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Endurance of titanium and titanium alloy structural elements subjected to simulated acoustic loading



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THE PREPARATION OF THIS DATA ITEM

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ENDURANCE OF TITANIUM AND TITANIUM ALLOY STRUCTURAL ELEMENTS SUBJECTED TO SIMULATED ACOUSTIC LOADING

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ENDURANCE OF TITANIUM AND TITANIUM ALLOY STRUCTURAL ELEMENTS SUBJECTED TO SIMULATED ACOUSTIC LOADING

1. NOTATION

a	fatigue strength exponent (Basquin exponent)		
b	$-1/a$		
K	constant (Equation (2.1))	MPa	lbf/in ² × 10 ³ (ksi)
K_{rms}	constant (Equation (2.2))	MPa	lbf/in ² × 10 ³ (ksi)
S_{rms}	root mean-squared value of stress at reference position	MPa	lbf/in ² × 10 ³ (ksi)
N	equivalent endurance (number of cycles to failure)		
R	ratio of minimum to maximum stress		

Abbreviations

ASTM	The American Society for Testing and Materials
C.P.	Commercially pure
SPF/DB	Superplastic forming and diffusion bonding
$S-N$	Stress – life
STA	Solution treated and aged

2. INTRODUCTION

This Item gives the results of fatigue tests on titanium and titanium alloy specimens, excited by narrow-band loading of random amplitude mostly with zero mean load in order to simulate the stress response to acoustic loading. The specimens, also called coupons, are small structural elements which are typical of those used in aircraft and space structures. The coupons are either simple cantilevers or built-up T-pieces. The specimens were vibrated until failure occurred. For a narrow band Gaussian process the number of upward zero crossings per unit time is nearly equal to the centre frequency of the process, thus the number of cycles to failure, or the equivalent endurance, is equal to the product of the centre frequency (in Hz) and the time to failure (in s) (Reference 18). The equation relating S_{rms} , the root mean-squared value of alternating stress, to N , the number of cycles to failure, is assumed to have a form similar to the Basquin equation

$$S_{rms} = K N^a, \quad (2.1)$$

where a is the fatigue strength exponent or the Basquin exponent and K is a constant. The aim of the tests was to produce plots of stress against number of cycles to failure in a logarithmic coordinate system, and to find a line which is best fitted to the data. The common logarithm of the stress is plotted against the common logarithm of the endurance and a straight line is fitted to data by the method of least squares. The slope of the line is a . The constant $K = S_{rms}(1)$ refers to the value of S_{rms} at 1 cycle. Although the $S-N$ line is obtained from coupon tests, the results could be used to predict the life of more realistic stiffened panel structures. Extrapolation of the lines beyond 10^8 cycles, where no data is available, is expected to lead to an underestimate of endurance. The Item was originally published as ESDU 73010 (see also Reference 6). Equation (2.1) can be presented in another form (Reference 18) as,

$$NS_{rms}^b = K_{rms}, \quad (2.2)$$

where exponent $b (= -1/a)$, as well as K_{rms} , are constants. The constants K and K_{rms} are related to each other as

$$K = K_{rms}^{-a}. \quad (2.3)$$

Failure is characterised by a decrease in the resonance frequency of the coupon and an increase in damping. Cracks are sometimes visible at failure. The stress is measured by a reference strain gauge or transducer, located approximately at a position where a crack is expected.

The materials used are commercially pure titanium, a titanium alloy with 2% copper and a titanium alloy with 6% aluminium and 4% vanadium. Additionally, results are available for titanium alloys which are suitable for aircraft in high speed flight (Reference 17). Further details of the materials are given in Section 5. In one series of tests superplastic forming and diffusion bonding was used in the preparation of the coupons. Some tests were carried out at elevated temperatures.

2.1 Statistical Analysis

Statistical analysis of the results has been carried out in accordance with the scheme outlined by the ASTM standard (Reference 16). In the analysis the number of cycles to failure, N , is regarded as the dependent variable and the stress, S_{rms} , as the independent variable. In the logarithmic coordinate system a straight line has been drawn through the data points using the method of least squares fit. Additionally, 95% confidence intervals have been estimated in terms of Student's t function, as described in standard texts, such as Reference 19. It is expected that 95% of the calculated intervals (for a large number of samples) will include the value of $N = (S_{rms}/K)^{1/a}$ at a specific value of S_{rms} . In other words, the statement can be made that for a given stress the number of cycles to failure lies within the obtained confidence interval and there is 95% probability that this statement is correct.

