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ACRYLIC ME(:HANICAL BOND TESTS*

Jan M. Wouters and Peter J. Doe
Los Alamos National Laboratory
Los Alamos, NM 87545

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Abstract

The tensile strength of bonded acrylic is tested as a function of bond joint thickness. 0.125" thick bond joints were found to posses the maximum strength while the acceptable range of joints varied from 0.063" to almost 0.25"

Introduction

A large detector, The Sudbury Neutrino Observatory (SNO), is being designed to detect neutrinos produced by the solar fusion processes and possible supernova explosions. The primary purpose of this detector is to measure simultaneously both the flux and spectral shape of electron neutrinos and the total flux of all neutrino flavors originating from the sun. A comparison of these two measurements is expected to shed light on whether the present discrepancy between the theoretically predicted and experimentally observed flux of electron neutrinos is a result of

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deficiencies in solar models or is a result of new, as yet unverified properties of the neutrinos themselves.

The key element of the detector that makes the above measurements possible is 1000 tons of heavy water that is surrounded by approximately 7000 tons of light water. A large (12 meter diameter) clear acrylic vessel fabricated from over 100 rectangular panels is required to separate the two volumes of water. The panels comprising the vessel must be bonded together with the resulting joints being both structurally strong and impermeable to water. This report describes a series of tensile strength tests that have been done to ascertain the optimum bond thickness and the permitted variation in bond thickness between the panels.

Experimental technique

General testing procedure

Two sets of five tests each were conducted to determine the variation in tensile strength with bond thickness because when the tests were planned the final thickness of the acrylic panels had not been decided. The two tests used 1" and 2" thick acrylic sheets, respectively (the actual thicknesses used were 25 mm and 50 mm). Each set consisted of making up bonded panels that had joint thicknesses of 1/32" (0.79 mm), 1/16" (1.59mm), 1/8" (3.18mm), 3/16" (4.76mm), and 1/4" (6.36mm). These panels were then cut and polished to produce ASTM (American Society for Testing and Materials) tensile test coupons and used to determine the tensile strength of the bonds. As a reference, six test coupons (no bond) were fabricated from the 1" thick acrylic material and tested.

Sample preparation

All samples were prepared according to the specifications listed in ASTM D638-89 for the tensile strength testing of acrylic. The material used was ultra violet transmitting cast acryic sheet

(ROHAGLAS GS218 UVT acrylic) purchased from Rohm - Germany, a large supplier of scientific grade acrylic. Ten rectangular pieces measuring 3.5" wide by 6.0" thick. were cut from both the 1" and 2" thick acrylic material. The top and bottom surfaces were not disturbed while the edges were all milled to an approximately 63 finish. Special care was taken in all machining operations to use only water for lubrication. No alcohol or other organic solvents were used since several of these liquids are known to induce crazing in stressed acrylic.

These small rectangular panels were then sent for bonding to Reynolds Polymer Technology (RPT) in Irvine, California. This company has extensive experience in the casting, thermoforming, polishing and bonding of very large acrylic panels. They were asked to use their best proprietary bonding procedure for joining the panels. In outline, this procedure consists of sanding with 240 grit paper the two surfaces to be bonded (the 6.0" long sides of the panels). The panels are then separated using 1" x 2" and 1" x 3" aluminum shims in the thicknesses listed above. All joints are taped to contain the bonding compound and the shims are removed prior to bonding to allow the panels to "relax" while the bond cures. This relaxation is important since the bonding compound shrinks by several percent and we wanted to minimize the stresses on the bond joints.

In this test, RPT used their proprietary formulation of methyl methacrylate, the acrylic monomer (lot PMI 44-32), for bonding the panels. Once the bonding compound is applied to the bond gap, the samples are cured at temperatures from ambient upto 160°F. Finally the samples are probed to assure a good cure and the tape is removed. The bonded samples were not annealed since such annealing will not be possible during the construction of the acrylic vessel.

