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Contents

WELDED CONNECTIONS INALUMINIUM ALLOY STRUCTURES

F. Soetens
TNO Institute for Building Materials and Structures,
Rijswijk, The Netherlands

Abstract

The results of a research programme on welded connections in statically loaded aluminium alloy structures are reported.
First, the motives for research on the structural behaviour of aluminium alloys are given and the research programme is briefly described.
In the following chapters the results of the various parts of the research programme are discussed and evaluated.

Welded connections in aluminium alloy structures

1 Introduction

Although a lot of research on aluminium alloys has been carried out in the past, relatively little attention has been given to their structural behaviour. Therefore, most design rules for aluminium alloys are based on design rules for steel, which – for example – is illustrated by the ECCS Recommendations [1], DIN 4113 [2] and TGB-Aluminium [3]. Applying similar design rules is permissible, since aluminium and steel structures do have very similar structural behaviour. This means in particular the application of limit state design methods which allow a better description of the real (non-linear) behaviour of a structure than allowable stress methods are capable of. This, however, requires knowledge of the structural behaviour of the members. Except for strength and stiffness this behaviour is determined by the deformation capacity which enables redistribution of forces to occur in a structure.
The aim of this study was to investigate the structural behaviour of aluminium alloy members and in particular the deformation capacity, in order to realize full application of limit state design methods.
It was decided to investigate welded connections in statically loaded aluminium alloy structures for that reason as well as some other reasons which are listed below:

- Welded connections are well suited for studying the relationship between mechanical properties and structural behaviour, since stress and strain concentrations occur.
- Design rules based on ultimate limit states, are concerned with failure of the structure. In spite of many investigations carried out, characteristic strength values of weld metal and heat-affected zone, respectively, do not exist.
- There are no uniform design rules for butt welds, fillet welds and welded connections in aluminium alloys. The use of rules similar to those for steel has to be investigated.
- Connections form an important part of the cost of structures as beam-column and truss-joints. Therefore simple, unstiffened connections are preferred. However, this means that stress and strain concentrations are introduced which have to be studied in relation to the strength, stiffness and deformation capacity of the joint.

Summarizing, it is of interest to investigate welded connections in statically loaded aluminium alloy structures because – for the reasons stated above – the design rules for aluminium are more restrictive than those for steel and moreover because many design codes differ considerably from one another in the rules they give.

2 Research programme for welded connections

In September 1981 the research programme "Welded connections in aluminium alloy structures" was started and it was finished in December 1984. It was carried out by TNO

together with Alcoa Nederland, Alurage, Bayards, ICB and UCN, and supported by the Netherlands Government.
The programme was subdivided as follows:

State of the art
In this literature study the materials, i.e. the alloys and filler metals, the welding technology, and the mechanical properties of welds and welded connections, have been reviewed.

Theoretical and experimental research
This part of the programme was subdivided in:
- *Experimental research on mechanical properties.* In this study the mechanical properties of weld metal and heat-affected zone was investigated.
- *Experimental research on fillet welds.* In this study the strength of fillet welds was investigated and the design of fillet welds in aluminium alloys structures was considered.
- *Theoretical and experimental research on welded connections in hollow sections.* In this study *X*- and *T*-connections of rectangular hollow sections were investigated with particular reference to the relation between the mechanical properties and structural behaviour of the joint.

Evaluation
Finally, the results of the programme described above have been evaluated and recommendations have been given for the design of welded connections in statically loaded aluminium alloy structures.

3 State of the art

The results of the literature study are reported in [4]. The most important results are summarized below.

3.1 *Aluminium alloys and welding technology*

Aluminium alloys of the series 5xxx, 6xxx and 7xxx are commonly used for load-bearing structures. The 5xxx series is mainly concerned with rolled material, while for the 6xxx resp. 7xxx series extrusions are applied.
Material thicknesses commonly are smaller than $t=20$ mm.
Many applications can be found in thin-walled structures with thicknesses below $t=6$ mm.
Filler metals most frequently used are: 5356 (=Al Mg 5), 5183 (=Al Mg 4,5 Mn) and 4043 (=Al Si 5). Filler metal 5356 can be combined with nearly all parent metal alloys and is therefore the most commonly applied filler metal. For some combinations filler

metal 5183 is preferred to 5356, while filler metal 4043 is mostly combined with parent metal of the 6xxx series.
As far as the welding processes are concerned, the MIG (=Metal Inert Gas welding) and the TIG (=Tungsten Inert Gas welding) processes are generally applied. With the MIG process the following can be distinguished: spray-arc, pulsed-arc, sometimes plasma - MIG, while short-circuit MIG is not used because of poor results for the welding of aluminium alloys. With TIG welding, mainly TIG-AC (=Alternating Current) is used.

3.2 *Mechanical properties of weld metal and heat-affected zone*

Mechanical properties of weld metal are often given for prescribed combinations of parent and filler metal. For the heat-affected zone of non heat-treatable alloys in the strain-hardened condition the mechanical properties of the parent metal in the annealed condition are applied, while for heat-treated alloys mechanical properties are given for a limited number of treatments (often only T6).
In [2] allowable stresses are given both for the weld metal and the heat-affected zone. In many standards only the lowest allowable stress or the design strength of the weld metal and heat-affected zone is given (see [1], [3], [5] and [6].
Besides, as shown in Fig. 1, the values for the mechanical properties differ significantly according to [1], [2] and [5].

Allowable stresses weld metal/heat-affected zone in N/mm²							
parent metal	7020-T6		6082-T6		6060-T5	5083-O	5454 / 5754 } H24
filler metal	5356	4043	5356	4043	5356	5356	5356
ECCS	112	82	75	75	50	80	50
DIN 4113	95		75	75	45	75	45
CP 118	124		51	51	31	82	62

Fig. 1. Allowable stresses according to ECCS [1], DIN 4113 [2] and CP 118 [5].

As can be inferred from the results of investigations carried out in recent years (see [7], [8], [9] and [10]), so far as the weld metal is concerned, the mechanical properties depend on the combination of parent metal and filler metal, but also on the welding process, the plate thickness and the weld type. For the mechanical properties of the heat-affected zone the heat-input is of course very important. Thus, the welding process, plate thickness and weld type as well as the condition of the alloy affect the values. To give some idea of the variation in values, the main results for the ultimate strength (mean values!) of weld metal and heat-affected zone - according to [7] - are shown in Fig. 2. It is noted that these results were derived from butt-welded test specimen with a thickness $t=20$ mm!

Ultimate strengths (tests*) heat-affected zone (σ_{uHAZ}) and weld metal σ_{uw} in N/mm²							
		Germany		Italy	Netherlands	Poland	
parent metal	filler metal	MIG	TIG	TIG	TIG	TIG	remarks
6082-T6	4043	σ_{uw} = 227	σ_{uw} = 164** σ_{uHAZ} = 169	σ_{uw} = 142** -	σ_{uw} = 168 σ_{uHAZ} = 175	σ_{uw} = 178 -	mean valu from tests
5083-F	5356	σ_{uw} = 309 σ_{uHAZ} = 306	- σ_{uHAZ} = 304	σ_{uw} = 274** -	- σ_{uHAZ} = 305	σ_{uw} = 272 -	see above
7020-T6	5356	σ_{uw} = 322 -	σ_{uw} = 214** -	σ_{uw} = 212** -	- σ_{uHAZ} = 220***	σ_{uw} = 203 -	see above

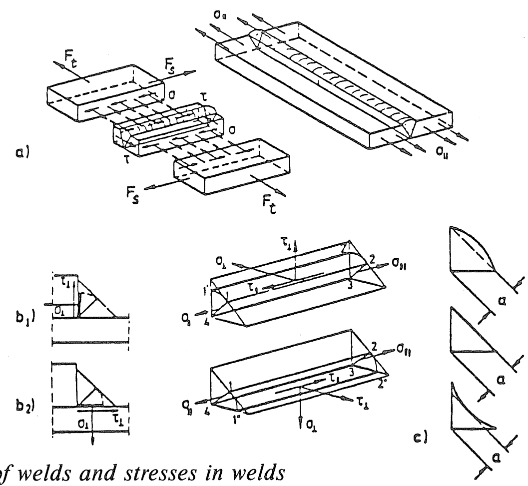
* test on butt-welded connections, X-type weld and thickness t = 20 mm
** weld defects as lack of penetration, lack of fusion and porosity were observed
*** failure heat-affected zone at a low stress level, caused by wrong pre-heating

Fig. 2. Main results for butt welds according to IIW research programme [7].

3.3 *Design of welds*

3.3.1 Butt welds

The design of butt welds (see Fig. 3) presents few difficulties. The distribution of forces acting in the weld is similar to that in the connected members; the stressed area is known (for fully-penetrated butt welds: weld throat a $\geq$ thickness t), which means that the mechanical properties of the weld metal and heat-affected zone are the only design parameters.



Definition of welds and stresses in welds
a. butt weld
b. fillet weld
b_1. rupture section 1234 = throat section turned into the vertical position 1′ 2′ 3 4
b_2. rupture section turned into the horizontal position 1″ 2″ 3 4 (general case)
c. throat thickness for the calculation

Fig. 3. Definition of rupture section and stresses according to [1] and [2].

3.3.2 Fillet welds

Besides the mechanical properties of the weld metal and heat-affected zone, with fillet welds the definition of the rupture section of the weld and the definition of the stresses in that section are difficult.

In [1] and [2] for *transverse fillet welds,* in which the direction of the force is perpendicular to the axis of the weld (see Fig. 3), the rupture section (= throat section of the weld) is turned to the horizontal or the vertical position, parallel to the direction of the force. This gives a shear stress $\tau_{\perp}$ perpendicular to the axis of the weld. For *longitudinal fillet welds,* in which the direction of the force is parallel to the axis of the weld, the shear stress $\tau_{/\!/}$ (= force divided by the area of the throat section) governs the design.

Another approach which is frequently given in design rules is to divide the force or the resultants of all forces by the total weld throat area ($F/\Sigma a \cdot l$) independently of the orientation of the force and the weld. This means that – for reasons of simplicity – no distinction is made between the strength of transverse and that of longitudinal fillet welds. In [5] a similar approach is used, however, distinguishing between the strengths of transverse and of longitudinal fillet welds. For transverse fillet welds similar allowable *tensile* stresses are given as for butt-welded joints while with longitudinal fillet welds the allowable *shear* stresses coincide. This means that the transverse fillet weld is presumed to be 60% stronger than the longitudinal fillet weld. In [1] a figure of 45% and in [2] a figure of 20% is given.

A third approach to determining the strength of fillet welds is to apply the β-formula which is commonly used for steel structures (IIW, ISO and ECCS Recommendations for steel). In [3] and [6] the β-formula is prescribed, which can also be used successfully for aluminium alloy structures as shown in [11]. With the β-formula it is assumed that:

- failure occurs in the minimum throat section of the weld;
- the stress distribution in the throat section satisfies equilibrium; the stresses are defined in Fig. 4.

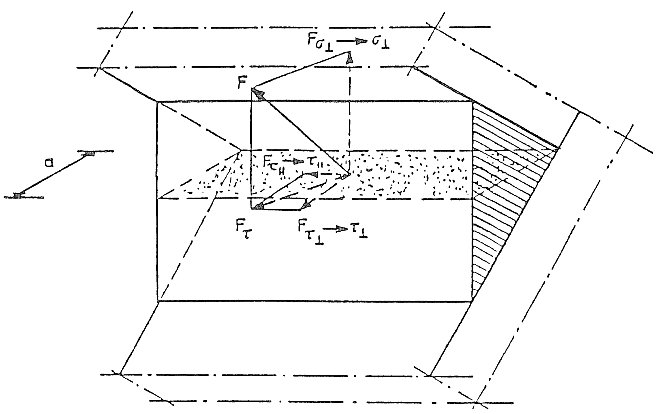


Fig. 4. Definition of stresses in minimum throat section of fillet welds according to [3] and [6].

According to the β-formula the stresses in the throat section have to satisfy:

$$\beta\sqrt{\sigma_{\perp}^{2}+3(\tau_{\perp}^{2}+\tau_{//}^{2})}\leq\sigma_{\mathrm{d}}$$

where:

σ_d = design strength of weld metal (in [3], [6]: $\sigma_d = \sigma_{0,2_w}$)
β = factor to compensate for the difference in strength and ductility of fillet weld metal and butt weld metal and to correct the value 3 which in reality is 2.6 for failure

Applying the β-formula, a difference in design strength between transverse and longitudinal fillet welds of $\sqrt{3}/\sqrt{2} = 1.22$ is assumed.
In [7], [8] and [10] results from tests on transverse and longitudinal fillet welds are reported. It appears that:

- The rupture section is very close to the minimum throat section of the welds, except in the case of low strength parent metals and high-strength filler metal, with which failure at the legs of the weld occurred, as was expected!
- Transverse fillet welds are at least 20% stronger than longitudinal fillet welds. An "exact" figure cannot be derived from these tests.
- Except for parameters similar to those mentioned in 3.2 and influencing the mechanical properties of fillet welds, it was observed that the shear strength of longitudinal fillet welds was below the shear strength of the weld metal (butt weld test).
- The deviation in results was considerable, which meant a considerable difference between mean value and characteristic stength (95% confidence level).
- Many weld defects were found such as lack of fusion, lack of penetration and porosity. In short: MIG welding yielded better results than TIG, while longitudinal fillet welds showed fewer defects than transverse fillet welds.
- The results of [7] and [8] are based on the rupture section while for [10] the nominal section is considered. This makes a comparison of results difficult.

The results have been analysed and, where possible, characteristic values for the ultimate strengths have been determined. The main results of [7] and [8] are shown in Fig. 5, while comparable results of [8] and [10] are given in Fig. 6. However, it should be noted that these results have no general validity, since:

- The number of parameters varied is too small (in [7] - two filler metals, two thicknesses $t = 12$ and 20 mm; in [8] - one thickness $t = 8$ mm and only MIG welding; in [10] - only MIG welding).
- The number of tests per parameter did not always allow a statistical evaluation of results; only mean values were given.

Thus, the conclusions and design values for the strength of both butt and fillet welds given in these studies cannot be endorsed!

