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Test Equipment

Friction properties of moulding thermoplastics

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Abstract

During the ejection phase of the injection moulding cycle the parts are mechanically forced to separate from the moulding surfaces, this aspect being more relevant with deep cores. The design of the ejection system depends on factors such as the draft angles, the surface finish, and the properties of the moulding material at the ejection temperature and the dimensioning of actuation devices (e.g., hydraulic or pneumatic cylinders). Knowledge of the friction properties of the mating metal and plastics surfaces is important to optimize the ejection system. The coefficient of friction at the ejection stage depends on the surface texture of the core and the temperature at ejection.

This paper reviews recent research on the static coefficient of friction in moulding conditions. It also reviews results obtained with a prototype apparatus that reproduces the conditions occurring during the ejection phase.

Keywords: Friction test; Coefficient of friction; Injection moulding; Thermoplastics

1. Friction in injection moulds

Thermoplastics are the most widely used materials in components for applications that range from noncritical packaging products to very demanding technical parts. The majority of these products are obtained by injection moulding. Injection moulds are typically complex tools that are expected to be efficient and reliable in operation, and cost and time effective at their design and manufacturing stages. An injection mould consists of several functional systems that guarantee not only the fulfilment of the product specifications (dimensions, mechanical properties) but also smooth operation of the mould in production. The ejection system, especially for the production of parts that are difficult to extract from the mould cores, assumes a relevant importance in the product quality [1–3]. For the design of this system, knowledge of the involved forces is required. During the ejection phase, friction forces develop between the polymer surface and the surface of the mould, which is usually made of steel [4]. These frictional forces result from polymer shrinkage onto the mould cores. In the particular case of deep cores, due to the difference between the thermal expansion coefficients of the thermoplastics and the steel ($0.6–1.4\times10^{-4}$ and $12\times10^{-6}\,K^{-1}$, respectively), these forces can be significant. In the injection moulding process, during the injection phase the melt polymer is driven into the mould impression. Upon cooling, due to the mentioned phenomena, the polymer surface tends to replicate the superficial texture of the mould surface.

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In the ejection stage of injection moulding, parts with deep cores are mechanically forced to separate from the moulding surfaces (Fig. 1). The forces to be overcome at this stage result from the combined effect of the shrinkage of the moulding material and the coefficient of friction between the moulded material and the core. The efficiency of the ejection depends on a number of factors that are of concern to the designer, namely the draft angles of the core and its surface finish, the properties of the plastic material at the ejection temperature and the actuation devices (such as hydraulic or pneumatic cylinders). The aesthetics and functionality of the products may require the use of small draft angles. However, small draft angles lead to an increase of the overall ejection forces [5].

Good surface finish is obtained by time-consuming techniques like polishing, leading to more expensive moulds. Economy in the mould making industry puts pressure on to the use of not so smooth surface finish of the cores (responsible for the smoothness of the inner part of mouldings that are normally invisible). In addition, it is known that mirror-like very polished surfaces can be difficult to separate due to the local build up of adhesion forces. To minimize these problems it is a common practice to make the surface finishing in the ejection direction.

Productivity in injection moulding requires the minimization of the cooling time at the cost of higher ejection temperatures and poorer mechanical properties of the moulded products. These additional factors further contribute against an easy and safe ejection of the parts from the mould.

Moreover, after cooling from melt temperature, the plastic tends to stick over the surface of the cores, reproducing closely its surface finish. This unusual circumstance may lead to significant variation of the coefficient of friction, since in common standard test methods this condition is never considered. This was the motivation to develop a prototype equipment to study the effective coefficient of friction under those conditions.

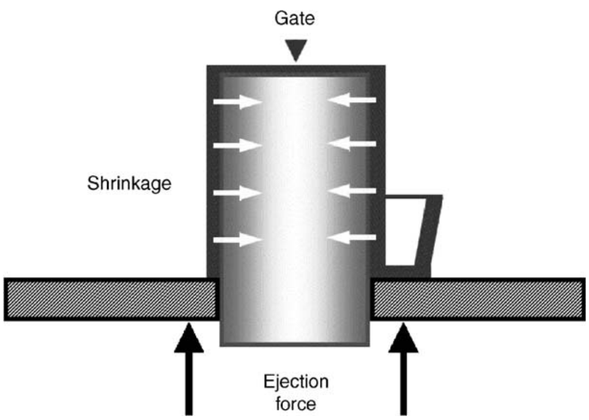


Fig. 1. Shrinkage and ejection force in deep core mouldings.

