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16. Abstract

Weldable strain gages have shown excellent high temperature characteristics for supersonic cruise aircraft application. The spotwelding attachment method, however, has resulted in serious reductions in the fatigue life of titanium alloy (Ti-6Al-4V) fatigue specimens. The reduction is so severe that the use of weldable strain gages on operational aircraft must be prohibited.

The cause of the fatigue problem is thought to be a combination of the microstructure changes in the material caused by spotwelding and the presence of the flange of the strain gage. Brazing, plating, and plasma spraying were investigated as substitutes for spotwelding. The attachment of a flangeless gage by plasma spraying provided the most improvement in the fatigue life of the titanium.

Changes in the configuration of the flange were examined in an attempt to determine a favorable shape. Configurations that improved the fatigue characteristics had the adverse effect of not transferring strain efficiently to the strain sensor.

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INTRODUCTION

The measurement of loads with calibrated strain gages on supersonic aircraft is complicated by aerodynamic heating. Strain sensors on these aircraft must perform well at elevated temperatures if the strain gage data are to be valid. Weldable strain gages perform well at elevated temperatures (ref. 1). However, the fatigue life of the titanium alloys commonly used on supersonic aircraft is reduced when spotwelding is used to attach the strain gages (refs. 2 to 4). Because of this problem, unpublished laboratory studies (M. M. Lemcoe, O. L. Deel, H. E. Pattee, T. J. Roseberry, and G. R. Schaer, "Development of Methods for Attaching Weldable Strain Gages to Titanium and Rene 41," Battelle Columbus Laboratories, Mar. 1974; and M. M. Lemcoe and H. E. Pattee, "Refinement of Methods for Attaching Weldable Strain Gages to Titanium," Battelle Columbus Laboratories, Dec. 1975) were made to gain an understanding of what caused the fatigue life sensitivity and to determine whether another method of metal-to-metal bonding could be developed that did not cause such a severe fatigue problem. This paper presents selective information basic to strain gage and fatigue technology.

SPOTWELDING ATTACHMENT METHOD

Strain Gage Description

A typical weldable strain gage (fig. 1) has a tube containing a strain element and flanges on both sides of the tube to transfer strain from the aircraft's structure to the sensing element. The gage is attached to the aircraft structure by spot welds along the flanges. When attached, the strain gage becomes an integral part of the structure and undergoes the same strain as the structure.

Fatigue Test Results

In the tests reported in references 2 to 4, spotwelding was used to attach strain gages to fatigue specimens of titanium alloy Ti-6Al-4V (fig. 2). The subsequent fatigue tests showed the fatigue life of the titanium to be reduced so severely as to preclude the use of this strain gage attachment method on aircraft.

It was observed during the Battelle Columbus Laboratories' fatigue tests that the first fatigue cracks occurred near or at the ends of the strain gage flanges, as depicted in figure 3. The consistency with which the first failure occurred near the ends of the gage flange suggests that the flange causes a stress concentration that contributes to the premature failure of the specimens. An investigation was initiated to determine the ways in which the flange might be modified to reduce this stress concentration.

Another factor in the failure of the fatigue specimens that must be considered is that a spot weld on the surface of a metallic matrix results in a discontinuity which may be described as a stress raiser. Figure 4 shows that this type of discontinuity is caused by the local melting of the material beneath and around the spot weld. This change in the microstructure of the base material causes a stress concentration that plays a role in the premature failure of the fatigue specimen.

Another factor that must be considered is the degree to which the spot welds interact to concentrate stress at a discrete point. Since the interaction depends partly on the spotweld configuration, and there are many spotweld arrangements, the investigation of this factor is quite complex.

In order to address the total fatigue problem it is necessary to determine the role of each of these factors in the failure of the specimen.

Tab Test Results

A set of tests was run to investigate the relative importance of these factors. A single small tab was attached to each of several fatigue specimens, using a single spot weld as the attachment mechanism. This provided a situation in which no gage flange loads, constraints, or other spot welds were present on the specimen. The resulting data therefore revealed the fatigue life degradation due to the changes in the microstructure of the base material resulting from the spot weld. As shown in figure 5, the spot weld alone caused a significant reduction in the fatigue life of the titanium specimens. The figure also shows the fatigue life of titanium specimens to which strain gages were attached. The data show that, in combination, the spotweld interactions and the other effects of the presence of the flange significantly reduced fatigue life.

These data revealed that no single factor was responsible for most of the fatigue life degradation. Therefore, any of the following approaches might be used in an effort to improve fatigue life: using a flange of a different shape, rearranging the pattern of the spot welds on the flange, and using a method other than spotwelding to attach the strain gage to the titanium. Each of these approaches was investigated.

Flange Configuration Test Results

In an effort to learn the effects of the flange shape and the arrangement of the spot welds on the fatigue life of the titanium, strain gages with various flange shapes and spotweld arrangements were constructed and attached to Ti-6Al-4V fatigue specimens. The test configurations are shown in figure 6. Accelerated (i.e. flexural) fatigue tests were used so the effects of the configuration changes could be determined more quickly. All tests were conducted at the same stress level to make the results comparable. The results of the tests are documented in table 1. The effects of flange shape and spotweld arrangement were not obvious from these data. However, when the number of spot welds was plotted against the number of cycles to failure, a trend did appear. As shown in figure 7, configurations with many spot welds tended to fail slightly earlier than configurations with only a few spot welds.

