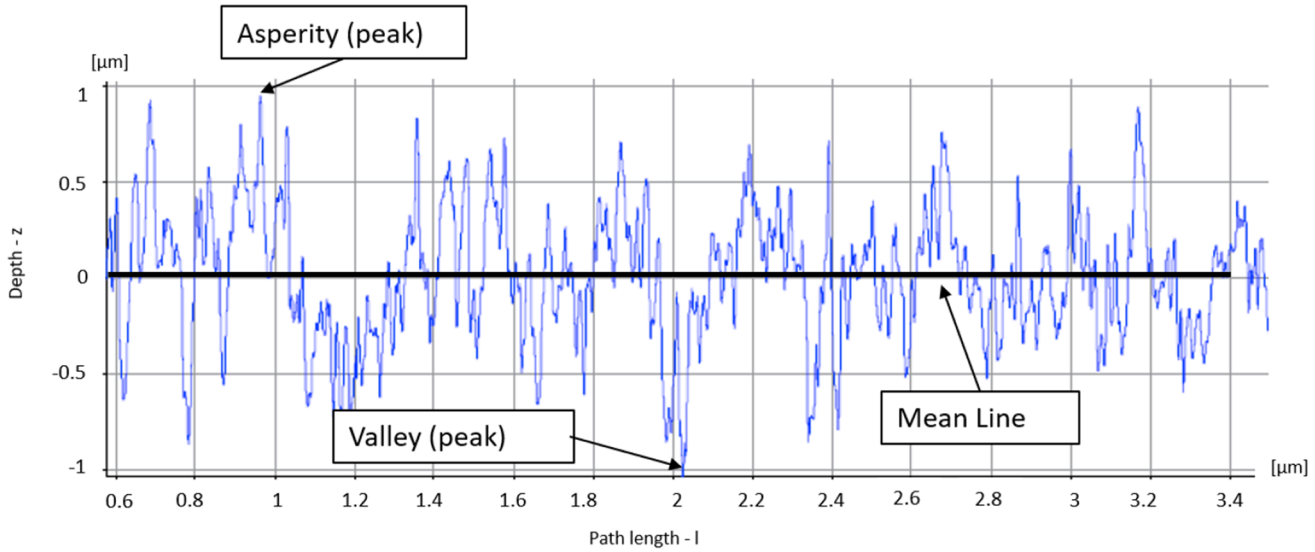


**Fig. 7** Example of a surface profile z(x)

Another way to achieve lower coefficient of friction between the mould walls and the processed parts is to change the mould surface. This can be done by applying coatings to the mould surface through the deposition of thin films. These films will act as a lubricant between the surfaces. Thin film application is a known method for surface modification, which can improve surface quality, reduce the coefficient of friction, wear rate and in other cases are simply for decoration [98–102]. Several studies have been conducted on thin films produced by diamond-like carbon (DLC) [103–120], aluminium (Al) [114, 121–123], tungsten (W) [73, 74, 124–128] and other types of coatings [73, 74, 129]. These coatings are used to reduce the coefficient of friction and ejection forces in the injection moulding process.

Diamond-like carbon (DLC) has been widely used for various purposes and processes over the years [103–115]. These types of coatings offer a range of properties when applied to a substrate, including physical (optical and electrical), chemical, mechanical (hardness and elastic modulus) and tribological properties [103]. These thin films are interesting because the carbon atoms, which are the only component of the structures, can be arranged in different types of multi-atomic structures. These structures are known called allotropes (or polymorphs) and include diamond, graphite, fullerenes, nanotubes, graphene, glassy carbon and amorphous carbon [103, 130]. Amorphous carbon thin films exhibit desirable properties such as high hardness, chemical inertness, optical properties, biocompatibility and excellent tribological behaviour in a wide range of engineering applications [131, 132].

Several studies have been conducted on DLC films containing other types of atoms such as titanium (Ti) [107], chromium (Cr) [107, 108, 120, 123], silicon (Si) [109, 120], silver (Ag) [110–112] and molybdenum (Mo) [113]. The incorporation of Cr has been found to improve hardness, modulus and roughness [107], while the wear resistance of Ti, Cr and C DLC films decreases.

The incorporation of aluminium (Al) in the production of thin films has been studied in the literature [106, 114, 121, 122]. The aluminium atoms are used to improve the friction behaviour and reduce surface wear of a surface.

Kilman et al. [114] investigated the addition of Al atoms to a -C:H coating using a hybrid technology that employs plasma and magnetron sputtering with two deposition configurations for the substrate, namely dynamic and static deposition. The first approach leads to a multi-layered structure with alternating layers that are rich in aluminium and those that are poor in aluminium with each period having a thickness of approximately 40 nm. The tests conducted for tribological characterisation showed that the coefficient of friction was reduced by the introduction of aluminium, with values decreasing from 0.2 to less than 0.1 for all Al-doped films.

Recent studies have shown that the incorporation of tungsten (W) in thin films promotes a reduction in the coefficient of friction and excellent wear resistance [124–128]. These types of atoms are typically added to carbon (C), sulphur (S) and diamond-like carbon (DLC) to form thin films.

Dai et al. [124]conducted a study on a multi-layered film consisting of W/DLC/W-S-C. The study focused on the impact of $WS_x$ content on the structure and adhesion of the composite films. Additionally, tribological behaviour was investigated using a ball-on-disk tester under two different atmospheres: air and $N_2$ gas. The results showed that the composite films with high C content exhibit better wear resistance, with coefficient of friction measurements ranging

from 0.15 to 0.25. Under $N_2$ conditions, the coefficient of friction ranges from 0.03 to 0.1.

