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» Tests on Airbags: Analysis of Pyrotechnical Performance, Gases, Dusts, Acoustics, Structures and Squibs

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1. Abstract

Performance: The performance of gas pressure development in a closed can by a gas generator, by pellets and by squibs are measured by tank tests. The instrumentation delivers data about internal pressure, ignition current and burning rate.

Passenger exposure: On-line gas analysis of up to 17 toxicologically relevant gases is performed. For this purpose, the gas is filtered appropriately and fed into four analysis instruments (MS, FTIR, CLD und NDIR). The time dependent progress of concentration for a period of 30 minutes after ignition allows the evaluation referring to known limit values. Dust exposure is determined by fractional precipitation and chemical analysis.

Materialography (destructive testing): Squibs may be characterized by sectioning; this includes evaluation of the igniting mixture regarding fissures, inhomogeneities, glow bridge contact and corrosion resistance. For cold gas cylinders the tests associated with the development apply to I) body, II) plugs, III) membranes, and IV) welding as well as assembling engineering.

Failure analysis: To determine the cause of a failure the module is dismantled down to the glow bridge. Common failure sources are faulty assembly or missing components, possible moisture diffusion and corrosion plus welding methods and composite materials which are inadequate for long time utilization.

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2. Passenger exposure

To exert their functions, pyrotechnic substances (energetic matters) are used for squibs and gas generators. To assure a safe application, the knowledge of the emitted substances is mandatory. The procedures for qualitative and quantitative analysis of gases and dusts are defined by common standards AK-ZV01 and SAE J1794/USCAR. With the exception of the additional analysis of some inert gases (Ar, He) as cold gas filling, analyzing requirements have not changed substantially with the introduction of cold gas cylinders (hybrids). Confronted with the challenging task of conducting a reliable analysis concerning gas concentrations of the dust contaminated effluents, the chemist has to employ a combination of analysis methods and suitable know-how for artefact free gas handling.

This is also the case with the associated dust – usually inorganic residues (ashes) of the pyrotechnical mixtures – which has to be characterized to avoid potentially dangerous occupants' exposures. Thus, for the reliable analysis of dust, both care and experience are a prerequisite.

2.1. Gas Analysis

Long term development studies over a period of 25 years resulted in a concept of on-line gas analysis characterized by:
- conditioning of the sample gas flow without changing the actual gas concentration by filtering and heating,
- continual measurement of the progress of concentration development during 30 minutes after ignition instead of integral measurements,
- simultaneous analysis of up to 21 airbag relevant gases.

This method has had some influence on the AK-ZV01 ("Arbeitskreis Zielvereinbarung", task force for target agreement) of the German automobile Industry.

2.1.1. Threshold Limits

Table 1: comparison of known thresholds values of some gaseous compounds as mentioned in the AK-ZV01:

gas	chemical designation	MAK	STEL	TWA	IDLH	AKZV01	SAE J1794
		ppm	ppm	ppm	ppm	ppm	Ppm
CO	carbon monoxide	30	25	25	1200	500	-*)
CO2	carbon dioxide	5000	30000	5000	40000	20000	-
NO	nitric oxide	35	35	35	100	50	-
NO2	nitrogen dioxide	5	5	3	40	10	-
NH3	ammonia	50	35	25	300	150	-
HCHO	formaldehyde	0,5	2	2	20	10	-
HCN	hydrogen cyanide	10	10	-	50	25	-
H2S	hydrogen sulphide	10	15	10	100	50	-
COCl2	phosgene	0,1	-	0,1	2	1	-
HCl	hydrogen chloride	50	5	5	50	25	-
SO2	sulphur dioxide	2	5	2	100	50	-
Cl2	chlorine	0,5	1	0,5	10	5	-

*) SAE values illustrate a method but not limits; exact threshold limits are often agreed upon customer and producer.

For industrial and toxicological needs, different authorities established limits of relevant gases. The best-known are the MAK value ("Maximale Arbeitsplatzkonzentration" = maximum concentration at work), TRK value ("technische Richtkonzentration" = technical reference concentration) and TLV (threshold limit value) from the U.S. divided into STEL value (short time exposure limit) as well as TWA value (time weighted average), OEL value (occupational exposure limit) from the UK, also divided into STEL and TWA values as well as IDLH value (immediate danger for life and health). Some threshold values collected from literature are enumerated in table 1; indications are in ppm (precisely vppm, this means, volume parts per million: 1 vol% corresponds to 10.000 vppm, 1 ppm corresponds to 1 mL m^{-3}). AKZV and SAE data refer to the atmosphere in the vehicle after ignition of the airbag(s), otherwise to the ambient air.

Beside threshold limits relevant to health there are also lower explosion limits for hydrogen of 4,0 v% and ammonia of 15,4 v% in the resulting atmosphere.

2.1.2. Analysis concept

Basically, preliminary laboratory tests identify the gaseous compounds which have to be quantified. The identification of occurring gases in vehicles is made by spectroscopy (FTIR, MS). Quantification requires the knowledge of the most appropriate physical or chemical properties of the gases that have to be analysed, in order to select the proper methods of analysis. Indications to problems that may arise in analyzing a gas correctly are 1) information on the chemical reactivity in connection with other present gases, air, dust, humidity and tubing/pump materials, 2) known robust analysing methods and 3) possible chromatographical effects, that have to be expected, like adsorption of passing assays to tubes and dust (such effects may occur at boiling points of the pure gases of more than about - 100 °C). The development of quantitative analytical methods, which show a low cross sensitivity against contaminations from air bag exhausts, represents important know-how of the GWP:

Table 2: selection of analysis methods for airbag relevant gases:

gas	chemical designation	method	boiling point	particularities
-	-	Acronym	°C	-
CO	carbon monoxide	FTIR,NDIR	- 191,5	CO2- und H2O-cross-sensitivity
CO2	carbon dioxide	MS, FTIR	-78,5	about 500 ppm city background
NO	nitric oxide	CLD, MS	-152,0	ad-/absorption to dust and so on; oxidation to NO2
NO2	nitrogen dioxide	CLD	21,2	consumed by reduction and decomposition
N2O	nitrous oxide	FTIR, GC	-88,5	mass 44 amu similar to CO2
NH3	ammonia	FTIR	-33,4	strong chromatographic effects during gas handling
HCHO	formaldehyde	FTIR	-21	danger of polymerisation, adsorption
(CN)2	dicyan	FTIR	-21,2	highly toxic
HCN	hydrogen cyanide	FTIR	25,7	calibration gases difficult to handle
H2S	hydrogen sulphide	FTIR	-60,2	strong adsorption in low concentrations
COCl2	phosgene	FTIR	7,6	calibration requires very low humidity in the system
HCl	hydrogen chloride	FTIR	-85,1	strong adsorption in low concentrations
COS	carbonyl sulphide	FTIR, MS	-50,2	highly toxic
SO2	sulphur dioxide	MS	-183,0	corrosive for most affected materials
H2O	water/Humidity	MS, FTIR	100	naturally about 10.000 – 50.000 vppm

H2	hydrogen	MS	-256	up to about 20 v% in combustion gases; explosive
O2	oxygen	MS	-252,8	danger of suffocation below 13% O2
Ar	argon	MS	-186,0	surroundings about 10.000 vppm (corresp.to 1 v%)
He	helium	MS	-269	surroundings about 4 vppm; in fillings for leaks test
C6H6	benzene	MS	80,1	combustion product in reducing atmosphere
Cl2	chlorine	EZ, IT	-34,1	unique application for electrochemical or test tube
CH4	Methane	FTIR, GC	-162	combustion product
C2H2	acetylene	FTIR	-83,8	combustion product in reducing atmosphere
C2H4/6	ethene, ethane	FTIR	-104	combustion product in reducing atmosphere
∑Arom.	arom. compounds	FTIR	-	combustion product in reducing atmosphere

At the moment, we employ four on-line methods: MS, FTIR, CLD and NDIR. For this purpose, GWP only uses commercially available instruments (invested sum about 350.000 €), see table 3.

Table 3: Used analytical equipment for gas analyses in airbag effluents.

acronym	method	type	remark
MS	mass spectroscopy	Balzers GAM 500	quadrupol mass filter
FTIR	fourier-transform infrared spectr.	Nicolet Antaris IGS	10 m gas cell
CLD	chemiluminescence	EcoPhysics 700 CLS	principle NO->NO2 + hν
NDIR	non dispersive IR-spectrometry	Maihak Unor	photo acoustic detector

Test or indicator tubes (i.e. from Dräger) are based on chemical colour reactions. In most cases they are not suitable for gas analyses in airbag effluents because of the potential – and partially considerable – cross sensitivity to other compounds of the analysed gas mixture, as the following reactive gases can often be observed simultaneously: CO, NO, NO2, C2H2, HCN. For example, a CO-indication may be influenced by other oxidable compounds like hydrocarbons (i.e. C2H2). Chlorine test tubes are only recommended, if an electrochemical cell with ion-selective electrode is unavailable.

