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Environmental Stress Testing of Wafer-Level Al-Al Thermocompression Bonds: Strength and Hermeticity

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Abstract

Hermeticity, reliability and strength of Al-Al thermocompression bonds realized by applying different bonding parameters have been investigated. Laminates of diameter 150 mm were realized by bonding wafers containing membrane structures to wafers with patterned bonding frames. The laminates were bonded applying a bond force of 36 or 60 kN at temperatures ranging from 300 to 400 °C for 15, 30 or 60 minutes. The hermetic properties were estimated by membrane deflection measurements with white-light interferometry after bonding. Reliability was tested by exposing the laminates to a steady-state life test, a thermal shock test, and a moisture resistance test. Bond strength was measured by shear test and pull tests. Laminates bonded applying a bond force of 60 kN at temperatures of 350 or 400 °C resulted in hermetic bonds. No significant change in membrane deflection was observed after the steady-state life test or the thermal shock test. However, a gross leakage was observed in 1–11% of the dies after exposure to the moisture resistance test. The maximum leakage rate (MLR) estimated from membrane deflection measurements was below 10^{-11} mbar·l·s^{-1} for all laminates. The measured average bond strength of dies from selected laminates ranged from 28 to 190 MPa.

Introduction

Micro electro-mechanical systems (MEMS), especially inertial sensors such as mechanical resonators, gyroscopes and accelerometers, have fragile parts which need to be sealed in a vacuum environment for high performance and a long life time. A controlled ambient pressure is required in these sensors because of their mechanical damping characteristics. MEMS absolute pressure sensors require a vacuum cavity as a zero pressure reference. Therefore, a hermetic package is an essential requirement for such environment sensitive MEMS devices.[1]

Metal thermocompression bonding is a promising technology for hermetic encapsulation of MEMS devices. Metals have lower gas permeability than other reported intermediate bonding materials, thus they allow narrower seal frames which will yield a significant reduction in die size.[2] Al is an attractive choice of metal due to its CMOS compatibility. Successful Al thermocompression bonding has been reported[3-6], but reports about a combination of hermetic and reliability properties are missing.

Hermeticity testing is commonly done in accordance with MIL-STD-883 test methods. Due to shrinkage of the device packaging size below 0.05 cm^3, rejection leak rates mentioned in MIL-STD-883 are no longer valid.[7] More stringent rejection rates for volumes below 0.01 cm^3 are given in MIL-STD-750E. Traditionally, hermeticity was determined by a gross bubble test along with a He fine leak test. Now, depending on the application, more sensitive and accurate hermeticity testing methods are available. Optical measurement of changes in membrane deflection, Fourier transform infrared spectroscopy (FTIR), Q-factor testing and residual gas analysis are some of the commonly applied hermeticity test methods.[8] Various reliability tests are performed for sealed MEMS devices to study the effect of various harsh environmental conditions relevant for the target application. Such tests are also mainly done in accordance with the MIL-STD-883 standards.

This paper presents a study of hermeticity and reliability aspects of laminates with membrane dies bonded by Al-Al thermocompression bonding, using different bonding parameters. An initial screening of the sealed dies was done after bonding by measuring their membrane deflection with white-light interferometry. A maximum leak rate (MLR) was estimated by measuring the membrane deflection at two different times. To look into some reliability aspects of the bonded laminates, a steady-state life-, a thermal shock- and a moisture resistance- test were performed. The bond strength of individual dies was estimated by measurements from shear test and pull test before and after the environmental stressing.

Experimental

Wafer design

Top Si wafers (150 mm) consisting of cavities with pressure-sensitive membranes were bonded to bottom Si wafers with bond frames of different widths. The wafers with cavities had 481 square membrane structures with a nominal thickness of 36 μm and a nominal side edge length of 2.5 mm. Pressure sensitive membranes deflect depending on the pressure difference between the inside and the outside of the cavity. The relation between the pressure difference and deflection is given by the following equation.[9]

$$w= (a^4 * (1-v^2)*\Delta P)/(66*d^3*E) \qquad [1]$$

Here, *w* is the deflection, *a* is the membrane side edge length, *d* is the membrane thickness, *v* is the Poisson's ratio, *E* is the Young's modulus, and Δ*P* is the pressure difference.

The bottom wafers were designed to have 3 µm high protruding frame structures of width 20, 40, 80 and 200 µm, which defined the bonding area. All frame designs had rounded corners, but a version with square corners was added with a 40 µm wide frame, see Figure 1. Also one design of each frame width having a 200 µm gap in the sealing frame at two different positions was added in order to have a few intentionally unsealed cavities for reference purposes. All frame structures had inner dimensions of 3.3 mm × 3.3 mm. The various designs were distributed evenly across the wafer. The total bonding area of all bond frames on a 150 mm wafer was 590 mm^2. The number of dies of each frame type, their description and their nominal bond areas are listed in Table I.

Laminate preparation

Laminates were prepared by bonding top Si wafers containing membrane structures with bottom Si wafers containing frame structures. Eight laminates were prepared, see Table II. The thickness of the top wafers was 280 µm. The membrane structures in the top wafers were made using tetra-methyl ammonium hydroxide (TMAH) etching. A 750 nm layer of thermal SiO_2 was used as masking material and the mask was not removed after the etching. The remaining layer of SiO_2 on the front side of the wafer was patterned for die numbering. The membranes were fully covered by SiO_2 on the resulting outside. The bottom wafers with frame structures were 400 µm thick. The structures were made by etching 3 µm into the silicon using deep reactive ion etching (DRIE) in an AMS 200 I-Prod (Alcatel). A thermal SiO_2 of 150 nm was used as masking material for this etching process. The mask was not removed after the etching. Before bonding, a layer of 1 µm thick pure Al (99.999 %) was sputter deposited on all the top and bottom wafers. For the bottom wafers with protruding structures, the Al was left unpatterned. On the top wafers containing membranes, the Al was patterned, leaving Al only in the bond frame areas. The Al frames patterned on the top wafers were 40 µm wider than their corresponding protruding bond frame structure on the bottom wafers. The advantage was a tolerance for a certain misalignment during bonding. Figure 2 shows a schematic cross-section of a bonded die.

Bonding

The wafers were aligned in an EVG 620 bond aligner and bonded in an EVG 510 wafer bonder. The wafers were kept in place separated by spacers in the bonder after alignment. The ambient pressure of the bonding chamber was reduced to below 1×10^{-3} mbar before the spacers were removed. An initial bond force of 1 kN was applied and the temperature of the bonder was raised to the desired value, after which the specified bond force was applied. The thermocompression bonding was performed by applying a bond force of 36 or 60 kN at bonding temperatures of 300–400 °C for bonding durations of 15, 30, or 60 minutes. An overview of the bonding parameters of the 8 bonded laminates is given in Table II. During the subsequent cool down, the bond force was reduced to 1 kN and was removed after the bonding tool temperature was below 50 °C.

