Shear strength of adhesively bonded polyolefins with minimal surface preparation

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ABSTRACT

Interest in polyethylene and polypropylene bonding has increased in the last years. However, adhesive joints with adherends which are of low surface energy and which are chemically inert present several difficulties. Generally, their high degree of chemical resistance to solvents and dissimilar solubility parameters limit the usefulness of solvent bonding as a viable assembly technique. One successful approach to adhesive bonding of these materials involves proper selection of surface pre-treatment prior to bonding. With the correct pre-treatment it is possible to glue these materials with one or more of several adhesives required by the applications involved. A second approach is the use of adhesives without surface pre-treatment, such as hot melts, high tack pressure-sensitive adhesives, solvent-based specialty adhesives and, more recently, structural acrylic adhesives as such 3M DP-8005[S] and Loctite 3030[S].

In this paper, the shear strengths of two acrylic adhesives were evaluated using the lap shear test method ASTM D3163 and the block shear test method ASTM D4501. Two different industrial polyolefins (polyethylene and polypropylene) were used for adherends. However, the focus of this study was to measure the shear strength of polyethylene joints with acrylic adhesives. The effect of abrasion was also studied. Some test specimens were manually abraded using 180 and 320 grade abrasive paper. An additional goal of this work was to examine the effect of temperature and moisture on mechanical strength of adhesive joints.

Keywords
A. Structural acrylics, S. Polyolefins
M. Lap-shear

1. Introduction

Polyolefins are strong, lightweight and recyclable polymers. All these characteristics are positive and desirable for industrial applications. However, these less expensive low surface energy polymers tend to be harder or more expensive to bond than many other plastics. Polyolefins are very difficult to bond due to their non-polar, non-porous and chemically inert surfaces. Surface preparation and pre-treatment is necessary for most adhesives when applied to polyolefins for adhesive bonding. The more traditional approach is to pre-treat the surface. The pre-treatments which are widely accepted include chemical etching, flame treating, corona discharge, plasma etching, UV irradiation or the use of chemical primers [1–9]. This fact makes the process slow and expensive and, consequently, less attractive to industry.

Fortunately, things have been made a great deal easier by the on-going development of adhesive technology. Acrylic adhesives are now available, which are particularly adapted for joining this type of materials. These adhesives are two-part acrylic-based and can bond many low surface energy plastics, including several grades of polypropylene and polyethylene, without special surface preparation. These bonds have structural characteristics and can replace screws, rivets, plastic welding and processes that include surface treatments. These specially formulated two-part structural acrylic adhesives eliminate the pre-treatment time and costs associated to them, which can lead to important advantages in industrial applications. An important characteristic of the acrylic adhesives is the possibility to bond many plastics to dissimilar materials such as metal and glass. Room temperature curing helps reduce the cost and oven space, heaters and UV lamps. Open time after mixing can vary from 2 to 15 min and gives assembly flexibility for alignment and repositioning. After a few minutes it is possible to handle the bonded assemblies. These adhesives can also be robotically applied.

2. Experimental

2.1. *Materials selected*

Single-lap joints were used in this study. The substrates were made from plates of polyethylene (PE500, Dehoplast) and

polypropylene (PP, Dehoplast). Material properties are shown in Table 1. Two structural acrylic adhesives (3M DP-8005^{S} from Minnesota, USA, and Loctite 3030^{S} from Düsseldorf, Germany) were selected. As referred by manufacturers, these adhesives can bond many low surface energy plastics without special surface preparation. The mechanical tensile and other properties of the adhesives used are shown in Table 2.

2.2. Surface preparation

Two types of surface preparation—not abraded and abraded—- were used. In the first case, the bonding surfaces were only cleaned with isopropanol using dry paper. In the other case, bonding surfaces were cleaned with isopropanol and then manually abraded with 180 or 320 grit papers until no evidence of surface gloss was visible. Fig. 1 illustrates, as an example, the surface of an abraded specimen obtained by scanning electron microscopy. Fig. 2 shows a typical roughness profile (*R* profile) for the two types of surface preparation used. After the mechanical process of abrasion, the surfaces were cleaned again with isopropanol and allowed to dry before the application of the adhesives. It is noted that this type of cleaning is not ideal but is suited for cleaning processes in industrial applications.

