Modelling and minimization of hydro-abrasive wear when mixing in glass-lined agitated tanks

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Summary

The technical paper describes the phenomenon of hydro-abrasive wear of glass-lined equipment which occurs in the chemical industry when processing abrasive fluids containing solids, especially in reactors. Using a hydroabrasion test station which is based on the pot wear test [general performance wear test] a methodology is described showing how hydroabrasion resistance of glass linings can be checked quickly and easily in a practical setting. The results of our own measurements on the hydroabrasion resistance of different chemical glass linings are shown. It was proven that the abrasion of glass-lined surfaces during mixing follows a linear function over time. Finally, a special technical glass is presented which has been specifically developed for hydro-abrasive processes.

1 Introduction

The respective economies of industrialised countries make annual losses of about 5% of GNP from abrasion and wear and tear; for Germany that means approx. 35 billion Euros per year /1/. Thus economic losses as a result of abrasion are the same as those caused by corrosion /2/. Taking tribological knowledge increasingly into account can therefore mean considerable savings in energy, materials used, production and maintenance. In addition, energy and raw materials resources can be conserved, environmental damage avoided and safety at work improved.

Glass-lined equipment is used in the chemical and process engineering industry for the manufacture of chemicals and for the production of pharmaceutical active ingredients. Glass-lined surfaces are highly resistant to strong acids, are free of heavy metal ions, are smooth, anti-adhesive and thus easy to clean. In addition, glass-lined equipment is in many cases a particularly economic solution when compared to equipment made of high alloy stainless steels or materials such as nickel base alloys and Tantalum. Reactors lined with technical glass therefore have a firm place in a variety of process engineering processes and often form the "heart" of the processes. It comes down to maximum availability and longevity. Because of the high risk potential of the media processed in the equipment, it is also important that damage as a result of corrosion or abrasion is avoided as much as possible.

The abrasion mechanisms which occur when mixing liquids containing solids in glass-lined reactors will be examined more closely in this paper. The erosion of the glass lining as a result of abrasive processes especially can lead to an obvious reduction in the life of glass-lined equipment, because this damage, as presented in more detail later, although localised still can lead to a total failure of the glass-lined equipment as a consequence of corrosion throughout the affected components and thus to capital losses affecting the whole of the apparatus.

2 Glass-lined reactors

A glass-lined reactor comprises a tank with a corresponding volume. Today reactors with volumes of up to 100 m^3 can be manufactured. On average, the reactors today are sized between 8 m^3 and 16 m^3. In the case of a 16 m^3 agitated tank the diameter of the equipment is 2,600 mm, the height of the tank is about 3,750 mm and the glass-lined surface which according to ISO 28721 /3/ is non-porous and without defects is greater than 40 m^2. In the case of a 100 m^3 tank the non-porous glass-lined inner surface is greater than 150 m^2! The tank is equipped with a series of nozzles on the top and the bottom of the tank which the operator uses to introduce media or for emptying. The **agitating unit** is mounted above the so-called agitator nozzle in the centre of the upper head of an agitated tank. The agitator shaft, to which the agitating elements are fitted and which protrudes into the tank, is driven by an electric motor via a gear unit. With the aid of a shaft seal the agitator shaft is sealed pressure-tight with the agitated tank.

So-called **baffles** are installed in one or several nozzles on the upper head of the tank. Baffles are essentially tube-shaped components which, together with the stirrer, ensure the tank contents are thoroughly mixed when agitated. Without baffles the tank contents would mainly only rotate around the tank's central axis when the stirrer is operating and form a deep vortex. Only the baffle ensures that the tangential rotation flow is converted into a mainly axial flow which ensures a more effective mix /4/.

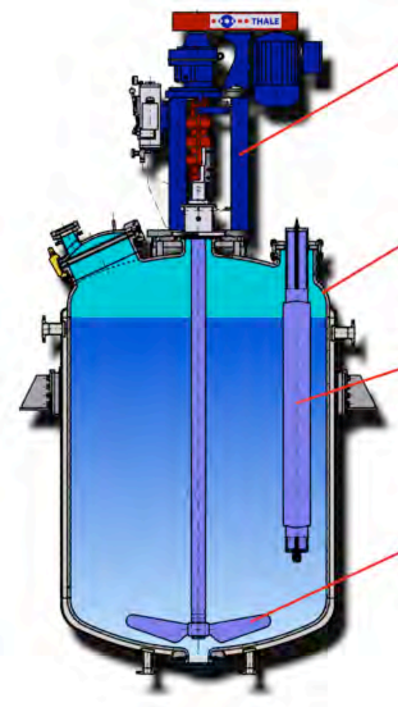

Fig. 1: Composition of a glass-lined reactor

Besides these components other elements can also be used, such as for example, dip pipes, inlet pipes, sensor carriers to measure process parameters such as temperature or pH value, probes to monitor the glass lining etc.

3 Erosion mechanisms on glass-lined surfaces

Erosion of the glass lining in glass-lined agitated tanks is mainly caused by two mechanisms which reinforce each other to some extent:

- Corrosion of the glass lining
- Erosion of the surface as a result of interaction with the solids in moving (stirred) liquids containing solids
- Glass lining erosion as a result of other mechanisms, e.g. cavitation.

Both of the first mechanisms mentioned lead to successive erosion of the glass lining. Whilst the mechanisms, which lead to corrosion of the glass lining are sufficiently well-known and the relevant corrosion rates of glass linings are described and defined in accordance with the relevant standards and guidelines for chemical glass linings depending on the corrosive media /5/, the aspect of resistance to abrasion has not been given enough consideration to the required extent. This may lie in the fact that the abrasion characteristics of surfaces depend upon a variety of circumstances, the unequivocal determination of and reproducible adherence to which is not simple under test conditions. Other effects which could lead to erosion of the glass lining, like cavitation, for example, shall not be taken into consideration below as they can almost be excluded under the working conditions in which glass-lined equipment is usually operated.

According to Uetz /6/, hydroabrasion constitutes a tribological stress on surfaces as a result of flows containing solids. Uetz uses the term of hydroabrasion especially in connection with wear and tear mechanisms, which could occur in hydraulic engineering, for example, the wearing of channels in which there is rubble and debris as a result of the flow of water /7, 8/. We also use the term hydroabrasion or hydro-abrasive wear for the abrasive effects when mixing fluids containing solids because this constitutes a comparable tribological system.

4 The tribological system "mixing" in the glass-lined equipment

If we look at mixing media containing solids in a glass-lined reactor more closely it prompts the definition of the system as a tribological system comprising several elements. A tribological system according to the definition of DIN 50320 (withdrawn) /9/ always comprises the elements fundamental body, counter body and intermediate medium as well as the system input parameters "collective demands" and the system output parameters "abrasion parameters". For agitated fluids containing solids the tribosystem is shown in accordance with Fig. 2.

