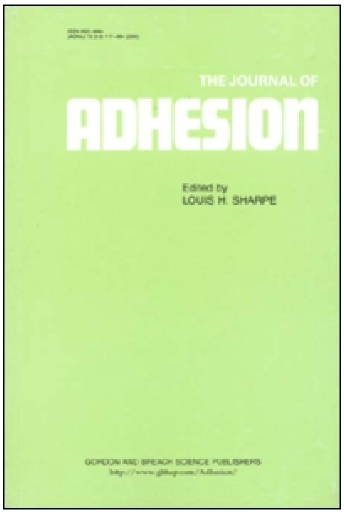

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Influence of Surface Topography on Strengths of Thermal Bonds

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The influence of the initial topography of fiber surfaces on the strength of thermally-induced autohesive bonds between thermoplastic fibers, such as those found in heat-bonded nonwoven textiles, has been studied for flat polypropylene monofilaments having imposed surface scratches. These monofilaments were bonded in various combinations using a laser beam to produce localized melting and bonding. Bond breaking strengths were measured in shear under tensile loading, and the resultant fracture surfaces were examined using scanning electron microscopy. Bonds were strongest when the scratches were aligned; furthermore, for the same alignment pattern, bonds were strongest when the degree of scratching was least. In no case was interfacial failure observed by microscopy. Moreover, more material was torn away from the failing fiber bonds of higher strength than was observed for lower strength bonds. The results are interpreted in terms of the effects on bond strength of the number and distribution of surface flaws present during bonding, which is determined by the initial pattern of surface roughness.

INTRODUCTION

Strengths of cohesive bonds depend appreciably upon the topography of the contacting surfaces prior to bonding. Surface roughness can be detrimental or beneficial depending on the geometry and general characteristics of the system.

The literature on adhesion is voluminous. A number of studies have been reported on the effect of roughness in mixed adhesive–adherend systems,[1-6] but autohesive or self-bonding systems have received little attention. Thermally-bonded autohesive joints, where surface topographies can change as the surfaces melt, are of particular interest since they represent a common form of bonding in nonwoven textiles. The work reported in this paper is devoted to this type of joint.

Selected references pertinent to conclusions proposed in this paper will be summarized briefly. Jennings[1] roughened the surfaces of aluminum and stainless steel by shotblasting and etching. He compared the strengths of metal-epoxy joints using these materials as well as polished specimens of the same metals. Joint strength was observed to increase as surface roughness increased. This finding was demonstrated to be associated with the roughness and not to prior removal of a surface layer. Jennings attributed the changes in strength to redistribution and subsequent lowering of stress concentrations at the interface. Other investigators [3-5] have reached similar conclusions with similar metal-adhesive systems.

Salomon[7] suggests the following reasons for this increase in bond strength with roughened surfaces, provided that the surface is fully wetted. First, the removal of surface material may create a cleaner bonding surface. Second, a greater number of reactive sites may be exposed for increased chemisorption. Third, a roughened surface may retard failure in the joint by mechanical interlocking, i.e., the equivalent of the microscopic scarf joints or snap fasteners postulated by Bikerman.[8]

Knowledge of failure mechanisms is helpful in predicting joint strengths or weaknesses. For example, Wang, Ryan and Schonhorn,[9, 10] for joints tested in tensile shear, note extreme differences in failure mechanisms for ductile and brittle adhesives. In the case of brittle adhesives, failure occurs by initiation of an edge crack; internal voids do not influence the strength of the joint. In contrast, strengths of joints with ductile adhesives, such as the polypropylene used in this project, are dependent upon the total joint area where voids act in two ways to reduce the strength, first by decreasing the bonding area, and second, by introducing regions of stress concentration. Stress concentrations can also be introduced by air trapped in a valley on a rough surface. Johnson and Dettre[11] predict the extent of such entrapment by theoretical consideration of the contact angles of a liquid wetting a rough solid surface.