The applied bond forces corresponded to bond pressures of 61 and 102 MPa. These pressure values are given just as a rough estimate and assume a perfectly stiff material (rigid body) with parallel surfaces. It should be noted that the actual local pressure can have non- uniformities that are pattern dependent caused by the pressure loading properties of the bonding chuck, pressure diffuser and the silicon wafer.[10] Additionally, the roughness and waviness of the surfaces will also cause the contact pressure to vary. It is still desirable to make comparisons between the different frame sizes (Table I), for which the difference in the contact pressure of different frames should be considered. We have chosen to roughly estimate the contact pressure of each bonding frame (σ_b) by the simple expression.

$$\sigma_b = A_d * F_{tool} / A_o * A_{bf} = 1.55\times10^{-3}\, F_{tool} / A_{bf} \qquad [2]$$

Here, F_{tool} is the applied force of the bonding tool (36 kN or 60 kN), A_{bf} is the nominal bonding area of the particular frame (see Table I), A_d is the area of each die (5200×5200 µm), and A_o is the area of the Si wafer (0.01745 m^2). This contact pressure is what one would have if each die was bonded separately as a rigid body with parallel surfaces under a pressure equal to the pressure on the whole wafer. This estimate ignores all horizontal components of stresses and maximizes the difference between the frame sizes. Using these simplifications, the calculated pressure on 20 µm wide frames is 214 MPa with 36 kN bond force and 357 MPa with 60 kN bond force. Similarly, the pressure on the 200 µm wide frames is 21 MPa with 36 kN bond force and 35 MPa with 60 kN bond force.

Reliability tests

The laminates were stored for a minimum of 3 months after bonding and then diced along the diameter into two halves, each here called a half laminate. One half laminate of each Laminate ID in Table I was subjected to environmental stress tests consisting of a steady-state life test, a thermal shock test, and a moisture resistance test. The other half was kept as a reference.

The first test was a steady-state life test in which the half laminates were exposed in an atmospheric ambient to 150 °C for 1000 hours in an oven (Heraeus Instruments). Secondly, the same half laminates were exposed to a thermal shock test where a two chamber system connected with a lift was employed (Heraeus HT7012 S2). The top chamber was maintained at a constant temperature of +200 °C and the bottom chamber was maintained at -65 °C. A dwell time in each chamber of 10 min and a transition time of ~7 s were employed. Consecutive exposure to both chambers was considered as 1 cycle and the samples were exposed for 50 cycles. Finally, the same half laminates were exposed to a moisture resistance test where a chamber with controlled humidity and temperature was used (Sunrise E series). A 24 h initial conditioning of the samples at 80 °C was done to completely dry out the samples. One complete cycle comprised of 7 steps and the humidity of the chamber was maintained at 90 % for all the steps, as described in MIL-STD-883E. The temperature was varied between 25 °C to 65 °C during one cycle. The samples were exposed to 10 cycles. A subcycle of step 7 was performed for 5 of 10 cycles where humidity was uncontrolled and temperature was maintained at -10 °C (see MIL-STD-883E).

Characterization

The amount of inward deflection of bonded membranes was measured by a Zygo NewView 6300 white light interferometer (WLI). The deflection measurements were done on all dies, and were repeated after a period of 3–5 months. The hermetic yield was defined as the percentage of membranes deflecting inwards by more than 2 µm. The open references were left out of the hermetic yield calculations. After environmental stressing, the membranes with inward deflection were identified by visual inspection and compared to a laminate map showing the membranes with inward deflection before environmental stressing.

MLR was calculated by measuring the deflection of 1–13 membranes (for some laminates the target sample number, 13, was not available for testing) for each laminate at two different times t_1 and t_2. Also the deflection of the membranes of the intentionally leaky dies was measured in order to measure possible deviations from a perfectly flat surface. MLR can be calculated by the following equation:

$$\mathrm{MLR} = \Delta P * V / \Delta t \qquad [3]$$

Here, V is the cavity volume ($\approx 1.6 \times 10^{-6}$ l), Δt is the time difference between times t_1 and t_2, and ΔP is the pressure difference in the cavity between times t_1 and t_2. According to Equation 1, a deflection decrease of 0.45 µm would correspond to a pressure increase of 65–99 mbar depending on the membrane thickness (ranged from 36.2–42.0 µm, see Table III). In the calculation E = 165 GPa and ν = 0.28 was used. Hence, if the measured deflection change was smaller than 0.45 µm, ΔP is lower than 99 mbar.

After environmental stressing, the two halves (stressed and un-stressed) of four laminates A400-60, B300-60, B350-15 and B400-60 were diced into individual dies. The dicing yield, defined as the percentage of dies that were not delaminated after the dicing process, was recorded.

The dies which survived dicing test were used for the subsequent bond strength measurements. The shear strength was measured by shear testing of the individual dies. A random selection of 10 dies of frame type F80R was made from both the stressed and unstressed halves. Selected dies were glued to a flat sample holder and shear tested using a Dage 4000 PLUS multipurpose bond tester. The time versus applied mass [kg] was recorded and the mass at which the first fracture occurred, designated as the fracture mass, was noted. The shear strength [MPa] was calculated by multiplying the fracture mass by the gravitational constant and dividing by the nominal bond area.

Similarly, the tensile strength was measured by pull testing of the individual dies. A random selection of 10 dies of frame type F40R was made from both the stressed and unstressed halves. Also, 15 dies of frame types F20R, F40, F80R and F200R were randomly selected from B350-15 stressed half laminate. Selected dies were glued to flat headed bolts and pull tested using a MiniMat2000 (Rheometric Inc.). The elongation versus applied force was recorded and the force at which the fracture occurred, designated as the fracture force, was noted. The tensile strength [MPa] was calculated by dividing the fracture force by the nominal bond area.

Results

Inward deflection of the membranes of sealed cavities (caused by the difference in pressure outside and inside the cavity) was observed directly after bonding. A typical picture of a bonded laminate is shown in Figure 3. The measured actual membrane thickness, inward deflection of membranes and calculated values of ΔP by Equation 1 are listed in Table III. The deflection measurements indicated that the laminate B400-60 had the lowest pressure and laminate A400-60 had the highest pressure inside the sealed cavity. No significant difference in cavity pressure was observed for the other laminates. After a storage period of 3–5 months, a positive average change of ~0.1±0.05 µm in membrane deflection was observed for all laminates. Using an over-estimate for the maximum change in deflection of 0.45 µm, an MLR value was calculated by Equation (3) and is listed in Table III. The difference in the MLR values only reflects the difference in storage times. The MLR was in the 10^{-11}–10^{-12} mbar·l·s^{-1} range for all laminates. There were no systematic differences in MLR for laminates bonded with different bonding parameters. Also there was no systematic difference in leak rates between the different frame widths. Almost 85 % of the intentionally unsealed dies were deflecting upwards while only 15 % of them were still deflecting downwards. An average upward deflection of 0.2±0.1 µm was observed for the intentionally unsealed dies.

The hermetic yield results of all bonded laminates are shown in Table II and Figure 4. Laminate B350-15, bonded applying a bond force of 60 kN at a bonding temperature of 350 °C for 15 minutes, had the highest hermetic yield of 92.6 %. Laminates B350-60 and B400-15 had a hermetic yield below 65 %, but the reason for their low yield was identified as misalignment of the wafers; the widest frame design (200 µm) of these laminates had almost 100 % yield while the narrower frames had lower yield. In addition, misalignment was observed in studies of cross sections of the laminates. On the other hand, laminates A350-30, A400-60 and B300-60 showed a low hermetic yield too, without any clear evidence of misalignments. This indicated that a bond force of 36 kN or a bonding temperature of 300 °C was not sufficient to provide a tight seal across the entire laminate. The results show that the laminates bonded at a bonding temperature ≥350 °C applying a bond force of 60 kN for at least 15 minutes (i.e. B350-15 to B400-60) had a high hermetic yield (except the misaligned ones). The hermetic yield for the different frame types of laminates with an overall hermetic yield above 75 %, i.e. B350-15, B350-30 and B400-60, is shown in Figure 5. Frame type F40, F40R and F80R had high hermetic yield for all laminates, while F20R and F200R frame types had low hermetic yield for at least one laminate.