3.4 *Design of welded connections*

For the design of welded connections it is often required that a prescribed allowable

		results according to [7]							results according to [8]	
welding processes →		MIG				TIG			MIG	
type of fillet weld →		longitudinal			transv.	longitudinal		transv.	long.	transv.
throat dimension →		4 mm	7 mm	10 mm	7 mm	4 mm	7 mm	7 mm	4 mm	4 mm
filler metal	parent metal									
5154	6082-T6								(52)	135 (172)
	5754-H34								(127)	153 (191)
5356	7020-T6	149	(121)	(155)	(203)	(140)	111 (135)	106 (142)	(164)	181 (207)
	6082-T6								(142)	153 (182)
	5754-H34								(150)	178 (204)
	5083-F	161 (214)	(157)	(168)	(160)	(152)	132 (151)	89 (155)		
5183	7020-T6								(167)	170 (216)
	6082-T6								(72)	170 (205)
	5754-H34								(144)	177 (206)
4043	6082-T6	118 (151)	(127)	(116)	(164)	(90)	72 (92)	67 (110)	(123)	125 (151)

Fig. 5. Ultimate shear strengths for fillet welds according to [7] and [8], characteristic and mean values (in brackets) for stresses $\tau_{/\!/}$ and $\tau_{\perp}$ in N/mm^2.

		results according to [10]		results according to [8]			
welding process →		MIG		MIG		column 2 divided by column 1	
type of fillet weld →		long.	transv.	long.	transv.		remarks
parent metal	filler metal	1	2	3	4	5	6
5754-H111	5154	81	107	(127)	153	1.32	[8]: results for 5754-H34
5085-H111	5183	96	169/201	–	–	1.76	column 3 and 4 according to [7]
	5356	103	148/228	161	(160)	1.44	
6060-T5	4043	71	132	–	–	1.86	
6060-T6	5356	95	135/167	–	–	1.42	
6082-T6	4043	82/90	100/152	118	125	1.22	
	5356	86	161	(142)	153	1.87	
7020-T6	4043	76/100	142	–	–	1.87	
	5356	110	187	149	181	1.70	
	5280	132/147	159/207	–	–	1.20	
7051-T6	4043	86/110	116	–	–	1.35	
	5356	102/126	116/148	–	–	1.14	
	5280	94/118	164/196	–	–	1.74	

Fig. 6. Ultimate shear strengths for fillet welds according to [10] and [8]; characteristic and mean values (in brackets) for stresses $\tau_{/\!/}$ and $\tau_{\perp}$ in N/mm^2. Note: in columns 1 and 2 sometimes two values are given, the higher for $t = 4$ mm and the lower $t = 20$ mm!

stress is nowhere exceeded in the connection. This approach is followed in [2], among others. Even with simple connections elaborate calculations have to be carried out. Thus, simplifications are applied which lead to over-dimensioning of the connection. Besides, in reality the allowable stress will locally always be exceeded because of stress and strain concentrations.
A second approach is to distribute the forces acting on the connection over the respective welds in a convenient way and take care to satisfy equilibrium. Then it should be checked if the welds are capable of carrying the loads distributed to them. This approach is recommended in [1] and [6].
A third approach is very similar to the second, but gives additional rules for the design, i.e. it should be checked whether the forces distributed over the welds can occur in reality! In other words, do the welds possess sufficient deformation capacity to allow the assumed force distribution over the welds? This approach is given in [3]. Alternatively, it is permissible to calculate the welds for the stresses occuring in the connected parts of a member; for example, in a beam-column connection loaded by moment and shear forces, the flange welds balance the tensile stresses in the flange due to the moment force, and the web welds the balance tensile and shear stresses due to both moment and shear forces, see [11].
The results of the literature study as reported above, determined the parameters which have been studied in the experimental and theoretical research described in the next chapters.

4 Experimental research on mechanical properties

4.1 *Choice of parameters*

In view of the results of the literature study concerning mechanical properties of the weld metal and heat-affected zone, it was decided to carry out an experimental research into the parameters which really influence the above mechanical properties. The following parameters were chosen:
- 4 alloys, namely, 5083-0, 6063-T5, 6082-T6 and 7020-T6;
- 2 filler metals, namely, 5356 and 4043;
- 2 plate thicknesses, namely, $t=4$ mm and $t=12$ mm;
- 2 weld types, namely, T-weld (square-groove weld) and V-weld (single V-weld);
- 2 welding processes, namely, MIG (spray-arc) and TIG (AC).

In this programme, comprising specimens all welded by one firm, the following were not varied: the welder, the welding position (1G) and the welding parameters (determined by the weld quality which was chosen at level 2AaAb according to the IIW classification of radiographs (see also 4.2)).

In order to restrict the number of tests and because all combinations of parameters need not be investigated (for instance: $t=4$ mm and a V-weld), the combinations as shown in Figs. 10 and 11 were studied.

Note: 1. The plate thicknesses and the weld types are combined.
2. Filler metal 4043 is not combined with alloy 5083.
3. TIG welding is only used for thin plates.

Besides the above test specimens, which were welded by Bayards, butt-welded plates were welded by other firms participating in this research programme (see 2). In that additional programme were investigated: the alloys 6063 and 6082 (and additionally: 1060, 5005 and 5052), filler metals 5356 and 4043 (and additionally: 5554), plate thickness $t = 4$ mm, TIG and MIG welding.

4.2 *Welding test specimens*

The test specimens were welded according to a detailed specification concerning edge preparation, cleaning, tacking, qualification of welding procedure and welder, and recommendations for the welding parameters to be used. Approval of the welding procedure, welder and choice of welding parameters based on the results of radiographic testing which were compared with the reference radiographs of IIW.
The specimens used in this programme are butt-welded plates as shown in Fig. 7.
In this test programme qualification specimens as well as test specimens were used, provided both received a similar classification. If this classification deviated from 2AaAb, the location and the dimension of the origin of this deviation (the "weld defect") was recorded on the plates. A period of six weeks separated welding and testing.

4.3 *Test results*

To determine the mechanical properties of the parent metal, weld metal and heat-affected zone, standard tensile coupons taken parallel to the weld axis as shown in Fig. 7 were tested. The results have been summarized in Fig. 8.

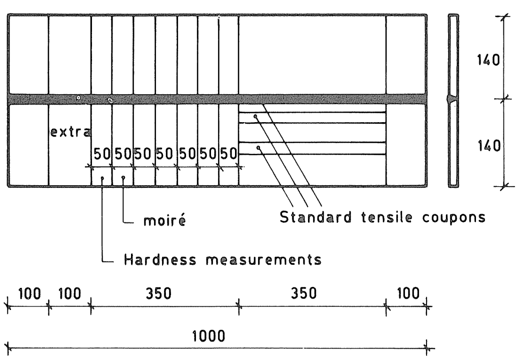


Fig. 7. Butt welded joint; dimensions in mm; position of the weld; position and dimensions of different test specimens.

welding process	filler metal	thickness	mech. prop.	5083-0	6063-T5	6082-T6	7020-T6
parent metal							
		$t=$ 4 mm	$\sigma_{0.2}$ (N/mm^2)	142	178	284	408
			σ_u (N/mm^2)	300	218	316	442
			A5 (%)	26	12	13	14
		$t=$ 12 mm	$\sigma_{0.2}$ (N/mm^2)	184	188	310	404
			σ_u (N/mm^2)	334	210	338	448
			A5 (%)	19	18	14	12
heat-affected zone							
MIG		$t=$ 4 mm	$\sigma_{0.2}$ (N/mm^2)	150	134	166	276
			σ_u (N/mm^2)	298	172	238	388
			A5 (%)	25	14	14	12
		$t=$ 12 mm	$\sigma_{0.2}$ (N/mm^2)	160	136	208	262
			σ_u (N/mm^2)	320	172	256	400
			A5 (%)	21	18	13	14
TIG		$t=$ 4 mm	$\sigma_{0.2}$ (N/mm^2)		88	118	
			σ_u (N/mm^2)		150	190	
			A5 (%)		17	16	
weld metal							
MIG	5356	$t=$ 4 mm	$\sigma_{0.2}$ (N/mm^2)	134	87	128	174
			σ_u (N/mm^2)	240	174	220	258
			A5 (%)	13	14	13	7
		$t=$ 12 mm	$\sigma_{0.2}$ (N/mm^2)	128	99	106	170
			σ_u (N/mm^2)	268	212	228	296
			A5 (%)	17	22	16	6
	4043	$t=$ 4 mm	$\sigma_{0.2}$ (N/mm^2)		89	116	170
			σ_u (N/mm^2)		156	204	239
			A5 (%)		9	9	4
		$t=$ 12 mm	$\sigma_{0.2}$ (N/mm^2)		83	108	140
			σ_u (N/mm^2)		180	204	229
			A5 (%)		13	9	4
TIG	5356	$t=$ 4 mm	$\sigma_{0.2}$ (N/mm^2)		104	101	
			σ_u (N/mm^2)		204	227	
			A5 (%)		16	14	

Fig. 8. Typical mechanical properties of the parent metal, heat-affected zone and weld metal.

A macro section of all the welded joints was made perpendicular to the weld axis to measure the hardness of parent metal, heat-affected zone and weld metal according to the Brinell Method. One example is shown in Fig. 9.
All the results of the hardness measurements, including those of the fillet welded joints (see 5), are given in [12].
To determine the ultimate strength of the weld metal and heat-affected zone with sufficient reliability and to check the influences-mentioned in the literature – on these

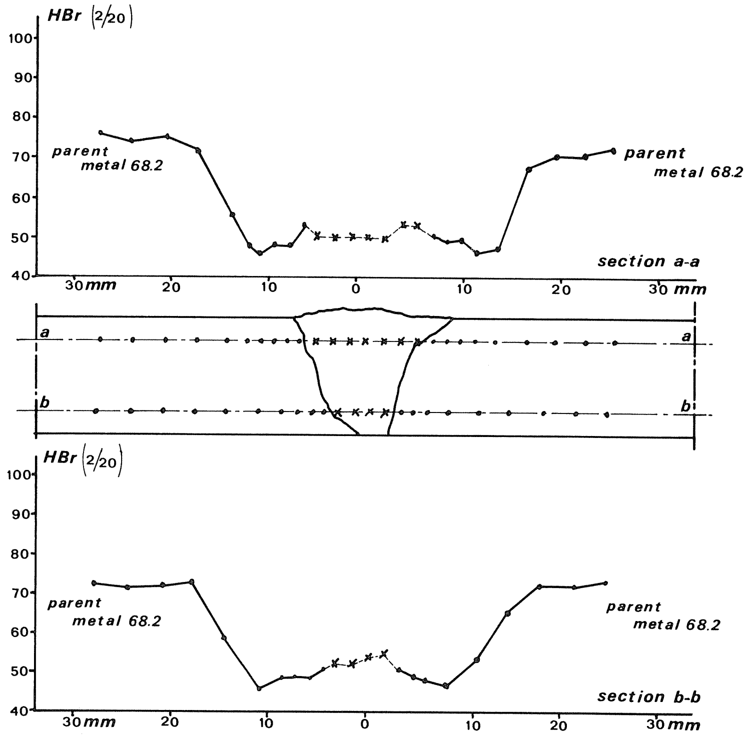


Fig. 9. Brinell hardness measurements. Butt-welded specimen, thickness $t = 12$ mm. Alloy: 6063-T5. Filler metal: 4043. Welding process: MIG.

strengths, at least five tensile specimens were taken from each butt-welded joint perpendicular to the weld axis, as shown in Fig. 7. Specimens with weld defects (see 4.2) were included in these five specimens. The weld reinforcement of the tensile specimens was removed.

The results of these tensile tests are given in Fig. 10. For the alloys 5083, 6063 and 6082 failure occurred in the heat-affected zone, while for alloy 7020 weld failure occurred. To determine the ultimate strength of the weld metal for the alloys 5083, 6063 and 6082 and the ultimate strength of the heat-affected zone for the alloy 7020, five tensile coupon specimens were taken from each butt-welded joint parallel to the weld axis. The results of these tests are given in Fig. 11.

Besides the ultimate strengths, the deformations occurring both in heat-affected zone and weld were measured using the moiré-method. One tensile specimen perpendicular to the weld axis was taken from each welded joint, see Fig. 7. Fig. 12 shows, moiré photographs of the specimen [6063-T5/5356/4T/TIG-welded]. Failure occurred in the heat-affected zone. Specimen [7020-T6/5356/12V/MIG-welded] is shown in Fig. 13. Failure occurred in the weld.

The results of the tensile tests for determining the ultimate strength of the weld metal and heat-affected zone and for measuring the deformations are given in [13].

welding process	filler metal	thickness	5083-0	6064-T5	6082-T6	7020-T6
MIG	5356	$t = 4$ mm	$\sigma_{uHAZ} = 296$	$\sigma_{uHAZ} = 150$	$\sigma_{uHAZ} = 206$	$\sigma_{uw} = 265$
			295	150	216	244
			298	151	210	251
			298	152	212	260
			298	149	216	253
		$t = 12$ mm	$\sigma_{uHAZ} = 304$	$\sigma_{uHAZ} = 159$	$\sigma_{uHAZ} = 223$	$\sigma_{uw} = 299$
			318	157	222	284
			313	159	224	296
			323	162	228	305
			320	158	216	302
	4043	$t = 4$ mm		$\sigma_{uHAZ} = 151$	$\sigma_{uHAZ} = 216$	$\sigma_{uw} = 224$
				151	198	245
				154	217	248
				152	210	239
				151	214	244
		$t = 12$ mm		$\sigma_{uHAZ} = 155$	$\sigma_{uHAZ} = 217$	$\sigma_{uw} = 217$
				150	225	243
				151	226	223
				151	222	229
				152	224	239
TIG	5356	$t = 4$ mm		$\sigma_{uHAZ} = 142$	$\sigma_{uHAZ} = 167$	
				154	169	
				141	174	
				140	171	
				143	170	

Fig. 10. Ultimate strenghts σ_u (N/mm^2) of tensile specimens $\perp$ to the weld axis (see Fig. 7). Failure of heat-affected zone: σ_{uHAZ}, failure of weld: σ_{uw}.

4.4 *Evaluation of results*

The results of the ultimate strengths of the weld metal and heat-affected zone (Figs. 10 and 11) have been evaluated statistically by means of an analysis of variances (see [14]). The influence of parameters varied (or combinations of parameters) on the total deviation of the test results is measured by this method.

In Fig. 14 the table of the analysis of variance as determined for the ultimate strength of the weld metal is given, and similarly in Fig. 15 for the ultimate strength of the heat-affected zone. By comparing the variances due to the different sources and listed in the last column of Figs. 14 and 15 with the residual variance, which is an estimate of the magnitude of the "experimental error", and using the variance ratio test of Snedecor ("F-test"), it can be ascertained whether or not a source of variation has a significant influence on the deviation of the test results. If a higher order interaction proves to be significant, it is not permissible to test lower-order combinations against the residual.

welding process	filler metal	thickness	5083-0	6063-T5	6082-T6	7020-T6
MIG	5356	$t=$ 4 mm	$\sigma_{uw}=245$	$\sigma_{uw}=177$	$\sigma_{uw}=232$	$\sigma_{uHAZ}=390$
			258	174	223	384
			255	176	238	385
			259	173	229	379
			251	174	231	382
		$t=$ 12 mm	$\sigma_{uw}=277$	$\sigma_{uw}=217$	$\sigma_{uw}=230$	$\sigma_{uHAZ}=409$
			278	221	240	422
			285	217	236	420
			258	218	241	420
			268	212	228	400
	4043	$t=$ 4 mm		$\sigma_{uw}=168$	$\sigma_{uw}=210$	$\sigma_{uHAZ}=384$
				172	219	381
				172	208	379
				150	205	367
				169	212	378
		$t=$ 12 mm		$\sigma_{uw}=178$	$\sigma_{uw}=222$	$\sigma_{uHAZ}=411$
				182	210	417
				187	211	416
				186	205	414
				180	212	415
TIG	5356	$t=$ 4 mm		$\sigma_{uw}=149$	$\sigma_{uw}=227$	
				186	218	
				184	209	
				192	230	
				185	236	

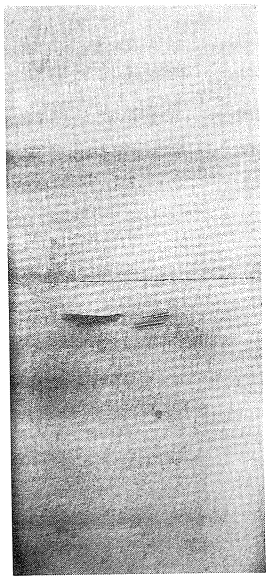
Fig. 11. Ultimate strenghts σ_u (N/mm^2) of tensile specimens // to the weld axis.
Failure of heat-affected zone: σ_{uHAZ}, failure of weld: σ_{uw}.