Eick *et al.*,[2] in studies of denture–adhesive–denture joints, also conclude that areas of stress concentration may be formed by occlusions of extraneous materials (e.g., air) at interfaces. Despite the weakening of the joint by these occlusions, the joint exhibits "proper" characteristics, that is, always fails cohesively within the adhesive.

The aim of this paper is to document the effect of surface roughness on the strength of thermally-bonded autohesive joints and to explain the observed adhesive behavior. Pairs of polypropylene filaments were placed in contact and thermally bonded. Shear strengths were measured on such autohesive bonds between filaments containing combinations of three different types of surface flaws. One type of flaw was the axial striations or die lines on the surfaces of the filaments arising from spinneret extrusion. The other two consisted of additional striations added deliberately to specimens by sanding the surfaces where bonding was to occur, the scratches being imposed either in the axial direction or at right angles to the axis.

EXPERIMENTAL

Autohesive bond formation

The bonds were formed between special filaments (*ca.* 1500 denier) having a rectangular cross section, approximately 330 micrometers by 660 micrometers, as described in detail elsewhere.[12] The filaments were formed from Hercules Profax 6423 polypropylene and cold drawn 4X. Bonds were formed in two configurations, filament axes parallel and crossed, as illustrated in Figure 1.

A Hadron model 1020 CO_2 laser, which produces a 10.6 μ wavelength beam, was used as the heat source to melt and bond the filaments. Filament position and tension applied during bonding were controlled by the jig

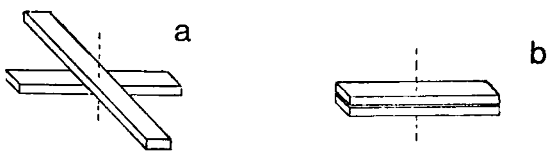

FIGURE 1 Fiber arrangements for laser bonding of rectangular monofilaments: (a) crossed fibers, (b) parallel fibers.

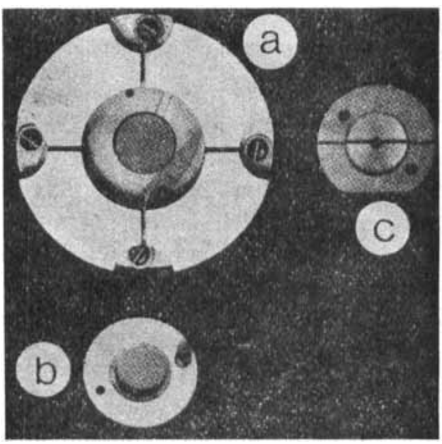

FIGURE 2 Jig for holding fiber pair between Irtran discs during laser bonding: (a) holder, (b) upper disc holder, (c) brace for parallel fibers.

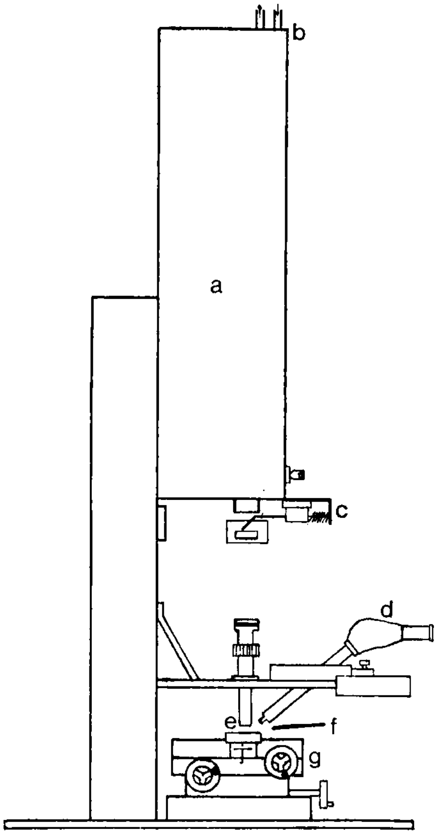

FIGURE 3 Laser bonding apparatus: (a) laser, (b) flowing CO_2 lines, (c) shutters, (d) microscope and beam for fiber alignment, (e) lens, (f) jig, (g) positioner.