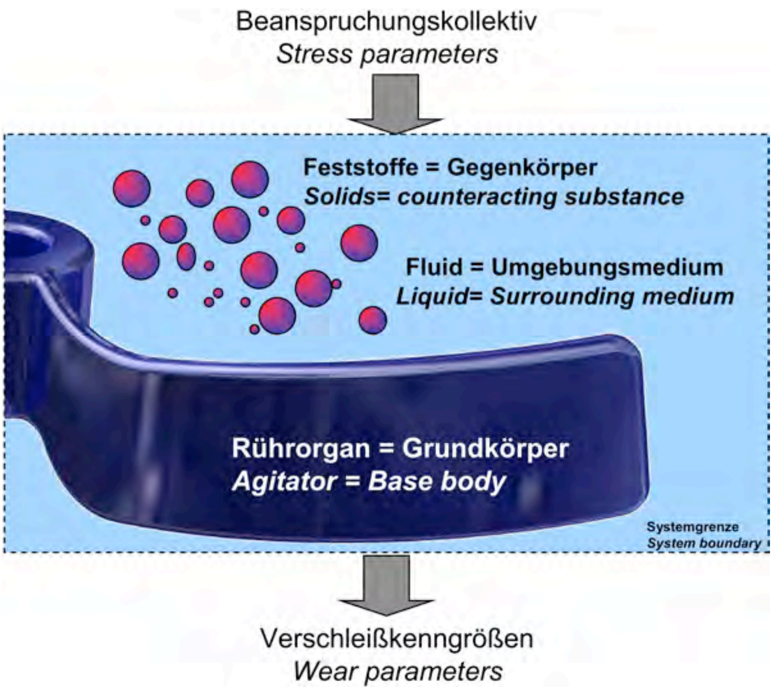

Fig. 2: Tribological system when mixing fluids containing solids

Thus the glass-lined surface (tank wall, agitating element) represents the fundamental body, the solids in the fluid the counter body and the fluid containing the solids the intermediate medium or the ambient medium.

To cause wear to a surface, a relative movement between the fundamental body and the counter body is also required. According to DIN 50320, wear is defined as "progressive loss of material from the surface of a solid body as a result of mechanical causes, i.e. contact between a solid, liquid or gas body and relative movement".

5 Hydroabrasion of glass-lined reactors

5.1 Damage sites

As already described, hydroabrasion is a mechanism which is mainly caused by the relative movement between the surfaces of the glass-lined equipment in contact with the media and the solids dragged along by or suspended in the fluid. Thus in the first instance all surfaces which come into contact with the fluid containing solids are at risk of hydroabrasion. Clearly the intensity of the relative movement also plays a major role, as will be subsequently shown. As already mentioned, damage as a result of hydroabrasion is always localised and concentrated in a few places in the glass-lined reactor. In practice, damage caused by hydroabrasion occurs especially in those places marked in Fig. 3:

1. on the tips and on the edges of the agitator blades in the direction of rotation
2. on the surfaces and the baffle edges which are directly facing the flow [of the liquid]
3. on the side wall of the tank at the height of the agitating elements
4. on the tank floor, predominantly below the agitator
5. on the wall of the tank in the area of the surface of the liquid, especially when floating solids cover the surface of the liquid
6. in the area of the swaged opening radii on the bottom outlet nozzle.

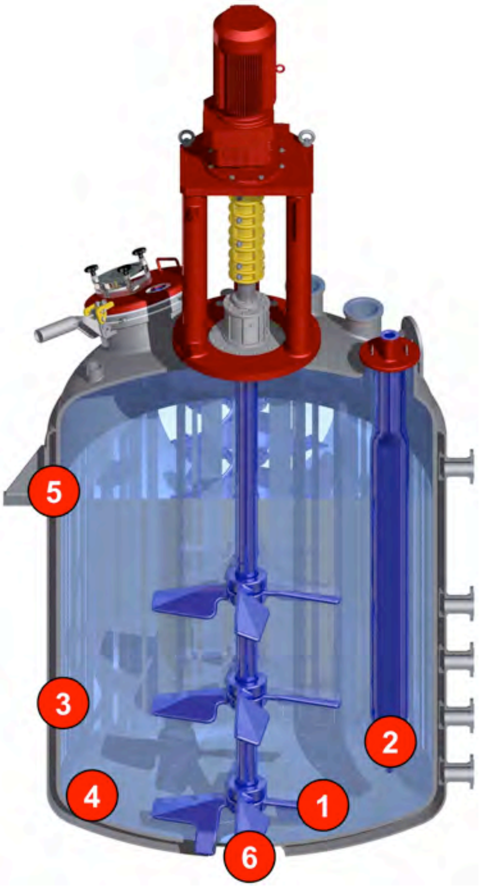

Fig. 3: Damage sites on the glass-lined reactor for damage caused by hydroabrasion

Evidently the damage occurs mainly in those places where the localised flow reaches high speeds during mixing or when the tank is emptied under pressure. Damage from hydroabrasion can also be anticipated in those sites where the flow is deflected powerfully and sharply as a result of the geometry of the components in the flow. Finally, sites can be affected where there are abrupt changes in the flow speed of the particle-laden fluid.

5.2 Characteristic damage pattern

The damage pattern of glass-lined surfaces damaged by hydroabrasion has some characteristic features. As described above, the damage is localised. In addition, there is increasing erosion of the glass lining which at those sites which are affected the most can extend to the surface of the steel component beneath the glass lining.

If the process is not very corrosive, then the hydro-abrasive damage continues at a reduced rate on the exposed steel surface. In the case of high steel corrosion however, there is generally immediate further damage (peeling of the glass lining as a result of undermining of the "sound" glass lining around the damage site until it is breached), so that the cause of the damage is normally no longer discernible. Then it is necessary to examine other components or other parts of the same component very closely for the typical hydroabrasion damage pattern.

Insofar as there is only hydro-abrasive stress on the glass-lined component, the area of hydro-abrasive damage can be seen particularly well because in these areas the glass lining is roughened, whilst the other surfaces continue to be glossy.

