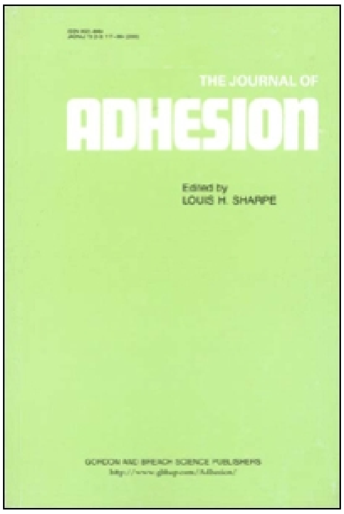

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Fatigue testing of taper press fits bonded with anaerobic adhesives

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FATIGUE TESTING OF TAPER PRESS FITS BONDED WITH ANAEROBIC ADHESIVES

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This article compares the static strength and the fatigue strength (under repeated stress) of axially loaded taper press fits, either dry or bonded with an anaerobic adhesive. A general increase of both static and fatigue strength with the contact pressure is observed, the strength buildup being greater for the dry joints than for the bonded ones. No significant difference between the static and the fatigue strength is measured for the dry joints. For the bonded joints, the fatigue strength decay is nearly independent (in absolute terms) of the assembly contact pressure.

Keywords: Taper press fits; Anaerobic adhesives; Fatigue strength; Staircase method

INTRODUCTION

Anaerobic adhesives (anaerobics) are one-part acrylic adhesives effectively used to enhance the performance of tightened metal assemblies [1, 2]. Interference fits, bolted connections, and flanged couplings are typical examples taken from this class. Once confined between the roughness of the mating parts, anaerobics harden due to the intimate contact with the metal and to the exclusion of oxygen from the space they occupy (hence the name). The benefits obtained include added sealing action, mitigation of fretting fatigue, and increase of the mechanical strength [3, 4]. This hybrid technology leads to smaller (and cheaper) constructions for given load capacity (new design) or to stronger constructions (with small investments) for given overall size (upgrade of existing design).

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Extensive experimental work carried out by the authors [5, 6] has so far dealt with the static strength of hybrid joints. A set of results representative of the general behavior is displayed in Figure 1. The data relate to the category of annular butt joints, either dry or bonded with a variety of anaerobics, mounted under pressure and broken in torsion. It is seen that the overall static strength of the bonded joints (solid lines) increases with the (mean) contact pressure induced by tightening. However, the strength buildup with the pressure is not always the same, and for most adhesives it differs from the dry joint's (dashed line from the origin). This outcome contrasts with the criterion, suggested by adhesive manufacturers [2], according to which the strength of the hybrid joints obtains as the sum of the frictional strength and the adhesive strength, calculated independently of each other. A likely interpretation [6] of the experimental evidence is that, however strong the tightening force, a thin layer of adhesive remains entrapped between the tips of the contacting asperities. Due to the very high local pressure, in this place it attains a shear strength comparable with [7, 8], but not necessarily equal to, the shear strength of the metal junctions featured by the dry joint (frictional strength).

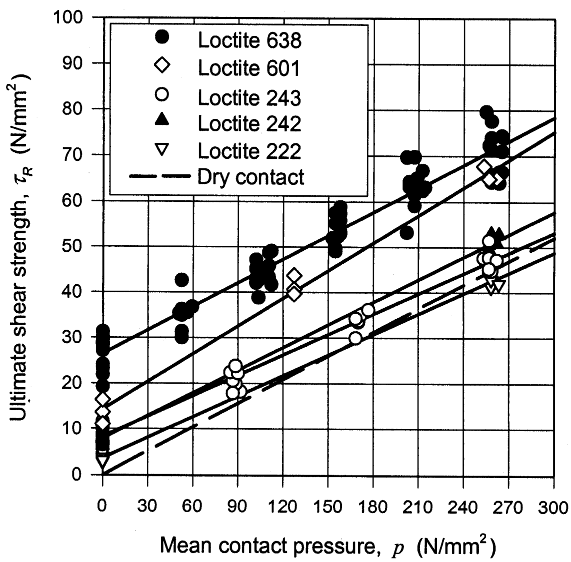

FIGURE 1 Variation of ultimate shear strength with contact pressure for dry and bonded annular butt joints.

