Closing force measurement on crimped closures

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Summary

The control of the crimped closures sealing is a serious problem for the quality control of the producers using such closures. The sealing of this closure is ensured by the pressure of a seal-ring between the container and the crimped closure. The sealing quality depends on the applied materials, crimped force on the crimping machines and other settings. However the closing force on the sealing can not be controlled directly, just in an indirect way by measuring the torque of the crimped closures. During the research we have specified the connection between the crimp force, the remaining closing force after the relaxation and the measurable torque, and we have also developed the right instrumentation for the quality control of crimped closures.

1. INTRODUCTION

Crimped closure is primarily used for airtight closing of pharmaceutical and cosmetic industry products packaged in bottles (e.g. ampoules). Airtight closure is provided by the rubber seal placed in the filled bottle, which is usually tightened to the opening of the bottle by an easily deformable aluminium plate. A special tool, a so-called crimping head is used for crimping. The tool compresses the rubber plug and bends the aluminium lid on the lower brim of the bottle mouth. Airtight closure is provided by the compression stress remaining in the rubber plug.

2. FUNDAMENTAL THEORY

Based on those written in the introduction, the sealing is formed between the bottle and the polymer surfaces, therefore let us introduce the main characteristics of these two materials and that of their getting into contact.

The framework of polymers is made up of carbon atoms. These are not arranged in a straight line within the polymer chain. The connecting lines between the atoms give a valence angle of 109.5^o. The different elements of the chain may swing by keeping up the value of the valence angle. Due to those mentioned above, polymer chains are rather flexible and in most cases are shaped like a clew. Decrease in temperature causes expansion of the chain, and vice versa. This is because heat-removal decreases the entropy of the polymer chain, and decreased entropy is coupled with a more arranged state, which in our case is the expanded condition. This means that by decrease in temperature the elastic closing element would expand, if it was not blocked by the closing brim. However, due to the blocking a higher force is developed in it. Glass is an *n*-type semi-conductor, which means that a low number of free electrons can always be seen in it, which can couple with the oxygen atom colliding with the surface. This way, an oxygen layer with a molecular thickness may develop on its surface. However, the potential barrier between the two surfaces is thin. It is known that electrons can penetrate through a thin potential barrier with the tunnel effect. Therefore, it is possible that oxygen atoms within the crystalline region of the polymer may bind the free electrons of the glass, due to their being electron-negative. In this case an application of force develops between the ions of the polymer and the ions of the glass, due to which the two materials create a strong molecular bond along the contact surface.

If force is applied parallel to the contact surface, the ions within the layer move related to each other. In case the maximum shear stress occurring due to symmetry causes is exceeded, the surfaces slide on each other. In this case sliding friction is created. More specifically, the above mentioned concern a local contact surface. The values of $\tau_{\max}$ at the different local contact surfaces may differ according to the degree and extension of the local order. The condition of sliding is that the shear stress values generated at the local contact surfaces should exceed the value of the local $\tau_{\max}$ everywhere.

So, the condition of shear cut of the surfaces is:

$$\sum_i \tau_{\max i} \Delta A_i = F_{ny}, \tag{1}$$

where F_{ny} is the force applied on shearing, ΔA_i is the i^{th} local contact surface size, and $\tau_{\max i}$ is the shear resistance on this surface. The average shear resistance can be defined from this:

$$\tau = \frac{F_{ny}}{A_{val}} = \sum_i \tau_{\max i} \frac{\Delta A_i}{A_{val}}. \tag{2}$$

where A_{val} is the size of the actual contact surface.

Based on the above physical formula it can be stated, that there is an average maximum shear stress, where sliding starts. This apparently corresponds to the shear stress introduced by metallic materials. Let's find out how the size of the actual surface can be defined. The polymer is an elastic material, in our case no plastic deformation is to be taken into calculation. So the actual contact surface is created due to plastic deformation, not in the way as by metallic materials. It is also apparent that it is enough to take the deformation of the polymer into consideration, as the elastic modulus of the glass is much greater. Since the actual contact surface is created as the resultant of deformations of small peaks, it is assumable that the ratio of the normal force compressing the surfaces and the actual contact surfaces can be given by a function *f(E,G)* made up of the elasticity (*E*) and shearing (*G*) modulus of the polymer:

$$A_{val} = \frac{F_N}{f(E,G)}. \tag{3}$$

Substituting this into formula (2), the shearing component of the friction force is given as

$$F_{nyir} = \tau \ A_{val} = \tau \frac{F_N}{f(E,G)}. \tag{4}$$

The force generated during the sliding of the surfaces on each other is the resultant of this and the cohesion force:

$$F_s = F_{nyir} + F_{koh} = \frac{\tau}{f(E,G)} F_N + F_{koh}. \tag{5}$$

shaped, where F_{koh} is the cohesion force.