After the steady-state life test, no membrane which had an inward deflection prior to stressing had turned flat. All laminates also survived the thermal shock test; dies that had deflecting membranes prior to this test, still had deflecting membranes after the thermal shock test. However, after the moisture resistance test, some dies that were originally deflecting, had turned flat. Figure 6 shows the percentage of dies that turned flat due to the moisture resistance test for the different laminates. For laminate A350-30, 11.1 % of the dies were flat, and for laminate B350-30, 0.5 % of the originally deflecting dies were flat after the moisture resistance test. No correlation between frame type and die leakage was observed. Some of the dies with originally flat membranes (i.e. leaky dies) were observed to deflect upwards after the moisture resistance test as seen in Figure 7.

The dicing yield results of the four diced laminates are shown in Figure 8 and 9. Figure 8 shows laminate halves that were not environmentally stressed, and Figure 9 shows laminate halves that were environmentally stressed. The Figures show that the dicing yield of laminates A400-60, B350-15 and

B400-60 was above 95 %, regardless of frame type. The unstressed laminate half of B300-60 had a dicing yield below 60 % for all frame types, while the stressed laminate half of B300-60 had a dicing yield above 65 % for all frame types. Hence, a higher dicing yield after exposure to the environmental tests was observed for laminate B300-60.

The shear strengths of frame type F80R from four stressed and unstressed laminates are shown in Figure 10. The mean shear strength of unstressed laminates ranged from 28–84 MPa, while the mean shear strength of stressed laminates ranged from 40–77 MPa. There was an increase of 56 MPa in shear strength for unstressed laminates when increasing the bonding temperature from 300 °C to 400 °C. However, from the strength measurements of the stressed laminates, the difference between the laminates bonded at the lower and the higher temperature was apparently reduced to 37 MPa. There was an increase of about 7 MPa in the shear strength for unstressed laminates when increasing the bond force from 36 kN to 60 kN at 400 °C. The same delta in bond strength was measured for the stressed laminates. The mean shear strength of the unstressed half laminate bonded at 300 °C was 12 MPa lower than that of the stressed half laminate, but it was 7 MPa higher for the unstressed versus the stressed half laminate bonded at 400 °C.

Figure 11 shows the pull test measurement results of frame type F40R from four stressed and unstressed laminates. The mean tensile strength of the unstressed laminates ranged from 40–186 MPa, while the mean tensile strength of the stressed laminates ranged from 64–190 MPa. There was an increase of about 55 MPa in the tensile strength when increasing the bond force from 36 kN to 60 kN at 400 °C. The tensile strength of unstressed laminates was lower than the tensile strength of the stressed laminates for all bonding parameters and more so for the lower temperatures; for a bonding temperature of 300 °C, the tensile strength was apparently increased by 23 MPa after stressing whereas for the laminate bonded at 400 °C an apparent increase of only 4 MPa was measured after stressing.

The results of pull tested dies of all frame types from stressed half laminate B350-15 are shown in Figure 12. Frame F200R had the highest fracture force of 82 N. Frames F40 and F40R had almost the same fracture force, while frame F20R had the lowest fracture force of 32 N. Bond frame 20R had the highest tensile strength of 124 MPa, while frame F200R had the lowest tensile strength of 31 MPa. Frames F40 and F40R had the same tensile strength of 91 MPa.

Discussion

From Figure 4 it can be seen that a bonding temperature of at least 350 °C was required to achieve sealed dies across the entire laminate. Laminate B300-60 bonded at 300 °C shows low hermetic yield, low dicing yield and the lowest tensile and shear strength, while laminate B350-15 bonded at 350 °C shows high hermetic yield, high dicing yield and higher tensile and shear strength. Our results indicate that there exists a threshold for the bonding temperature somewhere in the range between 300 and 350 °C. Dragoi et al.[4] reported a threshold in bonding temperature between 450 and 500 °C, but they applied a lower bond pressure. Dragoi et al.[4] used a bond pressure of 3.4 MPa and did not use an SiO_2 layer underneath bonding Al, while the bond pressure was estimated to be in the range of 21–357 MPa in our case, and we did have an SiO_2 underneath the bonding Al. These factors may account for the observed difference in the threshold temperature. An increase in the shear strength and tensile strength was observed for unstressed laminates with increase in bonding temperature, and the trend was still clearly measurable for the stressed laminates. Bonding temperature is important for the diffusion of metal atoms across the bonding interface. The diffusion of Al atoms increase with increase in the bonding temperature. Increasing the bonding temperature also softens the Al material, which can increase the area in atomic contact between the surfaces to be bonded. Once the opposing bonding surfaces are in atomic contact, the diffusion of atoms across the interface makes the bond between them stronger.

As seen from Figure 4, the bond force appeared to be critical and laminates bonded applying a bond force of 60 kN at 350 °C gave higher hermetic yield than laminates bonded applying 36 kN bond force at 350 or 400 °C. Thus, a high hermetic yield was achieved at a reduced bonding temperature by increasing the bonding force. Also, an increase in shear and tensile strength was observed with increase in bond force from 36 kN to 60 kN at 400 °C. We think that the higher bond pressure helped in bringing the opposing bonding surfaces into intimate contact. In addition, the higher bonding pressure may assist in breaking the native oxide present on the Al surface. The native oxide is physically very strong[11] and may be broken by increasing the bond pressure. The hermetic yield results in Figure 4 give an indication of the minimum bonding force that is required to achieve a hermetic bond.

The dicing yield results in Figures 8 and 9 show that a bonding temperature ≥350 °C was required to have a bond strong enough to survive the dicing process. This threshold temperature is the same as the threshold temperature required to obtain a high hermetic yield. The dicing yield of laminate A400-60, bonded applying a bond force of 36 kN, was 100 %. The shear and tensile strengths of A400-60 were higher than the laminates bonded at lower temperatures applying higher bond force, while its hermetic yield was lower than that of the other laminates. This result indicates that in the bond frames of laminate A400-60, there were enough contact points between the opposing Al surfaces to make the bond strong, but not hermetic. A higher bond force of 60 kN seems to have allowed contact between sufficient portions of the bonding surface to result in a hermetic bond. In Figure 8–11, it is seen that the dicing yield, shear strength and tensile strength of laminate B300-60 was increased after exposure to the environmental tests, while environmental stressing seemed to reduce or have no effect on the shear and tensile strengths of laminates bonded at higher temperatures. The reason for the increase in tensile strength of a weakly bonded laminate may be linked to grain boundary diffusion of Al atoms across the bonded interface, when annealing the laminate at 150 °C for 1000 h during the steady-state life test. There can be significant amount of grain boundary diffusion of Al atoms at low temperatures due to its low activation energy[12], which can be responsible for the increase in bonding strength of a weakly bonded laminate.

Figure 5 shows that frames F20R and F200R had lower hermetic yield for at least one laminate compared to the frames F40, F40R and F80R frame types. The low hermetic yield of the F20R frames, the narrowest frames, may be due to their limited tolerance for misalignment. The lower hermetic yield of F200R frame type may be due to the comparatively low local bond pressure because of the large frame area. A frame width in the range 40–80 µm seemed to be suitable for MEMS device sealing given a traditional commercial wafer bonder with alignment precision in the range of ±5–10 µm, as applied here. As seen from Figure 12, an increase in fracture force was observed with increasing bond frame area. Nevertheless, the calculated tensile strength decreased with increasing frame width, suggesting that the increase in fracture force was not proportional to the bond area.

