Fatigue of Steel Weldments

Literature review is interpreted to show that fatigue strength is determined primarily by the geometry of the weldment and the soundness of the weld metal

BY B. POLLARD AND R. J. COVER

ABSTRACT. The literature dealing with the fatigue of steel weldments has been reviewed and the effect on fatigue strength of testing conditions, weld geometry, weld metal soundness, residual stress and the microstructure of the weld metal and heat-affected zone has been examined. It has been clearly shown that weld geometry is the most important factor in determining the fatigue properties of a weld. For a given weld geometry, the fatigue strength is determined by the severity of the stress concentration at the weld toe or, with the weld reinforcement removed, by the stress concentration at weld metal defects. Different welding processes influence fatigue strength by producing welds with different degrees of surface roughness and weld metal soundness.

Residual stress due to welding only affects fatigue strength for alternating loading and under such conditions a moderate increase in fatigue strength is obtained by thermal stress relief. Larger increases in fatigue strength may be obtained by postweld treatments which produce compressive residual stresses, in place of the original tensile stresses, at the weld toe.

The microstructures of the weld metal and heat-affected zone have only a minor effect upon the fatigue strength of welds and are usually masked by the much greater effects of weld geometry and weld defects.

B. POLLARD is a Senior Research Metallurgist and R. J. COVER is a Research Metallurgist, Graham Research Laboratory, Jones & Laughlin Steel Corporation, Pittsburgh, Pa. Paper presented at the Canadian Welding Metalworking Exposition and Conference, Toronto, Canada, September 29, 1971.

Introduction

Almost all fabrication of structures today involves welding. Therefore the effects of welding on the life of structures subjected to cyclic loading must be considered for economical and safe design. Over the last 40 years the results of many fatigue tests on steel weldments have been published. In the present paper a selected portion of the literature is reviewed with the purpose of identifying and explaining the many variables which can influence the fatigue life of a steel weldment.

For brevity, certain references which deal with tests on less common joint geometries have been omitted because, while providing useful design data, they contribute little to the overall understanding of the factors which determine the fatigue life of weldments. Some early references have also been omitted because improvements in welding technology have made the data obsolete.

Major variables which may be expected to influence fatigue life of weldments are: (1) the testing conditions, (2) the geometry of the weldment, (3) the soundness of the weld metal, (4) the residual stress pattern introduced by welding, and (5) the microstructure of the weld metal and heat-affected zone. The testing conditions and to a lesser degree the weld geometry may be selected at will. The other variables are determined by the welding process and any post-weld treatment applied to the weldments.

Weld Fatigue Testing

The methods and equipment used for fatigue testing weldments are essentially the same as those used for determining the fatigue strength of the base metal. The type of specimen is determined by the geometry of the weldment. Examples of some commonly used fatigue specimens are shown in Figs. 1 and 2. Irrespective of the weld geometry, the test specimen should include a full cross-section of the weld. Round specimens, machined from transverse weld sections, are only satisfactory for comparing fatigue strengths of different weld metals but all-weld-metal specimens, machined with their axes coincident with the weld axis, are generally preferred for that purpose.

Specimen size is determined by the capacity of the fatigue machine available. Results of tests on base metals, using rotating beam specimens, have shown a decrease in fatigue strength with increase in specimen diameter[1-3] and it is reasonable to assume that the larger the test specimen, the greater the probability of a defect being present which could reduce fatigue life. However, the results of tests on traverse butt

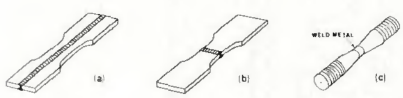

Fig. 1—Butt weld fatigue specimens.[83] (a) longitudinal butt weld, axial or flexural loading; (b) transverse butt weld, axial or flexural loading; (c) transverse butt weld, axial or rotary bend loading

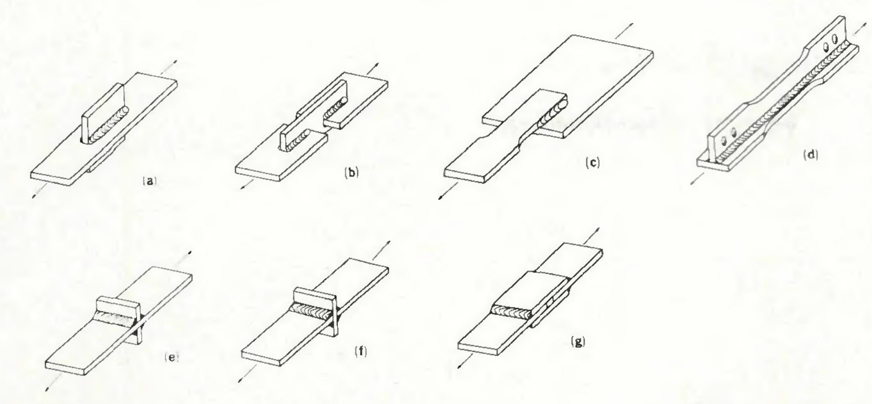

Fig. 2 — Fillet weld fatigue specimens. (a) non-load-carrying longitudinal fillet welds;[53] (b) "egg box" type load-carrying longitudinal fillet weld;[52] (c) cover-plate-type load-carrying longitudinal fillet weld;[11, 83] (d) continuous load-carrying fillet weld;[28, 83] (e) non-load-carrying transverse fillet weld;[61] (f) Tee-type load-carrying transverse fillet weld;[14, 27] (g) cover-plate-type load-carrying transverse fillet weld[14, 83]

welded specimens, varying in thickness from ½ to 1½ in. and in width from 1⅜ to 6 in., and on longitudinal specimens 1½ to 11½ in. wide of the same thickness range, revealed no significant effect of specimen size.[4] This indicates that the frequency of defects in welds is sufficiently high that the smallest specimen size commonly used covers a representative length of the weld. The fatigue load is usually applied axially although bending has also been used. With few exceptions, testing has been performed in air at ambient temperature, although it is well know that environment affects fatigue life.

The stress ratios

$$\left(R = \frac{\sigma_{min}}{\sigma_{max}} \right)$$

commonly used in laboratory tests correspond to loading conditions of full compression to full tension (alternating loading, R = −1), zero load to full tension (pulsating tension, R = O) and half tension to full tension (pulsating tension, R = ½). Without exception, the larger the value of R, the higher the fatigue strength for a given number of cycles. The results are reported either as complete S-N plots, depicting number of cycles to failure attained at various stress levels; or as the fatigue strength for a certain life, usually 10^5 or 2×10^6 cycles. When testing is performed at various values of R, the results are usually presented in the form of a modified Goodman diagram.

Effects of Weld Geometry

The effects of geometry by far override all other considerations in determining the fatigue strength of a welded joint. The fatigue strengths of different types of welded joints in mild steel are summarized in Table 1.[5] It can be seen that in all cases welding causes a significant decrease in fatigue strength.

Butt Welds

More fatigue testing has been performed on transverse butt welds than on any other type of weld. For a simple butt weld with the weld reinforcement intact, fracture occurs at the edge of the weld reinforcement (weld toe) because the stress concentration, caused by the change of cross-section, is a maximum at that point, Fig. 3(a).[6] The fatigue strength of transverse butt welds has been shown to increase in proportion to the included angle between the weld reinforcement and the base plate[7] (Fig. 4), approaching a maximum when the included angle equals 180 deg. The type of edge preparation also influences the fatigue strength of transverse butt joints.[4] Single-Vee and single-U welded joints have rather higher fatigue strengths than double-Vee welded joints, presumably due to the stress concentration at the weld toes, on opposite sides of the plate, being in different planes.