Yang et al. [126] investigated the incorporation of tungsten in hydrogenated DLC coatings against cast iron to study friction reduction mechanisms. Their results demonstrate how to characterise the structure of carbon coatings in lubricated conditions. It was concluded that the chemical decomposition of MoDTC to $MoS_2$ is the dominant process, rather than the possibility of formation of $WS_2$ in this type of system.

Despite the great improvement of the tribological behaviour, the coatings tend to wear after a certain number of cycles and thus require replacement. This can result in complications in the context of high-volume production, where there is a potential for coating deterioration and an associated increase in the coefficient of friction due to the presence of wear particles. The rate of coating wear is also influenced by the specific type of injection-moulded polymer, with reinforced polymers, particularly those containing glass fibres, exhibiting a heightened propensity for coating wear.

### 3.4 Processing conditions

Several authors have studied the factors that influence the coefficient of friction, including holding pressure, ejection speed, mould temperature and injection temperature.

Pontes et al. [77] concluded that increasing the mould temperature leads to a decrease in ejection force. They concluded that an increase in the holding pressure results in an increase in ejection force, which may be due to an increase in the coefficient of friction between the two surfaces. Martins et al. [133]studied the effect of several parameters, including mould temperature and holding pressure, on the ejection force in the injection moulding process of thin-walled tubular PLA and PS mouldings. For PS, it was found that increasing the mould temperature resulted in a decrease in ejection force. However, the decrease observed was not as significant as the results reported by Pontes et al. [77]. As for PLA, it was concluded that temperatures above $55°C$ caused the polymer to become stickier, resulting defects during the ejection stage. These results demonstrate that higher temperatures lead to an increase in adhesion forces between the polymer and the mould walls, resulting in a higher coefficient of friction.

Wróbel and Szymiczek [18] conducted a study on the impact of temperature on the coefficient of friction of low density polyethylene. The study concluded that temperature affects both static and dynamic friction. For low meshing samples, it was observed that the dynamic coefficient of friction decreases when the temperature exceeds $30°C$, while the static coefficient of friction increases at $30°C$. The effect of the mould temperature on the coefficient of friction was also studied by Worgull et al. [134, 135], but in their case was studied for the hot embossing process. They concluded that the temperature has a greater impact on static friction than on dynamic friction. The study shows a reduction in static friction with decreasing temperature. As demonstrated in the previous study, temperature plays a significant role, particularly in static friction. This indicates that temperature affects the static coefficient of friction, which corresponds to the initiation of movement. Therefore, it is crucial to understand the impact of temperature on the coefficient of friction in replication processes, such as injection moulding.

Dorin et al. [21] conducted a study on the quantitative correlation between the coefficient of friction and steel surface wear with glass fibres-reinforced polymers. The study concluded that at higher contact loads, the harden layer of the mould material is destroyed, resulting in an increase in the coefficient of friction due to the decrease in hardness. Higher contact loads resulted in increased wear on the mould surface, leading to an increase in the coefficient of friction. This is due to the presence of wear particles between the two surfaces under study, as well as the presence of asperities on the mould surface.

Unal and Mimaroglu [136] performed a study to investigate the friction and wear behaviour of unfilled thermoplastics in dry conditions. The study concluded that the coefficient of friction of polyamide 6, UHMWPE and POM increases with the contact load, as expected.

As previously mentioned, the ejection force is dependent on the coefficient of friction, which in turn depends on the processing conditions. Griffiths et al. [137, 138] demonstrate a direct relation between the pressure during the mould filling and the holding phases of the process with the ejection forces.

To reduce the coefficient of friction, it is essential to correctly use and vary all parameters known to influence this phenomenon. To achieve an accurate approximation of the coefficient of friction, it is necessary to select the most influential parameters that affect both deformation and adhesion during the demoulding phase of the injection moulding process.

## 4 Concluding remarks and future perspectives

Predicting the coefficient of friction and ejection forces is crucial during the design and development stages of injection moulds. This ensures the correct positioning of ejector pins, reducing ejection forces and minimising the risk of damaging the moulded product. Understanding the mechanisms that occur between the surfaces of the mould and the moulding is essential. Therefore, knowledge of the process and processing conditions that impact the coefficient of friction in the injection moulding process is vital. Numerous studies have confirmed the correlation between processing conditions and the coefficient of friction. The primary challenge in predicting ejection forces lies in the coefficient of friction.

The mechanisms contributing to its development between two surfaces during the process remain unclear. Currently, no prediction model accurately forecasts the coefficient of friction under conditions similar to the ejection phase of the injection moulding process. This results in the use of various methods with differing values, leading to discrepancies between predicted and measured ejection forces. Further advancements are needed in models that predict the coefficient of friction under demoulding conditions in the injection moulding process.

While some models account for adhesion between the asperities of the two surfaces, evaluating this contact is challenging, especially when replication occurs between the mould and the injection-moulded materials. Additionally, the impact of other contact factors must be considered in the coefficient of friction estimation, particularly the replication degree of the mould surface by the polymer, which varies with the contact temperature at the interface and the applied pressure. This should consider the mould and molten polymer temperatures to accurately determine the replication degree.