2. Friction

2.1. Solid friction

Friction is normally understood as the resistance to relative motion offered by bodies in contact. In injection moulding the bodies in contact are steel moulding surfaces and polymer mouldings.

The concept of coefficient of friction and the corresponding laws were originated, centuries ago, in the works by Leonardo da Vinci, Guillaume de Amontons and Charles Augustin de Coulomb. Those laws are used in many practical situations with good results and can be stated in very simple terms as:

- The static friction may be larger than kinetic (dynamic) friction.
- The friction force is proportional to normal force.
- The friction force is independent of the contact area.

Nevertheless, in the processes of moulding thermoplastics as injection moulding or thermoforming, there are situations in which these laws are not in agreement with experimental observations [6,7].

Friction is caused by forces acting at the interface between the surfaces of contacting bodies. The magnitude of those forces is related to the properties of the two contacting surfaces and the two materials. These forces are usually difficult to predict because the surface properties continuously change over time by deformation, wear, segregation of components or oxidation. Moreover, the effective contact area between the bodies is also different from the apparent area of bodies, owing to the roughness of the contact surfaces.

The friction properties of pairs of materials are usually represented by the coefficient of friction, μ. The coefficient of friction is associated with the frictional force needed to start or maintain motion, and is defined as

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

Table 1
Coefficients of friction between various polymers and mild steel [11]

Polymer	μ_k	μ_s
PP	0.08	0.11
PC	0.34	0.38
ABS	0.30	0.35
PA 6	0.22	0.26

in which F is the friction force and N the normal contact force.

The static coefficient of friction between two solid surfaces μ_s, is defined as the ratio of the tangential force required to produce sliding divided by the normal force between the surfaces. This is the situation that better describes the onset of the ejection process.

A kinetic coefficient of friction is obtained from the average friction force necessary to maintain the macroscopic relative motion between the two bodies. It is represented by μ_k. In our case, because of the draft angles used in injection moulds, this parameter is relatively less interesting.

The coefficients of static friction for typical bearing materials range from 0.03 in specially lubricated bearings to 0.5–0.7 in the case of dry sliding [8]. Typical values for the coefficient of friction of various polymers in contact with steel are listed in Table 1 [9].

3. Friction in injection moulds

3.1. Friction in the ejection stage of injection moulding

The static coefficient of friction in the context of polymer engineering was given specific attention in the early eighties. James and Newell, who were interested in describing the tribological behaviour of plastics and rubber, developed an apparatus that could assess the frictional forces under various contact loads, speed of testing and temperature [10]. In the context of injection moulding, where the prediction of ejection forces is relevant, the first attempts were made by Menges [4]. In the Menges work a mould was developed enabling the study of the effect of different moulding conditions. The surface roughness and the presence of a release agent were observed to be important parameters. The melt temperature and the mould temperature were identified as second order parameters as regards their influence on the coefficient of static friction for several materials (PE, PP, PS, ABS and PC). Scatter in their results was pointed out as a problem limiting the broadness of the conclusions obtained.

The dynamic friction between polymers and steel was later studied by Vaziri et al. [11]. This property is less interesting for the ejection stage in injection moulding owing to the draft angles used in deep core mouldings significantly reducing the ejection force after ejection is started. When studying the design of ejector pins, in the late eighties, Malloy and Majeski [12] reported the same difficulty of predicting the coefficient of friction as one of the key problems in designing the ejection system in injection moulds. In the early nineties Burke and Malloy [1] used the thermal expansion coefficient, the stiffness at the temperature of ejection and coefficients of friction obtained by Menges and Bangert [4] to predict ejection forces. The error in the predictions was of the order of 16% for ABS and HDPE.

