

STATIC AND FATIGUE STRENGTH OF BUTT WELDED JOINTS IN ALUMINIUM ALLOYS

1. INTRODUCTION

This Item provides data on the static and fatigue strength of metal-inert-gas (MIG) full penetration butt welded joints in aluminium alloys. The process of welding causes a local reduction in strength by destroying the effects of heat treatment, introducing stress concentrations at the weld bead and inducing residual stresses around the weld. However, some of the lost strength can be regained by post-weld treatment. Loading can be transverse or longitudinal (parallel) to the weld. Data are provided for parent aluminium alloys and transversely loaded butt welds in the as-welded condition and with various post-weld treatments. Longitudinally loaded joints are generally stronger than transversely loaded joints.

2. NOTATION

Both SI and British units are quoted.

f_t	tensile strength	N/m ²	lbf/in ²
N	endurance		
R	stress ratio, S_{min}/S_{max}		
S	nominal applied stress in absence of crack	N/m ²	lbf/in ²
S_a	alternating applied stress (half range) in loaded plate	N/m ²	lbf/in ²
S_m	mean applied stress in loaded plate	N/m ²	lbf/in ²
S_{max}	maximum value of S in loaded plate	N/m ²	lbf/in ²
S_{min}	minimum value of S in loaded plate	N/m ²	lbf/in ²
S_y	yield stress (0.2 per cent proof unless otherwise stated)	N/m ²	lbf/in ²
t	nominal thickness of loaded plate	m	in

3. EFFECTS OF WELDING ALUMINIUM ALLOYS

3.1 Metallurgy

Most aluminium alloys can be readily welded, but the process must be carefully controlled if good quality welds are required. Table A1.1 of Appendix A gives weldability ratings for some alloys using the MIG welding process. This rating is used in the Metallic Materials Data Handbook, DEF STAN 00-932 (Reference 23). It can be seen that all have good weldability apart from the 2XXX* and some of the 7XXX series.

* See Appendix B for an explanation of aluminium alloy designations.

Aluminium alloys are usually heat treated or cold worked to improve their properties. The main alloying components, magnesium, zinc and silicon, either singly or in various combinations, increase in solid solubility in aluminium with increasing temperature, thus allowing precipitation hardening by quenching to give increased strength. The 6XXX and 7XXX series alloys gain their strength in this way. The 1XXX, 3XXX, 4XXX and 5XXX series alloys are solution heat treated only. Their initial strength depends primarily on the hardening effects of alloying elements such as silicon, iron, manganese and magnesium. Magnesium is the most effective solution-strengthening addition giving alloys of the 5XXX series a relatively high strength. Solution heat treated alloys and commercially pure aluminium (1XXX series) can be further strengthened by strain hardening.

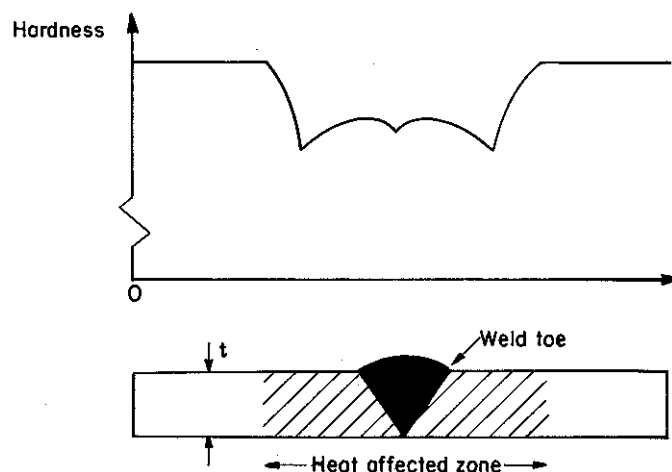
Filler metals for welding wrought aluminium alloys fall into the 1XXX to 5XXX series. Aluminium filler metal 1050 can be used to weld all of the 1XXX series alloys, as well as the 3003 and 5005 alloys. Filler metals 4043 and 4047 may be used to weld a wide variety of aluminium alloys. They exhibit low sensitivity to cracking during welding, moderate strength and good corrosion resistance. Welds made with one of the 5XXX series filler metals will possess higher as-welded strength than welds made with any other aluminium filler metal, due to the high strength of this filler in the annealed condition. They are particularly good for welded construction because of the nearly uniform mechanical properties of the various zones in a welded joint. Fillers of the 5XXX series are used for welding most 5XXX, 6XXX and 7XXX series alloys. From Table 7.2, it can be seen that all fatigue data presented in this Data Item are from specimens welded using a filler alloy from the 5XXX series.