A comprehensive range of factors must be included in the developed models for coefficient prediction. Many existing models lack at least one critical component. For instance, adhesion models often fail to account for the real area of contact due to temperature-related effects. Similarly, deformation models struggle to accurately represent the height of asperities responsible for elastic and plastic deformation and to correctly identify the roughness level responsible for each type of deformation.

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## Declarations

**Conflict of Interest** The author(s) declare no competing interests.

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## References

1. Sinha SK, J BB (2009) Polymer tribology. Imperial College Press, London
2. Blau PJ (2009) Friction science and technology: from concepts to application. CRC Press - Taylor & Francis Group, Boca Raton
3. Bhushan B (2013) Principles and application of tribology. John Wiley & Sons Inc, New York
4. Delaney KD, Bissacco G, D K (2012) A structured review and classification of demolding issues and proven solutions. Int Polym Process 27:77–90. https://doi.org/10.3139/217.2514
5. Correia MS, Miranda AS, Oliveira MC, Capela CA, Pouzada AS (2011) Analysis of friction in the ejection of thermoplastic mouldings. Int J Adv Manuf Technol 59:977–986. https://doi.org/10.1007/s00170-011-3573-2
6. Ferreira EC, Neves NM, Muschalle R, Pouzada AS (2002) Friction properties of thermoplastics in injection molding. Paper presented at Society of Plastice Engineers' ANTEC 2002 conference, San Francisco, 5–9 May 2002
7. Pouzada AS, C FE, J PA (2006) Friction properties of moulding thermoplastics. Polym Test 25:1017–1023. https://doi.org/10.1016/j.polymertesting.2006.06.009
8. Kinsella ME, Lilly B, Gardner BE, Jacobs NJ (2005) Experimental determination of friction coefficients between thermoplastics and rapid tooled injection mold materials. Rapid Prototyp 11:167–173. https://doi.org/10.1108/13552540510601291
9. Blau PJ (2001) The significance and use of the friction coefficient. Tribol Int 34:585–591. https://doi.org/10.1016/S0301-679X(01)00050-0
10. Delaney K, Bissacco G, D K (2010) A study of demoulding force prediction applied to periodic mould surface profiles. Paper presented at Society of Plastice Engineers' ANTEC 2010 conference, Orlando, 7–10 May 2010
11. Pontes AJ, Pouzada AS, Pantani R, Titomanlio G (2005) Ejection force of tubular injection moldings. Part ii: a prediction model. Polym Eng Sci 45:325–332. https://doi.org/10.1002/pen.20275
12. Popova E, Popov VL (2015) The research works of Coulomb and Amontons and generalized laws of friction. Friction 3:183–190. https://doi.org/10.1007/s40544-015-0074-6
13. Chang WR, Etsion I, Bogy DB (1988) Adhesion model for metallic rough surfaces. J Tribol 110:50–56. https://doi.org/10.1115/1.3261574
14. Tabor D (1981) Friction - the present state of our understanding. J Lubr Technol 103:169–179. https://doi.org/10.1115/1.3251622
15. Popov V (2016) What does friction really depend on? Robust governing parameters in contact mechanics and friction. Phys Mesomech 19:115–122. https://doi.org/10.1134/S1029959916020016
16. Griffiths CA, Dimov SS, Brousseau EB, Chouquet C, Gavillet J, Bigot S (2010) Investigation of surface treatment effects in micro-injection-moulding. Int J Adv Manuf Technol 47:99–110. https://doi.org/10.1007/s00170-009-2000-4
17. Vadivuchezhian K, Sundar S, Murthy H (2011) Effect of variable friction coefficient on contact tractions. Tribol Int 44:1433–1442. https://doi.org/10.1016/j.triboint.2011.03.022
18. Wróbel G, Szymiczek M (2008) Influence of temperature on friction coefficient of low density polyethylene. J Achiev Mater Manuf Eng 28(1):31–34
19. Mikhin NM, Amosov NI (1974) Temperature dependence of the coefficient of friction. Sov Phys J 17:873–875. https://doi.org/10.1007/BF00890233