The finished bonded panels were returned to Los Alamos for the machining of the ASTM test coupons. A minimum of 10 such coupons were cut out of each test panel (see Fig. 1). The coupons are in the shape of dogbones (see Fig. 2.) and were milled out on a Hurco numerically controlled milling machine. A carbide fly cutter turning at approximately 1200 rpm was used for cutting with roughing cuts limited to 0.1" or less and finish cuts kept below 0.01". Again, only water was used as a lubricant. The reference (no bond) test coupons, of which there are only six, were milled out of the 1" thick acrylic after the bonded test coupons were prepared.

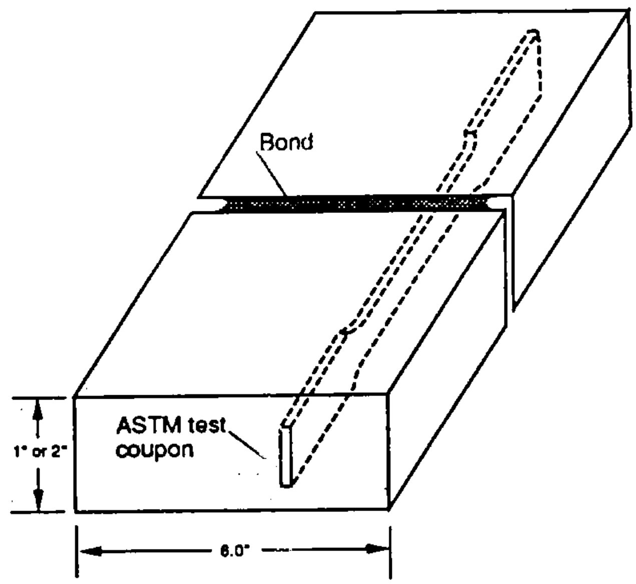

Figure 1: Schematic of test sample with outline of one test coupon

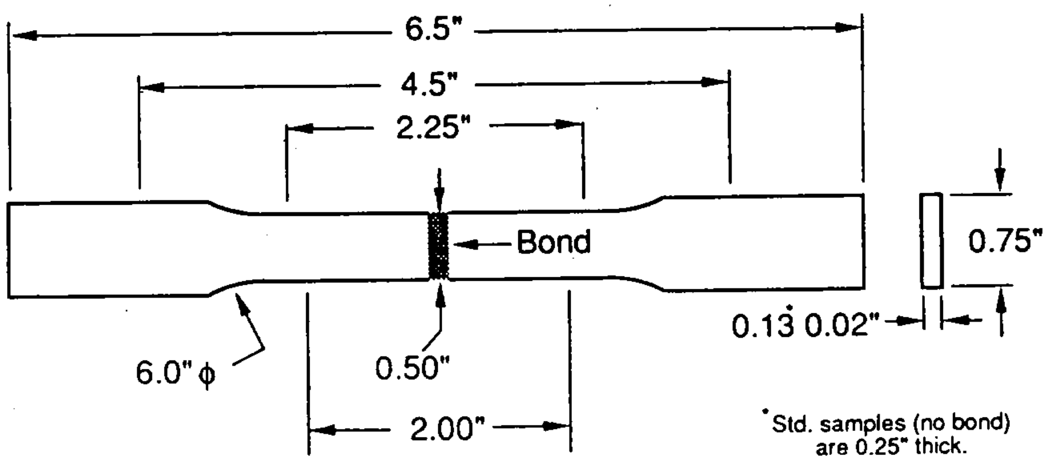

Figure 2: Schematic of test coupon.

All samples were polished to prevent surface imperfections from initiating a premature failure of the material. The polishing procedure consisted of using first 400 and then 600 grit sandpaper. Samples were then placed in a holder and turned on a polishing wheel spinning at between 30 and 100 rpm. The wheel itself was covered with billiard cloth and lubricated with water containing 1 micron alumina in suspension (Linde C and Streurs alumina were both used). Finally the samples were polished using 0.3 micron alumina on a wheel covered with velveteen.

