Optimization of Fillet Weld Sizes

An HAZ hardness criterion is used to predict the minimum size fillet welds that can be deposited on certain steels without preheat

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ABSTRACT. The increasing evidence suggesting that, from a load carrying point of view, presently required minimum fillet sizes may be safely reduced, raises the question of whether the accompanying reduction in heat input increases the risk of cracking. This prompted the present study aimed at determining the minimum size fillet welds that can be deposited without cracking.

The heat-affected zone (HAZ) hardening behavior of a number of steels has been examined using small bead-on-plate specimens. The results, together with data from the literature, have enabled a relation to be established between carbon equivalent and cooling rate to produce a given hardness. Controlled thermal severity (CTS) tests were carried out using the submerged arc process and, to a lesser extent, the manual shielded metal arc and flux cored welding process. Results showed that very high HAZ hardnesses could be tolerated without cracking when using the submerged arc process, shielded metal arc with E7018 electrodes and solid wire gas metal arc processes. HAZ or weld metal cracking occurred at high HAZ hardness levels in a few of the steels tested with the flux cored gas metal arc and the gasless flux cored process. Extensive HAZ and/or weld metal cracking occurred in all steels tested using E6010 shielded metal arc welding.

The results have been used to establish the minimum size single pass fillet welds that can be deposited without a preheat (10 C) and without HAZ cracking using the submerged arc process based on a HAZ hardness limit of 350 HV. Because of the need for close control of the energy input in using a procedure based on a hardness criterion it is considered that the results should be used at present only for fully automatic submerged arc welding. The method is valid for such steels as A36, A441 but is not applicable to the more hardenable steels such as A514.

Introduction

There is increasing recognition of the fact that the permissible stress in fillet welds may be safely increased above those currently allowable in several codes and standards. The main reasons for this are the higher strength and more consistent quality of modern weld metal and the increased penetration of welds made with automatic processes. Measurements of penetration and mechanical tests on fillet welds have led to several recommendations (Refs. 1,2) for increasing the permissible stress that would allow smaller fillet welds to be used in a given situation.

This raises the question of whether the associated reduction in heat input accompanying a reduction in fillet weld size could increase the probability of cracking. Clearly any increase in preheat required by an increased chance of cracking could offset the economic benefits to be obtained from a reduction in fillet size. It is therefore necessary to examine the effect of fillet size on the susceptibility to cold cracking. The present work has attempted to do this using weld cracking tests.

In particular the work is aimed at determining the minimum size fillet weld that can be made without preheat based on a heat-affected zone (HAZ) hardness criterion. At the present stage it is not possible to go further and predict preheat levels (except in a very general sense) in situations where preheat is required, since this requires a knowledge of restraint, and the study of restraint in fillet welds is still at an early stage.

An extensive study of cracking in fillet welds has recently been undertaken by Bailey at the Welding Institute (Ref. 3). His work was confined to the manual shielded metal arc and the CO_2 solid wire processes and consisted of determining continuous cooling transformation (CCT) diagrams for a variety of steels and then performing controlled thermal severity (CTS) tests. The CCT diagrams provided information on critical cooling rates for specific hardness levels while the CTS tests provided information on critical hardness levels for cracking. Joint simulation tests were

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then carried out to confirm the adequacy of the procedures based on this method.

In general, the results showed that for both low hydrogen electrodes and rutile electrodes, a critical HAZ hardness level of 350 HV existed below which HAZ cracking did not occur. Hydrogen determinations, however, showed that the low hydrogen deposits contained levels of hydrogen which would normally be considered high. Results of the CO_2 process indicated a critical hardness level of about 400 HV.

The work reported here has been concerned mainly with the submerged arc process, because it is with this process that maximum benefit from reduced fillet size would be obtained and because there has been very little work published on the tendency for hydrogen cracking using the submerged arc process.

The materials used in the project were structural steels of types such as ASTM A36, A441, A588 and A514. Chemical analyses of the plates used are shown in Table 1. The program in essence comprised three main stages:

1. Determine the heat-affected zone hardening behavior of a range of steels in relation to cooling rate.
2. Relate cooling rate in fillet welds to welding parameters that can be controlled in practice, such as welding energy input which might relate to the weld size.
3. Study the relationship between heat-affected zone hardness and cracking probability using a restrained fillet weld test.

Hardening Behavior

The HAZ hardening characteristics of several steels have been studied using small bead-on-plate (BOP) type specimens and CTS tests. The BOP test piece consisted of a block of the

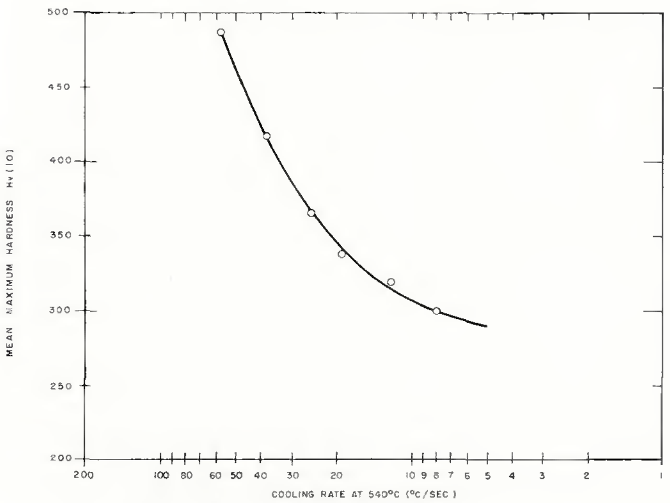

Fig. 1 — Hardening curve for E steel (0.36 C - 0.77 Mn - 0.24 Si - 0.019 P - 0.032 S)