The effect of base metal strength on the fatigue strength of transverse butt welds has been summarized by Munse[4] for steels with UTS values up to 110 ksi. These data are replotted in Fig. 5 together with further data for steels with tensile strengths up to 150 ksi.[8,9] For steels with strengths of 55 to 110 ksi, weld fatigue strength increases slightly with increase in UTS. The increase in fatigue strength is 0.3 (increase in UTS) at 10^5 cycles but only 0.17 (increase in UTS) at 2×10^6 cycles. Considerable scatter exists in the data and this has caused many investigators to conclude that the fatigue strengths of welds in high strength steels are no better than those of similar welds in mild steel. The wide variation in fatigue strengths shown in Fig. 5 is probably the result of variations in weld quality. The leveling off and apparent decrease in fatigue strength at strengths above 110 ksi is due to an increase in notch sensi-

Table 1 — Fatigue Strength of Mild Steel Under Pulsating Tension Loading [(a)]

Type of joint	Fatigue strength at 2 x 10^6 cycles: UTS, ksi	% BMFS [(b)]
Plain plate with millscale surface	35.8	100
Longitudinal butt welds, including full penetration web to flange welds in beams	21.9 - 28.9	61 - 81
Continuous longitudinal manual fillet welds (e.g. web/flange welds)	19.6 - 24.0	55 - 67
Transverse butt welds, made manually, as-welded	15.7 - 29.1	44 - 81
Transverse non-load-carrying fillet welds	11.6 - 22.4	33 - 63
Longitudinal non-load-carrying fillet welds	10.1 - 14.6	28 - 41
Transverse load-carrying fillet welds	10.3 - 20.1	29 - 56
Longitudinal load-carrying fillet welds	7.8 - 13.0	22 - 36
Plate with longitudinal attachment on its edge	8.95 - 11.2	25 - 31

(a) See reference 5.
(b) BMFS = base metal fatigue strength

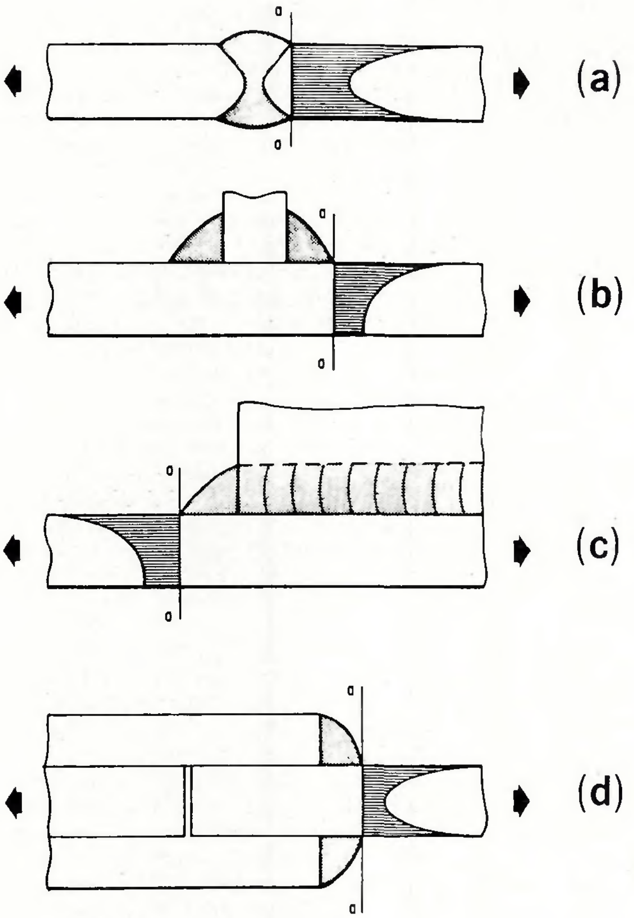

Fig. 3 — Axial stress distribution in welded plate on section a-a[6]

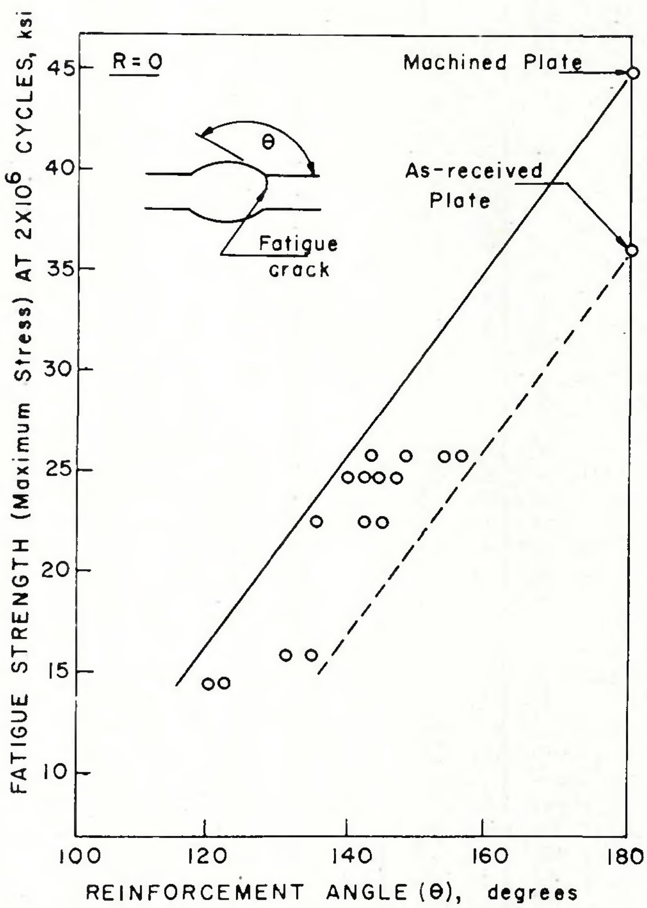

Fig. 4 — Fatigue strength of butt welded joints as a function of the angle between the weld reinforcement and the base plate,[7] *axial loading, stress ratio (R = O)*

tivity with increase in UTS. The same effect is observed for base metals but at higher strength levels.[10]

The results for steels with UTS values of 110-150 ksi are as low as any fatigue strengths obtained and are comparable with the lowest strengths obtained for mild steel welds. Since these are the only results available for steel of this strength level, it is impossible to say if these are the highest fatigue strengths possible but, at the present time, for design purposes, welds in high strength steels, with no post-weld treatment, must be considered to have fatigue strengths no higher than the same welds in mild steel.

Longitudinal butt welds have slightly higher fatigue strengths than comparable transverse butt welds because the applied stress is parallel to the weld axis and the stress concentration at the weld toe is lower (compare Tables 2 and 6).

Fillet Welds

A greater variation in specimen geometry is possible with fillet welds than with butt welds but all joints can be divided into two classes: load-carrying and non-load-carrying. The test welds, which may be transverse or longitudinal with respect to the stress axis, are used to attach a gusset (Tee joint) or cover-plate (lap joint) to the main member. Details of the different specimen types are shown in Fig. 2.

Transverse load-carrying fillet welds have slightly lower fatigue strengths than non-load-carrying fillet welds, which are, in turn, lower than transverse butt welds. Similarly, longitudinal load-carrying fillet welds have slightly lower fatigue strengths than non-load-carrying fillet welds but both types of longitudinal fillet welds have much lower strengths than longitudinal butt welds. Fillet welds usually have incomplete penetration so they contain a built-in "crack" in addition to the "notch" caused by the change of cross-section at the weld toe. However, provided that the weld fillet cross-sectional area is of adequate size, failure of longitudinal fillet welds occurs in the base metal at the end of the weld.[11, 12]

The low fatigue strength of longitudinal fillet welds has therefore been attributed to stress concentration at the end of the weld. The explanation is supported by the fact that continuous longitudinal fillet welds, as used for joining flanges to the web of an I-beam, have fatigue strengths only slightly lower than longitudinal butt welds. It is worth noting that data for longitudinal fillet welds show less scatter than for transverse fillet or butt welds. This indicates that the stress concentration at the end of a fillet weld is fairly constant and outweighs all other variables.

The fatigue strength of transverse fillet welds depends upon the plate thickness, the fillet size and the included angle between the weld face and the base plate.[7] For both Tee-type and lap-type joints there is a critical fillet size for a given plate thickness, below which failure occurs at the root of the weld and above which failure occurs in the base metal at the toe of the weld.[13] The critical fillet size is also the optimum fillet size since further increase in fillet size produces no further improvement in fatigue strength. The critical fillet size has been found to obey the empirical relationship:

$$\frac{2S}{t} = \text{a constant, } k$$

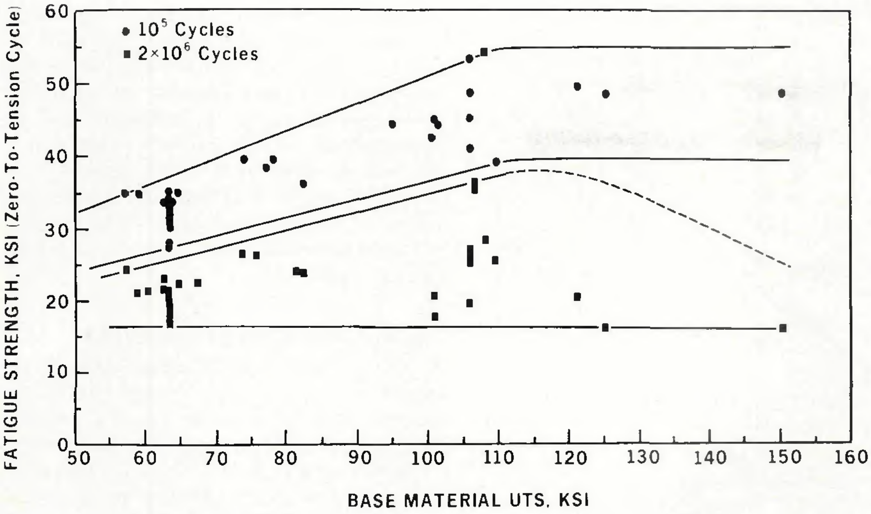

Fig. 5 — Effect of base metal UTS on weld fatigue strength for transverse butt welds tested in pulsating tension (R = O)

where
S = critical fillet size
t = plate thickness

For pulsating tension (R = O), k $\approx$ 2 for Tee-type specimens[13,14] and 1.5 for lap type specimens.[14] The critical fillet size may be reduced by beveling the web plate.[13] When failure occurs at the root of the weld, increases in fatigue strength of 40-50% can be obtained by this technique.[13,15,16]