In case F_{koh} is negligible by the shear force, the well-known formula

$$F_s = \frac{\tau}{f(E,G)} F_N = \mu F_N \tag{6}$$

is the result for the friction force.

3. APPLYING THEORY ON THE ASSESSMENT OF THE DEGREE OF TIGHTNESS

Tightness is total, if the sizes of the above introduced two surfaces are identical, that is, if

$$A_{val} = A \tag{7}$$

It is evident that this state cannot be reached in practice, since extraordinary normal force is necessary for this. Therefore, there is such a surface ratio

$$\eta = \frac{A_{val}}{A} \tag{8}$$

which corresponds to practical requirements. The question is, whether this can be related to friction force. We will show that it can. The actual surface from (8) is actually:

$$A_{val} = \eta A \tag{9}$$

From another point of view, the same from (3):

$$A_{val} = \frac{F_N}{f(E,G)} \tag{10}$$

Normal force can be expressed from (6) this way:

$$A_{val} = \frac{F_N}{f(E,G)} = \frac{F_s}{\mu\, f(E,G)} = \frac{F_s}{\tau} \propto F_s \tag{11}$$

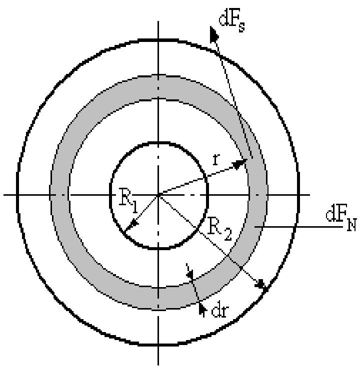


Figure 1 Relationship between the actual surface and the torque

So the measurement of the size of the actual surface can be reduced to the measurement of the friction force. The question is, whether this statement is true on the torque necessary for turning the closure element, since no friction force, but torque is measured. It will be shown that it is.

From the aspect of the generation of friction force and torque it is assumable that the polymer plug and the glass bottle get in contact along a circular ring (*Figure 1*). dF_N normal compressing force is applied on the *dr*-thick circular ring-shaped contact surface. This force according to (4) generates

$$dF_s = \mu dF_N \tag{12}$$

friction force and

$$dM = \mu dF_N r \tag{13}$$

torque. The resultant torque generated on the sealing surface is:

$$M = \int dM = \int r\mu\, dF_N \tag{14}$$

Let the normal force compressing the surfaces be

$$f_N(r) = \frac{dF_N}{2\pi r dr} \tag{15}$$

its distribution function is known, then the resultant torque can be calculated using the relationship

$$M = \int dM = \int r\mu \; dF_N = \mu \int_{R_1}^{R_2} r \, 2\pi \, r f_N(r) dr \tag{16}$$

At the same time, according to (8) the actual contact surface is in relation with the normal force compressing the surfaces:

$$dA_{val} = \frac{dF_N}{f(E,G)} = \frac{1}{f(E,G)} 2\pi r f_N(r) dr \tag{17}$$

So even the actual surface can be calculated from the distribution function:

$$A_{val} = \int dA_{val} = \frac{dF_N}{f(E,G)} = \frac{1}{f(E,G)} \int_{R_1}^{R_2} 2\pi \, r \; f_N(r) dr \tag{18}$$

Applying the mean value theorem of integral calculus on (16), the result is as follows

$$M = \int dM = \int r\mu \; dF_N = \mu R^* \int_{R_1}^{R_2} 2\pi \, r f_N(r) dr \tag{19}$$

where R^* is the defined radius value within the interval (R_1, R_2). Comparing relationships (18) and (19) the following relationship arises

$$\begin{aligned} M &= \int dM = \int r\mu \; dF_N = \mu R^* \int_{R_1}^{R_2} 2\pi \; r f_N(r) dr = \\ &= \mu R^* f(E,G) A_{val} = \tau R^* A_{val} \propto A_{val} \end{aligned} \tag{20}$$

which is the proof for our statement.

4. RHEOLOGY AND MECHANICAL MODEL OF THE CLOSING PROCESS

Rheology in our case means that the material behaviour of the polymer plug (*Figure 2*) serving as a seal can be described as elastic and viscous behaviour. The resultant stress generated in the polymer plug is the sum of an elastic and a viscous stress:

$$\sigma = \sigma_{rug} + \sigma_{visz} \tag{21}$$

The closing process is assessed according to the mechanical substitute picture shown on *Figure 3*. On the figure, *m* is the mass of the crimping head, on which the crimping force is applied through the spring characterized by spring constant *D*. Due to the crimping force the spring suffers deformation x_1, and the polymer plug substituted with *Poyinting-Thomson*-test suffers deformation x_2.

