Tensile and Toughness Properties of Arc-Welded 5083 and 6082 Aluminum Alloys

CTOD and CCT test results are a possibility for the prediction of permissible discontinuity sizes in welded aluminum structures

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ABSTRACT. Tensile, Charpy and crack tip opening displacement (CTOD) tests were carried out on two weld-pass GMA welds in 13 mm (approx. ½ in.) thick plates of the Al-4.5%Mg-0.8%Mn alloy 5083 and the Al-1%Si-0.8%Mg-0.7%Mn alloy 6082. For 5083, Al-5.2%Mg-0.8%Mn alloy (5556A) was used as filler metal, and for 6082 the same filler metal or Al-5%Si alloy (4043A) was used. Welded 5083 was tested in the as-welded condition, while for welded 6082 the effects of postweld heat treatment were also investigated.

Tensile and center crack tension (CCT) tests were carried out on single weld-pass GTA welds in 3 mm (0.12 in.) thick 6082 sheet, welded with 5556A or 4043A filler metals. The tests were carried out as-welded and after postweld heat treatment.

The strength and toughness properties of welded 5083 compared favorably with those of base metal. Welds in 6082 had poorer tensile properties than the base metal in the as-welded state. Artificial aging gave some increase in strength, full postweld heat treatment much more. Welds made with 5556A filler metal were always tougher than the equivalent welds made with 4043A filler metal, the latter also being more sensitive to heat treatment.

Tolerable discontinuity sizes for welds in 13 mm (approx. ½ in.) thick plate and critical discontinuity sizes for welds in 3 mm (0.12 in.) thick sheet were calculated using published procedures.

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Introduction

There are two main classes of Al alloy:

1. Those in which the strength is increased by solid solution hardening, possibly in association with cold work.
2. Those in which the strength is increased by age hardening.

With the former alloys, the strength is only affected by welding if the alloy is cold-worked. With the latter alloys, the strength is reduced by overaging in the heat-affected zone (HAZ) and can only be recovered by postweld heat treatment. The weld metal is also weaker than the base metal (the composition of the filler metal is different from that of the base metal to prevent weld metal cracking). Even after heat treatment, the weld metal may still be weaker than the base metal, depending on the filler metal and dilution.

Wrought Al alloys of the type being investigated are normally regarded as tough materials, with no tendency for brittle failure. This view has been supported by work on notched tensile tests (Ref. 1), small and large scale tear tests (Ref. 2), unsuccessful attempts to measure plane strain fracture toughness (Refs. 3-7), and by service experience. This is the probable reason why there is no requirement for toughness testing in the British and American pressure vessel standards (Ref. 8, 9). Nor does the British Standard (Ref. 10) which covers low temperature cylindrical storage vessels impose such requirements for Al alloys.

Japanese workers have, however, shown that the impact strength of welded 5083 was reduced at −196°C (−320°F) compared with room temperature results; this also was true for the notched/unnotched tensile strength ratio (Ref. 11), a finding opposed to that of earlier work (Ref. 1). Moreover, some national standards (Refs. 12, 13) do require impact tests. Therefore, it was considered necessary to carry out tensile and toughness tests on welded plate and sheet alloys.

Because of its widespread use, and as a basis for comparison, the Al-Mg alloy 5083 was chosen. For the other, 6082 was selected as typical of the Al-Mg-Si age hardening alloys. Nearly all other reported work on toughness has been carried out on thick material. However, in the program discussed in this paper thicknesses appropriate to the majority of Al alloy fabrications were used.

Method of Investigation

Welds were made in butt joints of 13 mm (0.51 in.) thick alloy 5083 and 6082

Table 1—Abbreviations, Conversion Factors, Definitions

AA	-artificially aged
AR	-as-received
AW	-as-welded
BM	-base metal ("parent metal" in Figs. 5-9)
BS	British Standard
CCT	-center crack tension
CTOD	-crack tip opening displacement
GL	-gauge length
HAZ	-heat-affected zone
R-curve	-crack growth resistance curve
RT	-room temperature
ST	-solution treated
+ve	-positive polarity
WM	-weld metal

1 mm = 0.04 in.
1 N/mm^2 = 0.145 ksi
1 N/mm$^{3/2}$ = 0.029 ksi $\sqrt{\text{in.}}$
1 J = 0.737 ft-lb
−196°C = −320°F
175°C = 347°F
530°C = 986°F

Table 2—Chemical Analyses of Base metals and filler metals, Wt-%

	13 mm plates							
	5083		6082		3 mm 6082 sheets		Filler metals	
	Plate 1	Plate 2	Plate 1	Plate 2	Sheet 1	Sheet 2	4043A	5556A
Si	0.13	0.11	0.88	0.96	0.94	1.2	5.00	0.09
Fe	0.37	0.32	0.30	0.32	0.34	0.30	0.37	0.23
Cu	0.03	0.06	0.03	0.06	0.03	0.04	0.02	0.07
Mn	0.67	0.63	0.47	0.6	0.51	0.74	0.02	0.64
Mg	4.7	4.3	0.72	1.1	0.72	0.72	0.13	5.46
Cr	0.11	0.1	<0.005	0.02	<0.005	0.03	–	0.14
Zn	0.02	0.04	0.01	0.01	0.02	0.11	0.01	0.1
Ti	0.02	0.03	0.03	0.02	0.04	0.04	–	0.10
Al	Remainder	Remainder	Remainder	Remainder	Remainder	Remainder	Remainder	Remainder

Table 3—Welding Conditions

	For 13 mm plates	For 3 mm Sheet
Process	GMAW DC electrode + ve	GTAW AC
Shielding gas	Ar	Ar
Flow rate, liters/min	25	12
Nozzle diameter, mm	25	16
Torch angle	Forward 10 deg	Vertical
Arc voltage, V	24	20
Electrode extension, mm	15	–
Electrode to work distance, mm	–	2.4
Current, A	300	235
Weld progression speed, mm/min	480 for 5556A and 370 for 4043A	145
Linear arc energy, kJ/mm	0.9 for 5556A and 1.2 for 4043A	1.9
Filler metal diameter, mm	1.6	1.6
Filler metal feed speed, mm/min	–	580