Balsamo et al. [2] were possibly the first researchers to report on a standard test procedure adequate to injection moulding, using a temperature-controlled chamber. Steel, nickel-plated steel and PTFE/nickel-plated steel specimens were studied in contact with PS, PP, PC/polyester alloy and 10% glass fibre reinforced PC specimens. The effect of the test temperature on the coefficient of friction was also analyzed. The method was also adequate to assess the influence of plating and the use of release agents on the coefficient of friction polymer/steel. More recently, a study on the friction force developing between rings of polymer moulded over a ring of steel with different surface roughnesses was reported by Dearnley [13]. Good correlation was observed between the roughness of the steel and of the polymer ring. Coatings of TiN, CrN and MoS_2 were studied in terms of the friction force against polyacetal. CrN coatings in P20 steel lead to the lowest observed friction forces in spite of the slightly higher surface roughness. This result was attributed to the chemical behavior of the coating at the interface.

The coefficient of friction between the part and the mould core does have a significant influence on the ejection process as already shown by Malloy [1,2]. Sasaki et al. [14] studied the effect of the core roughness and injection pressure on the ejection force, to clarify the factors that cause it to increase.

Elsewhere, we have reported on the existence of an optimal surface roughness when the ejection force is lower, using a special mould that produced a lateral gated tube [6]. This mould enabled the direct measurement of the ejection force but was inadequate for the analysis and modelling of the ejection process due to the complex radial injection flow pattern and the existence of a long weld line in the mouldings. More recently, new data was produced in a mould where the results enabled a clearer correlation between processing and the shrinkage to be established [3]. Within the scope of this work a model was developed to correlate the thermomechanical environment and the material properties with the prediction of ejection forces [15].

An important factor arising from the model is that the static coefficient of friction between the plastic and metal surfaces in contact is greatly influenced by the surface roughness, contact temperature and some processing variables, such as cooling time, melt temperature and holding pressure. The comparison between experimental data and simulation suggested that substantial errors could derive from not using a coefficient of friction adjusted to the actual processing conditions.

The analysis of the data available in the literature (e.g. [16]) also indicated the non-existence of data on this property that could be used for exactly predicting the ejection process of mouldings.

4. A new testing equipment

The ISO 8295 standard establishes how to determine the coefficient of friction of plastics film and sheeting [17]. It has been used for the determination of the friction properties of plastics in relative motion with other materials (e.g. [7]). This test can be run at temperatures different from room temperature but there are practical difficulties. The early James and Newell apparatus [10] uses the temperature cabinet of a tensile machine to achieve different test temperatures but does not reproduce a major feature of the ejection mechanism of mould plastics: the replication of the moulding surface onto the part surface.

The concept for an equipment enabling study of the effect of different parameters on the coefficient of friction relevant for the ejection of plastic parts from injection moulds was developed and is illustrated in Fig. 2 [18].

According to this concept a solution was engineered (Fig. 3) to the following specifications:

- Range of operating temperatures enabling the reproduction of actual ejection temperatures (20–180 °C).
- Range of testing speeds (1–100 mm/min).
- Replication of the surface roughness of the moulding surface into the plastic specimen.
- Control of the normal contact force between moulding surface and specimen.
- Control of the evolution of the friction force with time.

To meet the specifications, functional systems are required for temperature control, control of contact pressure for replication of the surface and for testing, and movement guiding. A brief description of the functional systems follows.

Temperature control: The control of the temperature is important for good replication of the surface at temperatures close to melt temperature of semicrystalline materials or above the glass transition temperature in the case of amorphous materials under study. It is also important to maintain the temperature during the friction test.

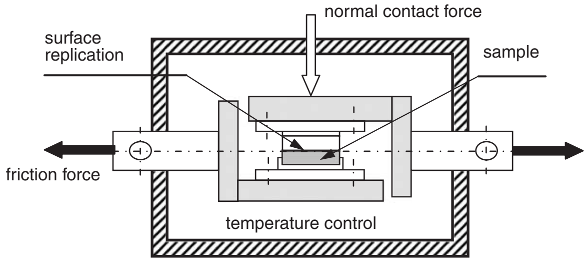


Fig. 2. Concept for the friction testing equipment.

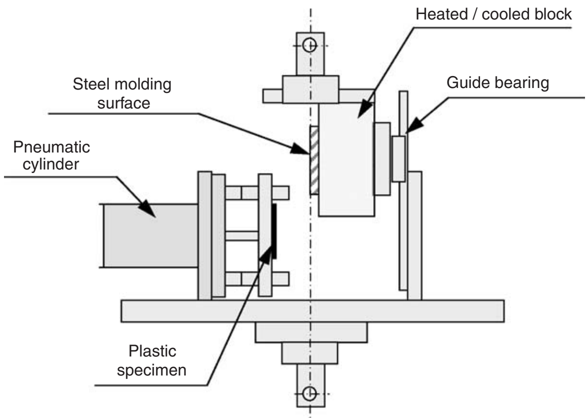


Fig. 3. Technical drawing of the friction testing equipment.