shown in Figure 2. The bond area was approximately circular having a diameter about half the width of the filaments. Infrared-transparent crystal discs (Irtran 2), 2-mm thick, acted as support and cover for the filaments in the jig and permitted the beam to pass through to melt the polymer. During irradiation the temperature of the Irtran disc remained below the melting point of the polymer, so that the top crystal acted as a heat sink thereby preventing the top surface of the upper fiber from melting. The laser system, which is shown in Figure 3, has been described elsewhere in detail.[13]

Bond testing

The thermally-bonded polypropylene filaments were broken in shear under applied tensile loading. Those with crossed fiber axes were held in a brass

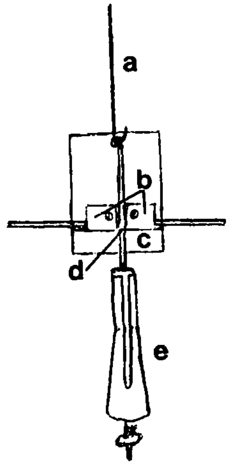

FIGURE 4 Breaking apparatus for perpendicular-axis bonds: (a) hook connected to Instron load cell, (b) screw clamp, (c) end stop, (d) fiber-to-fiber bond, (e) spring clamp connected to Instron load cell.

clamp, shown in Figure 4, and strained at a rate of 1.0 in./min on an Instron tensile tester. Bonds with parallel fiber axes were held between two spring clamps, as illustrated in Figure 5, and strained under the same conditions.

FIGURE 5 Breaking apparatus for parallel-axis bonds: (a) hook connected to Instron load cell, (b) upper spring clamp, (c) parallel-axis bond pair, (d) lower spring clamp connected to Instron load cell.

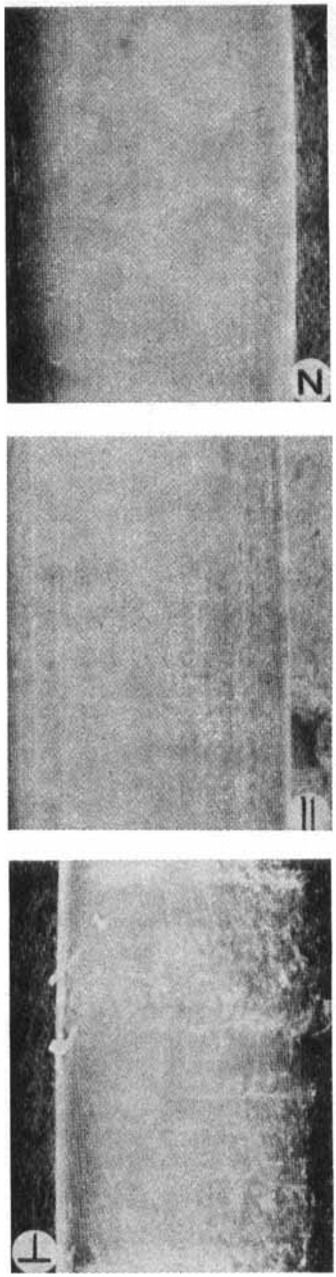

FIGURE 6 Scanning electron micrographs ($\times 100$) of monofilament surfaces: original nominal scratches, N; parallel scratched, ||; perpendicularly scratched, $\perp$.