Table 4—Heat Treatment Conditions

Minimum natural aging period at room temperature – 30 days
Solution treatment – ½ h at 530 ± 10°C, water quench
Holding time at room temperature before artificial aging – 5 days
Artificial aging – 8 h at 175 ± 5°C, air cool

plate by the GMA process. Alloy 5556A filler metal was used for the 5083 alloy and 5556A or 4043A for the 6082. Base metal, transverse weld and all-weld-metal tensile tests were carried out in the as-welded state for both alloys and in two postweld heat-treated states for the 6082 welds, namely:

1. Artificially aged.
2. Solution treated and artificially aged.

Charpy V-notch impact tests and crack tip opening displacement (CTOD) tests were carried out on most of these welds, again testing the base and weld metals.

Welds were made in 3 mm (0.12 in.) thick 6082 sheet by the GTA process with 5556A or 4043A filler metals. Transverse tensile tests were carried out on these welds in the as-welded state and in the same postweld heat-treated states as for the 6082 plate welds; center-cracked tension (CCT) specimens were used for the fracture tests, notches being located in base metal or weld metal.

Materials

Two plates were obtained of both 5083 and 6082, and two 6082 sheets. The 6082 plates and sheets were in the solution-treated and artificially aged condition, the 5083 in the annealed condition. 1.6 mm (0.06 in.) diameter 5556A and 4043A filler metals were used for the tests.

All materials complied with the compositional requirements of the relevant standards (Refs. 14, 15); their analyses are given in Table 2.

Welding

13 mm Plates. Machine welding using the GMA process with argon shielding was employed. Plates, each 300 × 150 mm (11.8 × 5.9 in.), were cut and the 300 mm (11.8 in.) long edges prepared as shown in Fig. 1. Immediately before welding, the prepared edges were degreased with acetone, wire brushed and degreased and bolted in a heavy restraining jig to minimize distortion. The welding conditions are given in Table 3.

Welds were completed in two weld passes, using the same welding conditions for each pass.

3 mm Sheets. Machine GTA welding with argon shielding was used. Sheets, each 200 × 330 mm (7.87 × 13 in.), were cut, and the 330 mm (13 in.) long edges were welded using a single-square-groove preparation after cleaning and clamping as above. Each weld was completed in a single weld pass, using the welding conditions given in Table 3.

Heat Treatment

In practice, full heat treatment will usually be impracticable. Because of this, tests were made on 6082 weldments which had been given a simple artificial aging treatment as well as those given full heat treatment. Details are given in Table 4.

Mechanical Testing

Plate and All-Weld Metal Tensile Tests. The tensile properties of base metal plates and the weld metals were determined by extracting and testing round tensile specimens – diameter 6.4 mm (¼ in.), gauge length 32 mm (1.26 in.) – at room temperature. The gauge length of the all-weld-metal specimen was parallel to the welding direction for the filler metals. The 0.2% proof stress was estimated from the load-time trace.

Transverse Tensile Testing. Transverse tensile specimens were machined to the dimensions shown in Fig. 2 after heat treatment as required. Duplicate specimens were tested at room temperature.