Heating is achieved by cartridge heaters allowing the temperature to rise from room temperature up to the replication temperature within a reasonable time (typically 5 min). 5 mm-insulating plates are used to minimize heat losses.

Cooling down from replication temperature to the testing temperature is obtained by circulating water in the cooling circuit.

Control of contact pressure: A pneumatic cylinder is used to produce the contact pressure. The control of the pressure is obtained with a piezo-resistive pressure sensor.

Monitoring of friction force: The use of a tensile test machine is an easy and reliable way to control and acquire the friction force data during the test. The prototype apparatus (Fig. 4) was designed to be mounted and work with a universal tensile test machine (in a similar manner as the James and Newell apparatus).

4.1. Test routine

The testing routine includes the following steps:

1. Heating of the moulding surface up to the replication temperature.
2. Stabilization of the temperature.
3. Application of contact pressure to get surface replication.
4. Cooling down to the testing temperature.
5. Friction test at selected cross-head speed.

The cycle time for the complete routine is typically 15–20 min.

4.2. Testing data

Reproducibility: The equipment yields reproducible results with variation of the order of magnitude of 1% in terms of the calculated coefficient of friction [19].

Sensitivity to temperature: The experiments with the equipment demonstrate that the test temperature influences the coefficient of friction. The data in Fig. 5 shows that dependence for polycarbonate moulded on a surface of roughness $R_a = 0.5\,\mu m$.

Influence of normal force: Upon using the apparatus it was also observed that the coefficient of friction is also dependent on the applied compressive force. This is a clear result from the replication of the plastics material over the topography (roughness) of the metal plate.

Fig. 4. View of the equipment installed in a universal testing machine.

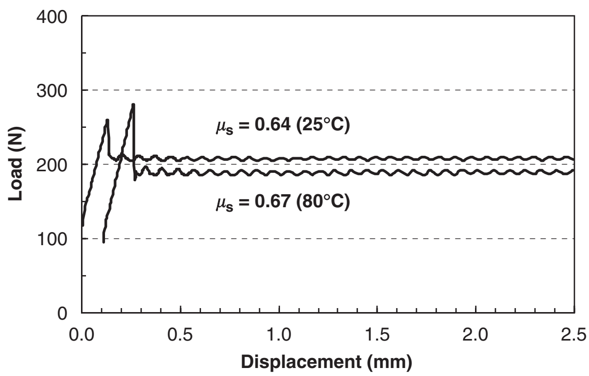


Fig. 5. Dependence of the friction force on the testing temperature for the case of a polycarbonate (Lexan 141 R from GE Plastics).

5. The relevance of roughness

5.1. Friction vs. temperature and roughness

Tests with semi-crystalline and amorphous materials showed that there is a dependence of the coefficient of friction on the temperature and also on the roughness of the metal surface.

Concerning the temperature effect, there is a general trend for the coefficient of friction to increase, this effect being less pronounced at higher temperatures. This aspect can be observed in the case of ABS moulded over surfaces of different roughnesses (Fig. 6).

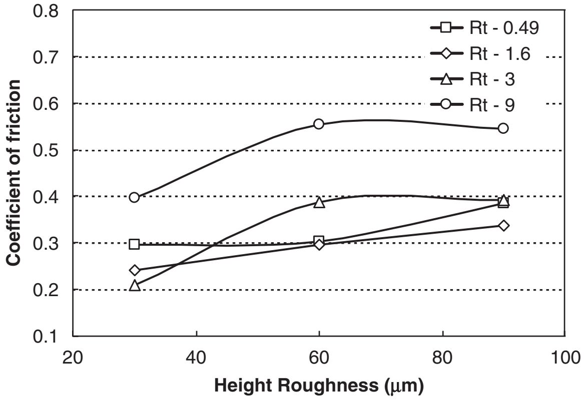


Fig. 6. Dependence of the coefficient of friction on the surface roughness and the testing temperature for the case of an ABS (Cycolac G 360 from GE Plastics).

