A Quantitative Analysis of Different Fiber-Fiber Bonding Mechanisms

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1 OVERVIEW

First we are introducing results from calculating the area in true molecular contact between two fiber surfaces. We use an approach from tribology which uses indentation hardness of the surface, surface roughness and surface pressure to calculate the area in molecular contact. Evidence is presented that the contact area between two pulp fibers bonded together is in molecular contact to a very high degree, maybe even full contact. Theoretical work and analysis of literature is carried out to quantify the contribution of different physical bonding mechanisms: hydrogen bonding, van der Waals forces, Coulomb forces, capillary forces, mechanical interlocking and interdiffusion. Finally the calculated contributions from the different fiber-fiber bonding mechanisms are compared to bond breaking energy values obtained from breaking individual fiber-fiber bonds under tensile load using an atomic force microscope.

2 Bonding mechanisms

One key aspect in analyzing the different bonding mechanisms in fiber-fiber bonds is the quantification of their contribution to the bonding. A crucial point here is the determination of the area in molecular contact. This is the major variable that controls the absolute bond strength, because it directly affects the size of the molecular interaction zone between the fibers. We believe that a rather large fraction of the fiber-fiber bond is indeed in close enough contact for molecular interactions [1].

It was somewhat surprising to see that the estimates for the individual bonding mechanisms are fairly close, all values are within one decade. Capillary forces seems to be the only one that, according to or estimates, is playing a minor role. Also the role of mechanical interlocking does not seem to be so prominent. The molecular interactions, enhanced by interdiffusion, seem to be the key players.

It is interesting that the bonding energy from hydrogen bonding - the most often mentioned fiber-fiber bonding mechanism - seems to be one of the less important ones. According to our calculation van der Waals interactions are more prominent. While the van der Waals bonds are considerably weaker than hydrogen bonds, they outnumber the hydrogen bonds and thus is stronger. In combination with the low contribution we found for hydrogen bonding this would shift our understanding of how fiber-fiber bonding in paper works.

The uncertainty of our estimate for Coulomb interaction is very large. Due to the high bonding energy of individual Coulomb bonds this mechanism has the potential to become the dominating contributor for fiber fiber bonding, especial under consideration that it is relatively easy to add charges to the fiber surface. However, the spatial distribution of the charges on the fiber surface are determining if Coulomb interaction between the surfaces occurs.

Capillary bridges do not seem to play a role for bonding energy, their contribution is lower than for most of the other mechanisms. This must especially be seen under the light that on a given piece of bonding surface only either capillary forces or molecular interactions can take place. It impossible that the surfaces are separated by a water film, and, at the same time, are close enough for molecular interactions.

The actual contribution of mechanical interlocking is also rather uncertain. It is likely to be under the maximum value given in figure 1. The literature regarding this mechanism is contradictive, some find a large effect on bonding energy, others find none.

Similar to Coulomb interaction, the bonding potential for interdiffusion is large. Considering its large potential only little research dealing with this bonding mechanism has been published, quantitative work on the degree of interdiffusion in fiber-fiber bonds is scarce.

Figure 1 shows the contribution of the different bonding mechanisms (blue) and values measured from single fiber-fiber bond testing using Atomic Force Microscopy [2]. Overall, the calculated bonding energy values fit surprisingly well with the dissipated energy measurements on fiber-fiber bonds. Still, the calculated bonding energy is too high compared to the dissipation energy measured. Further analysis is necessary to improve our quantitative analysis of the fiber-fiber bonding mechanisms.

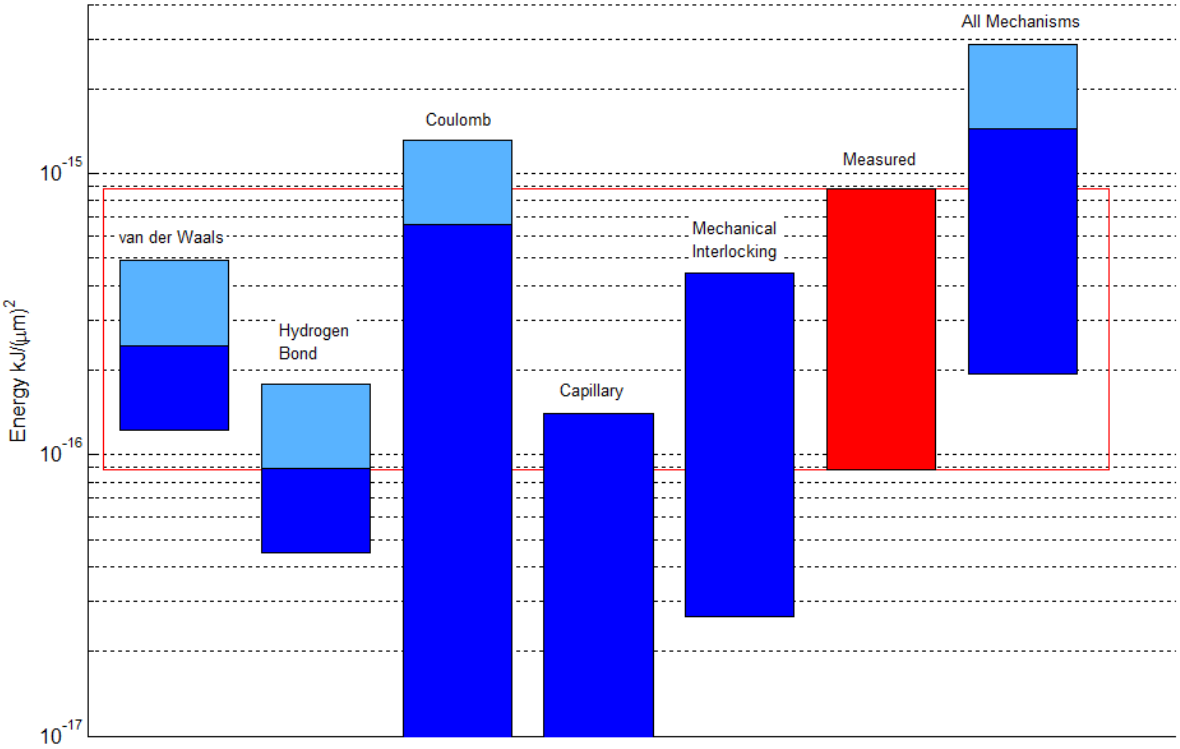

Figure 1. Estimated Contribution of different bonding mechanisms (blue) and the dissipated energy measured for fiber-fiber bonds (red). The light blue parts show the possible contribution from interdiffusion.

REFERENCES

[1] U. Hirn, R. Schennach, C. Ganser, M. Magnusson, C. Teichert, S. Östlund. The Area in Molecular Contact in Fiber-Fiber Bonds. Trans. of the 15th Fundamental Research Symposium, Cambridge, 201–226, (2013)

[2] F. Schmied, C. Teichert, L. Kappel, U. Hirn, W. Bauer, R. Schennach. What holds paper together: Nanometre scale exploration of bonding between paper fibres. Scientific reports 3, p. 2432 - 1-6, (2013)