For specimens from the plate welds, the 0.2% proof stress was measured on a

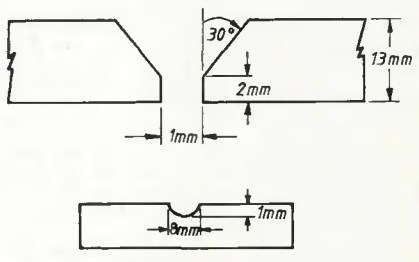

Fig. 1 – Welding preparation and temporary stainless steel backing bar

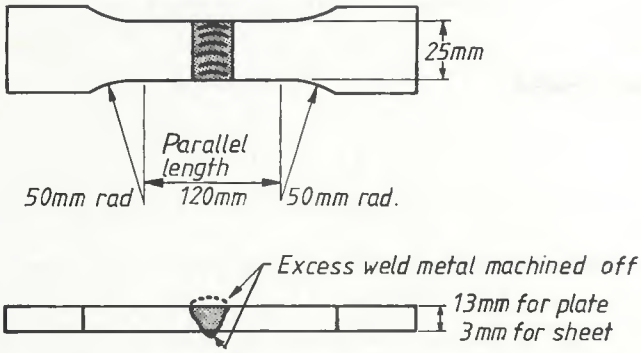

Fig. 2—Reduced transverse tensile test specimen

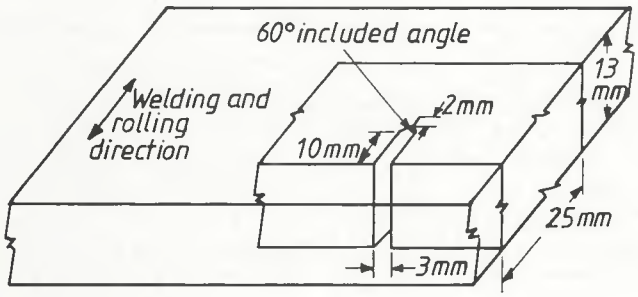

Fig. 3—Extraction of CTOD specimens

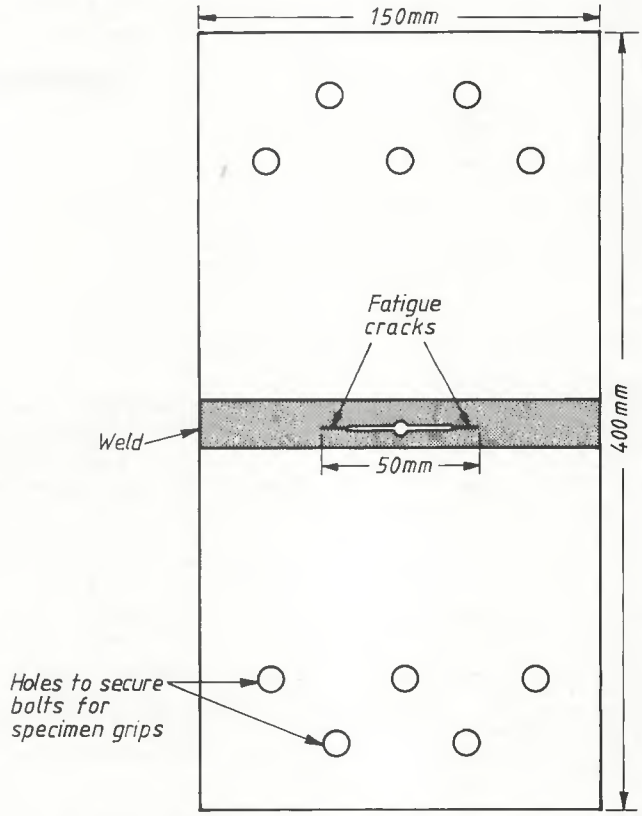

Fig. 4—Geometry of center-cracked tension specimens

Table 5—Tensile Tests on 13 mm Thick Base Metal

Alloy/plate number	Condition	Estimated 0.2% proof stress, N/mm²	Tensile Strength, N/mm²	Elongation, %	Reduction of area, %
5083/1	AR	199	335	18	15
		201	335	19	20
5083/2	AR	179	332	22	22
		186	332	22	24
		184	332	23	24
6082/1	AR	240	296	21	34
		257	296	21	35
		258	299	19	35
	AR	296	304	17	41
		296	304	19	39
		296	302	17	36
6082/2	AA	280	300	10	19
		284	302	12	26
	ST and AA	263	304	20	36
		273	310	18	39
		258	302	18	40
5083	Annealed	125	275	14	BS 1470 minimum properties
6082	ST, AA	240	295	8	

50 mm (1.97 in.) gauge length centered on the weld center line as specified in BS CP118 (Ref. 16); elongations were measured on 50 and 75 mm (1.97 and 2.95 in.) gauge lengths. For specimens from sheet welds, the 0.2% proof stress was estimated from the load-time trace, and elongation was measured on a 125 mm (4.92 in.) gauge length.

Charpy Testing. Standard 10 × 10 mm (0.39 × 0.39 in.) square Charpy V-notch specimens were tested in accordance with BS 131:Part 2:1972 (Ref. 17) with through-thickness notches in the base metal or weld metal, at room temperature or at −196°C (−320°F).

CTOD Testing. CTOD tests at room temperature or −196°C (−320°F) were conducted on specimens of full plate thickness extracted from the base material and weld metal (25 × 13 mm, or approx. 1 × ½ in., section) notched in the through-thickness direction.

Fatigue cracks were grown from the machined notches to the required crack position as shown in Fig. 3. Three point bend tests under displacement control were carried out according to BS 5762 (Ref. 18) at a crosshead speed of 0.2 mm/min (0.008 in./min). To mark the tear depth, the cracks were infiltrated with engineers' layout dye before the specimens were broken apart after test. For most welds, the tests were used to obtain only the CTOD at first attainment of maximum load (δ_m) but in some cases specimens were unloaded after increasing amounts of crack growth to enable crack growth-resistance curves (R-curves) to be constructed.

Center-Cracked Tension Testing. Center-cracked tension specimens were used to test 3 mm (0.12 in.) thick 6082 sheet and weld metals at room temperature. For the welded specimens, the excess weld metal was removed and specimens prepared to the dimensions shown in Fig. 4.

Specimens were tensile tested at a crosshead speed of 0.2 mm/min (0.008 in./min). Crack opening at the center of the notch was monitored with a clip gauge between a pair of knife edges bolted to the test sheet. Crack length measurements were made at the surface after stopping the crosshead and waiting for the load to stabilize.

Table 6—All-Weld Metal Tensile Tests from 13 mm Thick Plate

Base metal	Filler metal	Condition	Estimated 0.2% proof stress, N/mm²	Tensile strength, N/mm²	Elongation, %	Reduction of area, %
5083	5556A	AW	152	318	31	30
			158	318	26	25
6082	5556A	AW	141	283	19	17
			138	289	22	23
		AA	176	296	16	15
			184	298	17	14
			179	295	15	15
		ST and AA	178	304	19	28
			173	299	24	25
	4043A	AW	129	240	12	12
			126	242	13	10
			119	219	10	11
		AA	234	283	6	6
			228	273	4	3
			234	278	5	5
		ST and AA	295	350	7	7
			298	354	6	5
5083	–	Annealed	125	275	14	BS 1470 minimum properties for base metal
6082	–	ST and AA	240	295	8	

Table 7—Transverse Tensile Tests on Welds in 13 mm Thick Plates

Base metal	Filler metal	Condition	0.2% proof stress, N/mm²	Tensile strength, N/mm²	Elongation, % 50 mm GL	Elongation, % 75 mm GL	Position of failure
5083	5556A	AW	152	309	16	14	WM
			156	308	15	13	WM
6082	5556A	AW	135	233	9	7	HAZ
			132	232	9	7	HAZ
		AA	196	247	6	5	HAZ
			199	246	6	4	HAZ
		ST and AA	191	282	6	5	WM
			188	286	7	5	WM
	4043A	AW	128	220	7	5	WM
			130	224	6	5	WM
		AA	210	246	5	4	HAZ
			219	252	6	5	HAZ
		ST and AA	269	291	3	11	PM, outside GL
			273	294	3	10	PM, outside GL
5083	–	Annealed	125	275	14	BS 1470 minimum properties for base metal	
6082	–	ST, AA	240	295	8		

Table 8—Transverse Tensile Tests on 3 mm Thick 6082 Sheet Welds

Filler metal	Condition	Estimated 0.2% proof stress, N/mm²	Tensile strength, N/mm²	Elongation, % on 125 mm gauge length	Position of failure
5556A	AW	152	193	3	HAZ
		178	198	3	HAZ
	AA	221	223	1	HAZ
		222	223	2	HAZ
	ST and AA	305	308	2	WM
		302	305	2	WM
4043	AW	152	194	3	HAZ
		155	196	2	HAZ
	AA	221	221	1	HAZ
		214	216	2	HAZ
	ST and AA	321	332	7	BM
		315	323	7	BM

Results

Tensile Tests

Results of the tensile tests are given in Tables 5-8.