The use of the confidence intervals may be illustrated in relation to Figure 3, where the confidence intervals are shown by the dashed lines. It is expected that, for example, at a stress of 60 MPa, 95% of the calculated number of cycles to failure (for different samples) lies within the interval between 5×10^6 and 1.6×10^7 cycles.

3. DESCRIPTION OF COUPONS

The coupons with their dimensions are illustrated in Figures 1a to 1k. The positions of the monitoring transducers and strain gauges are indicated. Where possible, typical cracks are shown. The plain specimens are representative of sheet material away from the effects of attachments. The built-up coupons represent conditions in sheet material with attached stiffeners without jointing compounds, where adjacent plates are vibrating in phase.

3.1 Plain Cantilever Coupons (Ti-6Al-4V) (Reference 2)

The plain cantilevers with their dimensions are shown in Figure 1a. They were manufactured from an annealed alloy of titanium with 6% aluminium and 4% vanadium (see Section 5). The results for S_{rms} against N , the equivalent endurance, are shown in Figure 2. The method of least squares fit gives for the constant K a numerical value of 4.109×10^3 MPa and for the exponent a gives a value of -0.1914 . Hence, the equation of the $S-N$ curve is

$$S_{rms} = 4.109 \times 10^3 N^{-0.1914} \quad (3.1)$$

and has been obtained by the method of least squares. An alternative form for the $S-N$ curve is

$$NS_{rms}^{5.226} = 7.684 \times 10^{18} \quad (3.2)$$

The stress is in units of MPa. For example, when the root mean-squared value of the measured alternating stress is 300 MPa, the number of cycles to failure, N , is 8.713×10^5 . In terms of British units the equivalent expression of Equation (3.1) is

$$S_{rms} = 596.0 N^{-0.1914}, \quad (3.3)$$

where S_{rms} is in ksi ($1000 \text{ lbf/in}^2 = 1 \text{ ksi}$). Thus for $S_{rms} = 30 \text{ ksi}$ ($30 \times 10^3 \text{ lbf/in}^2$), $N = 6.089 \times 10^6$ cycles. The 95% confidence intervals for the data are shown in Figure 2.

3.2 T-piece Coupons

Several types of T-piece coupons were used, as shown in Figures 1b to 1h. The main part of the coupon is referred to as the skin and the component at right angles is the stiffener or web.

3.2.1 Single row of riveted joints (Ti-2Cu) (Reference 1)

A single stiffener was riveted to the skin by a single row of rivets, as shown in Figure 1b, where the position of a typical crack is indicated. The coupons were made from titanium alloyed with 2% copper (aged). The skin thickness was 0.71 mm. The rivets were solid, 3.2 mm (0.125 in) diameter, made from Monel (a nickel/copper alloy), countersunk and spin-dimpled. The $S-N$ data are presented in Figure 3. There were 12 coupons tested and in one case there was no failure.

The experimental data for the Ti-2Cu coupons with a single row of riveted joints has been combined with experimental data for the Ti-2Cu coupons with a double row of riveted joints. A least squares fit procedure, applied to the combined data has resulted in the $S-N$ curve expressed by the equations given in Section 3.2.2, as well as in Figure 3.

3.2.2 Double row of riveted joints (Ti-2Cu) (Reference 3)

The coupons considered in this section have two stiffeners, each riveted to the skin by a row of rivets. An example of a coupon is shown in Figure 1c with a typical crack near one of the rows of rivets. Material is Ti-2Cu and the skin thickness is 0.71 mm. The rivets were made from Monel, 3.2 mm. diameter, snap-headed and provided metal to metal contact. The $S-N$ data are shown in Figure 3. Sixteen coupons were tested, four of which were obtained at an elevated temperature of 250°C and the rest at room temperature, of which four resulted in no failure.

For the combined data for single and double rows of riveted joints the equation of the $S-N$ curve is

$$S_{rms} = 6.081 \times 10^3 N^{-0.2891} \quad (3.4)$$

where the constant K and the root mean-squared value of the alternating stress, S_{rms} , are expressed in MPa.