For Al-Si (4XXX series) and Al-Mg (5XXX series) alloy weld metals, sensitivity to cracking is greatest when the weld metal contains about 0.5 to 2 per cent silicon or magnesium, respectively. Cracking tendencies decrease when the weld metal composition is above or below this range. For example, when 5052 alloy (2.5 per cent Mg) is welded with 5554 filler (2.7 per cent Mg), the weld would exhibit greater susceptibility to cracking than if it were welded with 5356 filler (5 per cent Mg).

Cracking during welding is not usually a problem when the appropriate filler and welding technique are used.

3.2 Thermal Effects

During welding, the effects of precipitation heat treatment or cold work are undone, resulting in a softened heat affected zone. Sketch 3.1 illustrates this by showing a typical mid-thickness plot of the hardness distribution across a transverse butt weld and heat affected zone, indicating the variation in static strength.



Sketch 3.1 Example hardness distribution across an aluminium alloy butt welded joint

For 1XXX to 5XXX series alloys, the heat of welding will partially remove strain hardening effects, leading to a reduction in strength. For commercially pure aluminium, the weld joint strength will be that of the fully annealed parent alloy.

Heat treatable 6XXX and 7XXX series alloys require a substantial time at temperature to soften them fully. The loss of strength due to welding is dependent primarily on the size of the welded assembly and the thermal control of the welding process. The material surrounding the weld acts as a sink to the heat input. If the heat sink is large enough, the heat of welding dissipates quickly and a quenching effect results. The resulting strength in the weld area will then approach that of the solution heat treated condition of the base alloy. If the heat sink is relatively small, for example in thin plates, the heat affected zone strength will approach that of the annealed parent alloy as no quenching will occur.

Welding also induces residual stresses due to local thermal expansion, plastic deformation and subsequent shrinkage on cooling. In the critical region of the parent-to-weld interface, surface residual stresses are tensile in directions transverse and parallel to the joint. The magnitude of residual stress is dependent on the material thickness and number of weld passes used. The residual stress near the weld surface can approach the yield strength of the weld metal when the combination of number of passes and plate thickness is such as to cause large temperature gradients through the thickness. Single pass welds made in thin plate or double pass welds in thicker plate tend to leave low residual welding stresses transverse to the weld.

4. STATIC STRENGTH

The static strength of aluminium alloys is reduced by welding owing to the through-thickness heat affected zone softening. This must be taken into consideration when dealing with static strength requirements. Static strength design of aluminium joints is covered in design codes such as the British Standard CP 118* (Reference 21).

Table 7.1 shows an analysis of the results of tests on the static strength of four butt welded aluminium alloys. Five coupons were taken from each welded specimen and tested individually, so the results indicate the variation of strength within one welded component only. The tests were carried out for alloys with differing thickness, filler and welding process. A statistical analysis giving standard deviations and coefficients of variation has been carried out for the sample of five test specimens.

Defects such as inclusions or gross porosity may appear in the weld metal which can lead to a reduction in static strength.

Post-weld heat treatment can increase the static strength of a welded joint, but relatively few commercial applications utilise a strengthening heat treatment of completed welds.

5. FATIGUE STRENGTH

5.1 Introduction

This Data Item presents fatigue test data on parent aluminium alloys and butt welds in the as-welded state and with various post-weld treatments. Design codes such as CP 118 provide fatigue design curves for various classes of joint. Such curves are usually placed below the lower bound of test data and should therefore be conservative. However, where sufficient data are available, more accurate failure predictions can be made. The factors affecting fatigue strength of welded joints are therefore discussed and, where possible, their influence shown. This provides insight into the actual behaviour of welded joints for

* BS 8118 Part 1: Code of practice for the design of aluminium structures will replace CP 118.

individual aluminium alloys, allowing improved design with respect to fatigue strength.