During the testing of some transverse specimens from 6082 plate welds, it was noted that small cracks opened up in the HAZ at or near the fusion line, more commonly with welds made with 5556A filler metal. However, no HAZ liquation cracks of the type reported elsewhere (Ref. 19) were observed during testing or metallography.

Impact Tests

Results of the impact tests are given in Table 9.

CTOD Tests

The δ_m values from the CTOD tests are given in Table 10. No unstable fractures were observed.

Two types of load-clip gauge displacement records were obtained in the CTOD tests, typified by traces shown in Fig. 5. The first type of trace passed smoothly through maximum load with no signs of irregular crack extension and was observed with 5083 base material and weld metal and 6082/5556A weld metal. The second type showed a discontinuity at or close to maximum load followed by irregular crack extension with falling load, and was observed with 6082 base material and 6082/4043A weld metal.

The R-curves are presented in Fig. 6 and 7. For 5083, similar behavior was observed in weld and base metal. For 6082, the base metal R-curve was quite flat with little increase in CTOD as the crack extended. All welds in this material

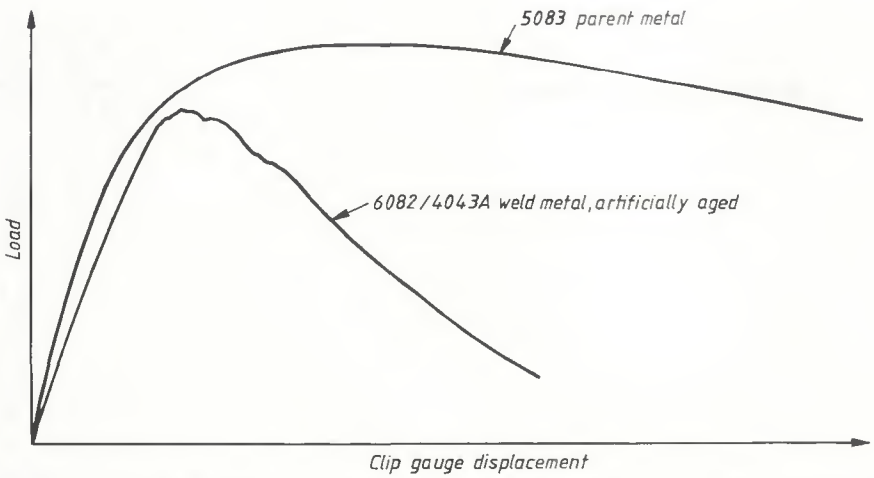

Fig. 5—Load-clip gauge displacement records showing different trace types obtained in CTOD tests

had steeper R-curves except for artificially aged 4043A welds.

Center-Cracked Tension Tests

Load-clip gauge displacement traces and crack length measurements were used to calculate the effective stress intensity factor (K_e) after ASTM E561-78T (Ref. 20). The resulting curves are given in Fig. 8 and 9. The points are presented as solid where values of K_e are valid on the basis of Schwalbe's suggestion that the net section stress should be less than 90% of the 0.2% proof stress (Ref. 21) and open where K_e becomes invalid.

Base metal curves for 6082 are included in Figs. 8 and 9 for comparison. It can be seen that lower values of K_e are observed in weld metals, both as-welded and heat treated.

Metallography

Metallographic examination of typical welds showed no unusual features. There was good fusion and acceptable shape. As is common with Al alloy welds, there was some microporosity. In addition, there were very small hot tears in 6082/4043A weld metals. Overall dilutions measured graphically are given in Table 11.

The weld metal microstructures were cellular whether Si or Mg-rich. Intermetallic particles were smaller than in the base materials and were distributed along cell boundaries. In the 5556A weld metals, a fine dispersion of intermetallics was formed. However, in the 4043A weld metal, the increased volume fraction of second phase produced an almost continuous cellular network. In the HAZ, the only observable effects were minor changes in intermetallic inclusions. Scanning electron microscopic examination of broken Charpy and CTOD specimens showed that microvoid coalescence was the fracture mechanism in all cases.

Discussion

Tensile Tests on Welds

The tests on as-welded 5083 plate showed that, although the strength was lower than that of the base metal, it was still well above the specified minimum for the latter. This was far from true for 6082 whether welded with 5556A or 4043A, the strength of the weld zone being markedly below that of the base metal; with 4043A, the weld metal was the

Table 9—Charpy Impact Tests

Base metal	Filler metal	Condition	Test temperature, °C	Charpy impact energy, J	
				BM	WM
5083	5556A	AW	RT	24, 24, 24	23, 23, 24
			−196	18, 19, 19	14, 15, 15
6082	5556A	AW	RT	12, 12, 12	18, 20, 20
			−196	14, 14, 14	11, 11, 15
		AA	RT	14, 16, 18	11, 11, 12
			−196	15, 15, 16	5, 5, 7
		ST and AA	RT	12, 12, 12	26, 27, 27
			−196	12, 12, 14	19, 20, 20
	4043A	AW	RT	12, 12, 12	9, 9, 9
			−196	14, 14, 14	8, 8, 9
		AA	RT	14, 16, 18	2, 2, 2
			−196	15, 15, 16	1, 2, 2
		ST and AA	RT	12, 12, 12	3, 4, 4
			−196	12, 12, 14	3, 3, 4