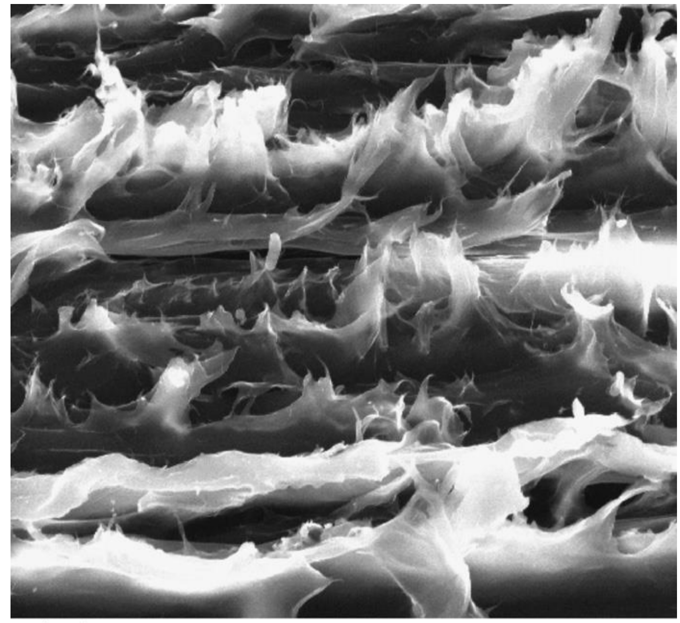

Fig. 1. Polyethylene surface after abrasion.

2.3. Test methods

The lap shear test method ASTM D1002 [10] is typically used to determine the average shear strength of a single-lap joint adhesively bonded. In our first experiments we used this test method. The substrates measured 114 x 20 x 3 mm^3 . Two different bond lengths were considered: 12.5 and 20 mm. It was found that for specimens on which the substrates, of polypropylene or polyethylene, were not abraded rupture or yield of adherends always occurred. This makes the comparative analysis of different adhesives very difficult. Due to this limitation, the lap shear test method ASTM D3163 [11] and the block shear test method ASTM D4501 [12] were adopted. The first method (ASTM D3163) is a test similar to D1002, but it allows the use of substrates with larger thickness. The block shear testing (ASTM D4501) places the load on a thicker section of the test specimen; the specimen can withstand higher loads before experiencing substrate failure. Besides, with method D4501 the adherends are not subjected to a tension loading, unlike with D1002 and D3163 test methods. In addition, due to the geometry of test specimens and the block shear fixture, peel and cleavage loads in the joint are minimised.

Thus, for the majority of this study, the shear strength of joints was determined by lap shear test method ASTM D3163 and block shear test method ASTM D4501. The specimen dimensions used are reported in Figs. 3 and 4. At this stage, only polyethylene substrates were used. The samples were cut from a polyethylene plate with a nominal thickness of 6 mm. Cutting was done using a guillotine and then the edges milled to the sample size of 114 x 25 mm^2 for lap shear tests and 25 x 25 mm^2 for block shear tests. This was carried out without the use of cutting fluid. The bonded area of adhesion was nominally 25 x 12.5 mm^2 and pressure was applied to the lap joint during the curing cycle by one spring clamp. To ensure that the overlapping of specimens was 12.5 mm, a special manufactured tool was designed. This allowed the standardised joint preparation technique to be repeatedly used. Tabs at the ends of single-lap joints were bonded to improve alignment, as shown in Fig. 3. The specimens were left in ambient conditions for 1 week prior to testing.