There is a wide range of aluminium alloys, heat treatments and possible welding process variables. The available data are limited and can therefore only give a guide to the factors that influence fatigue strength. However, most of the factors that influence the fatigue strength of steel welds, such as the weld bead shape and joint size will also apply to aluminium welds. These influences are described for steel welds in Data Item No. 86013*.

The fracture mechanics approach is commonly used in analysis of materials and joints. However, owing to lack of suitable data on fatigue crack growth rates, this approach is not possible at present for the commonly welded aluminium alloys.

In the absence of severe weld defects, fatigue failure will start at the material surface in the transition region between the parent and weld materials.

5.2 Fatigue Data

The fatigue data are presented in Figures 1 to 22 as a series of endurance curves. Where possible, parent metal fatigue strengths are also given to show the loss of fatigue strength resulting from welding. The test process variables, alloy, filler, stress ratio, dimensions and postweld state are given for each curve in Tables 7.2 and 7.3, together with a summary of fatigue strengths at endurances of 10^6 and 10^7 cycles.

Fatigue tests are usually performed on coupons ($t < 12$ mm (0.5 in)) which do not contain the high residual stresses present in sections thicker than about 20 mm (0.8 in). Another effect of size, discussed in Data Item No. 87016†, is that for the same initial size of weld toe defect, a thicker section will experience faster crack propagation at the initial stages, thereby reducing fatigue life. **For both of these reasons, fatigue test data on small scale or thin specimens are optimistic for prediction of fatigue life of thicker sections or welded fabrications.**

The following sections discuss the primary factors that affect fatigue strength.

5.3 Factors Influencing the Fatigue Strength of Butt Welds

The main factors affecting fatigue strength include parent and weld material properties, welding process and the presence of small initial defects in the material. In general, butt weld fatigue strength will increase with parent material tensile strength (see Tables 7.3 and 7.4); however, this effect is reduced at high endurances. Welding speed and other parameters such as arc voltage (see Figure 3) will determine the weld quality and bead shape, therefore affecting the fatigue strength of the resulting joint. A butt weld will usually contain small defects, typically up to 0.5 mm (0.02 in) in depth, so that the initial stages of fatigue life may be bypassed.

The other main factors affecting the fatigue strength are as follows.

Loading : *axial or bending, stress ratio.*

Joint geometry : *plate thickness, weld size and profile.*

Residual stress levels

Post-weld improvements: *weld profiling, shot peening, heat treatment.*

* Data Item No. 86013 "Guide to the use of Data Items on the fatigue strength of welded joints in steels".

† Data Item No. 87016 "Effect of size on fatigue strength of steel components".

5.3.1 Loading

The stress ratio (minimum to maximum stress) describes the form of varying applied stress. Data are given in the form of S - N curves where stress range is the ordinate and the stress ratio, R , is given on each figure. Tensile residual stresses, where present, will increase the actual stress levels, making the actual stress ratio higher than the applied stress ratio. Figure 8 shows test results for similar specimens under stress ratios of 0.3 and -0.8 . The higher stress ratio of 0.3 gives a higher mean stress, leading, as expected, to a lower fatigue strength.

The majority of test data are for axially loaded joints; however, Figures 6, 11, 12, 16 and 19 give data for tests under applied bending. It can be seen, from Figure 16, that fatigue strengths for specimens subjected to bending tests ($R = -1$) are greater than for those under axial load ($R = 0$) tests.

5.3.2 Joint geometry

The weld bead introduces a stress concentration at the weld toe, the magnitude of which is determined by the local geometry of the bead. Welding speed and other parameters such as arc voltage will determine the bead shape and stress concentration. Figure 3 shows the effect of arc voltage level on fatigue strength. In general, the smoother the transition from the parent material surface to the weld bead, the lower the stress concentration and, consequently, the higher the endurance.

5.3.3 Residual stresses

As-welded joints contain a highly localised system of residual stresses (see Section 3.2). Residual stresses in the direction of welding are high, usually of the order of the material yield strength, whereas stresses perpendicular to the direction of welding are generally lower.