Table 10—CTOD Test Results

Base metal	Filler metal	Condition	Test temperature, C°	CTOD δ_m, mm					
				BM			WM		
5083	5556A	AW	RT	0.13	0.16	0.16	0.20	0.20	0.22
			−196	0.16	0.16	0.21	0.15	0.17	0.17
6082	5556A	AW	RT	0.12	0.12	0.13	0.21	0.24	0.26
			−196	0.06	0.07	0.08	0.14	0.16	0.18
		AA	RT				0.10	0.11	0.11
		ST and AA	RT	0.05	0.06	0.12	0.18	0.22	0.22
			−196	0.08	0.08	0.10	0.21	0.23	0.24
6082	4043A	AW	RT	0.12	0.12	0.13	0.11	0.11	0.15
			−196	0.06	0.07	0.08	0.08	0.08	0.10
		AA	RT				0.01	0.01	0.01
		ST, AA	RT	0.05	0.06	0.12	0.02	0.02	0.02
			−196	0.08	0.08	0.10	0.02	0.02	0.02

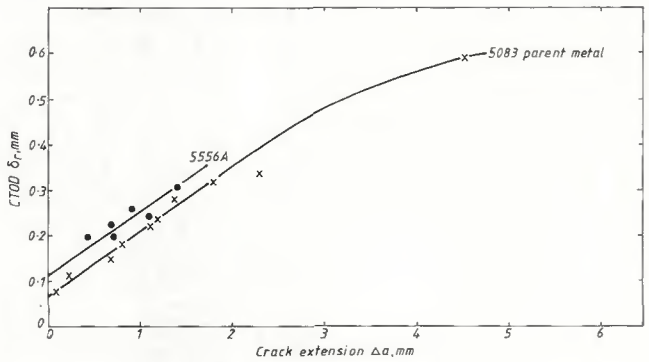

Fig. 6 — CTOD R-curves for 13 mm (approx. ½ in.) thick 5083 welded with 5556A filler metal

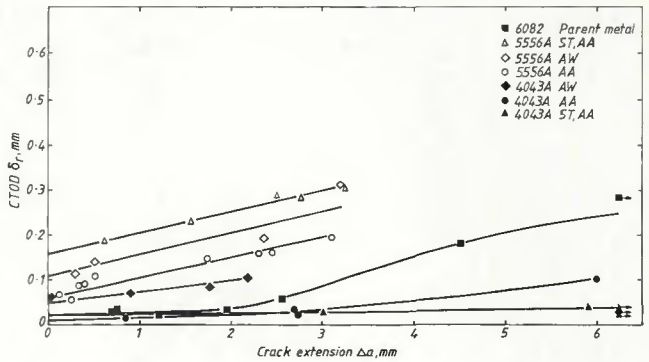

Fig. 7 — CTOD R-curves for 13 mm (approx. ½ in.) thick 6082 plate and weld metals made with 4043A and 5556A filler metals

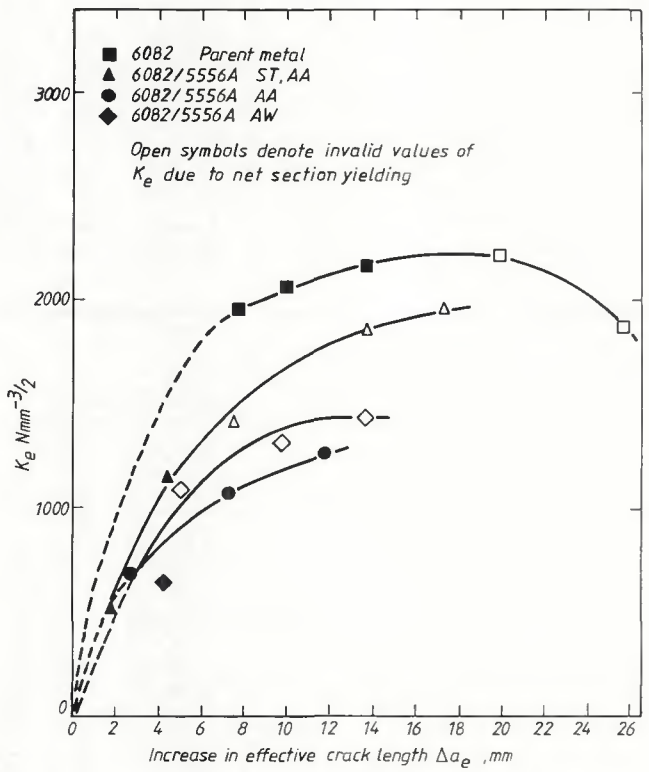

Fig. 8 — R-curves for 3 mm (0.12 in.) thick 6082 welded with 5556A filler metal

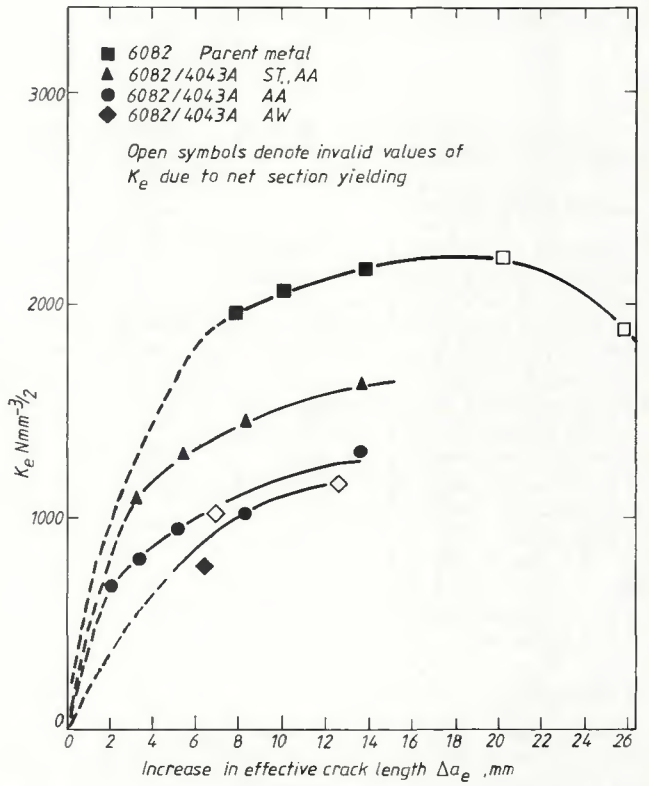

Fig. 9 — R-curves for 3 mm (0.12 in.) thick 6082 welded with 4043A filler metal

weakest part of the joint — with 5556A, the HAZ.