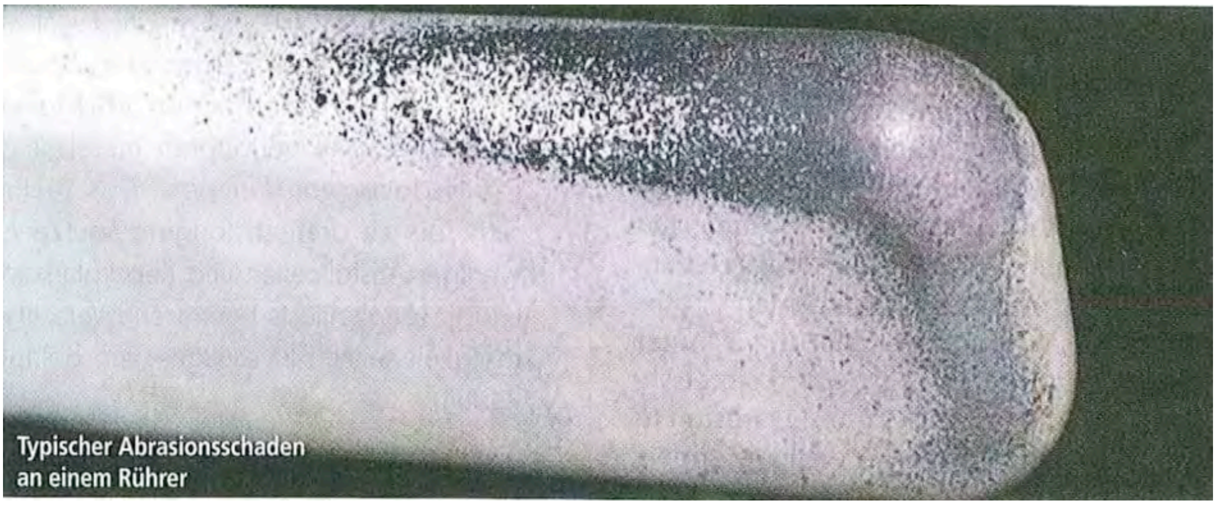

Fig. 4: Damage to a glass-lined agitating element caused by wear /13/

6 Examination of the hydroabrasion-resistance of glass-lined surfaces

In order to examine the hydro-abrasive properties of glass-lined surfaces, THALETEC designed a hydroabrasion test station. The test station was developed with the following individual objectives:

- Create a simple way of making a **quantitative comparison** of the wear-resistance of different surfaces under defined, abrasive conditions in particle-laden liquids with a particle content of up to 50%.
- Practical **simulation** of hydro-abrasive wear conditions (liquid, particle in the mixing process) and as a basis for deducing the likely useful life of glass-lined surfaces for actual customer applications
- Create the fundamentals to **further develop** glass linings with regard to their wear resistance under hydro-abrasive stress
- Develop the fundamentals to **determine a standardised test procedure which could become the norm** for glass-lined surfaces in respect of wear resistance under hydro-abrasive operating conditions.

Crucial for designing a test procedure for glass-lined surfaces subject to hydro-abrasive stress is to ensure that the procedure is modelled on and can reproduce the tribological system which takes place when mixing particle-laden liquids. Procedures to test attrition which work in accordance with the principle of a ball mill essentially following the concept of a wear test for solid particles /10/ however, do not reproduce the hydro-dynamic effects of process engineering mixing and are therefore quite unsuitable to assess wear under hydroabrasion. Equally, the wear test procedure according to ISO 6370 /11/ cannot be called upon either to model the active mechanisms of hydro-abrasive wear.

6.1 Test concept

A modified pot wear test [general performance wear test] in accordance with /6/ has proved itself to be a suitable test concept. In the original pot wear test one or more samples rotate in a cylindrical tank which can also be rotated. The rotational speed of the tank is slow compared to the sample. The axis of the sample lies off-centre to the axis of the tank. There is a dominant prevalence of abrasion. The intensity of the abrasion is varied by pressure on the surface of the abrasive matter or by an increase in speed. Particles up to a size of about 20 mm can be used. The degree of moisture can be changed and thereby permit a way of ascertaining also tribochemical or corrosive effects. In general, in the tests there is increased inflow wear. Therefore the test samples are allowed to run until there is even wear over the time period, measured by loss of mass. This procedure is often used in wear testing with loose particles. Natural soils, building materials, that is gravel, damp sand, chippings etc. can also be used as abrasive agents /2/.

This original procedure was modified for the simulation of hydro-abrasive wear processes in agitated tanks, see Fig. 5. A stainless steel tank is fitted with four wall baffles. In order to reproduce the conditions in agitated tanks as closely as possible, the tank bottom is configured as torispherical heads in accordance with DIN 28011. The tank cannot be rotated. As in the glass-lined reactor, a shaft is fitted concentrically to the tank axis. At the end of the shaft, a four-blade 45°-pitched blade agitator is attached. The geometric parameters of the test set-up are summarised in

Table 1. At the end of each agitator blade there is a mounting bracket into each of which one test sample can be screwed. To determine the erosion of the glass lining a device of the type Elcometer 456F Basic was used to measure the thickness of the layer. In order to be able to determine the thickness of the glass layer always at the same place on the test sample, a measuring template was made and the thickness of the glass layer determined at three measuring points. The measuring template is designed in such a way that measurements are taken at distances of 12 mm, 22 mm and 32 mm away from the tip of the test sample. In order to minimize measurement errors and other deviations, four test samples are always installed in each test and the measuring values averaged across the respective measuring points as well as the test samples. Silicon carbide has proved itself to be particularly suitable as a solid with an average grain size of 50 µm with a density of 3,210 kg/m^3 and a Mohs hardness of 9. With a total volume of 20 l of water 2 kg of Silicon carbide are added (10% ratio of the solids content to the volume of liquid).

