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High Fatigue Life Results from Titanium Spot Welding Innovations

Procedures are outlined to produce spot welds with a fatigue life greater than the fatigue life of conventional spot welds

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ABSTRACT. This paper is the result of an investigation into the cause of low fatigue life in titanium spot welds. From collected data, a process has been developed by which spot welds with a high fatigue life can be produced—spot welds with a fatigue life that is comparable with that of fatigue-resistant rivets. The causes of low fatigue life are attributed to:

1. A mechanical notch at the perimeter of the nugget.
2. Degradation of the metallurgical structure at the periphery of the nugget.
3. Residual stresses at the periphery of the nugget.
4. Metallurgical discontinuities across the nugget.
5. Surface stress concentration.

Premature fatigue failure, with cyclic loading, occurs because the first three discontinuities mentioned are coincident at the periphery of the nugget. The use of accepted practices for producing conventional welds causes these discontinuities. The present standards for accepting conventional weld would be cause for rejecting high fatigue life spot welds.

With only a moderate tooling and facilities investment, the preweld and postweld treatments selected to produce high fatigue life spot welds can be implemented for production welding applications. The cost savings, and weight reduction, to be gained in replacing mechanical fasteners with resistance spot welding in aircraft component assembly, will substantially exceed the cost of implementation.

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Introduction

The resistance welding of structural and nonstructural aircraft components has decreased approximately 80% in the last 20 years. This decrease is primarily due to the unsatisfactory fatigue life of the weld, and is compounded by the increased fatigue life requirements of present-day aircraft structures.

Many research programs have been conducted in the past 10 years to determine the cause of low fatigue life of resistance welds and how to correct them. However, no previous work has successfully concluded with a process suitable for production resistance welding.

Because of the inherent economics and weight savings to be gained by replacing presently used mechanical fasteners, resistance spot welding is regarded as a highly desirable process for joining aircraft hardware.

Concern about the low fatigue life of resistance spot welds in titanium prompted the Manufacturing Research and Development organization at The Boeing Company to conduct an engineering study to determine the causes of low fatigue life, and to develop a process to increase fatigue life to equal that of fatigue-resistant rivets. Accordingly, this paper covers the preweld, and postweld treatments that were developed to overcome the inherent problems causing the low fatigue life of resistance spot welds.

Analysis of a Resistance Spot Weld

The work in this paper was concentrated on spot welds because they constitute 80% of the production resistance welding of aircraft hardware. From a literature survey and an analysis of fatigue data, it is concluded that low fatigue life of spot welds is caused by five types of discontinuities:

1. A mechanical notch at the periphery of the nugget.
2. Degradation of the metallurgical

Table 1—Treatments or Effect of Process Changes on Fatigue Life Compared to a Conventional Spot Weld

Treatment or effect of process changes	Effect on fatigue life		
	Increase	No effect	Decrease
Small equiax grain structure	X		
Diffusion grain structure	X		
Hole in coupons before welding	X		
Hole in center of electrode face	X		
Preheat interval	X		
Increased electrode radius	X		
Increased nugget diameter	X		
Coining	X		
Shot peening	X		
Columnar grain structure			X
Temper heat			X
Elongated electrodes			X
Less impulses			X
Cycle forge			X
External clamp ring			X
Large equiax grain structure		X	
Foil interface		X	
Increase impulses		X	
Stress relieve 1250°/hr		X	
Beta anneal		X	
Hole drilled after welding		X	

structure at the periphery of the nugget (commonly called heat-affected zone).

3. A concentration of residual stresses at the periphery of the nugget.

4. Metallurgical discontinuities across the nugget.

5. Surface stress concentration.

Premature fatigue failure of spot welds is a result of the first three of these discontinuities falling at the periphery of the nugget; this results in a structure with low resistance to cyclic stresses.

A review of basic metallurgy indicates that low fatigue failure of metal can be caused by: stress concentration, corrosion, temperature overload, metallurgical structure, and residual stresses combined with applied stresses. Fatigue studies indicate that the following surface conditions can be related to low fatigue life:

1. Surface roughness (stress risers).

2. Low notch strength of the surface layer.

3. Residual stresses in the surface layer.

Fatigue life of a metal is substantially increased when the surface stresses are compressive rather than tensile.

The conventional method of making a resistance spot weld inherently produces most of the discontinuities known to cause low fatigue life in metal. The metal is held between two electrodes and heated rapidly by passing a high current through a resistance, which causes the metal to expand (with no space provided for the expansion); the metal is then rapidly quenched, causing shrinkage. The melting, which causes a change in structure (from wrought to cast), creates a metallurgical discontinuity. The high temperature gradient, which causes localized expansion and subsequent shrinkage from the rapid quenching, causes internal tensile stresses that are proportional to the temperature gradient that existed when the cast structure was formed. The mechanical notch caused by the formation of the nugget is increased, because the expanding metal tries to extrude at the interface.