Artificial aging of weld metal considerably increased the strength (proof and tensile), more so with 4043A filler metal than with 5556A — Table 6. But as in the as-welded case, differences in weld metal properties had little effect on the overall joint properties, because the weakest part of the weld zone was the overaged HAZ.

Solution treatment and artificially aging after welding had practically the same effect on the tensile properties of 5556A weld metal as did artificial aging on its own (Table 6), showing that the weld metal was solution treated by the weld thermal cycle. In the transverse tests (Table 7), failure was in the weld metal, the tensile properties being below the BS 1470 values for base metal, particularly the proof stress. For the 4043A weld, the transverse tensile tests gave base metal failures at just below the BS 1470 minimum tensile strength, but well above the proof stress.

Compared with welded plate, the transverse results on 6082 sheet (Table 8) showed that, in the as-welded and artificially aged conditions, the sheet welds were weaker. In both cases, failure occurred in the HAZ, and the higher linear arc energy of the GTA process presumably caused greater overaging in the sheet welds. After solution treatment and artificial aging, the latter had higher strengths; the cause was probably the differences in weld metal composition between plate and sheet welds, particularly when 5556A filler metal was used.

An investigation by Metzger (Ref. 22) into the effect of heat treatment on 6061 sheet welded with 5556 or 4043 filler metals, artificially aged or fully heat treated after welding, gave comparable results to those obtained in the present investigation. Where the two investiga-

Table 11—Weld Dilution

Base metal	Thickness, mm	Filler metal	Dilution, %
5083	13	5556A	45
6082	13	5556A	25
6082	3	5556A	74
6082	13	4043A	30
6082	3	4043A	77

tions do not agree (where Al-Mg filler metals had been used), it is probably because the welds used by Metzger contained HAZ liquation cracks.

Impact Tests

For 5083, whether base metal or weld metal, the impact energy at −196°C (−320°F) was lower than at room temperature, as also found by Kobayashi (Ref. 23). There was a similar effect with 6082/5556A weld metal, but not with 6082 base metal [as found earlier for 6061-T6 (Ref. 24)] or 6082/4043A weld metal.

There was no effect on 6082 base metal from solution treatment and artificial aging, and possibly a slight increase from artificial aging. Weld metal made with 5556A filler metal showed a drop in absorbed energy on artificial aging but an increase when solution-treated and aged. Weld metal made with 4043A showed a decrease to a low level with either heat treatment. The trends are the same as those shown earlier for sheet welds in 6061 (Ref. 22).

CTOD Tests

The CTOD traces for welded and unwelded 5083 reflected their known high toughnesses (Ref. 6). The 6082 base metal showed discontinuities on the trace as did 6082/4043A weld metal, suggesting lower toughness. The behavior of 6082/5556A weld metal, at 30% dilution, was similar to that of welded and unwelded 5083. The δ_m values in Table 10 show the same overall trend; in addition, the data show that 6082/4043A weld metal is markedly affected by artificial aging, on its own or preceded by solution treatment. Temperature of testing did not affect the type of traces obtained. There were differences in δ_m values, but they were inconsistent.

It may be noted that the δ_m values as a whole are low. For example, the base metal values are below those that would be expected for maximum load behavior in structural ferritic steel of similar thickness.

Tolerable Discontinuity Size

Crack tip opening displacement (CTOD) test results have been correlated with larger scale tests to develop a design curve (Ref. 25) relating the size of tolerable discontinuities to measured CTOD values for given stresses. The procedure is based largely on results obtained from ferritic steel plates and weldments. Although this method was not originally developed for use when stable maximum load behavior is observed, it is possible to use δ_m to derive a conservative estimate of tolerable discontinuity size (Ref. 26). This approach has been applied mainly to ferritic steels but can in principle be applied to Al and its alloys; however, the experimental basis for so doing has not been fully established. Therefore, the following analysis must be regarded as tentative.

As examples, values of tolerable through-thickness discontinuity size (defined as l, the length of the discontinuity) in a large flat plate have been calculated for various conditions using the procedure given in PD 6493 (Ref. 27). This covers Al alloys. However, in view of the lack of data, they are grouped with "other materials" and a more pessimistic design curve used than for ferritic steels.

The effective stress used in the analysis has been taken simply as the sum of the residual stress at the weld plus a uniform applied stress. The appropriate residual stress is that perpendicular to the weld, which is principally controlled by the strength of the weakest part of the weld zone. This was the weld metal for 5083 and 6082/4043A, and the average estimated proof stress from Table 8 has been taken as the residual stress. For 6082/5556A, the HAZ was weaker than the weld metal; comparison of the relevant tensile test results (Tables 6 and 8) shows that the HAZ of 6082/5556A was similar to the weld metal of 6082/4043A. Therefore, the same residual stress was assumed to apply.

It is considered that this approach is more realistic than the simple procedure given in PD 6493. The same level was taken also for artificially aged welds in 6082, since the aging temperature and time would not materially alter the residual stress. Where solution treatment was used, the residual stress was taken as zero. For the applied stresses, the design stresses given in CP 118 (Ref. 16) for welded material were used, but with an exception. The exception occurred with base metals and for fully heat treated 6082 welds (where the purpose of the heat treatment would be to allow a higher applied stress) where the stresses for unwelded material were also used. In addition, for 5083 (unwelded and welded), the design stress appropriate to welded 6082 was also included as a comparison.

Table 12 gives the tolerable lengths of defects calculated on the above basis, using the mean values of δ_m. The two most obvious features are the very wide range and the marked effect of the assumptions about residual stress.