Filament preparation

Three types of roughness were studied: "as spun" filaments, with nominal scratches, i.e., spinneret die lines on the surfaces parallel to the fiber axis (N); filaments sanded in the axial direction (||); and filaments sanded perpendicular to their axes (⊥). Surfaces were roughened by sanding 150 back-and-forth strokes under a 1-lb load on a Universal Wear Tester, using 3 M crocus cloth taped to the upper plate. The resulting surfaces are illustrated in the scanning electron micrographs in Figure 6. Scratches introduced by the spinnerets are obviously fewer than those formed mechanically, but not necessarily smaller. Before bonding, all specimens were washed with isopropanol to remove grit and oils and subsequently vacuum-dried overnight at room temperature.

Ten replicate pairs of filaments were bonded in each of the following combinations: both with nominal spinneret scratches (N, N); both scratched parallel to the axes (||, ||); both scratched perpendicular to the axes (⊥, ⊥); filaments with parallel scratches over ones nominally scratched (||, N); filaments with perpendicular scratches over ones nominally scratched (⊥, N); and finally, filaments with perpendicular scratches over ones with parallel scratches (⊥, ||). Specimens in these six combinations were prepared in both configurations of the filaments (i.e., for crossed pairs and for parallel pairs). The bonds having aligned scratches on the two filaments in a crossed configuration (Figure 1a), had crossed scratches in an aligned configuration (Figure 1b), and vice versa.

The data were analyzed by comparing strengths of bonds with different levels of scratches, types of scratches, and scratch alignment within the bonding configuration. The configurations provide a means to test alignment separate from scratch type.

DISCUSSION OF RESULTS

The bond strengths in shear under applied tension for the various pairs of fibers are summarized in Table I. Some slight twisting of the clamped fiber is, of course, unavoidable, so that minor components of peel are included. Scanning electron microscopy of the fracture surfaces showed that none of the bonds failed at the interface. Since all the bond areas appeared nearly identical, they were not measured, and the applied tensile forces were considered proportional to the bond shear strengths.

The data are arranged in Table I so that bond strengths decrease from left to right. Many nonindependent comparisons were drawn among the bond strengths in each group. Because of this plan, of the unequal numbers of replicates used for calculating the various averages, and the potentially nonhomogeneous variances of the averages, the Scheffé test[14] for multiple comparisons was chosen. All judgments regarding significance were drawn according to the criteria for this technique.

Strengths of bonds are compared primarily with others in the same configuration. Fibers bonded in the crossed configuration were consistently stronger than those in the parallel configuration, a phenomenon of the bonding and testing techniques.

TABLE I

Bond strengths

	Aligned scratches, lesser amount		Aligned scratches, greater amount		Crossed scratches, lesser amount		Crossed scratches, greater amount	
Crossed Pairs								
Scratch pattern[a]	$\perp$, N		$\perp$, $\parallel$		$\parallel$, N	N, N	$\perp$, $\perp$	$\parallel$, $\parallel$
Avg. max. load, g	431		375		279	276	269	250
Std. dev. of avg.	16.4		10.4		6.65	13.2	6.29	7.14
Number of bonds[b]	5		6		8	6	6	6
Parallel Pairs								
Scratch pattern[a]	N, N	$\parallel$, N	$\parallel$, $\parallel$	$\perp$, $\perp$	$\perp$, N		$\perp$, $\parallel$	
Avg. max. load, g	309	294	287	268	245		226	
Std. dev. of avg.	13.8	8.81	11.0	12.6	8.81		12.2	
Number of bonds[b]	6	5	7	7	7		3	

[a] Top fiber listed first.
[b] Ten bonds of each type were formed, but data from off-center bonds were discarded.