Concerning the ultimate strengths of the weld metal it can be stated that:

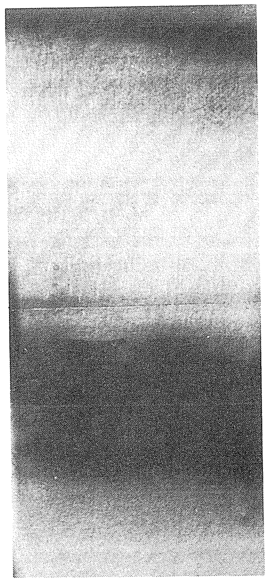
- The influence of the combination alloy/filler metal/thickness is very significant. In other words, each combination yields different values for the ultimate strength of the weld metal.
- Mutual comparison of variances reveals a significant influence of the alloy in all cases, whereas the influences of filler metal and thickness are not significant.
- The residual variance is small, i.e. the deviation in results due to the experimental error and no other source of variation, is small.

Proceeding from the above results, in Fig. 16 *characteristic values for the ultimate strength of the weld metal* are given for the combinations of alloy/filler metal/thickness that were studied. These values were determined by:

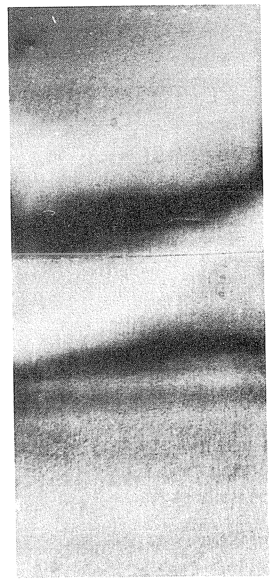
- The residual variance as a measure for the standard deviation (see fig. 14: $\sigma=\sqrt{48}=$ 6,93 $\rightarrow \sigma=7$ N/mm^2).
- ISO Standard 3207 “Statistical interpretation of data determination of a statistical tolerance interval” for characteristic values with a confidence level of 95%.



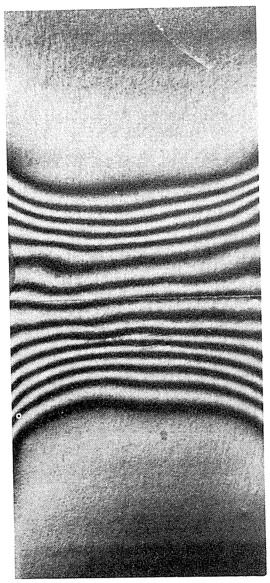
$F = 0$ kN



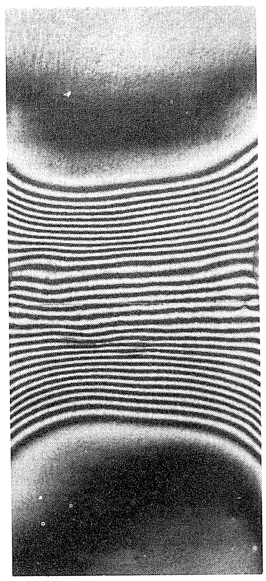
$F = 10$ kN



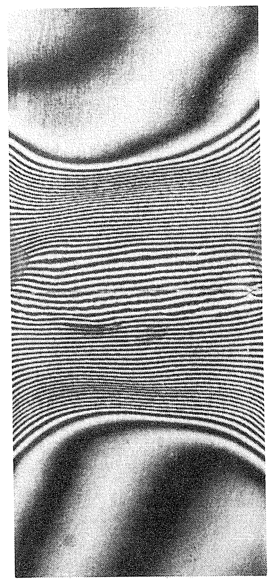
$F = 15$ kN



$F = 20$ kN
$\varepsilon_{weld} = 1{,}6\%$
$\varepsilon_{HAZ} = 2{,}1\%$



$F = 23$ kN
$\varepsilon_{weld} = 3{,}2\%$
$\varepsilon_{HAZ} = 4{,}4\%$



$F = 25$ kN
$\varepsilon_{weld} = 4\%$
$\varepsilon_{HAZ} = 10\%$
(failure: $F_u = 25{,}1$ kN)

Fig. 12. Moiré-pictures at different load levels, specimen 6063-T5/5356/4T/TIG; Scale 100 : 135; undeformed grid: 20 lines/mm, so each moiré-line means a displacement of 0.05 mm.
Moiré-pictures at load levels close to failure, failure heat-affected zone.

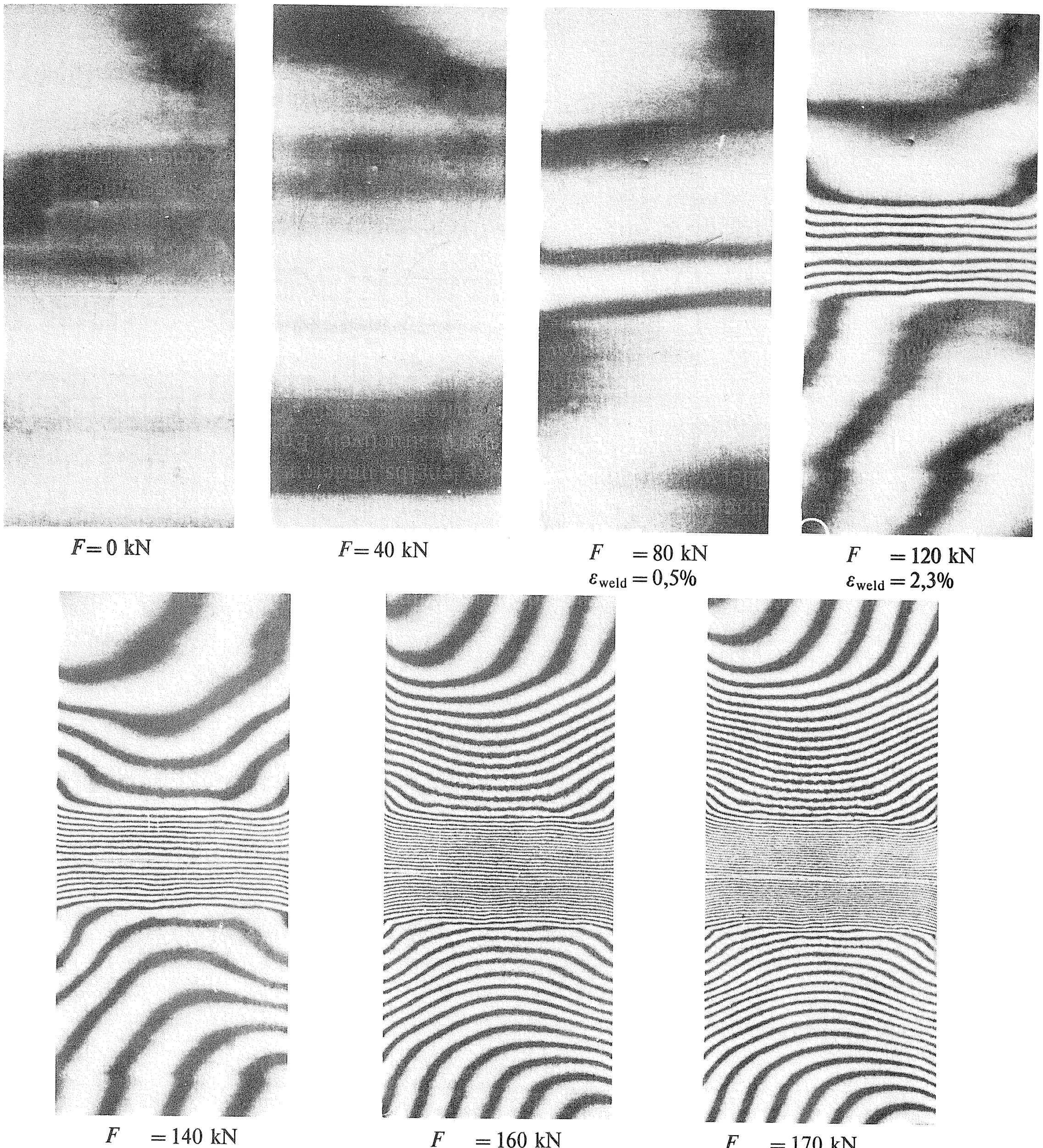


Fig. 13. Moiré-pictures specimen 7020-T6/5356/12V/MIG; Scale 100 : 135.
Moiré-pictures at load levels close to failure, failure weld.

nature of effect	source	sum of squares	degrees of freedom	variance estimate
main parameters	A	49534	2	24767
	F	11677	1	11677
	t	3921	1	3921
interaction between 2 parameters	AF	1247	2	624
	At	1755	2	878
	Ft	2760	1	2760
interaction between 3 parameters	AFt	1547	2	774
replication	residual	2300	48	48
	total	74741	59	

Fig. 14. Table of analysis of variance of the ultimate strengths of the weld metal σ_{uw} (Figs. 10 and 11). Parameters varied were: Alloy-A, Filler metal-F and thickness $-t$.

nature of effect	source	sum of squares	degrees of freedom	variance estimate
main parameters	A	642710	2	321355
	F	64	1	64
	t	4002	1	4002
interaction between 2 parameters	AF	21	2	11
	At	2329	2	1165
	Ft	0	1	0
interaction between 3 parameters	AFt	148	2	74
replication	residual	1090	48	23
	total	650364	59	

Fig. 15. Table of analysis of variance of the ultimate strengths of the heat-affected zone σ_{uHAZ} (Figs. 10 and 11). Parameters varied were: Alloy-A, Filler metal-F and thickness t.

welding process	filler metal	thickness	5083-0	6063-T5	6082-T6	7020-T6
MIG	5356	$t=$ 4 mm	237	158	214	238
		$t=$ 12 mm	257	200	218	281
	4043	$t=$ 4 mm	-	150	194	223
		$t=$ 12 mm	-	166	195	214
TIG	5356	$t=$ 4 mm	-	163	207	-

Fig. 16. Characteristic values (95% confidence level) for ultimate strength of the weld metal σ_{uw} in N/mm^2.

Concerning the ultimate strengths of the heat-affected zone the analysis of variance arrived at the following:
- The influence of the combination alloy/filler metal/thickness is hardly significant.
- The influence of the combination alloy/thickness is very significant.
- Mutual comparison of variances shows a very significant influence of the alloy, whereas all other parameters and combinations of parameters are not significant.
- The residual variance again is small (see also the results for the weld metal), so the deviation in results due to the experimental error is small.

In Fig. 17 *characteristic values for the ultimate strengths of the heat-affected zone* are given for combinations of alloy and thickness, which are determined in the same way as for the weld metal. (In this case: $\sigma = 5$ N/mm²).

welding process	thickness	5083-0	6063-T5	6082-T6	7020-T6
MIG	$t = 4$ mm	285*	140	200	370
	$t = 12$ mm	304*	145	212	404
TIG	$t = 4$ mm	–	132	158	–

* Hardly any influence of heat-input, mean values $\sigma_{uHAZ} = 297$ ($t = 4$ mm) and 316 ($t = 12$ mm) N/ mm² (see also Fig. 10)

Fig. 17. Characteristic values (95% confidence level) for ultimate strength of heat-affected zone σ_{uHAZ} in N/mm².

Finally, all the relevant results, both from the literature (see 3.2) and the present study, concerning ultimate strengths of the weld metal and heat-affected zone are presented in Figs. 18 to 22 for the respective alloys and filler metals. With respect to the results in the above diagrams the following can be observed:
- Comparable results from literature and from the present study, are in reasonably good agreement with a few exceptions.
- For the ultimate strengths of the weld metal:
  - Thicker plates yielded higher values, contrary to the literature, but the influence of the thickness is not significant.
  - The TIG results for thin plates agree very well with comparible results for MIG.
- For the ultimate strengths of the heat-affected zone:
  - For "normal" choices of welding parameters and welding process similar values are found in the present study and in the literature. In "abnormal" circumstances (see Fig. 2: TIG + $t = 20$ mm) considerably lower values may be found especially for 6082-T6.
  - The results of series 4 (see 4.1) in Figs. 19 and 20, which correspond to the numbers 9 and 10 in the plots, appeared to be within the scatter band of the results of the reference programme (series 1, 2 and 3).

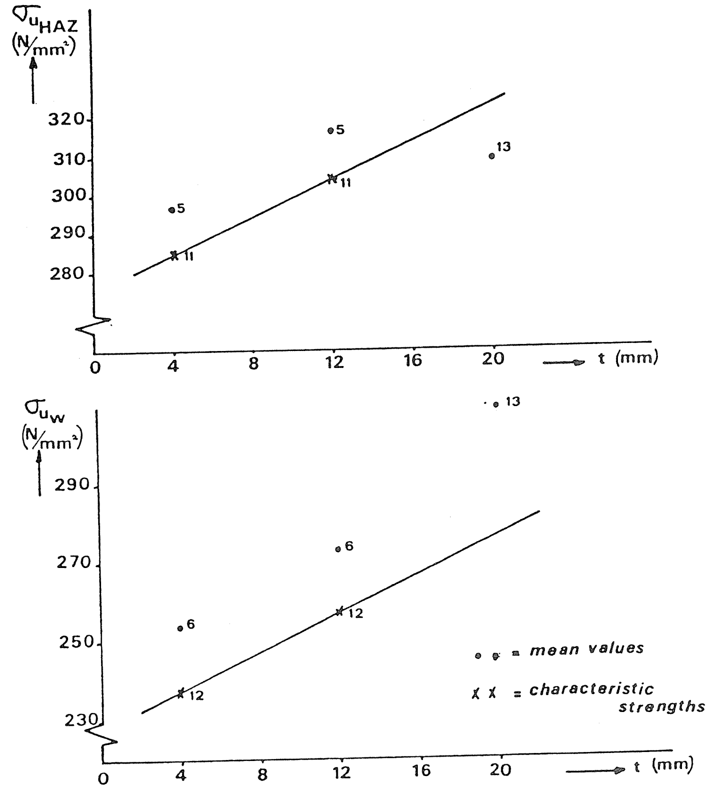


Fig. 18. Failure strengths 5083-0 and F + 5356.
The numbers in the diagrams correspond to:
.5, 6, 11 and 12 → TNO research [13],
.13 → IIW research [7].