CCT Tests

The fact that the different weld regions can have markedly different proof stresses gave some difficulties in the analysis of the results. Where the proof stress was low (that is, as-welded weld metal), the values of K_e quickly became invalid with crack extension because of net section yielding. In addition when the plastic zone size became large (>5 mm or 0.2 in.), plasticity had probably extended into regions where the weld metal proof stress was no longer appropriate. In such cases an average proof stress between weld and base metal values was used.

From Figs. 8 and 9 it can be seen that

Table 12—Tolerable Sizes of Through-Thickness Discontinuities in 13 mm Thick Plate at Room Temperature

Alloy	Region and condition	0.2% proof stress, N/mm²	Assumed residual, stress N/mm²	Applied stress, N/mm²	Effective stress, N/mm²	CTOD at maximum load δ_m, mean, mm	Tolerable through-thickness discontinuity size, l, mm
5083	BM	183	0	80	80	0.15	96
				82	82		90
				51	51		236
5083/5556A	WM AW	155	155	82	237	0.21	12
				51	206		17
6082	BM	296	0	132	132	0.12	46
				51	51		304
6082/4043A	WM AW	124	124	51	175	0.12	10
6082/4043A	WM AA	232	124	51	175	0.01	2
6082/4043A	WM ST, AA	297	0	51	51	0.02	50
				132	132		8
6082/5556A	WM AW	140	124	51	175	0.24	24
6082/5556A	WM AA	180	124	51	175	0.11	14
6082/5556A	WM ST, AA	176	0	51	51	0.21	316
				132	132		47

the weld metals made with 5556A filler metal were less tough than the 6082 base metal, unlike the CTOD R-curves—Fig. 7. This is consistent with the higher dilution of the sheet welds and the difference in aging response observed in the tensile tests.

Critical Discontinuity Sizes

It was desirable to determine the critical crack lengths likely to cause unstable crack propagation. Thus, the relationship between effective stress intensity factor and effective half length of a through-thickness crack in an infinite sheet $K_e = \sigma_1 \sqrt{\pi a_e}$ (where σ_1 = effective stress) was used to construct driving force curves for the design stresses given in CP118 (Ref. 16) for unwelded and welded 6082. It was assumed that the residual and applied stresses were the same as for the plate welds. (It should be noted that discontinuity sizes calculated in this way have no built-in safety factor, unlike the tolerable discontinuity sizes calculated above).

Instability is predicted when the driving force curve is tangential to the R-curve as determined by superimposition of the R-curves on the appropriate driving force curve—Fig. 10. At the points of tangency, the values of K_e and a_e were obtained from the driving force curve. The effective crack lengths were converted to physical crack lengths by subtracting the plastic zone correction term calculated as in ASTM-E561-78T. (Ref. 20)

In some cases, the R-curve did not extend far enough to reach a point of tangency. When this occurred a calculation was made for the highest K value on the R-curve, giving a conservative estimate of the "critical" discontinuity size. Where the relevant portion of the R-curve was invalid, the estimated size is again conservative. The procedure is invalid when the effective stress exceeds the proof stress of the material and cannot be applied in the as-welded case where it is assumed that the residual stress is already at the proof stress level.

The results are given in Table 13. A pronounced effect of the assumptions about residual stress is again apparent.

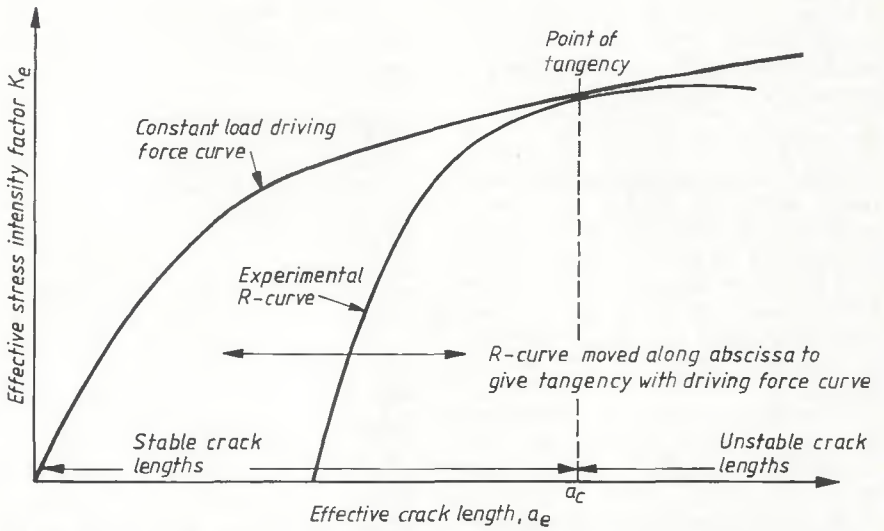

Fig. 10—Schematic diagram showing instability prediction from driving force and R-curves at critical effective crack length a_c

General

The overall results of the tests on welded 5083 agreed with general experience of this type of alloy. The weld metal was the weakest part of the joint, but its strength comfortably exceeded the specified minimum values for the base metal. To some extent, this is due to the high Mg levels in the plate and filler metal used (Ref. 28). The Charpy impact results were also in accord with those of other workers (Ref. 11).

The CTOD tests showed behavior characteristic of ductile material, with stable maximum loads being observed. Table 14 summarizes the toughness data for 5083 and 6082 and their welds. For such a material as 5083, it is somewhat surprising to find that the tolerable discontinuity length for a through-thickness crack should be as low as 12 mm (0.47 in.). In part, this reflects the conservative nature of the procedure given in PD 6493 and, in particular, the importance of assumptions about residual stress.

Other workers in the field of fracture toughness testing of Al have ignored residual welding stress in calculations of discontinuity size (Ref. 29), although this seems to be going to the other extreme. Residual stresses may well be less important when crack growth occurs by microvoid coalescence (as for Al alloys) and not cleavage, but some effect seems likely, particularly at crack growth initiation.