20. Jiang J, Ulbrich H (2001) Deviation of coefficient of friction at high sliding speeds from energy conservation over the frictional interface. Wear 247:67–75. https://doi.org/10.1016/S0043-1648(00)00509-3
21. Dorin R, Capitanu L, Badita L (2014) Quantitative correlation between friction coefficient and steel surface wear in the case of linear friction dry contact with reinforced polymers with glass fibres. J. Mater. Sci. Eng. A. 4(5):135–145
22. Titomanlio G, Jansen MB (1996) In-mold shrinkage and stress prediction in injection molding. Polym Eng Sci 36:2041–2049. https://doi.org/10.1002/pen.10599
23. Pontes AJ, Oliveira MJ, Pouzada AS (2002) Studies on the influence of the influence of the holding pressure on the orientation and shrinkage of injection molded parts. Paper presented at Society of Plastice Engineers' ANTEC 2002 conference, San Francisco, 5–9 May 2002
24. Suh NP, Mosleh M, Howard PS (1994) Control friction. Wear 175:151–158. https://doi.org/10.1016/0043-1648(94)90178-3
25. Correia MS (2013) Modelling the ejection friction in injection moulding. PhD Thesis - University of Minho
26. Berger GR, Friesenbichler W, Freudenschuss G (2008) A new practical measurement apparatus for demolding forces and coefficients of friction in injection molding. Paper presented at PPS-24 Polymer Processing Society 26th Annual Meeting, Salerno, Italy, 15–19 May 2008
27. Rodrigues AR, Correia MS, Pontes AJ (2021) Friction and adhesion force measurement using a new developed equipment. International polymer process innovation conference (PPI2021) - Online, 15–16 December 2021. (ISBN 9789464517811)
28. Rodrigues AR, Correia MS, Pontes AJ (2022) Friction and adhesion force measurement using different materials for the tool material. International polymer process innovation conference (PPI2022) - Lavrion Technological Cultural Park Athens - Greece, 15–16 September 2022. (ISBN 9789464667615)
29. Rodrigues AR, Correia MS, Pontes AJ (2023) Surface roughness effect on friction and adhesion coefficient in demolding parts in a similar injection molding process. International polymer process innovation conference (PPI2023) - University of Minho, Guimarães, Portugal, 13–15 September 2023. (ISBN 978-989-33-5033-1)
30. Delaney K, Kennedy D, Bissaco G (2010) A study of friction testing methods applicable to demoulding force prediction for micro replicated parts. Paper presented at Matrib 2010, Croatia, 23–27 June 2010
31. Greenwood JA, Williamson JBP (1966) Contact of nominally flat surfaces. Proc R Soc Lond A 295:300–319. https://doi.org/10.1098/rspa.1966.0242
32. Ciavarella M, Delfine V, Demelio G (2006) A 're-vitalized' Greenwood and Williamson model of elastic contact between fractal surfaces. J Mech Phys Solids 45:2569–2591. https://doi.org/10.1016/j.jmps.2006.05.006
33. Ciavarella M, Delfine V, Demelio G (2006) A new 2D asperity model with interaction for studying the contact of multiscale rough random profiles. Wear 261:556–567. https://doi.org/10.1016/j.wear.2006.01.028
34. Kim DE, Suh P (1993) Frictional behavior of extremely smooth and hard solids. Wear 162–164 Part B:873–879. https://doi.org/10.1016/0043-1648(93)90089-5
35. Archard JF (1957) Elastic deformation and the laws of friction. Proc Roy Soc A 243:190–205. https://doi.org/https://www.jstor.org/stable/100445
36. Meine K, Schneider T, Spaltmann D, Santner E (2002) The influence of roughness on friction: Part II. The influence of multiple step. Wear 253:733–738. https://doi.org/10.1016/S0043-1648(02)00160-6
37. Onions RA, Archard JF (1973) The contact of surfaces having a random structure. J Phys D Appl Phys 6:289–304. https://doi.org/10.1088/0022-3727/6/3/302
38. Chen J-Y, Huang S-J (2013) Design and fabrication of an adhesion force tester for the injection moulding process. Polym Test 32:22–31. https://doi.org/10.1016/j.polymertesting.2012.09.004
39. Chen J-Y, Huang S-J (2012) Investigation of adhesion phenomena in thermoplastic polyurethane injection molding process. Polym Eng Sci 52:1571–1580. https://doi.org/10.1002/pen.23094
40. Delaney K, Kennedy D, Bissaco G (2011) Investigating polymer-tool steel interfaces to predict the work of adhesion for demoulfing force optimisation. Paper presented at MTSM 2011, Split, 29–30 September 2011
41. Gonçalves MW, V SG, Ahrens CH, Pouzada AS (2007) Study of tribological properties of moulds obtained by stereolithography. Virtual Phys Prototyp 2:29–36. https://doi.org/10.1080/17452750701295765
42. Eustathopoulos N, Sobczak N, Passerone A, Nogi K (2005) Measurement of contact angle and work of adhesion at high temperature. J Mat Sci 40:2271–2280. https://doi.org/10.1007/s10853-005-1945-4
43. Butt MA, Chughtai A, Ahmad J, Ahmad R, Majeed U, Khan H (2010) Theory of adhesion and its practical implications a critical review. J Fac Eng Technol 15:21–45. https://doi.org/api.semanticscholar.org/CorpusID:12388619
44. Berger G, Steffel C, Friesenbichler W (2016) A study on the role of wetting parameters on friction in injection moulding. Int J Mater Prod Technol 52:193–211. https://doi.org/10.1504/IJMPT.2016.073632
45. Bhushan B (2013) Introduction to tribology. Wiley, New York
46. Myshkin N, Kovalev A (2018) Adhesion and surface forces in polymer tribology – a review. Friction 6:143–155. https://doi.org/10.1007/s40544-018-0203-0
47. Bely VA, Sviridenok AI, Petrokovets MI, Savkin VG (1982) Friction and wear in polymer-based materials. Pergamon, Oxford
48. Heise R, Popov L (2010) Adhesive contribution to the coefficient of friction between rough surfaces. Tribol Lett 39:247–250. https://doi.org/10.1007/s11249-010-9617-1
49. Berardo A, Costagliola G, Ghio S, Boscardin M, Bosia F, Pugno MN (2019) An experimental-numerical study of the adhesive static and dynamic friction of micro-patterned soft polymer surfaces. Mater Des 181:107930. https://doi.org/10.1016/j.matdes.2019.107930
50. Lucchetta G, Marinello F, Bariani PF (2011) Aluminum sheet surface roughness correlation with adhesion in polymer metal hybrid overmolding. CIRP Ann 60:559–562. https://doi.org/10.1016/j.cirp.2011.03.073
51. Reid JV, Schey A (1987) The effect of surface hardness on friction. Wear 118:113–125. https://doi.org/10.1016/0043-1648(87)90008-1
52. Valkis AI, Yastrebov VA, Scheibert J, Nicola L, Dini D, Minfray C, Almqvist A, Paggi M, Lee S, Limbert G, Molinari JF, Anciaux G, Aghababaei R, Restrepo SE, Papangelo A, Cammarata A, Nicolini P, Putignano C, Carbone G, Stupkiewicz S, Lengiewicz J, Costagliota G, Bosia F, Guarino R, Pugno NM, Müser MH, Ciavarella M (2018) Modeling and simulation in tribology across scales: an overview. Tribol Int 125:169–199. https://doi.org/10.1016/j.triboint.2018.02.005
53. Derjaguin BV, Muller VM, Toporov YP (1975) Effect of contact deformations on the adhesion of particles. J Collloid Interference Sci 53:314–326. https://doi.org/10.1016/0021-9797(75)90018-1
54. Myshkin N (2009) Kovalev: adhesion and friction of polymers and polymer composites. In: Sinha K, Briscoe BJ (eds) Polymer Tribology. Imperial College Press, London, pp 3–37