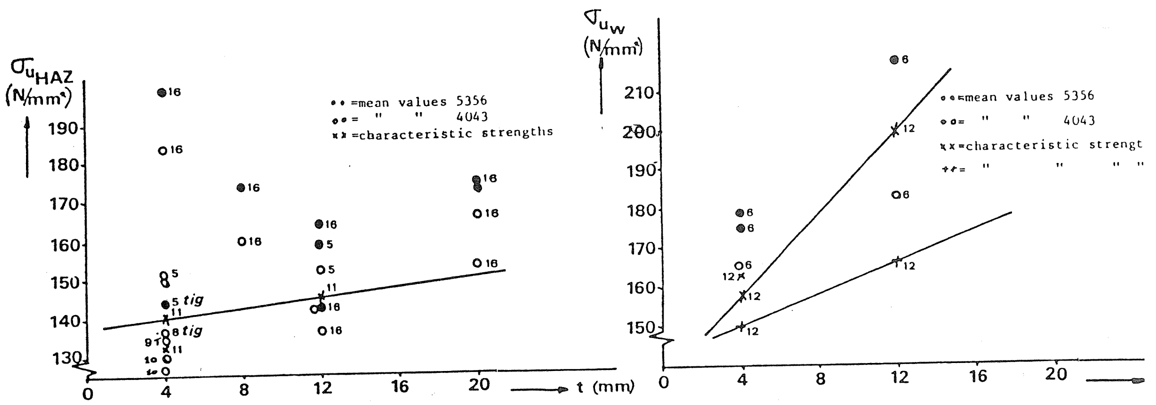


Fig. 19. Failure strengths 6063-T5 + 5356 and 4043.
The numbers in the diagrams correspond to:
.5, 6, 8, 9, 10, 11 and 12 → TNO [13],
.16 → Pechiney [10].

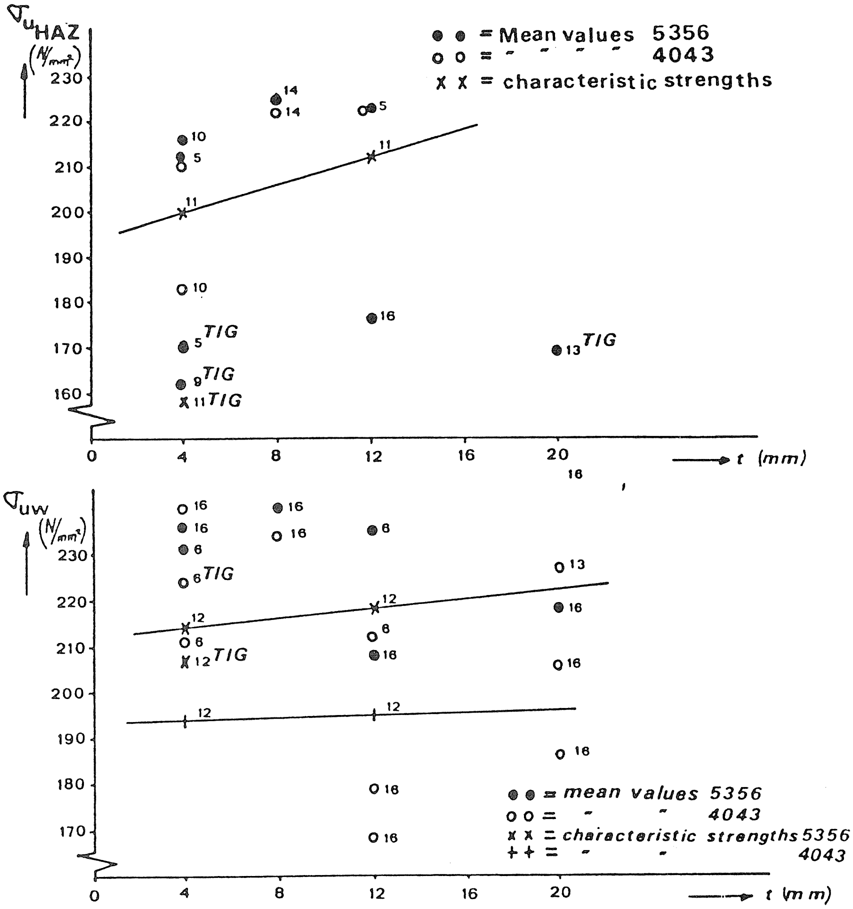


Fig. 20. Failure strengths 6082-T6 + 5356 and 4043.
The numbers in the diagrams correspond to:
.5, 6, 9, 10, 11 and 12 → TNO [13],
.13 → IIW (TIG results) [7],
.14 → FMPA (Germany) [8],
.16 → Pechiney [10].

4.5 *Conclusions relating to mechanical properties*

The following conclusions can be drawn from the results relating to mechanical properties as discussed in this chapter:

- The results from this study - both for the weld metal and the heat-affected zone - agree reasonably well with comparable results from literature.
- Based on the statistical analysis of the results, it was pointed out that:
  - The ultimate strength of the weld metal depends on the combination alloy/filler metal/plate thickness (weld type). However, the welding process has no significant influence. (TIG and MIG yield similar results in the case of relatively thin plates).

- The ultimate strength of the heat-affected zone depends on the combination alloy/time-temperature relationship in the plate material.
  The TIG-process yields less good results than the MIG-process.
- Both for the ultimate strengths of the weld metal and for the heat-affected zone characteristic values have been determined which provide a suitable basis for the design of welded connections in aluminium alloys.

- The results of the additional programme (series 4) proved to be within the scatter band of the results of the reference programme.
- The results of the hardness measurements do not allow a better approximation of the dimensions of the heat-affected zones than the "1-inch" rule.

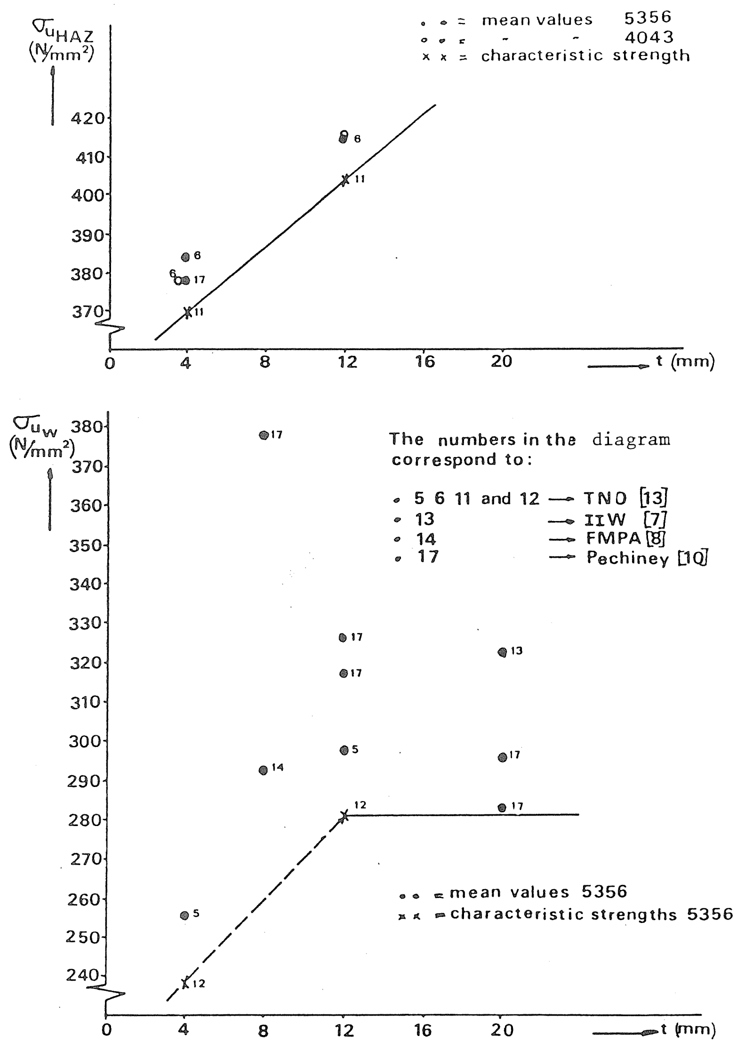


Fig. 21. Failure strengths 7020-T6 + 5356 and 4043.

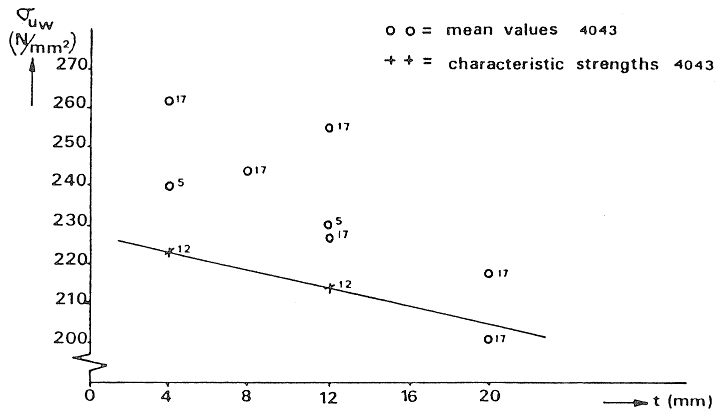


Fig. 22. Failure strengths 7020-T6 + 4043.
The numbers in the diagram correspond to:
.5, 12 → TNO [13],
.17 → Pechiney [10].

5 Experimental research of fillet welds

5.1 *Choice of parameters*

In view of the results of the literature study concerning fillet welds and the investigation of mechanical properties an experimental research on fillet welds was carried out with the following parameters:

- alloys and filler metals identical to the research on mechanical properties (see 4.1);
- 2 types of connections, see Figure 23;
- 1 plate thickness, namely $t = 12$ mm;
- 1 throat thickness fillet weld, namely $a = 5$ mm;
- 1 welding process, namely MIG (spray-arc).

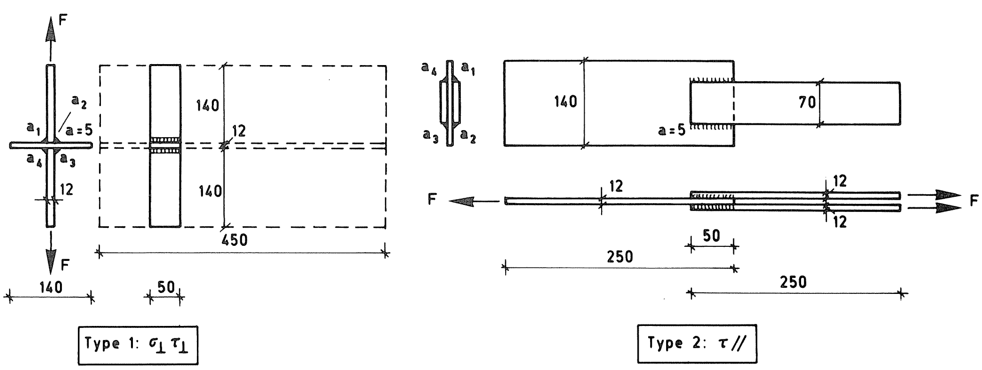


Fig. 23. Test specimens for fillet welds, types 1 and 2; dimensions in mm.

In this programme the following were not varied:
- the welder, all plates were welded by the same, qualified welder;
- the welding position, only the flat position (2F) was applied;
- the welding parameters, the choice of the welding parameters was determined by the weld quality which was prescribed in the welding procedure specification.

Under the test programme on mechanical properties, the combinations of parameters as shown in Figs. 28 and 29 were investigated in the experimental research on fillet welds.

5.2 *Welding test specimens*

Welding of the test specimens was carried out according to a detailed welding procedure specification concerning edge preparation, cleaning, tacking, welding position, i.e. 2 F, welding sequence, qualification of welding procedure and welder, and recommendations for the welding parameters to be used. The qualification was based on visual inspection of the fillet welds (throat a, equal leg lengths, undercut, overlap and cracks), except for the root penetration which was tested destructively. Ensuring sufficient root penetration appeared to be most difficult of all criteria to satisfy. In [5] it was concluded that sufficient root penetration is achieved when the arc voltage and the current are as high as possible, namely just below burning of weld metal occurs.
The specimens used in this programme are shown in Fig. 23. With the specimens of type 1 four welds (a_1 up to a_4) of 450 mm length were laid down. From this length 5 test specimens, each 50 mm in length, were taken (at both ends a length of 100 mm was not used).
In the case of type 2 each test specimen was welded separately, namely 5 test specimens for each combination of alloy and filler metal. For welding these specimens, "run-on, run-off" plates were used.

5.3 *Testing*

The specimens of types 1 and 2 were loaded as shown in Fig. 23. With these tests only the failure strength of the specimens was recorded. Before testing, the dimensions of the throat section, length and throat thickness (a) were measured. After testing, the dimensions of the rupture section and the angle (ϕ), as indicated in Fig. 24, were measured.
The throat thickness (a) was measured from the outside. Besides, for each combination of alloy and fillet metal one macro-etch was made in order to measure the effective throat thickness (a_{eff}) and the penetration (p), see Fig. 24.
In Figs. 25, 26 and 27 the results of these measurements are summarized, i.e. only average values are given.
A period of about six weeks elapsed between welding and testing.

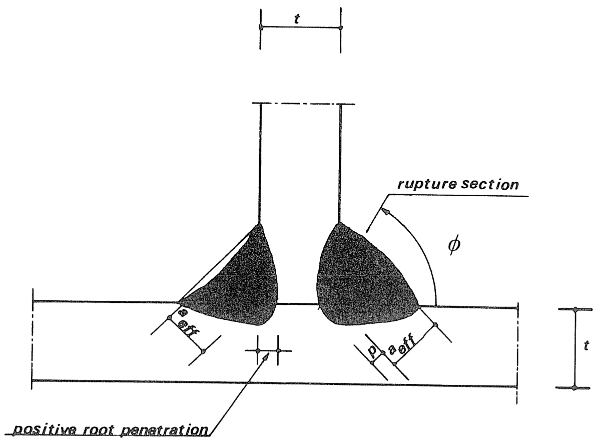


Fig. 24. Fillet weld: effective throat thickness (a_{eff}), and penetration (p) both measured in the throat section; positive root penetration. The situation and the angle ϕ of the rupture section are also indicated.

test specimen			throat section			rupture section			
type	filler metal	alloy	a [mm]	a_{eff} [mm]	p [mm]	a_1 [mm]	a_2 [mm]	ϕ_1	ϕ_2
1	5356	5083	5,9	6,1	2,0	8,7	8,5	55°	65°
		6063	5,5	6,0	2,3	8,2	8,5	55°	65°
		6082	5,5	6,0	2,6	8,3	7,7	60°	70°
		7020	6,5	6,4	2,3	8,2	8,6	55°	70°
	4043	6063	5,5	5,8	2,1	8,0	7,6	60°	70°
		6082	5,5	6,1	1,6	8,6	8,0	55°	70°
		7020	5,8	5,8	4,0	8,7	8,3	45°	60°

Note: throat section - average values of 4 welds (each weld length 450 mm)
rupture section - average values of 5 tests, rupture 2 welds a_1a_2 or a_3a_4 (each weld length 50 mm, see Fig. 23)

Fig. 25. Test specimen type 1.
Average values dimensions of throat section and rupture section.