This trend is not without explanation. Configurations with many spot welds are more rigidly attached than those with fewer spot welds. The more rigid attachment causes larger stress concentrations.

There is another factor to be considered. If there were no spot welds, the fatigue problem would not exist, but no strain would be transferred to the strain sensor. Therefore, in evaluating a strain gage attachment method, the amount of strain transferred from the specimen to the strain tube must be considered in addition to the installation's fatigue characteristics. The effectiveness of strain transfer can be measured by using a strain transfer factor defined as follows:

$$\text{Strain transfer factor} = \frac{\text{Strain at middle of strain tube}}{\text{Strain in the specimen}}$$

Strain transfer factors were determined for the configurations shown in figure 8. The first configurations tested are shown on the left (an adhesive-bonded gage was tested to provide a standard for comparison). Modifications were made on the basis of the test results, and several of the resulting strain gages (strain gages 1, 2, 5, 6, 9, 10, 21, and 25) were tested. Flange shapes like those for strain gages 2 and 5 resulted in generally lower strain transfer factors in both test groups. The highest strain transfer factors resulted from rectangular flanges with many spot welds, but these configurations also resulted in the poor fatigue performance of the base material. Thus, in this study no way was found to combine good fatigue life with high strain transfer for the spotwelding attachment method.

BRAZING, PLATING, AND PLASMA SPRAYING ATTACHMENT METHODS

Attachment Method Description

Three alternative methods of attaching strain gages to titanium were explored: brazing, plating, and plasma spraying. All three methods involve metal-to-metal bonding. The evaluation of nonmetallic attachment methods such as glue was beyond the scope of this effort.

Extensive efforts were made to develop and evaluate the integrity of the three attachment methods. Many techniques for preparing the surface of the titanium for strain gage attachment were investigated. These preparation methods involved cleaning solutions, solutions for oxide removal, and abrasion.

The brazing attachment method includes such techniques as resistance brazing, hot gas brazing, and furnace brazing. Numerous filler materials were tested, and the overall performance of the bond was evaluated by pull (lap shear) tests, bend tests, peel tests, and photomicrographs of the joint. The most promising approach involved brazing a weldable gage with a Ti-6Al-4V foil flange 0.051 millimeter (0.002 inch) thick to the Ti-6Al-4V parent structure (which was nominally 1.57 mm (1/16 in.) thick) with an Al-12Si filler material that was 0.0254 millimeter (0.001 inch) thick. The braze joints were produced at a temperature of 880.37 K (1125 °F), in a brazing time of 15 minutes, and in a vacuum.

In the plating approach, a nickel coating is brush plated on the Ti-6Al-4V material. The flange is perforated by electrical discharge machining and placed upon this nickel coating. A bath of the plating solution is placed around the flange, and a nickel coating is then electrodeposited over the flange and in the perforations. Figure 9 shows a gage to which this has been done.

Figure 9 also shows the results of a pull test made to evaluate the strength of the bond. In the pull test, the strain tube and flange were cut with a saw, and the extending piece of the gage was pulled. As a result the strain gage pulled apart in the middle. This resulted from a shear failure of the flange in the area between the perforations and the strain tube. This type of failure indicates that the static bond is very strong; the gage itself failed before the bond.

Plasma spraying was selected instead of flame spraying because it produced a somewhat stronger bond and because it resulted in fewer contaminants. It was found that flanges were unnecessary with plasma spraying; it was possible to attach only the strain tube itself. Several strain tube configuration changes were investigated, including indentations, which produced strain tubes like those that are embedded in concrete (fig. 10); electrodeposited annular projections, which resulted in deformations like those on concrete reinforcing bars; and roughening, which was produced by depositing a nickel aluminide coating on the grit-blasted surface of the strain tube. The strain tubes were then plasma sprayed to the Ti-6Al-4V parent material. A commercially available powder was used to embed the tube.

More detailed descriptions of the installations and evaluations are given in the Battelle Columbus Laboratory reports.

The only criteria used in the development of these bonding procedures were static test results (the results of such tests as pull (lap shear) tests, peel tests, and bend tests). It was revealed in the Battelle Columbus Laboratory study that good performance in static strength tests did not necessarily imply good performance in fatigue tests.

Fatigue Test Results

These brazing, plating, and plasma spraying attachment methods were used to attach strain gages to Ti-6Al-4V specimens, and the specimens were subjected to fatigue tests. The results are shown in figure 11. The plating approach offered little improvement in fatigue life. Brazing the gages to the Ti-6Al-4V material proved to be better than plating; it improved the specimens' fatigue life by as much as a factor of 10 over the spotwelded installations. Clearly, however, the best method of installation is plasma spraying. The fatigue life of specimens with plasma sprayed strain gages was as much as 100 times longer than specimens with spotwelded strain gages.

A typical installation of a strain gage that was attached by using plasma spraying is shown in figure 12. The best fatigue performance was achieved by plasma spraying a strain tube without flanges to the base material. A cross sectional view of the installation (fig. 13) shows that the material plasma sprayed becomes built up beneath and around the strain tube.

CONCLUDING REMARKS

Spotwelding strain gages to titanium alloy Ti-6Al-4V results in a fatigue life degradation of the titanium so severe that it rules out the use of this attachment method for aircraft. The reduction in fatigue life of the titanium results from changes in the microstructure of the titanium at the spot welds and from local stress concentrations due to the presence of the strain gage and its flange. A third possible factor is the interaction due to the close proximity of numerous spot welds.