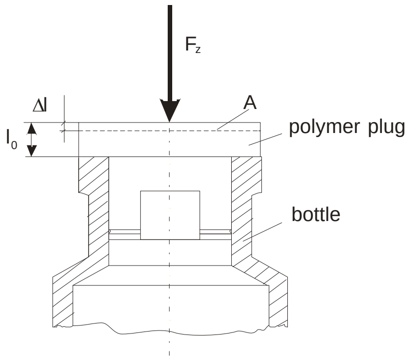


Figure 2 Simplified scheme of the

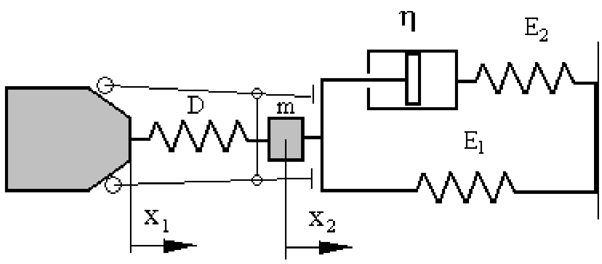


Figure 3 Mechanical model of the closing process

polymer plug and the bottle

Applying *Newton's* 2nd axiom on the model, the differential equation

$$m\frac{d^2x_2}{dt^2} = -D(x_2 - x_1) - \sigma\ A \tag{22}$$

is given, where σ is the stress generated in the polymer plug, which can be defined from the following equation expressing the relationship between the generated stress and extension.

$$\sigma + T_2\frac{d\sigma}{dt} = E_1\varepsilon + E_1T_1\frac{d\varepsilon}{dt}, \tag{23}$$

where the time constants are:

$$T_1 = \eta\frac{E_1 + E_2}{E_1E_2},\ T_2 = \frac{\eta}{E_2}. \tag{24}$$

In this case the specific extension of the plug is given, which can be related to the displacement x_2 shown in *Figure 5*:

$$\varepsilon = \frac{x_2}{l_0}. \tag{25}$$

Using relationships (23) and (25) the following differential equation is given

$$\begin{aligned} &\frac{d^2x_2}{dt^2} + \omega_0^2x_2 + \sigma(x_2)\frac{A}{m} = \omega_0^2x_1, \\ &\sigma + T_2\frac{d\sigma}{dt} = \frac{E_1}{l_0}x_2 + \frac{E_1T_1}{l_0}\frac{d\,x_2}{dt},\ \omega_0 = \sqrt{\frac{D}{m}} \end{aligned} \tag{26}$$

where the time function of displacement x_1 is the known function given by the parameters of the machine. Assuming that while the machine reaches its greatest displacement, transient effects take place, then the steady displacement of the plug can be defined from the above equations:

$$x_2 = \frac{\omega_0^2}{\beta + \omega_0^2}x_1,\ where\ \beta = \frac{AE_1}{ml_0}. \tag{27}$$

According to this, the steady force generated in the plug is:

$$F_z(\infty) = \frac{AE_1}{l_0}x_2 = \frac{AE_1}{l_0}\frac{\omega_0^2}{\beta + \omega_0^2}x_1. \tag{28}$$

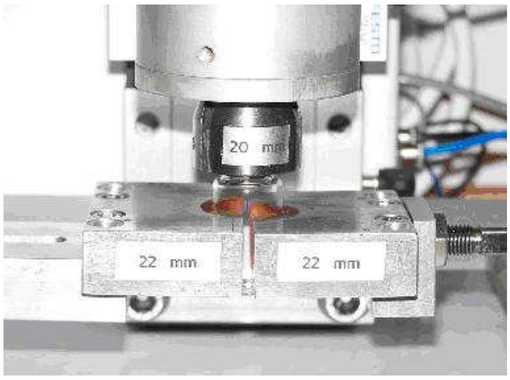
Dynamical behaviour of the system of equations can be tested using the *Laplace* transformation method. Using this method, the *Laplace* transformed displacement of the plug is given as

$$x_2(s) = -\frac{\omega_0^2}{s^2 + \beta\dfrac{1+sT_1}{1+sT_2} + \omega_0^2}x_1(s),\ where\ \beta = \frac{AE_1}{ml_0}. \tag{29}$$

5. INSTRUMENTS ELABORATED FOR THE MEASUREMENTS

In order to certify the theory introduced in the former points, measuring instruments were elaborated. *Figure 4* shows the instruments used for measuring closing force and torque. Closing force is detected by the transmitter built in the measuring cell, and the measurement sign appears on the display of the force-meter (*Figure 4/a*).

a/ closing force measuring instrument



b/ sample holding for torque measurement

Figure 4 Instruments measuring closing force and torque

Figure 4/b shows the instrument measuring the closing element torque of the samples crimped with the known closing force. The figure shows the control panel of the torque-meter and the instrument used for clamping the sample. Due to volume causes we do not give measurement results here, but it is to be noted that they support the theoretical concepts described in details.

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