Table III shows that the MLR of the bonded dies was in the range of 10^{-11}–10^{-12} mbar·l·s^{-1} for all laminates. The actual leak rate of the bonds may be significantly lower, but a more precise estimate could not be made based on the applied method. In our work, the change in the membrane deflection measured at two different times was ~0.1 µm. Considering possible errors in the membrane thickness measurements, the varied WLI scan positions, and natural variations in the atmospheric pressure, a maximum change in membrane deflection was estimated to be 0.45 µm based on the following assumptions: A change in atmospheric pressure by 51 mbar would correspond to a change in membrane deflection by 0.3 µm, an error of 25 µm in measuring the same spot by WLI would correspond to a change in deflection by 0.05 µm, and 0.1 µm was the measured change in deflection. Leak rates between 10^{-11} and 10^{-16} mbar·l·s^{-1} are needed for various industrial applications.[13]

The slight bow observed for the intentionally leaky membranes is suspected to be related to thermo-mechanical stress built into the system during cool down from the bonding temperature caused by the difference in coefficient of thermal expansion of Al and Si. However, as seen from the environmental stress testing results, the bonds were strong enough to withstand the thermo-mechanical stress evolving during the thermal shock tests. On the other hand, leakage in dies was observed after the laminates had been exposed to the moisture resistance test. As seen from Figures 4 and 5, there was a correlation between a low hermetic yield and a high number of leaking dies. The cause of the leakage is under investigation. We expect that water molecules could have leaked into the originally leaky membranes during exposure to a high humidity at an elevated temperature. This could have caused membranes to deflect upwards after the test.

Conclusion

Hermeticity, reliability and strength of 8 laminates bonded by wafer-level Al-Al thermocompression bonding applying different parameters were investigated. All originally well bonded dies survived a steady-state life test and a thermal shock test, irrespective of bonding parameters, but leakage in 1–11% of the dies was observed after a moisture resistance test. Our results showed that a bond force of 60 kN and a bonding temperature of 350 °C kept for 15 min resulted in hermetic, reliable and strong bonds for more than 75 % of the dies on a 150 mm laminate. On the other hand, bonding at a temperature of 300 °C or applying only 36 kN bond force resulted in a lower hermetic yield and a higher risk for leakage after the moisture resistance test. The average bond strength of shear and pull tested dies from selected laminates was in the range of 28 to 190 MPa. The estimated maximum leak rate for all bonded laminates was in the range of 10^{-11}–10^{-12} mbar·l·s^{-1}.

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Figure Captions

Figure 1. The mask layout for the various frame designs of widths 20, 40, 80, and 200 µm. In the lower left corner of each die there is a key describing the design. For F80R, "F" is for Frame, "80" is for 80 µm frame width, and "R" is for rounded corner.

Figure 2. Schematic cross-section of a bonded die. The top wafers contained membrane structures and the bottom wafers contained protruding frames.

Figure 3. Picture of the bonded laminate B300-60. The hazy spots on the laminate are the inward deflecting membranes. The wavy stripes are a mirror image of the laboratory ceiling, used to make the membrane deflection visible.

Figure 4. Hermetic yield based on inspection of 401 dies on 8 bonded laminates before environmental testing. The dashed line indicates 75% hermetic yield.

Figure 5. Hermetic yield for the different frame types for the three laminates B350-15, B350-30 and B400-60 before environmental testing. The dashed line indicates 75% hermetic yield.

Figure 6. Percentage of originally deflecting membranes that had turned flat after exposure to the moisture resistance test for all eight laminates.

Figure 7. The three black squares on right show the membranes that are deflecting upwards. These dies were identified as leaky and had a flat membrane before exposure to the moisture resistance test. Inset on left shows membrane deflecting inwards while inset on right shows membrane deflecting upwards.

Figure 8. Dicing yield of the four unstressed half laminates for the different bond frame designs. The dashed line shows a 90% dicing yield.

Figure 9. Dicing yield of the four stressed half laminates for the different bond frame designs. The dashed line shows a 90% dicing yield.

Figure 10. Mean shear strength and standard deviation of frame type F80R from four stressed and unstressed half laminates, calculated for minimum 6 dies. Prefix A in the name of laminate corresponds to a bonding force of 36 kN while prefix B corresponds to a bonding force of 60 kN.

Figure 11. Mean tensile strength and standard deviation of frame type F40R from four stressed and unstressed half laminates, calculated for minimum 6 dies. Prefix A in the name of laminate corresponds to a bonding force of 36 kN while prefix B corresponds to a bonding force of 60 kN.

Figure 12. Mean fracture force, mean tensile strength and their standard deviation from five different frame types of stressed half laminate B350-15. The results were calculated for minimum 7 dies. The mean tensile strength and its standard deviation are calculated by dividing the fracture force by the frame area.

Table I. Overview of chip designs. The number of dies is per wafer.

Frame ID	Frame Description	Number of dies	Nominal bond area (mm^2)
F20R	Width 20 µm, rounded corners	79	0.26
F40	Width 40 µm, square corners	80	0.54
F40R	Width 40 µm, rounded corners	82	0.48
F80R	Width 80 µm, rounded corners	80	1.06
F200R	Width 200 µm, rounded corners	80	2.68
Open	Width 20,40,80 and 200 µm, opening in bond frame	4	0.25–2.6

TABLE II. Overview of laminate types, bond parameters and hermetic yield. The hermetic yield was defined as the percentage of membranes deflecting inwards by more than 2 µm after bonding, before dicing, see the "Characterization" section. Laminate B350-60 and B400-15 were found to be misaligned.

Laminate ID	Force (kN)	Temperature (°C)	Time (minutes)	Hermetic Yield (%)
A350-30	36	350	30	11
A400-60	36	400	60	58
B300-60	60	300	60	64
B350-15	60	350	15	93
B350-30	60	350	30	80
B350-60	60	350	60	64
B400-15	60	400	15	44
B400-60	60	400	60	88

TABLE III. Measured membrane deflections and ΔP as calculated from the inward membrane deflections. The Max. Leak Rates were calculated based on various storage times.

Laminate ID	Membrane Thickness (µm)	Measured Deflection (µm)	ΔP Calculated from Deflection (mbar)	Max. Leak Rate ($mbar \cdot l \cdot s^{-1}$)
A350-30	40.5	5.1	1011	1.3×10^{-11}
A400-60	36.3	5.9	849	1.4×10^{-11}
B300-60	42	4.5	1003	2.0×10^{-11}
B350-15	36.6	7.0	1040	1.5×10^{-11}
B350-30	36.3	7.1	1027	1.2×10^{-11}
B350-60	36.4	7.4	1077	9.6×10^{-12}
B400-15	36.5	7.2	1062	1.3×10^{-11}
B400-60	36.2	7.7	1105	1.6×10^{-11}

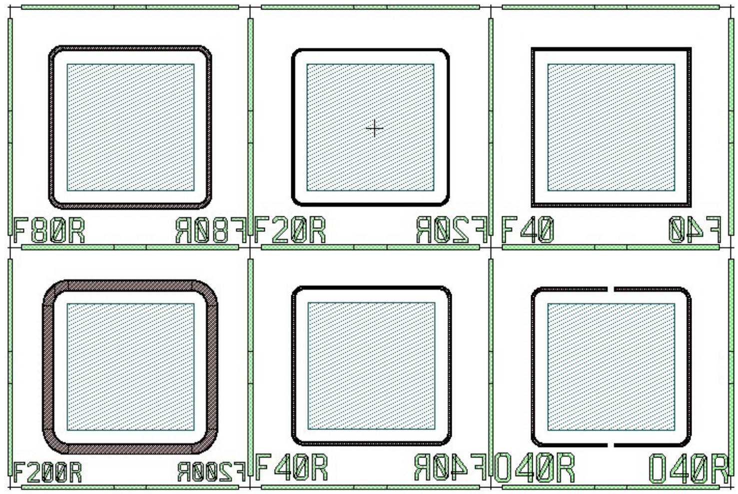

Figure 1. The mask layout for the various frame designs of widths 20, 40, 80, and 200 µm. In the lower left corner of each die there is a key describing the design. For F80R, "F" is for Frame, "80" is for 80 µm frame width, and "R" is for rounded corner.