The line formed from this equation is shown in Figure 3 with the 95% confidence intervals. In British units with the stress in ksi

$$S_{rms} = 881.9 N^{-0.2891} \quad (3.5)$$

3.2.3 Single row of resistance spot welds (Ti-2Cu) (Reference 1)

Coupons are shown in Figure 1d and are similar to those described as in Section 3.2.1, *i.e.*, Figure 1b, except that the rivets are replaced by resistance spot welds. The skin thickness of 0.71 mm is the same. The $S-N$ data are shown in 4. The spot welding was carried out either before or after ageing of the material. The grain direction of the material is either normal to the line of the welds or parallel with the welds, as indicated in the caption for Figure 4. A typical failure crack is indicated in Figure 1d. Although in this case there is considerable scatter and reliable statistical analysis is of limited value, a line based on a least squares fit has been drawn through the data points which represent the resistance spot welds after ageing (triangular points). For this limited data the 95% confidence intervals are shown.

3.2.4 Single row of gas tungsten-arc spot welds (C.P. Ti) (Reference 1)

The skin of the coupon is attached to the web by a capping strip (the web and capping strip form together a T-shaped stiffener), as shown in Figure 1e. The $S-N$ data are shown in Figure 5. The coupons are made from commercially pure titanium and the skin thickness is 0.41 mm.

3.2.5 Double row of gas tungsten-arc spot welds (C.P. Ti) (Reference 1)

Attachment is by two rows of spot welds, as shown in Figure 1f. Cracks occur across the weld surface, as shown. The fatigue results are given in Figure 5.

3.2.6 Double row of resistance spot welds (C.P. Ti) (Reference 1)

Coupons are similar to those described in Section 3.2.5. Cracks occur around the periphery of the welds, as seen in Figure 1g. The majority of the data for the $S-N$ plots is for the resistance spot welds, as indicated in Figure 5. The equation of the $S-N$ curve for the coupons with the resistance spot welds is

$$S_{rms} = 1.312 \times 10^3 N^{-0.3141} \quad (3.6)$$

with the stress in MPa and

$$S_{rms} = 190.3 N^{-0.3141} \quad (3.7)$$

with the stress in ksi. The line shown in Figure 5 and the confidence intervals are for the coupons with the resistance spot welds only.

3.2.7 T-pieces with superplastic forming and diffusion bonding (SPF/DB) (Ti-6Al-4V) (References 11, 12 and 13)

In these coupons the property of superplastic forming of titanium is combined with diffusion bonding. A one-piece structure is formed without welding or rivets, as shown in Figure 1h. The skin thickness is 0.61 mm. At the intersection of the skin and web a spandrel-shaped void is formed. At failure cracks were observed at the web-skin junction, as shown in the inset diagram in Figure 1h (Reference 12). The $S-N$ data are presented in Figure 6 for tests at ambient temperature and in Figure 7 for results at 200°C. The equation of the $S-N$ curve (Figure 6) is

$$S_{rms} = 2.625 \times 10^3 N^{-0.2454}, \quad (3.8)$$

where S_{rms} and constant K are expressed in units of MPa, and $S_{rms} = 380.7 \times 10^3 N^{-0.2521}$ for the stress in ksi. In the case of Figure 7 at 200°C and the stress in MPa

$$S_{rms} = 2.423 \times 10^3 N^{-0.2521} \quad (3.9)$$

and $S_{rms} = 351.4 N^{-0.2521}$ for the stress in ksi.

3.3 Plain and Riveted Base-vibrated Cantilever Coupons (Ti-6Al-4V) (References 7 and 9)

The plain coupons are cantilevers which are vibrated at the base, as shown in Figure 1i. The skin thickness is 1.27 mm. In the case of the riveted coupons the cantilevers are strengthened at the base by an additional strip of material 1.27 mm thick, see Figure 1j. The material is annealed titanium alloy with 6% aluminium and 4% vanadium. The $S-N$ data results are presented in Figures 8 and 9 for the plain coupons for both room temperature (21°C) and an elevated temperature (316°C).

For the plain coupons at 21°C the estimated equation of the $S-N$ curve with the stress and constant, K , in MPa is

$$S_{rms} = 2.862 \times 10^3 N^{-0.1948} \quad (3.10)$$

and $S_{rms} = 414.8 N^{-0.1948}$ for the stress in ksi.