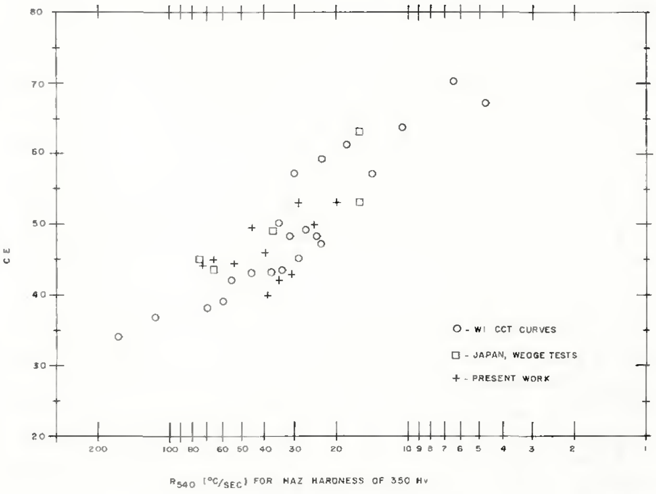

Fig. 2 — Carbon equivalent plotted against critical cooling rate at 540 C for HAZ hardness of 350 HV

Table 1 — Chemical Analyses of Steels Used in C.T.S. Tests

Code	Type	Thickness in.	C	Mn	Si	S	P	Ni	Cr	Mo	Cu	B	V	CE[a]
A	A588C	2-5/8	0.15	1.12	0.23	.026	.010	0.36	0.38	—	0.31	.003	.043	.504
B	A588C	2-5/8	0.13	0.95	0.20	.028	.010	0.35	0.33	—	0.32	.004	.043	.440
E	unspecified	3/4	0.36	0.77	0.24	.032	.019	—	—	—	0.025	—	—	.529
G	A36	1/2	0.26	1.16	0.04	.026	.012	—	—	—	0.020	—	—	.481
J	A588B	1-1/4	0.12	1.12	0.27	.026	.015	0.39	0.43	—	0.43	.004	.061	.504
Q	A517F	2-1/2	0.17	0.71	0.19	.021	.011	0.89	0.57	0.31	0.23	.004	.030	.637
RC	A 36	2-1/2	0.19	1.08	0.25	.046	.020	—	—	—	0.30	—	—	.531
TA	A517H	1-1/2	0.19	1.12	0.29	.022	.012	0.53	0.54	0.21	0.09	.005	.056	.626
U	A517F	1	0.18	0.83	0.24	.019	.011	0.82	0.53	0.40	0.27	.005	.060	.629
BC	A441	2-5/8	0.16	1.11	0.24	.028	.021	—	—	—	0.22	—	.040	.407
EA	A441	1	0.19	1.13	0.21	.018	.008	—	—	—	0.23	—	0.05	.438
EB	A441	3/4	0.22	1.25	0.21	.018	.008	—	—	—	0.23	—	0.06	.490
EC	A441	1/2	0.21	1.11	0.18	.026	.009	—	—	—	0.22	—	0.04	.447
ED	A441	1-1/2	0.18	1.05	0.20	.017	.008	—	—	—	0.25	—	0.05	.415
EE	A441	2-1/2	0.17	1.15	0.20	.024	.018	—	—	—	0.26	—	0.04	.420
TB	A517H	1-1/2	0.18	1.18	0.27	.021	.013	0.40	0.56	0.19	0.03	.004	0.043	.608
RB	A 36	2	0.21	1.11	0.25	.015	.012	—	—	—	0.17	—	—	.446
DA	A 36	2-1/2	0.24	1.13	0.22	.020	.016	—	—	—	0.04	—	—	.468
BG	A441	2-5/8	0.13	1.14	0.28	.030	.026	—	—	—	0.29	—	.050	.395
TC	A517H	1-1/2	0.18	1.18	0.27	.021	.010	0.43	0.55	0.19	0.02	.005	.042	.607
TB	A517H	1-1/2	0.18	1.18	0.27	.021	.010	0.43	0.55	0.19	0.02	.005	.042	.607
RA	A 36	2	0.21	1.11	0.25	.015	.012	—	—	—	0.17	—	—	.447

(a) CE = C + (Mn + Si)/6 + (Cr + MO + V)/5 + (Ni + Cu)/15 steel that was large enough to represent an infinite heat sink down to temperatures below the finish of transformation. A block 6 × 3 × 2 in. was found to be adequate. With this condition the weld cooling rate could be calculated from the energy input for submerged arc welding, using relations developed in other work (Ref. 4). Beads of given energies were deposited on the blocks under standard conditions.

Table 2 — Submerged Arc CTS Tests

Test no.[a]	Steel	Thickness, in.	Energy input, kJ/in.	Preheat C	(F)	HAZ Avg max HAZ hardness HV10kg	Results
B1X	A588C	2-5/8	39	30	(84)	307	no crack
B1Y	A588C	2-5/8	39	94	(200)	265	no crack
B2X	A588C	2-5/8	136	30	(84)	248	no crack
B2Y	A588C	2-5/8	94	94	(200)	236	no crack
B3X	A588C	2-5/8	39	67	(150)	293	no crack
B3Y	A588C	2-5/8	39	150	(300)	255	no crack
B4X	A588C	2-5/8	136	67	(150)	238	no crack
B4Y	A588C	2-5/8	94	150	(300)	233	no crack
G5X	A36	1/2			(78)	297	no crack
G5Y	A36	1/2	39	67	(150)	286	no crack
G6X	A36	1/2	94	25	(78)	248	no crack
G6Y	A36	1/2	94	67	(150)	223	no crack
J7X	A588C	1-1/4	39	27	(80)	340	no crack
J7Y	A588C	1-1/4	39	67	(150)	338	no crack
J8X	A588C	1-1/4	94		(80)	296	no crack
J8Y	A588C	1-1/4	94	27	(150)	298	no crack
E9X	unspecified	3/4	39	27	(80)	381	hot crack 3/4 × 1/8
E9Y	unspecified	3/4	39	67	(150)	336	hot crack (small)
E10X	unspecified	3/4	94	27	(80)	251	no crack
E10Y	unspecified	3/4	94	67	(150)	257	no crack
U11X	A517F	1	39	22	(71)	416	no crack
U11Y	A517F	1	39	67	(150)	409	no crack
U12X	A517F	1	94	-6	(22)	418	no crack
U12Y	A517F	1	94	67	(150)	399	no crack
Q13X	A517F	2-1/2	39	20	(67)	464	no crack
Q13Y	A517F	2-1/2	39	67	(150)	417	no crack
Q14X	A517F	2-1/2	94	21	(69)	426	no crack
Q14Y	A517F	2-1/2	94	67	(150)	399	no crack
EE49Y	A441	2-1/2	39	20	(68)	317	no crack
RB51X	A36	2	21	23	(74)	455	no crack
R851Y	A36	2	94	32	(87)	469	no crack
A52X	A588C	2-5/8	21	23	(74)	396	no crack
A52Y	A588C	2-5/8	94	32	(87)	405	no crack
Q53X	A517F	2-1/2	21	23	(74)	440	no crack
Q53Y	A517F	2-1/2	94	32	(87)	444	no crack
E54X	unspecified	3/4	21	23	(74)	468	no crack
E54Y	unspecified	3/4	94	32	(87)	511	no crack
TB63X	A517H	1-1/2	21	25	(78)	442	w.m.c.l. cracking
TB63Y	A517H	1-1/2	94	25	(78)	459	w.m.c.l. cracking
ED64X	A441	1-1/2	21	25	(78)	394	no crack
ED64Y	A441	1-1/2	94	25	(78)	417	no crack
G65X	A36	1/2	21	25	(78)	389	no crack
G65Y	A36	1/2	94	25	(78)	457	no crack
DA66X	A36	2-1/2	94	30	(84)	431	no crack
DA66Y	A36	2-1/2	21	25	(78)	414	no crack
EC67X	A441	1/2	94	30	(84)	427	no crack
EC67Y	A441	1/2	21	25	(78)	389	no crack
EB68X	A441	3/4	94	30	(84)	457	no crack
EB68Y	A441	3/4	21	25	(78)	433	no crack