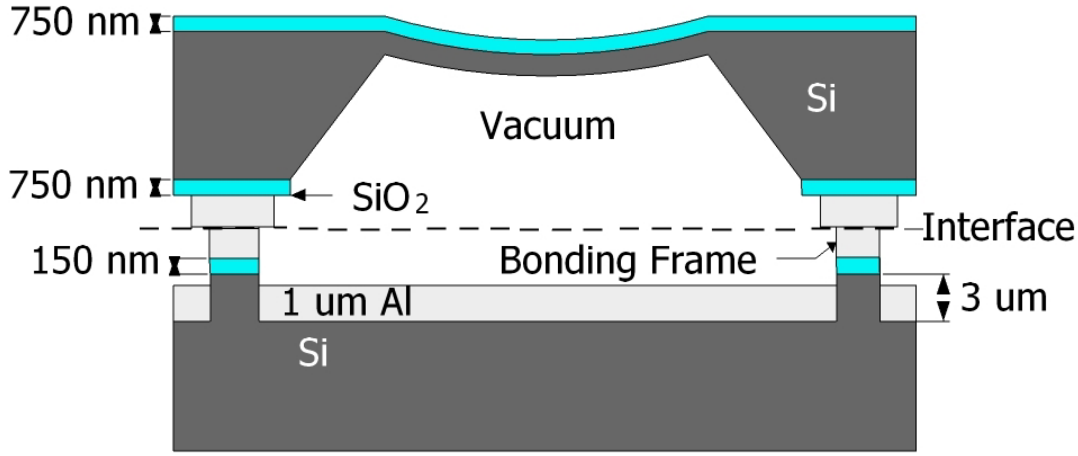

Figure 2. Schematic cross-section of a bonded die. The top wafers contained membrane structures and the bottom wafers contained protruding frames.

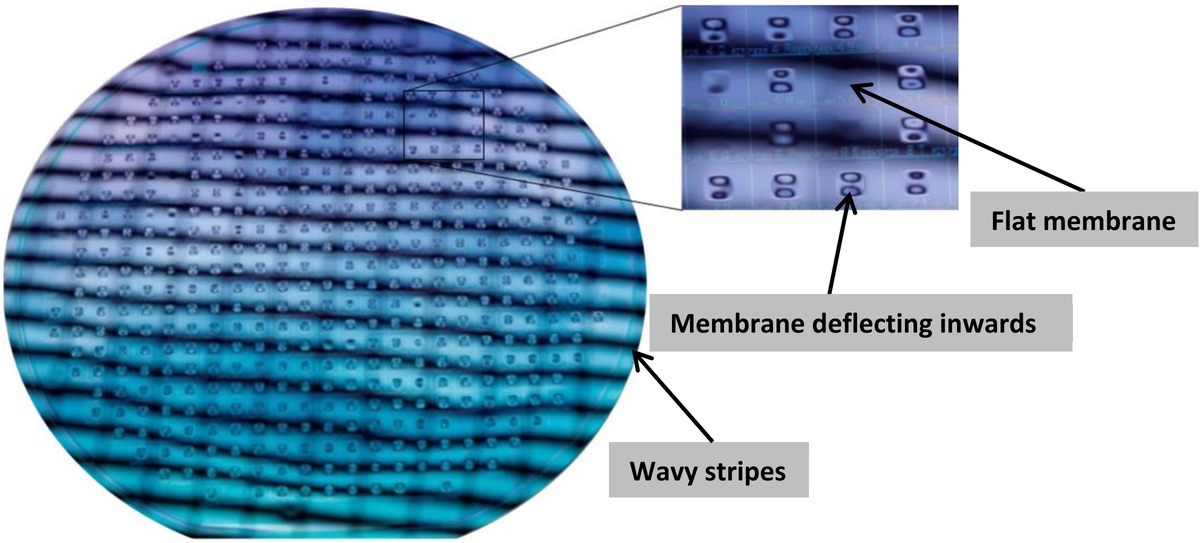

Figure 3. Picture of the bonded laminate B300-60. The hazy spots on the laminate are the inward deflecting membranes. The wavy stripes are a mirror image of the laboratory ceiling, used to make the membrane deflection visible.

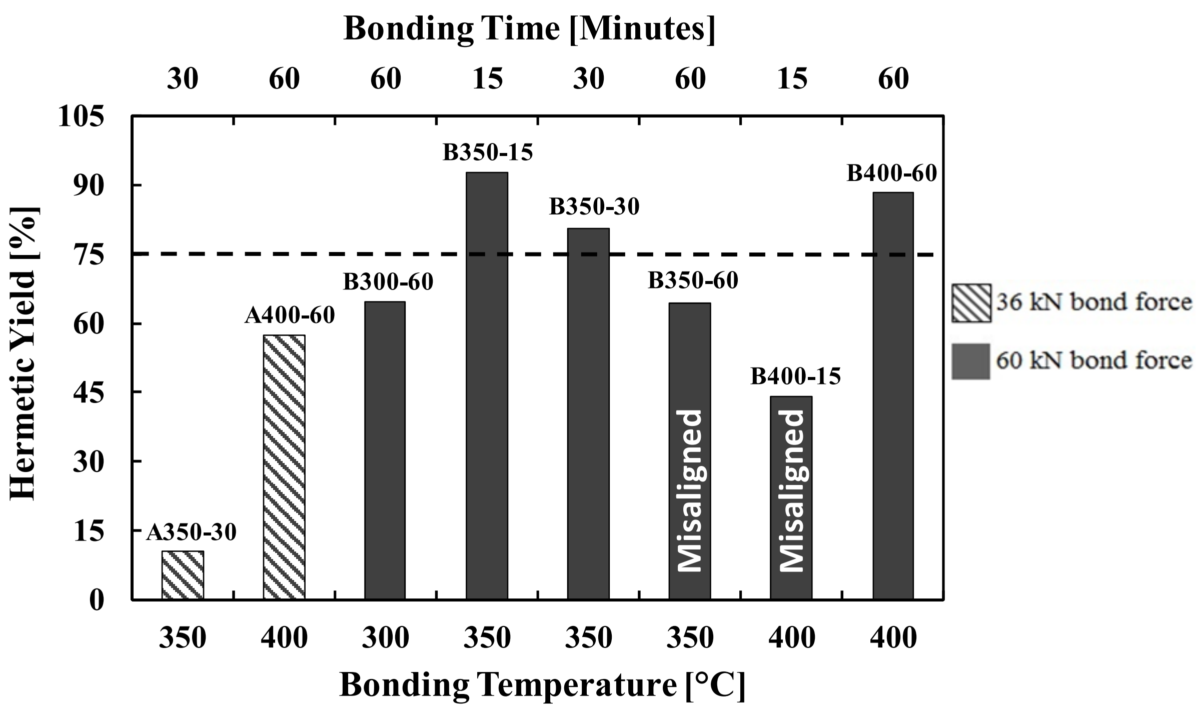

Figure 4. Hermetic yield based on inspection of 401 dies on 8 bonded laminates before environmental testing. The dashed line indicates 75% hermetic yield.

