Mechanical properties of glass/metal-joints produced by ultrasonic torsion welding

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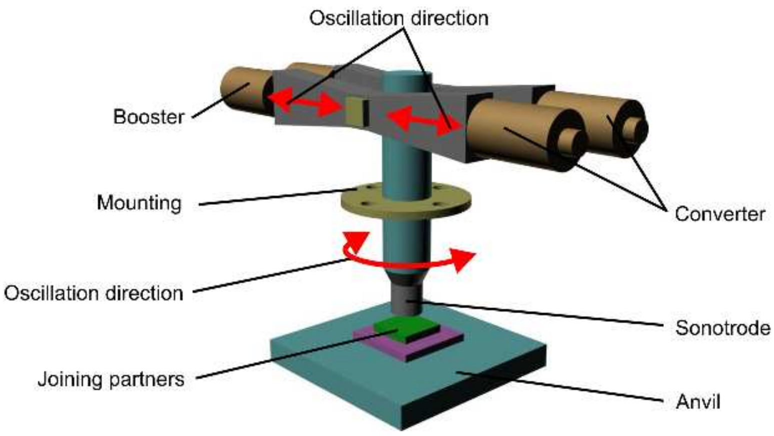
The development and industrial introduction of efficient joining methods between glass and metals which combine the individual advantages of both material groups are of great technical importance. One research field of the institute of materials science is the joining of glass with metals by means of ultrasonic oscillations. Industrial applications are for example the sealing of glass vessels, fixtures in the vacuum technique or lens sockets. For this reason an industrial ultrasonic torsion welding system normally used for metal weldings was modified to be sufficient for the demands of sensitive glass/metal-joints. The developed welding system can produce helium-tight joints between glass and metals. In comparison to the conventional welding techniques[1] for glass, ultrasonic torsion welding is characterized by very short welding times (< 1s) as well as relatively low welding temperatures[2] (≤ 550°C). Further advantages of this joining technique are the high automation capability and the environmental sustainability. The welding method can be employed under normal or special atmospheric conditions. The following paper describes the functionality of the welding system, the temperature distribution during the welding process and static respectively dynamic ultimate stress values.

Introduction

The main components of the ultrasonic torsion welding system used for the examined glass/metal-joints are shown in figure 1.

Fig. 1: Principle of an ultrasonic torsion welding system



An ultrasonic generator converts the 50 Hz alternating voltage into a high frequency alternating voltage of 20 kHz. A converter uses the reversed piezoelectrical effect to transform this high frequency alternating voltage into mechanical oscillations of the same frequency. The necessary oscillation amplitude of 10 to 30 μm of the welding tool, called sonotrode, is achieved by an appropriate design of the booster and the sonotrode. Prior to welding a static pressure of 20 to 60 MPa is implemented pneumatically on the joining partners which are positioned on an anvil. The actual bonding of the joining partners takes place through the insertion of high frequency torsional shear oscillations via the connecting surface of the sonotrode into the metallic joining partner. The static pressure perpendicular to the oscillation direction is still brought up during the joining process. From high importance is the absolutely plane parallel alignment of the joining partners and the sonotrode. If the sonotrode is tilted for some degrees in relation to the metal sheet the static pressure is not built up uniformly. For this reason a pneumatic anvil was developed which automatically adjusts the parallelism between the joining partners and the sonotrode. This adjustment provides a uniform circular welding seam.

Test material and specimen geometry

For the investigations the brittle joining partner was the borosilcate glass DURAN®, which is especially used in chemical applications. It mainly consists of SiO_2 (79.7 ma.-%) and B_2O_3 (10.3 ma.-%). The metal sheet is the iron base alloy NiCo2917 which has a low thermal coefficient of expansion which is only $1.88 \cdot 10^{-6}\ K^{-1}$ higher than the one of the glass. This alloy was chosen in consideration of low thermally induced residual stresses. Due to the fact that direct joining of this metal sheet to glass is up to now not possible[3] a thin interlayer of pure aluminium is inserted between the glass and the sheet. The relatively high coefficient of expansion of the aluminium in relation to the glass (factor 7.5 higher) may counteract bonding due to the resulting thermal residual stresses. Investigations show that this disadvantage is more than compensated by the good flow characteristics and the low yield point of the aluminium[4]. The physical and mechanical properties of the used materials are shown in Tab. 1.