In order to allow the generated gas atmosphere in the test container (can of 60 litre tank of 2.5 m3 or vehicle) to be fed into analytical instruments, particles have to be separated. The demand, that the composition of the gas may not be influenced by percolation and passage through tubes resulted in the development of a gas handling unit (GHU, figure 1).

Important characteristics of the experiment and the developed instruments included in the GHU are:
- heated steel membrane pump to handle the sample gas flow,
- heated and polished steel tubes, no Teflon,
- fractionated percolation to minimize chromatographical adsorption and absorption effects,
- thinning effects avoided by recirculation back into the compartment,
- test gas may be fed out of the set of calibration gas cylinders into the experiment.

2.1.3. Preconditioning/Percolation

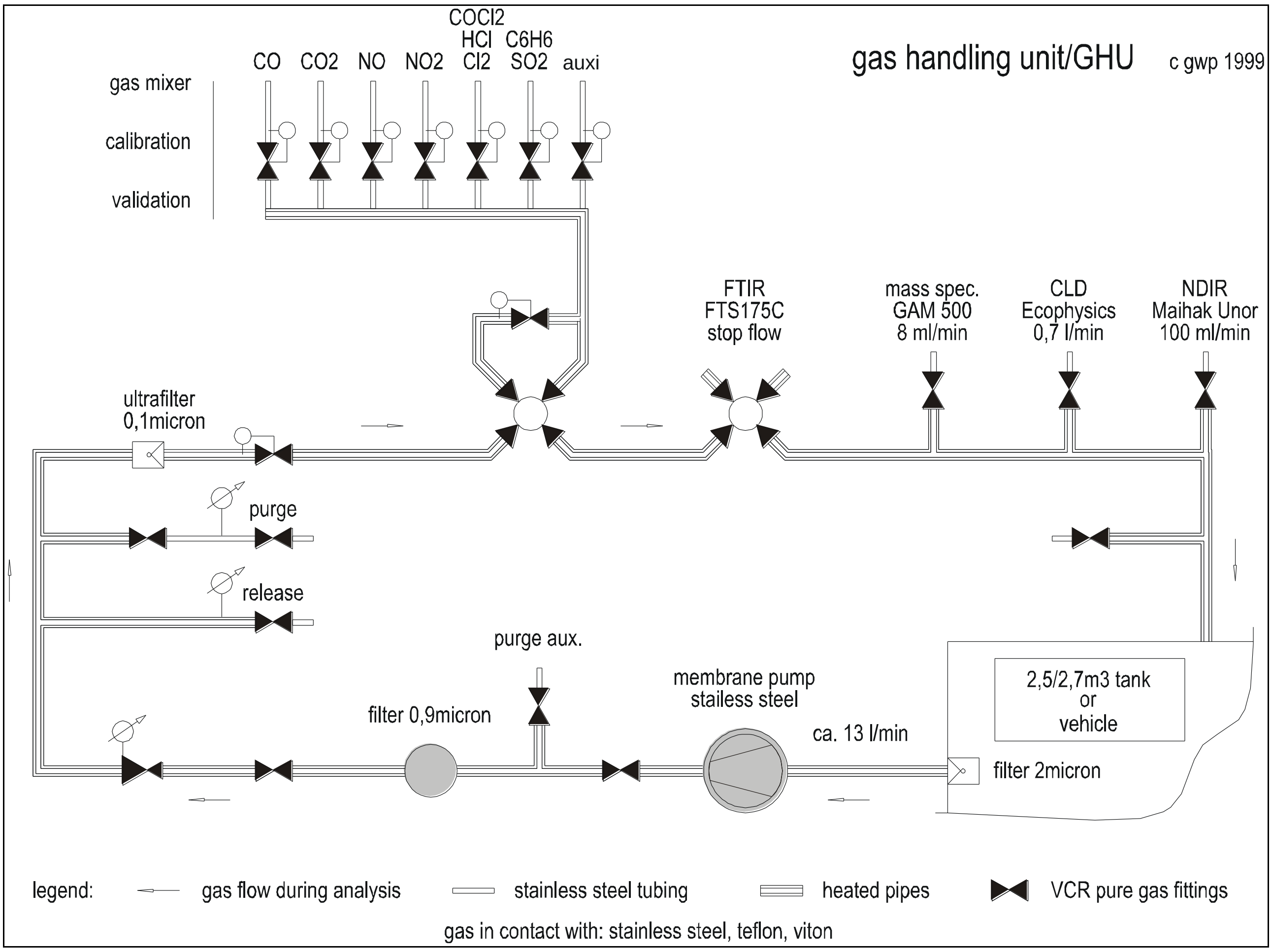


Figure 1: Scheme of gas handling unit (GHU).

This is the configuration we used to calibrate and validate the GWP-method, which we then laid down in our standard guideline RL 08 GasL[1].

[1] Accredited test method according to DIN EN ISO 17025

2.1.4. Results

The GWP-method is applied to analyze the progress of the gas concentration succeeding ignition in a 2.5m3tank. The analysis is conducted for a period of 30 minutes. Finally, the test can is vented.

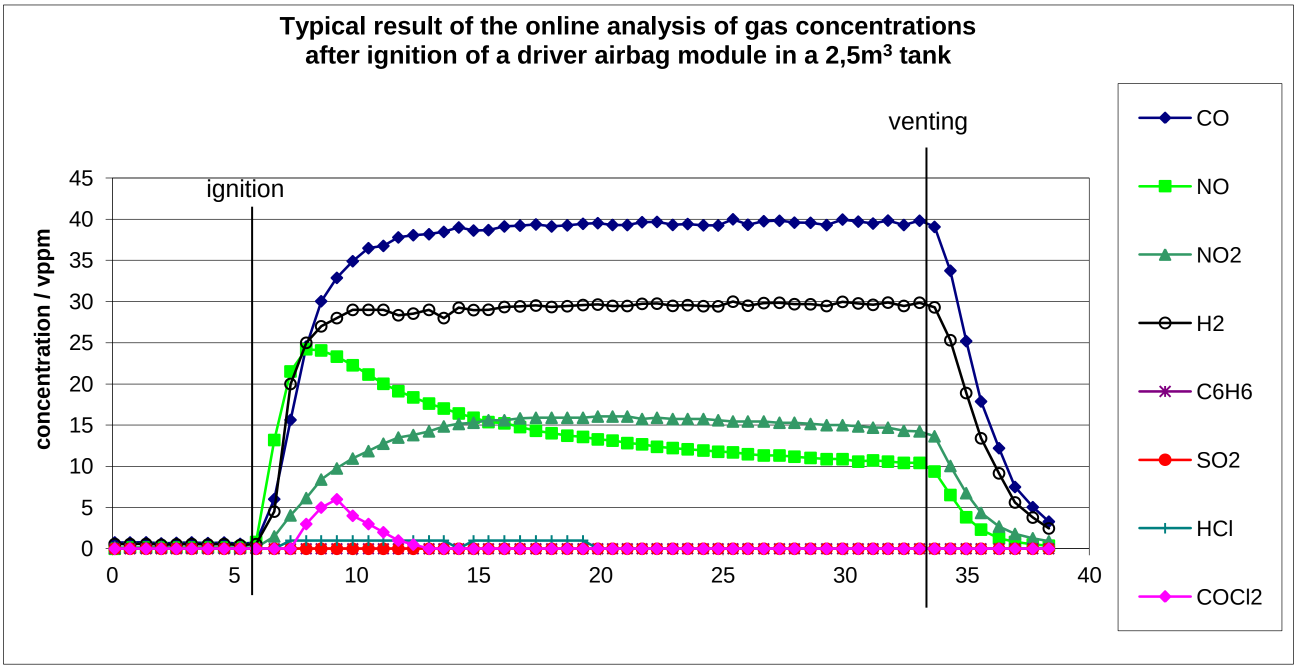


Figure 2: Progress of concentration of reactive (NO, $COCl_2$) and stable (H_2, CO) gases

Figure 2 illustrates the dynamical progress of the concentration profiles of some reactive gases. In the trace region, spontaneous oxidation of NO to NO2 by air is recognizable. After a few minutes, not very reactive (CO, H2) or inert (He) gases show constant concentrations due to diffusion in the whole tight content of the tank.