Table continued next page

Five transverse sections of the welds were cut and hardness surveys conducted using a Vickers machine with a 10 kg load. Five indentations in the HAZ close to the fusion boundary and two in the weld metal were made. All hardness tests were randomized to reduce systematic errors. The maximum value of HAZ hardness observed in each section was taken as an independent estimate of maximum hardness. The five maximum values of the five sections were then averaged to give the mean maximum hardness for that weld.

Mean maximum hardness was plotted against weld cooling rate at 540 C to provide a hardening curve. A typical curve for a 0.36 C - 0.77 Mn steel is shown in Fig. 1. Similar curves have been constructed using data from CTS tests and also data from the literature including results from wedge tests done in Japan and CCT diagrams made at the Welding Institute (U.K.) using a dilatometer.

For C, C/Mn and some low alloy steels the HAZ hardness decreases rapidly with decreasing cooling rate as in Fig. 1 and it is possible to select a critical cooling rate for each steel for a given hardness level. The critical cooling rate depends on the chemical composition of the steel and results are plotted in the form of a carbon equivalent (CE) against critical cooling rate. Results are shown in Fig. 2 for a critical hardness level of 350 HV. The carbon equivalent used is

$$CE = C + \frac{Mn + Si}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

This carbon equivalent has been used by Bailey and gives quite good correlation although other carbon equivalents may give equally good correlation. Because of the limited amount of data presently available it was felt that a regression analysis to determine a more accurate carbon equivalent was not warranted.

Reasonable agreement exists between the various methods for determining hardening curves although the influence of the transformation on cooling behavior sometimes creates difficulties in interpreting the cooling rate in the dilatometry experiments. The scatter band, however, is fairly wide particularly over the rather narrow range of carbon equivalents normally encountered in structural steels. This makes it necessary to take a lower bound curve for design purposes which inevitably leads to some conservatism. Lower bound design curves for critical hardnesses of 280, 350 and 400 HV are shown in Fig. 3.

Welding Tests

To study the effect of fillet weld sizes on the susceptibility to cracking a series of CTS (controlled thermal severity) tests were carried out. The form of the test piece is shown in Fig. 4 and includes a root opening (0.05 in. approximately) since this has been shown to increase the likelihood of cracking (Ref. 5). The test piece also includes a 4 in. wide top and bottom block allowing attachment of run on/off tabs (Ref. 6).

Test welds were deposited in the flat position under various conditions of fillet size. Tests were left for a three day incubation period before being sectioned for examination. In all tests HAZ and weld metal hardnesses were measured which provided information for the construction of hardening curves. Full details of the tests and results are listed in Table 2-9.

The majority of the testing was done with the submerged arc process and limited testing was done with manual and semiautomatic processes. Submerged arc welding (Table 2) showed no HAZ cracking in any of the tests. In two cases weld metal cold cracking occurred, one when wet flux was used. Hot cracking occurred in a few tests and was usually associated with a small fillet and high welding speed. No cracking of any kind occurred with CO_2/solid wire welding (Tables 4,5) or manual shielded metal arc welding with low hydrogen electrodes (Table 3) HAZ and weld metal cracking occurred with E6010 electrodes (Table 8), CO_2/flux cored welding (Table 7) and fine HAZ cracking occurred with the self shielding flux cored process (Table 6).

Modified Tests

The lack of cracking with the submerged arc process and low hydrogen manual electrodes raised the question of whether the test piece being used was sufficiently severe — particularly since other workers (Refs. 3,7) obtained cracking in comparable steels in CTS tests with the low hydrogen process. A number of tests was therefore carried out (Table 9) using a modified form of the CTS test with a slot cut in the top block (Fig. 5). The test (known as the compact restraint test) was developed to increase the severity of the fillet weld test. Although the test represents a situation that could arise in practice, such situations would be rare.

It is believed that one of the main reasons why fillet weld tests are less likely to crack than butt weld tests (such as Lehigh or Tekken) is that the degree of contraction occurring at low temperatures is much smaller. Thus even in a high restraint test (such as the CTS) lower strain levels are applied to the weld metal and HAZ. The low temperature shrinkage can be increased by cutting a slot in the top block. Although the restraint is somewhat reduced by this means the shrinkage is increased.