Sample testing

The completed samples were tested following the procedure described in ASTM D-639-89. Our samples were sent to the University of New Mexico where the Engineering department has a 20000 LBS Instron universal testing machine. The thickness and height of each bond joint were accurately measured using a micrometer. The sample was then mounted in the jaws of the Instron machine and an Instron extensometer was attached in such a way that it spanned the bond joint. A crosshead rate of 0.2 inches/minute was used to stretch the sample. The force was recorded using a 5000 LBS load cell. A digital voltmeter recorded the highest force experienced by the sample which was that just prior to failure. A typical sample took approximately 30 seconds to fail corresponding to a total extension of 0.1" in a sample measuring about 5" between the jaws or 2% extension.

Results

Figures 3, 4 and 5 show the results of the raw testing for the 1" thick acrylic, the 2" thick acrylic, and the solid 1" test coupons, respectively. Figure 6 shows the distribution of the individual test results about the average failure stress where the 1" and 2" bonded samples have been summed separately. The third curve in this figure 1" mod is the 1" data with two test coupons removed from the data (see the discussion below). The detailed results for each sample are included in appendix A.

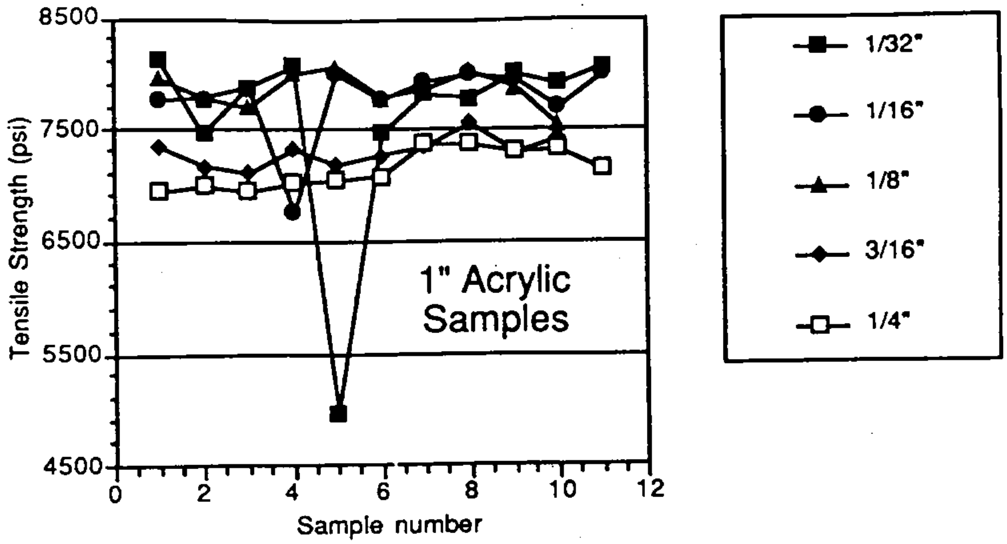

Figure 3: 1" (25 mm) acrylic material test results

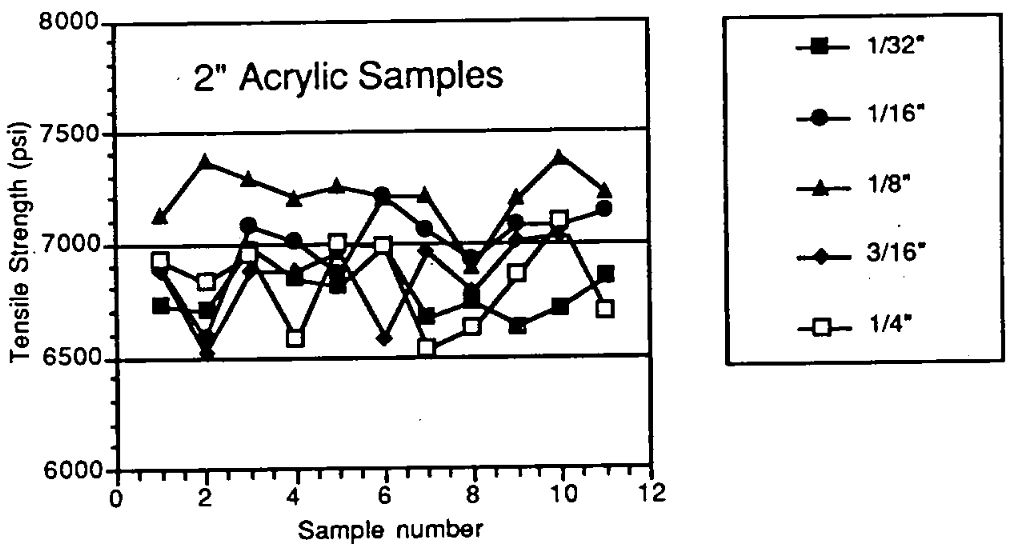

Figure 4: 2" (50 mm) acrylic material test results

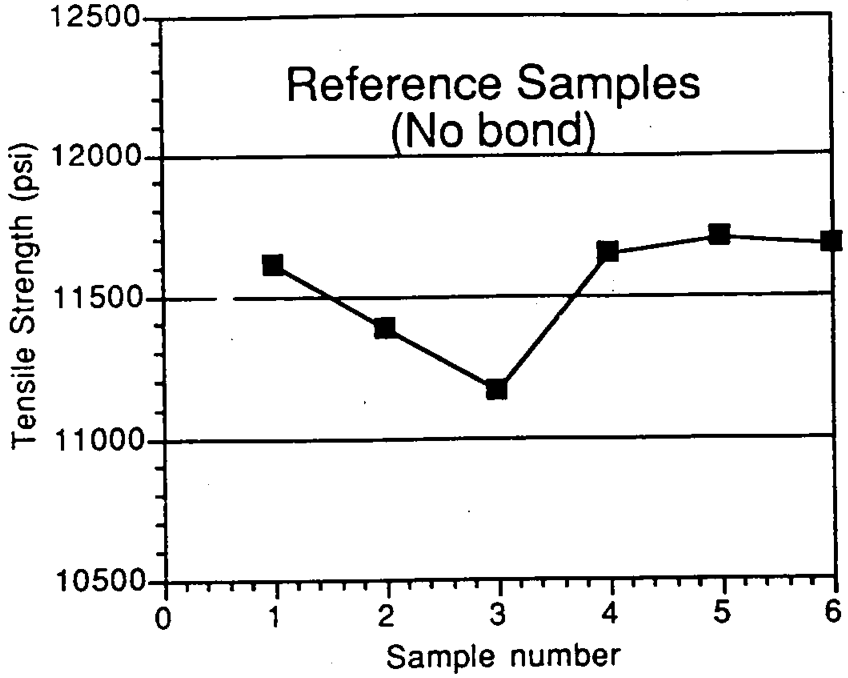

Figure 5: 1" (25 mm) solid reference samples

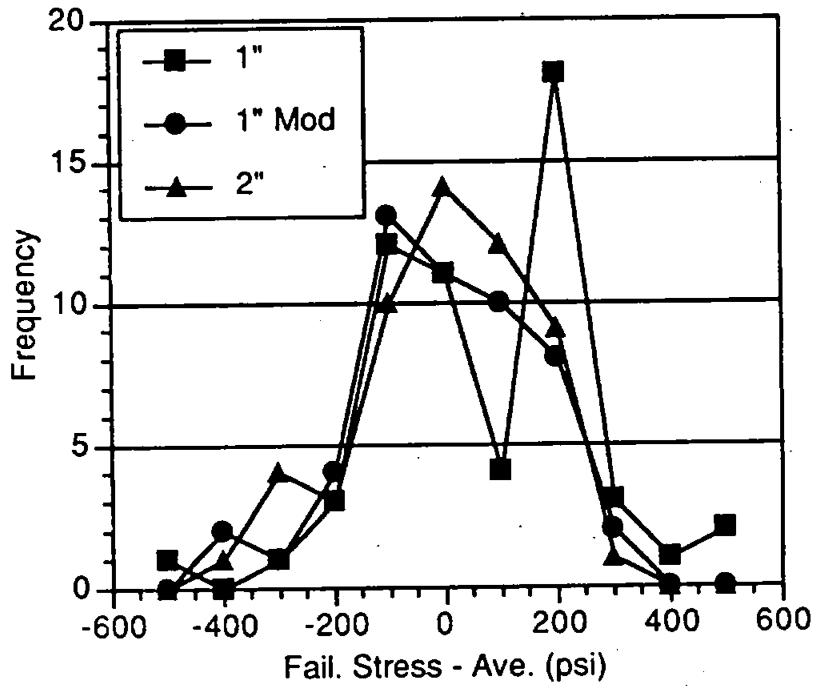

Figure 6: Distribution of individual results about average

Table 1 gives the averaged results for each bond thickness and original sheet thickness. In Table 1 are listed the thickness of the parent acrylic sheets, the initial and final bond thicknesses (before and after curing), the stress at failure and the standard deviation in the stress failure. The standard deviation is calculated as follows: STD DEV = $\sqrt{\dfrac{(X-X_{ave})^2}{N-1}}$ where X is the failure stress and N is the number of test coupons. Note that for these measurements the systematic errors in the testing procedure are considered to be negligible.

