COMPARISON OF BOND IN ROLL-BONDED AND ADHESIVELY BONDED ALUMINUMS

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ABSTRACT

Lap-shear and peel test measurements of bond strength have been carried out as part of an investigation of roll bonding of 2024 and 7075 aluminum alloys. Shear strengths of the bonded material in the 'F' temper are in the range of 14-16 ksi. Corresponding peel strengths are 120-130 lb/inch. These values, which are three to five times those reported in the literature for adhesively bonded 2024 and 7075, are a result of the true matallurgical bond achieved. The effects of heat-treating the bonded material are described and the improvements in bond strength discussed relative to the shear strength of the parent material. The significance of the findings for aerospace applications is discussed.

INTRODUCTION

Roll bonding is one of a number of methods used for joining metals by the production of a solid-phase weld at their interface. Bonding is carried out continuously by sqeezing constituent metal sheets together between a set of work rolls. The pressure from the rolls causes the metals to deform so that the interfacial contact is intimate enough to produce atomic bonding between virgin metal surfaces - i.e., to produce a solid-phase weld. An exhaustive treatment of solid-phase welding - including history, theory, methods, research and results - has been given by Tylecote.[1] A shorter review is contained in a book by Schwartz[2] while current work has been summarized by Melhorn.[3]

The first definitive experimental research on roll bonding was done by Vaidyanath et al.[4] The analytical mechanics of roll bonding have been presented in detail by Parkins [5] and summarized by Backofen.[6]

Roll bonding has been in use at Texas Instruments (TI) - Attleboro for a number of years in the production of metallurgically bonded metals and alloys, commonly called clad metals.[7] From its origin as a method for bonding decorative gold or silver surfaces onto base metals, the cladding process has been developed to the point where it is today sophisticated technology used in hundreds of applications.[8,9] These range from electronic connectors and automobile trim to composite coins with the density and appearance of those made from silver.

Developmental work at TI has recently been concerned with roll bonding of the high-strength, precipitation-hardening aluminum alloys 2024 and 7075.

This paper summarizes the results of the studies to date as they pertain to the strength of the metallurgical bond which is achieved in these materials.

BONDING

The roll bonding was done in the Metallurgical Laboratory on a two-high mill with 6-inch roll diameters. Following standard preparation, the sheets of material to be bonded were assembled into a layered "pack" which was introduced between the rolls manually. All roll bonding was performed at room temperature.

Initial experiments with 7075 produced a rather weak and brittle metallurgical bond. This problem was eliminated by using a sheet of softer aluminum between the 7075 sheets. The same situation was found with the 2024 alloy. The use of a soft interliner has been noted briefly in generic terms by Tylecote.[1]

Excellent results have been obtained using 6061 as the interliner. This was chosen for two reasons. First, its chemical composition is similar to that of the 2024 or 7075 alloy. Consequently the interdiffusion that occurs in subsequent thermal treatment of the bonded material does not cause significant strength reduction due to alloy dilution. Second, if a heat-treatable interliner is used, then some strengthening in the interliner can be anticipated when the composite is heat-treated to attain maximum strength - i.e., the effect of property dilution due to the presence of the interliner is reduced.

POST-BONDING TREATEMENT

Consistent with the findings of Tylecote and Wynne,[10] the morphology and consequently the strength of the bond are enhanced significantly by a post-bonding thermal treatment. The standard schedule selected was one hour at 260°C, with heating and cooling rates uncontrolled. This treatment produces about a five-fold increase in bond strength. The metallurigical mechanisms of bonding during rolling, and the formation of the solid phase weld, have been discussed by a number of authors.[4,10,11] Fig. 1 is a typical photomicrograph of the interface between the 6061 and 2024 of a bonded and heat treated 2024-T6 sample. The elemental diffusion and consequent grain growth that has occurred across the interface demonstrate clearly the formation of a metallurgical bond.

MEASUREMENT OF BOND STRENGTH

Bond strength was measured by both peel and lap-shear tests as described below:

Peel Testing

Peel specimens in the form of strips one inch wide and 15 inches long were cut from bonded packs. To permit separation of the bonded layers for testing, a stop-off medium was introduced at the interface at one end of the pack prior to bonding. Specimen edges were smoothed before testing to eliminate stress concentrators.