For each adhesive/substrate couple, the shear strength was determined using an Instron 4208 tensile machine, equipped with a 5 or a 100 kN load cell. For the block shear test method, the two blocks were bonded together and the load required to shear them apart was measured using a special fixture. Adhesives contained glass microspheres with a size of 0.008^{00} (E0.200 mm) for bond line thickness control. Prior to each test, the bond line thickness of each specimen was measured and recorded. The adhesive thickness was measured and values ranging from 0.165 to 0.198 mm were obtained. In the block shear tests, the adhesive excess at the overlap edges was always removed. In the lap shear tests, the specimens without surface abrasion were tested with and without removal of the adhesive excess, and identical results were obtained. Consequently, in the remaining tests, the adhesive

Table 1
Substrate mechanical properties (manufacturer data)

	PE 500	PP
Yield strength (MPa)	428	32
Elongation at yield stress (%)	X8	X14
Ultimate tensile strength (MPa)	36	–
Elongation at break (%)	450	–
Modulus of elasticity (MPa)	X800	X1150

Table 2
Adhesive properties (manufacturer data)

	3M DP-8005^{S}	Loctite 3030^{S}
Chemical type	Acrylic	
Components	Two component: requires mixing	
Viscosity	Medium, thixotropic	
Mix ratio, by volume; Part A:Part B	10:1	
Cure	Fast curing at room temperature and ambient humidity	
Full cure time	E8–24 h	
Open time or work life (min)	2.5–3	3
Tensile strength (MPa)	13	6.3
Elastic modulus (MPa)	590	43.4

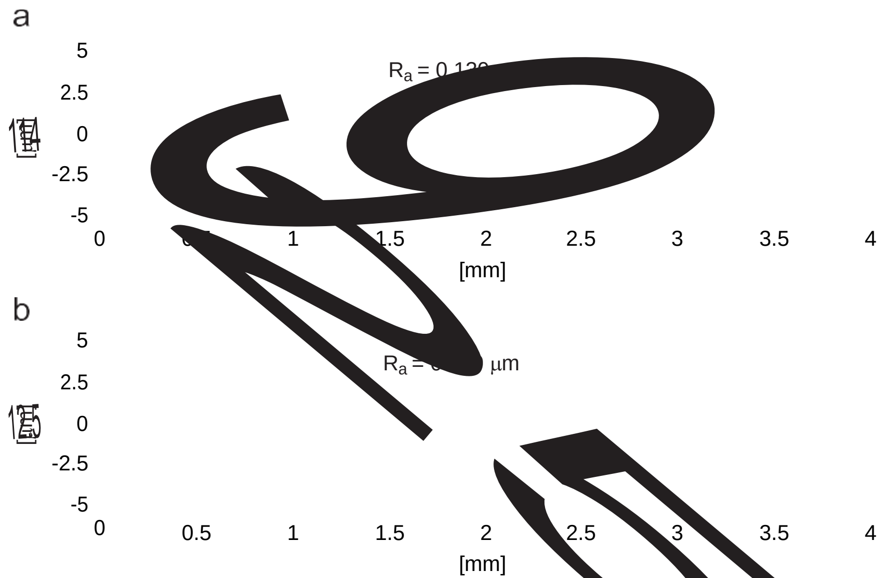

Fig. 2. Surface roughness profiles (*R* profiles) of polyethylene surfaces: (a) without abrasion and (b) abraded with 320 abrasive paper.

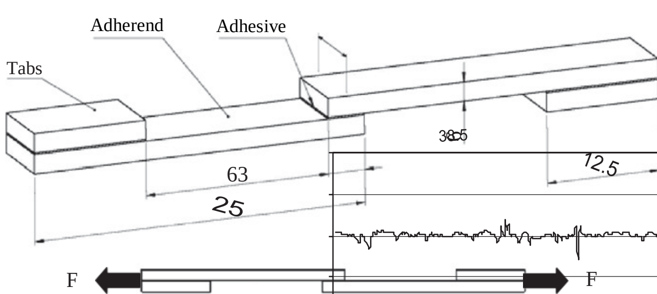

Fig. 3. Joint geometry for lap shear test method (ASTM D3163) (dimensions in mm).

