INTRODUCTION

Glass containers are one of the favorite options for storing of food, beverages and pharmaceuticals because of their chemical inertness and infinite recycling ability. In view of demands for the reduction of embodied CO$_2$ and further sustainability goals, recent years have seen a steady increase in the use of glass containers. On the other hand, today's processes of container glass forming were established about 100 years ago, going back to the introduction of carousel forming machines and the individual section (IS) machine by Hartford Empire. Despite the maturity of the general production process, state-of-the-art efficiencies of a production line are often not more than 92%, meaning that 8% of molten glass is not sold to customers. Around 2% points of that yield loss is due to the lubrication of molds during the forming process.

The lubricant is required because the glass melt otherwise sticks to the cast iron molds and hence disrupts the production process or creates optical defects such as wrinkles on the glass surface. Until recent years, the lubricant application was done manually, which (among other issues) bears the risk of accidents and injuries for the operator and introduces issues in process reproducibility and process stability. Recent installations of robots on one side of the IS machine facilitate the application of lubricants on the molds, but still introduce residues and dirt on the forming equipment. They may achieve a certain (smaller) rejection rate, but this comes with an increase in the complexity and cost of the IS machine for glass container forming: per production line, the robot installation is a significant investment for glass container producers. Currently, robots are available only for the blank mold side of the IS machine and not for the blow mold side, whereas both types of molds require lubrication.

Since the beginning of automated glass forming, it has been clear that the contact interaction between the glass melt and the employed mold material is crucial for process efficiency and product quality. Despite this realization,
however, there is still a fundamental lack of understanding in order to overcome the daily process downsides in current glass container production. The objective of this study is the increase such understanding of contact interaction in the glass forming process. To this end, a measurement device for the controlled investigation of the tribological system glass melt-metal was assembled in an industry-scale facility.

2 | BASICS – DEFINITION TRIBOSYSTEM

A tribological system or tribosystem describes two contact bodies, an interface medium and a surrounding medium.3-5 In the system’s parametrization, the properties of the two contacting bodies as well as the properties of the environment are both relevant, for example, temperature, relative humidity, potential lubricants, etc. For the basic principles of tribology and the corresponding laws of friction, we refer to the pertinent literature.

Heilmann et al developed an energy-based approach of the friction contact.6-8 In this theory, a qualitative relation between the friction coefficient and parameters such as the maximum shear strength \( \tau_{\text{max}} \), the applied load \( P \), number of contacts \( N \), and the contact area \( A_c \), were introduced:

\[
\mu \propto \frac{\tau_{\text{max}}}{P} \cdot N \cdot A_c
\]

This offers a relative, qualitative, and simple description of tribological phenomena.

The difficulty in comparing tribosystems explains the fact that no global approach in tribology is available so far, and that so called “laws” only apply to certain tribosystems4,9-13 with strict boundary conditions.

Re-creating a tribosystems for industry-scale investigations is a crucial step, as it is not appropriate to compare and transfer results and conclusions from different tribosystems, in particular, using overly simplified laboratory set-ups.3,4

Therefore, the target tribosystem of the glass-metal contact from the container glass forming process was recreated by controlling conditions such as gob weight, gob temperature, contact material temperature, and gob speed during entry in a sensor and monitoring section. In this way, an industrially relevant approach for the measurements was developed; the employed measurement device will be described in the following chapter. The installation of the measurement device in a R&D facility of a glass-forming machine supplier enabled gobs of a weight of 400 g for all trials, loading speeds of 6 to 8 m/s, and a gob delivery frequency to the measurement device of about 10 min\(^{-1}\).

This resembles the typical set-up in the production of a 400 g bottle in an IS machine. Due to an integrated recycling system, the measurements could be done for several hours, enabling testing of several thousand gobs per contact material, in a single run.