	Bond Thickness			Failure Stress	
	Initial inches(mm)		Final inches/mm	Stress psi/Mpas	dev psi/Mpas
1"	No bond			11530/79.50	212/1.46
1"	1/32	(0.79)	0.046/1.17	7588/52.32	899/6.20
1"	1/16	(1.59)	0.058/1.47	7764/53.53	356/2.46
1"	1/8	(3.18)	0.123/3.12	7845/54.09	162/1.12
1"	3/16	(4.76)	0.185/4.70	7292/50.28	129/0.8.9
1"	1/4	(6.35)	0.233/5.92	7127/49.14	173/1.19
2"	1/32	(0.79)	0.037/0.94	6786/46.79	119/0.82
2"	1/16	(1.59)	0.052/1.32	6993/48.22	169/1.17
2"	1/8	(3.18)	0.109/2.77	7213/49.73	130/0.90
2"	3/16	(4.76)	0.152/3.86	6847/47.21	175/1.21
2"	1/4	(6.35)	0.217/5.51	6821/47.03	192/1.32

Table 1: Summary of acrylic tensile strength tests as a function of bond thickness

Figure 7 plots these results (initial bond thickness versus failure stress) with the error bars being the standard deviation in each data set. In figure 8 the summary results are replotted, but all data points (2 out of approximately 100) that are outside of 2.5 standard deviations have been eliminated and the average and standard deviations have been recalculated.