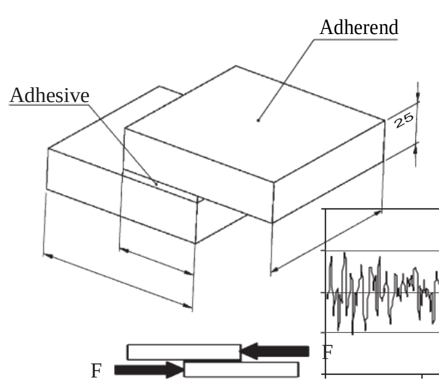

Fig. 4. Joint geometry for block shear test method (ASTM D4501) (dimensions in mm).

excess was not removed. All specimens were tested at a crosshead speed of 1.3 mm/min. The average shear strength was calculated as the measured peak load divided by the bonded area. The reported test values are the average of five measurements. Failure modes were determined by visual inspection.

2.4. Temperature and moisture effects on shear strength

The shear strength of adhesive joints was obtained after an exposure to 50 1C and 80% relative humidity. Forty joints (8 sets of 5 joints) were placed in a Weiss Technik environmental chamber. The time of exposure for each set of joints is indicated in Table 3.

Table 3
Joints time of exposure inside the environmental chamber

Adhesive	Type of specimen	Time of exposure inside the environmental chamber (h)
3M	Single-lap joint	500
3M	Block shear test specimens	
Loctite	Single-lap joint	
Loctite	Block shear test specimens	
3M	Single-lap joint	1000
3M	Block shear test specimens	
Loctite	Single-lap joint	
Loctite	Block shear test specimens	

Forty joints (8 sets of five joints).

3. Results and discussion

The mean lap shear strength measurements, and respective standard deviations, for joints composed of each adhesive and the various surface preparations are shown in Figs. 5 and 6. These graphs show that the surface abrasion gives the worst results, independently of the adhesive and the test method. For 3M DP-8005^{S} adhesive and block shear testing, e.g., the maximum mean value of shear strength was 15.01 MPa (surfaces not abraded) and the lowest mean value was 10.26 MPa (surfaces abraded with 180 abrasive paper). For Loctite 3030^{S} adhesive and for the same test method, the maximum mean value of shear strength was 18.52 MPa (surfaces not abraded) and the lowest mean value was 10.85 MPa (surfaces abraded with 180 abrasive paper). For the joints with not abraded substrates the failure was cohesive, but in the joints with abraded substrates the failure was adhesive.

The bond strength achieved by surfaces abraded with 320 abrasive papers was higher than that obtained by surfaces

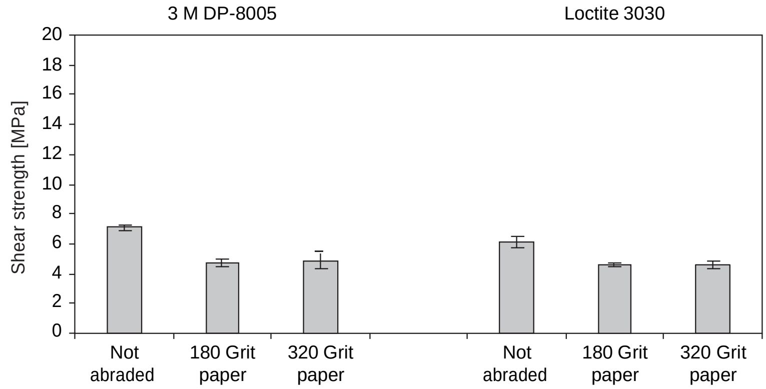

Fig. 5. Shear strength vs. surface preparation and adhesive. Lap shear test method.