The detailed theory of the test is beyond the scope of this paper. Results of tests with this type of specimen (Table 9) indicated that cracking

Table 2 — Submerged Arc CTS Tests (cont'd)

Test no.	Steel	Thickness, in.	Energy input kJ/in.	Preheat C	(F)	Avg max HAZ hardness HV10kg	Results
BC30X	A441	2-5/8	39	23	(72)	344	no crack
8C30Y	A441	2-5/8	39	67	(150)	332	no crack
BC31X	A441	2-5/8	94	23	(72)	302	no crack
BC31Y	A441	2-5/8	94	67	(150)	283	no crack
RC33X	A36	2-1/2	39	–15	(7)	404	no crack
RC33Y	A36	2-1/2	21	22	(70)		no crack
TA34X	A517H	1-1/2	39 21	–15 22	(7) (70)	502	no crack hot crack in weld
E35X	unspecified	3/4	39	–13	(10)	442	no crack
E35Y	unspecified	3/4	21	22	(70)		hot crack in weld 1/8 × 1/2
BC36X	A441	2-5/8	21	22	(70)		no crack
U37X	A517F	1	21	22	(70)		no crack
B38X	A588C	2-5/8	21	22	(70)		no crack
EA39X	A441	1	39	20	(68)	380	no crack
EA39Y	A441	1	39	67	(150)	341	no crack
EA40X	A441	1	94	20	(68)	276	no crack
EA40Y	A441	1	94	67	(150)	333	no crack
ED45Y	A441	1-1/2	39	20	(68)	326	no crack
EB46Y	A441	3/4	39	20	(68)	372	no crack
EA47Y	A441	1	39	20	(68)	378	no crack
EC48Y	A441	1/2	39	20	(68)	293	no crack
TA15X	A517H	1-1/2	39	23	(83)	449	no crack
TA15Y	A517H	1-1/2	39	67	(150)	458	no crack
TA16X	A517H	1-1/2	94	23	(73)	452	no crack
TA16Y	A517H	1-1/2	94	67	(150)	433	no crack
RC17X	A36	2-1/2	39	20	(68)	388	no crack
RC17Y	A36	2-1/2	39	67	(150)	348	no crack
TC18X	A36	2-1/2	94	20	(68)	289	no crack
TC18Y	A36	2-1/2	94	67	(150)	281	no crack
B19X	A588C	2-5/8	39	22	(70)	296	no crack
B19Y	A588C	2-5/8	94	17	(62)	268	no crack
E20X	unspecified	3/4	39	22	(70)	359	no crack
E20Y	unspecified	3/4	94	17	(62)	269	no crack
*A21X	A588C	2-5/8	39	14	(56)	355	no crack
*A21Y (W5)	A588C	2-5/8	39	19	(66)		gross porosity
*E22X	unspecified	3/4	39	14	(57)	383	no crack
*E22Y (W1)	unspecified	3/4	39	17	(62)	386	no crack
*TA23X	A517H	1-1/2	39	18	(63)	481	no crack
*TA23Y (W1)	A517H	1-1/2	39	18	(64)	487	no crack
*Q24X (W1)	A517F	2-1/2	39	19	(66)	427	H_2 cracks in weld

(a) First letters in Test no. correspond to Code in Table 1.
(W1) Wet Flux (1% moisture by weight)
(W5) Wet Flux (5% moisture by weight)
*Water cooled to room temperature

Table 3 — Manual (E7018) CTS Tests [a]

Test no.[b]	Steel	Thickness in.	Energy input kJ/in.	Preheat C	(F)	Avg max HAZ hardness HV10kg
ED45X	A441	1-1/2	47	18	(65)	378
E846X	A441	3/4	54	18	(65)	405
EA47X	A441	1	48	18	(65)	387
EC48X	A441	1/2	47	18	(65)	324
EE49X	A441	2-1/2	52	18	(65)	319
A50X	A588C	2-5/8	36	18	(68)	396
RB55X	A36	2	23	32	(87)	469
RB55Y	A36	2	23	32	(87)	448
A56X	A588C	2-5/8	31	23	(74)	400
A56Y	A588C	2-5/8	20	32	(87)	400
Q57X	A517F	2-1/2	35	23	(74)	442
Q57Y	A517F	2-1/2	20	32	(87)	421
EE58X	A441	2-1/2	34	23	(74)	351
EE58Y	A441	2-1/2	21	32	(87)	384
TB59X	A517H	1-1/2	31	23	(74)	444
TB59Y	A517H	1-1/2	21	32	(87)	453
ED60X	A441	1-1/2	30	25	(78)	391
ED60Y	A441	1-1/2	19	25	(78)	403
G61X	A36	1/2	28	25	(78)	356
G1Y	A36	1/2	20	25	(78)	421
DA69X	A36	2-1/2	20	30	(84)	429
DA69Y	A36	2-1/2	30	25	(78)	407
EC70X	A441	1/2	19	30	(84)	398
EC70Y	A441	1/2	27	25	(78)	365
EB71X	A441	3/4	21	30	(84)	433
EB71Y	A441	3/4	26	25	(78)	440
Q27X	A517F	2-1/2	42-59	20	(68)	435
Q27Y	A517F	2-1/2	42-59	150	(300)	442
E28X	unspecified	3/4	42-59	20	(68)	395
E28Y	unspecified	3/4	42-59	150	(300)	341
B29X	A588C	2-5/8	42-59	20	(68)	314
B29Y	A588C	2-5/8	42-59	150	(300)	288
Q32X[c]	A517H	2-1/2	42-59	20	(68)	452
Q32Y[d]	A517H	2-1/2	42-59	150	(300)	452
BC36Y[e]	A441	2-5/8	42-59	22	(70)	382
U37Y[e]	A517F	1	42-59	22	(70)	436
B38Y[e]	A588C	2-5/8	42-59	22	(70)	354

(a) Results uniformly showed no cracking for all tests.
(b) First letters in Test no. correspond to Code in Table 1.
(c) E11018 electrode used.
(d) Water cooled to room temperature; E11018 electrode used.
(e) Electrode coverings contained approximately 1.4% moisture.

Table 4 — CTS Tests Using 75% Argon/25% CO_2 Shielding Gas (Solid Wire) [a]

Test no.[b]	Steel	Thickness, in	Energy input kJ/in.	Preheat C	(F)	Avg max HAZ hardness HV 10kg
BG76X	A441	2-5/8	19.1	22	(70)	383
BG76Y	A441	2-5/8	10.0	22	(70)	417
A77X	A588C	2-5/8	19.1	22	(70)	417
A77Y	A588C	2-5/8	10.0	22	(70)	450
RB78X	A36	2	18.4	22	(70)	519
RB78Y	A36	2	9.5	22	(70)	390
TC79X	A517H	1-1/2	18.4	22	(70)	503
TC79Y	A517H	1-1/2	9.5	22	(70)	508
Q25Y[c]	A517F	2-1/2	33	20	(69)	439
B25X[c]	A588C	2-5/8	33	19	(66)	307
E26X[c]	unspecified	3/4	33	22	(71)	422

(a) Results uniformly showed no cracking for all tests.
(b) First letters in Test no. correspond to Code in Table 1.
(c) 75% Argon/25% Co_2 at 40 cfh.

from the root in the bottom block occurred under certain conditions where no cracking occurred in the conventional CTS test. Since the compact restraint test represents a very severe condition the results have not been used in forming general recommendations. The results do, however, indicate that in extreme situations the critical hardness criterion can break down.