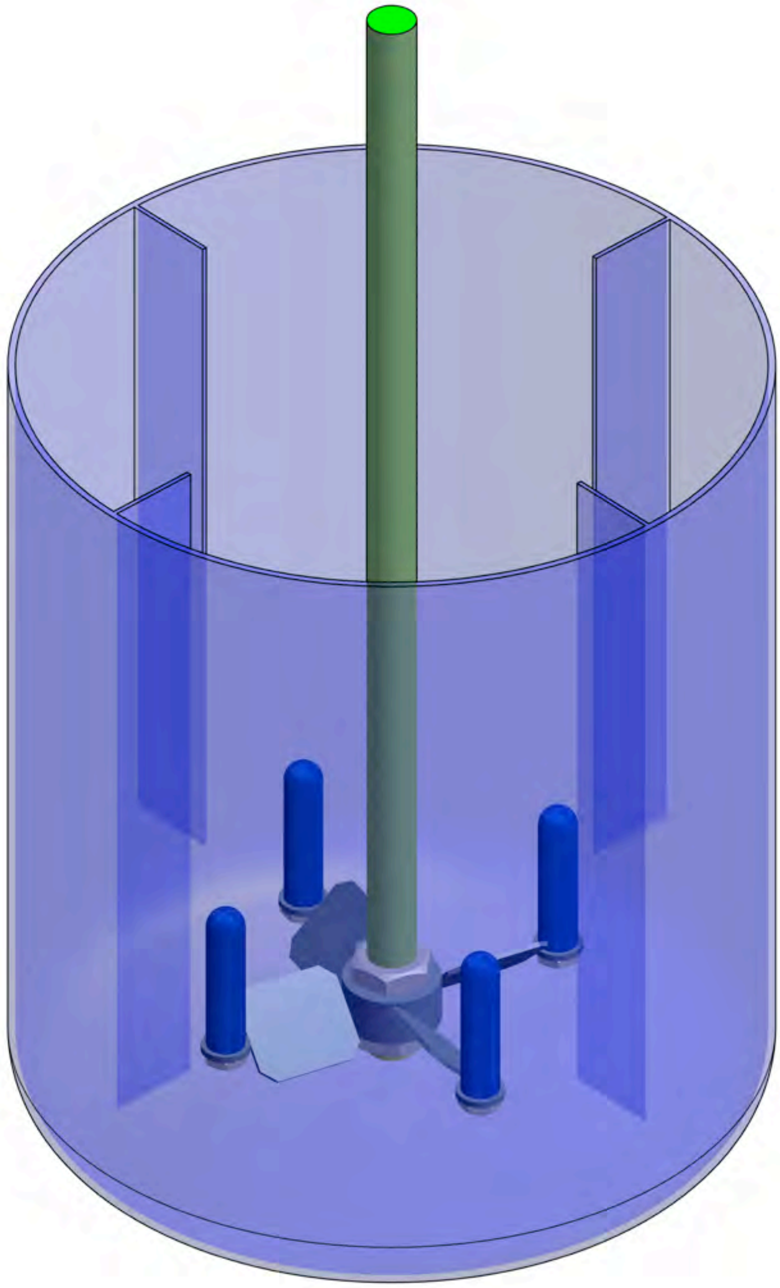

Fig. 5: Test set-up for hydroabrasion tests

Table 1: Geometric and other parameters for conducting the experiment

Geometric data:			
D	[mm]	Tank diameter	300
H	[mm]	Filling level	300
H/D	[-]	Filling level/tank diameter ratio	1
Agitator type	4x45° pitched blade agitator		
d	[mm]	Agitator diameter (central axis of the test sample)	180
d/D	[-]	dimension-less diameter ratio	0.6
h_r	[mm]	average agitator installation height	80
h_{rm}/D	[-]	relative agitator installation height	0.267
Test data:			
N	[min^{-1}]	Rotational speed	500
w_{Tip}	[m/s]	Agitator peripheral speed (for rotational speed N)	4.71
t	[min]	Test duration (between 2 measurements)	30min
N_E	[-]	No. of glass-lined test samples	2
N_G	[.]	No. of test samples made of borosilicate glass 2	
M	[-]	No. of measuring sites per test sample	3

6.2 Positioning of the test samples

In several orientating tests the position and direction of the test samples in relation to the axis of the agitator shaft were varied. Thus the test samples were fixed on the one hand radially above and below the agitating element. On the other hand, an alignment parallel to the agitator axis at the ends of the agitator blade was examined. This position proved to be the best. When positioned at a constant distance from the agitator shaft the same speeds apply along the axis of the test sample at least nominally. Although it has been shown that the erosion of the material even at a constant speed at the side of the test sample facing the direction of the flow (w_{tip}) is not consistent along the longitudinal axis of the test sample. Rather there is increased wear at the (upper) end of the test sample in the transitional area from the cylindrical form to the dome-shaped tip; actually the erosion increases in a linear way along the length of the test sample from the bottom (screwed-in end) to the top (dome-shaped tip)

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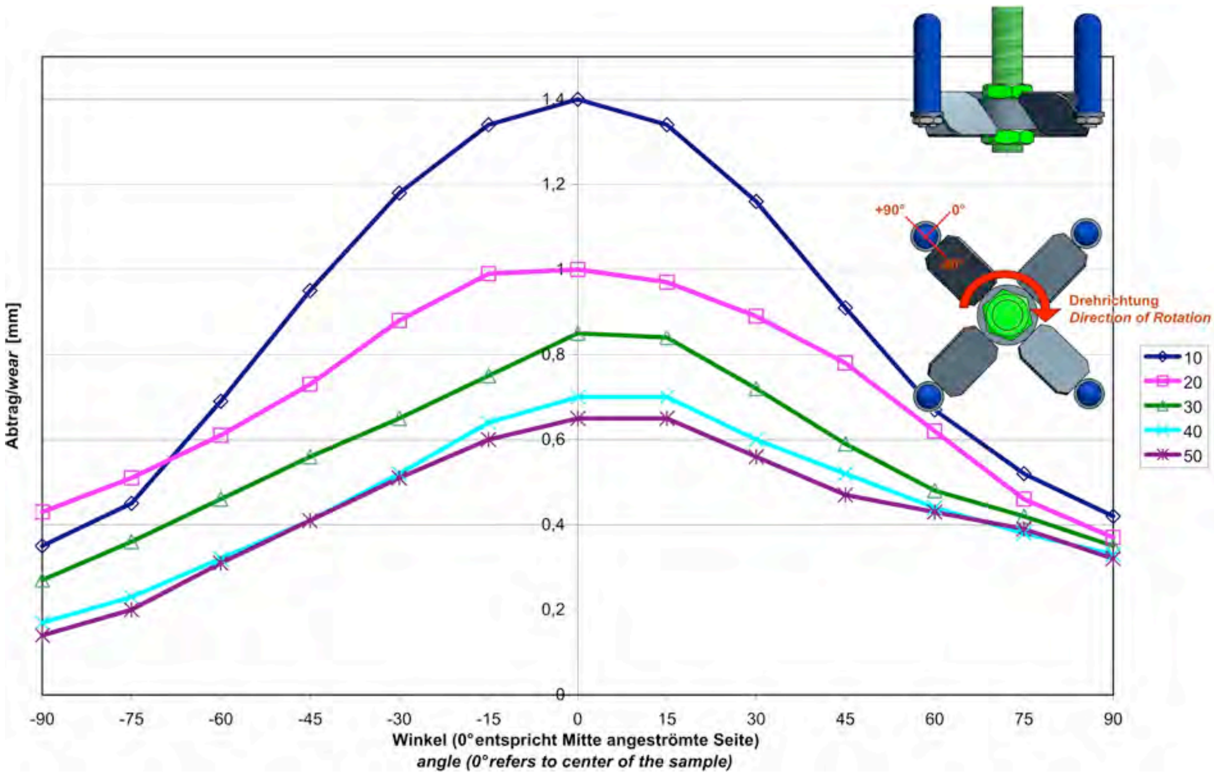
Abtrag/wear [mm]
Winkel (0°entspricht Mitte angeströmte Seite)
angle (0°refers to center of the sample)
+90°
0°
Drehrichtung
Direction of Rotation
10
20
30
40
50

Fig. 6).