GWP Gaslabor — Gas- and Dust Analysis in Vehicle: Driver and Passenger Airbag (DAB, PAB)

Order	xyz
Customer	Musterkunde
Sample	DAB, PAB
Test	n.n.
Date	21.1.2000
Experimental set up	Vehicle, GHU, Massenspektrometer, CLD, FTIR, Andersen-Impaktor
Remark	demonstration only

	file	CO		CO2		NO		NO2		Cl2		H2		COCl2		SO2		HCl		N.N.
DL; AK [ppm]		2 ; 500		5 ; 20000		0,15 ; 50		0,19 ; 10,0		0,6 ; 5,0		- ; 30000		0,1 ; 1,0		0,4 ; 50		1,0 ; 25		
Sample		max.	mean	max.	mean	max.	mean	max.	mean	max.	mean	max.	mean	max.	mean	max.	mean	max.	mean	
DAB PAB 1	439	177	155	2530	2200	33	26	4,3	4,1	-	-	482	321	4,3	<DL	<DL	<DL	<DL	<DL	
DAB PAB 2	440	245	229	2312	2010	36	28	3,4	3,3	-	-	518	345	5,5	<DL	<DL	<DL	<DL	<DL	
DAB PAB 3	441	211	188	2092	1819	32	25	3,2	3,1	-	-	452	301	1,9	<DL	<DL	<DL	<DL	<DL	
DAB PAB 4	442	267	240	2268	1972	36	28	4,5	4,3	-	-	482	321	4,0	<DL	<DL	<DL	<DL	<DL	
DAB PAB 5	443	276	230	2194	1908	33	25	4,2	4,0	-	-	534	356	0,9	<DL	<DL	<DL	<DL	<DL	
DAB PAB 6	444	265	221	2657	2310	37	29	5,3	5,1	-	-	557	371	3,9	<DL	<DL	<DL	<DL	<DL	

	file	Argon		Helium		H2O		HCN		HCHO		NH3		H2S		C6H6		Dust		pH
DL; AK [ppm]		- ; -		- ; -		- ; -		0,4 ; 25		0,7 ; 10		0,7 ; 150		2,0 ; 50				mg/m3	mg/m3	pH
Sample		max.	mean	max.	mean	max.	mean	max.	mean	max.	mean	max.	mean	max.	mean	max.	mean	total	tot. resp.	-
DAB PAB 1	439	104679	104670	1086	905	3321	3163	4,0	2,2	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	234	200	5,5
DAB PAB 2	440	138943	126312	1222	1018	3964	3775	5,4	3,0	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	267	213	5,1
DAB PAB 3	441	122945	111768	1186	988	3495	3329	3,8	2,1	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	211	221	4,9
DAB PAB 4	442	134387	122170	1402	1168	3447	3283	7,2	4,0	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	203	182	4,8
DAB PAB 5	443	112134	101940	1270	1058	3251	3096	5,8	3,2	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	193	176	5,1
DAB PAB 6	444	123979	112708	1308	1090	4276	4072	5,0	2,8	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	272	245	4,7

Figure 3: : Demonstration report of gas concentrations with highest occuring (max.), and 30 minutes mean values; in addition, dust data are included in the „one sheet report"

In the case of the determination of air bag exhaust gases inside a vehicle, the results are overlaid by diffusion (passive aeration openings in the vehicle) and adsorption (plastic surfaces, textiles, foamed material), so that after some minutes the values decrease continually. In this case the resulting average value is lower than in the tank analyses.

2.2. Dust analysis

Generally, particles are produced by pyrotechnics and dust may affect, amongst other things, the respiratory system of the passengers. This is reflected, for example by a threshold value for total dust concentration of 5 mg m^{-3} for an 8 hour working shift (maximum work place concentration, MAK limit), independent of the chemical composition of the dust.

Particles with an aerodynamical diameter of less than 10 µm precipitate in air only very slowly. Occupants are exposed to these airborne particles, so methods for quantifying them are necessary. In a first step, employing a fractioned impaction, particles of the size of about 10 µm are deposited inside the Andersen-impactor by impact precipitation after acceleration through a set of nozzles. In seven successive steps, smaller fractions are deposited due to decreasing diameters of nozzles, corresponding to impaction of finer particles.

In special cases the analysis comprises size distribution and morphology of particles (nodular or fibrous) as well as their chemical composition, especially concentrations of heavy metals, the general elemental composition, the percentage of quartz as well as the basicity (pH-value).

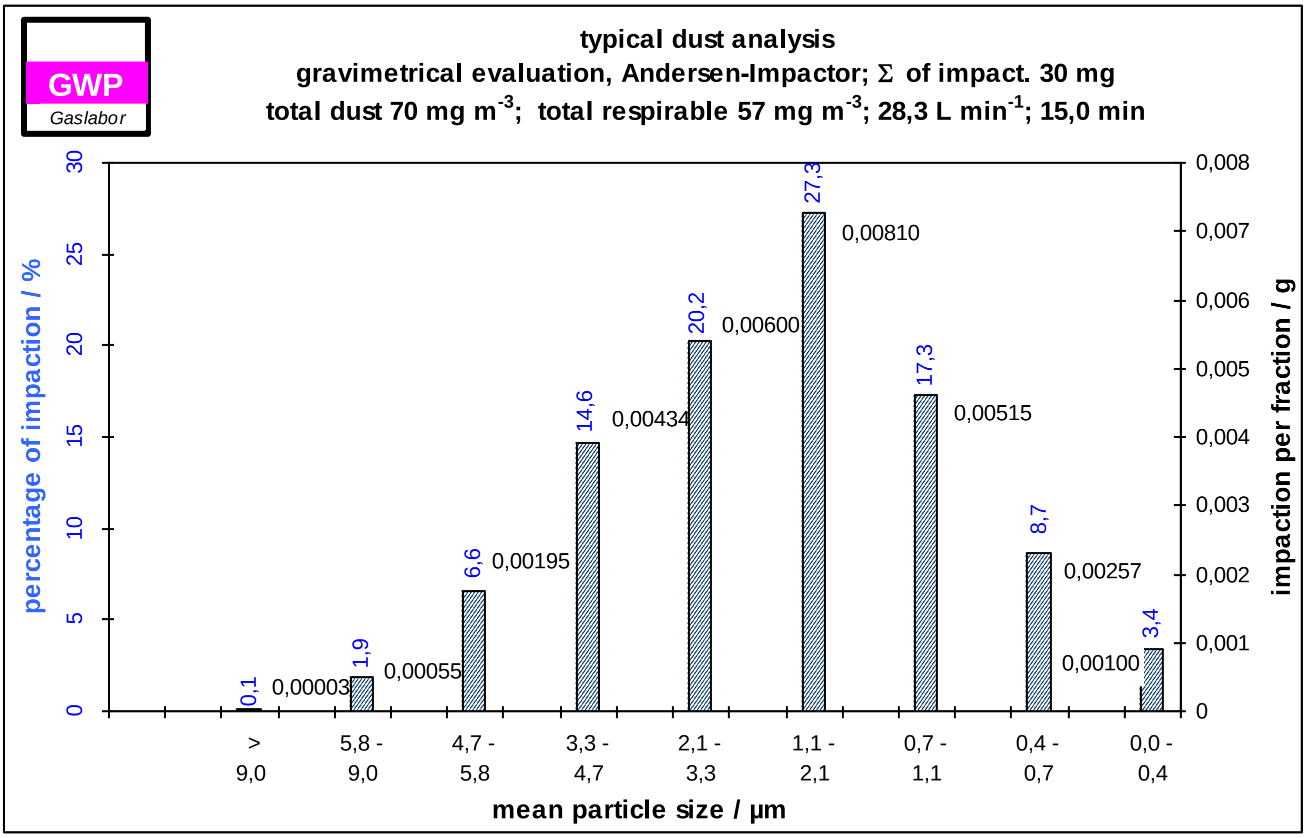


Figure 4: Histogram of an Andersen impactor dust analysis.

2.3. Comparison of GWP-AV122 GasL, AKZV01 and SAE-J1794

All three methods allow expressive, and above all, comparable analyses. Slight adaptations are possible and technically recommended, i. e. run times of impactors for the correct total loading due to variable dust concentration in individual cases. Table 4 compares important parameters of the different methods again.

Table 4: Important characteristics of comparable methods

		- - - - - - - - - Method	- - - - - - - - -		
parameter	unit	AV122 GasL	AK ZV01	SAE J1794	remark
volume for ignition	litre	2700	2500	2830	inert surface to avoid adsorption
homogenizing fan	-	without	without	without	bag is not deflated, gas diffuses (tissue/vents)
test tube accepted	-	yes	yes	yes	test tubes show cross sensitivities
measurement time	min	30	30	20	-
evaluation of measured value	-	mean, max (option)	mean	mean	average of individual values via measurement time
number of ana-lyzed gases	-	up to 21	12	12	-
impactor operating time	min	variable	15	20	GWP: depending on dust concentration/charge
analysis of dust compound	-	individual	individual	30*)	depending on pyrotechnic and materials
analysis of ions in dust	-	individual	6	6	indications in mg m^{-3}

*) example of a design specification to one company

Every supplier and car manufacturer in Germany will establish their own specification for bilateral uses independent of these known conditions, i. e. by means of AKLVs.

2.4. Performance characteristics of propellants (closed vessel tests)

The complete gas generator as well as the pyrotechnic may be ignited in a chamber of 28, 60 or 100 L.

The resulting pressure profile describes the performance of the propellant in the applied environment.