A set of fatigue tests with various strain gage flange configurations revealed that although fatigue life could be slightly improved by reducing the number of spot welds, this also reduced the strain transfer factor. Altering either the strain gage configuration or the spotweld arrangement failed to provide a solution to the basic fatigue problem.

Therefore, three new methods of attaching the same type of strain gage without spotwelding were studied—brazing, plating, and plasma spraying. Plating improved fatigue life very little. Brazing improved fatigue life by as much as a factor of 10. Plasma spraying improved fatigue life by as much as a factor of 100.

It was discovered that even though the results of static tests such as pull tests, peel tests, and bend tests were favorable, good fatigue life did not necessarily correlate with good static strength.

Dryden Flight Research Center
National Aeronautics and Space Administration
Edwards, Calif., November 18, 1976

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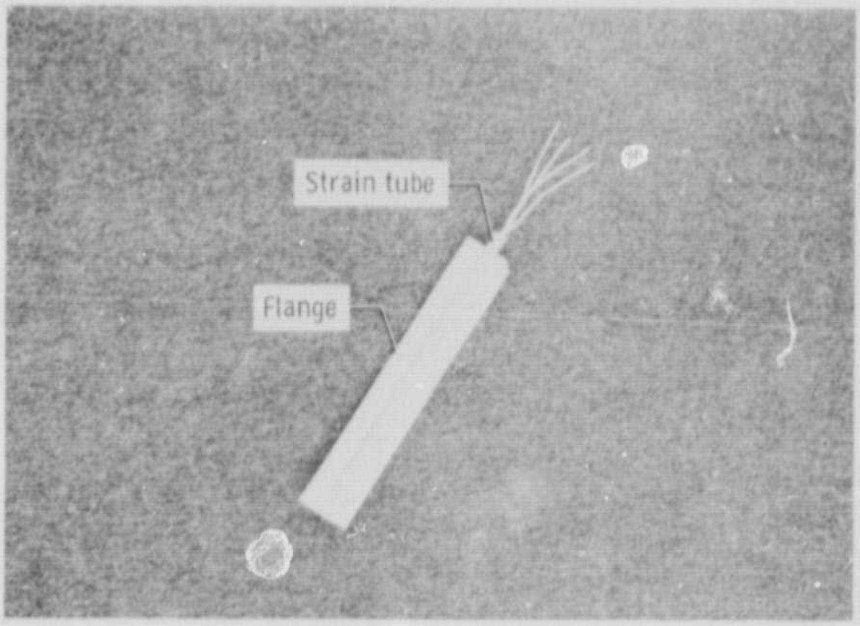
TABLE 1.—ACCELERATED FATIGUE TEST DATA OBTAINED FOR FLANGE CONFIGURATION VARIATIONS

Specimen	Number of cycles to failure
1	53,300
2	57,600
3	76,600
4	105,700
5	67,700
6	50,900
7	97,900
8	126,400
9	71,400
10	72,800
11	[a]229,800; 315,000
12	[a]109,900; 106,200
13	56,800
14	54,700
15	4,166,600
16	69,000
17	87,100
18	10,412,100
19	[a]237,100; 310,500
20	91,000
21	100,100
22	[a]262,900; 298,200
23	[a]331,800; 320,200
24	84,700
25	101,400
26	324,000
27	196,600

[a]Two specimens were tested.



E-30567

Figure 1. Weldable strain gage.

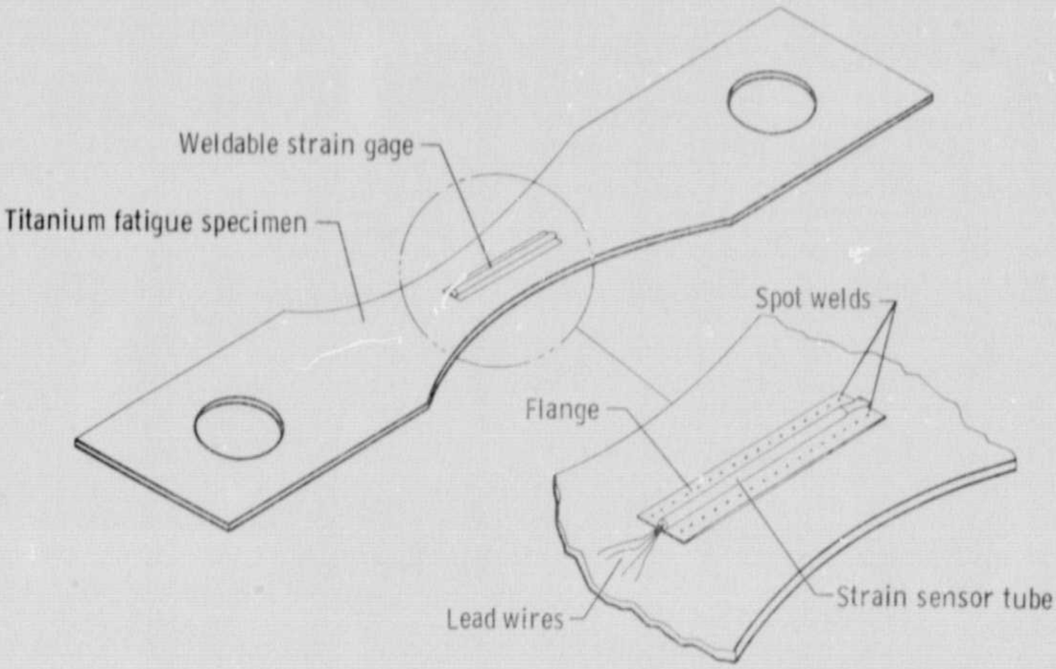


Figure 2. Strain gage spot welded to Ti-6Al-4V fatigue specimen.