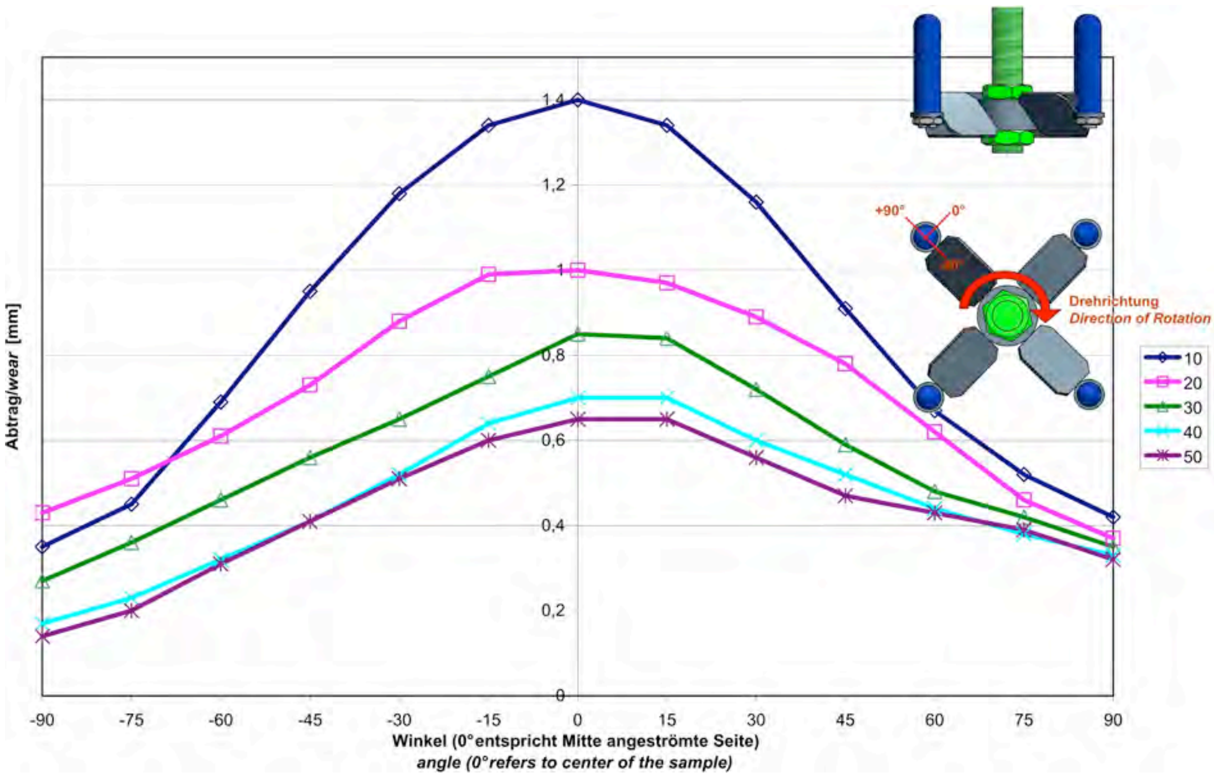
Abtrag/wear [mm]
Winkel (0°entspricht Mitte angeströmte Seite)
angle (0°refers to center of the sample)
+90°
0°
Drehrichtung
Direction of Rotation
10
20
30
40
50

Fig. 6: Progression of the erosion of the glass lining around the circumference or along the longitudinal axis of the test sample. The 0° line corresponds to the test sample longitudinal axis facing the direction of the flow

Furthermore, one could ascertain that erosion of the glass lining occurs exclusively on the side of the test sample facing the direction of the flow

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Fig. 7). Whilst the glass lining on the side facing the flow appears dull and worn, the glass lining of the test sample on the other side still has its original shine.

Fig. 7: Worn side of a test sample facing the flow with uneven wear of the glass lining. The greatest erosion of the glass lining is found at the beginning of the tip of the test sample

Fig. 8 shows the erosion of the glass lining measured along the main axis facing the flow of a test sample at three measuring points. Measuring point 1 is located at the upper tip of the test sample, Measuring point 2 in the centre of the cylindrical area of the test sample and Measuring point 3 in proximity to the mounting of the test sample on the sample holder. In order to simplify the measuring procedure and ensure that for each measurement the thickness of the glass lining is always determined at the same place with a device for measuring the thickness of the layer, a template was made in the form of a sleeve in which the measuring points are set using drilled holes. The linear progression of the wear of the glass lining over time can be easily seen in the diagram on the one hand and on the other hand it can be determined that, as shown above, the erosion of the glass lining is greatest in the area of the tip and least in the mounting area.