Peel strength was measured using a fixture developed by Aero Research, Ltd. during the 1950's to evaluate adhesive materials and is described in detail by Benson.[12] As shown in Fig. 2, the specimen is clamped around a rotating drum sector with one of the separated layers free for peeling. Fig. 3 is a photograph of the fixture installed in the Instron testing machine, where the force required to peel the bond is measured. Note that the application of the peel force is always perpendicular and that as the material is peeled the drum rotates to maintain this geometry. In this way a quasi-steady state peel process is obtained. A typical autographic record of the peel force as a function of displacement is shown in Fig. 4. The force increases to a maximum as peeling is initiated, then falls off to an essentially steady-state value. Peel strength in pounds per unit width is determined by dividing the steady-state peel force by specimen width. The peel rate in all experiments was 0.05 inches/min (0.02 mm/sec).

To establish the repeatability of the method, a series of peel tests was run over a three-day period on two specimens with significantly different bond strengths. The results for both specimens were normally distributed, with standard deviations in the range of 6 to 8 percent of the mean as seen from Table 1.

Lap-Shear Testing

Lap-shear specimens one inch wide and nominally 7 1/2 inches long were cut from bonded packs. A groove was machined on opposite sides to approximately half the specimen thickness to produce the desired overlap area as shown in Fig. 5. The edges of the specimen were smoothed as for peel specimens. The specimen was placed in the Instron tester and pulled in tension at 0.01 inches/min (0.004 mm/sec). The force required to pull the specimen apart at the lap joint was recorded and the ultimate shear strength determined from:

$$\text{Ultimate Shear Strength} = \frac{\text{Maximum Load}}{\text{Overlap Length} \times \text{Sample Width}} \qquad (1)$$

Peel and lap-shear testing as described above was carried out on 2024 and 7075 laminates after post-bonding thermal treatment and after further heat-treatment to a T6 temper. The thermal histories of the samples are given in Table 2.

RESULTS

The results of peel and lap-shear tests on the 2024 and 7075 are presented in Tables 3 and 4 for 'F' and 'T6' temper materials, respectively. Typical values for the bond strength of adhesives reported in the literature[13-16] are also given for comparison. The superior bond strength of the metallurgically roll bonded material is evident.

It should be noted that in determining the bond strength adhesives a piece of 2024-T3 0.032 inches thick (0.8 mm) is used for the face material.

In this way some uniformity is brought to the test and the adhesive quality of the "glue" is tested.

This is remarkably different for roll bonded materials, where the shear strength of the bonded materials is tested. Consequently any improvement in the strength of the bonded materials, whether by further cold rolling or thermal treatments, can produce an improvement in the bond strength. This is clearly seen in Table 4, where the lap shear strength of the materials, heat treated to a T6 temper, is 30% higher than that presented in Table 3 for the 'F' temper material.

Peel test results for the T6 temper materials are not presented since meaningful peel tests could not be performed. In any peel test, the value for the peel strength is affected by the size of the radius of the bend in the peeled member at the advancing disbond. This is, in turn, related to the flexural strength of the member and can, as discussed elsewhere,[17] significantly affect the results due to the introduction of a sizable bending load.

DISCUSSION

The results given in Tables 3 and 4 show that the strength of the bond produced in roll-bonded 2024 and 7075 aluminum is in the range of three to five times that reported in the literature for adhesive bonding. This is a direct consequence of the true metallurgical bond achieved during roll bonding and its ready enhancement by subsequent thermal processing.

The bond strength of roll-bonded metals can be determined theoretically if the shear strength of the material is known. Vaidyanath et al.[4] have discussed the use of a constraint factor developed by Orowan et al.[18] and have shown that for aluminum alloys that have been work hardened, the shear strength of the bond (σ_b), relative to the shear strength ofthe parent material (σ_p), is given by

$$\frac{\sigma_b}{\sigma_p} = R(2-R), \qquad (2)$$

Where R is the fractional thickness reduction during bonding.

In the present work, R = 0.6 and Eq. (2) predicts that the theoretical ratio is

$$\frac{\sigma_b}{\sigma_p} = 0.6\ (1.4) = 0.84. \qquad (3)$$

Since the mechanical properties of aluminum alloys are a function of the theromechanical history, values of the shear strength of the parent material, σ_p, for the 2024 and 7075 were determined by measuring the shear strength of monolithic material subjected to the same process schedule.

The value of the ratio of the bond/parent shear strength can thus be experimentally determined and is presented in Table 5 for the 'F' temper samples. Recall that Equation (2) is only valid for materials which have been significantly strain hardened and cannot be applied to the case of thermally treated (i.e., T6) samples. The shear strength of the bond for both materials is 16-17 ksi shich is 90% of the parent material yield strength. This bond strength is significantly better than the shear strengths of adhesives which are typically in the range of 1-5 ksi.[15,16] The similarity of the bond shear strength for the 2024 and 7075 presented in tables 3 and 4 may be coincidental; however we believe it is because the failure is through the 6061 interliner. This subject is being investigated further.