Relation Between Energy Input and Leg Length

Although the heat input to the plate is of prime consideration in regard to cooling rate and potential HAZ hardness, it is often more practical to specify weld size. Furthermore, if specified fillet weld sizes are to be reduced in order to take advantage of the greater penetration of automatic welds then it is necessary to relate the fillet sizes to energy input. The relation between energy input and fillet weld size, i.e. leg length, is not unique but depends on process, polarity and other factors. Some workers (Ref. 8) have suggested that relationships exist between cooling rate and the total cross-sectional area of fused metal. The latter, however, is difficult to measure and would not be a suitable way of specifying weld sizes in practice.

The weld dimensions and welding parameters were measured in the CTS tests and this data used to make plots of leg lengths squared versus energy input. Other data from the literature was also included together with information derived from deposition rate data where it was assumed that all of the metal deposited went into forming an ideal fillet. Where a root opening was present the leg length was smaller for the same energy input than for the condition of perfect fit-up.

The results of these plots are shown in Figs. 6 and 7. For manual covered electrodes there is very little effect of polarity or electrode type except for those electrodes with large quantities of iron powder in the covering. For submerged arc welding, polarity and electrode extension have a marked effect as would be expected. For the normal practical range of welding parameters a single scatter band can be considered and a lower bound curve selected as a basis for welding procedure design.

Penetration

The amount of penetration in fillet welds was measured in the CTS tests. The definition of penetration, throat thickness and other weld dimensions is shown in Fig. 8, for the case where a root opening is present.

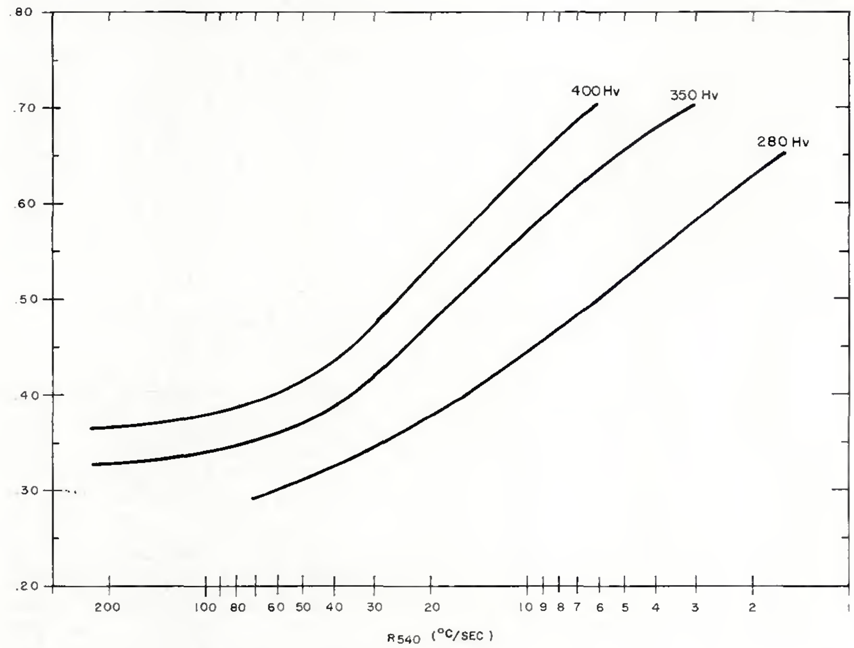

Fig. 3 — Lower bound design curves based on HAZ hardness

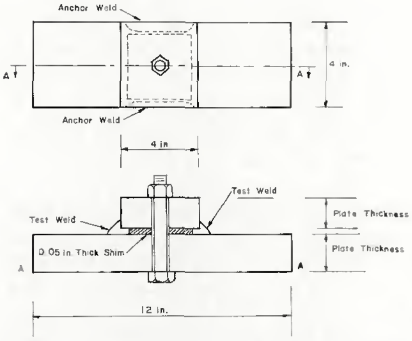

Fig. 4 — The form of the CTS test used in the welding tests

The results of measurements of effective throat thickness against leg length are shown in Fig. 9. The lines plotted for assumed effective thickness versus leg length for automatic welds represent a proposal recommended to AISC* and that currently allowed in CSA** W59.1 - 1970. It is to be noted that in the presence of a root opening (0.050 in.) sufficient throat thickness is not always achieved when following the proposal to AISC. The size of the root opening is not as large as the 1/16 in. at which the fillet size would need to be increased. The CSA recommendation appears to fit quite well the present results. It is important to note that welding parameters — in particular the current and welding speed, have marked effects on the penetration. It is therefore suggested that any recommendations taking advantage of the increased penetration of automatic welds should be suitably qualified in this regard.

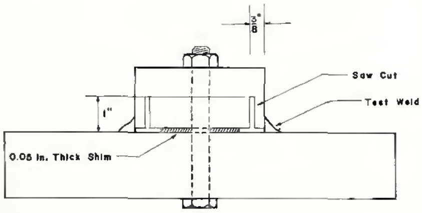

Fig. 5 — The compact restraint test (modified form of CTS test)

Cooling Rates

Cooling rates in fillet welds made with the submerged arc process between plates of equal thickness were measured both in the CTS test and in large tests that would more nearly approach infinite heat flow conditions. A Pt/Pt13% Rh thermocouple was manually plunged into the weld pool immediately behind the arc and the cooling cycle traced on a strip chart recorder. The results were analyzed according to a method described in detail elsewhere (Ref. 4) and gave the cooling rate at 540 C. No significant difference was found between the CTS tests and the large tests. The results are summarized in Fig. 10 which relates the energy input for submerged arc welds to the cooling rate for several thicknesses where the plates being welded are of equal thickness. For a given energy input the cooling rate is independent of thickness above certain thicknesses (previously termed 'saturation thickness', (Ref. 4) and all results fall on a single line.