Effect of Weld Defects

If the weld reinforcement is removed from a butt weld (either transverse or longitudinal) the fatigue strength is raised and failure occurs in the weld metal. Examination of fracture surfaces has shown that failure is then initiated at weld defects such as porosity, slag inclusions, undercutting and lack of penetration.

The fatigue strength of a mild steel butt weld can be reduced to less than one-third the fatigue strength of a defect-free weld by very dense porosity[17] and, in general, the fatigue properties of a weld are much more sensitive to defects than the static tensile properties. For example, a 5% defective area in a mild steel butt weld with the reinforcement removed has negligible effect upon the UTS[18] but reduces the fatigue strength by 30–45%.[18-20] The sensitivity to weld defects increases with the strength of the steel. Munse[21] showed that for transverse butt welds in HY-80 steel, with the weld reinforcement removed, 5% porosity reduced the fatigue strength at 10^5 cycles by 45% and a flaw area as small as 0.1% reduced the fatigue strength by 18%.

Slag inclusions have long been recognized as possible sites for fatigue fracture initiation in welds but the first attempts to correlate fatigue strength with defect size did not isolate the effect of inclusions from effects due to porosity.[19] Moreover, these attempts could not deal with slag inclusions of irregular shape.[22] More recently, techniques have been developed for the production of slag inclusions of a reproducible shape and size, [23,24] thus permitting systematic investigations of the effect of slag inclusions on fatigue strength. For transverse butt welds in ½ in. thick mild steel a close correlation between strength has been observed.[24,25] Increasing the inclusion length by an order of magnitude resulted in a 20-30% reduction in fatigue strength, single inclusions giving slightly higher fatigue strengths than multiple inclusions of the same size. For welds in 1½ in. thick plate a more complex situation was found to exist.

Harrison[26] examined the effect of three ¼ in. inclusions and one continuous slag line and found that the effect of slag inclusions depended upon their location. The effect of inclusions at the center of the weld thickness was blanketed by compressive residual stress — large and small defects giving similar fatigue strengths. When the compressive residual stresses were relieved prior to testing, the fatigue strength increased when the defects were discrete but decreased when the defect was a continuous slag line. Harrison explains this anomaly as being due to the stress relief treatment removing hydrogen from the weld defects. Slag inclusions near the weld surface reduced fatigue strength approximately 40% relative to specimens with the inclusions in the center of the weld.

Inadequate joint penetration is inherent in fillet welds and a common defect in butt welds but is frequently tolerated in lightly stressed butt welds for reasons of economy. Its effect on fatigue strength depends upon the weld geometry. The part played by inadequate joint penetration in determining the fatigue strength of Tee-type transverse fillet welded joints has already been discussed and that improvement in fatigue strength that can be obtained by increasing penetration has been clearly demonstrated.[27] In contrast, lack of penetration has little effect upon the fatigue strength of continuous longitudinal fillet welds[28] because the maximum principal stress is parallel to the faying surface. Likewise, partial penetration longitudinal butt welds were found to have fatigue strengths as high as full penetration longitudinal butt welds,[29] thereby justifying the common practice of using partial penetration butt welds when their axes lie in the direction of the major applied stress. When the applied stress is transverse to a partial penetration butt weld the fatigue strength is severely reduced — for defects covering up to 50 % of the joint area, the percent reduction of fatigue strength is approximately equal to twice the percent reduction of area by the defect.[30] The type of fatigue loading may modify the effect of inadequate joint penetration. It has been reported that the fatigue strengths of butt welds tested in alternating bending are less affected by partial penetration than when similar joints are tested under alternating tension and compression.[31]

Incomplete fusion has not been systematically investigated but may be expected to have a similar effect upon fatigue strength as inadequate joint penetration, as both are essentially two-dimensional defects.

In addition to defects within the weld, surface defects such as over-

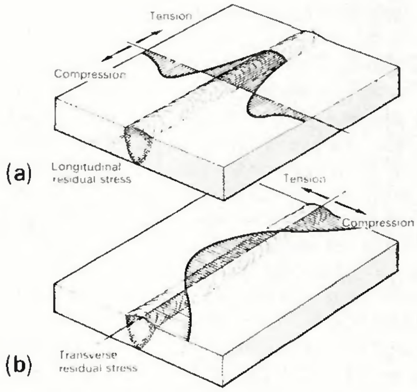

Fig. 6—Schematic representation of the residual stress distribution in a single-Vee butt weld[84]

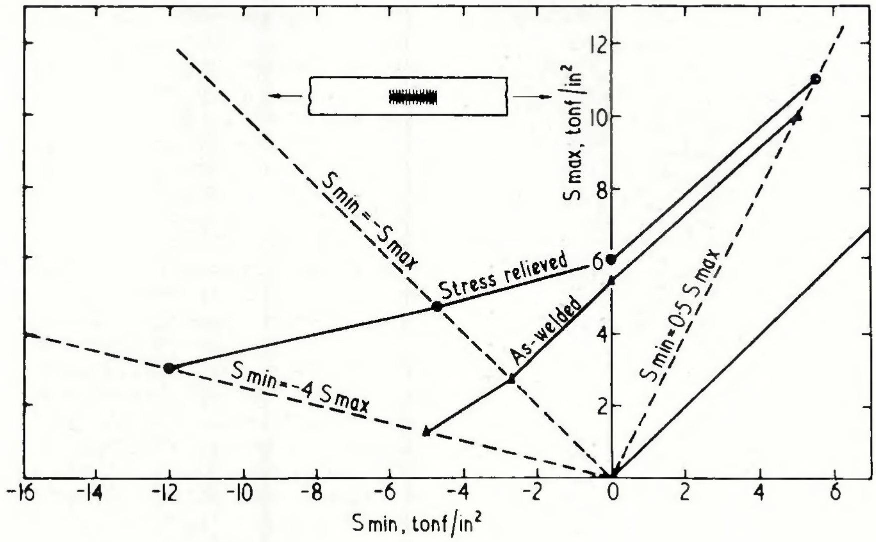

Fig. 7 — Effect of stress relief on the fatigue strength at 2×10⁶ cycles of fillet welded mild steel specimens[5]

lap, undercut and excessive weld reinforcement reduce fatigue strength. Overlap and undercut both occur at the weld toe and reduce fatigue strength by causing an increase in the stress concentration at that point. An undercut depth of 0.0354 in. reduced the fatigue limit of mild steel welds by nearly 50% for pulsating tensile fatigue[32] while an undercut depth of about 0.050 in. reduced the fatigue life of HY-80 welds to about one-third.[32] Excessive weld reinforcement increases the included angle between the weld face and the base plate and thereby increases the stress concentration at the weld toe, which in turn reduces the fatigue strength of the weld.

Although no investigation has been reported in the literature of the effect of hot tears in the weld metal or of heat-affected zone cracks due to hydrogen embrittlement upon the fatigue strengths of welds, both defects can result in a serious deterioration in static properties and may be expected to have an even more marked effect upon fatigue strength.

Effect of Residual Stress

When a weld cools, contraction of the weld metal relative to the cool plate results in the creation of tensile residual stresses in the weld metal and balancing compressive stresses in the plate. The residual stress distribution parallel to the weld is shown schematically in Fig. 6(a). The longitudinal tensile stress approaches the yield strength of the weld metal. The stress transverse to the weld is generally lower but much more variable, as it depends upon joint geometry, the number of weld passes and their sequence and heat input. For welds made from one side (single-Vee butt, single-U butt and fillet welds), the residual stress at the weld toe is tensile but for welds made from both sides of the plate (double-Vee butt) the residual stress at the weld toe may be either tensile or compressive in nature. Moreover, in order to maintain equilibrium, the stress changes sign between the middle and the ends of the weld, as shown in Fig. 6(b).