The correlation between experimental and theoretical predictions for the bond strength ratio is excellent. Work is continuing on a theoretical understanding of the bond strength and the influence of subsequent thermomechanical processing schedules in roll bonded materials.

The physical attributes of roll-bonded high-strength aluminum alloys 2024 and 7075 suggest a number of advantages. However, because roll bonding cannot be done in situ, the applications would be restricted to parts having dimensions compatible with the width limit imposed by the bonding process.

The superior bond strength relative to adhesives with no penalty in weight could permit weight reductions, since for equivalent overall strength, joint area might be made smaller. Another advantage could be the replacement of fasteners such as rivets with a roll-bonded joint. This would not only eliminate problems with pronounced stress concentrations, but could also reduce fabrication costs incurred in the labor-intensive process of installing fasteners.

The metallurgical bond is hermetic. Thus, its resistance to environmental degradation by temperature of moisture would be superior to that of adhesives.

Finally, the fatigue response is expected to be better than that of an adhesive bond and probably better than that of a riveted joint. Fatigue studies on roll-bonded 2024 and 7075 are just getting under way at TI. There are some preliminary indications that the fatigue crack growth may be arrested at the bond interface.

AEROSPACE APPLICATIONS

The interest at TI in the bond strength of roll bonded aluminum alloys is prompted by development efforts to produce finished parts without using rivets or adhesives. This technology[9] holds the promise of reduced weight and cost due to the elimination of heavy sections for riveting and the associated assembly costs. Figure 6 shows a demonstration part, typical of a number of access panels, which was fabricated using this cladding process. There are no rivets or adhesives used in this part, which results in a 30% weight reduction and a potential cost reduction of 30%. Other applications of this technology are being developed and the bond strength of the clad metal is of paramount importance. From the work reported here, and ongoing in our laboratory, it is clear that the strength of roll-bonded materials is significantly higher than that usually thought of in the aerospace industry. The shear strength of the bond is typicaly 3 to 10 times greater than that for adhesives and approaches the strength of the parent or face material.

CONCLUSIONS

The strength of the solid-phase weld produced in roll-bonded 2024 and 7075 aluminum has been examined. Bond strength was measured by the peel-test and lap-shear methods for material given an isothermal post-bonding treatment and for material subsequently heat-treated to a T6 temper. Bond strengths were found to be in the range of three to five times those reported in the literature for adhesively bonded 2024 and 7075. Lap-shear strength of bonded material after a thermal treatment was in excellent agreement with theoretical predictions. Potential aerospace applications of roll-bonded 2024 and 7074 aluminum were discussed.

ACKNOWLEDGMENTS

The authors extend their thanks and appreciation to C. Britton, L. Carter, A. Crable and D. Winslow for assistance in material preparation, bonding and mechanical testing.

We are grateful for the continued support of Texas Instruments during this work and to D. Martin, President of Materials and Controls Group, for permission to publish the results.

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TABLE 1

RESULTS OF PEEL-TEST REPEATABILITY STUDY

SPECIMEN ID NUMBER	MEAN PEEL STRENGTH lb/in (N/mm)	STANDARD DEVIATION OF THE MEAN lb/in (N/mm)
A-1	113 (19.8)	9.1 (1.6)
A-2	96 (16.8)	5.9 (1.0)

TABLE 2

THERMAL HISTORIES OF THE BONDED SAMPLES

THERMAL PROCESS	2024 TEMP °F(°C)	TIME	7075 TEMP °F(°C)	TIME
POST-BONDING THERMAL TREATMENT	500(260)	1 HR	500(260)	1 HR
HEAT-TREATMENT TO T6				
SOLUTIONIZATION	920(493)	35 MIN	900(482)	35 MIN
ARTIFICIAL AGING	375(191)	9 HRS	250(121)	24 HRS

TABLE 3

BOND STRENGTH AFTER POST-BONDING THERMAL TREATMENT. THE ERROR QUOTED IS ONE STANDARD DEVIATION.

	PEEL STRENGTH lb/in (N/mm)		SHEAR STRENGTH ksi (MPa)	
MATERIAL	TI	ADHESIVE	TI	ADHESIVE
2024	131 ± 12 (22.9 ± 2.1)	22-60[a]	15.7 ± 0.7 (108 ± 5)	1-5[b]
7075	136 ± 15 (23.8 ± 2.6)	"	17.0 ± 0.6 (117 ± 4)	"

(a) REFERENCES 13 AND 14

(b) REFERENCES 15 AND 16

TABLE 4

BOND STRENGTH IN MATERIAL HEAT-TREATED TO T6 TEMPER. THE ERROR QUOTED IS ONE STANDARD DEVIATION.