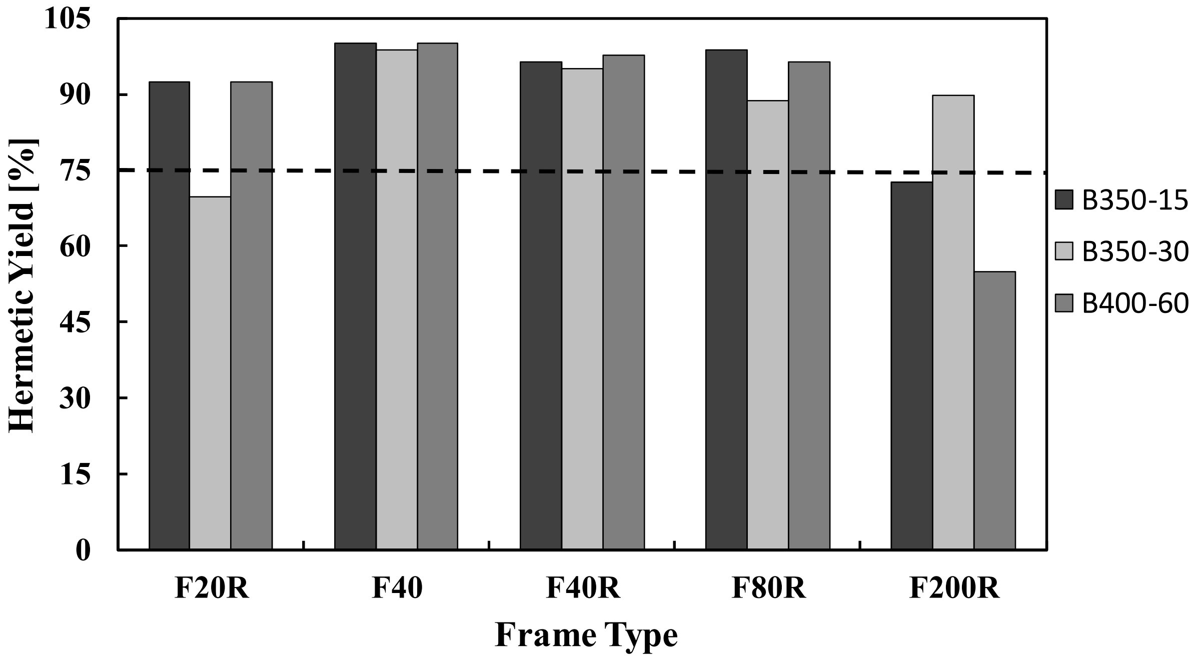

Figure 5. Hermetic yield for the different frame types for the three laminates B350-15, B350-30 and B400-60 before environmental testing. The dashed line indicates 75% hermetic yield.

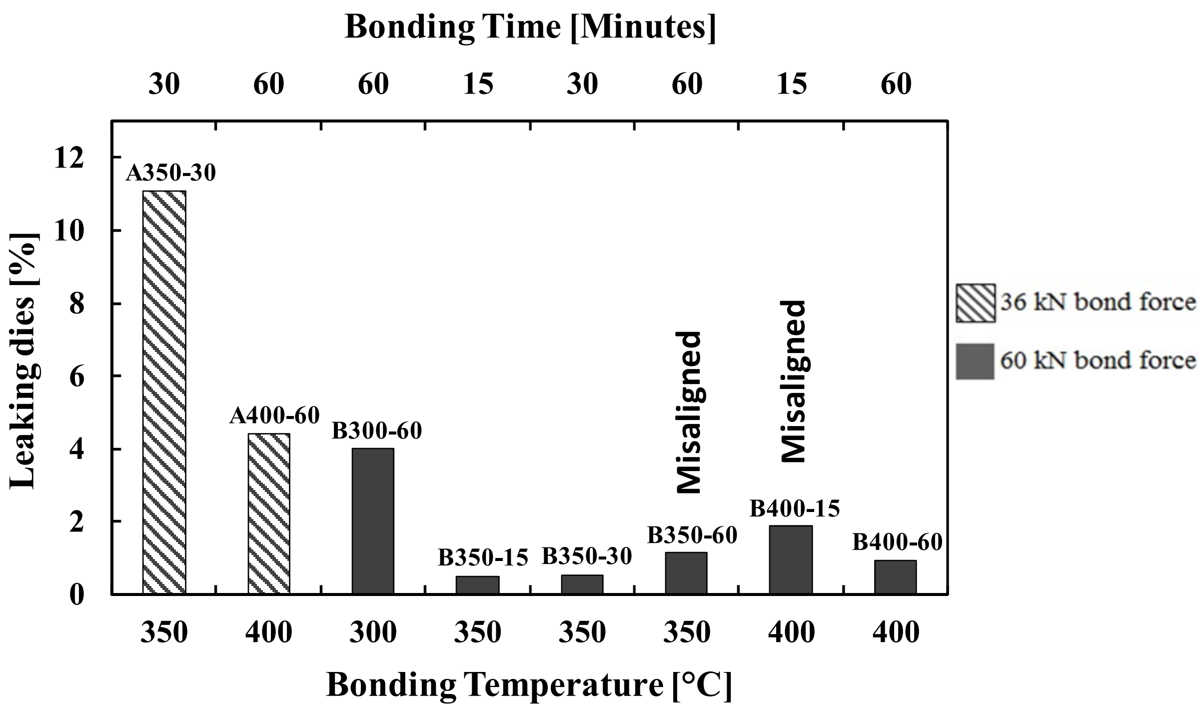

Figure 6. Percentage of originally deflecting membranes that had turned flat after exposure to the moisture resistance test for all eight laminates.

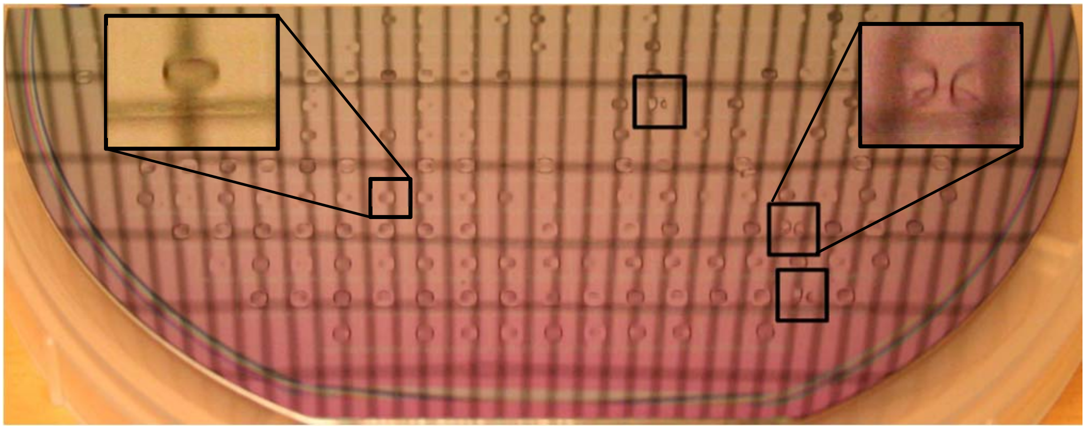

Figure 7. The three black squares on right show the membranes that are deflecting upwards. These dies were identified as leaky and had a flat membrane before exposure to the moisture resistance test. Inset on left shows membrane deflecting inwards while inset on right shows membrane deflecting upwards.