In the older literature, conflicting claims were made for the effect of residual stress on the fatigue strength of structures. Ross[33] and Hebrant[34] considered residual stresses to have little effect on the fatigue strength of weldments but Dugdale[35] showed that tensile residual stresses reduced the fatigue strength of notched base metal specimens and would therefore be expected to have a similar effect on the fatigue strength of welds, where a notch condition exists at the edge of the weld reinforcement or at defects. The confusion was caused by several factors: (1) the effect of residual stress was determined by fatigue testing before and after a thermal stress-relief treatment, which could have produced significant microstructural changes; (2) direct measurements of residual stress were not made; (3) relatively small test specimens were cut from the welded plates. It has subsequently been shown that cutting up a welded plate can result in a redistribution of residual stress which reduces the residual stress in a fatigue specimen to a relatively low level[36] (17 ksi at the edge of a weld in a 50 ksi yield strength steel); and (4) the specimens were tested in pulsating tension.

Stress ratio has since been shown to have an important influence on fatigue strength when residual stresses are involved.[37, 38] For transverse butt welds stress relief causes negligible improvement in fatigue strength for pulsating tension[39] but a substantial improvement for alternating loading.[36,40] As shown in Fig. 7, the effect of residual stress in general becomes greater the larger the compressive component of the stress cycle.

Microstructure of the Weld

When welds are tested with the weld reinforcement intact, fatigue cracks are nucleated in the weld metal, near the edge of the weld reinforcement[41] and then propagate through the heat-affected zone. The fatigue life is the sum of the number of cycles required for crack nucleation plus the number of cycles of crack growth to failure. The latter one would expect to be determined by the microstructure of the heat-affected zone. However, since the heat-affected zones of welds in structural steels are either bainitic or martensitic, or a mixture of the two structures, and measurements of crack growth rate for martensitic steels[42] and bainitic weld metal[43] gave similar values, the crack growth period and hence the fatigue life is more or less independent of heat-affected zone microstructure. This has been confirmed by Gerbeaux and Videau,[44] who found no significant difference in the fatigue lives of welds in St 52 steel with heat-affected zone hardnesses of 350 and 450 HV.

When fatigue failure starts in the weld metal near the edge of the weld reinforcement, the microstructure of the weld metal has been shown to affect the fatigue strength of the weld.[41] Improved fatigue strengths with certain electrodes were attributed to a fine Widmanstätten structure.

Effect of Process Selection

Since the frequency of a particular type of weld defect will vary from one welding process to another, it is to be expected that the fatigue strength of a weld will be dependent upon the process used to make it. The bulk of the fatigue data available applies to shielded metal arc welding (SMAW) which therefore serve as a base for comparing the efficiency of other arc welding processes. The most important distinction between SMAW and other welding processes is that SMAW is a manual process whereas the others are primarily semi-automatic (flux cored arc welding (FCAW) and gas metal-arc welding (GMAW) or fully automatic processes (submerged arc welding (SAW) and electroslag welding (EW). The automatic processes are capable

Table 2 — Effect of Removing Weld Reinforcement on Fatigue Strength of Transverse Butt Welds (SMAW)

Steel	UTS, ksi	Stress system[a]	Fatigue strength, ksi, 2x10⁶ cycles: Reinf. on	% BMFS[b]	Reinf. off	% BMFS[b]	% Change	Ref.	Remarks
Carbon, structural	60.0	PT	22.5	71.2	28.4	89.9	+26.2	61	Single-U weld
Carbon, structural	55.4	PT	20.2	58.1	21.8	62.1	+ 7.9	62,63	Double-Vee weld, E6012 electrode
Carbon, structural	54.9	PT	23.8	67.8	29.1	82.9	+22.3	63	Double-Vee weld, E7016 electrode
A7	57.4	PT	22.3	64.5	26.4	74.8	+18.4	64	Double-Vee weld
A242	77.0	PT	26.5	60.9	27.6	63.5	+ 4.2	65,66	Double-Vee weld
Silicon	—	PT	24.0	—	23.7	—	- 1.0	67	"
St 52	—	PT	19.2	—	36.3	—	+89.0	68	"
St 52	—	PT	36.3	76.7	40.1	84.7	+10.5	69	"
Q&T	108.5	PT	25.8	60.2	28.7	67.4	+11.5	70	"
15 Kh SND	—	PT	—	—	—	—	+60.0	40	"
10 G2S1	—	PT	—	—	—	—	+100.0	40	"
A7	60.0	PT	23.2	76.5	28.7	94.7	+23.7	29,67	Single-Vee weld
St 37	—	PT	29.1	—	28.4	—	- 2.4	17	Single-Vee weld, porous
Carbon, structural	56-72	PT	23.2	—	28.2	—	+21.6	71	Single-Vee weld
Siemens Martin	—	PT	24.1	—	29.6	—	+22.8	72	Single-Vee weld
HS 42/50	—	PT	21.0	—	23.7	—	+12.9	73	Single-Vee weld
B.S. 15	63.0	PT	25.B	71.9	35.8	100.0	+39.1	39	Single-Vee weld
NES 65	80.0	Bending (R=.33)	48.0	72.7	57.5	87.1	+19.8	36	Single-Vee weld
T1	120.0	Bending (R=-1)	14.0	39.0	28.0	78.0	+100.0	9	Double-Vee weld

(a) PT = pulsating tension (R = O).
(b) BMFS = base metal fatigue strength.

Table 3 — Fatigue Strength of Transverse Submerged Arc Butt Welds Tested in Pulsating Tension (R = O)

Steel	UTS, ksi	Fatigue strength at 2×10⁶ cycles, ksi: Reinf. on	% BMFS[a]	Reinf. off	% BMFS[a]	Ref.	Remarks
Carbon, structural	~65	19.5	—	—	—	62	
ST 37	52-63	30.0	100	—	—	69	Manual weld
B.S. 15	63	14.5-24.5	41-69	35.8	100.0	39	Stress relieved
M.S.	62.6	25.0	~ 70	—	—	74	4-max. stress range
15 KhSMD	71.4	41.0	88	41.0	88.0	75	
15 KhSMD	91.8	37.5	83	46.0	100.0	75	
A 517	100-120	20-30	50-55	35-45	82-88	76	

(a) BMFS = base metal fatigue strength

Table 4 — Comparison of the Fatigue Strengths of Transverse Butt Welds Made with the GMAW and SMAW Processes

Steel	UTS, ksi	Welding process	Stress system[a]	Fatigue strength at 2×10⁶ cycles, ksi: Reinf. on	% BMFS[b]	Reinf. off	% BMFS[b]	Ref.	Remarks
22K	77	CO_2	RB	19	73	20.5	79	77	Tempered 620 C
22K	77	SMAW	RB	11	41	20.5	79	77	Tempered 620 C
VAN-80	110	A/5% O_2	RB	34	64-81	42.0	79-100	45	
VAN-80	110	SMAW	RB	22	42-52	30.5	59-73	45	
HY-130	150	A/2% O_2	PT	16.5	44	—	—	8	
HY-130	150	SMAW	PT	16.5	44	—	—	8	

(a) RB = reverse bending; PT = pulsating tension (R = O)
(b) BMFS = base metal fatigue strength

of producing welds with fewer internal defects and with a smoother weld surface than is possible with manual welding. The effect of the weld bead smoothness is observed by comparing the fatigue strengths of welds with the reinforcement intact whereas the effect of weld metal soundness is shown by comparing welds with the reinforcement removed.

With the weld reinforcement on, the fatigue strength in pulsating tension of transverse butt welds in mild steel is 58-77% of the base metal fatigue strength (BMFS, Table 2); whereas the fatigue strength of submerged arc welds is 41-100% of the BMFS (Table 3). With the weld reinforcement removed, the fatigue strength of mild steel transverse butt welds was equal to the BMFS for the SAW process, compared to 75-95% of the BMFS for welds by SMAW. For high strength steels (UTS > 80 ksi), tested in pulsating tension, the fatigue strength of transverse butt welds with the reinforcement on was 50-83% of BMFS for submerged arc welds, compared to 60% of BMFS for welds by SMAW. With the weld reinforcement removed, the fatigue strength increased to 82-100% of BMFS for SAW and 67% of BMFS for SMAW. The SAW process, therefore, appears to be capable of superior welds, compared to the SMAW process, both with respect to the smoothness of the weld bead and the soundness of the weld metal.