From this analysis it is provable that fatigue life could be improved by developing treatments that would reduce or minimize the mechanical notch, the residual stresses and the metallurgical discontinuities.

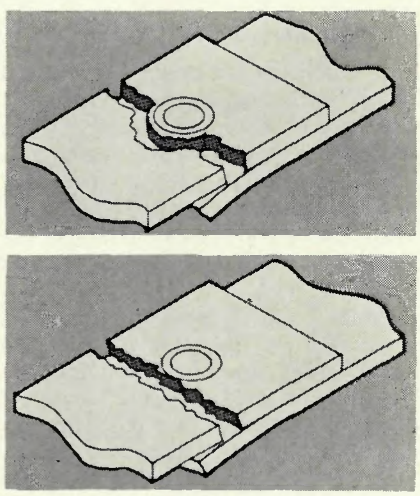

Fig. 2—Typical resistance spot weld fatigue failures. A (top)—conventional weld; B (bottom)—high fatigue weld

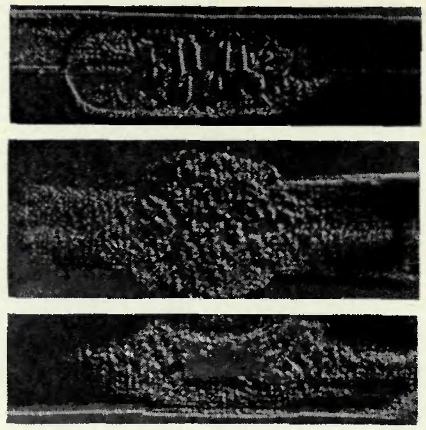

Fig. 1—Resistance spot weld macro sections: A (top)—conventional weld; B (center)—as-welded high fatigue spot weld; C (bottom)—high fatigue spot weld with postweld treatment

The methods available to control or eliminate undesirable discontinuities are:

1. Preheat to minimize the high temperature gradient and stress concentration.

2. Control the energy density which in turn controls the micro structure.

3. Provide for expansion of the metal during welding.

4. Reverse the internal stresses by mechanical cold-work after welding.

5. Apply compressive stresses at the surface of the material, by mechanical means such as shot peening or cold rolling.

The treatments devised to eliminate the inherent discontinuities of a spot weld and their effects on fatigue life are covered in the following sections.

Material

The material used in this study was 0.090 in. thick 6Al-4V titanium (condition 5). This thickness was selected so that direct correlation could be made with previous fatigue data on fatigue-resistant titanium rivets.

Equipment and Tooling

The equipment used for this study was a 400 kva frequency converter spot welding machine. The welding control was arranged for seven heat intervals, with seven phase-shift controls of three heat-and-cool times, three force levels, and a cyclic forge control. The flexibility of this control made it possible to study the effects of many combinations of preheat, weld heat, temper heat, and force variations during the weld sequence.

Tooling was made for drilling, and welding a 1 in. wide, two-spot overlap fatigue coupon, with a 1 in. center-to-center spot spacing. The tooling was designed to hold close tolerances on centerline of spots, centerline of coupons, and spot spacing. This fatigue specimen was identical to those used for rivet fatigue studies.

Tension-tension fatigue tests were made on a SF-10-V fatigue testing machine at a speed of 1800 cycles/min, with a minimum to maximum stress ratio of 0.06. The coining was done cold in a tensile machine, with