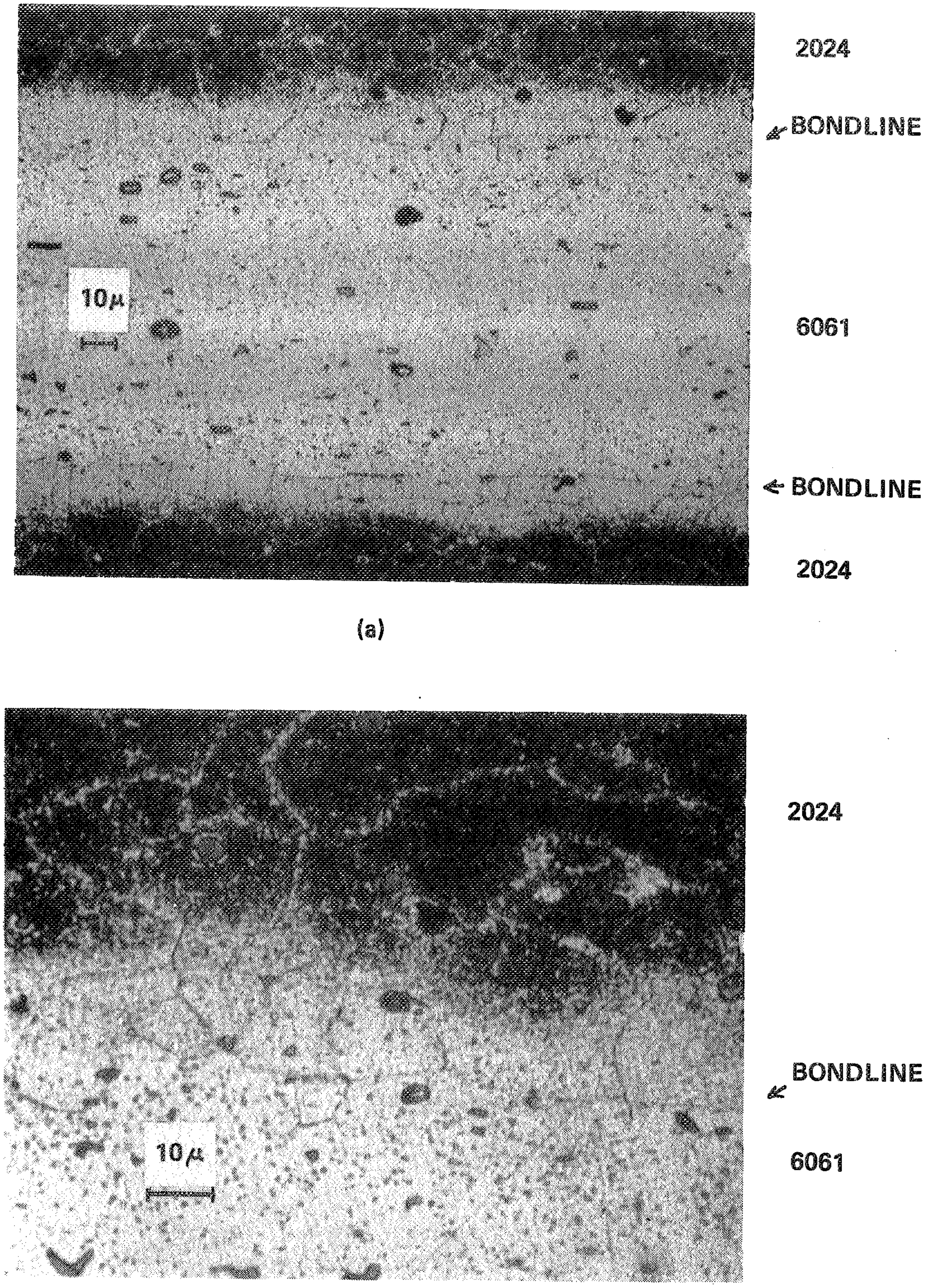
	SHEAR STRENGTH KSI (MPa)	
MATERIAL	TI	ADHESIVE
2024-T62	21.3 ± 1.3 (147 ± 9)	1-5[a]
7075-T6	20.6 ± 1.3 (142 ± 9)	"

(a) REFERENCES 15 AND 16.

TABLE 5

COMPARISON OF SHEAR STRENGTH OF THE BOND WITH SHEAR STRENGTH OF THE PARENT MATERIAL. THE QUOTED ERROR IS ONE STANDARD DEVIATION.