For the plain coupons at 316°C the estimated equation of the $S-N$ curve with the stress in MPa is

$$S_{rms} = 1.724 \times 10^3 N^{-0.1832} \quad (3.11)$$

and $S_{rms} = 250.1 N^{-0.1832}$ for the stress in ksi.

In the case of the riveted, cantilevered coupons, the $S-N$ data are shown in Figures 10 and 11 for temperatures of 21°C and 316°C, respectively. The equations of the $S-N$ curves for stresses in MPa at 21°C and 316°C are, respectively,

$$S_{rms} = 2.228 \times 10^3 N^{-0.2201} \quad (3.12)$$

and

$$S_{rms} = 1.604 \times 10^3 N^{-0.2296}. \quad (3.13)$$

In Figure 12 the results presented in Figures 2 to 6, 8 and 10 have been obtained from tests at ambient temperature. They have been collected together for comparative purposes.

3.4 Cantilever Coupons of Alloys for High Speed Applications (Reference 17)

The cantilever specimens were clamped between two blocks to the mechanical shaker. The coupons were cut from sheet material between 0.05 and 0.07 in (1.27 and 1.78 mm) thick. Sometimes a beam amplification section was used to increase the strain levels at the gauge, as shown in Figure 1k. Failure was observed to occur in the straight section of the cantilever, where there were no stress concentrations. The alloys tested were Ti 6Al-4V, Ti 6-2-2-2-2, SP700, IMI550 and β 21s. The results quoted in Reference 17 are in terms of the logarithms of the root mean-squared strain as a function of the logarithms of the number of cycles to failure. Strain has been converted to stress by means of the appropriate Young's modulus of the material. The root mean-squared stress in MPa at room temperature is plotted against number of cycles to failure and the results shown in Figures 13 to 17.

For the alloy Ti 6Al-4V the results are shown in Figure 13, where the straight line leads to the formula for S_{rms} in MPa:

$$S_{rms} = 682 N^{-0.0844} \quad (3.14)$$

Results for this titanium alloy are provided in Figure 8 with the equation for the root mean-squared stress given as Equation (3.10). The results in Figures 8 and 13 refer to the same alloy with similar heat treatment, but the tests were conducted in different laboratories, although in both cases the coupons were in the form of cantilevers. In Figure 8 the endurance at 10^6 cycles is 194 MPa, compared with 213 MPa in Figure 13. At 10^7 cycles the endurance, as shown in Figure 8, is 124 MPa, whereas the comparable result in Figure 13 is 175 MPa.

The alloy Ti 6-2-2-2-2, which is suitable for high speed applications, has been tested at room temperature with different mean stresses and the results shown in Figure 14. For zero mean stress (stress ratio $R = -1$) linear regression of order one, applied to the logarithmic values of both the root mean-squared stress in MPa and the number of cycles to failure, leads to:

$$S_{rms} = 372 N^{-0.0403} \quad (3.15)$$

For the Ti 6-2-2-2-2 alloy some results have been obtained with a mean stress applied, such that the mean stress equals the root mean-squared stress for each measurement. The endurance is shown also in Figure 14 and is slightly lower than that for zero mean stress:

$$S_{rms} = 342 N^{-0.0389} \quad (3.16)$$

Some additional results are shown in Figure 14 for the case when the mean stress is equal to one third of the root mean-squared stress, but there is insufficient data for a straight line to be plotted.

The results in Figure 15 refer to tests at room temperature on the titanium alloy, SP700, for two heat treatment conditions. The first is for the alloy mill-annealed

$$S_{rms} = 615 N^{-0.0717} \quad (3.17)$$

and the second is for the alloy super-plastically formed and aged

$$S_{rms} = 302 N^{-0.0368} \quad (3.18)$$

Similar results are shown in Figure 16 for the alloy, IMI550, for mill-annealed

$$S_{rms} = 434 N^{-0.0390} \quad (3.19)$$

and SPF and aged

$$S_{rms} = 309 N^{-0.0275} \quad (3.20)$$

Results for the root mean-squared stress in MPa are shown in Figure 17 for the alloy β 21s solution treated and aged, when measured at room temperature

$$S_{rms} = 351 N^{-0.0389} \quad (3.21)$$

Some results are available at a temperature of 350°F (176.7°C) and indicate an endurance that is slightly less than at room temperature, namely,

$$S_{rms} = 339 N^{-0.0391} \quad (3.22)$$

4. METHOD OF TESTING

The results used in this Item were taken from work in different laboratories. The general principles of the testing methods are described in Reference 10. Three methods of testing can be identified.