5.4 *Test results for fillet welds*

To determine the ultimate strength of the fillet welds, five tensile tests per type of connection were carried out for every combination of parameters investigated.

The results of the tensile tests on the two types of connections are given in Figs. 28, 29 and 30: in Figs. 28 and 30 results of connection type 1, loaded perpendicularly to the weld axis, and in Fig. 29 results of connection type 2, loaded parallel to the weld axis.

test specimen			throat section			rupture section	
type	filler metal	alloy	a [mm]	a_{eff} [mm]	p [mm]	a_1 up to a_4 [mm]	ϕ_1 up to ϕ_4
2	5356	5083	5,8	5,4	3,3	8,0	55°
		6063	6,5	not measured	not measured	7,8	57°
		6082	6,0	5,8	3,2	7,9	58°
		7020	5,9	5,8	2,2	7,9	57°
	4043	6063	5,5	not measured	not measured	6,8	49°
		6082	5,3	4,9	3,8	7,0	53°
		7020	5,2	4,8	3,8	7,1	49°

Note: throat section - average values of 5 test specimen; per test specimen 4 welds of 50 mm length, see Fig. 23
rupture section - see above

Fig. 26. Test specimen type 2.
Average values dimensions of throat section and rupture section.

test specimen			throat section			rupture section			
type	filler metal	alloy	a [mm]	a_{eff} [mm]	p [mm]	a_1 [mm]	a_2 [mm]	ϕ_1	ϕ_2
1	5356	5083	5,5	5,8	2,4	8,0	7,8	55°	70°
		6082	5,5	5,4	2,1	7,8	7,6	55°	70°
		7020	6,3	5,9	2,5	8,1	8,1	57°	65°
	4043	6082	5,6	5,9	4,6	8,9	8,3	55°	60°

Note: throat section - average values of 4 welds (each weld length 450 mm)
rupture section - average values of 5 tests, rupture 2 welds a_1a_2 or a_3a_4 (each weld length 50 mm, see Fig. 23)

Fig. 27. Test specimen type 1, Additional tests.
Average values dimensions of throat section and rupture section.

The ultimate strength of the respective welds was determined by dividing the failure load (F_u) by the total area of the rupture section (Σ al). For the connection of type 2 this yields the ultimate shear strength $\tau_{uw_{//}}$ and for the connection of type 1 the ultimate shear strength $\tau_{uw_{\perp}}$. However, the latter is not correct since failure is due to a combination of tensile and shear actions on the rupture section, so this is not a "real" shear strength! But, in order to make a comparison with similar results from the literature study (see 3.3.2), for the connection of type 1 the value of $\tau_{uw_{\perp}}$ was calculated.
The results of *additional* tests on connections of type 1 are given in Fig. 30. After the specimens for the reference tests had been welded (Fig. 28), additional specimens were welded with similar welding parameters except for a higher travel speed. This yielded higher results (up to 15%) as can be inferred by comparing corresponding results of Figs. 28 and 30.

Besides the reference programme described above, an additional programme was carried out by the other firms, similar to the one described in 4.1, applying different alloys, filler metals, plate thicknesses, throat thicknesses and welding processes (MIG and TIG).

All the results are discussed in [16], except the results of the latter additional programme, which have been summarized in [21].

specimen type	filler metal	alloy	F_u [kN] (1)	b [mm] (2)	t [mm] (3)	σ [N/mm²] (4)	rupture section welds a_1 [mm] (5)	a_2 [mm] (6)	l [mm] (7)	Σal [mm²] (8)	$\tau_{uw\perp}$ [N/mm²] (9)	$\frac{\sigma_c}{\beta}$ [N/mm²] (10)
1	5356	5083	143,5	51,0	13,0	216	8,4	8,4	51,0	857	167	236
			144,0	50,5		222	9,2	9,1	50,0	915	157	222
			143,4	50,5		218	8,3	8,9	50,5	869	165	233
			150,5	50,5		228	8,6	7,9	50,5	833	180	255
			149,9	51,2		224	9,1	8,4	51,2	896	166	235
		6063	107,5	49,2	12,3	179	8,1	8,2	49,2	802	134	190
			114,0	50,7		184	8,1	8,1	50,7	821	139	197
			107,2	50,8		178	8,0	8,5	49,4	817	131	185
			106,0	51,0		170	8,9	8,9	51,0	801	118	165
			114,0	50,5		184	8,0	8,6	50,7	906	135	191
		6082	147,5	49,7	12,0	247	–	–	–	–	> 175	> 248
			144,0	49,0		247	–	–	–	–	> 173	> 247
			145,2	50,2		241	8,3	8,4	50,2	838	173	247
			139,5	48,9		238	9,0	8,0	48,9	831	168	238
			149,5	50,9		245	9,3	8,0	50,9	881	170	240
		7020	145,8	50,2	12,2	238	9,2	8,2	50,5	873	167	236
			146,2	51,6		232	8,0	9,3	51,6	893	164	232
			146,5	50,3		239	8,8	8,4	50,3	865	169	239
			138,1	49,5		229	7,8	8,2	49,5	792	174	246
			134,5	49,6		222	7,2	8,7	49,6	789	171	242
	4043	6063	93,8	50,2	12,2	153	8,2	7,7	50,2	798	118	167
			95,5	50,2		156	8,1	7,7	50,2	793	120	170
			96,5	51,6		153	7,7	7,5	51,6	784	123	174
			90,3	51,5		144	8,0	7,8	51,5	814	111	157
			95,2	50,7		154	8,2	7,2	50,7	781	122	173
		6082	106,2	50,4	12,2	172	8,8	7,9	50,4	842	126	178
			108,9	49,2		181	9,0	8,3	49,2	851	128	181
			114,0	50,8		184	8,7	8,0	50,8	848	134	190
			104,5	50,3		170	8,4	7,9	50,3	820	127	180
			107,4	52,4		168	8,2	8,1	52,4	854	126	178
		7020	133,0	50,2	12,2	217	9,0	8,0	50,2	853	156	221
			136,5	50,4		222	9,0	8,0	50,4	857	159	225
			130,5	50,0		218	9,0	8,5	50,5	875	149	211
			129,0	50,5		209	8,6	8,6	50,5	869	149	211
			131,0	51,5		209	8,0	8,6	51,5	855	153	216

Fig. 28. Results for ultimate strengths of fillet welds loaded ⊥ to the weld axis ($\tau_{uw\perp}$).

specimen			F_u [kN]	b [mm]	t [mm]	σ [N/mm²]	rupture section welds				σ_c / β [N/mm²]
							a_1–a_4 [mm]	l_1–l_4 [mm]	Σal [mm²]	$\tau_{uw\,//}$ [N/mm²]	
type	filler metal	alloy	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
2	5356	5083	254,0	69,9	12,4	147	8,3	51,0	1693	150	260
			239,8	69,8		139	7,9	51,0	1612	149	258
			257,0	69,9		148	8,5	51,0	1734	148	256
			235,0	70,0		135	7,5	51,0	1530	154	267
			234,0	69,9		135	7,7	50,0	1540	152	263
		6063	172,8	70,0	12,2	101	7,8	49,0	1529	113	196
			172,0	70,0		101	7,5	50,0	1500	115	199
			173,0	69,8		102	7,5	50,0	1500	115	199
			176,8	69,8		104	8,4	49,0	1646	107	185
			174,0	69,9		102	8,0	50,0	1600	109	189
		6082	188,0	69,9	12,2	110	8,2	51,0	1673	112	194
			189,0	70,0		111	7,7	51,0	1571	120	208
			202,0	69,6		118	8,1	51,0	1652	122	211
			188,0	70,0		110	7,4	51,0	1510	125	217
			184,1	70,0		108	8,3	51,0	1693	109	189
		7020	248,2	69,9	12,2	146	7,9	51,0	1612	154	267
			260,5	70,0		147	8,1	51,0	1652	152	263
			229,8	69,6		135	7,5	50,0	1500	153	265
			233,5	69,6		137	7,9	52,0	1643	142	246
			247,0	69,3		146	8,1	51,0	1652	150	260
	4043	6063	159,0	69,5	12,2	94	7,2	51,0	1469	108	187
			140,0	69,4		83	7,3	41,0	1197	117	203
			146,2	69,4		86	6,5	51,0	1326	110	191
			150,0	69,7		88	6,3	52,0	1310	114	197
			140,0	69,7		82	6,6	51,0	1346	104	180
		6082	172,4	69,9	12,2	101	7,2	51,8	1492	116	201
			177,5	70,0		104	7,0	52,0	1456	122	211
			172,9	69,6		102	6,8	51,5	1401	123	213
			187,2	69,5		110	7,7	51,3	1580	118	204
			183,0	69,7		108	7,1	52,5	1491	123	213
		7020	191,0	69,5	12,2	113	6,7	51,3	1375	139	241
			191,0	69,0		113	7,1	51,0	1448	132	229
			195,0	69,2		115	7,0	50,4	1411	138	239
			217,5	69,7		128	7,4	50,7	1501	145	251
			189,0	69,0		112	7,1	50,8	1443	131	227

Fig. 29. Results for ultimate strengths of fillet welds loaded // to the weld axis ($\tau_{uw\,//}$).

5.5 *Evaluation of results*

5.5.1 Weld areas

Although the welding was not a parameter in this test programme (see 5.1) the following can be observed regarding the weld areas (see also Figs. 25, 26 and 27):

- For the throat sections:
  - The throat thickness of 5 mm was achieved in almost all cases (according to the welding procedure specification: throat thickness minimum 5 mm and almost equal for all welds per test specimen).
  - The effective throat thickness (a_{eff}) is satisfactorily estimated by the throat thickness measured from the outside (a). This is the case so long as the welds possess equal leg length, the welds are not too convex (Fig. 24: right fillet weld), and positive root penetration is ensured (required according to the welding procedure specification).
  - With positive root penetration the values of the penetration p, measured along the throat section of the weld, see Fig. 24, were found to be rather high.
- For the rupture sections:
  - The thicknesses a_1 and a_2 (type 1) and a_1 to a_4 (type 2) are significantly higher than the values of the corresponding throat sections, which is due to the considerable penetration observed. Although the situation and the orientation (angle ϕ) of the rupture section differs from the throat section (see Fig. 24), the thickness of the rupture section can be satisfactorily estimated from the effective throat thickness plus the penetration p (a_1, a_2 resp. a_1 up to $a_4 \simeq a_{eff} + p$).

test specimen			F_u [kN]	rupture section a_1 [mm]	a_2 [mm]	l [mm]	Σal [mm]	$\tau_{uw\perp}$ [N/mm²]	$\frac{\sigma_c}{\beta}$ [N/mm²]
type	filler metal	alloy	(1)	(2)	(3)	(4)	(5)	(6)	(7)
1	5356	5083	146,4	7,5	8,2	50,3	790	185	262
			147,0	7,5	7,5	51,0	765	192	272
			163,5	8,6	7,6	52,0	842	194	274
			158,5	8,2	7,9	50,5	813	195	276
			156,5	8,4	7,7	50,0	805	194	274
		7020	154,2	8,1	8,5	49,1	815	189	267
			156,5	8,6	7,6	50,5	818	191	270
			154,5	8,1	7,8	50,3	800	193	273
			146,5	8,0	8,4	49,8	817	179	253
			155,2	8,7	7,5	50,3	815	190	269
			154,9	8,1	8,8	49,3	833	186	263
			157,0	8,0	8,3	50,0	815	193	273
			150,4	7,6	8,1	49,4	776	194	274
			155,2	7,7	7,7	50,3	775	200	283
	4043	6082	118,0	8,7	8,6	49,8	862	137	194
			134,5	9,2	8,0	52,2	898	150	212
			129,5	7,8	8,9	50,5	843	154	218
			133,0	9,0	7,9	51,0	862	152	218
			135,7	9,7	7,9	51,5	906	150	212

Fig. 30. Results for ultimate strenght of fillet welds (additional tests), loaded perpendicularly to the weld axis ($\tau_{uw\perp}$).

- The variation of the rupture thicknesses was small; generally: a_1, a_2 and a_1 to $a_4 \simeq 8{,}0 \pm 0{,}5$ mm, except for the connection of type 2 combined with filler metal 4043 (see Fig. 5): a_1 up to $a_4 \simeq 7{,}0 \pm 0{,}5$ mm. Differences between the type 1 reference tests and the additional tests with respect to the thickness of the rupture sections were not significant.
- The values of the angle ϕ varied between 40° and 75°. For the connection of type 1: mean values $\phi \simeq 60°$, for type 2: $\phi \simeq 55°$; in combination with filler metal 5356 higher values were found than with filler metal 4043.

With respect to the above-mentioned the ultimate strength of the fillet welds was based on the area of the rupture section.

5.5.2 Ultimate strengths

The results of the ultimate strengths of the fillet welds investigated were evaluated statistically by means of an analysis of variances, as was also carried out in the research programme on mechanical properties (see 4.4). In [16] such an analysis was performed using the results of Figs. 28 and 29, i.e. the reference tests. The table of analysis of variance is given in Fig. 31. With this analysis it was ascertained that:

- The influence of the combination alloy/filler metal/type of specimen (load direction) is very significant. Each combination yields different values for the ultimate strength of the fillet welds.
- The residual variance is small, i.e. the deviation in results due to the experimental error and no other source of variation is small.

Besides the analysis of variances as described, the results of the tests on fillet welds were compared with those of the literature study (see 3.3.2). In the Figs. 32 up to 35 all the

nature of effect	source	sum of squares	degrees of freedom	variance estimate
main parameters	A	11738	2	5869
	F	2898	1	2898
	t	6469	1	6469
interaction between 2 parameters	AF	375	2	188
	At	729	2	365
	Ft	1420	1	1420
interaction between 3 parameters	AFt	1527	2	764
replication	residual	1191	48	25
	total	26347	59	

Fig. 31. Table of analysis of variance of the ultimate strength of fillet welds (results Figs. 28 and 29).
Parameters varied: A = Alloy,
F = Filler metal,
t = type of specimen.

results per combination of alloy and filler metal are given, i.e. mean values for the ultim-shear strengths of fillet welds, loaded perpendicularly ($\tau_{uw\perp}$) or parallel ($\tau_{uw//}$) to the axis of the weld for different throat thicknesses (a).