MATERIAL	σ_b (ksi)	σ_p (ksi)	σ_b/σ_p
2024	**15.7 ± 0.7**	**17.1 ± 1.5**	**0.92 ± 0.09**
7075	**17.0 ± 0.6**	**18.6 ± 1.0**	**0.91 ± 0.06**



(a)

(b)

FIG. 1. BOND INTERFACE IN 2024-T6 MATERIAL. (a) 500X. (b) 1000X. KELLER'S ETCH.

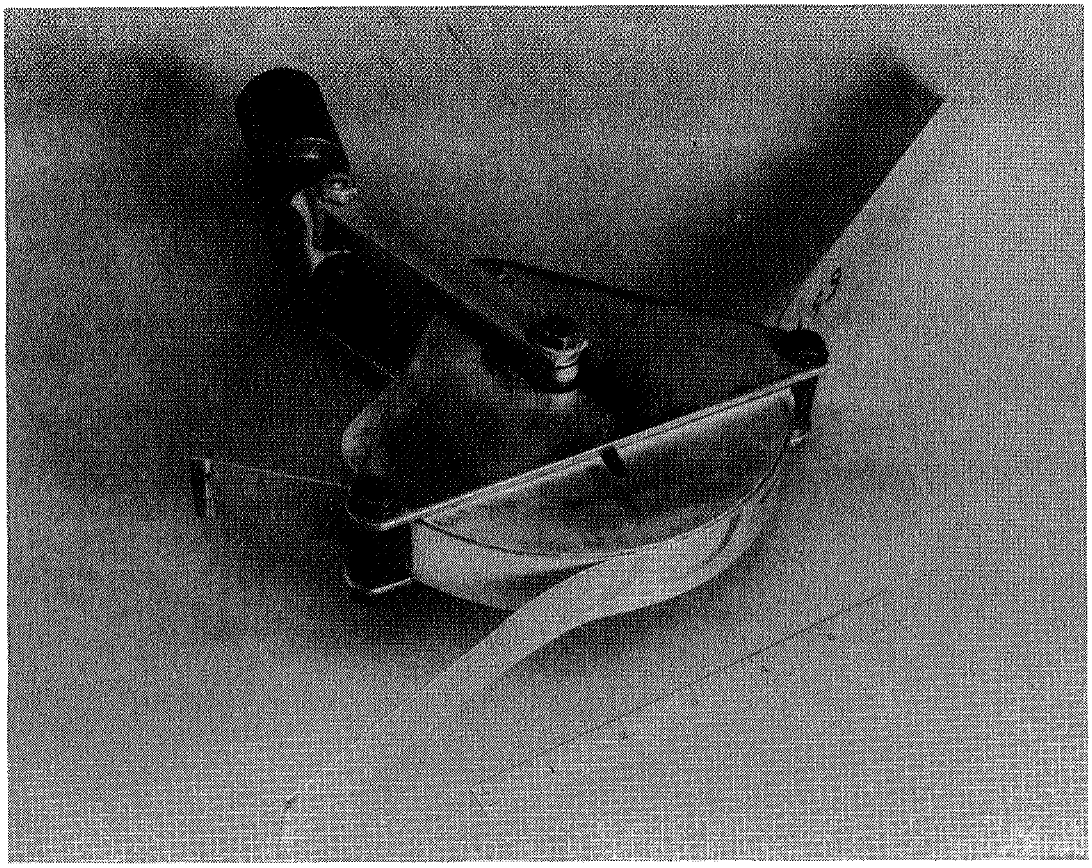


FIG. 2. PEEL-TEST FIXTURE.