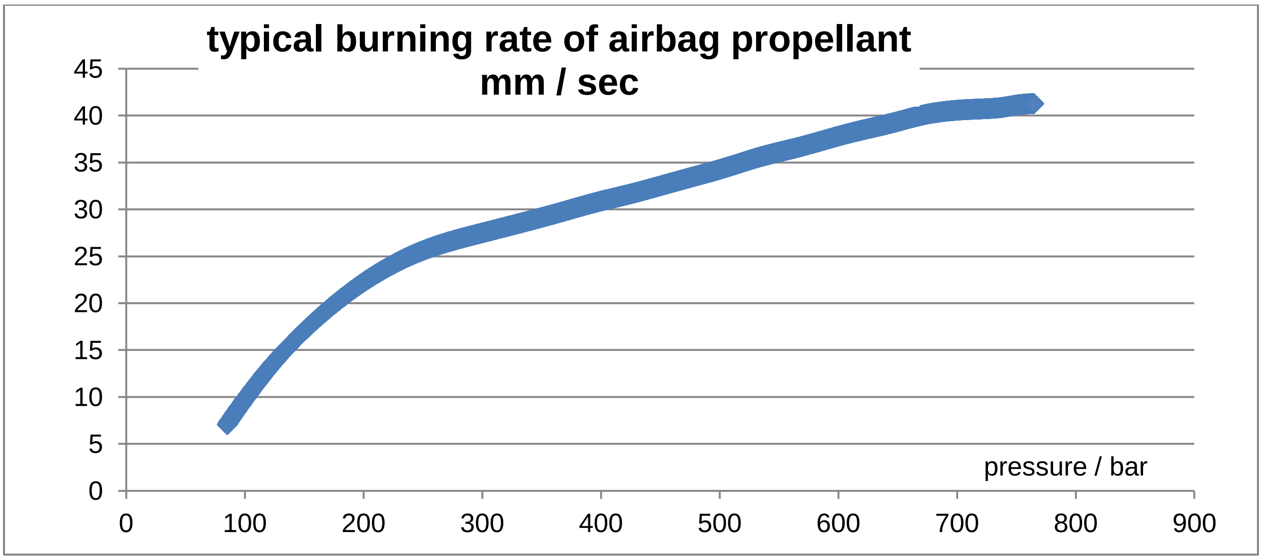


Figure 5: integral burning rate measured in a closed vessel

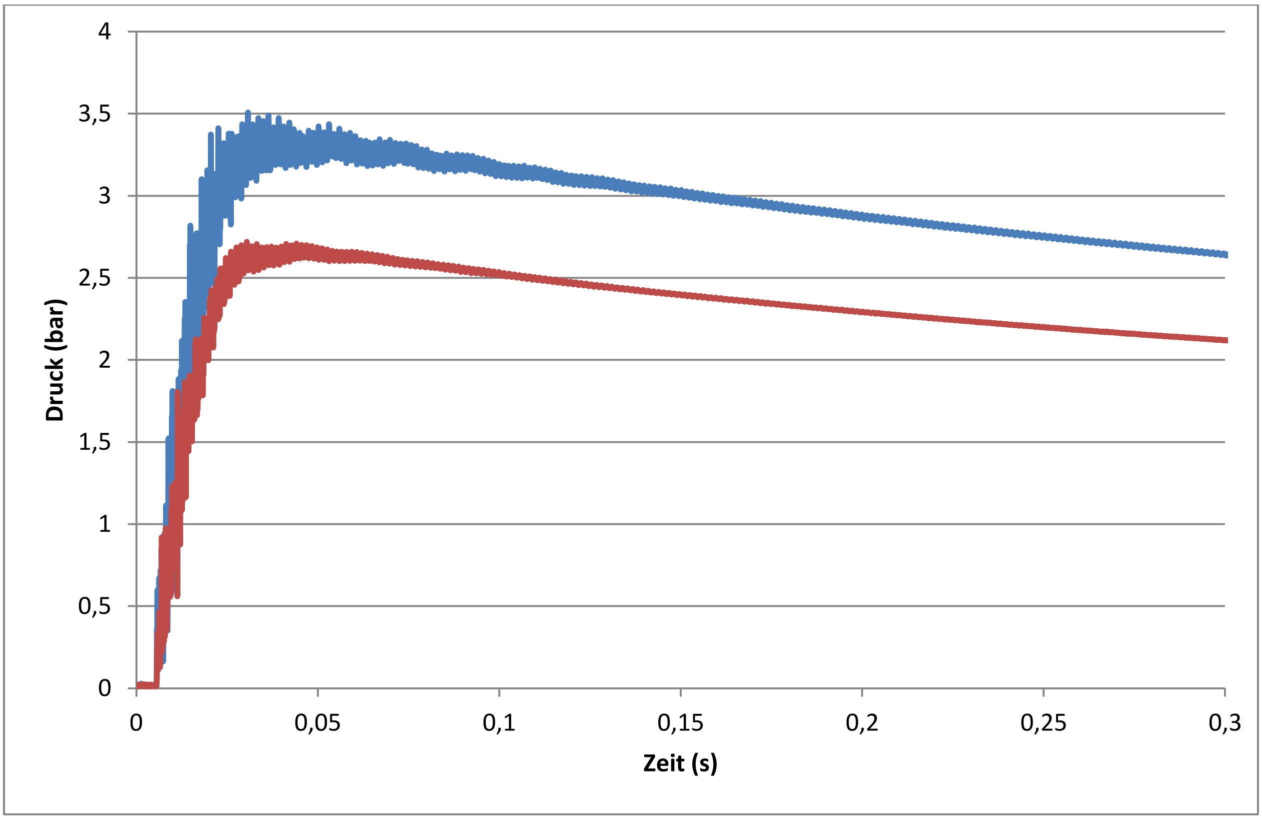


Figure 6: pressure development of two DAB in 28 L

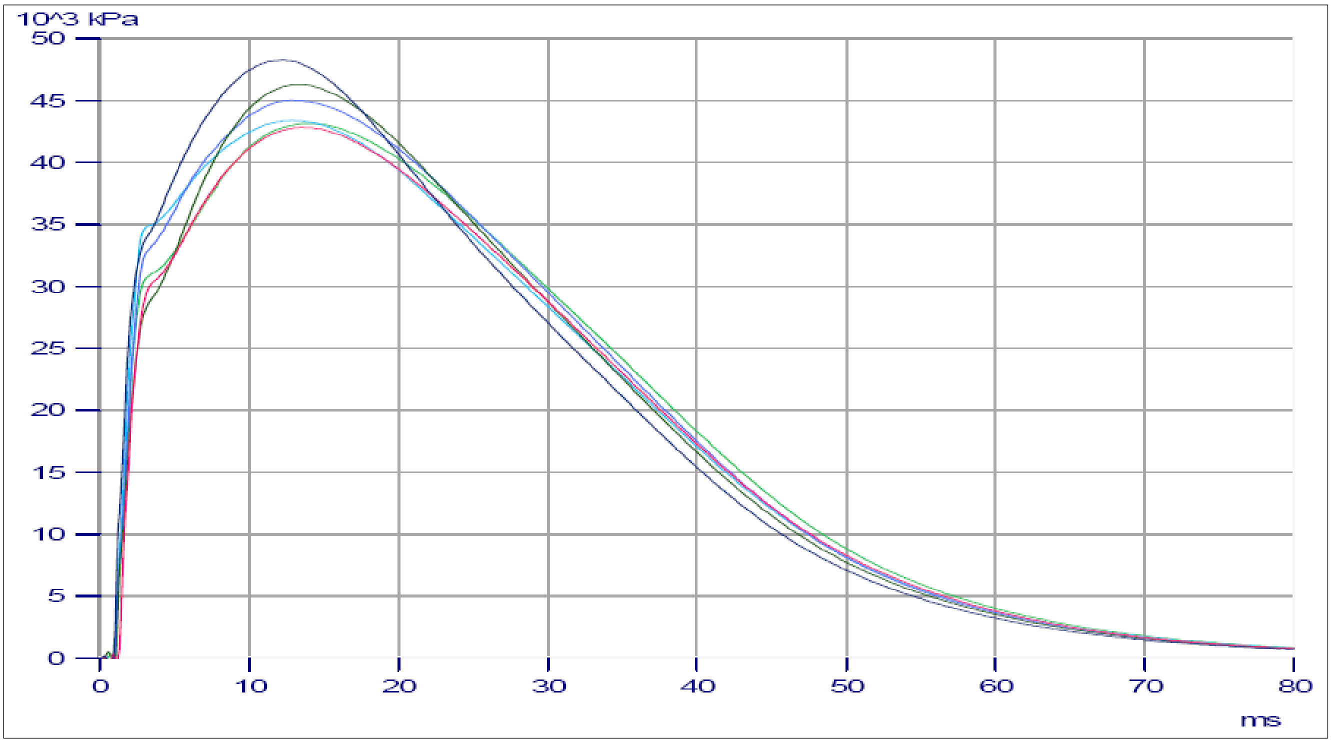


Figure 7: typical chamber pressure of DAB gas generators

3. Materialography in the Development of Inflators and Squibs

3.1. Joint Weldings in Cylinders for Cold Gas

To allow the qualification of manufacturing processes, the manufacturing parameters with respect to their effect on materials and joinings have to be examined.