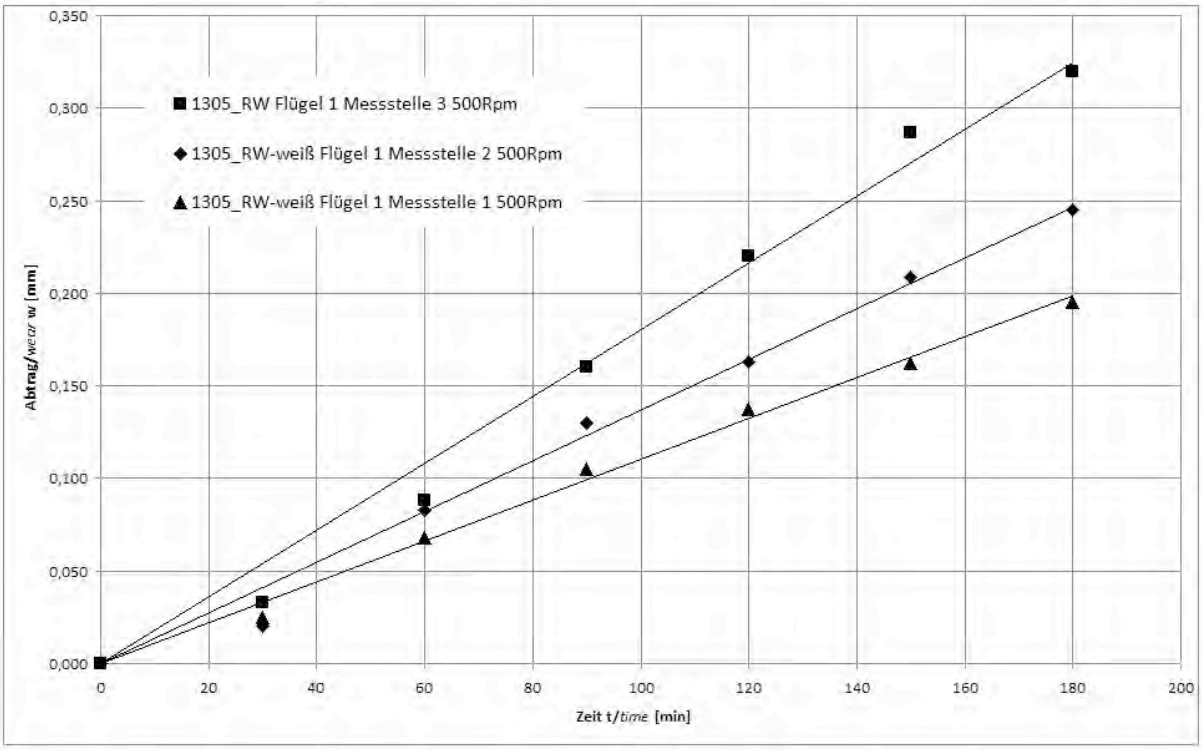

Fig. 8: Erosion of the glass lining depending on the measuring site on the test sample for a selected type of glass lining under given test conditions

The measurement values in Fig. 8 refer to the presentation of a single measurement. For all other measurements the average value of all measurements of this configuration respectively are used. This generally means at least two or three measurements per speed of rotation and test sample, with a value arising from the average of the measurements of two test samples.

7 Conducting the experiment and the results

7.1 Conducting the experiment

Besides a number of other parameters the duration of the action is decisive for the amount of wear. Therefore the tests are conducted in such a way that the remaining thickness of the glass lining is determined at regular timed intervals with the aid of a device to measure the thickness of the layer at the three sites exclusively on the side facing the flow of the liquid. With the chosen suspension of water with silicon carbide particles and at the chosen rotational speed of the agitator of 500 U/min a time interval of 30 min has proved to be suitable. For greater particle loads shorter time intervals are more sensible. The experiment is conducted until the glass coating on the tip is worn down to the base coating which can be easily seen with white or light blue glass test samples.

7.2 Glass types tested

The tests were conducted using glass types as they are used by THALETEC in the current production as well as with different development versions and modifications of existing production glass. In this paper the glass types are given a letter code. Borosilicate glass is designated "G".

Table 2: Glass-lined surfaces tested

Code	Description
AB	Blue chemical glass optimized for high resistance to hydroabrasion
AW	White chemical glass optimized for high resistance to hydroabrasion
RB	Dark blue chemical glass
RW	White chemical glass
G	Normalised borosilicate glass (test tube glass) as reference material

7.3 Erosion W in relation to time

It has been shown that glass-lined surfaces show linear erosion W over time when subject to purely hydro-abrasive stress.

$$W = m \cdot t \qquad (1)$$

The proportionality factor m, which represents the rise of the approximate straight lines of the erosion over time and can be described as the erosion rate, can therefore be used directly as a gauge for the wear resistance of a glass lining. It is the case that glass linings with a smaller "m" under the same test conditions in other respects show less erosion per time unit than those with a larger "m".

7.4 Hydroabrasion-resistance of different glass types

If one compares the glass lining types tested as well as glass with the agitator rotational speed of N=500 U/min and applies the erosion in relation to the test duration, this results in the picture presented in Fig. 9. Clearly, borosilicate glass shows the highest resistance to wear compared to glass linings. This can be explained insofar as the glass is an amorphous but intrinsically homogenous material with no bubble-like structure at all whilst the glass lining [enamel] is not quite a homogenous material in itself. The bubble-like structure of the glass lining has less material volume relative to homogenous glass in terms of exposure to wear and therefore will wear minimally faster.

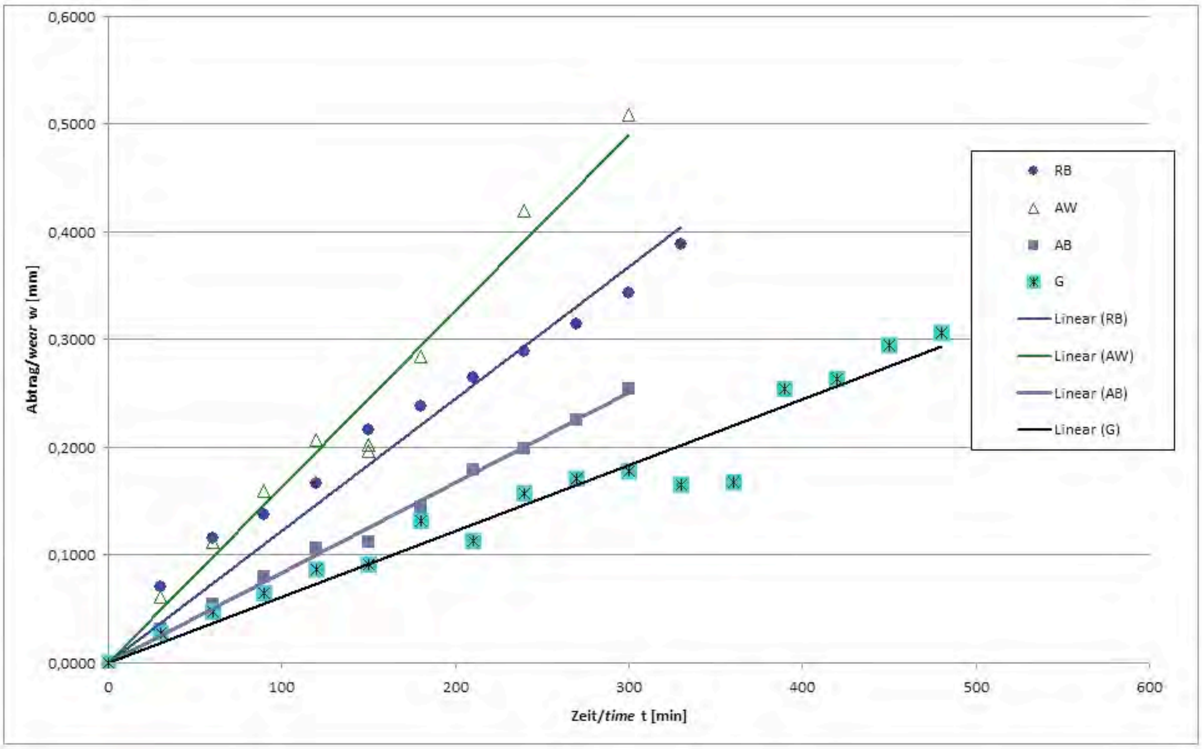

Fig. 9: Erosion W as function of the test duration for different glass lining types as well as glass at N= 500 U/min

If one compares the erosion rate m of the glass linings tested, this results in the situation presented in Table 3. If the erosion rates of the glass linings are applied to those of a reference sample made of borosilicate glass (Sample G), it becomes clear that the glass lining of the type AB which is closest to glass only shows approximately a 10% higher erosion rate than the intrinsically homogenous glass and thus behaves in an absolutely comparable way to a homogenous glass material.