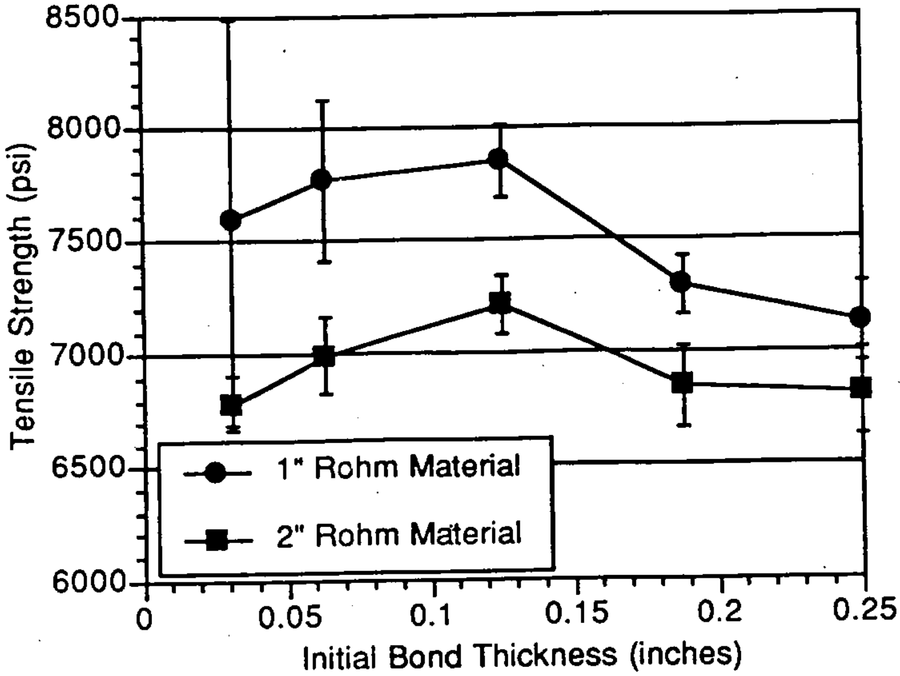

Figure 7: Summary results for bond thickness tests

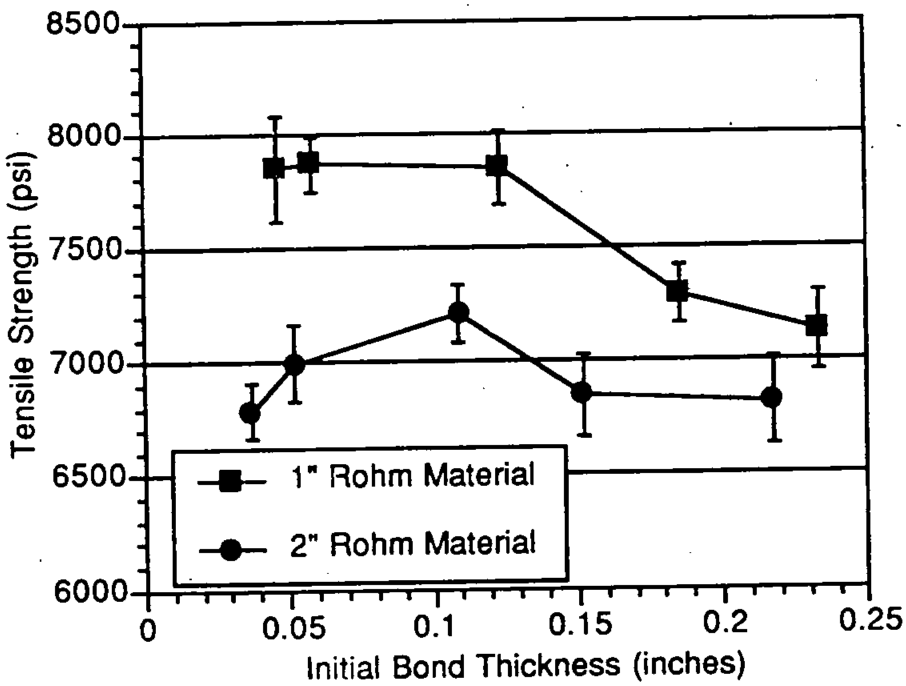

Figure 8: Summary results with individual measurements deviating by more than 2.5 standard deviations removed

One unanticipated result that we have from these tests is the percentage of bond shrinkage during the curing process as a function of both bond thickness and parent acrylic material thickness. These results are graphed in Figure 9. Unfortunately, these results were not collected in a systematic fashion and thus the uncertainty in the results is not known. The negative shrinkage (i.e. expansion) for the thinnest bond joint occured because the initial bond width was probably not quite 1/32" due to the difficulty in making such a bond. Thus the shrinkage results from this bond width are suspect and should be disregarded.