When joining techniques, such as condenser discharge welding, are applied it is essential to avoid lacks of fusion, extended hardened regions in the used materials or other undesired structural transformations. The metallographic examination of such welding is shown with the example of a joint welding of the plug and the cold gas cylinder as well as the support of the membrane and the membrane itself. Critical influences are on the one hand the jointing of a high-alloy austenitic, stainless steel with a low-alloy ferritic material and on the other hand the joining of thin membranes on a solid support.

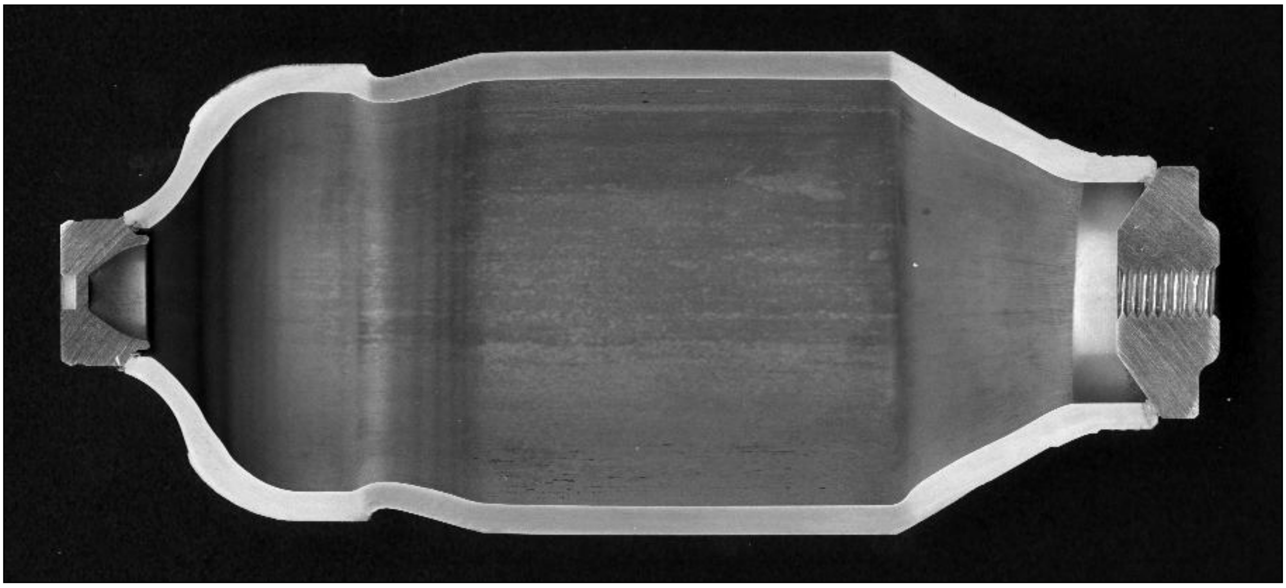


Figure 8: transformed cold gas cylinder with welded plug (right) and welded support of the membrane (left).

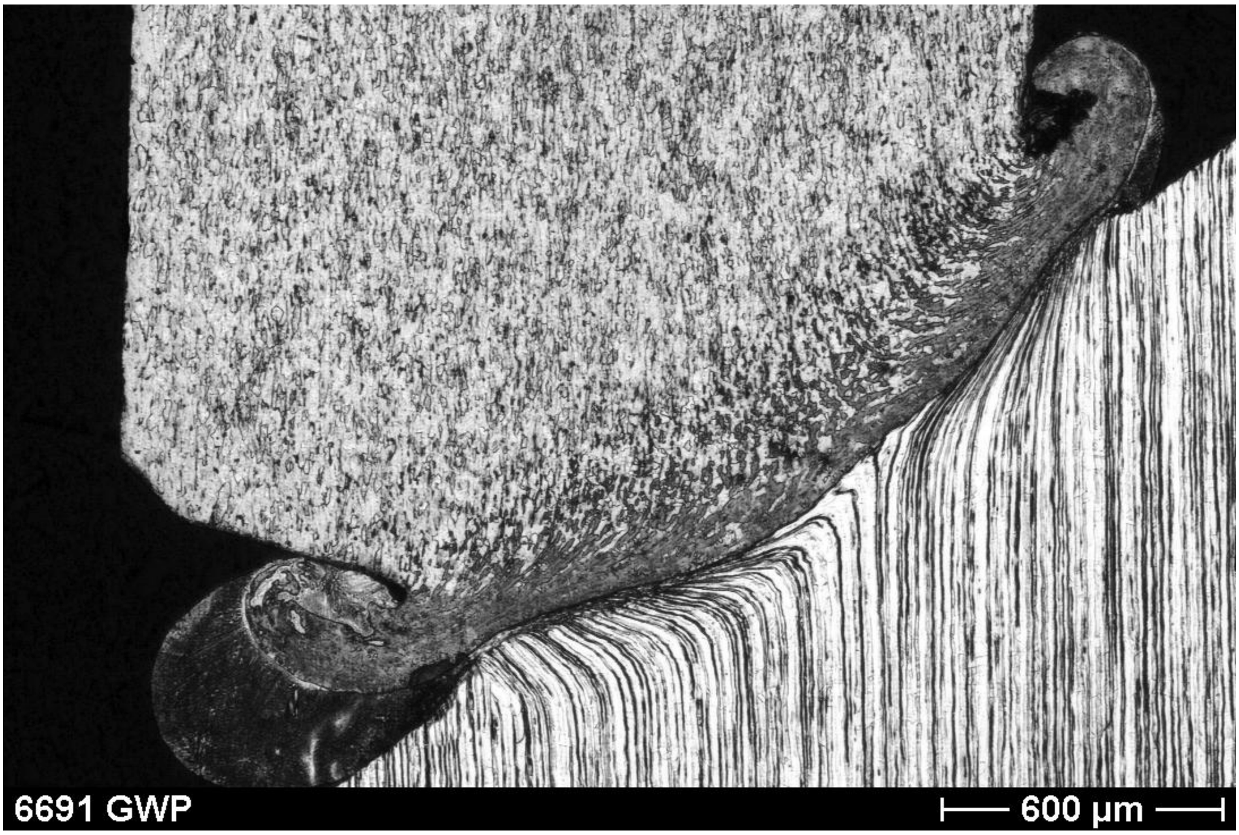


Figure 9: condenser discharge welding of the plug (above; ferrite steel) and cold gas cylinder (below; austenitic steel).

When evaluating the base metal of the cold gas cylinder, it is mostly a matter of the influences of the hot transformation process on the structural constitution, where strength reducing or embrittling influences have to be avoided or prevented (figure 8).

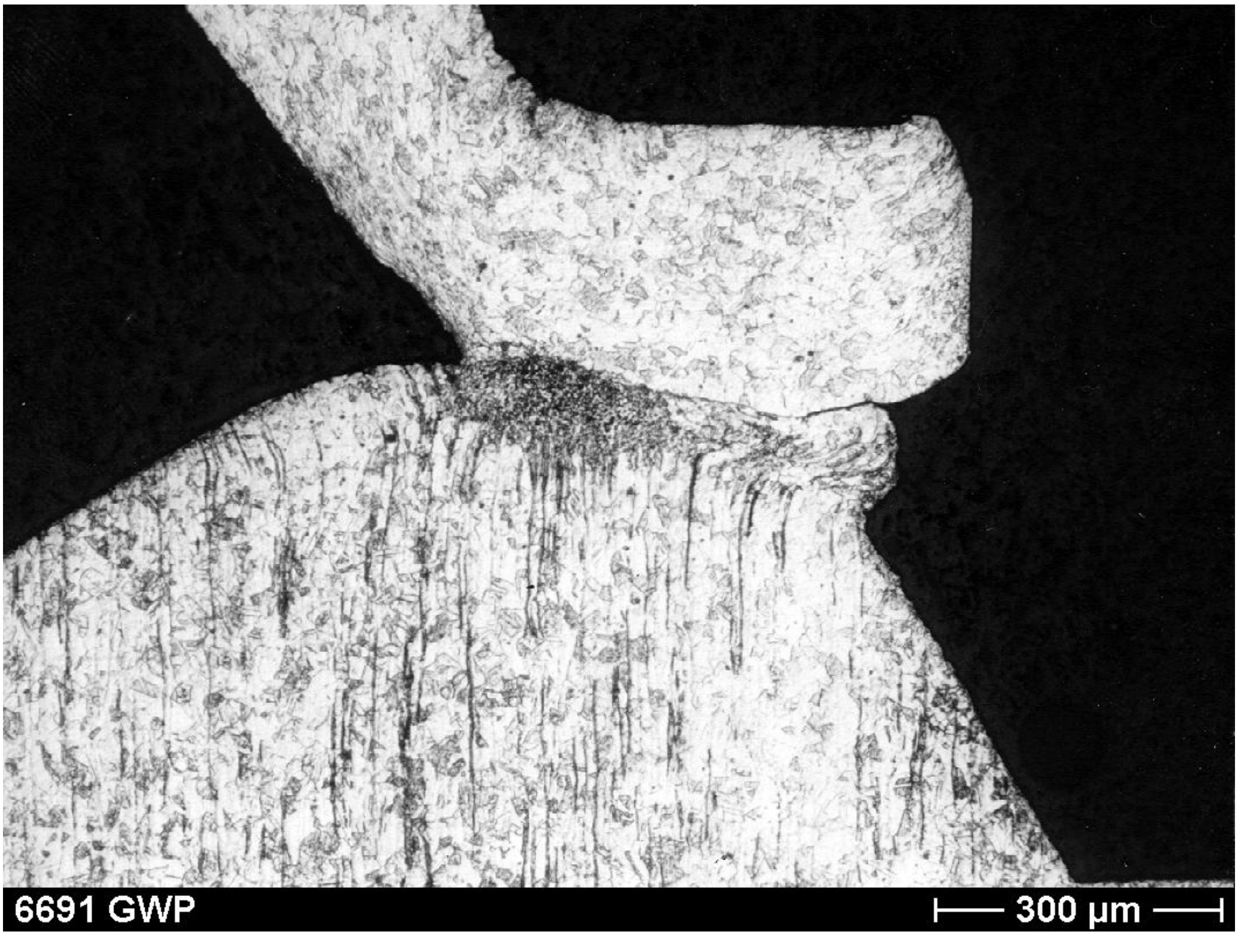


Figure 10: high quality condenser discharge welding of a membrane (above) with neck of calotte (above left) and support (below).