General Discussion

The results of CTS tests indicate that high hardnesses may be tolerated in the HAZ without cracking when using the submerged arc process. Comparison with other work suggests that this is due mainly to lower hydrogen contents of the process. In many cases, however, it is not desirable to weld C, C/Mn and low alloy steels under conditions which would lead to these high hardnesses even though they may be tolerated without cracking. Reasons for this include: lack of tolerance to process variables, e.g. a small change in hydrogen content may lead to gross cracking; increased susceptibility to service problems such as stress corrosion cracking; the hard-microstructure may be brittle and increase the chance of brittle cracks in service or erection. Exceptions to this approach would include situations where there was immediate postweld heat treatment or where multipass welding caused adequate tempering of the HAZ.

It is therefore reasonable to use a HAZ hardness criterion for C, C/Mn and low alloy steels for many structural applications particularly where single pass welding is involved. The exact choice of hardness level would depend on a number of factors such as service requirements, critical hardness for cracking, and control over the welding process. It is also clear that a hardness criterion for design of welding procedures can only be used for those steels that show marked change in hardness with cooling rate. This would cover most carbon steels, carbon manganese and some low alloy steels. It would not include quenched and tempered steels such as A514 and that have a high hardenability and in which a hard HAZ is always to be expected, and, in most cases, desirable.

The most useful application of a hardness criterion for designing welding procedures would be for determining the minimum size fillet weld for single pass welds that would enable the joint to be welded without preheat. The critical hardness criterion could also be used for calculating preheats for any given weld size, but this application is less likely to be as useful. There are a number of reasons for this. For most structural steels the effect of preheat on heat-affected zone hardness is rather small, and the use of the critical hardness criterion and relations between welding parameters and cooling rates to predict the preheat would usually result in excessively high preheats. This would be satisfactory for some medium carbon materials (for example A515 Grade 70) where a hard heat-affected zone would give very high sensitivity to cracking because of the higher carbon, and a

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*American Institute of Steel Construction
**Canadian Standards Association

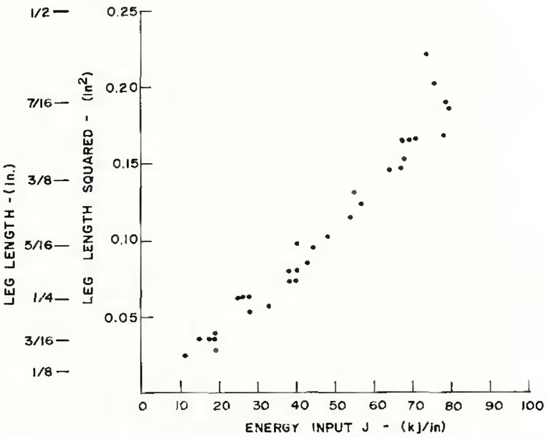

Fig. 6 — Relation between energy input and fillet weld leg length for manual shielded metal arc welding process

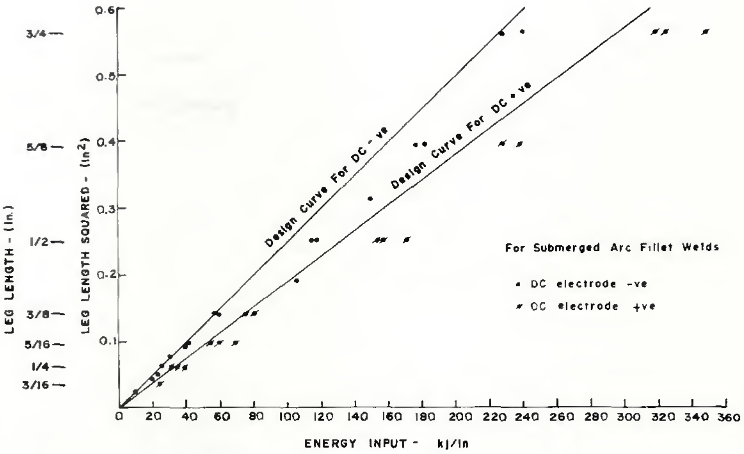

Fig. 7 — Relation between energy input and fillet weld leg length for the submerged arc process

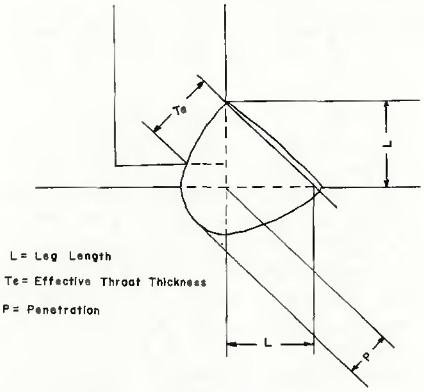

Fig. 8 — Definition of the various weld dimensions

Table 5 — CTS Tests Using CO_2 Shielding Gas (Solid Wire)[a]

Test no.[b]	Steel	Thickness, in.	Energy input, kJ/in.	Preheat C	(F)	Avg max HAZ hardness HV10kg
BG72X	A441	2-5/8	21.2	18	(64)	376
BG72Y	A441	2-5/8	10.6	22	(70)	401
A73X	A588C	2-5/8	21.2	18	(64)	429
A73Y	A588C	2-5/8	10.6	22	(70)	455
B25Y	A588C	2-5/8	33.0	18	(65)	319
E26Y	unspecified	3/4	33.0	20	(68)	409
RB74X	A36	2	21.2	18	(64)	514
RB74Y	A36	2	10.6	22	(70)	503
TC75X	A517H	1-1/2	16.4	18	(64)	493
TC75Y	A517H	1-1/2	10.6	22	(70)	488

(a) Results uniformly showed no cracking for all tests.
(b) First letters in Test no. correspond to Code in Table 1.