4.1 Vibration of Plain Cantilever Coupons

In this method the cantilevers were fixed at the base and an electromagnetic vibrator was attached to the cantilever at a position close to the free end (Reference 2). The signal to the vibrator was either a harmonic wave or a narrow band random signal. A microscope and capacitive transducer system, positioned close to the base, were used to obtain the stress (Reference 2). The beams were excited at their resonance frequency which was approximately 300 Hz (Reference 2). The narrow band random signal was truncated at ± 4 times the root mean-squared value of the stress. For a stationary Gaussian random process the number of peaks above the truncation level is very small (Reference 18). Truncation of the signal provides protection for the equipment without compromising the random nature of the signal. Failure was considered to have occurred when the resonance frequency of the beam was 98% of its initial value. The random loading was interrupted at intervals to test for failure, using a constant amplitude excitation. A diagram of the specimen used in the tests is shown in Figure 1a. A typical crack is shown also in Figure 1a. The results of Figure 2 were produced with this apparatus.

4.2 Vibration of T-piece Coupons

A series of tests were carried out on different types of T-piece specimens (References 1, 3, 11 and 12). The T-pieces used are shown in Figures 1b to 1h. The web (or stiffener part) of the coupon was held in an electromagnetic shaker and excited, as indicated in Figures 1b to 1h, at the fundamental resonance frequency of the specimen. The input to the shaker was a random signal, which is reported to have a bandwidth equivalent to a one-third octave centred on the resonance frequency, although a 100 Hz band-pass filtered signal has been applied (Reference 1). For such a signal the ratio of zero crossings of the stress function per unit time with positive slope to the number of peaks per unit time (the irregularity factor) would be expected to be close to one (Reference 18). Thus, for a signal with an equivalent one-third octave bandwidth with a centre frequency equal to the resonance frequency, the number of zero crossings per unit time is

equal to the resonance frequency. At failure the equivalent endurance, N , is equal to half the number of zero crossings of the stress-time function. The truncation level applied in this case was between ± 3.0 and ± 3.5 times the root mean-squared level.

The stress was obtained from monitor strain gauges on the specimens. In the case of at least one coupon, several gauges were positioned on the coupon and the stress estimated at the likely position of cracks at failure. For the majority of specimens the stress at failure was based on the measurement of strain at this position. Failure was normally recognised by a sharp reduction in resonance frequency, accompanied by a large fluctuation in strain amplitude. Visual failure was normally apparent at this stage (Reference 1). The aim of the tests on the built-up T-pieces was to produce $S_{rms} - N$ data curves for the material which could be used to predict the life of more realistic stiffened panel structures.

In the case of the superplastically-formed and diffusion-bonded coupons the stiffener part of the coupon (of length 46 mm) was held in a vibrator and subjected to a random excitation which was varied to produce root mean-squared stress levels of 64, 80 and 106 MPa at a reference strain gauge at ambient temperature (Reference 12). Tests were carried out also at a temperature of 200°C. The high temperature has been achieved by blowing hot air in an environmental chamber, at stress levels of 58, 73 and 97 MPa (Reference 12). Failure was assumed to occur when the resonance frequency of the coupon decreased from a settled value by 2%, although this method of assessing failure was found difficult to apply (Reference 12). Visible cracks were observed at the web-skin junction (Reference 12).

4.3 Base Vibration of Plain and Riveted Cantilever Coupons

For these tests the coupon was set into bending vibrations by motion of the base of the cantilever, as shown in Figures 1i and 1j. The test specimen was clamped at the base between steel backs mounted on an electromechanical shaker and excited at a resonance frequency, using narrow band random loading with a bandwidth of approximately 30 Hz. The upper cut-off frequency of the random input was chosen at a slightly greater frequency than the resonance frequency, so that as the resonance frequency decreased during failure it was always within the bandwidth of the narrow band random signal. For these tests the truncation level was ± 3.0 times the root mean-squared value of stress.