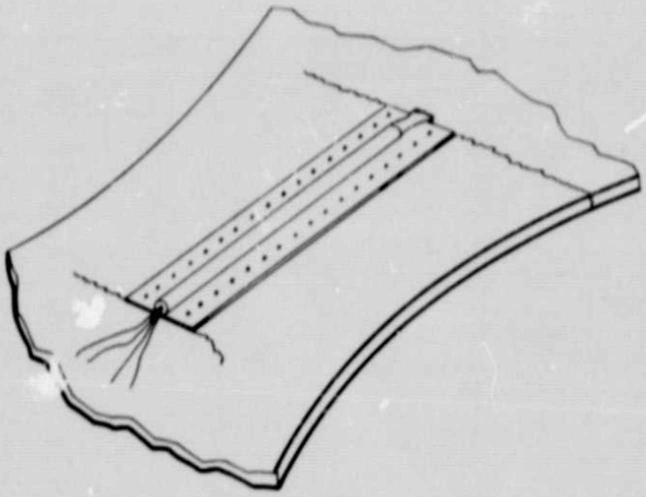
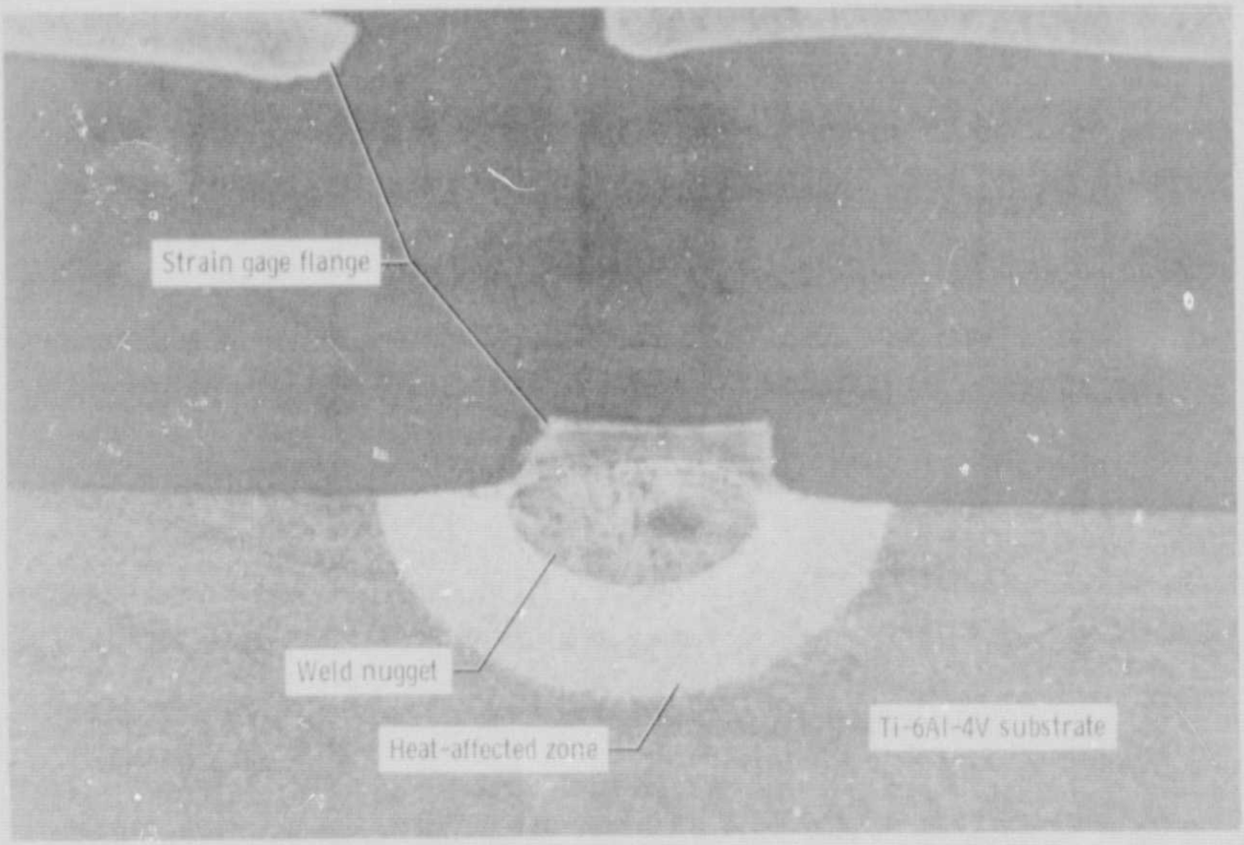


Figure 3. Fatigue cracks in specimen near ends of flange.



E-31063

Figure 4. Photomicrograph of strain gage flange spot weld. Substrate is Ti-6Al-4V.