55. Johnson KL, Kendall K, Roberts AD (1971) Surface energy and the contact of elastic solids. Proc R Soc Lond A 324:301–313. https://doi.org/10.1098/rspa.1971.0141
56. Johnson KL, Kendall K, Roberts AD (1997) An adhesion map for the contact of elastic spheres. J Colloid Interface Sci 192:326–333. https://doi.org/10.1006/jcis.1997.4984
57. Prokopovich P, Starov V (2011) Adhesion models: from single to multiple asperity contacts. Adv Colloid Interface Sci 168:210–222. https://doi.org/10.1016/j.cis.2011.03.004
58. Ciavarella M, Joe J, Papangelo A, Barber JR (2019) The role of adhesion in contact mechanics. J R S Interface 16:20180738. https://doi.org/10.1098/rsif.2018.0738
59. Tabor D (1977) Surface forces and surface interactions. J Colloid Interface Sci 58:2–13. https://doi.org/10.1016/0021-9797(77)90366-6
60. Maugis D (1992) Adhesion of spheres: the JKR-DMT transition using a Dugdale model. J Colloid Interface Sci 158:243–269. https://doi.org/10.1016/0021-9797(92)90285-T
61. Fuller D, Tabor KNG (1975) The effect of surface roughness on the adhesion of elastic solids. Proc R Soc London A 345:327–342. https://doi.org/10.1098/rspa.1975.0138
62. Persson BNJ (2001) Theory of rubber friction and contact mechanics. J Chem Phys 115:3840–3861. https://doi.org/10.1098/rspa.1975.0138
63. Almqvist A, Campañá C, Prodanov N, Persson BNJ (2011) Interfacial separation between elastic solids with randomly rough surfaces: comparison between theory and numerical techniques. J Mech Phys Solids 59:2355–2369. https://doi.org/10.1016/j.jmps.2011.08.004
64. Carbone G, Scaraggi M, Tartaglino U (2009) Adhesive contact of rough surfaces: comparison between numerical calculations and analytical theories. Eur Phys J E 30:65–74. https://doi.org/10.1140/epje/i2009-10508-5
65. Putignano C, Afferante L, Carbone G, Demelio GP (2012) The influence of the statistical properties of self-affine surfaces in elastic contacts: a numerical investigation. J Mech Phys Solids 60:973–982. https://doi.org/10.1016/j.jmps.2012.01.006
66. Putignano C, Afferante L, Carbone G, Demelio GP (2013) A multiscale analysis of elastic contacts and percolation threshold for numerically generated and real rough surfaces. Tribology Int 64:148–154. https://doi.org/10.1016/j.triboint.2013.03.010
67. Putignano C, Afferante L, Carbone G, Demelio GP (2012) A new efficient numerical method for contact mechanics of rough surfaces. Int J Solids Struct 49:338–343. https://doi.org/10.1016/j.ijsolstr.2011.10.009
68. Ciavarella M, Demelio G, Baber JR, Jang YH (2000) Linear elastic contact of the Weierstrass profile. Proc R Soc A 456:387–405. https://doi.org/10.1098/rspa.2000.0522
69. Afferante L, Ciavarella M, Demelio G (2015) Adhesive contact of the Weierstrass profile. Proc R Soc A 471:20150248. https://doi.org/10.1098/rspa.2015.0248
70. Kashani MR, Behazin E, Fakhar A (2011) Construction and evaluation of a new tribometer for polymers. Polym Test 30:271–276. https://doi.org/10.1016/j.polymertesting.2011.01.003
71. Delaney K, Kenedy D, Bissacco G (2011) Development of a friction testing apparatus for demoulding force predictione. Paper presented at the IMC28, International Manufacturing Conference, Dublin, Ireland, 30th August–1st September 2011. https://doi.org/10.21427/ha7x-1c30
72. Rodrigues AR, Pontes AJ (2016) Coefficient of friction measurements in similar conditions to the ejection phase in injection moulding process. O Molde (111):48–53
73. Rodrigues A, Pontes AJ (2013) Assessment of the coefficiente of friction in ejection conditions in injection moulds. O Molde (99):39–41
74. Rodrigues AR, Pontes AJ (2014) Evaluation of coefficient of friction in conditions similar to ejection of moulding parts. Paper presented at PMI2014 - International Conference on Polymers and Moulds Innovations - Guimarães, Portugal, 10–12 September 2014. (ISBN: 978-972-8692-89-6)
75. Pontes AJ, Ferreira EC, Pouzada AS (2004) The effect of temperature and surface roughness on coefficient of friction between thermoplastics and molding surfaces. Paper presented at Proceedings of the regional meeting of the Polymer Processing Society - Florianopolis, Brazil, 193–194 November 2004
76. Garcia MCR (2014) Shrinkage and ejection forces in thermoplastics reinforced with glass fibres and nanoclays. PhD Thesis - University of Minho
77. Pontes AJ, Pouzada AS (2004) Ejection force in tubular injection moldings. Part I: effect of processing conditions. Polym Test 44:891–897. https://doi.org/10.1002/pen.20080
78. Shen K, Chen L, Jiang L (1999) Calculation of ejection force of hollow, thin walled, and injection moulded cones. Plast Rubber Compos 28:341–345. https://doi.org/10.1179/146580199101540493
79. Su Q, Gilchrist MD (2016) Demolding forces for micron-sized features during micro-injection molding. Polym Eng Sci 56:810–816. https://doi.org/10.1002/pen.24309
80. Santhapuram RR, Nair AK (2017) Frictional properties of multi-asperity surfaces at the nanoscale. Comput Mater Sci 136:253–263. https://doi.org/10.1016/j.commatsci.2017.05.001
81. Masato D, Sorgato M, Parenti P, Annoni M, Lucchetta G (2017) Impact of deep cores surface topography generated by micro milling on the demolding force in micro injection molding. J Mater Process Technol 246:211–223. https://doi.org/10.1016/j.jmatprotec.2017.03.028
82. Hopkinson N, Dickens P (2000) A comparison between stereolithography and aluminium injection moulding tooling. Rapid Prototyp J 6:253–258. https://doi.org/10.1108/13552540010373353
83. Westphal MG, Pouzada AS, Salmoria GV, Ahrens CH (2006) Performance and friction properties of injection hybrid moulds with stereolithography moulding zones. Mater Sci Forum 514–516:1673–1677. https://doi.org/10.4028/www.scientific.net/MSF.514-516.1673
84. Martinho PG (2021) Alternative materials in moulding elements of hybrid moulds: structural integrity and tribological aspects. Int J Adv Manuf Technol 113:351–363. https://doi.org/10.1007/s00170-021-06630-5
85. Pontes AJ, Queirós MP, Martinho PG, Bártolo PJ, Pouzada AS (2010) Experimental assessment of hybrid mould performance. Int J Adv Manuf Technol 50:441–448. https://doi.org/10.1007/s00170-010-2546-1
86. Benabdallah HS (2007) Static friction coefficient of some plastics against steel and aluminum under different contact conditions. Tribol Int 40:64–73. https://doi.org/10.1016/j.triboint.2006.02.031
87. Netto ACS (2008) Desenvolvimento de compósitos de resina epóxi e fibras curtas de aço para fabricação rápida de moldes para injecção de termoplásticos. PhD Thesis - Universidade Federal de Santa Catarina. http://repositorio.ufsc.br/xmlui/handle/123456789/91734
88. Correia MS, Martinho PG, Pouzada AS (2014) The ejection force effect on the life of hybrid mould inserts produced by additive manufacturinge. Paper presented at the PMI2014, International Conference on Polymers and Moulds Innovations, University of Minho, Guimarães, Portugal, 10–12 September 2014
89. Bhushan B (2000) Surface roughness analysis and measurement techniques. In: Bhushan B (ed) Modern tribology handbook, two volume set. CRC Press, Boca Raton, p 72
90. Geddes KO, Czapor SR, Labahn G (2003) Handbook of surface and nanometrology. CRC Press, Boca Raton