Table 3: Erosion rates of different glass lining types as well as borosilicate glass (G) in hydroabrasion tests at N=500 U/min

	m	m/m_G	$m_{maxEmail}/m$
RW	0.3550	2.70	0.41
RB	0.2381	1.81	0.61
AW	0.2848	2.17	0.51
AB	0.1448	1.10	**1.00**
G	0.131	**1.00**	1.10

If one applies the erosion rate m to the erosion rate of the glass lining with the highest wear resistance (Type AB), it becomes clear that it is possible to almost double the wear resistance in comparison with previous normal chemical glass linings.

8 ABRISIST – The glass lining for hydro-abrasive and corrosive processes

THALETEC has developed a new glass lining specifically for processes in which damage can occur through abrasion as well as through exposure to corrosion from strong acids at high temperatures. We have called this new glass lining “ABRISIST”.

8.1 Features of ABRISIST

Essentially compared to other standard glass linings ABRISIST has about 20% greater **corrosion resistance** in acids (hydrochloric acid), measured in accordance with DIN EN 14483. Therefore the glass lining is particularly suitable for universal use in acidic, corrosive environments. Just the increase alone in corrosion resistance would extend the operational life of a glass-lined reactor by about 2 years, insofar as no other influences were taken into account and one assumes an erosion rate of 0.1 mm/year with a layer thickness of 1.4 mm (of which 1.0 mm can be used as corrosion protection) under acid attack.

Besides the increase in the corrosion resistance it was the development objective to significantly improve **hydroabrasion resistance** in particular. Compared to normal chemical glass linings, the hydroabrasion resistance of ABRISIST is almost double in the tests conducted by THALETEC.

In principle and irrespective of the manufacturer and the composition of the glass lining, it has a bubble-like structure. The bubbles intersperse the whole

layer of the glass lining and are merged and closed on the surface of the lining

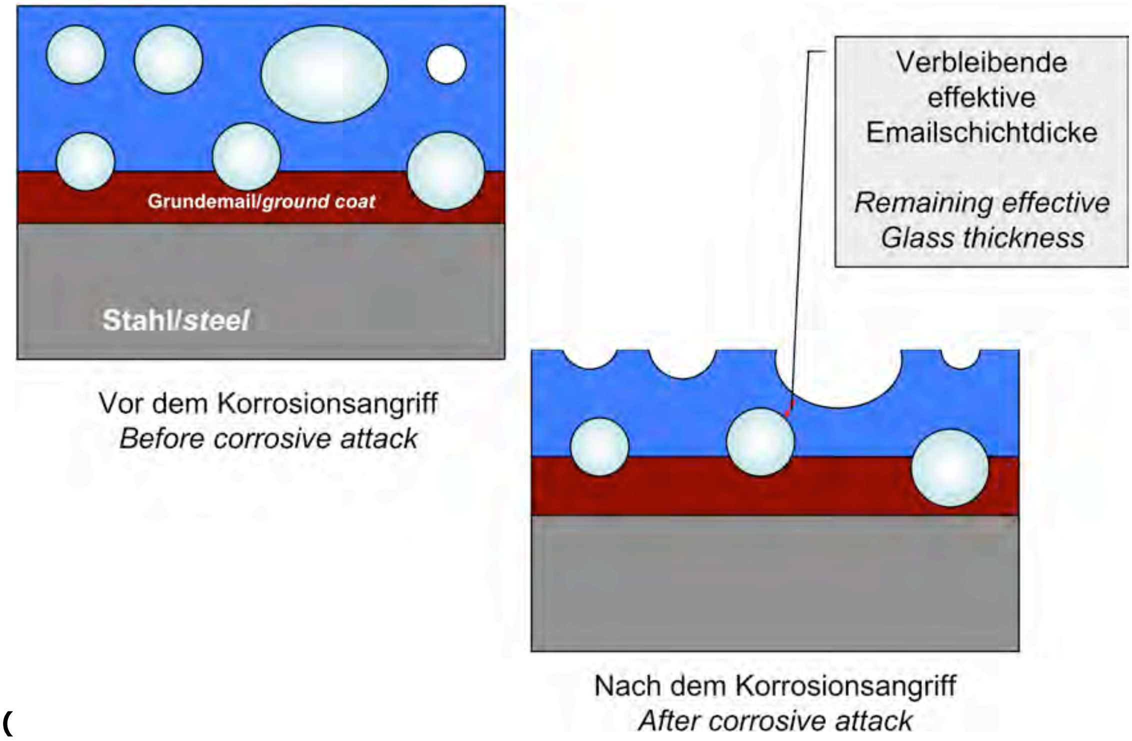

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Fig. 10).