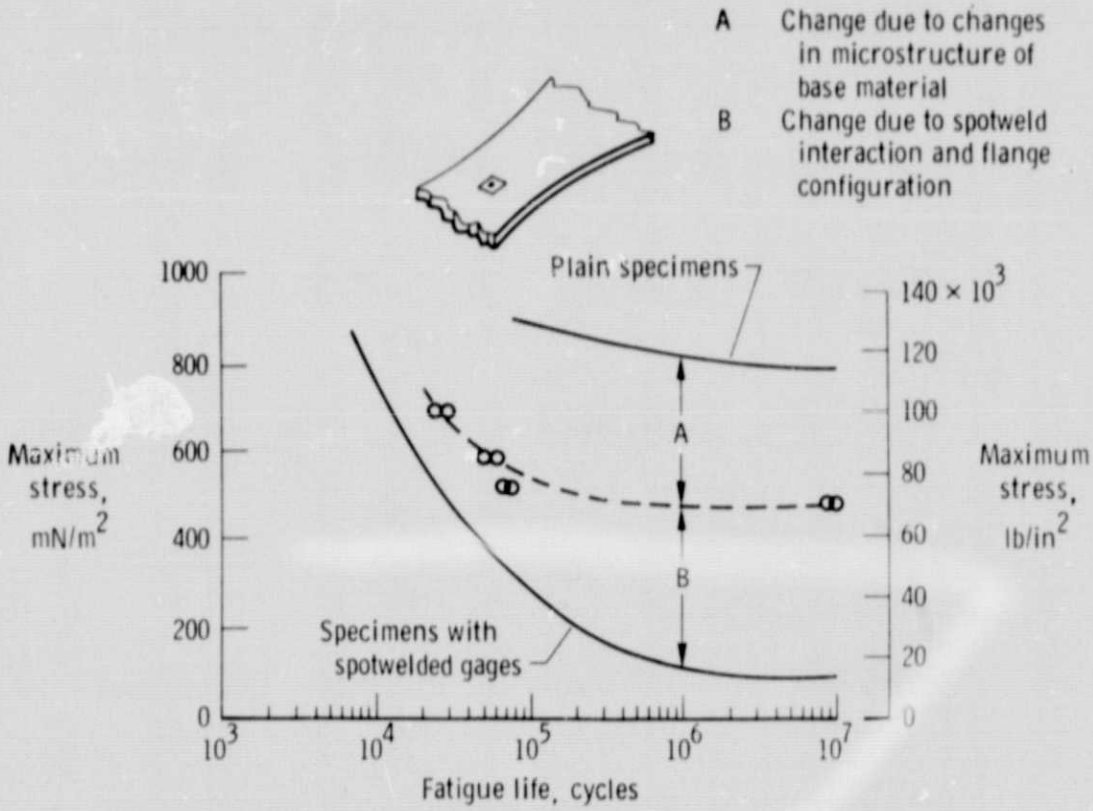


Figure 5. Constant-amplitude fatigue data showing effect of single spot weld on Ti-6Al-4V.

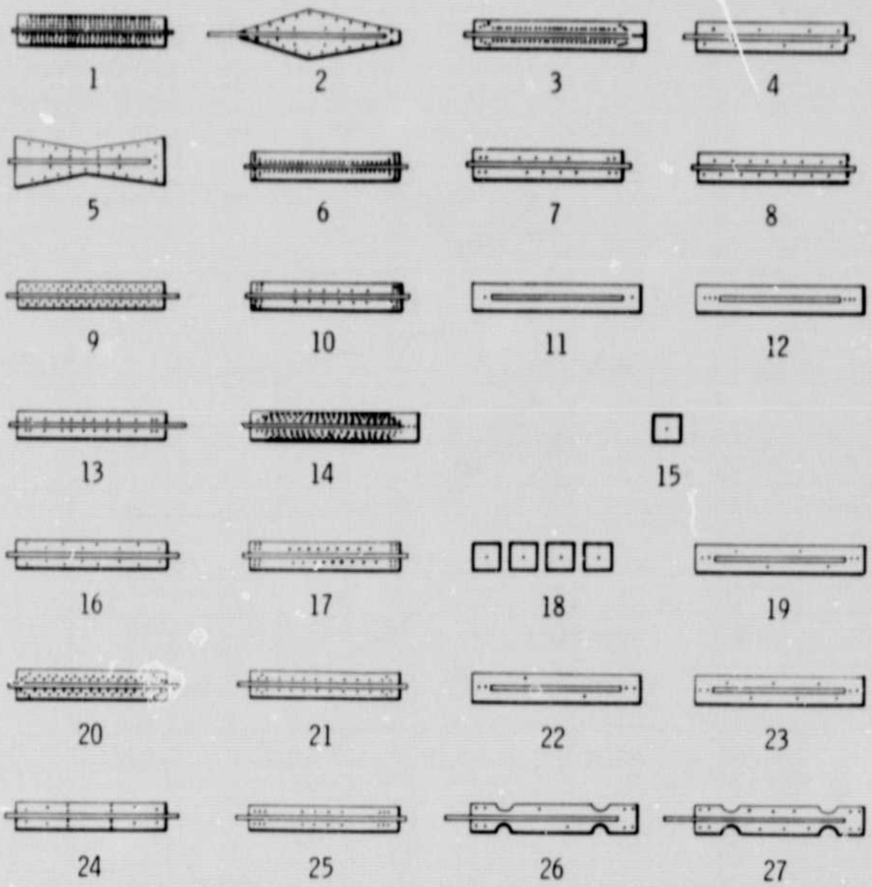


Figure 6. Variations in strain gage flange and spotwelding configurations.