The rather limited data for GMAW are summarized in Table 4. Transverse butt welds in mild steel made with the CO_2 process were clearly superior to those produced by the SMAW process when tested with the reinforcement on (73% BMFS versus 40.5% BMFS) but identical when tested with the reinforcement removed. The superior performance of the CO_2 welds was in this case therefore obviously due only to the smoother weld bead. However, Pollard and Aronson[45] obtained higher fatigue strengths for VAN-80 with GMAW than with SMAW, both with and without the weld reinforcement, when argon/5% O_2 shielding was used. This improvement was attributed to a combination of a smoother weld bead and a reduction in the size and number of micropores within the weld metal. Conflicting results have been obtained for HY-130 weldments. One investigator[46] found that weld metal deposited by GMAW was superior to that deposited by SMAW, but other investigators[8] did not report any difference in fatigue strength between welds made with the two processes.

Fatigue data for electroslag welds are summarized in Table 5. The results indicate that fatigue strengths up to 91% of the BMFS can be obtained with the reinforcement on and fatigue strengths equal to the base metal with the reinforcement removed. Harrison[47] found that the weld reinforcement shape and hence the fatigue strength with the reinforcement on was determined by how close the copper shoes, which are used to contain the weld puddle, fitted against the plate. The high fatigue strength of electroslag weld metal is due to a slow solidification rate, which allows gas bubbles and slag globules to float out.

Effect of Postweld Treatment

Although the selection of an automatic welding process over manual SMAW can result in an improvement, the fatigue strength of welds with the reinforcement intact is still not equal to that of the base metal. The low fatigue strengths of fillet welds are of particular concern. A number of postweld treatments have therefore been developed to improve the fatigue strengths of welds. These involve either: (1) a reduction in the stress concentration at the weld toe by changing the geometry of the weld; (2) modification of the residual stress system in the vicinity of the weld; or (3) protection of the weld toe from the environment.

Grinding the Weld Reinforcement

A substantial reduction in the stress concentration at the weld toe can be obtained by grinding off the weld reinforcement. The improvement in fatigue strength obtained by this technique depends upon the reinforcement angle (defined as shown in Fig. 4), the soundness of the weld metal and the type of joint. The results shown in Table 2 are for transverse butt welds made by SMAW. Improvement in fatigue strength ranges from 0-100%. If the weld contains major defects a reduction in fatigue strength is possible due to a reduction in the cross-sectional area of the weld metal. An improvement in fatigue strength can also be obtained for longitudinal butt welds. The improvement shown in Table 6 was only 14-21% because the fatigue strength with the reinforcement intact was fairly high.

Complete removal of the weld reinforcement is obviously only possible for butt welds but a significant improvement in the fatigue strength of fillet welds can be obtained by grinding the toes of the weld to obtain a smooth junction with the base plate. For non-load-carrying fillet welds in mild and low alloy steels grinding resulted in a 96.5% increase in fatigue strength for transverse fillet welds and a 50-70% increase for longitudinal welds tested in pulsating tension.[48] For load-carrying manual submerged arc fillet welds in an alloy steel, a 60% increase in the fatigue limit was obtained in alternating loading.[49]

Thermal Stress Relief

We have already seen that residual stress significantly reduces the fatigue strength of welds subject to alternating loading. The fatigue strength of welds stressed in this manner may therefore be increased by reducing the residual stress to a negligible level or modifying the stress distribution so that the residual stress at the weld toes is compressive instead of tensile. The first technique is the simplest. It requires only that the weldment be heated to a temperature at which the yield strength is low (usually about 1200 F) so that the residual stresses are relieved by plastic deformation and fall to a level corresponding roughly to the yield strength of the steel at the stress relief temperature. To prevent further formation of residual stresses during cooling, the weldment is then slowly cooled to ambient temperature.

For transverse butt welds improvements in fatigue strength of 14-32% have been obtained by stress relieving.[9, 36, 40] However, for continuous longitudinal load-carrying fillet welds Reemsnyder[28] observed no effect of stress relief for $R = -1$ and a slightly detrimental effect for $R = +1/4$. For a load-carrying fillet weld of finite length, Trufyakov and Mikeev[40] likewise found stress relief to reduce the fatigue limit by 14% for pulsating tension. The reduction in fatigue strength was probably due to decarburization during the stress relief anneal, although other metallurgical changes cannot be ruled out.

Reducing the tensile residual stress at the weld toe produces no significant increase in the fatigue strength for pulsating tension and only a moderate increase in fatigue strength for alternating loading. A much larger increase in fatigue strength can be obtained by producing compressive residual stresses at the weld toe, as shown in Fig. 8. The next five techniques to be described utilize residual compressive stresses to increase the fatigue strength of welds.

Localized Heating

The mechanism responsible for weld residual stresses may also be used to modify the residual stress distribution and improve fatigue strength. By heating a region in the vicinity of a weld locally with a gas torch, high compressive stresses are set up around the hot spot, which cause it to deform plastically. On subsequent cooling the hot spot is then subject to tensile stresses and the

Table 5—Fatigue Strengths of Electroslag Transverse Butt Welds

Steel	UTS, ksi	Stress system[a]	Fatigue strength at 10^6-10^7 cycles, ksi: Reinf. on	% BMFS[b]	Reinf. off	% BMFS[b]	Ref.	Remarks
22K	~77	RB	12	53	20	87.5	78	—
22K	~77	ROT B [c]	—	—	25	100	79	—
08GDNFL	64.6	RB	—	—	24	100	80	Cast steel
Not specified	—	PT	29	—	—	—	81	—
B.S. 15	61.8	PT	29	91	32	100	47	—
B.S. 15	61.8	PT	26	81	—	—	47	Consumable guide
40 KhN	110.8	RB	—	—	26	100	82	Forgings
40 KhN	116.6	RB	—	—	27	88	82	Forgings
34 KhM	108.8	RB	—	—	28	95	82	Forgings
15GN4M	109.4	RB	—	—	35	96	82	Forgings

(a) RB = reverse bending; PT = pulsating tension (R = O)
(b) BMFS = base metal fatigue strength
(c) ROT B = rotating bending

Table 6 — Effect of Removing Weld Reinforcement on the Fatigue Strength of Longitudinal Butt Welds (SMAW) Tested in Pulsating Tension (R = O)

Steel	UTS, ksi	Fatigue strength at 2×10^6 cycles, ksi: Reinf. on	% BMFS[a]	Reinf. off	% BMFS[a]	% Change	Ref.	Remarks
A7	63	26.2	82.6	29.8	94.0	+13.7	29	Single-Vee weld
Carbon, structural	60-66	24.5	77.3	29.6	93.4	+20.8	63	Double-Vee weld, E6010 electrode
Carbon, structural	60-61	26.3	83.0	30.2	95.3	+14.8	63	Double-Vee weld, E7016 electrode
A242	78	30.3	78.7	34.8	90.5	+14.9	65	Double-Vee weld

(a) BMFS = base metal fatigue strength

surrounding area to compressive stresses. If the heated region is located with respect to the weld so that the compressive stresses balance the tensile stresses at the edge of the weld reinforcement, an increase in fatigue strength is obtained.

The technique is limited to the treatment of discontinuous longitudinal welds where failure occurs at the weld end, for example, welds used to attach gussets. Using this technique, Puchner[50] increased the fatigue limit of mild steel plates with edge-welded gussets from 38% of BMFS to 96% of BMFS and Trufyakov and Mikeev[40] obtained 100% increase in the fatigue limit for a similar type of specimen. Using the same technique, the fatigue strength of discontinuous non-load-carrying longitudinal fillet welds was increased by 140%.[51] For load-carrying fillet welds[52] the increase in the fatigue limit for pulsating tension was 150% for failure in the main plate of a coverplate-type (lap joint) specimen and 88% for failure in the cover plate *per se*. The corresponding increases for alternating loading were 200% and 160%, respectively.

Induction heating has also been used for local heating.[53] The fatigue limit of mild steel flange type specimens was increased by 220 to 280% using this method.

Localized Heating and Quenching

This technique, first suggested by Gunnert,[54] for increasing the fatigue strength of fillet welds, involves slowly heating the end of the weld to a temperature just below the A , then quenching the "notch" with a jet of water. The notch cools much faster than the surrounding region so that initially the material at the surface of the notch contracts without appreciable restraint, since the surrounding metal is still soft. By the time the surrounding mass cools, the material at the notch is strong and resists the contraction of material around it. The result is that the notch is placed in a state of compression. Using this technique Gunnert raised the fatigue limit of mild steel plates with gussets butt welded to the edges by 29% and Harrison[55] obtained an increase of 120% in the fatigue limit of discontinuous longitudinal fillet welds.