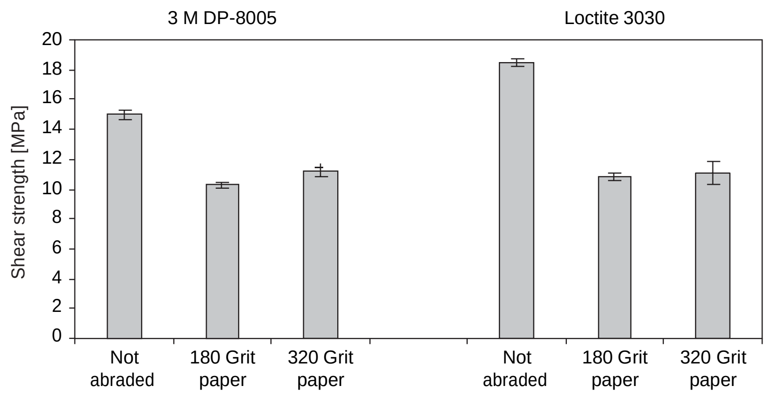

Fig. 6. Shear strength vs. surface preparation and adhesive. Block shear test method.

abraded with 180 abrasive paper. However, the difference is not significant. The surface roughening, in this case, degrades the bond strength. Although it does not change the surface energy, the grooves and valleys that it creates on the substrate surface will not be filled with adhesive before cure due to lack of wetting and air remains entrapped between the substrate and the adhesive. As explained by Petrie [13], this reduces the effective bond area and creates stress risers at the interface.

Considering the same conditions, bond strength obtained by the lap shear test method is much lower than the one obtained by the block shear test method. For example, not abraded joints with Loctite 3030^{s} adhesive had bond strengths of 6.14 and 18.52 MPa with lap shear and block shear test methods, respectively.

The lower strength obtained with lap shear method is due to the lower Young modulus of plastics when compared with metals. Plastics suffer considerable bending during testing, as indicated by Fig. 7, which introduces peel and cleavage forces on the joint. With the block shear method these forces are minimised [13,14].

With the lap shear test method, the 3M DP-8005^{s} adhesive joint gives a higher bond strength than Loctite 3030^{s} adhesive. However, with the block shear strength method, the Loctite 3030^{s} adhesive joint gives the highest shear strength, appearing to be more sensitive to peel and cleavage efforts.

Figs. 8 and 9 show the effects of constant temperature (50 1C) and moisture (80% relative humidity) exposure on the shear strength, for various periods of time up to 1000 h. The bond strength achieved by 3M DP-8005^{s} practically was not altered by the referred conditions. However, the bond strength achieved by Loctite 3030^{s} seems to suffer a reduction, as can be clearly seen

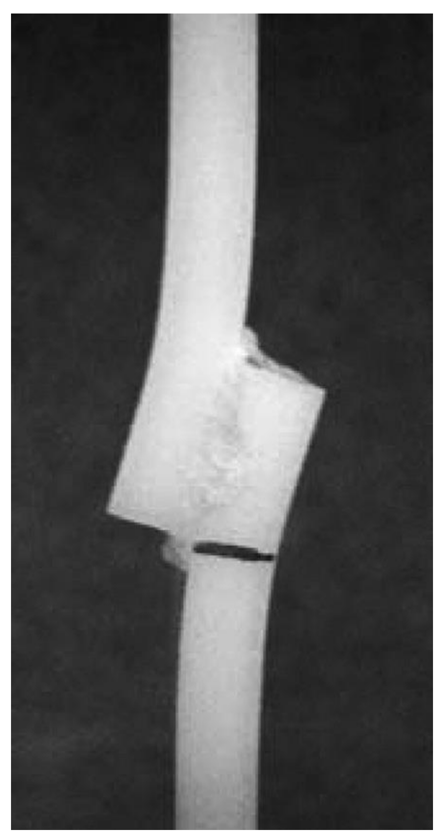

Fig. 7. Joint bending during lap shear testing.