3 | THEORETICAL CONSIDERATIONS OF THE GLASS-METAL CONTACT

The theoretical framework of this study is based on investigations done by Aleksennko, Abramovich, and Kalashnikov and later Falipou.14-16 One additional aspect of glass-forming refers to the sticking of the glass to the contact material. The corresponding theory is nowadays mostly accepted, being based on the hypothesis for sticking.1,13-15 It states that a viscoelastic glass melt starts to stick to the contact material at an interface viscosity of \( 10^{8.8} \text{ Pa-s} \), regardless of the contact material. Hence, the sticking temperature of a glass only depends on two factors, i) on its chemical composition which determines the respective temperature at which the critical sticking viscosity is reached and ii) on the thermal effusivity \( b \) of the respective contact material. The thermal effusivity \( b \) is defined according to

\[
b = (c_p \cdot \lambda \cdot \rho)^{\frac{1}{2}}
\]

with \( c_p \), \( \lambda \), and \( \rho \) being the isobaric heat capacity, thermal conductivity, and density of the contact material, respectively. The sticking temperature can be understood as the interface temperature between the glass and forming material. Therefore, if (at a constant glass gob temperature and chemistry) the thermal effusivity of the contact material is increased, the interface temperature is decreased, and sticking occurs at a higher glass bulk temperature (but still at the same interface temperature which belongs to the viscosity-level of \( 10^{8.8} \text{ Pa-s} \)).

4 | MATHEMATICAL MODEL FOR CALCULATION OF THE FRICTION LOSS

For measuring and modeling, a set-up is built in which two plates are aligned at a certain angle \( \alpha^{\text{incl}} \) and a glass gob is fed through that system (see Figure 1). An analytical model for calculating the loss of energy due to the friction contact between the glass melt and the tested material is taken from 17,18 and adapted as explained below. The calculated values are regarded as friction loss \( \mu \) to avoid thoughtless comparisons of absolute values from other friction tests.
In the ideal case, the gob falls centrically between two plates as explained in the experimental set-up section and illustrated in Figure 1:

The dissipated energy \( \Phi \) was calculated by the following equation:

\[
\Phi = 2 \cdot \eta \cdot \int_{0}^{h} S(z) \left[ A^2(z) + B^2(z) + v^2(z) \right] dz = q1 \cdot \eta \cdot \pi \cdot V_0^2 \cdot a_0 \tag{3}
\]

with, \( q1 = 4 \cdot a^{incl} \cdot a_0 \left[ \frac{1}{a_0 - a^{incl} \cdot h} - \frac{1}{a_0} \right] \tag{4} \)

The change in the radius \( A(z) \) and \( B(z) \) from cylindrical to elliptical and the area of the cross section of the gob \( S(z) \) was described using the conservation of flow between the entry and exit of the gob contact sensor.

\[
S(z) \cdot V_z = S_0 \cdot V_0 \tag{5}
\]

for the x-axis

\[
A(z) = -\frac{V_0 \cdot a_0^2 \cdot a^{incl}}{(a_0 - a^{incl} \cdot z)^2 \cdot (a_0 + \beta \cdot z)} \tag{6}
\]

for the y-axis

\[
B(z) = -\frac{V_0 \cdot a_0^2 \cdot \beta}{(a_0 - a^{incl} \cdot z)^2 \cdot (a_0 + \beta \cdot z)^2} \tag{7}
\]

with gob radius \( a_0 \) at first impact, sensor entry velocity \( V_0 \), angle of inclination of the plates \( a^{incl} \), \( z \) being the position of the gob along the z-axis and \( \beta \) being the angle of change along the y-axis.\(^{17,18}\)

In the second step, the movement of the glass gob was characterized. Two assumptions were made as follows: Consideration about the dissipated energies \( \Phi \) were valid independent of the speed of the gob and the glass viscosity \( \eta \) was constant during the transition of the gob through the sensor.

The conservation of energy between the change in kinetic energy of the gob during the transition through the sensor, the internal energy needed for the plastic deformation of the gob and the external energy considering the forces of gravity and friction was formulated as follows\(^{17,18}\):

\[
\frac{d}{dt} K = p^{ext} + p^{int} \tag{8}
\]

\[
V(t) = \left( V_0 - \frac{m \cdot g}{q2 \cdot \pi \cdot \eta \cdot a_0} \right) \exp \left( -\frac{q2 \cdot \pi \cdot \eta \cdot a_0}{m} \cdot t \right) + \frac{m \cdot g}{q2 \cdot \pi \cdot \eta \cdot a_0} \tag{9}
\]

with, \( q2 = q1 \cdot \left[ 1 + \frac{\tan \left( a^{incl} \right)}{\mu} - \frac{1}{\cos^2 \left( a^{incl} \right)} \right]^{-1} \)