In material greater than about 20 mm (0.8 in) thick, residual stresses perpendicular to the direction of welding will approach the yield strength of the base material. On loading, localised yielding is likely. In consequence, the actual stress experienced at the weld toe will vary from the yield stress to the yield stress less the stress range. Thus, application of high alternating and/or mean stress, magnified by the stress concentration at the weld toe and any residual stress present, will give a yield limited condition. However, if the mean stress and stress range are low, this yield limited condition may not apply. In general, a higher mean stress will result in a shorter component life. This is shown in Figure 4, where the yield limited condition of $S_{max} = S_y$ (variable R), with high mean stress, has a lower fatigue strength than the condition of $R = 0$ (variable S_{max}).

Residual stresses can increase the mean applied stress level, thus increasing the stress ratio. This factor must be taken into account as the higher mean stress will lead to a lower fatigue strength. Test data with an R value of about 0.5 or more, where $S_{max} = S_y$, may be used to account for residual stresses. Alternatively, the modified Goodman diagram, shown and explained in Data Item No. 75022*, may be used to estimate fatigue life at a high R value from existing data at $R = 0$, thus taking some account of residual stress.

5.4 Post-weld Improvements

Fatigue strength is strongly dependent on the shape of the weld bead, specifically the angle of the bead to the parent material surface and the weld toe radius. Machining a butt weld bead to give a smooth, flush surface removes the geometric stress concentration and so improves fatigue strength, as shown in Figures 1 and 14 to 19. Table 7.5 shows the mean percentage increase in fatigue strength of several alloys at 10^6 cycles gained by weld bead removal. Figures 1, 5 and 10 show base metal and as-welded fatigue strengths

* Data Item No. 75022 "Design against fatigue. Basic design calculations".

(bead intact), whereas Figures 1, 6, 9, 11 and 12 compare fatigue strengths of base metal and welded specimens with bead removed.

In the as-welded condition, surface finish and defects such as porosity, unless severe, do not affect fatigue strength significantly. With the bead machined flush, however, the weld is more sensitive to defects such as porosity, the most common welded aluminium defect, and surface finish. A roughly machined weld will have a rough surface from which fatigue cracks could develop.

Weld peening and stress relief can reduce surface residual stresses arising from welding. Figures 2 and 3 show the effect of weld toe peening. Figure 2 shows that the fatigue strength improvement is greatest if the stress range is small or close to the fatigue limit (toe peening doubles the fatigue strength at 10^7 cycles). The improvement effect is minimal if the stress range is high and lives are shorter, for example 10^4 cycles.

The effect of post-weld stress relief on fatigue strength of butt welds is shown in Figure 1. Fatigue strengths lie at a moderately high level within the range of variation of the fatigue strength values of as-welded joints.

6. DERIVATION AND REFERENCES

6.1 Derivation

This section lists selected sources that have assisted in the preparation of this Item.

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3. PERSON, N.L. Fatigue of aluminium alloy welded joints. *Welding research supplement*, Vol. 50, Part 2, February 1971.
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18. SOETENS, F. Welded connections in aluminium alloy structures. *HERON*, Vol. 32, No. 1, 1987.
19. KING, F. *Aluminium and its Alloys*. Ellis Horwood Series in Metals and Associated Materials, 1987.
20. OHTA, A.
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6.2 References

The references given are recommended sources of information supplementary to that in this Item.

21. BSI British Standard Code of Practice CP 118, 1969. The structural use of aluminium. UK, 1969.
22. – The Properties of aluminium and its alloys. Aluminium Federation, 1983.
23. ESDU Metallic Materials Data Handbook. DEF STAN 00-932, Volume 1. Published by ESDU.



7. TABLES

TABLE 7.1 STATIC STRENGTH TESTS ON BUTT WELDED ALUMINIUM ALLOYS. COMPARISON WITH PARENT METAL STRENGTH AND STATISTICAL ANALYSIS.