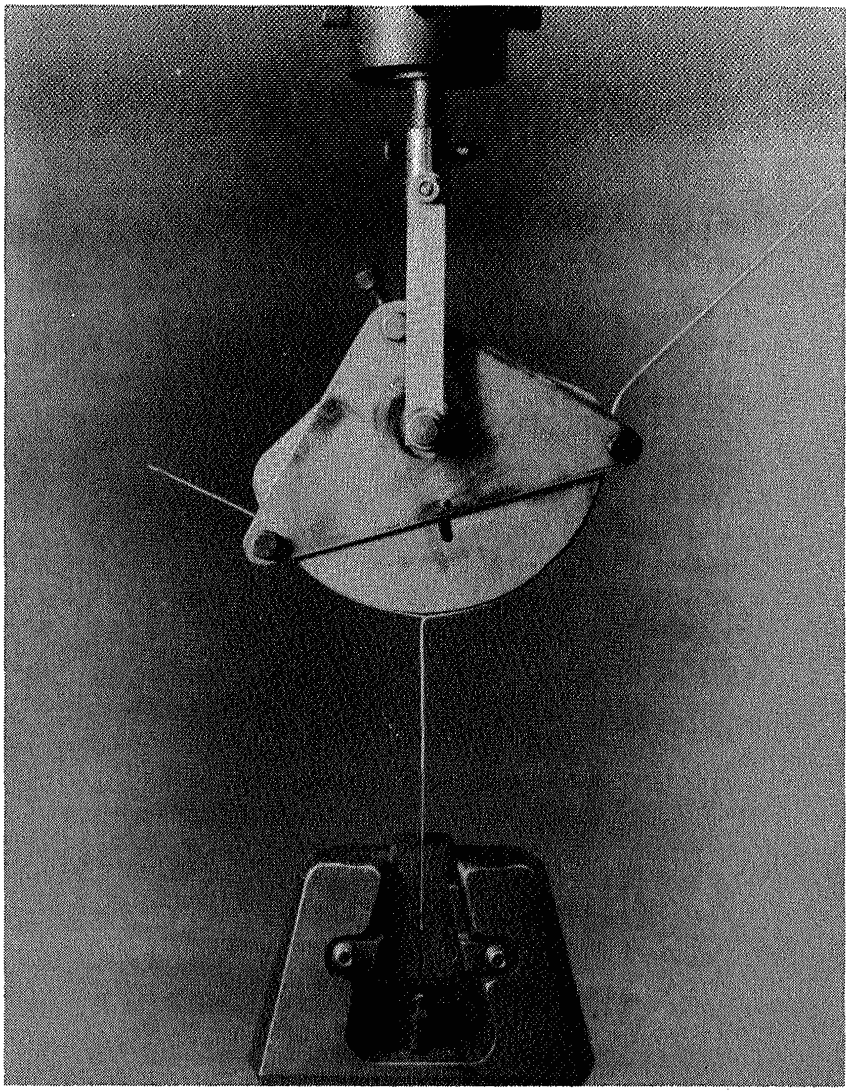


FIG. 3. PEEL-TEST FIXTURE IN INSTRON TESTER.