91. Correia MS, Martinho PG, Pouzada AS (2014) The ejection force effect on the life of hybrid mould inserts produced by additive manufacturing. Paper presented at the PPS2004, Americas Regional Meeting Proceedings, Florianopolis, Brazil, 2004
92. Sedlaček M, Podgornik B, Vižintin J (2012) Correlation between standard roughness parameters skewness and kurtosis and tribological behaviour of contact surfaces. Tribol Int 48:102–112. https://doi.org/10.1016/j.triboint.2011.11.008
93. Menezes PL, Kishore & Kailas SV (2009) Influence of roughness parameters and surface texture on friction during sliding of pure lead over 080 m40 steel. Int J Adv Manuf Technol 43:731–743. https://doi.org/10.1007/s00170-008-1756-2
94. Gadelmawla ES, Koura MM, Maksoud TMA, Elewa IM, Soliman HH (2002) Roughness parameters. J Mater Proces Technol 123:133–145. https://doi.org/10.1016/S0924-0136(02)00060-2
95. Jiang H, Browning R, Fincher J, Gasbarro A, Jones S, Sue H-J (2008) Influence of surface roughness and contact load on friction coefficient and scratch behavior of thermoplastic olefins. Appl Surf Sci 254:4494–4499. https://doi.org/10.1016/j.apsusc.2008.01.067
96. Mo Y, Turner K, Szlufarska I (2009) Friction laws at the nanoscale. Nature 457:1116–1119. https://doi.org/10.1038/nature07748
97. Sasaki T, Koga N, Shirai K, Kobayashi Y, Toyoshima A (2000) An experimental study on ejection forces of injection molding. Precis Eng 24:270–273. https://doi.org/10.1016/S0141-6359(99)00039-2
98. Mittal KL (2001) Adhesion aspects of thin films, vol 1. Zeist, VSP
99. Freund LB, Suresh S (2004) Thin film materials: stress, defect formation and surface evolution. Cambridge University Press, Cambridge
100. Bubert H, Jenett EH (2002) Surface and thin film analysis: principles, instrumentation, applications. Wiley-VCH, Weinheim
101. Steckelmacher W (2000) Introduction to surface and thin film processes. Cambridge University Press, Cambridge
102. Seshan K (2002) Handbook of thin-film deposition processes and techniques, 2nd edn. Noyes Publications, Norwich
103. Vetter J (2014) 60 years of DLC coatings: historical highlights and technical review of cathodic arc processes to synthesize various DLC types, and their evolution for industrial applications. Surf Coatings Technol 257:213–240. https://doi.org/10.1016/j.surfcoat.2014.08.017
104. Mabuchi Y, Higuchi T, Weihnacht V (2013) Effect of sp2/sp3 bonding ratio and nitrogen content on friction properties of hydrogen-free DLC coatings. Tribol Int 62:130–140. https://doi.org/10.1016/j.triboint.2013.02.007
105. Bhowmick S, Sen FG, Banerji A, Alpas AT (2015) Friction and adhesion of fluorine containing hydrophobic hydrogenated diamond-like carbon (F-H-DLC) coating against magnesium alloy AZ91. Surf Coatings Technol 267:21–31. https://doi.org/10.1016/j.surfcoat.2014.11.047
106. Fox-Rabonovich G, Dasch JM, Wagg T, Yamamoto K, Veldhuis S, Dosbaeva GK, Tauhiduzzaman M (2011) Cutting performance of different coatings during minimum quantity lubrication drilling of aluminum silicon B319 cast alloy. Surf Coatings Technol 205:4107–4116. https://doi.org/10.1016/j.surfcoat.2011.03.006
107. Hong-mei W, Wei Z, He-long Y, Qing-liang L (2011) Tribological properties of DLC films prepared by magnetron sputtering. Phys Procedia 18:274–278. https://doi.org/10.1016/j.phpro.2011.06.094
108. Zou CW, Wang HJ, Feng L, Xue SW (2013) Effects of Cr concentrations on the microstructure, hardness, and temperature-dependent tribological properties of Cr-DLC coatings. Appl Surf Sci 286:137–141. https://doi.org/10.1016/j.phpro.2011.06.094
109. Kalin M, Oblak E, Akbari S (2016) Evolution of the nano-scale mechanical properties of tribofilms formed from low- and high-SAPS oils and ZDDP on DLC coatings and steel. Tribol Int 96:43–56. https://doi.org/10.1016/j.triboint.2015.12.013