Table 6 — CTS Tests Using the Self Shielding Flux Cored Process (No Gas)

Test no.[a]	Steel	Thickness, in.	Energy input, kJ/in.	Preheat C	(F)	Avg max HAZ hardness HV10kg	Results
BC84X	A441	2-5/8	40	20	(68)	417	no crack
BC84Y	A441	2-5/8	51	22	(70)	357	no crack
TB85X	A517H	1-1/2	39	20	(68)	503	HAZ root cracking
TB85Y	A517H	1-1/2	49	22	(70)	483	HAZ root cracking
RA86X	A36	2	35	20	(68)	478	no crack
RA86Y	A36	2	51	22	(70)	488	no crack
A87X	A588C	2-5/8	39	20	(68)	417	no crack
A87Y	A588C	2-5/8	48	22	(70)	390	no crack

(a) First figures in Test no. correspond to Code in Table 1.

hardness criterion would be desirable in any event.

For many structural materials, however, a preheat based on a hardness criterion would not be the most economic. The reason why lower preheats can be used in practice is rather complex. When preheat is used, a higher hardness can be tolerated because hydrogen is allowed to diffuse out of the joint at a temperature where the degree of hydrogen embrittlement is small and by the time the joint cools to room temperature after welding less hydrogen is left in the weld. In some situations strains may also be reduced by the application of preheat. The level of preheat would thus depend upon such factors as the sensitivity of the heat-affected zone to hydrogen cracking, the hydrogen content and the strain in the heat-affected zone — the latter would depend upon such factors as the intensity of restraint, weld metal strength and fit up.

As an example of the use of a hardness criterion, the information obtained in this research program has been used to determine the minimum submerged arc fillet weld that can be used without preheat for a range of thicknesses and carbon equivalent. Using the information in the design curve shown in Fig. 3 the critical cooling rate for a hardness of 350 HV for a range of carbon equivalents is determined. Using the cooling rate data shown in Fig. 10, the equivalent minimum energy input for various thicknesses is determined from the critical cooling rate. Using the curve shown in Fig. 7, the equivalent fillet size is determined from the energy input. The results are presented in Table 10.

Several features of this table are to be noted.

First, the design curves are lower bound values and hence the table can be regarded as fairly conservative.

Second, it is to be emphasized that Table 10 is based on a hardness criterion. Thus if a steel had a high carbon equivalent but a low carbon content and a low susceptibility to cracking, a fillet weld, smaller than the one indicated could be put down without the occurrence of cracks, depending on the control of hydrogen, etc. If for example, the carbon content of a high strength low alloy

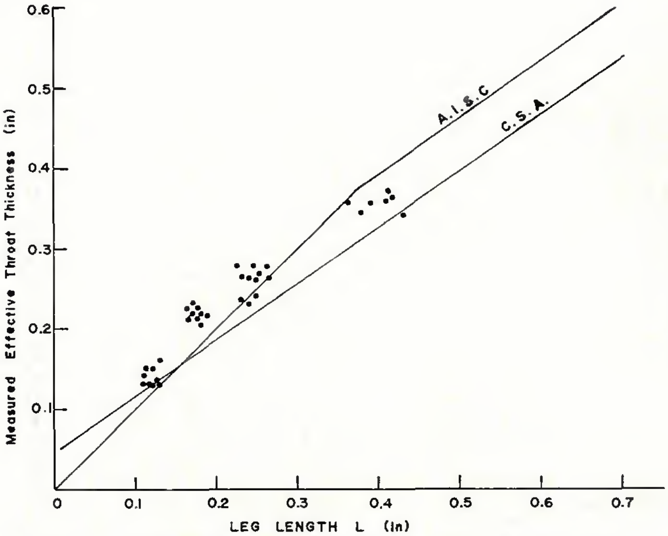

Fig. 9 — Results of measurements of effective throat thickness

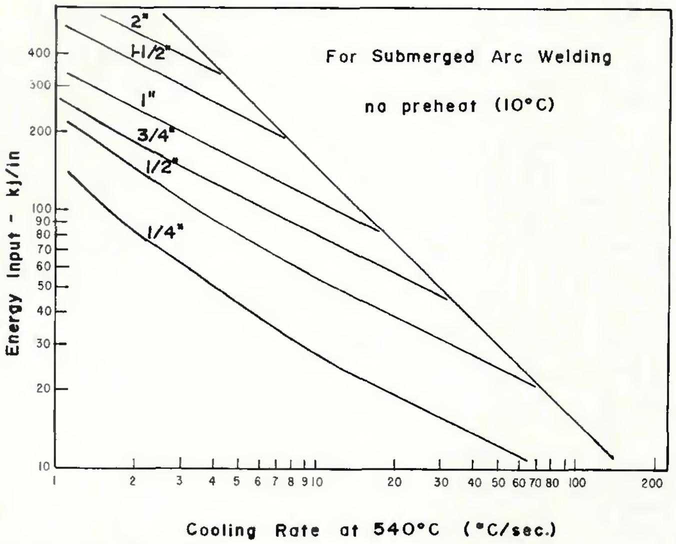

Fig. 10 —Relation between energy input and cooling rate at 540 C for submerged arc fillet welds between plates of equal thickness

Table 7 — CTS Tests Using the Flux Cored CO_2 Process

Test no.	Steel	Thickness, in.	Energy input, kJ/in.	Preheat C	(F)	Avg Max HAZ hardness HV10kg	Results
BG80X	A441	2-5/8	26.9	22	(70)	330	no crack
BG80Y	A441	2-5/8	12.7	22	(70)	387	no crack
RB81X	A36	2	21.3	22	(70)	503	no crack
RB81Y	A36	2	12.7	22	(70)	464	no crack
TC82X	A517H	1-1/2	25.8	22	(70)	478	HAZ cracking
TC82Y	A517H	1-1/2	12.7	22	(70)	488	HAZ cracking
A83X	A588C	2-5/8	25.8	20	(68)	413	no crack
A83Y	A588C	2-5/8	10.0	22	(70)	437	w.m. H_2 cracking

(a) First letters in Test no. correspond to Code in Table 1.