The friction loss \( \mu \) can be calculated by solving equation 9 and equation 10 with the given parameters for the sensor geometry (see above) and the velocities of the gob at sensor entry \( V_0 \) and sensor exit \( V(t) \).

\[
h_s = \int_{0}^{t} V(t) \, dt \tag{10}
\]
Equation 9 and 10 were solved with the computer algebra system Maple (Maplesoft, USA) with respect to $\mu$ and $t$ for each gob. A direct measurement of the gob radius was not possible, but the length of the gob $l$ could be measured with the speed sensors. With the assumption of a cylindrical gob shape with spherical ends, a gob radius $a_0$ is calculated using the gob weight $m$ and glass density $\rho$.

5 | EXPERIMENTAL SET-UP AND PROCEDURES

A system was built for quantitative investigation of the dynamic glass contact and integrated into a 10-section triple gob NIS container-glass forming machine (see Figure 2A). The device consisted of two heated plates adjustable in angle and distance. It enables continuous measurement of the dynamic glass melt contact under non-isothermal conditions. The installation of the sensor in the NIS section enables a velocity $V_0$ of the gobs of about 8 to 9 m/s. This is in the range of a standard glass container production facility. Furthermore, the installation created a non-isothermal temperature situation between glass gobs and the measurement plates which reproduces the situation of glass forming in the industry as well.

Each side of the plate is built up by a stack of three layers (see Figure 2B). The center plate is made of steel and holds six heating elements. An isolation plate is mounted at the back of the steel plate in order to minimize thermal loss. The contact plates are mounted in front of the steel plate and will contact the passing glass gob. A sheet of Al was set between the center plate and the testing plate to optimize the thermal contact. Three heaters are connected in series and set as one heater bank. Two heater banks and one type k thermocouple are placed in one center plate. For powering the heaters and controlling the temperature of the plate, two heater banks and the thermocouple are connected to a temperature controller.

The friction between the glass melt and a testing material is quantified by measurements of the speed loss (i.e., loss in kinetic energy) of the gob during the transition. Therefore, speed sensors are mounted before the first contact of the gob and testing plate (speed sensor at the sensor entry) and after the testing plates (speed sensor at the sensor exit, see Figure 1). The dynamic friction contact of the glass melt and a testing material was quantitatively captured by two-speed measurements before and after the friction contact with the testing plate. The friction loss was calculated with the speed information and data from gob and sensor geometry by solving equation 9 and 10.

A velocity measurement unit was assembled from two fiber optical sensors and positioned at a fixed distance $d_s$ (see Figure 3); fiber optical sensor 1 was passed first by the gob, fiber optical sensor 2 second (see Figure 4). Each fiber optic sensor ended on a photodiode installed in an electronic box. The photodiodes registered the light impulse, generated by the passing gob, and generated an analog signal which

![FIGURE 2](A) CAD model of the glass contact device for mounting different testing plates and the exposition to the dynamic glass contact. (B) Actual picture of the installation of the glass contact device in the section of the NIS machine. (C) Example of the measurement results for the samples hBN from the speed sensors at the entry and exit of the sensor.
was converted into a digital signal that was then evaluated by a custom PC program. The increase in the signal was correlated to the leading part of the gob and the decrease in the signal was related to the trailing part of the gob (see Figure 4). For the leading and the trailing end of the gob, two distinct speed values \( v \) and gob lengths \( l \) were calculated.

Time \( t_1 \) and \( t_2 \) were measured by the first sensor, time \( t_3 \) and \( t_4 \) by the second sensor; time \( t_1 \) and \( t_2 \) represented the leading part of the gob, time \( t_3 \) and \( t_4 \) the trailing part of the gob. The speed values \( v \) and the gob length \( l \) were calculated by the equation:

\[
v_{\text{leading}} = \frac{d_S}{t_3 - t_1} \quad (11)
\]

\[
v_{\text{trailing}} = \frac{d_S}{t_4 - t_2} \quad (12)
\]

\[
l_{\text{leading}} = v_{\text{leading}} \cdot (t_2 - t_1) \quad (13)
\]

\[
l_{\text{trailing}} = v_{\text{trailing}} \cdot (t_4 - t_3) \quad (14)
\]

For the calculations of the friction loss, \( V_0 \) was taken from the trailing part of the gob at the entry of the gob contact device; \( V(t) \) was calculated by the velocity of the trailing part of the gob at the exit of the gob contact device.