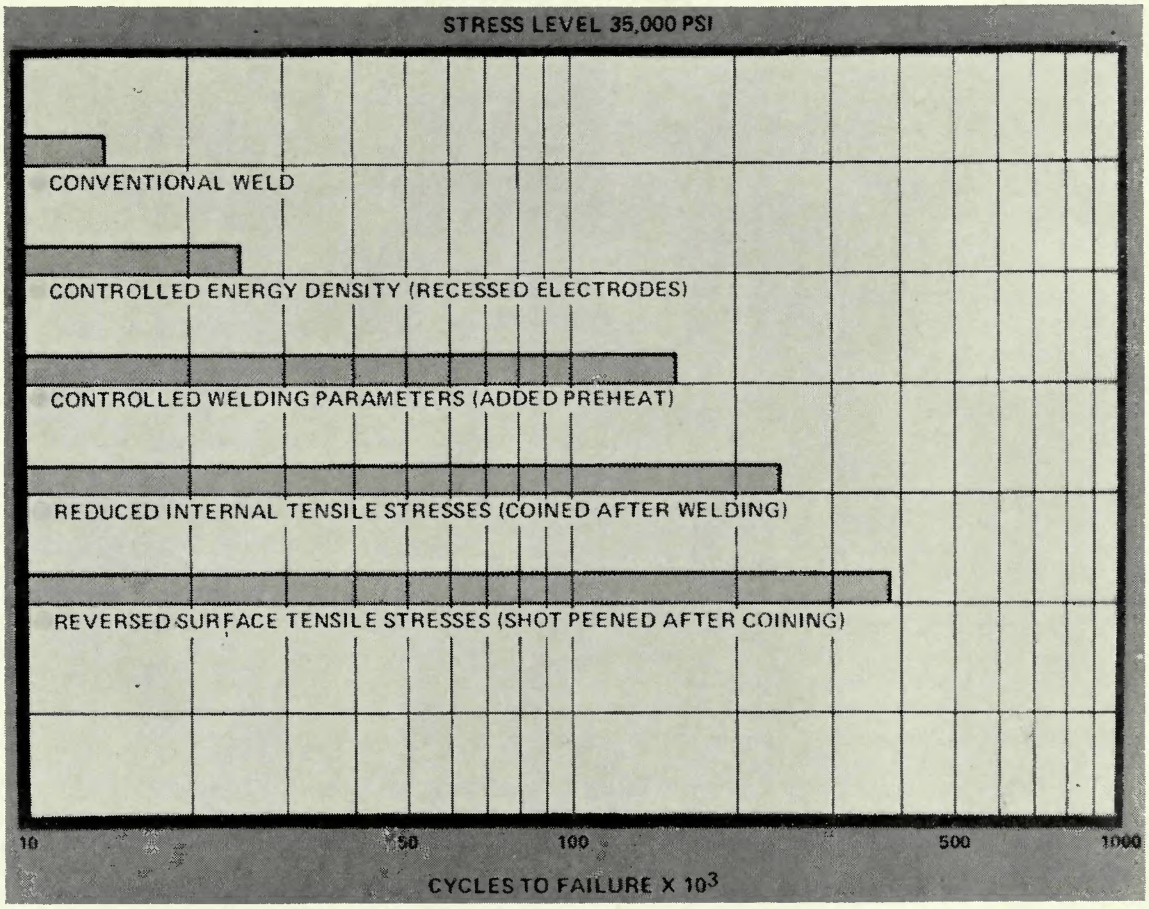

Fig. 3—Fatigue life spot welds

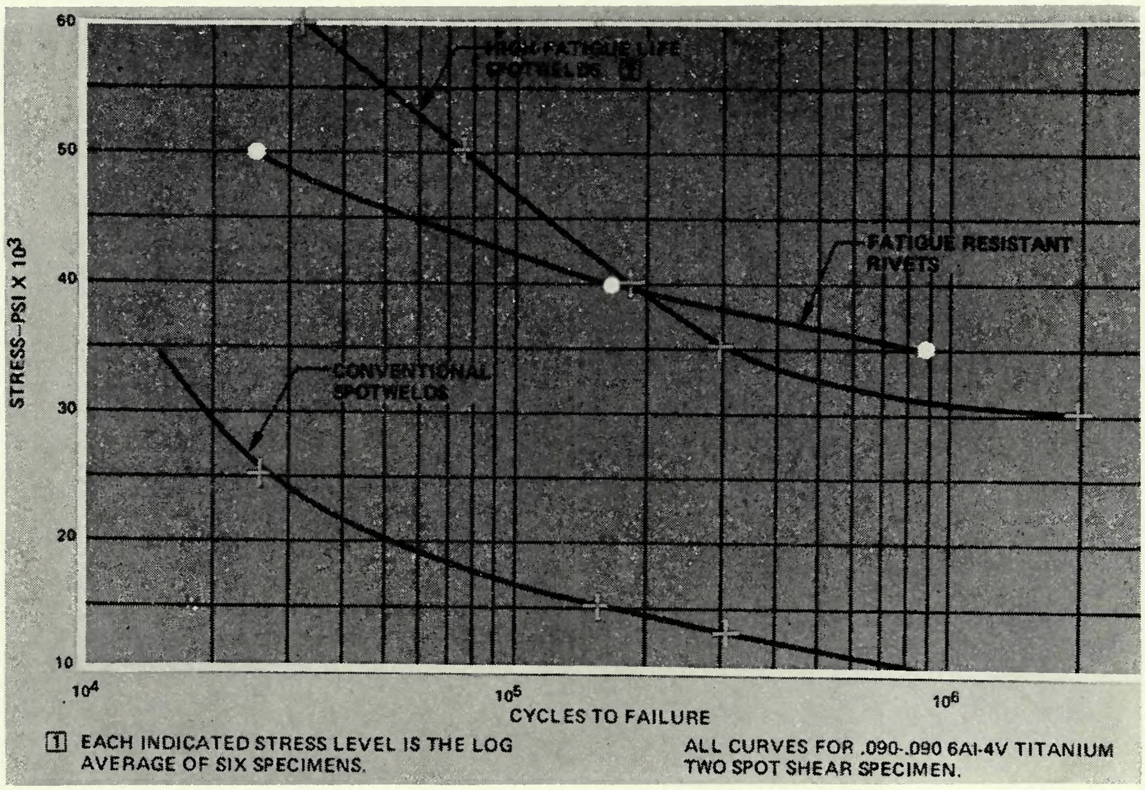

Fig. 4—S-N curves for spot welds vs. rivets

two heat-treated punches, and a locating fixture; the punches were 2 in. long, 1 in. diameter tool steel, with a 10 in. spherical radius machined on the face. The shot peening was done on conventional production equipment of the pneumatic or centrifugal type.

Testing and Results

Over 300 fatigue specimens were tested to determine the effects of preweld, weld, and postweld treatments. A summary of the treatments and their effect on fatigue life compared to the original conventional weld is compiled in Table 1.

The various treatments selected for fatigue testing were devised to reduce or change the location of the discontinuities falling at the periphery of the nugget. It was found that metallurgical discontinuities could be reduced by reducing the weld current density. This was accomplished by increasing the weld force, increasing the electrode radius, and drilling a hole in the center of the electrode. The severity of the mechanical notch was decreased by the hole in the electrode; this caused less sheet separation. Reduction of the internal tensile stresses during weld formation was accomplished with the addition of preheat to reduce the thermal gradient, and the hole in the electrode to provide room for expansion during weld nugget formation. Degradation of the structure at the periphery of the nugget was minimized with preheat and lower current density during weld formation, both of which reduced the temperature gradient.

Two postweld treatments were found to be most effective. These were (1) coining to reverse the internal tensile stresses to compressive stresses and (2) shot peening to create surface compressive stresses.

An attempt was made to determine the percentage increase in the fatigue life for the improvement of each discontinuity, thereby determining which discontinuity had the greatest effect on low fatigue life. The following values are relative, because some of the treatments affected more than one discontinuity.

Discontinuity	*Yielded by improvement Increase in fatigue life %*
Metallurgical continuity	5
Mechanical notch	28
Internal tensile stresses	21
Peripheral metallurgical structure	8
Surface tensile stresses	38