As a follow-up to the above research work, the present paper is focused on the fatigue behavior of the hybrid joint, for which the technical literature offers scanty information [9]. The new effort is aimed at finding an empirical relationship that allows the mechanical designer to predict the fatigue strength of the joint starting from its (more readily available) static strength. Through a simple pattern of conditions (setup, assembly, and loading), the tests performed provide useful indications to this aim and form a systematic experimental basis which orients future investigations.

SPECIMENS

Fatigue failures in the mating parts of a tightened connection are a common occurrence in mechanical constructions. Although the degradation of rubbing surfaces (fretting) is often a stimulus to fracture initiation [10–12], this behavior can be classified as a stress concentration problem [13] and is well documented elsewhere (see Kollmann [14] for the shaft-hub connection).

The present work is concerned with the intimate strength of the interface (be it dry, slip bonded, or hybrid), which represents the weakest link of the joint once the above stress concentrations have been eliminated. In order to achieve failure at the interface and gain information on its properties, the test specimens shown in Figure 2 have been adopted. The specimen comprises a tapered (1:50) pin (ø10 × 30 mm) and a collar (ø10 × 30 × 9 mm) with a tapered (1:50) center hole. The pin is a commercial item made of alloy steel, hardened to $S_u = 1500\ N/mm^2$ and ground on the conical surface. The collar, obtained by cutting, boring and reaming a ground round bar, is made of carbon steel, quenched and drawn to $S_u = 800\ N/mm^2$. The specimen dimensions are similar to those prescribed for cylindrical

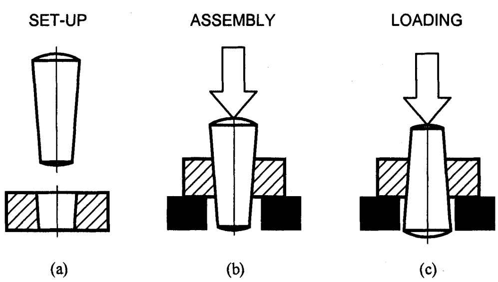

FIGURE 2 Geometry of specimens with assembly and loading arrangements.

pin and collars by ISO 10123, the main standard addressing the static strength of anaerobics. Cylindrical specimens of this type (pin ø12.7 × 50 mm, collar ø12.7 × 25.4 × 11 mm, both of mild steel) have been used in the present work (see below) for exploratory fatigue tests on slip-bonded (no tightening) assemblies.

The choice of the tapered specimens to perform the final tests has been driven by the following reasons:

- inexpensive fabrication and easy preparation of the parts (Figure 2a);
- simple adjustment of the contact pressure through control of the axial insertion force (Figure 2b);
- straightforward axial loading by compression on reverse (Figure 2c);
- certain accomplishment of failures at the interface (see above); and
- clear detection of failure by ejection of the pin from the collar.

The main limitation of the specimens lies in the irregularity of the contact pressure (upon assembly) and of the shear stress (upon loading) over the interface. Both distributions exhibit singularities at the edges of the contact [15, 16]. As a consequence, although significant for real joints with the same proportions as the specimens, the measured strength values are probably lower than the true properties of the interface.

Cylindrical and tapered specimens have been manufactured in homogeneous batches of 30 and 100 samples, respectively, all showing a roughness average of the mating surfaces in the range Ra = 1.2–1.6. From those batches, the single coupons to be used in each particular test have been randomly drawn. Before assembly, the parts have been cleaned by repeated soaking in liquid trichloroethane followed by wiping with cotton cloth and final drying (solvent evaporation) in still air. When applicable, the parts have been bonded with the anaerobic adhesive Loctite 638®, a high-grade retaining product widely used also in former studies [5, 6].

EXPERIMENTAL

Preliminary Tests

A first run of static tests on tapered specimens, variously set up and assembled, was performed on a hydraulic testing machine (INSTRON 8000 with 100 kN maximum load, Instron, Canton, Massachusetts, USA). The loading rate was set to 0.1 mm/s during assembly and to

0.02 mm/s at breakaway. The chief objectives of this static test run were as follows:

- familiarizing with the assembly procedure;
- identifying the most significant conditions to be adopted in the final fatigue tests; and
- estimating the coefficient of friction between pin and collar.