Tests were carried out at room temperature (21°C) and at an elevated temperature (316°C). For the elevated temperature tests the coupons were surrounded by a thermal enclosure and heated by tungsten-filament quartz lamps (References 7 and 9).

The stress is derived from a reference strain gauge positioned near the base of the cantilever. Failure was considered to have occurred when the resonance frequency decreased 2% below its initial value. The resonance frequency was monitored periodically through the test using low level sinusoidal loading.

For the series of tests on alloys with application to high speed aircraft (Ti 6Al-4V, Ti 6-2-2-2, SP700, IMI550 and β 21s) the base of the coupons were vibrated by an electromagnetic vibrator (Reference 17). The specimens excited by a narrow band random input, which was centred on the natural frequency of the second bending mode. The excitation frequency was designed to be between 400 and 600 Hz. It was possible to achieve a mean stress by a static load applied via a trapeze located at the node line of the second bending mode shape. It proved difficult to apply a mean stress and preload results were achieved only for the Ti-6-2-2-2 alloy. Strain gauges are located on the coupons at the position of maximum stress, as indicated by finite element analysis and initial testing. The coupons are shown in Figure 1k. Failure was designed to occur at the strain gauge location. Each specimen was monitored to track the response frequency and strain. The experiment was terminated, representing failure of the coupon, when the natural frequency decreased by 10%. Most tests were carried out at room temperature, apart from tests on the alloy β 21s, which were conducted additionally at 350°F (176.7°C). Some tests were carried out on the alloy Ti 6-2-2-2 with a non-zero mean stress.

5. DESCRIPTION OF MATERIALS

5.1 General Descriptions

The designations used in this Item are descriptive of the chemical composition and condition of heat treatment of the material.

C.P. Ti Commercially pure titanium. The material used in the tests was the high strength grade (specification tensile strength for this material is 620 to 770 MPa (89.6 to 112×10^3 lbf/in²) with commercial designation IMI 160. The UK specification for the material was DTD 5063, but this specification was superseded by British Standard TA 6, which covers a slightly lower range of tensile strength. The material is similar to the USA commercially pure titanium, Ti-75A (specification MIL-T-9046 E type 1 comp. B or AMS 4901) (Reference 15).

Ti-2Cu (aged) This is a weldable binary titanium alloy, susceptible to age hardening, containing 2 to 3% copper. The specification for the material used in the tests was BAC M.47 and the commercial designation was IMI 230 (aged). The specification tensile strength for this material is 695 MPa (100.8×10^3 lbf/in²). The UK specification was DTD 5233. There is no US military or AMS specification covering a similar material.

Ti-6Al-4V (annealed) The material tested had the nominal chemical composition: 6% aluminium, 4% vanadium, 0.08% carbon, low nitrogen and hydrogen, remainder titanium. The mechanical properties are: tensile strength, 960 MPa ($139\,000$ lbf/in²); yield strength, 890 MPa (129×10^3 lbf/in²); elongation, 10%. Young's modulus is 110 GPa (16×10^6 lbf/in²) at room temperature and 90 GPa at 316 °C (Reference 14). The density is 4420 kg/m³ and Poisson's ratio is 0.31.

The material is similar to US specification AMS 4911 or AMS-T-9046 AB-1 for annealed sheet or plate (AMS-T-9046 supersedes MIL-T-9046). It is similar also to the British Standard TA 10; other designations may be found in Reference 14.

Some metals with a fine grain structure, such as titanium, exhibit superplastic behaviour at an elevated temperature. In superplastic forming extensive elongation is possible without localised thinning. In the process of diffusion bonding, the mating surfaces are made to contact at an elevated temperature and the bond is produced by atomic diffusion across the interface. As both superplastic forming (SPF) and diffusion bonding (DB) occur at similar temperatures in the case of titanium (925°C and 950°C, respectively), the two processes are often exploited together. Some T-piece coupons were constructed from Ti-6Al-4V using the SPF/DB process and tested according to Section 4.2.

With the SPF/DB process, structures, such as panels and doors, can be formed in a single operation. Cellular structures are also possible.