					Butt welded, bead removed				
Alloy and temper designation	Weld* process	Filler	t mm (in)	Parent metal f_t MN/m ² (10 ³ lbf/in ²)	Mean f_t MN/m ² (10 ³ lbf/in ²)	Standard deviation (5 tests) [†]	Coeff. of variation [‡] (percentage)	f_t	
								welded parent metal	Average
5083-O	MIG	5356	4 (0.16)	300 (44)	297 (43)	1.26	0.4	0.99	0.96
			12 (0.47)	334 (48)	316 (46)	6.65	2.1	0.94	
6064-T5	MIG	5356	4 (0.16)	218 (32)	150 (22)	1.02	0.68	0.69	0.72
			12 (0.47)	210 (30)	159 (23)	1.67	1.05	0.76	
		4043	4 (0.16)	218 (32)	152 (22)	1.17	0.77	0.70	0.71
			12 (0.47)	210 (30)	152 (22)	1.9	1.2	0.72	
	TIG	5356	4 (0.16)	218 (32)	144 (21)	5.1	3.54	0.66	0.66
6082-T6	MIG	5356	4 (0.16)	316 (46)	212 (31)	3.8	1.8	0.67	0.66
			12 (0.47)	338 (49)	223 (32)	3.88	1.74	0.66	
		4043	4 (0.16)	316 (46)	211 (31)	6.93	3.3	0.67	0.66
			12 (0.47)	338 (49)	223 (32)	3.19	1.43	0.66	
	TIG	5356	4 (0.16)	316 (46)	170 (25)	2.3	1.36	0.54	0.54
7020-T6	MIG	5356	4 (0.16)	442 (64)	255 (37)	7.28	2.86	0.51	0.58
			12 (0.47)	448 (65)	297 (43)	7.25	2.44	0.66	
		4043	4 (0.16)	442 (64)	240 (35)	8.91	3.71	0.54	0.52
			12 (0.47)	448 (65)	230 (33)	9.7	4.2	0.51	

* MIG: Metal-inert-gas welding process; TIG: Tungsten-inert-gas welding process.

[†] 5 test coupons taken from a single specimen in each case

[‡] Coefficient of variation = standard deviation/mean.



TABLE 7.2 DETAILS OF FIGURES 1 TO 19 AND SUMMARY OF MEAN FATIGUE STRENGTHS FROM DATA

Alloy and temper designation	Figure Number	Filler	Loading type	Number of weld passes *	t mm (in)	R	Parent metal S_y (mean test values) MN/m ² (10 ³ lbf/in ²)	Test conditions	Mean fatigue strength ($2S_a$) MN/m ² (10 ³ lbf/in ²)	
									10 ⁶ cycles	10 ⁷ cycles
5052-H32	14	5356	Axial	1 [†]	4.8 (0.19)	0	–	as-welded	67 (9.7)	55 (7.9)
5052-H32	14	5356	Axial	1 [†]	4.8 (0.19)	0	–	bead removed	127 (18)	102 (15)
5052-H112	11	5456	Bending	2	6 (0.24)	–1	92 (13)	(parent metal)	215 (31)	180 (26)
5052-H112	11	5456	Bending	2	6 (0.24)	–1	92 (13)	welded, bead removed	215 (31)	148 (21)
5083-O	1	5356	Axial	2	4 (0.16)	0	143 (21)	(parent metal)	147 (21)	–
5083-O	1	5356	Axial	2	4 (0.16)	0	143 (21)	welded, bead removed	108 (16)	–
5083-O	1	5356	Axial	2	4 (0.16)	0	143 (21)	welded, toe ground	78 (11)	70 (10)
5083-O	1	5356	Axial	2	4 (0.16)	0	143 (21)	as-welded	52 (7.5)	45 (6.5)
5083-O	1	5356	Axial	2	4 (0.16)	0	143 (21)	welded, stress relieved	60 (8.7)	–
5083-O	2	5356	Axial	2	4 (0.16)	0	143 (21)	toe peened	102 (15)	83 (12)
5083-O	3	5356	Axial	2	4 (0.16)	0	143 (21)	as-welded, arc = 23V	82 (12)	70 (10)
5083-O	3	5356	Axial	2	4 (0.16)	0	143 (21)	as-welded, arc = 21V	65 (9.4)	55 (8)
5083-O	4	5356	Axial	2	20 (0.79)	0	167 (24)	as-welded	65 (9.4)	55 (8)
5083-O	4	5356	Axial	2	20 (0.79)	0.6–0.82	167 (24)	as-welded, $S_{max} = S_y$	50 (7.3)	33 (4.8)
5083-O	5	5356	Axial	2	12 (0.47)	0	–	(parent metal)	138 (20)	–
5083-O	5	5356	Axial	2	12 (0.47)	0	–	as-welded	83 (12)	–
5083-H113	15	5183	Axial	1	9.5 (0.37)	0	–	as-welded	92 (13)	80 (12)
5083-H113	15	5183	Axial	1	9.5 (0.37)	0	–	bead removed	127 (18)	110 (16)
5083-H113	16	5356	Axial	1	9.5 (0.37)	0	–	as-welded	73 (11)	58 (8.4)
5083-H113	16	5356	Axial	1	9.5 (0.37)	0	–	bead removed	120 (18)	95 (14)
5083-H113	16	5183	Bending	1	9.5 (0.37)	–1	–	as-welded	160 (23)	112 (16)
5083-H113	16	5183	Bending	1	9.5 (0.37)	–1	–	bead removed	218 (32)	–
5083-H113	15	5356	Axial	1	9.5 (0.37)	0	–	as-welded	68 (9.9)	–
to 6061-T6	15	5356	Axial	1	9.5 (0.37)	0	–	bead removed	129 (19)	–
5086-H116	12	5356	Bending	2	16 (0.63)	–1	–	(parent metal)	260 (38)	210 (30)
5086-H116	12	5356	Bending	2	16 (0.63)	–1	–	welded, bead removed	165 (24)	112 (16)