The coefficient of friction, needed to convert the axial assembly force into (mean) contact pressure, was retrieved (for both dry and adhesive joints) from two parameters. One parameter was the slope of the force-displacement diagram (Figure 3) recorded at assembly. The second parameter was the ratio between maximum assembly force and corresponding hoop strain in the collar as captured by an electrical-resistance strain gauge applied on the outer surface (Figure 4). Suitably elaborated by means of the formulas for taper connections and thick-walled cylinders (see Appendix), the above parameters provide the coefficient of friction between the parts.

A second run of exploratory fatigue tests on slip-bonded cylindrical specimens was carried out using an electromechanical resonant machine (RUMUL MIKROTRON with 20 kN maximum load amplitude,

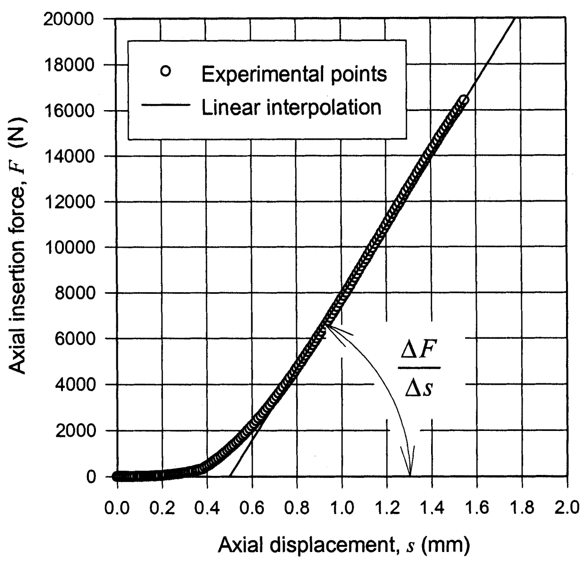

FIGURE 3 Typical plot of insertion force against axial displacement at assembly of a taper press fit.

FIGURE 4 Closeup of a collar instrumented with an electrical-resistance strain gauge.

RUMUL, Neuhausen am Rheinfall, Switzerland). The loading cycle adopted was nearly pulsating from zero (stress ratio $r = 1/19$), and the test protocol adhered to the full staircase method [17]. These fatigue tests were aimed at:

- finding out the temperature increase of the specimens under high frequency (110 Hz) loading, and
- assessing the accuracy of a reduced staircase method [18] in comparison with the full method.

The staircase method is a general technique for sensitivity experiments which applies very well to the fatigue characterization of engineering materials. In short, specimens are tested sequentially, one at a time, with the first specimen being tested at an arbitrary stress level. If the first specimen survives the chosen fatigue life value, the next specimen is tested at a stress level that is an increment higher. If it fails, the next specimen is tested at a stress level that is an increment lower. Specimen by specimen, the stress levels are incremented up or down (in a staircase fashion) depending on whether the current specimen survives or fails. The fatigue limit is obtained as a weighted mean of the stress levels applied, weights being the number of failed or surviving specimens at each level. For the (full) staircase method to work properly, a large number (typically 15 to 30) of tests are required. Otherwise, the results are affected by the particular value of the first stress level adopted. Due to the sequentiality of the tests, this implies a long experimental campaign. To overcome this limitation, a reduced staircase method has been developed which requires up to 7 specimens. By taking into account the outcome (failure or survival) of the first few tests, the reduced staircase provides good accuracy with minimum experimental effort. Details of the staircase methods are given in references [17] (full staircase) and [18] (full and reduced staircase).

Final Tests

The final tests, involving an assortment of taper fits, were performed according to a factorial design. The overall scheme of experiments was obtained by combining in all relevant ways the three following experimental factors (Figure 2), with each variable at two levels:

- set-up: dry or bonded (Loctite 638),
- assembly: slip or press fit (mean pressure of about 150 N/mm^2),
- loading: static or fatigue (repeated stress).