Tab. 1: Properties of the joining partners

	NiCo2917	Al99F14	Duran®
Density [gcm^{-3}]	8.36	2.7	2.49
Young`s modulus [MPa]	138000	65000	63000
Thermal coefficient of expansion α_{th} [$10^{-6}K^{-1}$]	5.13	23.9	3.25
Thermal conductivity λ_{th} [$Wm^{-1}K^{-1}$]	17.3	209	1.16
Melting point [°C]	1450	660	1240
Hardness	160 $HV_{0.2}$	40 $HV_{0.05}$	620 $HV_{0.2}$
Roughness (typical) R_a [µm]	⊥ 0.223 ; || 0.107	⊥ 0.362 ; || 0.053	0.018
Tensile strength R_m [MPa]	517	160	60
Yield strength R_e [MPa]	345	120	/
Fracture strain A [%]	30	4	/

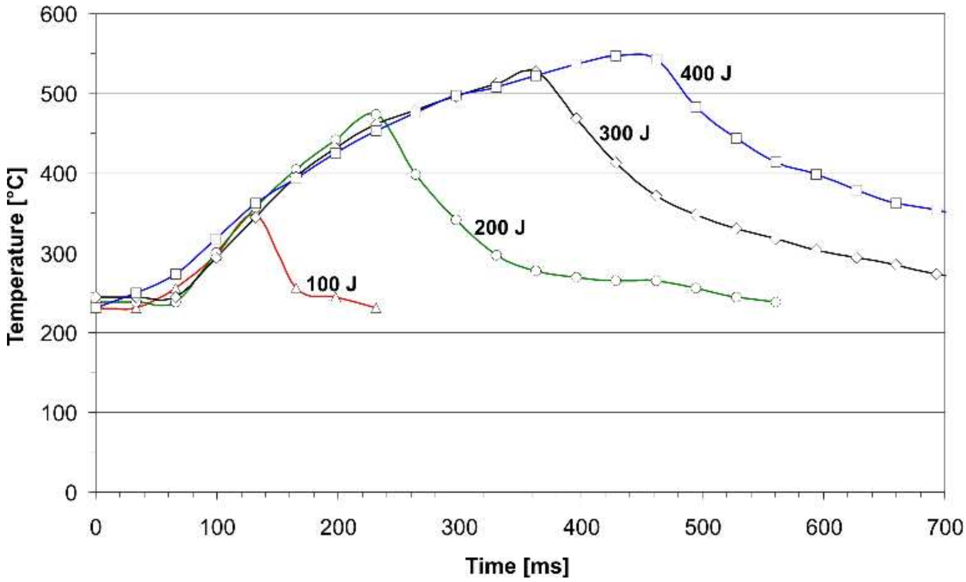
As alternative materials for the metal sheet it is also possible to use copper, AlMg3 or X5CrNi1810 with reduced attainable joint strength due to relatively high coefficients of thermal expansion. For the brittle joining partner also glass-ceramics or coated glasses can be used. Own investigations have shown that especially ceramics are very good joining partners for metals and the produced joints reach very high strength values. The geometry of the used specimens is a square piece of glass with an edge length of 40 mm and a thickness of 5 mm. The thickness of the metal sheet which is in contact with the sonotrode is limited to about 1.5 mm due to the absorption of ultrasonic energy. Thus for the metal sheet a thickness of 0.5 mm and a diameter of 30 mm was chosen. Investigations with quadrilateral metal sheets show a non-uniform connection due to unfavourable normal modes of the sheet. Between the glass and the iron base alloy an aluminium foil with a thickness of 0.1 mm is inserted.

Results

Temperatures during the joining process

The ultrasonic welding process leads to a time-dependent welding temperature. This effect results from the friction conditions in the interface caused by the simultanious influence of static clamping force and the oscillating shear force. To determine the welding temperature a shortwave infrared camera with a high local resolution is positioned perpendicular under the anvil. The temperature information is transmitted to a computer system for further processing. The use of an infrared wavelength of 2.5 µm provides the possibility to measure the temperature directly in the welding zone through the glass[5]. Joinings with different amounts of welding energy are leading to time-temperature-curves shown in figure 2. In this case the two other important machine specific welding parameters welding pressure and welding amplitude were held constant.

Fig. 2: Time-temperature curves for different amounts of energy input



Temperatures below ~230°C can not be measured exactly with the used infrared filter. It can be seen that the maximum temperature measured directly in the welding zone is nearly 550°C for an energy input of 400 J. This is below the melting temperature of the used aluminium interlayer of 660°C. It should be mentioned that with an amount of 100 J of energy input and a resulting temperature of about 350°C bonding between glass and metal already occurs. Tests with very small welding areas have shown that no particular temperature is needed to realize bonding. This fact is typical for pressure weldings.

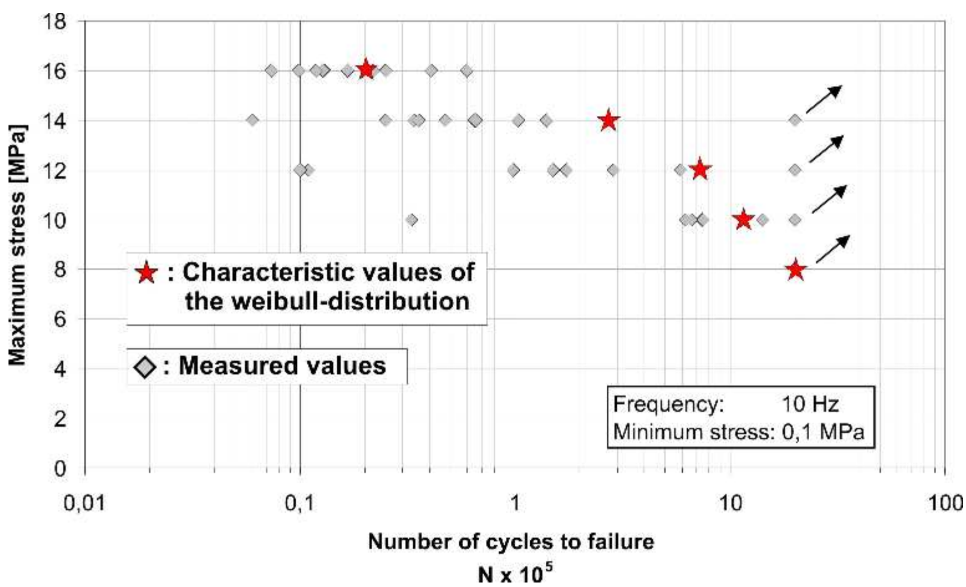
Joint strength under quasistatic loading conditions