* 1 indicates single v-groove, 2 indicates double v-groove.

† square groove.



TABLE 7.2 DETAILS OF FIGURES 1 TO 19 AND SUMMARY OF MEAN FATIGUE STRENGTHS FROM DATA (continued)

Alloy and temper designation	Figure Number	Filler	Loading type	Number of weld passes*	t mm (in)	R	Parent metal S_y (mean test values) MN/m ² (10 ³ lbf/in ²)	Test conditions	Mean fatigue strength ($2S_a$) MN/m ² (10 ³ lbf/in ²)	
									10 ⁶ cycles	10 ⁷ cycles
5086-H32	17	5356	Axial	1	9.5 (0.37)	0	–	as-welded	92 (13)	–
5086-H32	17	5356	Axial	1	9.5 (0.37)	0	–	bead removed	132 (19)	98 (14)
5456-H321	19	5556	Bending	1	9.5 (0.37)	–1	–	as-welded	138 (19)	102 (15)
5456-H321	19	5556	Bending	1	9.5 (0.37)	–1	–	bead removed	220 (32)	162 (23)
6063-T5	9	5456	Axial	2	3 (0.12)	0	243 (35)	(parent metal)	155 (22)	120 (17)
6063-T5	9	5456	Axial	2	3 (0.12)	0	243 (35)	welded, bead removed	75 (11)	59 (9)
7003-T5	6	5356	Bending	1	6 (0.24)	–1	–	(parent metal)	300 (44)	200 (29)
7003-T5	6	5356	Bending	1	6 (0.24)	–1	–	welded, bead removed	235 (34)	160 (23)
7005-T53	7	5356	Axial	1	5 (0.20)	0.3	305 (44)	welded, bead modified	–	–
7005-T53	7	5356	Axial	1	5 (0.20)	0.3	305 (44)	as-welded	–	–
7005-T53	8	5356	Axial	1	5 (0.20)	–0.8	305 (44)	bead removed	198 (29)	190 (28)
7005-T53	8	5356	Axial	1	5 (0.20)	0.3	305 (44)	bead removed	110 (16)	99 (14)
7005-T6	13	5056	Axial	1	6 (0.24)	0	–	as-welded	–	–
7005-T6	10	5456	Axial	2	6 (0.24)	0	322 (47)	(parent metal)	168 (24)	152 (22)
7020-T6	10	5456	Axial	2	12 (0.47)	0	322 (47)	(parent metal)	168 (24)	152 (22)
7020-T6	10	5456	Axial	2	6 (0.24)	0	322 (47)	as-welded	81 (12)	62 (9)
7020-T6	10	5456	Axial	2	12 (0.47)	0	322 (47)	as-welded	92 (13)	80 (12)
7039-T61	18	5183	Axial	1	9.5 (0.37)	0	–	as-welded	98 (14)	79 (11)
7039-T61	18	5183	Axial	1	9.5 (0.37)	0	–	bead removed	128 (19)	110 (16)
7039-T61	18	5039	Axial	1	9.5 (0.37)	0	–	as-welded	115 (17)	98 (14)
7039-T61	18	5039	Axial	1	9.5 (0.37)	0	–	bead removed	148 (21)	115 (17)

* 1 indicates single v-groove, 2 indicates double v-groove.