The combination of dry setup and slip fit assembly, obviously characterized by no strength at all, was not actually tested but included in the results as a virtual experimental point (see the section "Results" below).

For the purpose of ensuring homogeneity of treatment, all specimens were fabricated within one day and exposed to a curing cycle comprising one week in an oven (40°C) and one week at room temperature (20°C). The insertion rate of the press fits at assembly was set to 0.1 mm/s.

For each significant specimen type (dry press fit, bonded slip fit, bonded press fit), the static strength was assessed (at a loading rate of 0.02 mm/s) partly before and partly after the fatigue tests. This was done to compensate possible time effects on strength due to the relatively long period (15 days) required to complete each fatigue run.

The fatigue tests were carried out under cyclic loading (stress ratio $r = 1/19$) at a constant frequency of 110 Hz. The criteria adopted to terminate the single fatigue test were either the achievement of joint failure (testified by gross disengagement of the pin) or the attainment of a fatigue life of 10 million cycles (run-out). For one run-out (within each specimen type) that had survived the maximum stress amplitude, the loading was prolonged to either failure or completion of 200 million cycles. The other survived specimens were fractured statically and the residual ultimate strength recorded.

RESULTS

Preliminary Tests

The results of the static tests performed on the first set of (tapered) specimens are collected in Table 1. The meaning of the ratio $\Delta F/\Delta s$ appearing in the table is clarified in Figure 3, where a typical diagram is shown of axial insertion force against displacement at assembly. The ratio $\Delta F/\Delta s$ measures the slope of the linear steady-state portion of the diagram that follows the nonlinear run-in arc. The ratio $\Delta F/\Delta s$ was used to estimate the coefficient of friction (f) by means of Equation (A1) in the Appendix.

Based on the circumferential strain ($\varepsilon_{ce\ max}$) measured at the outside of the collar (Figure 4) under the maximum assembly force (F_{max}), an independent check of the coefficient of friction is provided for each specimen. The ratio $F_{max}/\varepsilon_{ce\ max}$ in Table 1 between force and strain was used in this case and elaborated by means of Equation (A2) in the Appendix.

TABLE 1 Results of the First Run of Preliminary Tests on Dry and Bonded Taper Press Fits

Specimen No.	Setup	Axial insertion force F_{max} (N)	Ultimate static load F_{cr} (N)	$\frac{\Delta F}{\Delta s}$ (N/mm)	$\frac{F_{max}}{\varepsilon_{cemax}}$ (N)	f Eq. A1	f Eq. A2
45	Dry	12,840	10,990	15,100	5.40×10^7	0.29	0.24
72	Dry	13,120	14,590	13,000	6.06×10^7	0.25	0.27
21	Dry	13,280	11,340	14,560	6.52×10^7	0.28	0.29
76	Dry	13,220	16,370	15,600	6.73×10^7	0.30	0.30
81	Dry	15,330	11,970	15,050	6.02×10^7	0.29	0.27
78	Dry	15,650	12,500	16,120	6.95×10^7	0.31	0.31
57	Dry	15,450	17,070	16,630	7.64×10^7	0.32	0.34
71	Dry	15,190	12,480	18,220	7.19×10^7	0.35	0.32
83	Dry	15,240	12,690	16,650	7.00×10^7	0.32	0.31
75	Dry	15,560	13,080	16,100	7.15×10^7	0.31	0.32
80	Bonded	6,010	15,860	9,360	4.27×10^7	0.18	0.19
68	Bonded	6,110	15,170	9,880	4.50×10^7	0.19	0.20
77	Bonded	6,090	16,320	9,410	4.06×10^7	0.18	0.18
48	Bonded	6,130	16,110	10,410	4.75×10^7	0.20	0.21
74	Bonded	8,140	15,820	11,440	4.01×10^7	0.22	0.18
82	Bonded	9,720	18,430	10,920	4.94×10^7	0.21	0.22
9	Bonded	9,050	17,640	9,880	4.71×10^7	0.19	0.21
79	Bonded	9,480	17,570	10,920	5.41×10^7	0.21	0.24
84	Bonded	10,430	17,680	11,440	4.90×10^7	0.22	0.22
73	Bonded	12,540	18,750	11,980	4.52×10^7	0.23	0.20