Both sets of data show that average strengths in the group ($\perp$, $\parallel$) and ($\perp$, N) were markedly different from those in the group ($\parallel$, $\parallel$), ($\parallel$, N), (N, N), and ($\perp$, $\perp$), with the Type I error (i.e., α) less than 0.1%. [In statistical terms the Type I error rate is the fraction of the time when, by pure chance, the magnitude of the observed differences among samples occurs when *no* real differences exist between the populations from which the samples were drawn.] Aligned scratches can then be concluded to produce stronger bonds than crossed scratches. For both configurations the ($\parallel$, $\parallel$) versus the (N, N) and the ($\perp$, $\parallel$) versus the ($\perp$, N) bonds also show significant differences (although not at values of α as low as 0.1%). In all four cases, the bonds for the pair containing one fiber with nominal scratching only have greater strengths than the corresponding bond where both fibers are artificially scratched. Extent of scratching is therefore also important, with extensive

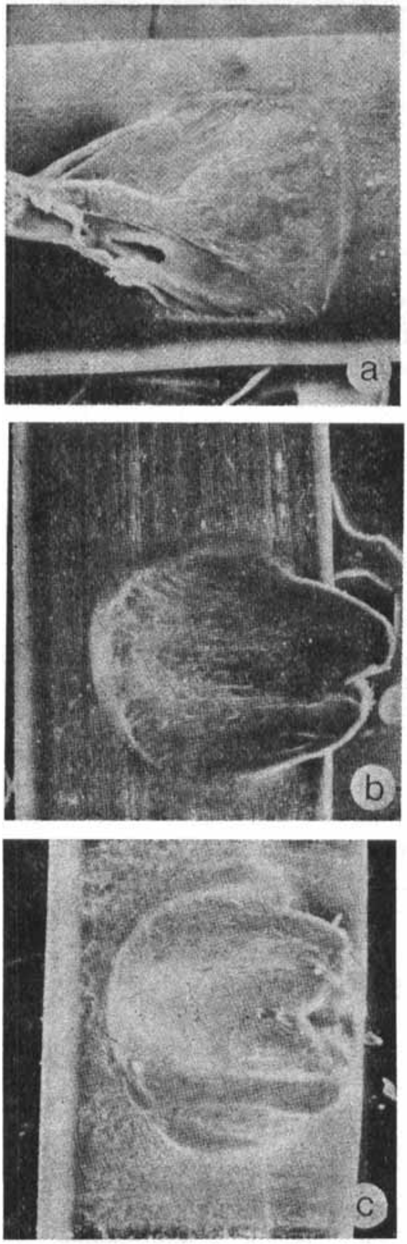

FIGURE 7 Scanning electron micrographs of bond regions after breaking crossed fiber bonds (×100); bottom fiber clamped horizontally, top fiber pulled vertically: (a) normal fiber from top of pair, (b) parallel-scratched fiber from bottom of pair, (c) perpendicular-scratched fiber from bottom.

scratching being detrimental to strength. No real difference could be detected, however, between the (N, N) and (||, N) pairs. Possibly some of the imposed scratches on the upper filament were lost during melting. This hypothetical action appears to be more effective in the crossed configuration where the bonds are weaker than in the parallel configuration in which striations are matched.

In general the data show that bond strengths are increased by meshing of scratches, as well as by reduction in intensity of scratches on the bonding surfaces. Lest one be led to believe that contact area prior to bonding is the controlling factor, several pairs can be noted to dispell this misconception. In the crossed pairs the (⊥, ||) pair should have more contact area than the (⊥, N) pair but the latter is the stronger. Also in crossed pairs (N, N) should have more contact area than (⊥, N) but the lack of alignment of flaws produces a much weaker bond. The same arguments can be proposed for the following parallel pairs: (⊥, N) versus (⊥, ||) and even (||, N) versus (||, ||) or (⊥, ||).

Scanning electron microscopy showed that no interfacial failures occurred, and further, more material was torn away from the failing fibers forming the stronger bonds than from the weaker ones. Figures 7a, 7b and 7c are scanning electron micrographs of fracture surfaces of untreated, parallel-scratched, and perpendicular-scratched fibers, respectively (from crossed fiber bonds). The fiber shown in Figure 7a was on top when broken, whereas the fibers shown in Figures 7b and 7c were on the bottom. The differences between the direction in which the bonds yield arise from the test configuration in that the bottom fiber was clamped horizontally while the top fiber was pulled vertically (see Figure 4). There was no discernible effect of fiber surface roughness before bonding on the appearance of the bond fracture surface as might be expected since rupture never occurred in the plane of an interface.