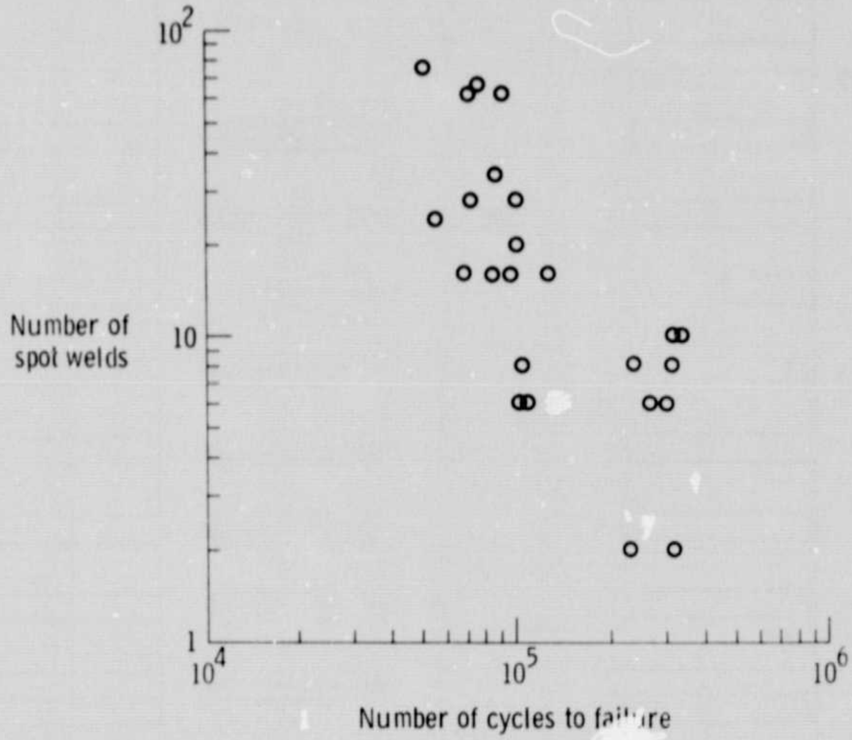


Figure 7. Relationship between number of spot welds and Ti-6Al-4V specimen fatigue life.

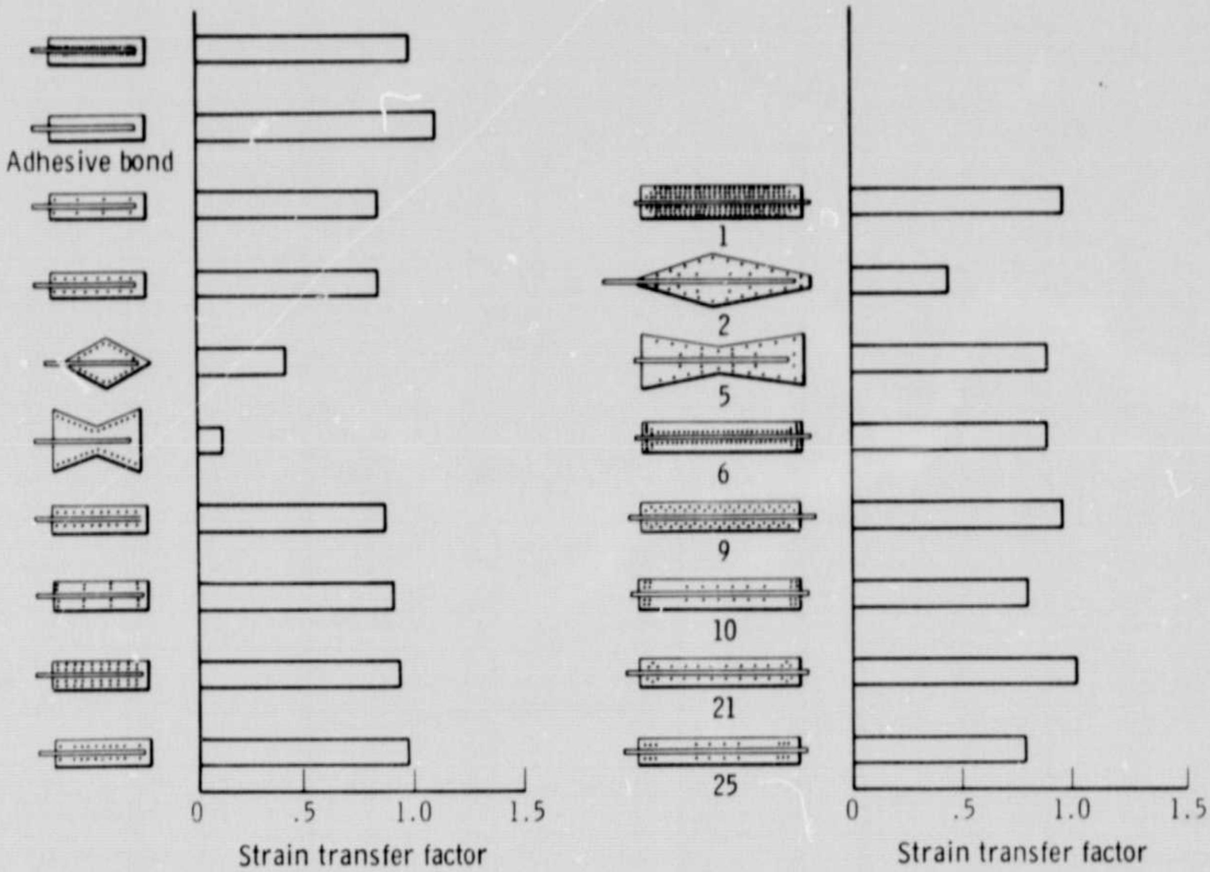


Figure 8. Strain transfer factors for various flange configurations.