The gob weight was kept at 400 g for all trials and the surface temperature of the samples was kept at 480 +/- 10°C.

A conventional flint soda-lime-silica glass with an idealized composition [wt%] of 72.5 SiO₂, 13% Na₂O, 11% CaO, 2% Al₂O₃, 1.5% MgO was used for this study. The glass reaches a viscosity of \( 10^{8.8} \) Pa·s at 651°C and 1012 Pa·s \((T_g)\) at 569°C.

### 5.1 Materials tested

Different metallic and non-metallic materials were tested as gob substrates (contact plate in Figure 2A, see Table 1).

The surface finish of the materials AA5052, Titanium grade 2, and Copper 110 was obtained by manual grinding with sandpaper, grit size of 180. EN GJL 250 was ground automatically with an Al₂O₃ grinding wheel.
Surfaces of the following materials were kept as received: AA1100, AA7050, AA7075, hBN, Al₂O₃ 99.6%, Borofloat® 33, and Graphite.

6 | RESULTS AND DISCUSSION

All materials mentioned in Table 1 are tested in the glass contact device. Gob speeds at the device entry and exit are measured; an example of the velocities at the entry and exit when using hBN as plate material is shown in Figure 2C.

The friction loss values are calculated by the velocities $V_0$ and $V(t)$ and equation 17. A measurement of the results of sample hBN is shown in Figure 5. For all measurements, the first 200 tested gobs are neglected for calculating the average and the standard deviation of the friction loss for the respective sample.

6.1 | Influence of shear strength of the contact material on friction loss between contact material and glass gob

The tribosystem discussed is more complex than typical tribosystems such as, for example, pin on disc experiments, because here the dynamic friction between a solid body and a viscous liquid is investigated. Additionally, the dimensions of the testing equipment are on an industrial scale. As mentioned in the beginning, the original equation of Heilmann et al considers the shear strength as a relevant parameter. Therefore, shear strength values from a material database “Matweb” (http://matweb.com, on 24. February 2016) of the tested materials were collected and related to the measured values of the friction loss (see Figure 6).

A trend for increasing friction loss with increasing shear strength (see Figure 6) is seen. This is in line with common understanding. Sample copper 110 is an exception. As
expected, the graphite sample shows a very low friction loss due to the lamellar crystal structure with weak bonding between the hexagonal crystal planes which facilitates shearing. But also, the thermal stability of graphite is rather poor with a burning temperature of about 600°C in the air.

Like graphite, hBN has a layered crystal structure with hexagonal planes but a higher thermal stability in the air. The measured friction loss of hBN is significantly higher than that of graphite (see Figures 6 and 7) and corresponds to greater bonding strength between the planes and a lower thermal conductivity which increases the contact temperature (please see also Figure 9). Furthermore, according to the material safety data sheet of the supplier hBN was sintered with a B$_2$O$_3$ binder. Remains of the binder could interact with the glass gob and B$_2$O$_3$ is known to have a strong affinity to bond to SiO$_2$. This also increases the friction.

To directly characterize the behavior of the glass gob against B$_2$O$_3$ glass, a Borofloat® 33 sample was used as a contact plate. As expected, the gob was not able to pass the Borofloat® 33 plates; sticking and bonding between this sample and the glass gob occurred immediately (see sample after the trial in Figure 8). After cooling down the sample, the glass could not be separated from the Borofloat® 33 which indicates chemical bonding due to the similarity of both materials.

Al alloys have higher shear strength due to their fcc crystal structure. Furthermore, alloying elements alter the mechanical properties in general. The almost pure Al alloy AA1100 has the weakest mechanical properties of all tested Al alloys and the good friction values of AA1100 are therefore due to the low shear strength of this alloy. AA7050 and AA7075 show no significant difference in the friction loss, which is reasonable due to their comparable composition. Al alloys of series 7000 are alloyed by Zn, Mg, and Cu which increase the mechanical properties and hence the shear strength (see Figure 6).

From equation 1 a relation between the hardness of a material and the friction loss can also be deduced by combining penetration load and contact area.