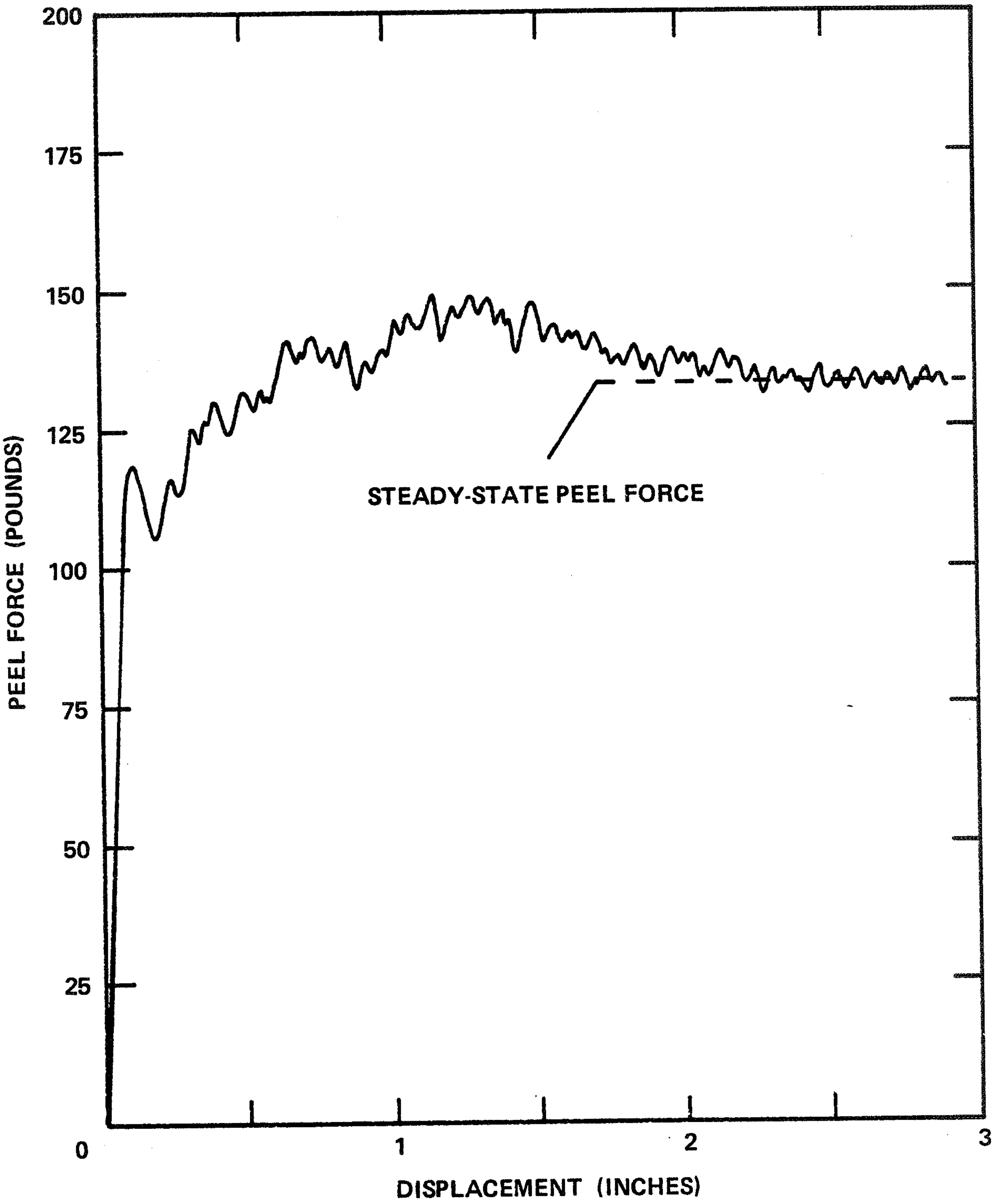


FIG. 4. TYPICAL AUTOGRAPHIC RECORDING OF PEEL FORCE (SCHEMATIC).

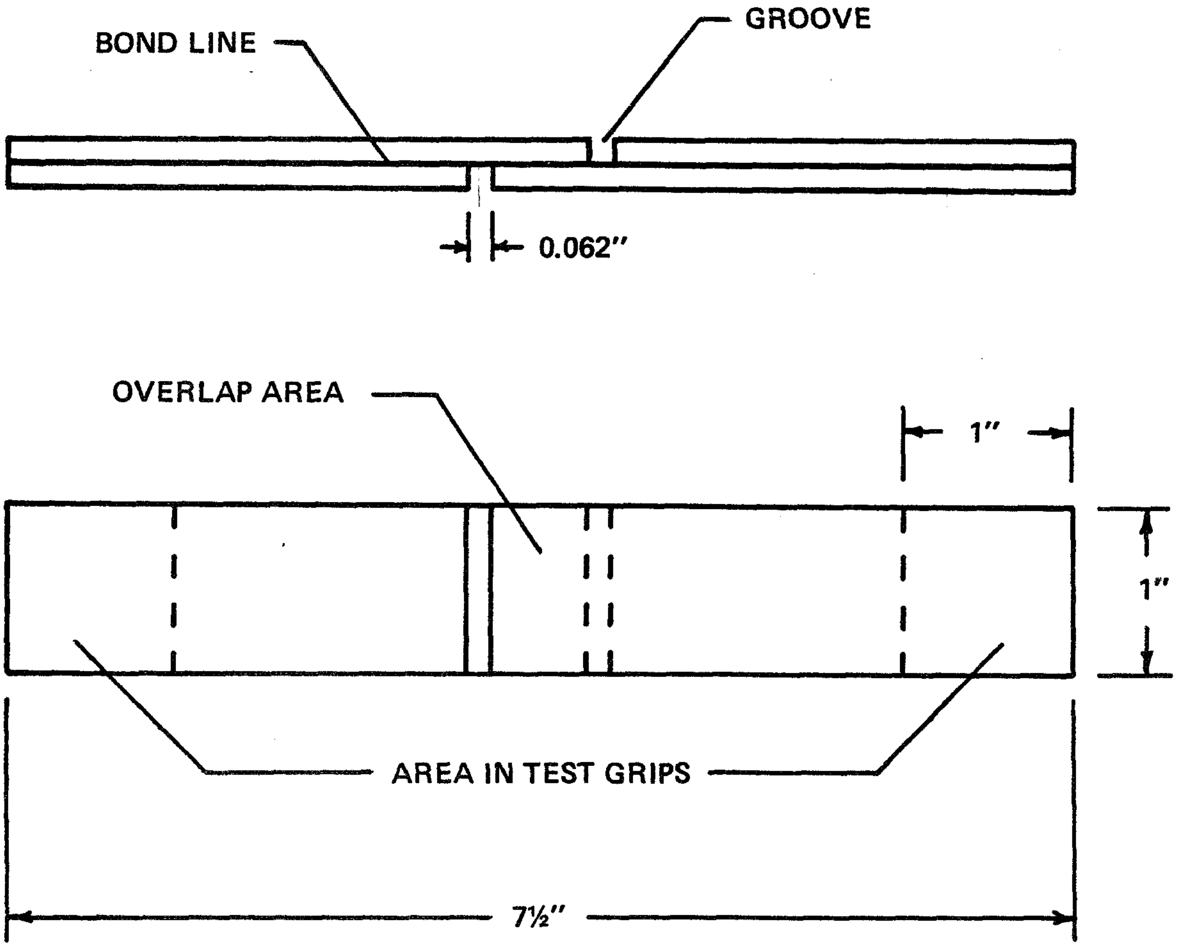


FIG. 5. LAP-SHEAR TEST SPECIMEN.