GENERAL DISCUSSION

The data and observations presented above demonstrate that the bond strength between roughened fiber surfaces depends on the alignment of flaws. When well aligned, the flaws can be imagined to mesh like two gears, with consequent improvement in bond strengths. When crossed, flaws greatly decrease bond strengths, even for those fibers having only the minor scratches produced in extrusion through the die.

The stronger joints with increased metal roughness observed by Jennings[1] were attributed to the random depth from the interface at which flaws existed. This explanation appears to be consistent with the results of the present investigation. Zisman[15] argues that when surface flaws lie in a single plane at the interface, as is the case with the crossed abraded fibers used here, zones of stress concentration overlap and thereby permit a crack to propagate easily from flaw to flaw as though the bond were unzipping. When the flaws are at irregular or random depths, as found after roughening the metal adherends, as in the work of Jennings or by aligning scratches of the same magnitude in the current work, bond strength is improved because the resistance to crack propagation is increased. Jennings concludes that this type of topographical condition implies that interfacial occlusions are more important to bond strength than is the specific work of adhesion.

In the present work, an additional effect of flaw alignment manifests itself with regard to the area of contact during bond formation. Bonds containing crossed flaws will have contact between the two fibers only at the points where the peaks cross. When the flaws are aligned, some peaks of one fiber will enter valleys of the other along the length of the flaw. Thus there will be continuous bands of contact rather than discontinuous points of contact when scratches are crossed, so that the true area of contact will be much greater when flaws are aligned.

Bair *et al.*[18] have experimentally determined, for polyethylene bonded to copper oxide, that the distance from the interface at which failure occurs relates directly to the stress concentration effect of flaws at the interface. The amount of residual polyethylene found on the copper increased as the strength increased due to a decrease in the number of interfacial flaws. In an analysis of stress interactions on modeled systems with hemispherical flaws, the same authors conclude that failure will occur at a distance from the interface equal to half of the average distance between flaws. This conclusion is consistent with the trend reported here for autohesive bonds, for which the bond strength and thickness of the layer removed decreases as the number of surface flaws increases.

Alignment of flaws can also serve to increase the probability of partial mechanical penetration at the bonding site prior to bonding. One can calculate the time for complete penetration of crossed flaws during bonding using Dahlquist's[16] relationship for determining the time required for an adhesive to flow into a microfissure. For total penetration the time t is given as $t = 4\eta_0/P$ where η_0 is the zero shear viscosity and P is the gross pressure. For molten polypropylene in the absence of shear the viscosity is about 10^5 poises (g/cm sec),[17] and the pressure from the Irtran disc and holder (Fig. 3b) is estimated to lie between 2 to 5 g or about 2000 to 5000 dynes for the 3.6×10^{-3} cm^2 of overlapping area. Based on these estimates, the time for complete penetration is calculated to be between 0.3 and 0.8 seconds. Since the time of bonding is less than 0.5 seconds, total penetration can be expected only for systems that are partially meshed prior to bonding. With crossed flaws, the area of contact increases from initial points to discontinuous regions; however, in a time longer than that necessary for total penetration the area of contact would become continuous.

CONCLUSIONS

1) At low contact pressures the interactions of surface flaws in a thermal autohesive bond have the paramount influence on bond strength.

2) Flaws that mesh to produce occlusions at irregular depths, or to eliminate occlusions completely, improve the bond strength.

3) Flaws located to provide large concentrations of occlusions or to provide a coplanar alignment of even a small number of occlusions are detrimental to bond strength.

4) An increase in the number of flaws increases the points of stress concentration and is detrimental to bond strength.

5) Longer bonding times can increase interpenetration of surface flaws and decrease the number of occlusions with improvement in bond strength.

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