110. Manninen NK, Ribeiro F, Escudeiro A, Polcar T, Carvalho S, Cavaleiro A (2013) Influence of Ag content on mechanical and tribological behavior of DLC coatings. Surf Coatings Technol 232:440–446. https://doi.org/10.1016/j.surfcoat.2013.05.048
111. Manninen NK, Galindo R, Carvalho S, Cavaleiro A (2015) Silver surface segregation in Ag-DLC nanocomposite coatings. Surf Coatings Technol 267:90–97. https://doi.org/10.1016/j.surfcoat.2014.12.029
112. Tamulevičius T, Tamulevičienė A, Virganavičius D, Vasiliauskas A, Kopustinskas V, Meškinis S, Tamulevičius S (2014) Structuring of DLC: Ag nanocomposite thin films employing plasma chemical etching and ion sputtering. Nucl Instruments Methods Phys Res Sect B: Beam Interact with Mater Atoms 341:1–6. https://doi.org/10.1016/j.nimb.2013.09.052
113. Masuko M, Ono T, Aoki S, Suzuki A, Ito H (2015) Friction and wear characteristics of DLC coatings with different hydrogen content lubricated with several Mo-containing compounds and their related compounds. Tribol Int 82 Part B:350–357. https://doi.org/10.1016/j.triboint.2014.04.037
114. Kilman L, Jaoul C, Colas M, Tristant P, Dublanche-Tixier C, Labord E, Meunier F, Jarry O (2015) Friction and wear performance of multilayered a-C:H: Al coatings. Surf Coatings Technol 284:159–165. https://doi.org/10.1016/j.surfcoat.2015.07.079
115. Banerji A, Bhowmick S, Alpas AT (2014) High temperature tribological behavior of W containing diamond-like carbon (DLC) coating against titanium alloys. Surf Coatings Technol 241:93–104. https://doi.org/10.1016/j.surfcoat.2013.10.075
116. Chen Z, He X, Xiao C, Kim SH (2018) Effect of humidity on friction and wear - a critical review. Lubricants 6(3):74. https://doi.org/10.3390/lubricants6030074
117. Bazrafshan M, Rooij MB, Schipper DJ (2019) The effect of adhesion and roughness on friction hysteresis loops. Int J Mech Sci 155:9–18. https://doi.org/10.1016/j.ijmecsci.2019.02.027
118. Bernal RA, Chen P, Schall JD, Harrison JA, Jeng Y-R, Carpick RW (2018) Influence of chemical bonding on the variability of diamond-like carbon nanoscale adhesion. Carbon 128:267–276. https://doi.org/10.1016/j.carbon.2017.11.040
119. Ding HH, Fridrici V, Geringer J, Fontaine J, Kapsa P (2019) Low-friction study between diamond-like carbon coating and Ti-6Al-4V under fretting conditions. Tribol Int 135:368–388. https://doi.org/10.1016/j.triboint.2019.03.026
120. Schoenherr M, Ruehl H, Guenther T, Zimmermann A, Gundelsweiler B (2023) Adhesion-induced demolding forces of hard coated microstructures measured with a novel injection molding tool. Polymers 15:1285. https://doi.org/10.3390/polym15051285
121. Qu J, Blau PJ, Higdon C, Cook BA (2016) Friction behavior of a multi-interface system and improved performance by AlMgB14-TiB2-C and diamond-like-carbon coatings. Tribol Int 99:182–186. https://doi.org/10.1016/j.triboint.2016.03.022
122. Schalk N, Mitterer C, Letofsky-Papst I, Czettl C, Sartory B, Penoy M, Michotte C (2013) Friction reduction by thermal treatment of arc evaporated TiAlTaN coatings in methane. Tribol Int 67:54–60. https://doi.org/10.1016/j.triboint.2013.06.020
123. Tillmann W, Dias NFL, Stangier D, Gelinski N (2019) Tribological performance of PVD film systems against plastic counterparts for adhesion-reducing application in injection molds. Coatings 9(9):588. https://doi.org/10.3390/coatings9090588
124. Dai M-J, Wei C-B, Zhou K-B, Zhu M, Hou H-J, Lin S-S, Tong X (2015) Properties of W/DLC/W-S-C composite films fabricated by magnetron sputtering. Trans Nonferrous Met Soc China 25(9):3002–3011. https://doi.org/10.1016/S1003-6326(15)63927-9
125. Mutafov P, Lanigan J, Neville A, Cavaleiro A, Polcar T (2014) DLC-W coatings tested in combustion engine - frictional and wear