TABLE 7.3 DETAILS OF FIGURES 20 TO 22 AND SUMMARY OF MEAN FATIGUE STRENGTHS FROM DATA

Alloy and temper designation (Current British Standard equivalent)	Figure Number*	Filler		Loading type	t mm (in)	Mean stress S_m MN/m ² (10 ³ lbf/in ²)	Mean fatigue strength (2S _d) MN/m ² (10 ³ lbf/in ²)	
		Old BS	Current BS				10 ⁶ cycles	10 ⁷ cycles
5251A-H14	20	NG6	5356	Axial	6.4 (0.25)	0 (0)	120 (17)	93 (13)
5251A-H14	20	NG6	5356	Axial	6.4 (0.25)	23 (3.3)	95 (14)	75 (11)
5251A-H14	20	NG6	5356	Axial	6.4 (0.25)	46 (6.7)	80 (12)	63 (9.1)
5251A-H14	20	NG6	5356	Axial	6.4 (0.25)	77 (11)	74 (11)	53 (7.7)
5251A-H14	20	NG6	5356	Axial	6.4 (0.25)	108 (16)	74 (11)	53 (7.7)
5083-F [†]	21	NG6	5356	Axial	6.4 (0.25)	0 (0)	135 (20)	100 (15)
5083-F [†]	21	NG6	5356	Axial	6.4 (0.25)	23 (3.3)	108 (16)	77 (11)
5083-F [†]	21	NG6	5356	Axial	6.4 (0.25)	46 (6.7)	85 (12)	63 (9.1)
5083-F [†]	21	NG6	5356	Axial	6.4 (0.25)	77 (11)	78 (11)	60 (8.7)
5083-F [†]	21	NG6	5356	Axial	6.4 (0.25)	108 (16)	78 (11)	52 (7.5)
6082-T6	22	NG6	5356	Axial	6.4 (0.25)	0 (0)	127 (18)	90 (13)
6082-T6	22	NG6	5356	Axial	6.4 (0.25)	23 (3.3)	120 (17)	79 (11)
6082-T6	22	NG6	5356	Axial	6.4 (0.25)	46 (6.7)	102 (15)	68 (9.9)
6082-T6	22	NG6	5356	Axial	6.4 (0.25)	77 (11)	73 (11)	53 (7.7)
6082-T6	22	NG6	5356	Axial	6.4 (0.25)	108 (16)	81 (12)	50 (7.3)

* All test specimens were welded from one side using a backing bar, backchipped and welded from the other side.

† Not exact equivalent, see Table 7.4.



TABLE 7.4 MATERIAL SPECIFICATIONS FOR ALLOYS IN FIGURES 20 TO 22

Alloy and temper (Old British Standard designations)	Thickness mm (in)	Content (per cent)					Tensile properties			Current British Standard (BS) designation
		Cu	Mg	Si	Fe	Mn	0.1 per cent proof stress MN/m ² (10 ³ lbf/in ²)	f_t MN/m ² (10 ³ lbf/in ²)	Elongation on 51 mm (per cent)	
NS 4½ H	6.4 (0.25)	0.027	2.11	0.11	0.31	0.11	201 (29)	246 (36)	12.5	5251A-H14
NP 5/6 M	6.4 (0.25)	0.025	4.36	0.12	0.28	0.60	204 (30)	305 (44)	19.5	corresponds to BS alloy 5083-F except in Cr content where BS specifies 0.05%< Cr < 0.25%
HP 30 WP	6.4 (0.25)	0.029	0.65	1.04	0.28	0.55	287 (42)	328 (48)	14	6082-T6