TABLE 2 Results of the Second Run of Preliminary Tests on Bonded Cylindrical Slip Fits

	Specimen No.														
ΔF (N)	15	16	12	3	10	4	2	6	34	28	38	37	8	17	9
6200															
6000								X		X				X	
5800			X		X		O		O		X		O		O
5600		O		O		O						O			
5400	O														
5200															

O = run-out, X = failure

The results of the full staircase test on cylindrical specimens are presented in Table 2 (O = run-out, X = failure). The load amplitude, ΔF, indicates the total (peak to peak) variation of axial force imposed on the specimens during the loading cycle. The temperature measurements, performed by a thermocouple applied to the upper edge of the bondline, have recorded a temperature increase of less than 3°C with respect to the ambient (20°C) at the operating frequency (110 Hz) under the maximum load (6000 N).

Final Tests

The outcome of the final tests (static and fatigue) are collected in Tables 3a, 3b, and 3c, for dry press fits, bonded slip fits, and bonded press fits, respectively. Each table is divided in four sections. The first section covers the static tests on fresh specimens ahead of the fatigue testing. The second section refers to the fatigue testing by means of the (reduced) staircase method (O = run-out, X = failure). The third section collects the results of the static tests on the fresh specimens performed after fatigue testing. The fourth section contains the static failure loads for the runouts of the fatigue stage. The elaboration of the results of Table 3 is given in Table 4 in the form of mean value (μ) and standard deviation (σ) of both ultimate static load (F_{cr}) and limit load amplitude (ΔF_{cr}) in fatigue (50% probability of failure).

All static results deriving from the preliminary tests (Table 1) and from the final tests (Table 3) are further elaborated and displayed graphically in Figure 5. The graph plots the ultimate unit shear strength against the mean contact pressure. The mean contact pressure is calculated by introducing in the relationships for the tapered joint (see Equation (A3)) the ultimate static load together with the coefficient of friction (0.2 and 0.3, see the "Discussion" section below)

TABLE 3 Results of the Final Tests on Dry and Bonded Taper Fits

(a) Dry Press Fit (insertion force $F_{max} = 13$ kN)

Static strength tests performed on fresh specimens before fatigue testing

Specimen No.	1	53	44	50	46	51	12
F_{cr} (N)	16 340	11 320	14 570	10 640	12 090	13 380	9 550

Fatigue strength tests (staircase method)

	Specimen No.						
ΔF (N)	52	31	7	18	62	29	60
11 000			X				X
10 000		O		X		O	
9 000	O				O		

Static strength tests performed on fresh specimens after fatigue testing

Specimen No.	38	19	4	5	11
F_{cr} (N)	10 880	12 750	14 010	11 990	13 380

Static strength tests performed on the run-outs (10^7 cycles) of fatigue testing

Specimen No.	52	31	62
F_{cr} (N)	12 060	12 830	12 440

(b) Bonded Slip Fit (insertion force $F_{max} = 0$)

Static strength tests performed on fresh specimens before fatigue testing								
Specimen No.	42	61	58	55	30			
F_{cr} (N)	10 050	9 330	9 730	9 680	9 640			
Fatigue strength tests (staircase method)								
	Specimen No.							
ΔF (N)	32	64	69	39	34	28	2	
4 800	X							
4 600		X		X		X		
4 400			O		O		O	
Static strength tests performed on fresh specimens after fatigue testing								
Specimen No.	70	37	25	59	8	26	56	43
F_{cr} (N)	12 660	11 130	11 760	9 700	11 200	10040	8 900	11350
Static strength tests performed on the run-outs (10^7 cycles) of fatigue testing								
Specimen No.	69	34						
F_{cr} (N)	8 550	8 140						

(*Continued*).

TABLE 3. Continued.