- Generally the results of FMPA [8] and TNO (both reference and additional results) are in very good agreement, whereas the results of IIW [7] and Pechiney [10] do not agree very well with the other results, especially for $\tau_{uw\perp}$; besides, these results show considerable scatter.

  The main reason for this deviation is that the results of IIW and Pechiney are based on the throat section (measured from outside), whereas the results of

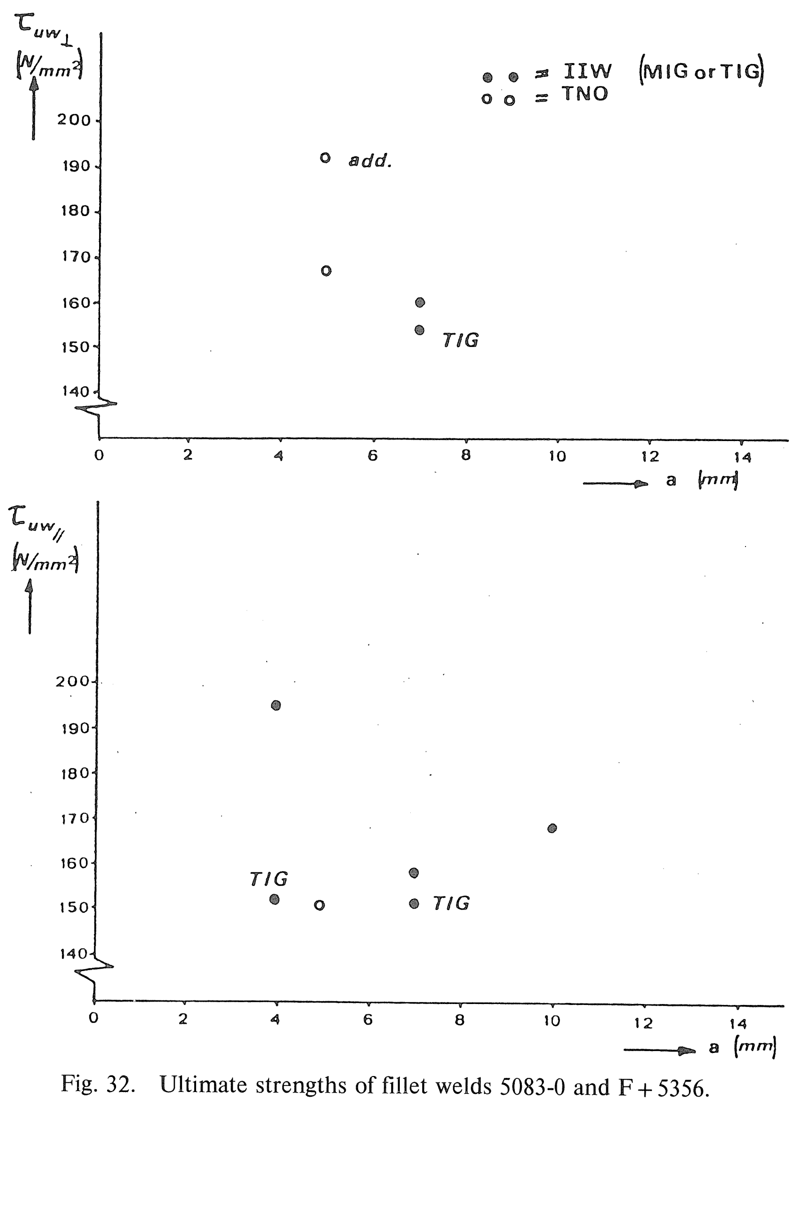


Fig. 32. Ultimate strengths of fillet welds 5083-0 and F + 5356.

FMPA and TNO are based on the rupture section. Besides, the type of specimen used by IIW and Pechiney is not very well suited to the determination of ultimate strengths of fillet welds.

- The TIG results - only IIW test [7] - are below the corresponding MIG results. (Most values in the diagrams are MIG results, except the values with a TIG label).

Summarizing, it is believed that the TNO results discussed are a reliable lower limit of the ultimate strengths of fillet welds. The literature results mostly are higher, sometimes lower, but these differences can be easily explained, as described before.

5.5.3 Design of fillet welds

As already stated (see 3.3.2 and also [11]), the actual strength of a fillet weld can be approximated very well by applying the β-formula, i.e.:

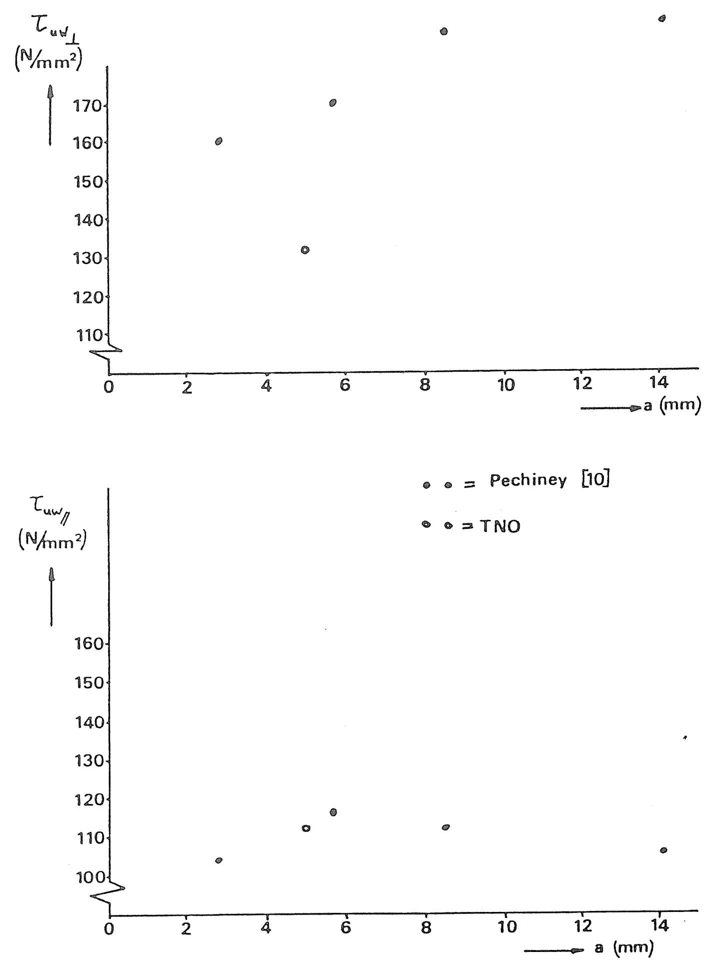


Fig. 33a. Ultimate strengths of fillet welds 6063-T5 + 5356.

$$\sigma_c = \beta \sqrt{\sigma_{\perp}^2 + 3(\tau_{\perp}^2 + \tau_{/\!/}^2)} \leq \sigma_d$$

with:

σ_c = comparison stress
$\sigma_{\perp}, \tau_{\perp}$ and $\tau_{/\!/}$ = stresses in throat section according to Fig. 4
σ_d = design strength
β = factor; the value of β is determined by differences in strength and ductility of fillet weld metal and butt weld metal, and the difference between the value 3 in the formula and the "exact" value 2.6

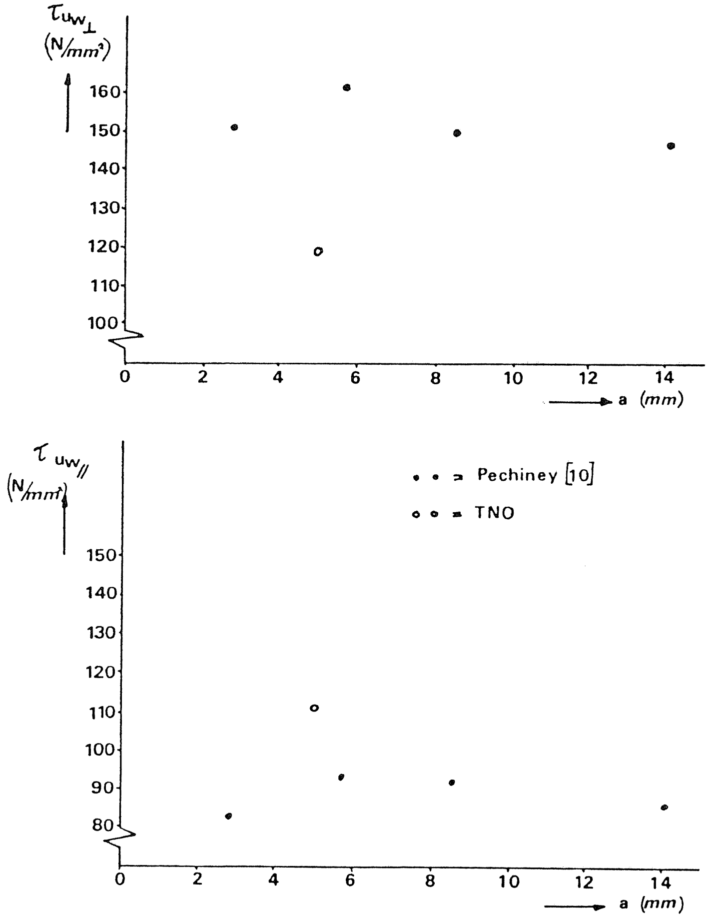


Fig. 33b. Ultimate strengths of fillet welds 6063-T5 + 4043.

For applying this formula the values of β and σ_d have to be known.
The design strength σ_d should be based on the ultimate strength of the weld metal σ_{uw} instead of $\sigma_{0,2_w}$ since the design rules are based on (ultimate) limit states for which the yield strength of the weld ($\sigma_{0,2_w}$) is of no significance. For this purpose the results of the experimental research on mechanical properties (see 4) can be used, i.e.

$$\sigma_d = \frac{\sigma_{uw}}{\gamma_u}$$

where

σ_{uw} = *characteristic value* for the ultimate strength of weld metal dependent on alloy and filler metal

γ_u = member resistance factor

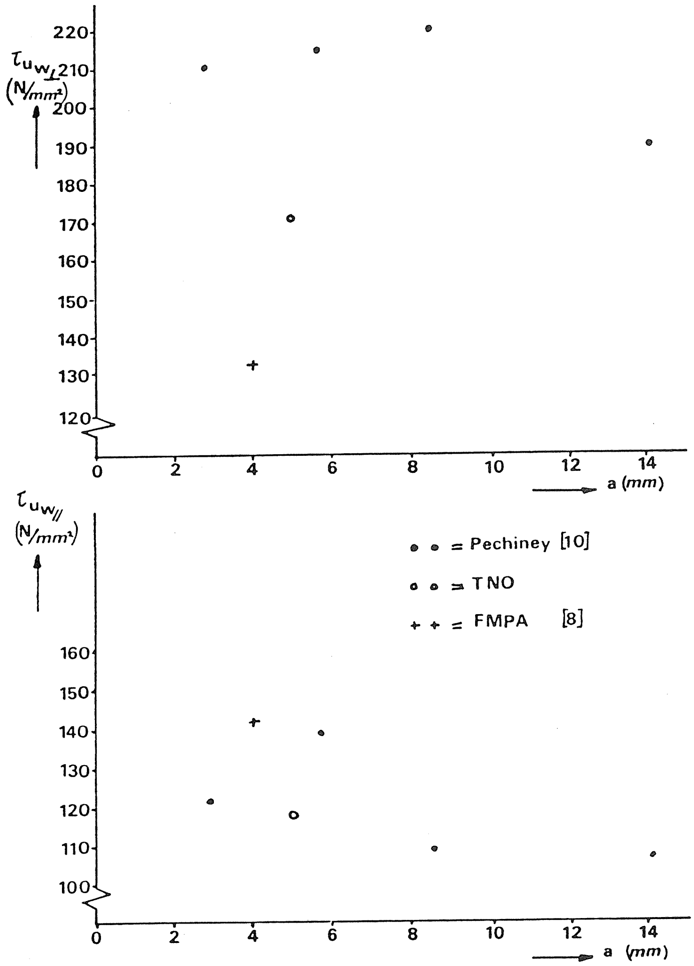


Fig. 34a. Ultimate strengths of fillet welds 6082-T6 + 5356.

Similarly to the determination of β in the case of steel structures (see [17]) the value of β has been calculated by comparing the ultimate strengths of fillet welds to the ultimate strengths of the corresponding weld metal.
Firstly, the values of σ_c/β have been determined for both types of specimens as follows:

Specimen type 1:

$$\sigma_\perp = \tau_\perp = \tfrac{1}{2}\sqrt{2}\tau_{uw_\perp} \rightarrow \frac{\sigma_c}{\beta} = \tau_{uw_\perp}\sqrt{2} \qquad \text{(see Figs. 28 and 30, column 7)}$$

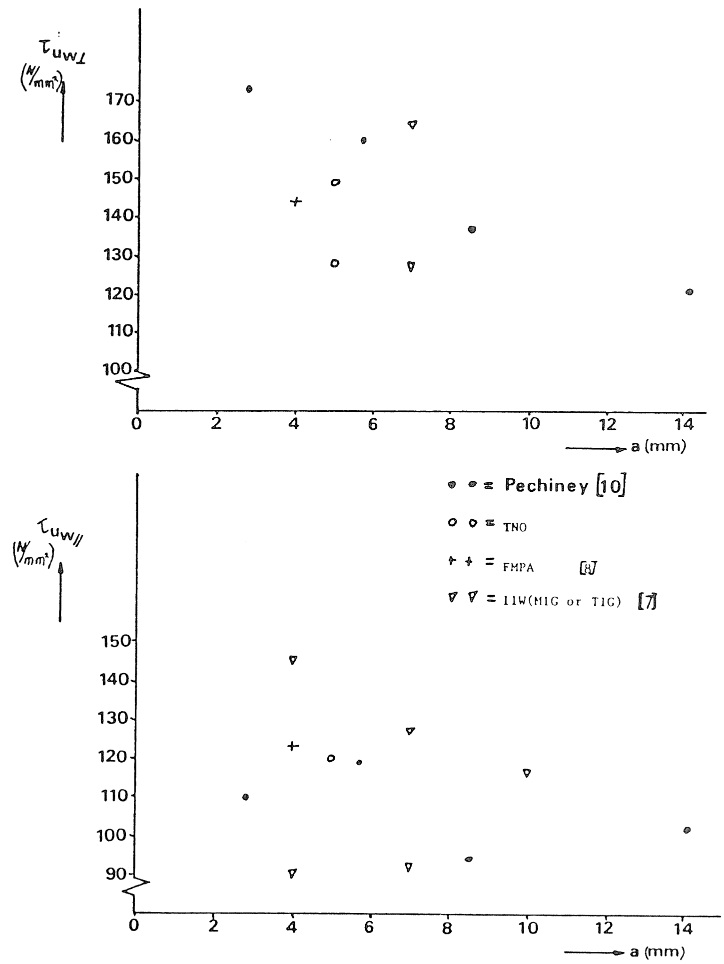


Fig. 34b. Ultimate strengths of fillet welds 6082-T6 + 4043.