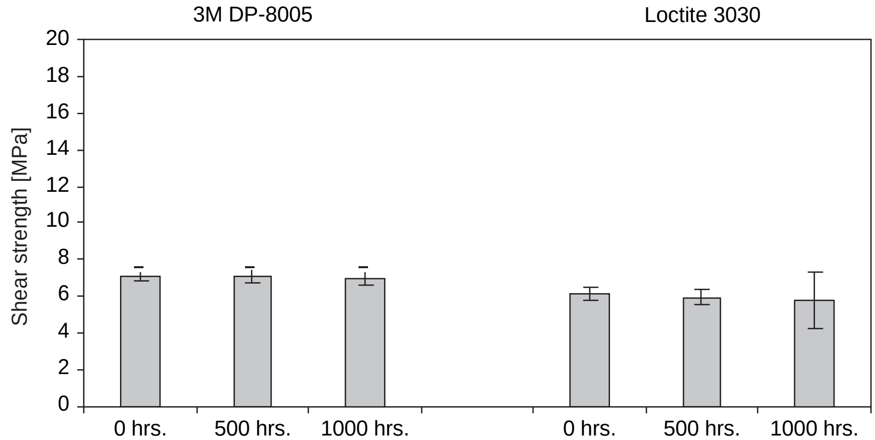

Fig. 8. Effect of temperature and moisture on the average shear strength. Lap shear test method.

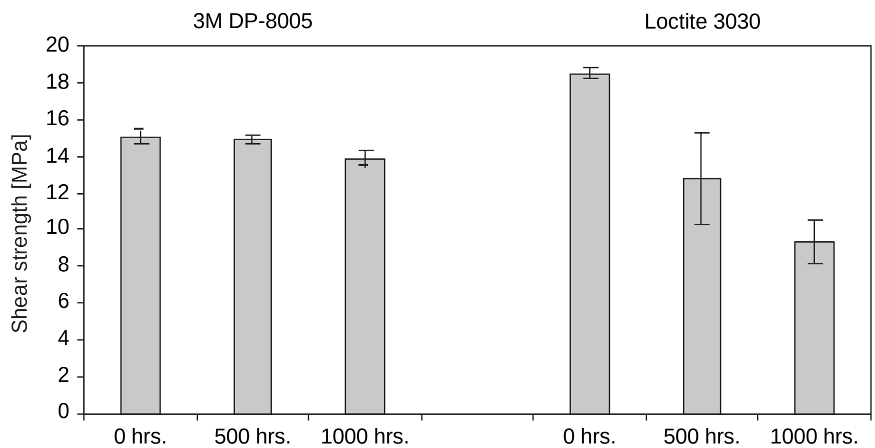

Fig. 9. Effect of temperature and moisture on the average shear strength. Block shear test method.

by the block shear tests results (Fig. 9). This result, obtained with Loctite 3030^{S}, gives the highest data dispersion and, for this reason, the influence of these conditions needs to be confirmed with further tests.

4. Conclusions

The specially formulated two-part acrylic-based 3M DP-8005^{S} and Loctite 3030^{S} adhesives can bond polyethylene and polypropylene without special surface preparation, and lead to high shear strength on structural bonding. With these adhesives, the bonding process is a one-step process, which means that no pre-treatment of the substrate is needed. However, all substrates should be clean, dry and free of paint, oxide films, oils, dust, mold release agents and other surface contaminants.

The surface roughening caused a large decrease in the bond strengths achieved by 3M DP-8005^{S} and Loctite 3030^{S}.

The block shear strength method ASTM D4501 is more suited to determine adhesive shear strengths of plastics with low modulus, than lap shear strength methods such as ASTM D3163 or ASTM D1002.

Considering the temperature and moisture conditions used, the bond strengths achieved by 3M DP-8005^{S} did not suffer statistically significant degradation with exposure to 50 1C and 80% RH for up to 1000 h.

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