Prior Overloading

Residual compressive stresses may be produced at the edge of the weld reinforcement and the fatigue strength of the joint increased by tensile loading until the weldment undergoes permanent plastic deformation. The fatigue limit of both transverse and longitudinal non-load-carrying fillet welds increases in proportion to the preload.[56,57] An increase in the fatigue limit of 45% was obtained for mild steel (B.S. 15, 41.4 ksi yield strength) transverse fillet welds preloaded to the yield point and tested with a pulsating cycle.[57] For longitudinal fillet welds, preloaded to 33.6 ksi, the fatigue limit increased 25% for pulsating tension and 58% for alternating loading.

Since the increase in fatigue

strength which can be obtained by this technique is limited by the yield strength of the material, greater increases in fatigue strength are therefore possible with high yield strength steels. For example,[57] the fatigue strength of transverse fillet welds in B.S. 968 steel (55.3 ksi yield strength), tested under pulsating tension, increased by 62% after preloading to the yield point and the fatigue strength of longitudinal fillet welds of the same steel, tested under alternating loading, increased by 125%. The technique has also been successfully applied to intersecting butt welds,[40] for which increases in fatigue limit of 50% were obtained for both pulsating and alternating loading.

Local Compression

Residual compressive stresses may be produced at the weld toe by local compression. For non-load-carrying longitudinal fillet welds, tested in pulsating tension, the fatigue limit was increased by 70-80% by local compression.[38, 40, 53]. The fatigue limit of load-carrying longitudinal fillet welds was increased 100% by local compression for both pulsating and alternating loading.[52] This technique has also been successfully applied to short transverse butt and non-load-carrying transverse fillet welds.[40] With alternating loading the fatigue limit was increased by 35% and 100%, respectively.

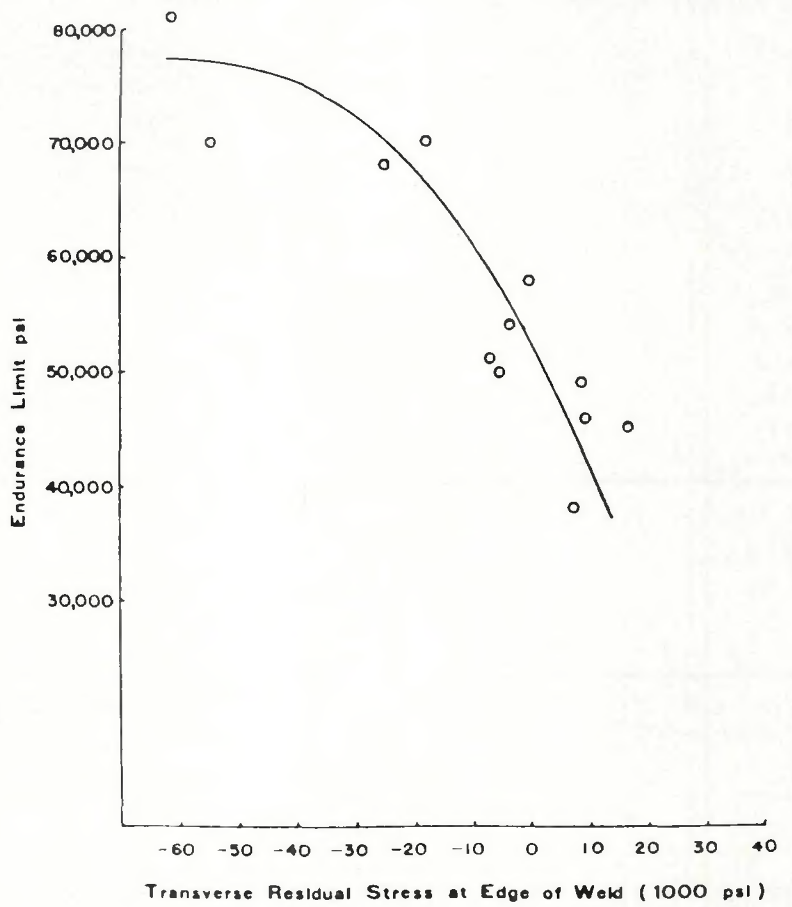

Fig. 8 — Fatigue strength for 10^6 cycles life as a function of transverse residual stress at edge of weld in Ni-Cu-Mo steel.[36] Various residual stress patterns obtained by stress relieving and/or peening; flexural loading, stress ratio R = 0.33

Peening

Compressive residual stresses at the weld toe may be produced by peening the surface with a pneumatic hammer. A solid tool is generally used but some investigators have reported good results with a tool containing a bundle of steel wires. Increases in the fatigue limit of the order of 30% have been obtained for axial specimens of transverse butt welds tested under pulsating tension[9] and alternating loading,[58] while Baren and Hurlebaus[36] obtained an increase of 46% for specimens tested in reverse bending. Larger increases in fatigue strength were obtained for non-load-carrying fillet welds when tested in pulsating tension; the fatigue limit of transverse welds increased by 75-90%[48, 55] and longitudinal welds by 42-80%.[48] The higher value for longitudinal fillet welds was obtained when the weld was continued around the end of the gusset.

Plastic Coatings

It has been shown that the application of a plastic coating to the toe region of the weld increases the fatigue strength.[59] Presumably the coating reduces corrosion by the atmosphere but only certain coatings produce an increase in fatigue strength so it must be admitted that the mechanism is not well understood. Using this technique Gilde obtained a 75% increase in the fatigue limit of transverse butt welds.

Application of Postweld Treatment Methods

Few of the methods described for increasing the fatigue strength of welds are widely applied in practice. Grinding of butt welds is the most frequently used treatment because of its simplicity. Peening is widely used for increasing the fatigue life of rotating machine parts but has not seen much use in the treatment of welded structures, although it is applicable to all weld geometries. Thermal stress relief is only beneficial if the weldment is subject to alternating loading and even then only a moderate increase in fatigue strength is possible. Furthermore, the heat treatment of complete welded structures is generally not possible because of their size, and localized stress relief if incorrectly applied can produce unfavorable stress distributions.

Local heating and local heating and quenching produce substantial increases in the fatigue strength of discontinuous longitudinal fillet welds but are not applicable to continuous welds. They have not seen any significant application in the Western hemisphere, perhaps because neither control systems nor inspection procedures have been developed for these techniques. In Russia[60] local heating has been used to stop the propagation of fatigue cracks in existing railway bridges. Local compression can be substituted for local heating in the treatment of discontinuous fillet welds and does not have the inspection problem associated with the latter, since the indentation, resulting from local compression, is readily visible and its location and depth provide convenient quality control parameters. However, it requires heavy

equipment which may limit its application for on-site fabrication.

No applications of plastic coatings or prior overloading, as a means of increasing the fatigue strength of welds in engineering structures, are known to the authors of this paper. The only disadvantage of plastic coatings would appear to be the difficulty of maintaining coating integrity in service. Prior overloading is, in principle, an attractive method of increasing the fatigue strength of welded joints since it is the weakest joints (under static loading) which receive the maximum benefit. It is readily applicable to structures such as pressure vessels and is in fact unwittingly used in the form of a proof test. However, for structures which have components subject to compressive loading, care must be taken to avoid buckling and the application of the technique is limited by the accuracy of the design.

Grinding and peening therefore appear to be the most generally applicable techniques for improving the fatigue strength of welded joints. Grinding is most readily applied to butt welds. Peening may be used on any type of joint. A combination of these two techniques, or of either technique with stress relieving, may sometimes be necessary to make the fatigue strength of a weldment equal to that of the base metal. Since the magnitude of the compressive stresses produced by peening is limited only by the yield strength of the steel, peening appears to be a highly suitable method for increasing the fatigue strength of welds in high strength steels.

Summary and Conclusions

The literature dealing with the fatigue of steel weldments has been reviewed and it has been shown that weld geometry is the most important factor in determining the fatigue properties of a weld. The fatigue strength of mild steel transverse butt welds made by SMAW is within the range 44-81% of BMFS, depending upon the severity of the stress concentration at the weld toe. The fatigue strength is somewhat higher for longitudinal butt welds (61-81%) and much lower (22-63%) for fillet welds. If the stress-raiser is removed by grinding the reinforcement off, then the fatigue strength of butt welds is raised to a level of 75-100% of the BMFS, the actual value depending on the soundness of the weld metal.

Different welding processes influence fatigue strength by producing welds with different degrees of surface roughness and weld metal soundness. In general, automatic processes are superior to manual processes because they are capable of producing welds with a smoother surface and with greater freedom from weld defects such as porosity and slag inclusions.