It became evident during this program that, when internal stresses increased during welding, the fatigue life decreased and the postweld treatments were less effective.

Figure 1 shows the cross sections of a conventional weld, a high fatigue life spot weld as welded, and a high fatigue life spot weld after coining. You will note that the high fatigue life spot welds have equiaxed structures, and less sheet separation.

Figure 2 shows failed fatigue specimens of a conventional weld, and of a high fatigue life weld. It will be noted that both the location and the shape of the fracture are different in each type weld.

Figure 3 shows the improvement in each treatment as it was sequentially added to the process. In this sequence, the addition of preheat yielded the greatest increase in fatigue life.

Figure 4 is a S-N curve showing the fatigue life of conventional spot welds, fatigue resistant rivets, and high fatigue life spot welds in 0.090-in. 6Al-4V titanium. It will be noted that, above 40,000 psi, the fatigue life of spot welds exceeds that of rivets.

Conclusions

It is apparent from the work conducted on this program that low fatigue life of a conventional spot weld is a direct result of the equipment and procedures that have for many years been considered acceptable. It is possible, by using the process outlined in this paper, to produce spot welds in titanium that have a fatigue life nearly equal to that of fatigue-resistant rivets. There is a need for a means of predicting fatigue life without fatigue testing.

Increased use of resistance spot welding to replace presently used mechanical fasteners will result in substantial cost savings in the fabrication of airplane components.

University Research Conference

The University Research Committee of the Welding Research Council has arranged for a Conference in conjunction with the 51st Annual Meeting of the AMERICAN WELDING SOCIETY in Cleveland on *Monday afternoon, April 20, 1970, from 4:30 to 6:00 P.M. in the Cleveland Room, on the Main Floor, Sheraton-Cleveland Hotel, Cleveland, Ohio.*

Subject: RESEARCH IN PROGRESS

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A number of professors will discuss the latest details of their current projects under WRC sponsorship, without the necessity of preparing a formal paper.

This represents a departure from previous AWS Annual Meeting sessions in the spring where we used to have a dinner meeting and an evening conference.