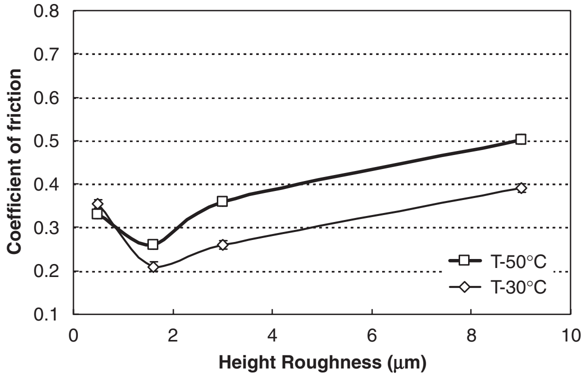


Fig. 7. Dependence of the coefficient of friction on the surface roughness for the case of a HDPE (HE 7013 from Borealis).

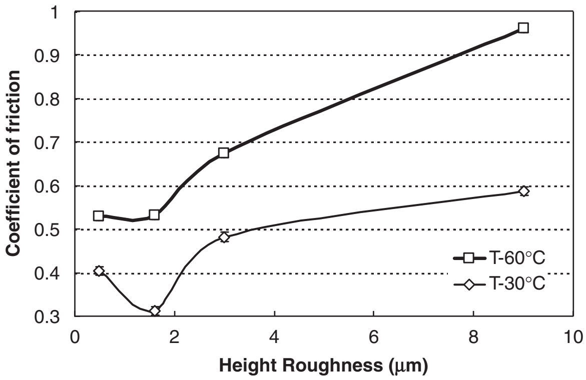


Fig. 8. Dependence of the coefficient of friction on the surface roughness for the case of a PMMA (Plexiglas 7N from Degussa).

For all cases, the trend of the coefficient of friction is to increase with the roughness, as an expected influence of the mechanical effect of the surface asperities. However, when the roughness is reduced to the level of highly polished surfaces (height roughness, R_t, below 1 µm) there is an increase in the value of the coefficient of friction corresponding to the preponderant effect of the adhesion forces between the surfaces. This aspect is observable in all types of polymeric materials, semi-crystalline (Fig. 7) and amorphous (Fig. 8).

5.2. Replication

An important feature associated with the de-moulding of injection moulded plastics products is that during moulding the polymer replicates the topology of the moulding surface. In standard friction tests this aspect is not included, but the testing method that is being described enables the replication of the plastics over the mould surface. The replication phenomenon was evaluated, both qualitatively and quantitatively [20]. Due to the soft nature of polymers, as compared to steel, traditional superficial topographic techniques, such as a stylus profilemeter, were shown to be inefficient. To achieve satisfactory results, the laser triangulation method was used for the superficial characterization of the surfaces using the prototype MICROTOP.06 MFC equipment [21].

As illustrated in Fig. 9, which shows images obtained by SEM for the moulding surface and the PC and PP mouldings, there is a clear replication of the moulding surface on the parts.

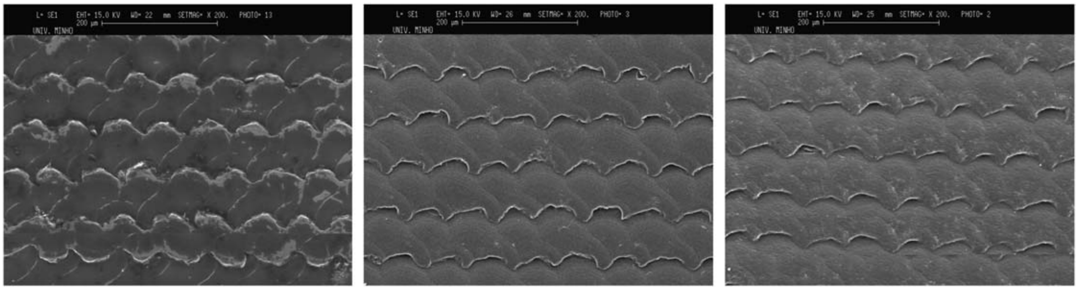
6. Final comments

The coefficient of friction of plastics during processing is very different from data published in the literature.