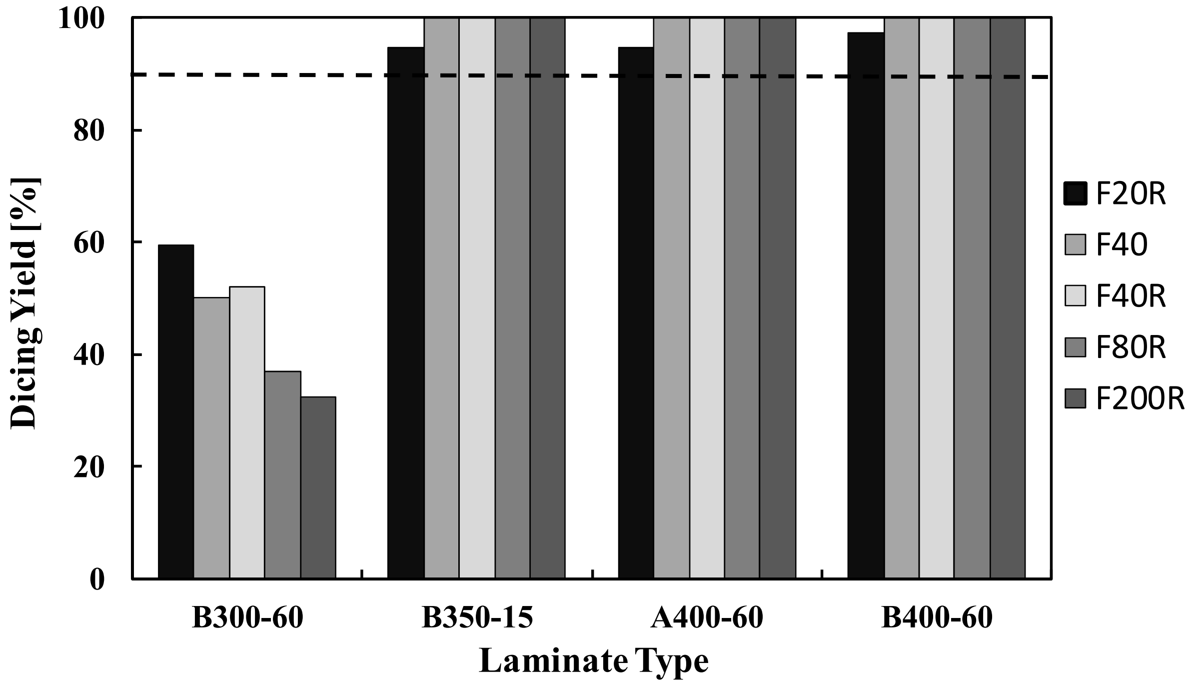

Figure 8. Dicing yield of the four unstressed half laminates for the different bond frame designs. The dashed line shows a 90% dicing yield.

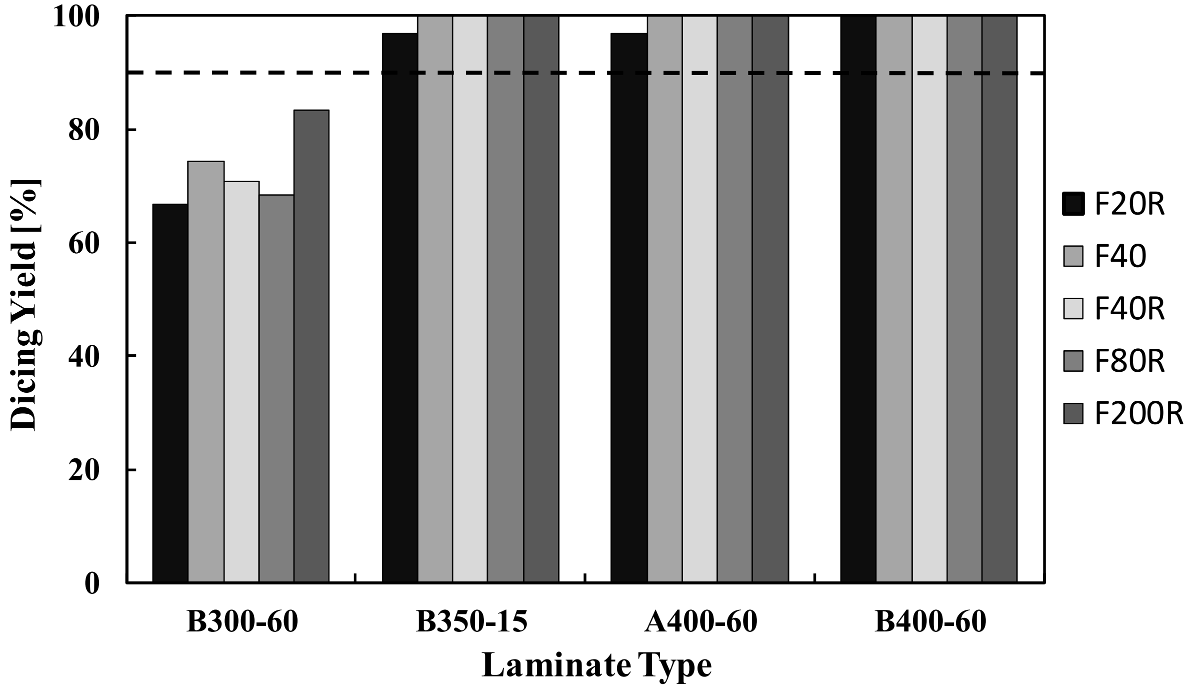

Figure 9. Dicing yield of the four stressed half laminates for the different bond frame designs. The dashed line shows a 90% dicing yield.