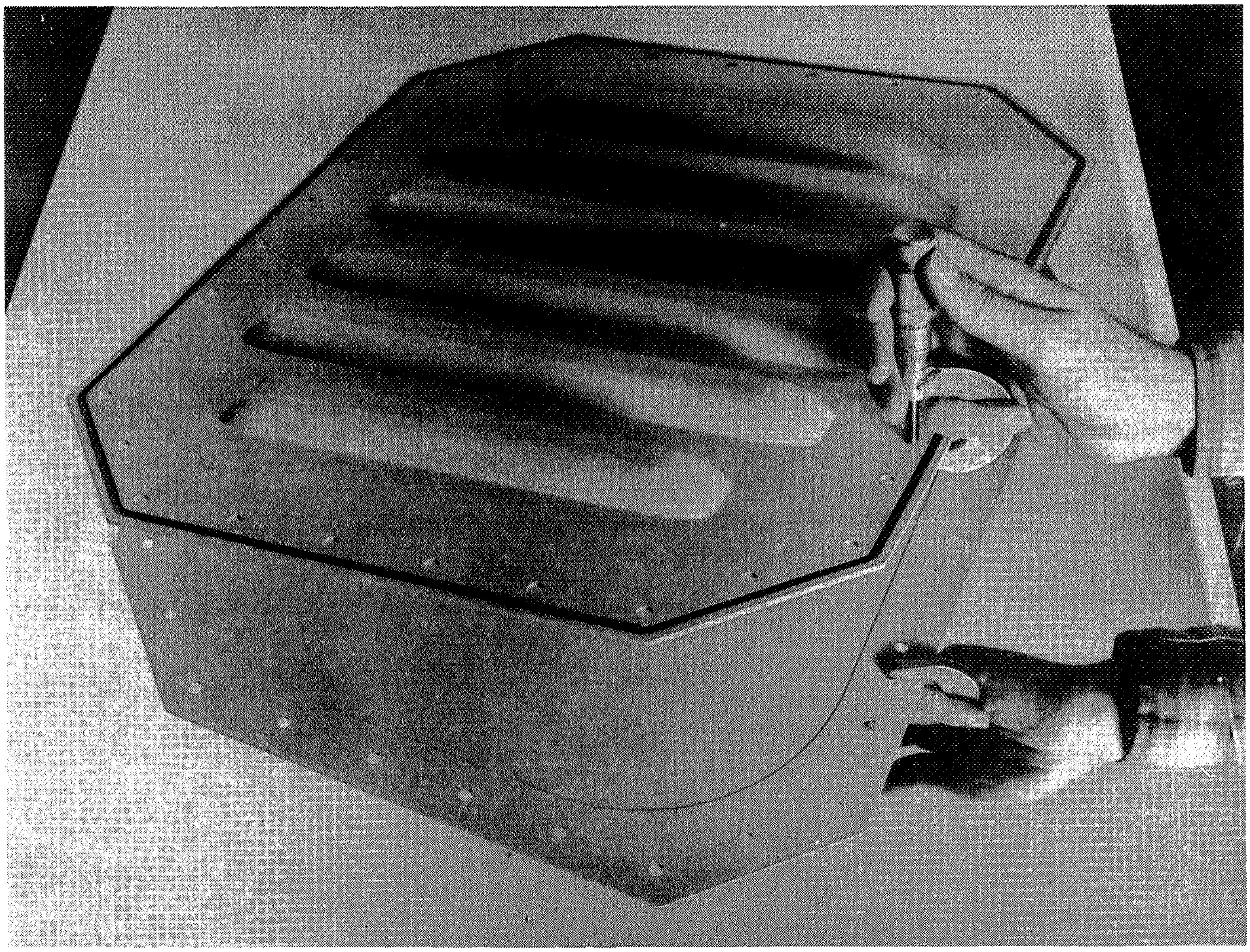


FIG. 6. ROLL-BONDED ACCESS PANEL.