New prototype equipment was developed to study friction in injection moulding. It enables the determination of an optimal surface roughness that corresponds to the minimum coefficient of static friction.

The test data obtained with this equipment is sensitive to temperature, the surface roughness and the pressure between the contacting surfaces. In general, the data obtained with this test are larger than previously published comparable coefficients of friction.

For thermoplastics, the coefficient of friction is very dependent on, and follows, the testing temperature. Furthermore, the variation of the testing temperature also affects the optimum



1 2 3

Fig. 9. Topography of the surfaces as seen by SEM. 1—steel moulding surface; 2—PC replicated surface; 3—PP replicated surface.

surface roughness that minimises the coefficient of friction.

At small levels of roughness adhesion mechanisms prevail over the mechanical components of the friction mechanisms, namely the ploughing and the deformation ones.

Acknowledgments

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References

[1] C. Burke, R. Malloy, An experimental study of the ejection forces encountered during injection molding, SPE ANTEC Tech. Pap. 37 (1991).

[2] R. Balsamo, D. Hayward, R. Malloy, An experimental evaluation of ejection forces: frictional effects, SPE ANTEC Tech. Pap. 39 (1993).

[3] A.J. Pontes, A.S. Pouzada, Ejection force in tubular injection moldings. Part I: Effect of processing conditions, Polym. Eng. Sci. 44 (2004) 891.

[4] G. Menges, H. Bangert, Measurement of coefficients of static friction as a means of determinating opening and demoulding forces in injection moulds, Kunstst. Ger. Plast. 71 (1981) 552.

[5] B.J. Araújo, A.S. Pouzada, Design of ejection systems for injection moulds, O Molde 54 (2002) 36.

[6] A.J. Pontes, A.M. Pinho, A.S. Miranda, A.S. Pouzada, Effect of processing conditions on ejection forces in injection moulds, O Molde 34 (1997) 25.

[7] P. Collins, E.M.A. Harkin-Jones, P.J. Martin, The role of tool/sheet contact in plug-assisted thermoforming, Intern. Polym. Process. 17 (2002) 361.

[8] P. Blau (Ed.), Friction, Lubrication and Wear Technology, ASM Handbook, vol. 18, ASM International, Ohio, 1992, p. 8.

[9] N.A. Waterman, M.F. Ashby, The Materials Selector, vol. 3, Chapman & Hall, 1997.

[10] D.I. James, W.G. Newell, A new concept in friction testing, Polym. Test. 1 (1980) 9.

[11] M. Vaziri, F.H. Stott, R.T. Spurr, Studies of the friction of polymeric materials, Wear 122 (1988) 313.

[12] R. Malloy, P. Majeski, Design of pin ejector systems for injection molds, SPE ANTEC Tech. Pap. 47 (1989).

[13] P.A. Dearnley, Low friction surfaces for plastic injection moulding dies—an experimental case study, Wear 229 (1999) 1109.

[14] T. Sasaki, N. Koga, K. Shirai, Y. Kobayashi, A. Toyoshima, An experimental study on ejection force of injection molding, J. Precis. Eng. 24 (2000) 270.

[15] A.J. Pontes, R. Pantani, G. Titomanlio, A.S. Pouzada, Ejection force in tubular injection moldings. Part II: A prediction model, Polym. Eng. Sci. 45 (2005) 325.

[16] Friction and Wear Testing Source Book, ASM International, Ohio, 1997.

[17] ISO 8295, Plastics—Film and Sheeting—Determination of the Coefficients of Friction, 1995.

[18] E.C. Ferreira, N.M. Neves, R. Muschalle, A.S. Pouzada, Friction properties of thermoplastics in injection molding, SPE ANTEC Tech. Pap. 59 (2001).

[19] E.C. Ferreira, N.M. Neves, R. Muschalle, A.S. Pouzada, Reibungsverhalten thermoplastischer Kunststoffe/Friction behaviour of thermoplastics, Kunstst. Ger. Plast. 91 (2001) 18.

[20] E.C. Ferreira, M.F. Costa, C.R. Laranjeiro, M.J. Oliveira, A.S. Pouzada, Mater. Sci. Forum 455–456 (2004) 467.

[21] M.F. Costa, Surface inspection by an optical triangulation method, Opt. Eng. 35 (1996) 2743.