Residual stress due to welding only affects fatigue strength for alternating loading and, even then, only a moderate increase in fatigue strength is obtained by thermal stress relief. Modification of the residual stress distribution by post-weld treatments which produce compressive residual stresses, in place of the original tensile stresses, at the weld toe, is, however, an effective means of increasing fatigue strength. Localized heating, localized heating and quenching, localized compression and peening have all been demonstrated to be effective in producing the required compressive stresses but those involving local heating or compression are only suitable for treating the ends of longitudinal fillet or gusset welds, whereas peening is applicable to all weld geometries.

The microstructures of the weld metal and heat-affected zone have only a minor effect upon the fatigue strength of welds and are usually masked by the much greater effects of weld geometry and weld defects.

References

1. Moore, H. F., "A Study of Size Effect and Notch Sensitivity in Fatigue Tests of Steel," *ASTM Proc.,* Vol. 45, pp. 507-521, 1945.

2. Johnston, W. W., "Methods of Investigating the Fatigue Properties of Materials," The Failure of Metals by Fatigue – A Symposium, Melbourne University Press, 1946.

3. Grover, H. J., *et al,* "Fatigue of Metals and Structures," Bureau of Aero., Dept of Navy, 1954.

4. Munse, W. H., and Grover,' La Motte, "Fatigue of Welded Steel Structures," Welding Research Council, New York, 1964.

5. Gurney, T. R., "Fatigue of Welded Military Structures," *British Welding Journal,* Vol. 15, No. 6, pp. 276-282, 1968.

6. Newman, R. P., "Significance of Weld Defects in Relation to Fatigue Fracture," *British Journal of N.D.T.,* Vol. 7, No. 4, pp. 90-96, 1965.

7. Mindlin, H., "Influence of Details on Fatigue Behavior of Structures," *Journal of the Structural Division, ASCE,* Vol. 94, No. ST12, December 1968.

8. Radziminski, J. B., and Lawrence, F. V., "Fatigue of High-Yield-Strength Steel Weldments," *Welding Journal,* Vol. 49, No. 8, Res. Suppl., pp. 365s-374s, 1970.

9. Doty, W. D., "Properties and Characteristics of a Quenched and Tempered Steel for Pressure Vessels," *ibid.,* Vol. 34, No. 9, Res. Suppl., pp. 425s-441s, 1955.

10. Bullens, D. K., *Steel and Its Heat Treatment,* Wiley Publications, p. 37, 1938.

11. Stallmeyer, J. E., *et al,* "Fatigue Strength of Welds in Low-Alloy Structural Steels," *Welding Journal,* Vol. 35, No. 6, Res. Suppl., pp. 298s-307s, 1956.

12. Gurney, T. R., "Fatigue Strength of Fillet Welded Joints in Steel," *British Welding Journal,* Vol. 7, No. 3, pp. 178-187, 1960.

13. Ouchida, H., and Nishioka, A., "A Study of Fatigue Strength of Fillet Welded Joints," *Hitachi Review,* April 1964, pp. 3-14.

14. McFarlane, D. S., and Harrison, J. D., "Some Fatigue Tests of Load Carrying Transverse Fillet Welds," *British Welding Journal,* Vol. 12, No. 12, pp. 613-623, 1965.

15. Stallmeyer, J. E., and Munse, W. H., "Fatigue of Welded Joints in High-Strength Steels," *ibid.,* Vol. 7, No. 4, pp. 281-287, 1960.

16. Wintergerst, S., and Ruckerl, E., "Investigations of the Fatigue Limit of St 37 Welded Joints," *Der Stahlbau,* Vol. 26, No. 5, pp. 121-124, 1957.

17. Hempel, M., and Moller, H., "The Effect of Weld Defects in Specimens of Steel St 37 on Their Tensile Fatigue Strength," *Arch. Eisen.,* Vol. 20, No. 11/12, pp. 375-383, 1949.

18. Clough, R., "Application of Weld Performance Data," *British Welding Journal,* Vol. 15, No. 7, pp. 319-325, 1968.

19. Masi, O., and Erra, A., "Radiographic Examination of Welds. A Complete Assessment of Defects in Terms of Tensile and Fatigue Strength," *Metallurgia Italiana,* Vol. 45, No. 8, pp. 273-283, 1953.

20. Homes, G. A., *Arcos,* Vol. 15, No. 89, pp. 1951-1967, 1938.

21. Munse, W. H., "Comments on 'Fatigue Properties of Materials' by E. G. Eeles and R. C. A. Thurston," *Ocean Engineering,* Vol. 1, No. 2, pp. 189-195, 1968.

22. Warren, W. G., "Fatigue Tests on Defective Butt Welds," *Welding Research,* Vol. 6, No. 6, pp. 112r-117r, December 1952.

23. Matting, A., and Neitzel, M., "The Production of Reproducible Welding Defects and Their Effect on Fatigue Strength," *Bander Bleche Rohre,* Vol. 7, No. 4, pp. 217-225, 1966.

24. Newman, R. P., and Gurney, T. R., "Fatigue Tests on ½ in. Transverse Butt Welds Containing Slag Inclusions," *British Welding Journal,* Vol. 11, No. 7, pp. 341-352, 1964.

25. Newman, R. P., "Significance of Weld Defects in Relation to Fatigue Fracture," *British Journal of N.D.T.,* Vol. 7, No. 4, pp. 90-96.

26. Harrison, J. D., "Further Fatigue Tests of 1½ in. Thick Butt Welds Containing Slag Inclusions," *British Welding Journal,* Vol. 15, No. 2, pp. 85-94, 1968.

27. Hoisveen, S., and Perrson, H. A., "The Effect of Penetration on the Fatigue Strength of Automatic Fillet Welds," *Welding Research Abroad,* Vol. 9, No. 10, pp. 10-14, December 1963.

28. Reemsnyder, H. S., "Some Significant Parameters in the Fatigue Properties of Weld Joints," *Welding Journal,* Vol. 48, No. 5, Res. Suppl., pp. 213s-220s, 1969.

29. Wilson, W. M., *et al,* "Fatigue Strength of Various Types of Butt Welds Connecting Steel Plates," University of Illinois, Engineering Experiment Station Bulletin No. 384, March 1950.

30. Newman, R. P., and Dawes, M. G.,

"Exploratory Fatigue Tests on Transverse Butt Welds Containing Lack of Penetration," *British Welding Journal*, Vol. 12, No. 3, pp. 117-120, 1965.
31. Gal'perin, M. A., and Sarkhosh'yan, G. N., "Determination of Mechanical Properties of Thin Sheet Steel Welds," *Automatic Welding*, No. 10, pp. 14-19, 1964.
32. Thielsch, H., "Weld Surface Contour Variations," *Welding Engineer*, Vol. 51, No. 11, pp. 60, 62-67, 1966.
33. Ros, M., "Experiments for the Determination of the Influence of Residual Stresses on the Fatigue Strength of Structures," *Welding Research BWRA*, Vol. 4, No. 5, pp. 83r-93r, 1950.
34. Hebrant, F., *et al*, "The Relaxation of Residual Welding Stresses by Static and Fatigue Loading," *Welding Research Abroad*, pp. 58-63, September 1957.
35. Dugdale, D. S., "Effect of Residual Stress on Fatigue Strength," *Welding Journal*, Vol. 38, No. 1, Res. Suppl., pp. 45s-48s, 1959.
36. Baren, M. R., and Hurlebaus, R. P., "The Fatigue Properties of a Welded Low Alloy Steel," *ibid.*, Vol. 50, No. 5, Res. Suppl., pp. 207s-212s, 1971.
37. Kudryavtsev, I. V., "The Influence of Internal Stresses on the Fatigue Endurance of Steel," *International Conference on Fatigue*, Inst. Mech. Engr., 1956.
38. Gurney, T. R., "Influence of Residual Stresses on Fatigue Strength of Plates with Fillet Welded Attachments," *British Welding Journal*, Vol. 7, No. 6, pp. 415-431, 1960.
39. Newman, R. P., and Gurney, T. R., "Fatigue Tests of Plain Plate Specimens and Transverse Butt Welds in Mild Steel," *ibid.*, Vol. 6, No. 12, pp. 569-594, 1959.
40. Trufyakov, V. I., and Mikeev, P. P., "Methods of Improving the Endurance of Welded Joints," *Automatic Welding*, No. 11, pp. 25-33, 1964.
41. Hultgren, A., "Metallographic Investigation of Butt-Welded Steel Specimens Tested in Fatigue," *Jernkont. Ann.*, Vol. 152, No. 4, pp. 170-178, 1968.
42. Barsom, J. M., "Fatigue Crack Propagation in Steels of Various Yield Strengths," Paper presented at the First National Congress on Pressure Vessels and Piping, San Francisco, California, May 10-12, 1971.