Different tests under quasistatic loading conditions were performed to determine the optimal welding parameters and to characterize the joints. For the tension loading test two T-profiles are glued at the top and the bottom of the joint for the application of the force. The tension load is applied path-controlled with a speed of 1 mm per minute in a tension-testing machine. In this investigation the average strength of the joints was 15 MPa. Under tensile shear loading the joints reach a tensile shear strength of up to 50 MPa. This value is much higher than under tensile loading due to the existing residual stress distribution in the glass. Another testing method which is from high interest especially for applications which needs a permanent seal is the helium leakage measurement. To test the joints it is necessary to braze a flange on the metal sheet which is drilled to form a volume between the metal sheet and the glas surrounded by the welding seam. The leakage tests are done by placing the joint in a helium atmosphere, evacuating the specimen volume and connecting the flange to a helium detector. The used leakage testing system is able to detect leakage rates of up to 10^{-12} mbar l s^{-1}. The investigations show that every joint consisting of NiCo2917, aluminium and borosilicate glass is tight against helium if the welding seam visible through the glass is shiny and circular without interruption. The determined leakage rates lie in-between 1 x 10^{-9} and 2 x 10^{-10} mbar l s^{-1}. Furthermore the joints can resist overpressure up to 500 bar.

Joint strength under dynamic loading conditions

The dynamic strength tests of the joints were carried out on a servohydraulic testing machine. The conditions for the test under cyclic tensile shear stress of varying amplitudes were a frequency of 10 Hz, a constant minimum stress of 0.1 MPa and a varying maximum stress. As a result the mean stress and the stress ratio are different. Due to the statistically distributed failure of the glass/metal-joints it is necessary to test 10 joints for each maximum stress and calculating the weibull-distribution of the number of cycles to failure. Figure 3 shows the results of the cyclic tensile shear tests.

Fig 3: Maximum stress versus number of cycles to failure for a cyclic tensile shear test



In this figure the quasi-static tensile shear strength of 44 MPa is not shown. The red stars mark the characteristic values of the weibull-distribution[6] of the load cycles for each maximum stress. These values are defined as the number of cycles when 63.2 % of the joints fail. As expected with an increasing maximum stress the number of cycles to failure decreases. This means that the joints underlie fatigue processes. Due to the fact that always the glass cracks during these tests it seems to be obvious that growing microcracks are decisive for the fatigue process. Furthermore the cyclic hardening and the higher strain rate of the aluminium foil under cyclic loading can effect the fatigue damage of the joint. While under quasistatic loading the ductile aluminium foil can relieve tensile stresses in the glass this is restricted under cyclic loading conditions. Additionally the fatigue resistance of the joint is influenced by the existing residual stress state.

Summary

The present paper introduces the ultrasonic torsion welding technique for glass/metal weldings until now only used to produce helium tight non-ferrous metal joints in different fields of industry. It could be shown that it is possible to join glass with metal by the use of an aluminium interlayer. The welding time is below 1 s for the discussed joint consisting of a 0.5 mm thick metal sheet, a 0.1 mm thick aluminium interlayer and a borosilicate glass. The achieved tensile strength up to 15 MPa could be realized by optimizing the welding parameters energy, static pressure and amplitude. The tensile shear strength reaches up to 50 MPa. Further investigations have shown that the joints are also tight against helium and they are usable in vacuum systems. The maximum process temperature in the investigated joints is ≤ 550°C directly in the welding zone and below 40°C at the bottom of the glass. These investigations show that melting during the pressure welding process can be excluded. Possible applications for these glass/metal joints could be widespread from the chemical and pharmaceutical industry to the manufacturing of sensors and the optical industry and whereever a direct seal between brittle materials and metals is needed. Former investigations have shown that it is not only possible to join glass but also glass-ceramic and ceramic with metals. Restrictions are to be made for the metal sheet which should not be thicker than 1.5 mm. Furthermore it is necessary to substitute the aluminium interlayer if the technique should be used for higher services temperatures or in corrosive media. Some first results in this direction could be obtained with a titanium-interlayer. Regarding the efficiency, automation, environmental sustainability and the achievable strengths, ultrasonic torsion welding could be an interesting alternative to the popular methods in the field of joining glass, ceramic or glass-ceramic to metals.

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