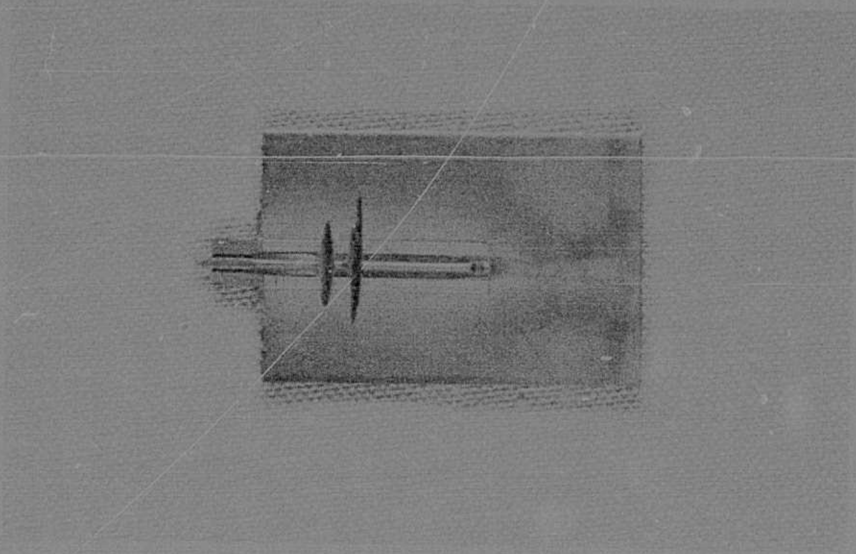


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Figure 9. Strain gage installation attached by flange plating and subjected to pull test.

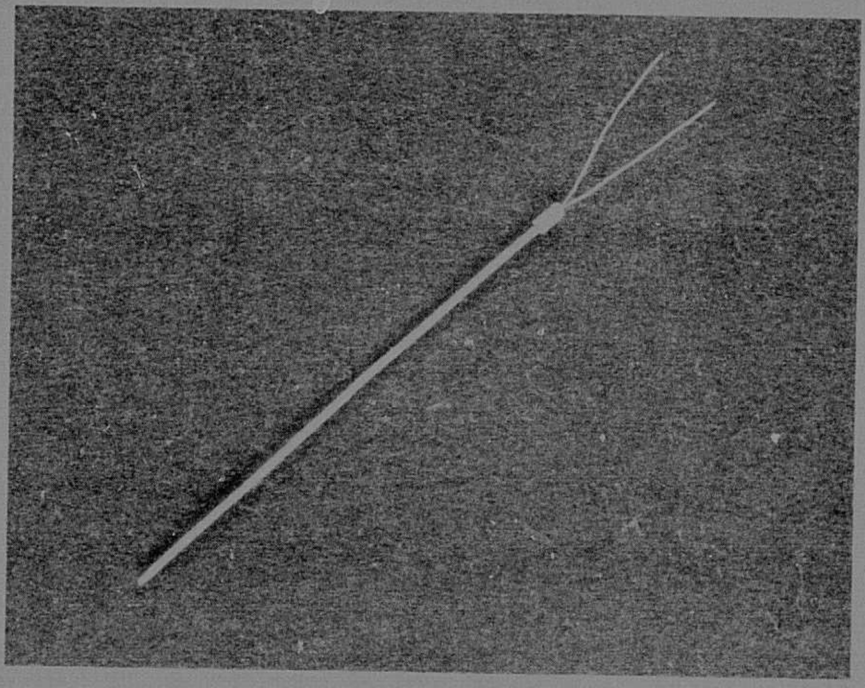

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Figure 10. Strain gage with indented strain tube.