(c) Bonded Press Fit (insertion force $F_{max} = 8\,kN$)							
Static strength tests performed on fresh specimens before fatigue testing							
Specimen No.	63	49	40	3	15		
F_{cr} (N)	15 830	16 550	15 830	14 450	16 120		
Fatigue strength tests (staircase method)							
	Specimen No.						
ΔF (N)	20	67	27	65	14	13	17
13 400							X
12 800						O	
12 200	X				O		
11 600		X		O			
11 000			O				
Static strength tests performed on fresh specimens after fatigue testing							
Specimen No.	33	66	10	36			
F_{cr} (N)	19 110	16 150	17 360	17 860			
Static strength tests performed on the run-outs (10^7 cycles) of fatigue testing							
Specimen No.	27	65	14				
F_{cr} (N)	12 890	14 880	12 390				

TABLE 4 Elaboration of the Data of Table 3

(a) Dry Press Fit (insertion force $F_{max} = 13\,kN$)			
Static strength tests on fresh specimens		Fatigue strength tests	Static strength tests on the runouts (10^7 cycles) of fatigue testing
Before fatigue testing	After fatigue testing		
$\mu(F_{cr}) = 12\,560\,N$ $\sigma(F_{cr}) = 2\,360\,N$	$\mu(F_{cr}) 12\,600\,N$ $\sigma(F_{cr}) = 1\,220\,N$		
$\mu(F_{cr}) = 12\,580\,N$; $\sigma(F_{cr}) = 1\,890\,N$		$\Delta F_{cr} = 10\,230\,N$	$\mu(F_{cr}) = 12\,440\,N$; $\sigma(F_{cr}) = 390\,N$
(b) Bonded Slip Fit (insertion force $F_{max} = 0\,kN$)			
Static strength tests on fresh specimens		Fatigue strength tests	Static strength tests on the run-outs (10^7 cycles) of fatigue testing
Before fatigue testing	After fatigue testing		
$\mu(F_{cr}) = 9\,690\,N$ $\sigma(F_{cr}) = 260\,N$	$\mu(F_{cr}) = 10\,840\,N$ $\sigma(F_{cr}) = 1\,220\,N$		
$\mu(F_{cr}) = 10\,400\,N$; $\sigma(F_{cr}) = 940\,N$		$\Delta F_{cr} = 4\,490\,N$	$\mu(F_{cr}) = 8\,350\,N$; $\sigma(F_{cr}) = 290\,N$
(c) Bonded Press Fit (insertion force $F_{max} = 8\,kN$)			
Static strength tests on fresh specimens		Fatigue strength tests	Static strength tests on the runouts (10^7 cycles) of fatigue testing
Before fatigue testing	After fatigue testing		
$\mu(F_{cr}) = 15\,760\,N$ $\sigma(F_{cr}) = 790\,N$	$\mu(F_{cr}) = 17\,620\,N$ $\sigma(F_{cr}) = 1\,230\,N$		
$\mu(F_{cr}) = 16\,590\,N$; $\sigma(F_{cr}) = 940\,N$		$\Delta F_{cr} = 12\,250\,N$	$\mu(F_{cr}) = 13\,390\,N$; $\sigma(F_{cr}) = 1\,320\,N$

μ = mean value.
σ = standard deviation.

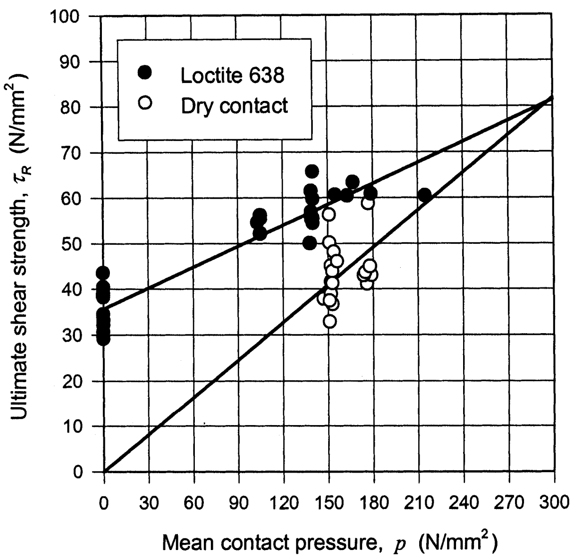

FIGURE 5 Variation of ultimate shear strength with contact pressure (from Equation (A3)) for dry and bonded taper fits.

disclosed by the preliminary tests. The unit shear strength is simply given by the ratio of the ultimate load over the area of engagement (291 mm^2) between pin and collar. In Figure 5, the linear interpolations for both dry and bonded joints are superimposed (lines) on the set of experimental points (circles). For the dry joints, the origin is used as a virtual point (see the "Specimens" section above) since no contact pressure implies no mechanical strength.