Specimen type 2:

$$\tau_{/\!/} = \tau_{uw_{/\!/}} \rightarrow \frac{\sigma_c}{\beta} = \tau_{uw_{/\!/}} \sqrt{3} \qquad \text{(see Fig. 29, column 6)}$$

Note: the values of $\sigma_\perp$, $\tau_\perp$ and $\tau_{/\!/}$ have been determined assuming that the throat and rupture section coincide, which simplifies the calculation and is permissible, as demonstrated in 5.5.1.

Secondly, the average values of σ_c/β have been compared with the average values of the ultimate strengths of the corresponding weld metal σ_{uw}. The latter values were taken from Figs. 18 up to 22 (see also 4.4), i.e. the values were calculated by linear inter-

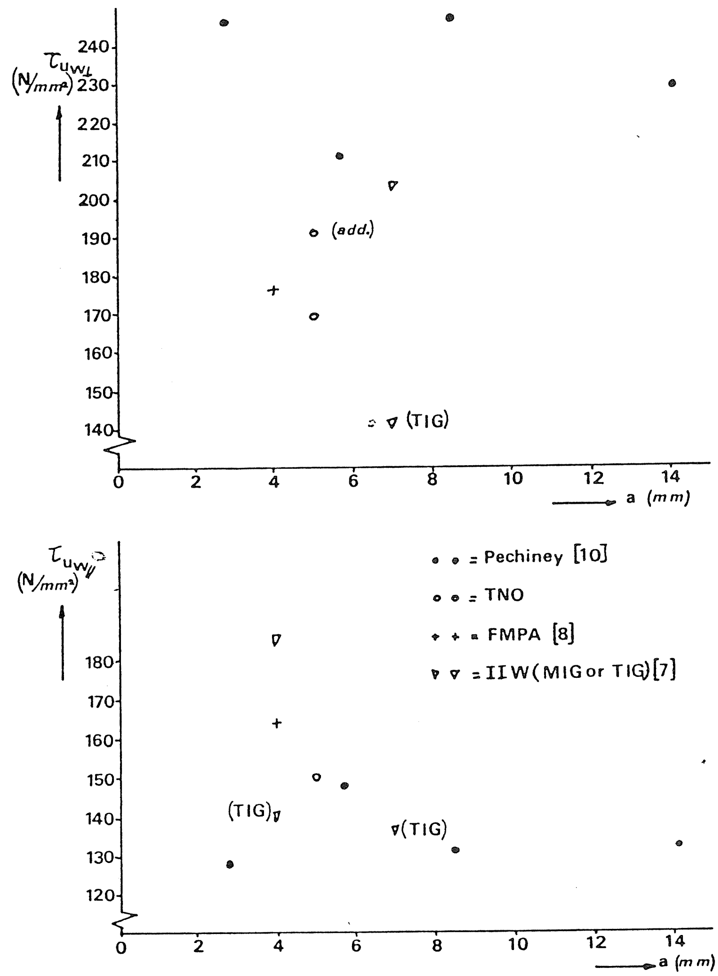


Fig. 35a. Ultimate strengths of fillet welds 7020-T6 + 5356.

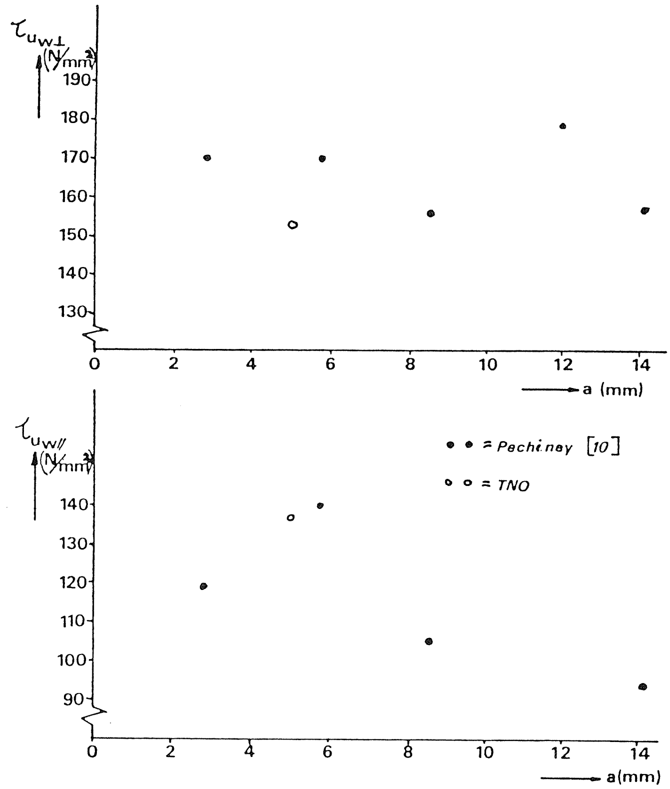


Fig. 35b. Ultimate strengths of fillet welds 7020-T6 + 4043.

polation for a thickness $t = 8$ mm, which almost equals the thickness of the rupture section of the fillet welds.

Comparing average values was preferred because:

- the number of test results was restricted due to the number of combinations investigated;
- the results of σ_c/β do not have a normal distribution.

The results used for this comparison and the results for β are given in Fig. 36. The results for β have been derived as follows:

$$\sigma_c \leq \sigma_{uw} \quad \text{or} \quad \frac{\sigma_c}{\beta} \cdot \beta \leq \sigma_{uw} \quad \text{or} \quad \beta = \frac{\sigma_{uw}}{\sigma_c/\beta}$$

Thus, in Fig. 36 the results of column (1) have to be divided by the results of column (2), (3) or (4), which yields the values for β as given in columns (5) and (6). For design purposes a value $\beta = 1{,}0$ can be applied based on the mean values of β in column (6) because:

- The higher the value of β, the lower the strength of the fillet weld.

alloy	filler metal	σ_{uw} [N/mm²] (1)	σ_c/β [N/mm²] type 1 (Fig. 27) (2)	type 1 (Fig. 30) (3)	type 2 (Fig. 29) (4)	β min–max (5)	mean values (6)
5083-0	5356	264	236	272	261	0,97–1,12	1,03
6063-T5	5356	196	191	203	194	0,97–1,03	0,99
	4043	175	168	–	192	0,91–1,04	0,98
6082-T6	5356	233	244	–	204	0,95–1,14	1,05
	4043	212	181	211	208	1,00–1,17	1,06
7020-T6	5356	276	239	272	260	1,01–1,15	1,07
	4043	235	217	–	237	0,99–1,08	1,04

Fig. 36. β-values for the design of fillet welds.

- An average value of β had been calculated because:
  - the lowest value of β is determined by the (relatively) low results of column (2);
  - in the design the throat section is used instead of the rupture section;
  - in applying the β-formula, the design strength σ_d is used instead of σ_{uw}.

5.6 *Conclusions relating to fillet welds*

From the results on fillet welds as discussed in this chapter the following can be concluded:

- The thickness of the rupture section of a fillet weld can be significantly higher than the throat thickness, this being due to positive root penetration. This penetration has to be ensured in the qualification procedure.
- The location and the orientation of the rupture section justify the assumption that the rupture and throat section of the fillet weld coincide.
- For the ultimate strength of fillet welds it is found that:
  - The influence of the combination alloy/filler metal/load direction (type of specimen) is very significant, which was demonstrated by the analysis of variances of the results.
  - The load direction influences the ultimate strength, although to a much lesser extent than sometimes asserted, see 3.3.2.
  - MIG results appear to be better than TIG results (from literature), which is possibly due to better penetration achieved with MIG welding.
  - The results of this experimental research on fillet welds are found to provide a reliable lower limit for the ultimate strength of fillet welds.
- For the design of fillet welds it is found that:
  - The β-formula, which can be similarly applied to steel structures, gives the best approximation of the strength of a fillet weld compared with other methods (see [1] and [2]).

- If, applying the β-formula, the design is based on the characteristic strength of the weld metal and the dimensions of the throat section, and a value $\beta = 1.0$ (see Fig. 36) is adopted, a design strength is obtained which is a reliable lower limit of the actual ultimate strength.
- For simple connections simple design formulas derived from the β-formula can be applied.

6 Experimental and theoretical research on welded connections

6.1 *General*

Welded connections of rectangular hollow sections, in which the brace section (vertical) was connected to the chord section (horizontal) by means of a fillet weld along the entire perimeter, were investigated in this research. These connections were chosen because:
- This type of connection yields a very unequal stress and strain distribution which is well suited for this research for investigating the influence of the mechanical properties on the structural behaviour of the connection, see 1.
- The type of connection chosen is relatively simple; besides, for steel structures much research has been devoted to similar connections.

With the experimental and theoretical research, which will be described in this chapter, it has been attempted – proceeding from the results obtained for the mechanical properties and fillet welds – within the scope of this research programme to ascertain the structural behaviour of welded connections in aluminium alloy structures.

6.2 *Choice of parameters*

Referring to the choice of the parameters in the foregoing studies (see 4.1 resp. 5.1) the following parameters were chosen in this research:
- 2 alloys, namely 6063-T5 and 7020-T6;
- 1 filler metal, namely 5356;
- 2 combinations of sections, namely $100 \times 100 \times 4 + 80 \times 80 \times 4$ and $100 \times 100 \times 4 + 50 \times 50 \times 4$;
- 2 types of connection, 2 different loadings (see Fig. 37);
- 1 throat thickness fillet weld, namely $a = 4$ mm;
- 1 welding process, namely MIG (spray-arc).

An important reason for this choice of alloys, filler metal and weld thickness was that – starting from the results of the foregoing studies – the strength of the weld is higher than the strength of the heat-affected zone for 6063-T5,while for 7020-T6 the reverse situation exists.

As in the preceding investigations, the following were not varied in these investigations: the welder, the welding position (2F) and the welding parameters (determined by the weld quality as prescribed in the welding procedure specification).

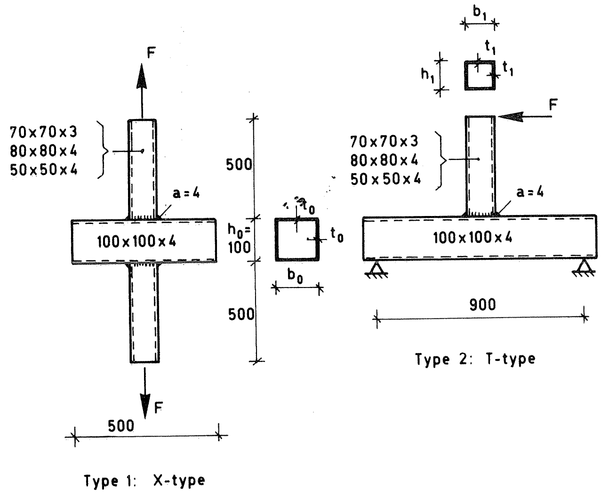


Fig. 37. Types of hollow sections investigated; dimensions in mm; loadings.

In connection with the foregoing test programmes on mechanical properties and fillet welds, the combinations of parameters as shown in Figs. 41 and 45, were investigated.

6.3 *Welding of hollow sections*

Welding of the test specimens was again carried out according to a detailed welding procedure specification, which was very similar to the one described in 5.2.
The dimensions of the test specimens and the throat thicknesses are given in Fig. 37. Actually the throat thickness (a), measured from the outside, varied between 4 and 6 mm.

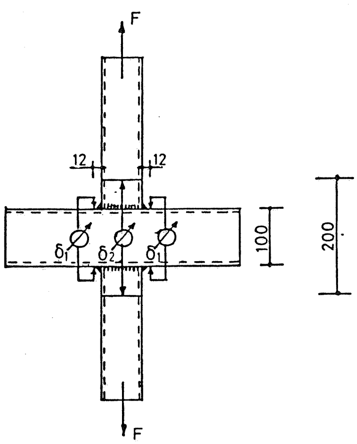


Fig. 38a.
X-type specimen, measuring displacements δ_1 and δ_2.

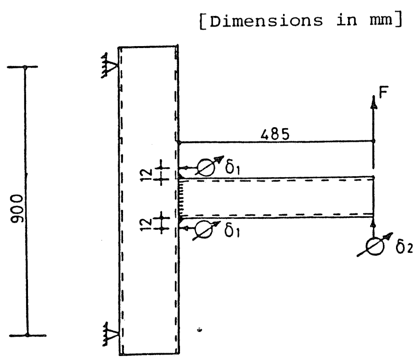


Fig. 38b.
T-type specimen, measuring displacements δ_1 and δ_2.

A detailed description of the welding qualification and test specimens is given in [18]. From a structural point of view it is important that the tacking and the start and stop sites of the welds were chosen in the middle of the side walls of the brace section.

6.4 *Testing*

The test specimens, type 1 (X-type) resp. type 2 (T-type) were loaded as indicated in Fig. 37. The following data were recorded in the tests:
- The loads (F) up to failure of the connection;
- The displacements (δ) as shown in Fig. 38;
- The strains measured by strain gauges as shown in Fig. 39 for a X-type specimen;
- Strains measured according to the moiré-method (see also 4.3, and Figs. 12 and 13).

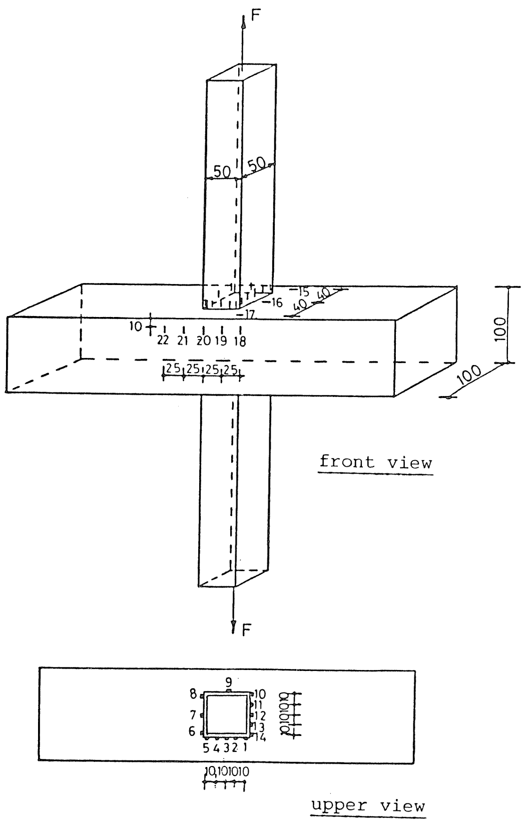


Fig. 39. X-type specimen; dimensions in mm; position and numbering strain gauges.