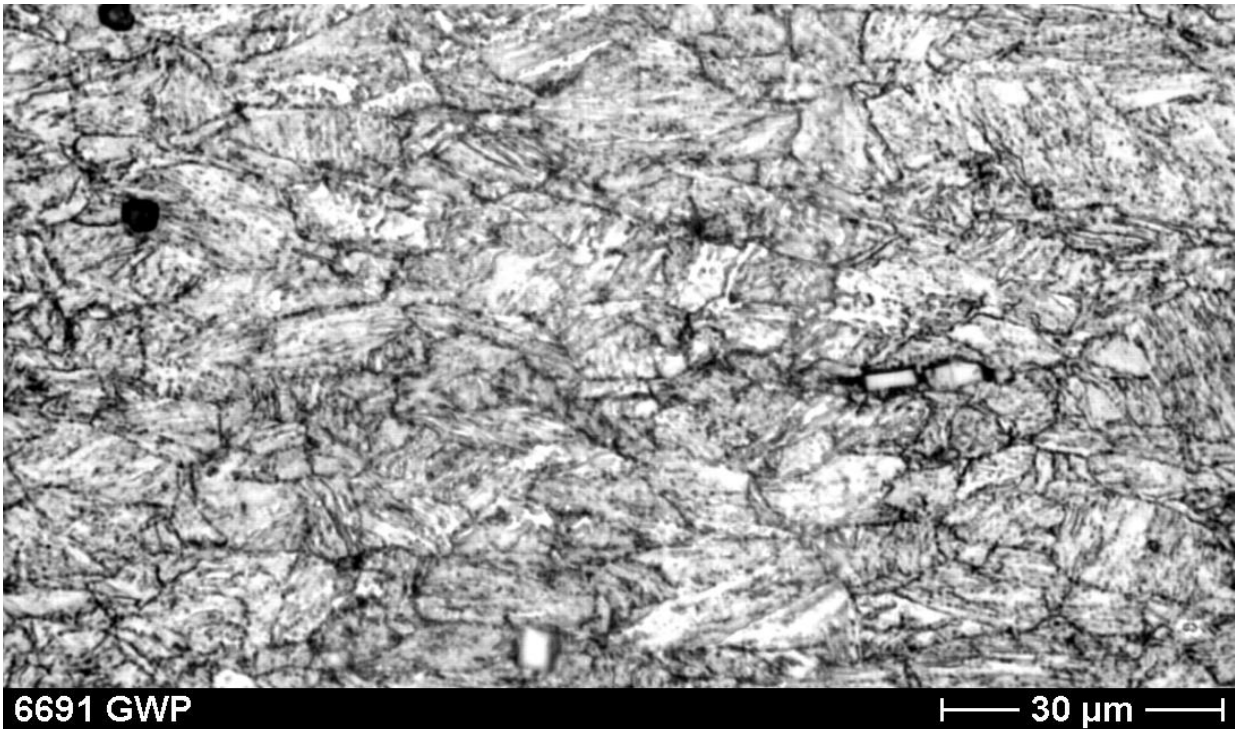


Figure 11: heat treated structure of a cold gas cylinder with non-metal inclusions.

3.2. Squib

When new processes are introduced, e.g. for feeding squibs with pyrotechnics, analyses of the igniting mixtures are made in the prepared and still explosive squib. Cracks, insufficient contacts or inhomogeneities of the used elements have to be avoided in order to allow an instantaneous ignition by effect of the glow bridge.

As testing methods radiography, macroscopic cross sections or light microscopy examination as well as scanning electron microscopy with elemental analyses of the compounds is used.

Long term experiences with examinations associated with development have shown that the following elements or functions of a squib are the most common sources of failure and should be tested:

1) gas-tight connection cap/support by means of welding or soldering, 2) defined predetermined breaking points of the cap, 3) corrosion protection especially of the surface of the cap, 4) gas-tight and mechanically resistant metallic glazing, 5) quality of contact of filament (thin filament on massive pin), 6) glow bridge with missing contact to pyrotechnics and 7) quality of pyrotechnics (moisture, fissures, bubbles, crumbles).

Moisture has to be excluded from inside the squib because of the danger of corrosion. This can be obtained by using on the one hand very dry substances and on the other hand sealing or tight joint techniques.

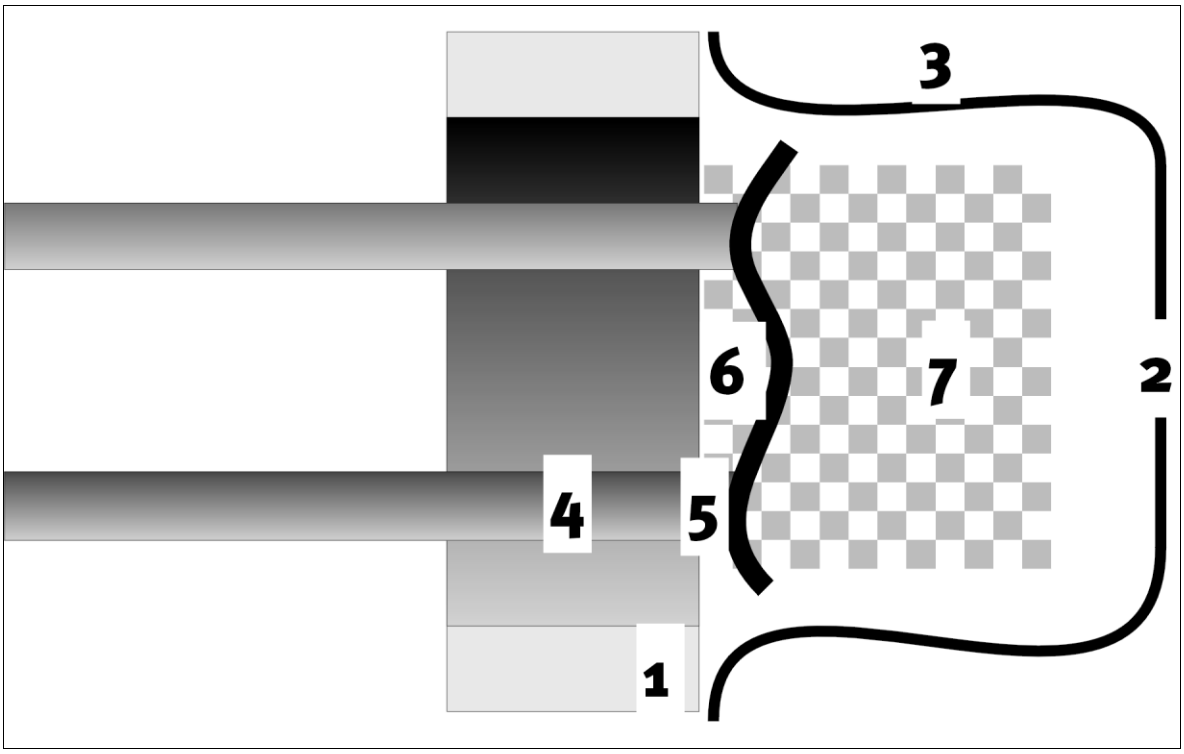


Figure 12: Scheme of a model squib. Process steps that have to be observed during the development are highlighted, see text.

3.3. Inflator

Radiography is the method of choice, when the correct position of the elements in the assembled inflator has to be verified.

It also allows the documentation of the correct function of the inflators' mechanical elements after ignition; see also figure 13.

4. Analyses of Failures

Besides regulatory safety measures, damage or failure analysis of air bag modules, inflators or squibs constitute a challenge to the analyst; he needs long term experience with materials and processes. In the case of other functional tests not being possible, our scientific workshop allows special mechanical and chemical delaborations. The most important analysis methods are listed in table 5.