Ti 6-2-2-2-2 The specimens used were annealed, aged and pickled. The composition is 6% aluminium, 2% zirconium, 2% chromium, 2% tin and 2% molybdenum, some iron and silicon, the remainder titanium. Ti 6-2-2-2-2 is an alpha-beta ($\alpha + \beta$) titanium alloy. The alpha phase is a hexagonal close packed structure (hcp), which occurs in pure titanium at low temperatures. At high temperatures the stable structure is body-centred cubic (bcc), which is referred to as beta titanium (Reference 20). The composition of the phases depends upon the alloying elements. Aluminium is important for the alpha phase and molybdenum for the beta phase. The values of Young's modulus are: 116.5 GPa (L tensile axis) and 121.9 (T tensile axis). The yield stress (2% offset) is 1122 MPa (L) and 1120 MPa (T). The ultimate tensile stress is 1161 MPa (L) and 1145 (T).

SP700 This alloy is super plastically formed, annealed and aged. It is a near beta alloy with a chemical composition of 4.5% aluminium, 3% vanadium, 2% molybdenum and 2% iron, remainder is titanium.

Young's modulus is 110 GPa, yield strength is 900 MPa and tensile strength is 960 MPa (Reference 20).

IMI 550 The alloy is also super plastically formed, annealed and aged. The chemical composition is 4% aluminium, 4% molybdenum, 2% tin and 0.5% silicon, the remainder titanium.

β21s This alloy is solution treated and aged. It is a beta titanium alloy with a chemical composition of 3% aluminium, 3% niobium, 15% molybdenum, some iron and silicon, remainder is titanium. Young's modulus is 104 GPa, yield strength is 1196 MPa (L), 1241 MPa (T) and tensile strength is 1300 MPa (L) or 1320 MPa(T).

6. COMMENTS ON $S - N$ DATA

For the endurance data of Figures 2 to 16, S_{rms} is plotted against N for the different coupons. The test results are grouped according to mode of testing, the type of structural element, material and method of attachment. When possible, straight lines have been fitted by the least squares method to the $S - N$ data in logarithmic coordinates and 95% confidence bands have been drawn, although in some Figures the confidence bands have been omitted for clarity. Extrapolation of the mean lines to higher endurance than indicated, where few data are available, is expected to lead to an underestimate of endurance.

The reference position for S_{rms} is taken as a point on the failure line away from the effects of stress concentrations and from fretting at fasteners; the test points plotted represent either mean stresses over the areas covered by monitoring strain gauges affixed across the failure line away from the fasteners, or stresses at that position estimated after calibration from strain monitors located elsewhere. When using this Item to estimate life using a root mean-squared stress level obtained from ESDU Items 72005, 73014 or 74026 (References 4, 5 and 8), it is assumed to be the same as at the failure position. In practice, away from the effects of stress concentration, this approximation is within the range of accuracy of the simple theory used for stress prediction in these Data Items. The loading simulated for the fastened-skin coupons is only applicable to modes where adjacent panels are in phase. Care should be taken in using the data for modes involving twisting of the stiffeners.

Effect of method of attachment

Skin specimens attached to stiffeners by snap-headed rivets (Figure 3) showed greater endurance and less scatter than resistance spot-welded specimens (Figure 4). The resistance spot-welded specimens in turn showed slightly greater endurance and less scatter than gas tungsten-arc spot-welded coupons, although in this case the materials were different. There are insufficient results to indicate that two rows of rivets provides more endurance than a single row, or that two rows of spot welds result in more endurance than a single row.

Effect of material specification and thickness

The available data for different materials are not directly comparable because of differences in specimen configuration and thickness. The large difference between the results for Ti-2Cu (aged) (Figures 3 and 4) and C.P. Ti (Figure 5) are thought to be due to effects of skin thickness on spot-weld performance rather than to the difference in material.

The results shown in Figures 2 and 13 are for the same material, namely annealed Ti-6Al-4V, and allow a comparison of measurements carried out in different laboratories. The results shown in Figure 13 are part of a series on materials suitable for use in high speed aircraft. The Ti-6Al-4V alloy, the mostly commonly used of the titanium alloys, was selected as a reference material. The exponent a in the Basquin Equation (Equation (2.1)) is larger in the high speed tests (-0.0844) than in the earlier tests (-0.1914). The root mean-squared stress required for failure at 10^7 cycles was 175 Pa for the high speed tests (Figure 13) and