analysis. Surf Coatings Technol 260:284–289. https://doi.org/10.1016/j.surfcoat.2014.06.072
126. Yang L, Neville A, Brown A, Ransom P, Morina A (2014) Friction reduction mechanisms in boundary lubricated W-doped DLC coatings. Tribol Int 70:26–33. https://doi.org/10.1016/j.triboint.2013.09.020
127. Nyberg H, Sundberg J, Särhammar E, Gustavsson F, Kubart T, Nyberg T, Jansson U, Jacobson S (2013) Extreme friction reductions during initial running-in of W-S-C-Ti low-friction coatings. Wear 302:987–997. https://doi.org/10.1016/j.wear.2013.01.065
128. Totolin V, Ripoll MR, Jech M, Podgornik B (2016) Enhanced tribological performance of tungsten carbide functionalized surfaces via in-situ formation of low-friction tribofilms. Tribol Int 94:269–278. https://doi.org/10.1016/j.triboint.2015.08.017
129. Fan N, Guo J, Jing G, Liu C, Wang Q, Wu G, Jiang H, Peng B (2020) A hillock-like phenomenon with low friction and adhesion on a graphene surface induced by relative sliding at the interface of graphene and the SiO 2 substrate using an AFM tip. Nanoscale Adv 2:2548–2557. https://doi.org/10.1039/c9na00660e
130. Pierson H (1994) Handbook of carbon, graphite, diamond and fullerenes - properties, processing and applications. Noyes Publications, New Jersey
131. Podgornik B, Sedlaček M, Vižintin J (2007) Influence of contact conditions on tribological behaviour of DLC coatings. Surf Coatings Technol 202:1062–1066. https://doi.org/10.1016/j.surfcoat.2007.07.040
132. Vitu T, Escudeiro T, Polcar T, Cavaleiro A (2014) Sliding properties of Zr-DLC coatings: the effect of tribolayer formation. Surf Coatings Technol 258:734–745. https://doi.org/10.1016/j.surfcoat.2014.08.003
133. Martins LC, Martins CI, Pontes AJ (2014) Study of ejection forces in injection moulding of thin-walled tubular mouldings. Paper presented at the PMI2014, International Conference on Polymers and Moulds Innovations, University of Minho, Guimarães, Portugal, 10–12 September 2014
134. Worgull M, Hétu J-F, Kabanemi KK, Heckele M (2008) Hot embossing of microstructures: characterization of friction during demolding. Microsyst Technol 14(6):767–773. https://doi.org/10.5555/1388686.1388692
135. Worgull M, Hétu J-F, Kabanemi KK, Heckele M, Karlsruhe F, Mikrostrukturtechnik I (2006) Characterization of friction during the demolding of microstructures molded by hot embossing. Paper presented at the DTIP 2006, Stresa, Lago Maggiori, Italy, April 2006, DOI: hal-00189317
136. Unal H, Mimaroglu A (2003) Friction and wear behaviour of unfilled engineering thermoplastics. Mater Des 24:183–187. https://doi.org/10.1016/S0261-3069(03)00018-9
137. Griffiths CA, Tosello G, Dimov SS, Scholz SG, Rees A, Whiteside B (2014) Characterisation of demoulding parameters in micro-injection moulding. Microsyst Technol 21:1677–1690. https://doi.org/10.1007/s00542-014-2269-6
138. Griffiths CA, Dimov SS, Scholz SG, Tosello G, Rees A (2014) Influence of injection and cavity pressure on the demoulding force in micro-injection moulding. ASME J Manuf Sci Eng 136(3):031014. https://doi.org/10.1115/1.4026983

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