Also addressing specific quantities (unit shear strength and contact pressure), Figure 6 contrasts the static strength (solid lines) with the (mean) fatigue strength (dashed lines) obtained in the final tests (Table 3). The values of the fatigue strength correspond to the loading amplitude at 50% probability of failure. The static strength results are accompanied by the confidence interval (plus or minus one standard deviation). The scatter is not provided for the fatigue strength results because the reduced test method adopted does not supply it.

DISCUSSION

Preliminary Tests

The values of the coefficient of friction given in Table 1 testify to a good homogeneity of behavior between specimens within each category (dry

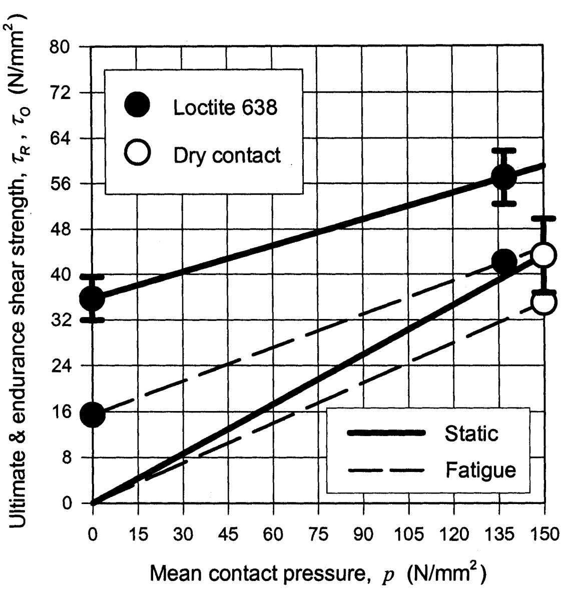

FIGURE 6 Comparison between static and fatigue strength for dry and bonded taper fits.

or bonded). The dry contact is characterized by a mean coefficient of friction of about 0.3 while the bonded contact is distinguished by a value of about 0.2. This smaller figure is explained by the lubricating effect played by the liquid adhesive at assembly. With respect to the load capacity of the testing machine (20 kN), the ultimate static loads of Table 1 suggested the adoption of insertion forces of 13 kN for the dry press fits and of 8 kN for the bonded press fits to be tested in fatigue. Combination of these assembly forces with the above coefficients of friction results (Equation (A3)) in a mean contact pressure of 149 N/mm^2 for the dry press fits and of 137 N/mm^2 for the bonded press fits.

Statistical treatment of the data in Table 2 confirms the consistency of the reduced staircase method [18] (use of 3 to 7 specimens) with respect to the full staircase method [17] (15 specimens or more) for rating the fatigue strength. According to the full method, the limit fatigue load (50% probability of failure at ten million cycles) based on all 15 data of Table 2 equals 5800 N. According to the reduced procedure, the limit fatigue load equals 5720, 5780, 5710, 5750, and 5880 N when calculated with as few as 1, 2, 3, 4, and 5 points, respectively, beginning with the first reversal of response (specimen 12). The good degree of agreement encouraged the use, for the final experiments, of a reduced staircase based on the testing of up to four specimens following the first reversal of response.

Another significant piece of information emerging from the preliminary tests is the small temperature increase (less than 3°C) experienced by the bondline under the testing frequency of 110 Hz. It is known that the thermal buildup due to internal damping represents the main concern in high frequency testing of polymers and bonded joints. In the present case, presumably the heat generated in the thin (about 0.025 mm) adhesive layer is effectively dissipated by the relatively massive adherends. The combination of high working frequency and reduced test procedure has led to a reasonably fast completion of the experimental campaign and opens the way to broader future investigations.