For increasing hardness values a principal trend of increasing friction loss with increasing hardness can be seen (see Figure 7), which is comparable to the correlation of the friction loss with the shear strength. Graphite, AA1100, AA7075, AA7050, AA5052, Nickel 200, Titanium grade 2, and EN GJL 250 have an increasing friction loss with increasing hardness values. Due to missing hardness values for sample hBN, the sample is not included in Figure 7.

As with the correlation between shear strength and friction loss, sample Copper 110 falls out of the trend twice. Al$_2$O$_3$ 99.6% falls in the trend of the other samples, too. Al$_2$O$_3$ 99.6% showed a sticking of the gobs to the substrate after the testing of five consecutive gobs. Therefore, the trial was stopped for this sample. The sticking of the glass gob to the Al$_2$O$_3$ 99.6% material can be explained by a strong affinity of the Al$_2$O$_3$ to bond to the SiO$_2$ from the glass that overlay the mechanical properties of the material.

The theory from Heilmann et al. can partly be confirmed. Shear strength and hardness influence the friction loss proportionally. Graphite and Al alloy AA1100 show a low friction loss with a low shear strength and hardness. Materials like Nickel 200 and EN GJL 250 had a higher friction loss. Results of copper 110 and Al$_2$O$_3$ 99.6% cannot be explained by the mechanical properties of the material and will be discussed later.
6.2 | Influence of the thermal properties of materials on the friction loss

According to the theory of RIESER et al and other authors, below a critical viscosity of \(10^{8.8}\) Pas at the interface, sticking between a glass and a metal happens. This is thought to be independent of the glass chemistry. The measured friction loss was correlated with values of the thermal effusivity of the plate material, but no clear trend could be identified for all tested samples (see Figure 9).

Tested Al alloys have a thermal effusivity of over 12 kJ/(Km²s^-0.5) and values of the friction loss from 0.18 to 0.40 and show a trend of decreasing friction loss with increasing thermal effusivity. This could vaguely correlate to the theory of RIESER et al as a higher thermal effusivity decreases contact temperature and increases the delta to the sticking temperature. hBN and Al₂O₃ 99.6% as inorganic non-metallic material have low thermal effusivity of 6 to 11 kJ/(Km²s^-0.5) and a friction loss of 0.43 to 0.45. Although hBN has a beneficial layered crystal structure, the low thermal effusivity seems to be limiting the friction contact.

The results of Al₂O₃ 99.6% are difficult to construe as the glass gob stuck to the substrate after five consecutive gobs indicating a strong bond between the SiO₂ and the Al₂O₃. As the thermal effusivity is in the range of other tested materials, it is unlikely that in this case the viscosity drops below the sticking viscosity.

Graphite has an anisotropic thermal effusivity due to the crystal structure. Therefore, two values are provided. Both values are lower than the friction loss of the other materials. This indicates that the mechanical properties such as hardness and shear strength are the predominant properties with respect to the glass contact.

The tested Al alloys, nickel 200 and EN GJL 250 show an increase in the friction loss with decreasing thermal effusivity, corresponding to increasing contact temperatures and therefore reaching the sticking viscosity. This relates to the explanation above. Copper 110 and titanium grade 2 as well as hBN, Graphite, and Al₂O₃ 99.6% do not fit this trend.

The consideration of the thermal effusivity may be important but not sufficient and punctuates only one factor of the tribosystem.

6.3 | Oxidation behavior of metals and its correlation to the friction loss

Metals oxidize in an O₂ containing atmosphere and certainly this oxidation is facilitated at high temperatures. Looking at the stability of such oxide layer, one can use the Pilling–Bedworth ratio (PBR) which gives an indication of the stability of the oxide-layer on its respective metal. The PBR is the volume of the elementary cell of a metal oxide \(V_{Me}^{M_{ox}}\) (the corroded species, \(V_{Corr}^{M_{Corr}}\)) in relation to the volume of the elementary cell of the corresponding metal \(V_{Me}^{M_{Me}}\) from which the oxide is created. The PBR can easily be calculated with \(n_{Me}\) being the number of metal atoms per one molecule of the oxide and \(\rho\) and \(M\) being the density and the atomic or molecular mass of the metal or oxide:

\[
PBR = \frac{V_{Corr}^{M_{Corr}}}{n_{Me} \cdot V_{Me}^{M_{Me}}} = \frac{M_{Corr}/\rho_{Corr}}{n_{Me} \cdot M_{Me}/\rho_{Me}} \quad (15)
\]