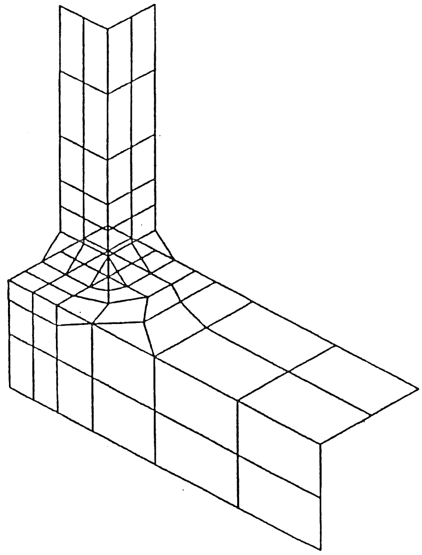


Fig. 40. X-type connection; element distribution combination 100 × 100 × 4 + 50 × 50 × 4 mm.

alloy	combination	test	F [kN]	δ_{1u} [mm]	δ_{2u} [mm]	failure mode
6063-T5	100 × 100 × 4	A	81,5	4,5	7,0	cracking at the toe of the weld
	+	B	89,6	6,2	8,3	of the bracings at front and back
	80 × 80 × 4	C	96,0	-	-	respectively
		D	104,0	7,6	10,4	cracking starts at the corners
		E	103,6	8,0	11,1	
	100 × 100 × 4	A	45,7	24,0	25,6	large deformations of chord
	+	B	48,0	25,3	29,4	section (chord faces) and
	50 × 50 × 4	C	61,3	28,0	30,0	subsequently tearing of chord
		D	49,0	27,5	29,8	side walls
		E	-	-	-	
7020-T6	100 × 100 × 4	A	105,8	2,3	3,1	→ see above, cracking at toe of bracing weld
	+					
	80 × 80 × 4					
	100 × 100 × 4	A	42,8	12,0	12,0	→ see above, cracking at toe of bracing weld
	+					
	50 × 50 × 4	B	49,0	12,0	12,0	→ cracking of welds at front and back and cracking of chord section at front and back respectively
	100 × 100 × 4	A	63,5	-	-	→ see above, cracking at toe of bracing weld
	+					
	70 × 70 × 3					

Fig. 41. X-type specimens. Results for failure load (F_u), ultimate displacements (δ_{1u} resp. δ_{2u}) and failure modes.

6.5 *Theoretical research*

For the theoretical part of this study the TNO-IBBC finite element programme DIANA [19] was used to simulate the behaviour up to failure of four X-type specimens. With these simulations physical nonlinearity ("true" stress-strain diagrams for parent metal, heat-affected zone and weld metal) and geometrical non-linearity (large rotations and displacements) were taken into account.
An example of an element distribution is shown in Fig. 40.

6.6 *Experimental and theoretical results*

The results of the tests on the X-type specimens are given in Fig. 41. A typical load-displacement diagram is shown in Fig. 42, and the corresponding theoretical results are also plotted in this diagram. For this test specimen the results of the strain gauge measurements are given in Fig. 43. For load step 9 the results of all 22 strain gauges have been compared with the theoretical results for this X-type specimen, see Fig. 44.
The results of the tests on the T-type specimens are summarized in Fig. 45.
A complete survey of all the results is given in [20].

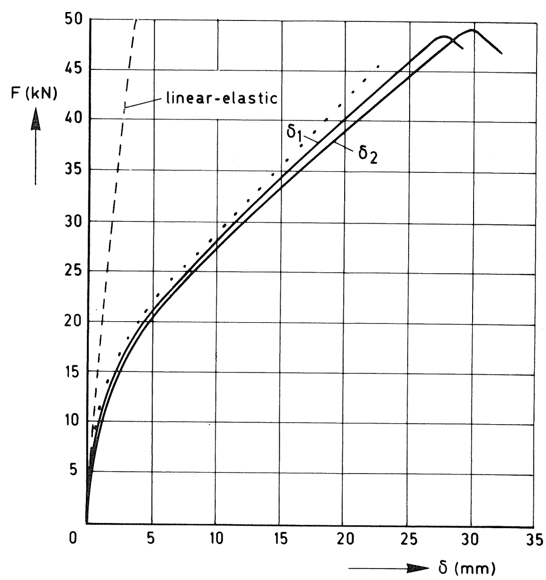
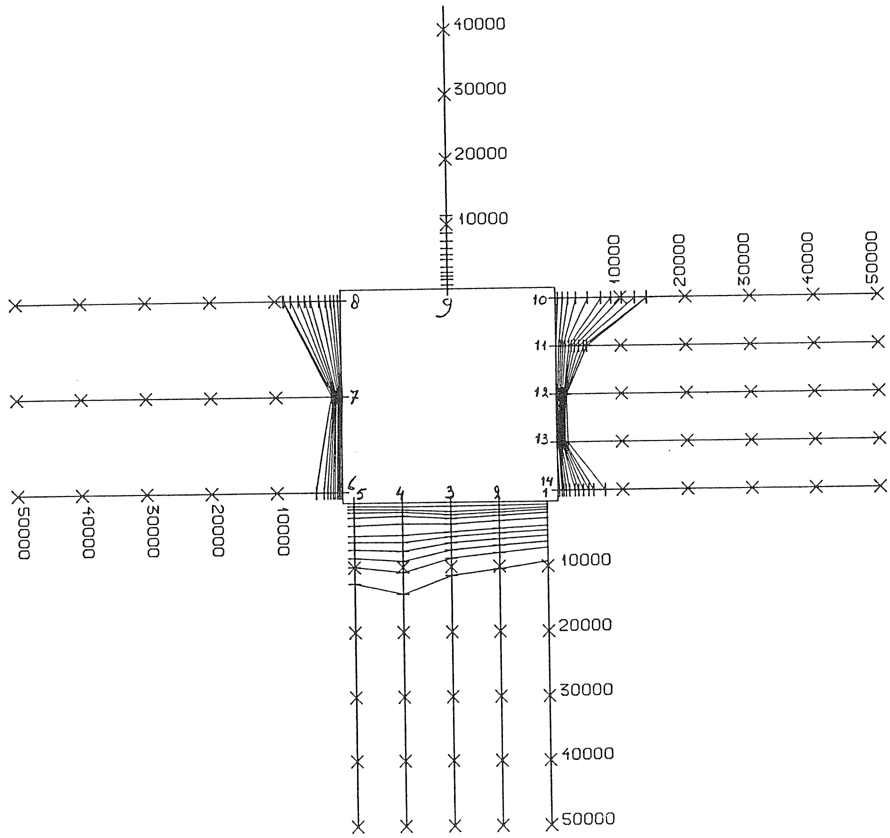


Fig. 42. Load-displacement diagram ($F-\delta$) specimen X-type, 6063-T5, 100 × 100 × 4 + 50 × 50 × 4 mm.

... = results of computer programme
— = results of tests



Load step	Load [kN]
1	0.0
2	10.0
3	20.0
4	25.0
5	30.0
6	35.0
7	40.0
8	42.0
9	45.0
10	47.0
11	50.0
12	48.0

Fig. 43. X-type specimen, alloy 6063-T5, combination 100 × 100 × 4 + 50 × 50 × 4 mm. Strain values gauges 1 to 14 (see Fig. 39); values in μm/m.

6.7 *Evaluation of results and conclusions*

From the results on welded connections in hollow sections as discussed in this chapter the following was inferred:

- For both types of connections investigated, namely X-type tensile loading and T-type moment plus shear loading, there is no difference in the ultimate strength of the connections for the alloys 6063-T5 and 7020-T6 respectively.
- With the X-type connections the deformations for the alloy 6063-T5 are 2 or 3 times higher as compared with 7020-T6.
- With the T-type connections the differences in deformations between the alloys 6063-T5 and 7020-T6 are negligible, since the geometry of the connection dominates other influences.
- For both types of connections the same failure modes have been observed for both alloys.

With the X-type connections there occurs:

- Cracking at the toe of the weld of the bracings (front resp. back side);
- Large deformations of the chord section (chord faces) and subsequently tearing of the chord side walls.

With the T-type connection there occurs:

- Cracking at the corners of the bracing or of the chord side walls;
- Cracking at the toe of the weld of the bracing or cracking of the chord face.

- For both types of connections the highest strain values are measured where failure finally occurs.

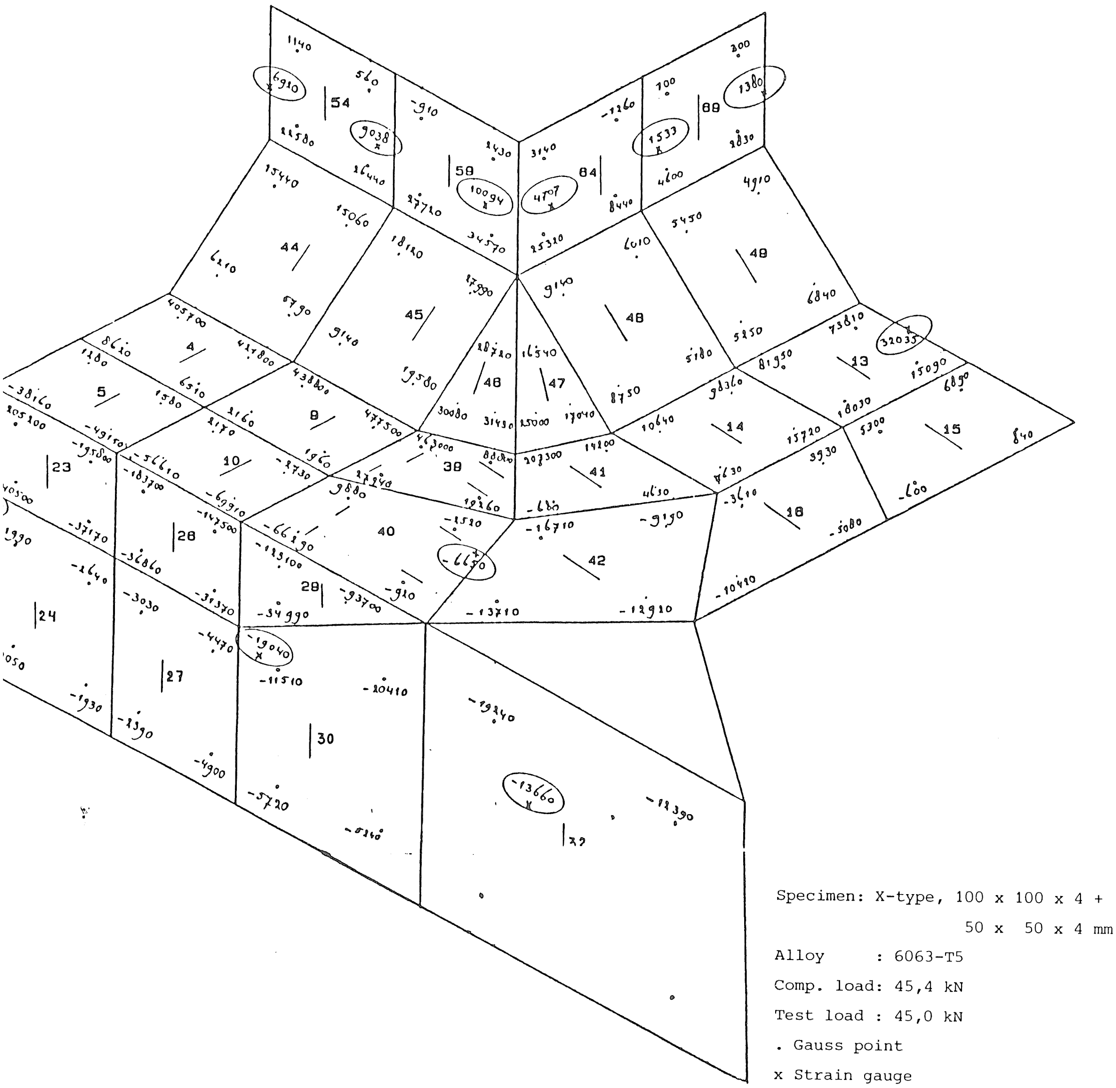


Fig. 44. Results of computer programme and strain gauges in direction indicated; the strain values are given in µm/m.

alloy	combination	test	F_u [kN]	δ_{1u} [mm]	δ_{2u} [mm]	M_u [kNm]	ϕ_u [rad]	failure mode
6063-T5		A	6,9	6,5	105	3,35	216×10^{-3}	→ cracking at the toe of the welds at the corners of the bracing
	100 × 100 × 4	B	7,1	7,5	120	3,44	247×10^{-3}	→ cracking of chord side walls
	+							
	80 × 80 × 4	C	6,3	8,1	120	3,06	247×10^{-3}	→ similar to Test A above
		D	4,8	5,9	90	2,86	186×10^{-3}	→ similar to Test B above
		A	5,6	-	-	2,72	-	cracking at toe of the welds
	100 × 100 × 4	B	2,7	7,0	140	1,31	289×10^{-3}	of the bracing
	+							
	50 × 50 × 4	C	4,7	9,0	180	2,28	370×10^{-3}	cracking chord face after
		D	3,9	8,5	170	1,89	350×10^{-3}	large deformations
7020-T6	100 × 100 × 4	A	6,9	6,5	94	3,35	194×10^{-3}	→ cracking at the toe of the welds at the corners of the bracing
	+							
	80 × 80 × 4							
	100 × 100 × 4	A	3,6	8,5	160	1,75	330×10^{-3}	cracking chord face after large deformations
	+							
	50 × 50 × 4	B	3,4	7,2	146	1,65	301×10^{-3}	
	100 × 100 × 4	A	5,6	-	118	2,72	243×10^{-3}	
	+							
	70 × 70 × 3							

Fig. 45. T-type specimens. Results for failure load (F_u), ultimate displacements (δ_{1u} resp. δ_{2u}), failure moment (M_u), ultimate rotation (ϕ_u) and failure modes.

- The strain values measured are much higher for the alloy 6063-T5 as compared with 7020-T6. With the latter alloy the highest strain values are restricted to the weld areas, whereas for the alloy 6063-T5 the highest strain values occur in the heat-affected zones, which causes better redistribution of stresses, resulting in a larger effective width of the connection for the alloy 6063-T5. This explains the relatively high ultimate strength of the connection for the alloy 6063-T5 as compared with 7020–T6.
- For the design of such connections it is advisable to pay attention to failure *not* occurring in the welds with respect to the strength and deformation capacity of the connection. For the alloy 7020-T6 it may be favourable to use a high-strength filler metal (for example 5280).

7 Evaluation

All the results of the research programme described in this report, have been summarized and evaluated in [21]. On the basis of these results, recommendations for the design of welded connections in aluminium alloy structures have been formulated which will be incorporated in [1] and [3] as well as in [5].

The main differences in relation to the existing regulations are:

- Qualification of welder and welding procedure is necessary to apply the "new" design rules.
- The strengths of the weld metal and heat-affected zone are dealt with separately.
- The design strength of the weld metal and heat-affected zone will be based on the respective ultimate strengths, see Figs. 16 and 17.
- The design of butt welds is based on the design strength of the weld metal, whereas for fillet welds the design is based on the β-formula taking into account the design strength of the weld metal, the throat section and the direction of the different stresses in that section.
- To obtain sufficient deformation capacity of the welded connection it is advisable to aim for a higher strength of the welds compared with the strength of the heat-affected zone.

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