43. Griffiths, J. R., *et al*, "Influence of Mean Stress on Fatigue-Crack Propagation in a Ferritic Weld Metal," *Metal Science Journal*, Vol. 5, pp. 150-154, July 1971.

44. Gerbeaux, H., and Videau, J. P., "Relation between Subsurface Hardness and Mechanical Behavior in Welded Assemblies of 52 Steel," *Soudage Tech. Connex.*, Vol. 20, No. 7-8, pp. 320-324, 1966.
45. Pollard, B., and Aronson, A. H., "Weldability of VAN-80 Steel," *Welding Journal*, Vol. 49, No. 12, Res. Suppl., pp. 559s-566s, 1970.
46. Evans, R. M., DMIC Review of Recent Developments in Metal Joining, August 25, 1971.
47. Harrison, J. D., "Fatigue Tests of Electroslag Welded Joints," *Metal Construction*, Vol. 1, No. 8, pp. 366-370, 1969.
48. Anon., "Effect of Peening and Grinding on the Fatigue Strength of Fillet Welded Joints," *British Welding Journal*, Vol. 15, No. 12, pp. 601-609, 1968.
49. Fergusson, H. B., "Strength of Welded T-Joints for Ships Bulkhead Plates," *Trans. Inst. Naval Architects*, Vol. 24, pp. 140-147, 1942.
50. Puchner, O., "Increase by Local Heating of the Fatigue Limit of Plates and Beams with Welded-on Gusset Plates," (IIW/IIS Doc. 27-59), *Welding Research Abroad*, Vol. 6, No. 6, June-July 1960, pp. 32-43.

51. Gurney, T. R., and Trepka, L. N., "Influence of Local Heating on Fatigue Behavior of Welded Specimens," *British Welding Journal*, Vol. 6, No. 10, pp. 491-497, 1959.

52. Gurney, T. R., "Influence of Artificially Induced Residual Stresses on Fatigue Strength of Load-Carrying Fillet Welded Joints in Steel," *ibid.*, Vol. 8, No. 11, pp. 541-553, 1961.
53. Gurney, T. R., "Further Fatigue Tests on Mild Steel Specimens with Artificially Induced Residual Stresses," *ibid.*, Vol. 9, No. 11, pp. 609-613, 1962.
54. Gunnert, R., IIW Doc. X-289-62, IIS/IIW-101-63.
55. Harrison, J. D., "Further Techniques for Improving the Fatigue Strength of Welded Joints," *British Welding Journal*, Vol. 13, No. 11, pp. 642-647, 1966.
56. Gurney, T. R., "Exploratory Fatigue Tests on Fillet Welded Specimens Subjected to Prior Overloading," *ibid.*, Vol. 10, No. 10, pp. 526-529, 1963.
57. Harrison, J. D., "Further Fatigue Tests on Fillet Welded Specimens Subjected to Prior Overloading," *ibid.*, Vol. 12, No. 5, pp. 255-258, 1965.
58. Nacher, A., "Fatigue Strength of Welded Joints," *WRC Progress Report*, X (7), July 1955.
59. Gilde, W., "Increasing the Fatigue Strength of Butt-Welded Joints," *British Welding Journal*, Vol. 7, No. 3, pp. 208-211, 1960.
60. Evgrafov, G. K., and Osipov, V. O., "Fatigue Strength of Welded Joints in Existing Railway Bridges," *Welding Production*, No. 8, pp. 11-15, 1965.
61. Wilson, W. M., *et al*, "Fatigue Tests of Welded Joints in Structural Steel Plates," University of Illinois, Engineering Experiment Station Bulletin No. 327, February 25, 1941. Also in *Welding Journal*, Res. Suppl., Vol. 20, No. 8, pp. 352s-357s, 1941.
62. Wilson, W. M., *et al*, "Fatigue Tests of Commercial Butt Welds in Structural Steel Plates," University of Illinois, Engineering Experiment Station Bulletin No. 344, October 12, 1943.
63. Harris, L. A., and Nordmark, G. E., "The Fatigue and Static Properties of Butt Welds in Structural Steels," University of Illinois, Civil Engineering Studies, Structural Research Series No. 81, August 1954.
64. Harris, L. A., *et al*, "Fatigue Strength of Butt Welds in Structural Steels," *Welding Journal*, Vol. 34, No. 2, Res. Suppl., pp. 83s-96s, 1955.
65. Nordmark, G. E., *et al*, "Fatigue and Static Properties of Welded Joints in Low Alloy Structural Steels, II," Univer-of Illinois, Civil Engineering Studies, Structural Research Series No. 90, January 1955.
66. Nordmark, G. E., *et al*, "Fatigue and Static Properties of Welded Joints in Low Alloy Structural Steels, II," University of Illinois, Civil Engineering Studies, Structural Research Series No. 114, January 1956.

67. Wilson, W. M., and Wilder, A. B., "Fatigue Tests of Butt Welds in Structural Steel Plates," University of Illinois Engineering Experiment Station Bulletin No. 310, January 20, 1939.
68. Weiss, E., and Hövel, Th., "Fatigue Limit of Welds in Variously Alloyed St 52," *Bautechnik*, Vol. 15, No. 43, pp. 549-552, 1937.
69. Kolmar, A., "Fatigue Tests on Base Metal and Butt-Welded Joints," *Der Stahlbau*, Vol. 25, No. 9, pp. 205-210, 1956.
70. Sahgal, R. K., *et al*, "Effect of Welding on the Axial Fatigue Properties of High Strength Structural Steels," University of Illinois, Civil Engineering Studies, Structural Research Series No. 172, March 1963.
71. Ros, M., "Strength and Calculations of Welded Connections," *Schweiz. Arch.*, Vol. 7, No. 9, pp. 245-271, 1941.
72. Zeyen, K. L., "Effect of Testing Procedure on the Ductility of Multi-Pass Welds in Soft Mild Steel," *Tech Mitt. Krupp*, Vol. 7, No. 5, pp. 96-120, 1939.
73. Soete, W., and Van Crombrugge, R., "Study of the Fatigue Resistance of Welded Structures," *Rev. Soudure, Lastijdscrilt*, Vol. 6, pp. 72-82, 1950.
74. Martin, G. C., and Falco, F. C., Fatigue Tests on Butt Joints Welded Automatically by the Unionmelt and Fusarc Processes," *Welding Research Abroad*, Vol. 5, No. 1, pp. 49-58, 1959.
75. Makurin, V. A., "Fatigue Strength of Heat Treated Steel 15 KhSMD Parent Metal and Joints," *Welding Production*, No. 11, pp. 50-54, 1970.
76. Signes, E. G., *et al*, "High Strength Steels Forum: Part II — Good Resistance to Fatigue," *Metals Progress*, Vol. 96, No. 2, pp. 70-72.
77. Naumchenkov, N. E., "Investigation of the Fatigue Strength of Joints in Steel 22K Made by Different Techniques," *Welding Production*, No. 7, pp. 58-63, 1965.
78. Kudryavstev, I. V., and Savvina, N. M., "The Fatigue Strengths of Welds in Heavy Sections Made by the Electroslag Process," *Svar. Proiz.*, Vol. 2, No. 11, pp. 1-6, 1956. Abstract in *Welding Journal*, Vol. 22, No. 8, Res. Suppl., p. 381s, 1957.
79. Sinadskii, S. E., and Grabov, I. N., "Fatigue Strength of Machined Joints Welded by the Electroslag Process," *ibid.*, Vol. 2, No. 11. Abstract in *Welding Journal*, Vol. 22, No. 8, Res. Suppl., p. 392s, 1957.
80. Kokh, B. A., *et al*, "The Fatigue Strengths of Electroslag Welded Joints in Type O8GDNFL Cast Steel," *Welding Production*, June 1959, pp. 63-68.
81. Soete, W., "Study of the Mechanical Properties of an Electroslag Weld," *Rev. Soud.*, Vol. 15, No. 4, pp. 199-203, 1959.
82. Kudryavstev, I. V., *et al*, Fatigue Strength of Electroslag Welded Joints in Alloy Steels," *Welding Production*, Vol. 8, No. 3, pp. 1-8, 1962.
83. Vagi, J. J., *et al*, "Weldment Evaluation Methods," DMIC Report 244, August 1968.
84. Richards, K. G., *Fatigue Strength of Welded Structures*, The Welding Institute, Cambridge, May 1969.