On the basis of the PBR, one can judge if an oxide-layer adheres strongly to its base-metal and hence a protective oxide layer is formed. A PBR between 1 and 2 means that a
stable oxide layer is formed. A PBR < 1 means that the oxide layer is under tensile stress and is likely to show cracks. A PBR > 2 indicates that the oxide layer is under compressive stress and chips of easily. It has to be remarked that the PBR is more an indication than a strict rule, as oxide layer growth often is sequential and mixed oxides in case of alloys can be formed. Furthermore, atmospheric corrosion regularly is via hydroxides and yields different layer formation.

As most samples tested are almost pure, the PBR can be considered in relation to the friction loss. In Figure 10, the acquired friction loss data are plotted against the PBR of the base-metal and its respective oxide. An increase in the friction loss with increasing PBR can be seen. Samples AA1100, nickel 200, and titanium grade 2 have rather thin oxide scales. The low friction loss of sample AA1100 with a thin layer of Al₂O₃ goes along with the low PBR. For this material, the other properties such as mechanical properties and thermal conductivity (and so thermal effusivity) of the bulk Aluminum have a higher influence on the friction loss than the Al₂O₃ layer. This is because the friction loss of bulk Al₂O₃ (sample Al₂O₃ 99.6%) is higher (see Figure 9) and differs significantly from the mechanical and thermal properties of the metal sample AA1100.

The friction loss of NiO and TiO₂ increases with a higher PBR. Data points of the iron oxides are from sample EN GIL 250, a cast iron alloy. Oxidation of the alloy is more complex than of the pure iron and might not be described totally by the PBR.

Copper 110 again exceeds the trend of the other samples. According to the high thermal conductivity and the low contact temperature, Cu is thought to be viable in the dynamic glass material contact. But the result of the experiment was contradictory as the first tested gob stuck in between the copper plates, resulting in a high friction loss. The copper 110 plates after testing exhibit a tremendous oxidation of Copper 110 with an irregular and complex oxide scale. The removal of the gob from the plates revealed some of the original Cu suggesting a locally poor adhesion of the oxide scale on Copper 110. So, the results of Copper 110 and the other metal samples can be explained by consideration of the PBR.

7 | CONCLUSIONS

The dynamic contact between a glass melt and a forming material is a frequently occurring and fundamental situation in an industrial glass forming processes. A set-up was constructed and installed in an industrial environment for quantification of the dynamic contact between glass melt and a molding or forming material. The characterization of the glass-to-forming material contact was done via measurement of the loss of kinetic energy when a glass gob passes through the sensor. The friction loss was calculated with a mathematical model and correlated to different material properties, such as shear strength, hardness, thermal properties, and Pilling–Bedworth Ratio. The results provided partial confirmation of established theories. Nevertheless, also limits of these theories became clear and the results open up the way for further investigations and a clearer understanding of the dynamic contact between a glass melt and a forming material.

In detail, the friction loss between two partners can be reduced by reducing the shear strength of one partner, which basically confirms the theory of Heilmann et al. Aluminum alloys showed good friction properties due to the low shear strength in the testing conditions. Different authors correlated the contact temperature of a glass melt and a metal with the sticking of the glass melt. The contact temperature depends on the temperature and the thermal effusivity of both partners. A clear correlation between thermal effusivity and friction loss of different materials could not be identified. Oxidation of metals needs to be considered for tests at elevated temperatures. For this, the Pilling–Bedworth ratio might be a relevant parameter. Literature values of the PBR of the tested materials were related to the measured values of the friction loss. Low PBR values, for example, such as in the case of aluminum, are beneficial for the friction loss. Copper and cast iron have high values for the PBR and high values in friction loss.

Furthermore, Van der Waals interaction could also be considered at the contact between two partners. These have previously been studied for different tribological systems. In particular, the polarizability of molecules is an important factor for the different types of Van der Waals interaction. Hence, further investigations on the glass-metal interaction to
explain better the atomistic nature of the glass-to-metal contact need to be undertaken.

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