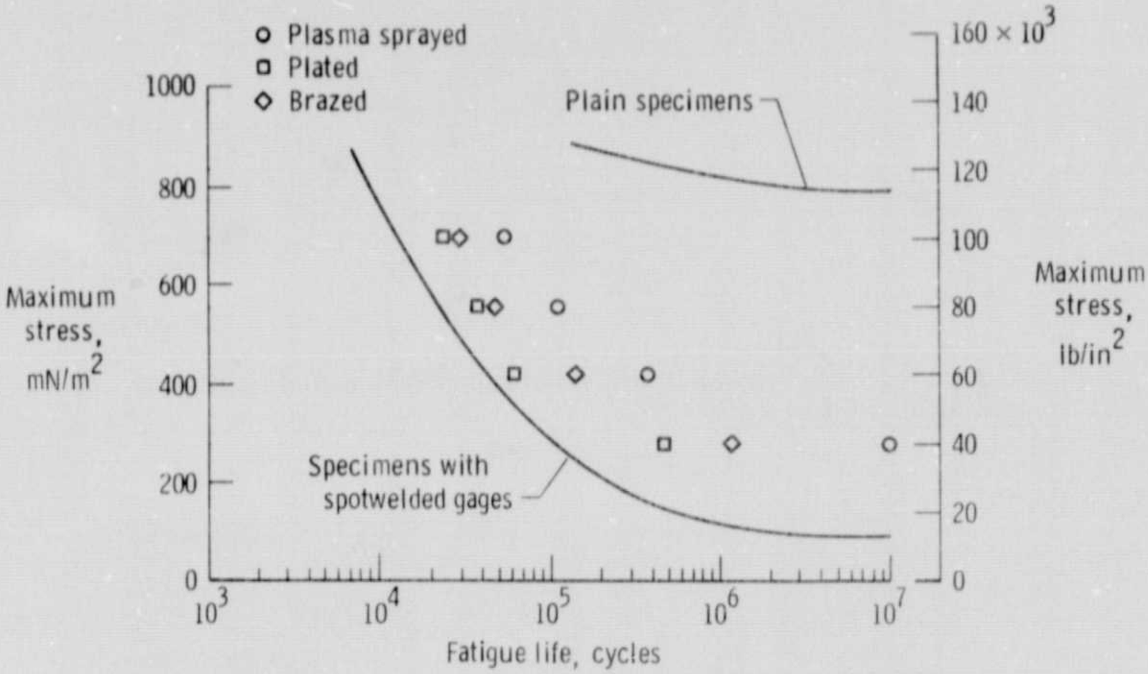

Figure 11. Constant-amplitude fatigue data showing improvement resulting from plasma spraying, plating, and brazing strain gages to Ti-6Al-4V.

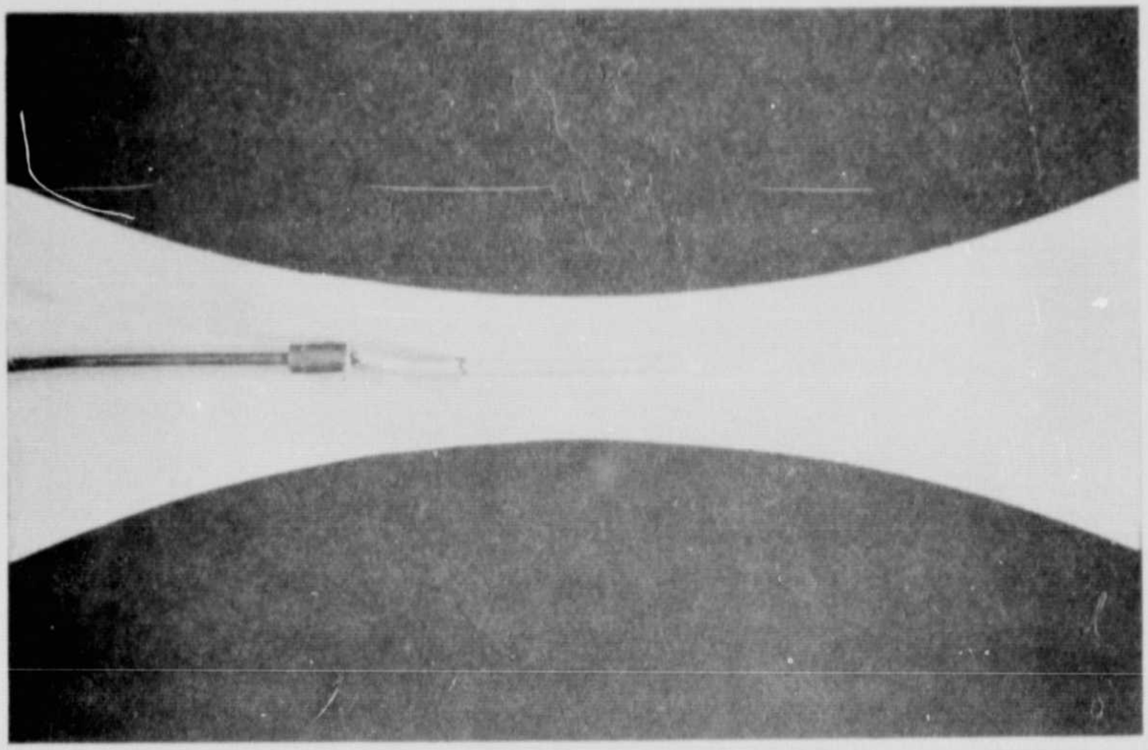

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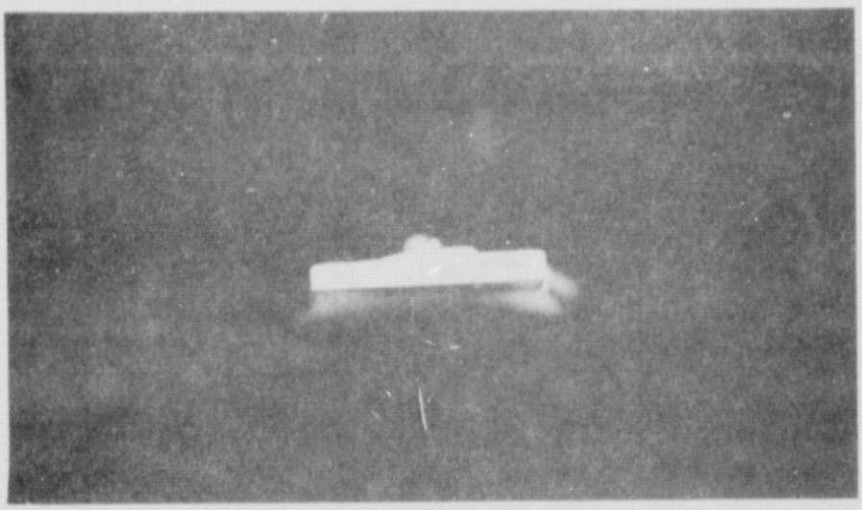
Figure 12. Weldable strain gage plasma sprayed to Ti-6Al-4V fatigue specimen.



E-30572

Figure 13. Cross section of weldable strain gage plasma sprayed to titanium fatigue specimen.