Comments on the article 'Metal–ceramic bond strength'

TO THE EDITOR: First, I agree with Magnus Persson and Maud Bergman that the torsion test is most suitable for the determination of shear strength (1). When, however, the relation $\tau_{max} = 2\,M/(\pi r_0^3)$ is used to calculate the maximum shear stress at the interface between alloy and ceramic from the applied torque M and the cylinder radius r_0, it must be ensured that the pure shear state of strain, as given by the theory of torsion of elastic cylinders, is achieved at the interface. The more the load already resembles this plane shear state, the better this is accomplished. The authors transfer the torsional load via the tip of a screwdriver meshing with a central slit in the loading surface. Saint-Venant's principle now states that a system of forces acting over a small region of the boundary can be replaced by a statically equivalent system of forces without introducing appreciable changes in the distribution of stresses in 'regions well removed from the area of load application'.

As is evident from Fig. 1 in the article, the loading region is less than one diameter of the specimen removed from the bond interface. As the load transferred in these experiments deviates significantly from the plane state of stress of the theory, it cannot be expected that the plane shear state is already reached in the bond region; experimental mechanics teach that the distance of loading to bond surface should be at least two (better, three) times the dimension of the loading surface (rod diameter).

These circumstances most likely explain the authors' result for the bond strength of the tested gold alloy, which is significantly smaller than results presented in Ref. 2. In that publication it has been shown that even under advantageous loading conditions the measured bond strengths grow when the distance of loading to bond surface is raised from twice to three times the rod diameter.

Second, the authors cite the paper (2) for evaluation of the experimental results, but for the sake of fairness they should have also stated in their introduction that the torsion test was introduced for the first time in Ref. 2 as a possible metal-ceramic bond strength test and applied to several alloy/ceramic combinations (under different conditions of the bond interface).

Turning to the three-point flexure bond test, M. Persson and M. Bergman state in the discussion of their article: 'However, the load applied [in the three-point flexure bond test] may exceed the yield limit for the metallic material [subjunctive!]. Some high gold alloys and commercially pure titanium of grade 2 have low yield limits, and the test method proposed by Lenz et al. is therefore not applicable to these metal–ceramic systems [indicative!]'.

Let us construct an upper boundary for the yield limit of the alloy by estimating the maximum stresses at the ends of the ceramic veneer. For the pure alloy strip (without ceramic armoring!), taking a high experimentally measured failure load $F_{fail} \approx 20\,N$ (3), the maximum bending stress would amount to $\sigma_{xx} \approx 480\,N/mm^2$. The highest calculated shear and normal bond stresses at the end of the ceramic layer can be taken (3, 4) as $\sigma_{xy} \approx \sigma_{yy} \approx 60\,N/mm^2$. Applying Tresca's yield criterion to these data, we arrive at a maximum yield limit of

$$\sigma_y \approx 436\,N/mm^2.$$

In the evaluation of the three-point flexure bond test it is indeed assumed for the sake of simplification that at the moment of debonding the alloy still is in the elastic state. If the yield limit of the alloy is already reached before debonding, the shear bond strength of such an alloy–ceramic combination is overrated—slightly for alloys with a higher and somewhat more for those with a lower yield point (note that this test is run only in the loading phase without being followed by unloading as in the provisional ISO flexure test).

Table 1 presents the proof stresses of gold alloys for ceramic veneering (5). Of 243 gold alloys 212 have a proof stress $R_{P0.2} \geqslant 450\,N/mm^2$, and 31 alloys (12.8%) a lower value (among these, 16 with a gold content of $\geqslant$ 85 mass %). Since most of these alloys show proof stresses rather close to the (extreme) value calculated above, I feel that a certain overrating of a very small number of gold alloys cannot be accepted as a major objection to this test.