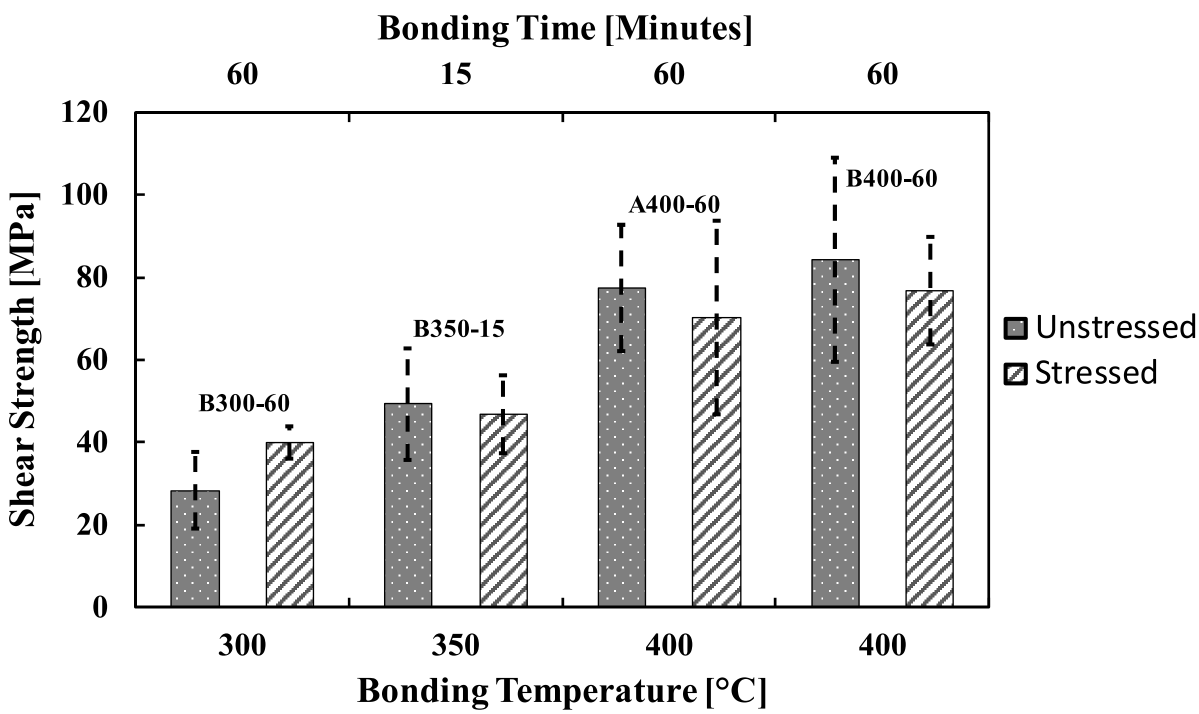

Figure 10. Mean shear strength and standard deviation of frame type F80R from four stressed and unstressed half laminates, calculated for minimum 6 dies. Prefix A in the name of laminate corresponds to a bonding force of 36 kN while prefix B corresponds to a bonding force of 60 kN.

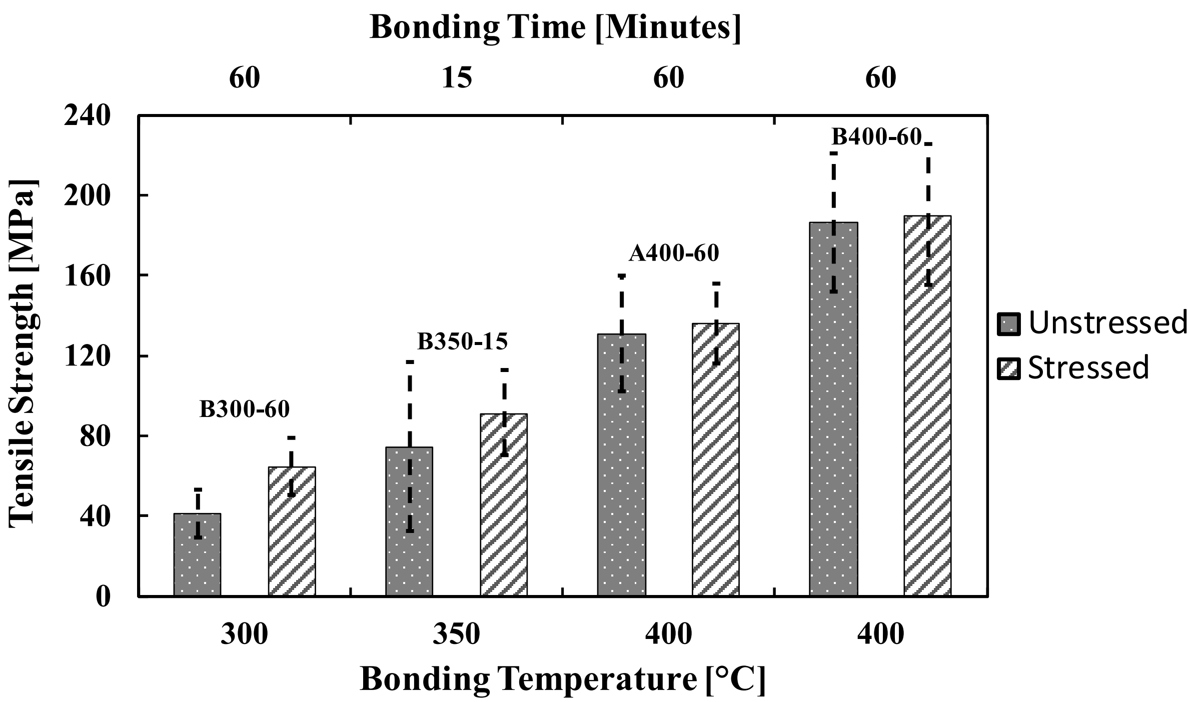

Figure 11. Mean tensile strength and standard deviation of frame type F40R from four stressed and unstressed half laminates, calculated for minimum 6 dies. Prefix A in the name of laminate corresponds to a bonding force of 36 kN while prefix B corresponds to a bonding force of 60 kN.

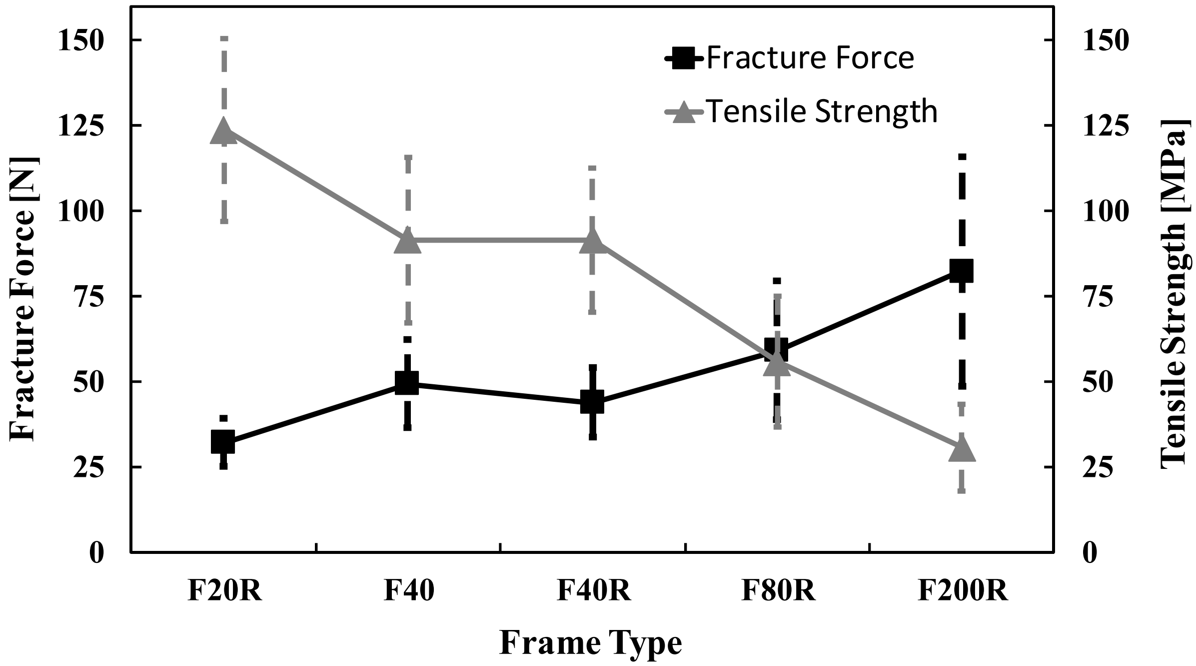

Figure 12. Mean fracture force, mean tensile strength and their standard deviation from five different frame types of stressed half laminate B350-15. The results were calculated for minimum 7 dies. The mean tensile strength and its standard deviation are calculated by dividing the fracture force by the frame area.