Final Tests

The diagram of Figure 5 supports the main finding of former work [5, 6] (Figure 1), that the static strength increases with the contact pressure but with different gradients for dry and bonded joints. The heuristic principle of superimposition of effects (of friction and adhesive) is again negated as a rational tool for calculating the static strength of the hybrid joint.

On the whole, the final static strength results of Figure 6 reproduce the trend of Figure 5. The high scatter affecting the response of the dry press fits can be explained by the uncertainty that accompanies the friction forces between unlubricated metals.

Most interesting in Figure 6 is the comparison of the fatigue strength with the static strength, from which distinct behaviors for dry and bonded joints emerge. The fatigue strength of the bonded specimens (solid line) shows a definite decay with respect to the static strength. In absolute terms, the decay is approximately independent of the contact pressure and equals roughly one-half of the static strength of the adhesive alone. This observation suggests a simple rule that can be usefully applied in design practice.

When we consider the fatigue strength of the dry joints, quite another conclusion is drawn. First of all, it must be remarked that all failures taking place in this case occurred at the launch of the test with the specimens not even undergoing the very first load cycle. In fact, the failures were of a static nature and the fatigue tests were actually static tests performed with the (reduced) staircase method. All specimens that could survive the first load cycle also survived the chosen threshold life of ten million cycles. From this it can be surmised that the dry interface is virtually unaffected by a fatigue decay. This explains why the fatigue data point of the dry press fits in Figure 6 falls almost within the scatter interval of the static strength for the same joint.

It is also to be stressed that the residual static strength of the dry press fits surviving the fatigue testing coincides with that of the fresh joints (Table 4a). In this respect, a decay affects the bonded joints (Tables 4b and 4c). This probably indicates the absence of a true fatigue limit for this category. This speculation is corroborated by the behavior of the runouts (one for each type of fit) for which the fatigue loading has been prolonged beyond the attainment of 10 million cycles. The dry press fit (29 in Table 3a) has endured a life of 200 million cycles with no signs of failure (after which the testing was terminated). By contrast, the two bonded specimens failed after a (total) life of 90 million cycles (slip fit 2 in Table 3b) and of 105 million cycles (press fit 13 in Table 3c).

CONCLUSIONS

Static tests (under monotonic loading) and fatigue tests (under repeated loading) have been carried out on an assortment of taper fits (conical pin and collar). The assortment included dry press fits together with slip and press fits bonded with an anaerobic adhesive. The static and the fatigue strength of all joints (dry and bonded) increases with the contact pressure induced at assembly (axial insertion of pin into collar). The strength buildup shown by the bonded joints is lower than that of the dry joints. The strength decay in fatigue exhibited by the dry joints with respect to static loading appears to be negligible. By contrast, in the bonded joints the strength decay is significant and seems to be independent (in absolute terms) of the contact pressure.

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APPENDIX

Consider the axial press fit between a tapered pin and a collar (with tapered bore) defined by the following quantities:

d = mean diameter of pin and collar (= 10.3 mm)
D = outside diameter of collar (= 30 mm)
L = axial length of engagement (= 9 mm)
α = half of opening angle of taper ($\mathrm{tg}\alpha = 0.01$)
E = Young's modulus of pin and collar (= 210.000 N/mm^2)
f = coefficient of friction between pin and collar
F = axial insertion force (N)
s = axial insertion displacement (mm)
ε_{ce} = circumferential strain at outer surface of collar
p = mean contact pressure between pin and collar (N/mm^2)

The following relationships [19] hold true:

$$f = \frac{\left(\frac{\Delta F}{\Delta s}\right)}{\pi E L \mathrm{tg}\alpha\left[1 - (d/D)^2\right]} \cong 1.95 \times 10^{-5} \times \left(\frac{\Delta F}{\Delta s}\right), \qquad (A1)$$

$$f = \frac{2}{\pi E L d\left[(D/d)^2 - 1\right]} \cdot \left(\frac{F}{\varepsilon_{ce}}\right) \cong 4.45 \times 10^{-9} \times \left(\frac{F}{\varepsilon_{ce}}\right), \qquad (A2)$$

$$p = \frac{\left(\frac{F}{f}\right)}{\pi d L} \cong 3.43 \times 10^{-3} \times \left(\frac{F}{f}\right). \qquad (A3)$$