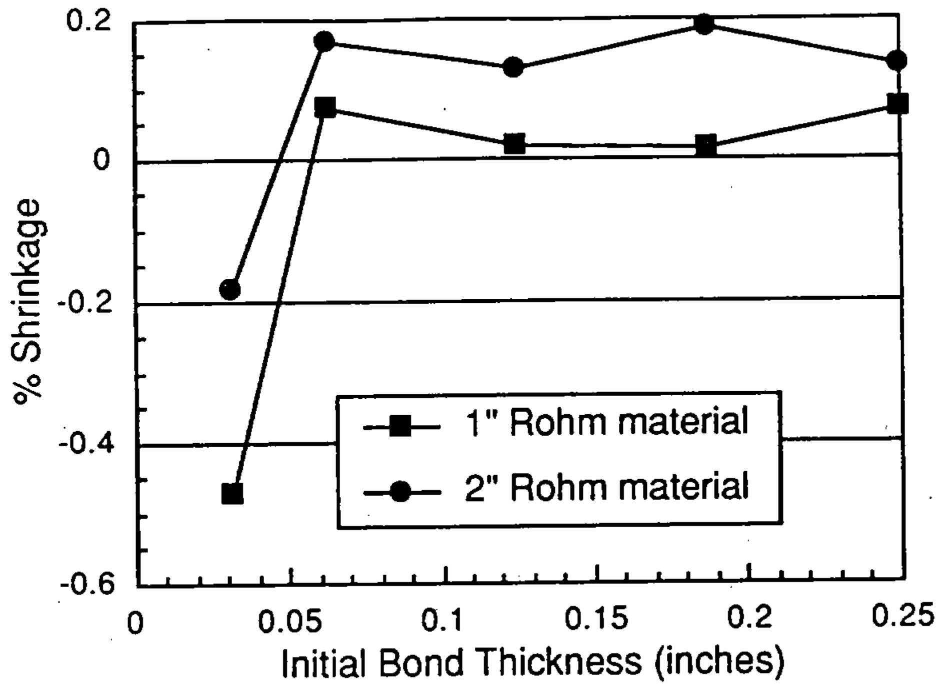

Figure 9: Percentage shrinkage in bond joint width as a function of initial bond thickness.

Discussion

Average bond properties

We begin this discussion by considering the average bond strength for both the 1" and 2" acrylic samples. For the 1" samples the weighted average bond strength is 7432 psi (51.2 Mp), while for the 2" material it is 6963 psi (4.80 Mp). Thus the 1" and 2" bonded acrylic samples are 64% and 60%, respectively, of the parent material strength. Also, the average bond strengths show that bonds formed with the 2" material are 6% weaker than those formed in the 1" material. If one now examines figures 7 or 8 one sees that this difference is greatest for the thinnest bond joints and decreases with increasing bond thickness. A plausible reason for this behavior is the increase in surface to volume area between the 1" and 2" inhibiting the curing process.

Looking at the individual data sets (Fig. 6) one sees that the 1" material has a significant scatter compared with the 2" material. Since the test coupons are cut from the center of the test samples (see fig. 1) the 2" material is more likely to have a uniform bond. No portion of the tested bond is closer than 0.5" from the edge of the bonded sample. For the 1" test coupons the tested bonds are as close as 0.125" from the edge of the test sample.

Two samples are particularly deviant in the 1" test samples and occur for the thinnest bond joints. Both are just within three sigma deviations of the average. In figure 8 is replotted the data with the two deviant data points removed. The data labelled 1" Mod. in figure 6 shows that the distribution without these two data point is more like that for the 2" data. Note that in the case of the 1/32" bond the average changes from 7589 psi (52.32 Mp) to 7851 psi (54.13 Mp) while the standard deviation is reduced from 899 psi (6.20 Mp) to 232 psi (1.60 Mp). For the 1/16" bond the average goes from 7764 psi (53.53 Mp) to 7866 psi (54.23 Mp) and the standard deviation is reduced from 356 psi (2.46 Mp) to 120 psi (8.27 Mp). Using these new numbers the average bond strength for the 1" samples is now 7591 psi (52.34 Mp) which further decreases the spread between the 1" and 2" tensile strengths.