The three-point flexure bond test presents a compromise between the bending test still contained in the working drafts of ISO 9693 and the torsion test. On the one hand, the ISO test, in which ceramometallic specimens are loaded (in a quite uncontrollable manner) far beyond actual debonding, enables at most a qualitative evaluation of the metal–ceramic bond. The torsion test, on the other hand, is, from a theoretical point of view, certainly superior to both flexure tests. But, in addition to laborious and time-consuming fabrication of test pieces, it has another disadvantage: since the results of the experiments depend strongly on

Table 1. Proof stresses $R_{P0.2}$ of gold alloys (hardened state) to which porcelain may be fused (5). The first four alloys do not fulfill the standard $R_{P0.2} \geqslant 250\,N/mm^2$

Proof stress $R_{P0.2}$ (N/mm^2) (hardened state)	No. of alloys	
$\geqslant$ 100–249	4	31 (12.8%)
250–299	0	
300–349	9	
350–399	7	
400–449	11	
450–499	40	212 (87.2%)
500–549	32	
550–599	45	
600–649	41	
650–699	40	
$\geqslant$ 700	14	
Without details	6	

the method by which torque is applied, a comparison of results measured at different institutions would only be admissible if both have at their disposal an identical testing device.

Compared with this, the 'compromise' three-point flexure bond test shows the following profitable features: 1) simple (and reproducible) manufacturing of specimens; 2) quantitative determination of the bond strength; 3) testing of all possible metal–ceramic combinations under similar stress conditions, if the geometry of the test pieces accords with the dimensions proposed in Ref. 3; and 4) (direct) use of a commercially available testing machine (without reconstruction as necessary for torsion tests).

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IN RESPONSE: When it comes to constructing a set-up for testing, some approximations always have to be made. Our aim was to establish a simple and reproducible test that was easy to perform and with quite inexpensive equipment. To apply the load with a screwdriver connected to the shaft of an electric motor was an easy and inexpensive set-up. However, there is a risk of introducing forces on the interface due to bending when applying the load. Therefore, we wanted to minimize the length of the upper part of the samples in order to minimize the bending moment. Complementary measurements will be made where the upper part of the samples will be extended. Finally, the results for the gold alloy do comply with results achieved by Lenz et al. with the three-point flexure bond test.

Our intention was never to say that we introduced the torsional test, and in fact we never say that. We are a little surprised by the second comment. It would have been more fruitful to have Lenz's comments on the other part of the work, namely the proposed coupling between the test and the clinical situation via FE analysis.

When it comes to the three-point flexure bond test, we do not follow the argumentation. Lenz presents an upper yield limit. Actually, the maximum shear stress for a certain yield limit would be more valid. For example, for unalloyed titanium as delivered, the yield strength is low, and the yield limit is reached at a shear stress of 20–50 N/mm^2 depending on how well the ceramic adheres to the surface. In the FE analysis the porcelain is assumed to adhere perfectly to the surface. This is of course not the case in reality for any material combination. Furthermore, the yield strength of the interface is not easily measured and hardly known. Since the whole interpretation of the results relies on an FE analysis performed when the metallic part is still in the elastic region, a load of 1 N, it is impossible to make any statements for a situation in which the yield limit is reached. There are no data in the work by Lenz et al. that state that reaching the yield limit would overrate the shear bond strength.

Finally, in the three-point flexure bond test there is a complex stress situation in the region where debonding is supposed to occur. The tensile and shear stresses are of the same magnitude. It is not obvious which of these caused the fracture, or if it was actually a combination of the two stresses. It is therefore difficult to make any statements about the clinical performance of the investigated material combination based on the three-point flexure bond test. Lenz et al. also admit that the three-point flexural bond test is not applicable to all metal–ceramic combinations for other reasons than mentioned above; see Lenz's Ref. 3.

Finally, since there is good consensus that the torsional test is the best test for shear strength, it seems like it would be possible to develop the test further to achieve a well-functioning and inexpensive test applicable to all metal–ceramic combinations.

We have not responded to some comments which we think are beyond the scope of our article.

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