Table 8 — Manual CTS Tests Using Non-Low Hydrogen Electrodes (E6010 except where indicated otherwise)

Test no.[a]	Steel	Thickness, in.	Energy input, kJ/in.	Preheat C	(F)	Avg max HAZ hardness HV10kg	Results
RC41X	A36	2-1/2	43	22	(70)	358	extensive w.m., HAZ cold cracking, HAZ toe cracking
RC41Y	A36	2-1/2	42	20	(68)	—	fine HAZ, w.m. cold cracking
BC42X	A441	2-5/8	50	22	(70	357	extensive w.m. cold cracking
Q43X	A517F	2-1/2	40	19	(66)	—	no cracking (E7024)
Q44X	A517F	2-1/2	39	19	(66)	425	extensive HAZ cold cracking
Q44Y	A517F	2-1/2	52	20	(68)	—	fine HAZ cold cracking
A50Y	A588C	2-5/8	43	23	(74)	378	no cracking (E7024)

(a) First letters of Test no. correspond to Code in Table 1.

steel (with average Mn, Cr levels) is less than 0.13% a maximum HAZ hardness greater than 350 HV is unlikely even with very low energy inputs. The table is therefore likely to become invalid or at least very conservative if the carbon content of the steel is less than about 0.13%.

It should be also noted that the 350 HV hardness criterion breaks down in situations represented by the compact restraint test. The conditions in the compact restraint test represent very high restraint with large contraction and although this situation could arise in practice it would be very rare to find it with fillet welds.

A number of steels are shown in Table 10 corresponding to the maximum in the steel specification. In most cases, however, common structural steels of the A36, A441 type would generally fall in the group with carbon equivalent equal to 0.40 to 0.45 and in many cases the carbon equivalent can be calculated from mill sheets to enable the steel to be placed in the appropriate group.

A fourth important point to note is that Table 10 is based on heat-affected zone hardness and it is assumed that sufficient control over the welding consumables and welding procedure is exercised so that weld metal cracking does not occur.

Generally speaking, the use of conventional mild steel electrodes in submerged arc welding is not likely to lead to hydrogen cracking in the weld metal, even in thick sections and where preheat is not used. However, weld metal cracking may occur with other processes, particularly those that do not maintain low hydrogen contents. For this reason, and also because the hardness criterion requires careful control of energy input, it is suggested that Table 10 be used only for fully automatic submerged arc welding.

In practice it is difficult with manual processes to control energy input to precise values, particularly when the possibility of arc strikes, short tack welds, or 'cosmetic' passes, exists. At present the AWS D1.1-72 code allows a hardness criterion to be used only for single pass multiple-electrode submerged arc welding. Table

10 would be valid for any single pass fillet weld, irrespective of the number of electrodes employed. The major benefits from the use of this approach would become apparent when welding conventional carbon and carbon manganese structural materials in thick sections where a 3/8 in. fillet weld is shown to be adequate to prevent excessive heat-affected zone hardening for most of the chemistries likely to be encountered.

It should be pointed out that hardnesses measured in the heat-affected zone in this present research project and in other research projects, tend to be higher than those observed during field measurements. This is because of the difficulties in placing the indentation close to the fusion boundary during a routine field test.

The use of 350 HV as a hardness criterion implies a significant tolerance to variations in hydrogen content. Bailey showed that with the manual process cracking did not occur in the heat-affected zone of the fillet welds when the hardness was less than 350 HV, even with high hydrogen electrodes having rutile or cellulose coverings. Thus the recommendations are likely to be valid for most submerged arc consumables and it is not expected that changes in flux type, for instance, would significantly affect the requirements.

Table 9 — Compact Restraint Tests

Test no.[(a)]	Steel	Thickness, in.	Type of electrode	Energy Input kJ/in.	Preheat C	Preheat (F)	Avg max hardness HV10kg	Results
SB1	A588C	2-5/8	E11018	38	23	(72)	327	HAZ root micro-cracking
SB2	A588C	2-5/8	E7018	48	24	(76)	285	HAZ root micro-cracking
STA1	A517H	1-1/2	E7018	35	23	(72)	401	HAZ root gross & micro-cracking
STA2	A517H	1-1/2	E11018	48	24	(76)	483	HAZ root micro-cracking
SEE1	A441	2-1/2	E11018	38	23	(72)	357	HAZ root micro-cracking
SEE2	A441	2-1/2	E7018	48	24	(76)	302	HAZ root micro-cracking

(a) First letters of Test no. correspond to Code in Table 1.

Table 10 — Minimum Size Single Pass Fillet Welds that Can Be Deposited Without Preheat (i.e., 10 C) Using the Submerged Arc Process that ensures an HAZ Hardness Less than 350 HV

Plate thickness, in.[(a)]	Fillet weld size in inches for plates having carbon equivalents[(b)] of: 0.35[(c)]	0.40[(c)]	0.45[(c)]	0.50[(d)]	0.55[(e)]	0.60	0.65
≤1/4	3/16	3/16	3/16	3/16	3/16	1/4	1/4
≤1/2	3/16	1/4	1/4	1/4	5/16	5/16	3/8
≤3/4	1/4	1/4	5/16	5/16	3/8	3/8	7/16
≤1	1/4	1/4	3/8	3/8	7/16	1/2	9/16
≤2	1/4	1/4	3/8	3/8	1/2	5/8	5/8
≥3	1/4	1/4	3/8	3/8	1/2	5/8	3/4

(a) For plates of equal thickness.
(b) CE = C + (Mn + Si)/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15.
(c) A36, A441, CSA-G40.21-grade 38W — normal compositions.
(d) A36 ≤1-1/2 in., A441, CSA-G40.21-grade 38W — maximum composition.
(e) A36 ≥1-1/2 in., A572 grades 55 and 65 — maximum composition.

Conclusions

The HAZ hardening behavior of a number of steels has been studied using small bead-on-plate specimens. The results, together with data from literature, have enabled a relation to be established between carbon equivalent and cooling rate to produce a given hardness. Controlled thermal severity tests have been carried out using the submerged arc, manual shielded metal arc and the flux cored welding processes to determine the effect of fillet weld size on susceptibility to cracking.

Results showed that very high HAZ hardness could be tolerated without cracking when using the submerged arc process. The results have been used to establish the minimum size fillet welds that can be deposited in some carbon, carbon manganese and low alloy steels, without using preheat (i.e. at 10 C, or 50 F) based on a HAZ hardness limit of 350 HV, and a significant tolerance to variations in hydrogen content. The proposed method is not applicable to the more hardenable type steels such as A514.

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