For 6082, the tensile results were also in accord with expectation. In the as-welded state, the proof and tensile strengths of the weld zone were well below those of the base metal minima, irrespective of filler metal. Some improvement in strength was obtained by artificial aging, but not up to base metal levels. Solution treatment and artificial aging gave a greater increase in strength than artificial aging alone: base metal strength levels were more easily attained with 4043A filler metal than with 5556A.

For 6082 in the as-welded condition, with either filler metal, the tolerable discontinuity lengths were comparable to those for welded 5083. These were reduced by artificial aging. Full heat treatment increased the tolerable discontinuity length considerably, despite the low Charpy and CTOD values recorded for 4043A filler metal, mainly because of the assumed relief of residual stress. The overall effects of heat treatment were similar for welded 6082 sheet as shown by the calculated "critical" discontinuity lengths.

Table 13—Instability Predictions from Center-Cracked 3 mm Thick Sheets at Room Temperature

Alloy	Region and condition	0.2% proof, stress, N/mm²	Assumed residual stress, N/mm²	Applied stress, N/mm²	Effective stress, N/mm²	Effective critical crack length a_c, mm	Effective stress intensity K_e, N/mm$^{3/2}$	Plastic zone correction r_y, mm	"Critical" through-thickness crack length l, mm
6082	BM	296	0	132	132	88	2195	9	158
4043A	AA	232	124	51	175	7	720	0	14
	ST, AA	297	0	51	51	>326	>1630	>5	>642
				132	132	49	1630	5	88
5556A	AA	180	124	51	175	6	680	2	8
	ST, AA	176	0	51	51	>458	>1930	>19	>886
				132	132	>68	>1930	>19	>98

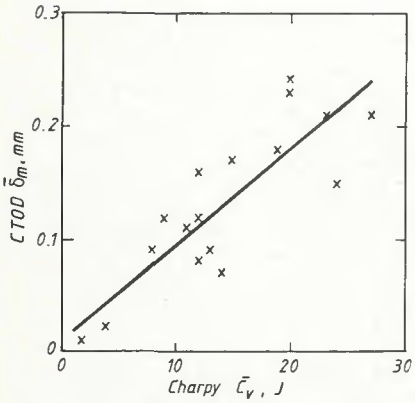

Fig. 11—Correlation of mean CTOD results against mean Charpy results. Regression line:

$$\bar{\delta}_m = 8.39 \times 10^{-3}\ \bar{C}_v + 0.01;\ r = 0.84.$$

The relation between Charpy and CTOD results is shown in Fig. 11. Because of the limited number of results available, all were used in calculating the regression line, despite the differences in base metal, filler metal and test temperature. Statistically, the correlation is highly significant. The Charpy test is easier to carry out than the CTOD test and, using the correlation in Fig. 11, could be used to calculate tolerable discontinuity size. However, an additional error would be introduced. Moreover, the correlation only holds for the size of CTOD specimen used—that is, the 13 × 25 mm (approx. ½ × 1 in.) cross section.

It is difficult to know how realistic the calculated values for tolerable or critical discontinuity sizes are in the absence of quantitative correlation with service experience. For 5083 the tolerable discontinuity size seems over conservative. For 6082, however, it is not possible to comment.

Work is planned to investigate more deeply the toughness analyses that can be made for welded Al alloys. Investigations are also planned on the assumptions needed to carry them out so that more accurate calculations of tolerable discontinuity size can be made, together with larger scale tests—that is, Wells' wide plate tests—to verify the results.

Conclusion

Tensile, Charpy and CTOD tests were used to evaluate the mechanical properties of two weld-pass GMA welds in 13 mm (approx. ½ in.) thick plates of 5083 and 6082. For 5083, 5556A was used as the filler metal; and for 6082, the same filler metal or alloy 4043A was used. Welded 5083 was tested as-welded while, for welded 6082, the effects of postweld heat treatment were also investigated.

Tensile and CCT tests were used to evaluate the mechanical properties of single weld-pass GTA welds in 3 mm (0.12 in.) thick 6082 sheet, welded with 5556A or 4043A filler metals. The tests were carried out in the as-welded condition and after various postweld heat treatments.

The following conclusions can be drawn:

1. The tensile and toughness properties of 5083 welded with 5556A filler metal compared favorably with those of the base metal.

2. The tensile properties of 6082, welded with 5556A filler metal, in the as-welded condition were appreciably poorer than those of the base metal, but the toughness was better. Postweld artificial aging improved strength but reduced toughness; full postweld heat treatment improved the strength further (although not necessarily to base metal level) without impairing the toughness.

3. In the as-welded condition, the tensile properties of 6082, welded with 4043A filler metal, were below those of the base metal, although the toughness was not reduced significantly. Postweld artificial aging gave some improvement in strength but markedly reduced the toughness. Full postweld heat treatment improved strength to base metal level, but toughness remained low.

4. Statistically, there was a highly significant correlation between Charpy and CTOD test results.

5. Tolerable and critical discontinuity sizes have been calculated from the CTOD and CCT data, respectively (Table 14). However, the results must be regarded as tentative, because of the assumptions that had to be made in carrying out the analyses, such as the level of residual stress.

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Table 14—Summary of Toughness Data

Base metal	Filler metal	Heat treatment	Charpy mean, J	δ_m, mean, mm	Design stress, N/mm²	Tolerable discontinuity length for 13 mm plate[a], mm	"Critical" discontinuity length for 3 mm sheet[a], mm
5083	—	—	24	0.15	80	96	—
5083	5556A	AW	23	0.21	82	12	—
6082	—	—	12	0.12	132	46	158
6082	4043A	AW	9	0.12	51	10	—
6082	4043A	AA	2	0.01	51	2	14
6082	4043A	ST, AA	4	0.02	51	50	>642
					132	8	88
6082	5556A	AW	19	0.24	51	20	—
6082	5556A	AA	11	0.11	51	12	8
6082	5556A	ST, AA	27	0.21	51	316	>886
					132	47	>98

(a) Applicable to large flat plate/sheet uniformly loaded in tension.

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