A closer examination of the systematic deviation between the 1" and 2" test samples shows that the difference decreases as the bond thickness increases (see figs. 7 and 8). In light of the above discussion, one might expect such a behavior because the decreasing surface area to volume ratio inhibits the cure and may result in a larger variance in the strength. Figure 9 shows that on average the bonds in the 2" material have over twice the shrinkage of the bonds in the 1" material. This increased shrinkage could magnify the locked in stresses of the bond joint lowering its tensile strength.

Optimum bond thickness

Both the 1" and 2" bonded samples show the same general trend which is that the bond strength reaches a maximum at about 1/8" initial thickness and then tapers off gradually with increasing thickness. This trend is more pronounced for the 2" material, though, the scatter at narrow bond thicknesses for the 1" material makes such generalizations difficult. One comforting conclusion is that as the joint width increases the bond strength does not drop precipitously, but only decreases by about 10-15%.

In figure 10 is plotted the bond strength versus final bond thickness as opposed to initial bond thickness. The results seem to indicate that the trend is more a function of initial than final bond thickness even though one might think that the amount of shrinkage could have an appreciable effect on the bond strength. The bond shrinkage for the 2" material is substantially more than for the 1" material as has already been discussed above.

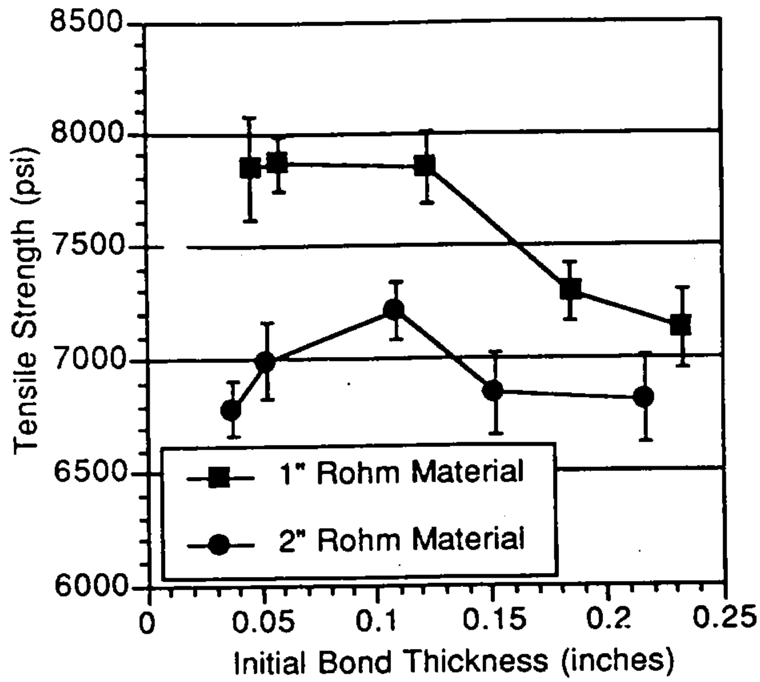

Figure 10: Test results plotted as a function of final bond thickness.

Conclusions and Recommendations

For the Sudbury Neutrino detector the results would seem to indicate that the thicker acrylic panels might be preferable to the thinner ones. Even though the average bonding strength is lower for these thicker panels the spread in the data for the 1" materials especially for the thinnest bond widths is worrisome. In the acrylic vessel the strength of the vessel will only be as good as its weakest link. Though the results are sparse one clearly prefers to use bonds that have the least amount of deviation around an average strength. Given the trend of the results it is recommended that the tests by repeated with 4" material.

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