Table 5: Different analysis possibilities of an inflator and a squib.

element, subjects	method of analysis *)
pyro and hybrid inflator	delaboration, LIM, REM
corrosion of squib	delaboration, REM, EDX
pressure of combustion space	piezo pressure detector
leak test (He)	mass spectrometer
grain form / pyrotechnic / feeding	LIM/REM
pyrotechnic / specific surface	BET

*) LIM: light microscopy, REM: scanning electron microscopy, EDX: X-ray microanalysis, BET: specific surface area.

Characteristics of electronic components, such as acceleration detectors or evaluations of signals are not tested by GWP.

4.1. Plug-in connections

One example: short-circuiting links are integrated in plug-in connections of airbags as safety measure to avoid unwanted releasing due to the influence of stray current during handling.

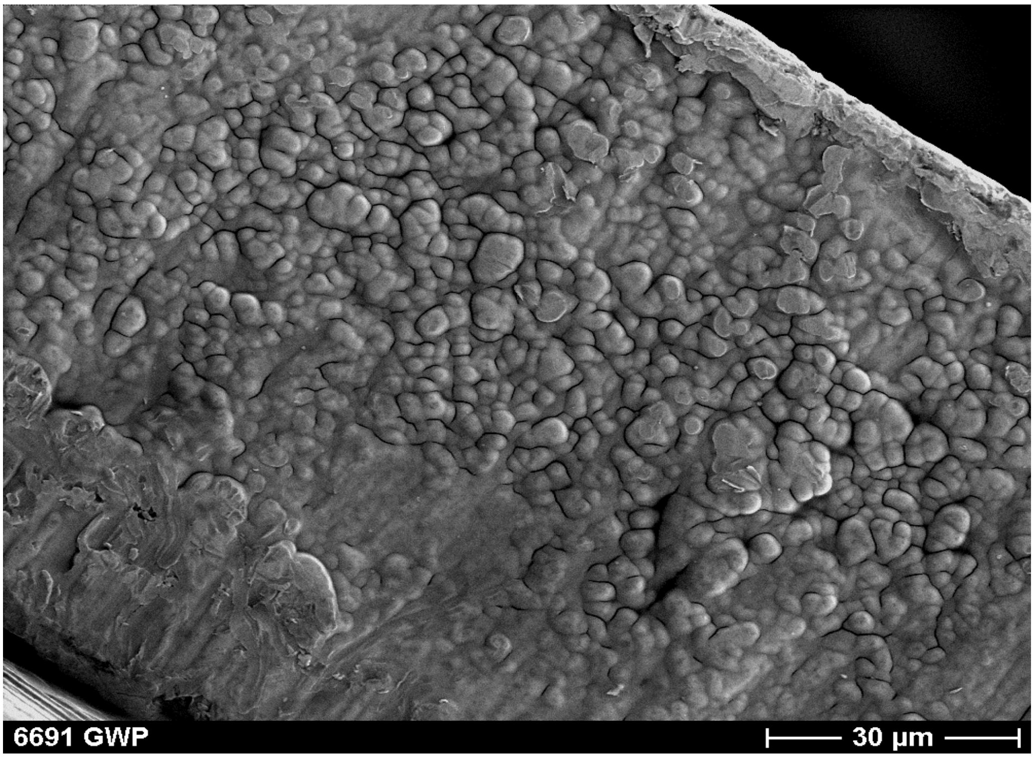


Figure 13: Gold plated contact surface of a short-circuit link: n.i.O.-quality due to dentritic formation of surface with inclusions.

In the present case, the effect of this is abolished by high electrical resistance (> 100 Ohm) at the short-circuit. When checking the plug-in contacts, a poor quality of the surface of the galvanically applied gold plate was identified as the cause (the structure was dendritically, columnar instead of a plane, smooth one). This resulted in contact points instead of contact surfaces with a higher electrical transition resistance.

4.2. Failure analysis of the squib

In case failures occurring during the function test of a squib, it can be dismantled and the filament can be tested to detect the cause.

In case the filament and welding points on the feed pins are intact, the failure can be caused by an electric defect. When the filament is molten, i. e., after glowing by current, the failure must be caused by the igniting mixture.

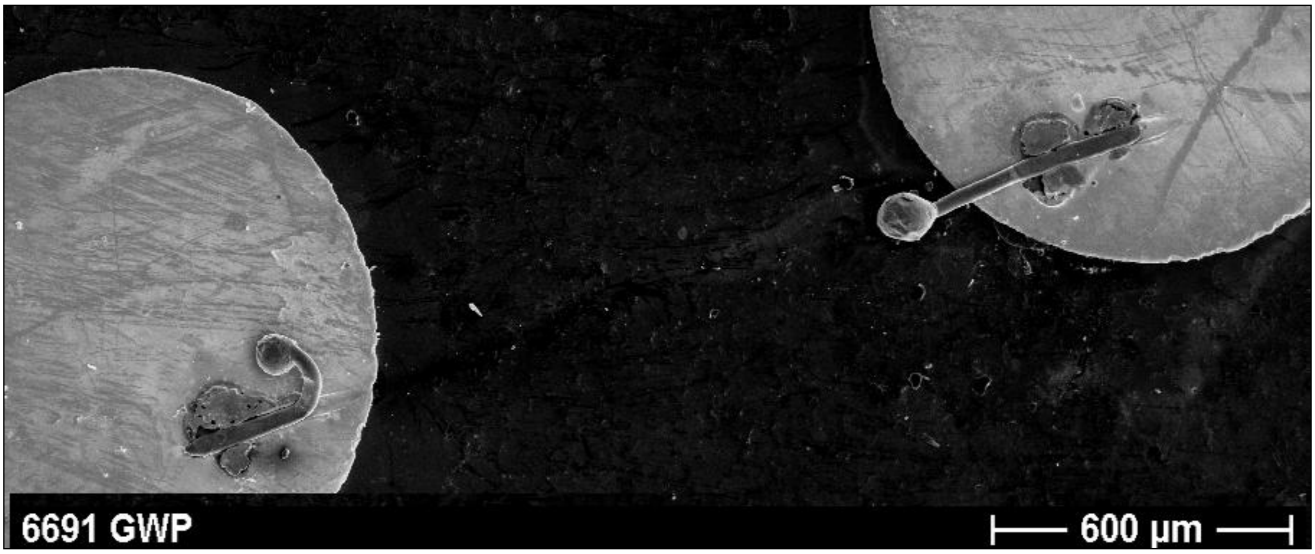


Figure 14: Molten filament (Glow Bridge).

An example for an observed failure mechanism might be the insufficient connection of glass and metal during the melting process. In case of a fissure between metal and glass, not later than connecting the plug to the pin, it can be dislocated inside. Thus, the way of the glow bridge is elongated until the filament breaks, which will render the squib dysfunctional.

4.3. Failure analysis inflator

The inflator is examined by non-destructive X-ray analysis; cross-sections through components are more time-consuming but more precise.

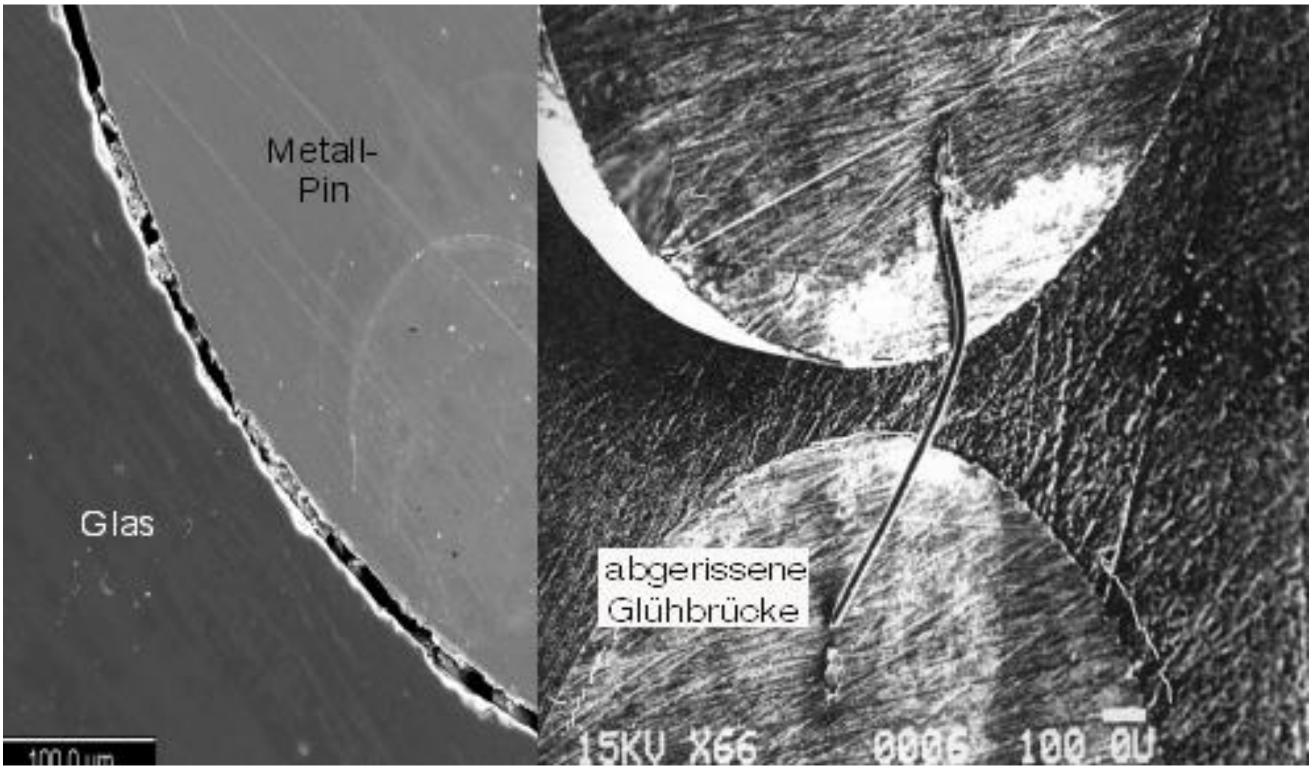


Figure 15: squib failures due to break of glow bridge; because of a fissure in the glazing (left) the pin is movable, so that it can be pressed inside (right side on top).