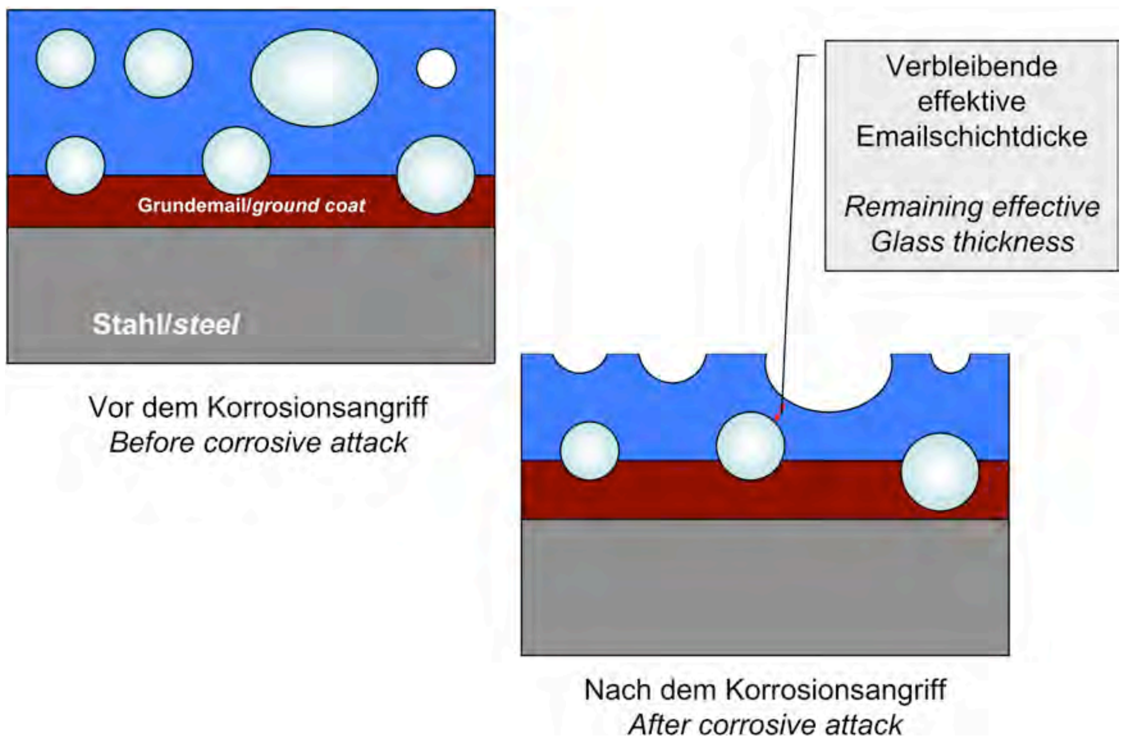

Fig. 10: Damage mechanism as a result of the bubble structure of the glass lining. A fine bubble structure often considerably prolongs the life of a glass-lined reactor

If the glass lining comes under chemical or hydro-abrasive attack, the layer of the glass lining will be continuously eroded and individual bubbles will be exposed and cut one after the other. If the glass lining has a coarse bubble structure, the remaining thickness of the glass lining can be drastically reduced suddenly if the large bubble extends almost to the base lining. The base lining only has minimal chemical resistance. Although the whole reactor, considered macroscopically, may still have quite a thick glass lining, it can however be the case that locally only a small amount of the glass lining is effective as a protective layer. In such places there is then localised steel corrosion although the rest of the apparatus is still fine.

The formulation of the ABRISIST-coating has the effect that the size of the bubbles in the glass lining is smaller than in normal glass linings. Furthermore, technological parameters, like the modified firing programmes, the regulated temperature control when heating up and cooling down the components, taking into consideration the parameters specific to the glass lining, as well as a special technique to apply the glass lining substrate onto the surface result in a fine bubble structure. In particular, the wet application of the glass lining in thin layers results in a fine bubble structure of the glass lining. A dry application or "powdering" on the other hand leads to a coarse bubble glass lining.

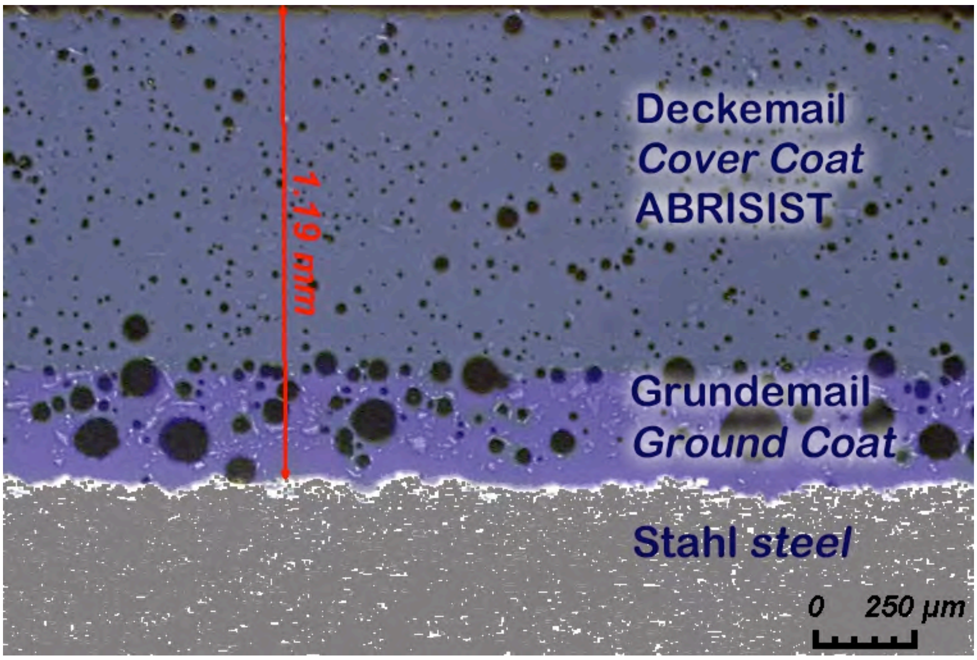

Fig. 11: Cross-section through the ABRISIST glass lining layer. At the bottom edge of the picture can be seen the bubble structure of the base lining; over that the particularly fine bubble structure of the upper glass lining layers. The upper glass lining determines the application characteristics of the glass lining

9 Outlook

Besides chemical corrosion, hydroabrasion is a significant cause of failure of glass-lined process engineering equipment. With the method presented to quantify the wear resistance of glass-lined surfaces under hydro-abrasive conditions, a step has been taken for the first time to examine the specifics of this wear mechanism in a reproducible form and thereby enable a quantitative comparison of glass-lined surfaces. Thus it is useful to refine this process further, if necessary, and to work on it in such a way and describe it so that in addition to the various wear test procedures known from the glass lining of thin metal sheets, such as the Taber procedure according to ISO 6370, the abrasive wheel procedure of Kaldewei/Polyvision and the "orbital shaker" from Silit /12/, it can also take its place as a wear test and evaluation concept for chemical glass linings. This will, of course, require the willingness of the relevant manufacturers of glass-lined equipment for the chemical industry as well as manufacturers of glass linings to work together to produce a standardized concept. It could prove important to combine different types of stresses and recognise and quantify their interaction with each other as well as their effects: one suggestion is to conduct tests under a combination of corrosive/ hydro-abrasive stress conditions in a correspondingly configured tribological system. This provides a challenge because the equipment cost and the safety-related aspects to be taken into account will considerably increase compared to the work conducted to date.

Furthermore, it is sensible to conduct a systematic comparison of the results of hydroabrasion tests with the results of other test procedures in order to recognise connections and regularities here, if applicable.

From the perspective of THALETEC, it could be shown with these test procedures in an impressive way that it has been successful in developing a glass lining with the new technical glass, ABRISIST, which compared to conventional chemical glass linings has almost twice the wear resistance. This forms a sound basis for further developments, the focus of which should now be on optimizing the design of components subject to abrasion such as agitators and baffles. Here, too, there have been initial results which shall be published at a later date.

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Acknowledgments

The scientific tests which form the basis of this publication were conducted within the scope of a research project sponsored by the Federal Ministry for Industry and Technology (ZIM-Project) in close co-operation with the technical department 7 of the technical college, Hochschule Anhalt, in Köthen. The authors wish to thank the staff of the Hochschule Anhalt, especially Frau Jeniffer Wirth, for her kind support.