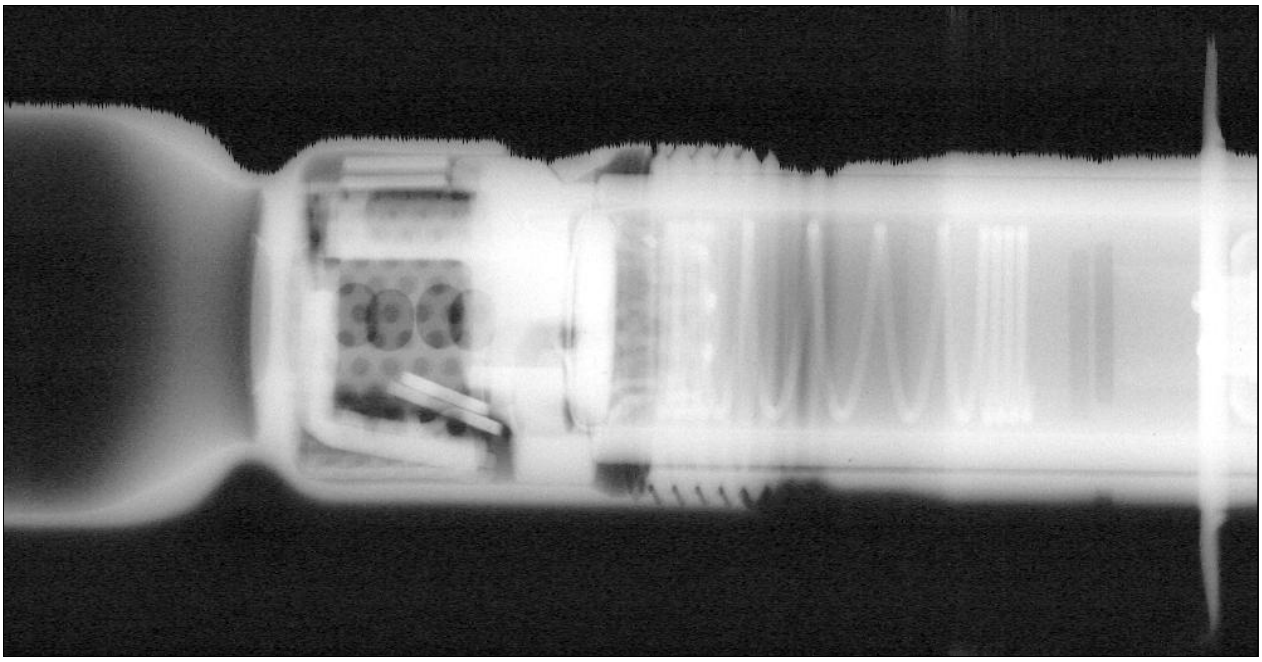


Figure 16: radiography of an ignited hybrid inflator; on the left side, cold gas cylinder with opening mechanism (perforated plate) and on the right side, the pyrotechnic part with squib.

In order to fix loose parts, the hollow space can be vacuum-casted with curing plastic. Thus, the final positions of the opening mechanisms, the correct assembly, the detection of failure mechanisms, etc. are determined by our metallographic services.

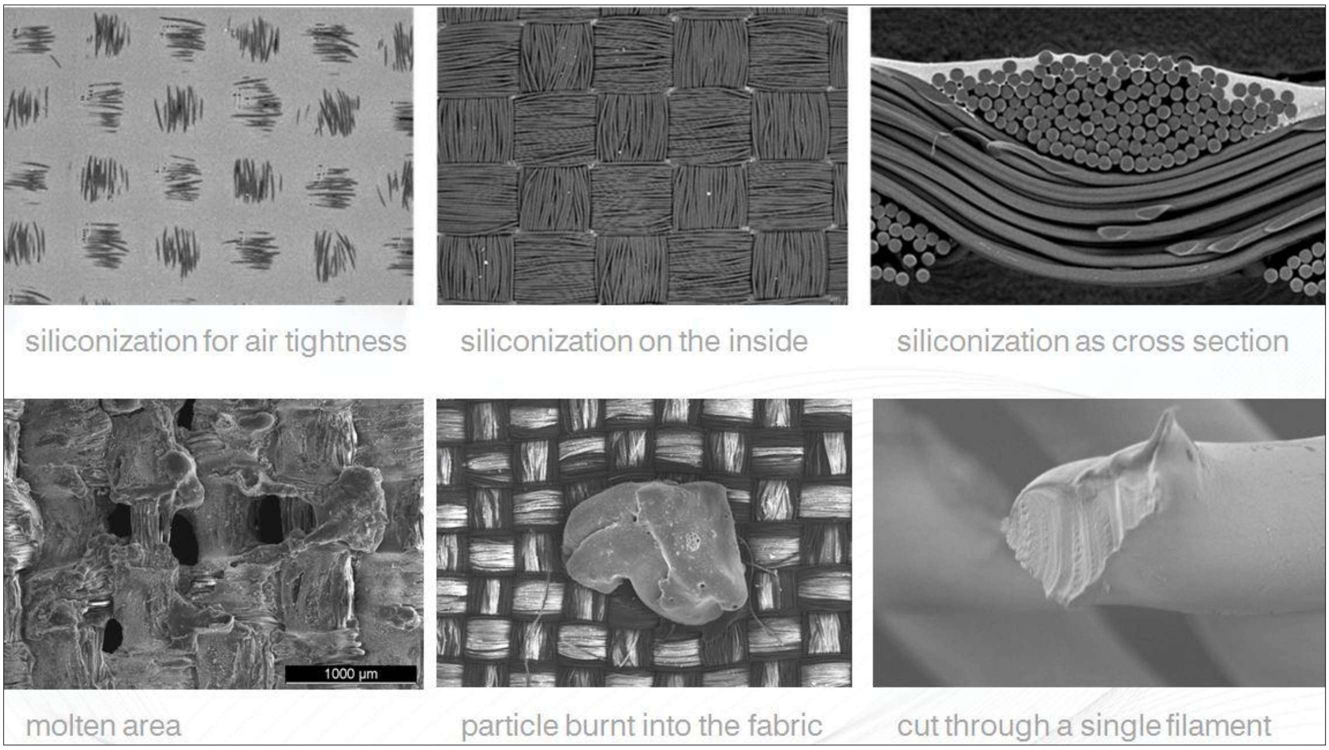
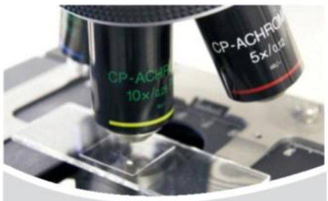


Figure 17: air bag fabric and possible defects

›› Gesellschaft für Werkstoffprüfung mbH

› Analytik

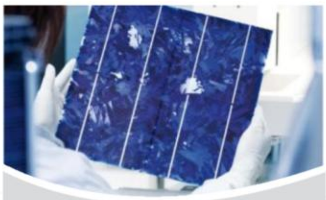
› Werkstoffprüfung



› Materialografie

› Qualitätssicherung

› Schadensanalyse



› Entwicklung

› Laborservices

- › Analytikum
- › Chemie & Korrosionslabor
- › Elektroniklabor
- › Gaslabor
- › Kunststofflabor
- › Materialografie
- › Mikroskopie REM/LIM
- › Umweltsimulation
- › Werkstatt
- › Werkstoffprüfung
- › Zerstörungsfreie Werkstoffprüfung

› Schadensanalyse

- › Airbag
- › Batterien
- › Baustoffe
- › Fraktographie
- › Heterogene Katalyse
- › Industrielle Prozesse und Produkte
- › Korrosion
- › Kunststoffe
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- › Metallische Gefüge
- › Oberflächentechnik
- › Zerstörungsfreie Prüfung

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