An Empirical Model for Weld Fatigue Resistance

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ABSTRACT

This study is a continuation of one reported in the 1st INTERNATIONAL SYMPOSIUM ON THE EFFECTS OF SHOT PEENING by Chang and Lawrence (Chang, 1981) in which an analytical model was developed to predict the effect of shot peening and other postweld treatments on the fatigue life of weldments. Recent work reported here includes a study of the effect of shot peening on ASTM A36 steel weldments and further refinements of the empirical model for predicting the fatigue strength of weldments both in the as-welded and post-weld-treated states.

KEYWORDS

Fatigue of weldments, shot peening, fatigue life prediction, fatigue.

IMPROVING THE FATIGUE RESISTANCE OF WELDMENTS

The three most important factors which are inherent properties of the discontinuity causing fatigue in weldments are: geometry - the severity of the stress concentration; residual stress - the sign and magnitude of the residual stresses at the root of the stress concentration; and material properties - the fatigue properties of the material at the root of the stress concentration. All post-weld treatments which cause improvement in weldment fatigue resistance do so by altering one or more of the above mentioned factors (Chang, 1983). Post-weld heat treatments which are often used to improve the fatigue resistance of weldments include: toe grinding, TIG dressing, plasma arc dressing, stress relief, peening, tensile overloading, local heating, and modification of material properties by surface treatments. Smith and Hirt (1983) have recently reviewed the methods of weldment fatigue life improvement.

EXPERIMENTAL PROCEDURES AND RESULTS

ASTM A514 grade F and ASTM A36 structural steels were used to fabricate bead-on-plate weldments using ASTM E110 and E60S-3 electrodes, respectively. The A514 plate surfaces were ground and the A36 plate surfaces were machined to remove mill scale and thus to avoid fatigue failure at the surface irregularities of plain plate. The welding process was G.M.A. Test pieces were cut from as-welded or post-weld treated panels and machined to the dimension. The test pieces were fatigued in a 445 kN MTS machine under ambient laboratory conditions, load control, a zero-to-max load cycle (R=0) and at a test frequency of 5 Hz. The test results are shown in Figs. 1 and 2.

POST WELD TREATMENTS AND THEIR EFFECTS

The shot peening parameters have been given by Chang (Chang 1981 and 1983). The uniformity and completeness of the coverage of the shot-peening treatment was ensured by fluorescent die and ultraviolet test method known as "Peenscan." Shot-peening may have slightly modified the local geometry of the weld toes, but generally not enough to eliminate the sharp notch root radii of as-welded welds as can be seen in Fig. 3. Though shot-peening does not alter the macro-geometry and the seriousness of the geometric notch associated with the weld toe, it does result in a higher K_{fmax} value than that of the as-welded condition through increases in the tensile strength (S_u). Despite this increase, shot-peening tremendously increases the fatigue life, partly through the improvement of the intrinsic fatigue resistance of the the notch-root material, but mostly by the induced compressive notch root residual stresses.

Several of the A514 and A36 as-welded plate weldments were TIG dressed to produce a more generous weld toe radius using a semi-automatic, TIG welding torch. Other weldments were laser dressed at their weld toes using a high-power CO_2 Laser and argon shielding gas. TIG and laser dressing melted together the original WM, HAZ, and BM produced a remelted zone and a new, associated HAZ. The remelted regions in the laser-dressed specimens are shallower and microstructurally much less distinct due to the lower effective heat input in the process and thus the more rapid cooling. Dressing treatments significantly altered the curvature of the original toe and produced a new toe at the intersection between the dressing bead and the plate surface with the associated new HAZ: see Fig. 3. This new toe generally was undercut to some degree. Properly executed laser-dressing could produce a very straight new fusion line with very smooth, nearly imperceptible undercut along the length of new toe. The less controllable TIG arc resulted in a somewhat erratic fusion line with significant periodic undercut along the length of the new toe at which fatigue failure invariably began.

MICROHARDNESS SURVEYS

In the as-welded HAZ, the grain-coarsened and grain-refined HAZs were inherently harder than any of the surrounding materials, but the subcritical HAZ had a hardness nearly the same as that of the BM: see Figs. 4 and 5. The elevation of hardness due to shot-peening was proportional to the original hardness of steels before peening. In fact, the hardness of the peened materials studied was invariably 1.2 times the original hardness. The hardness variation inward from the toe showed the same general profile as the reported distributions of residual stresses (Metal Improvement Company, 1980), suggesting that the residual stresses might be a function of hardness. After 112,900 cycles of fatigue cycling, the hardness of the peened surface decreased to a value of nearly those of the unpeened material: see Fig. 4. Generally, the new HAZs and dressed beads of both TIG and laser processed weld toes exhibited significantly higher hardness than found in the as-welded toe regions of both materials. However, hardnesses at potential fatigue crack sites (new toe) of the TIG and laser dressed A514/E110 were nearly the same (laser) or slightly higher (TIG) than the hardness at the toe of the as-welded A514/E110.

AN EMPIRICAL EXPRESSION FOR WELDMENT FATIGUE STRENGTH

In the previous study (Chang, 1981 and 1983), the authors suggested an analytical model for the long life fatigue strength of weldments based on Basquin's Law and the K_{fmax} concept which provides estimates for the fatigue notch factor associated with weld toes and like notches (Lawrence, 1981).

$$S_a = \frac{S_u + 344 - \sigma_r}{K_{fmax}} \cdot \frac{(2N_I)^{-b}}{1 + \frac{1 + R}{1 - R}(2N_I)^{-b}} \qquad (1)$$

where:
R = Stress ratio
S_a = Fatigue strength (amplitude)
S_u = Ultimate strength (of notch root material) (MPa)
K_{fmax} = $1 + .0015\,\alpha\,S_u t^{1/2}$
α = Constant for weld macro-geometry and loading
t = plate thickness (mm)
b = $-1/6 \log 2(1 + 344/S_u)$
σ_r = Residual stress at notch root.

Chang (1983) found that the hardness and hence S_u of HAZ material depended upon the base metal hardness and the welding process or postweld treatment. For as-welded fusion welds, the HAZ hardness was about 1.5 times the BM hardness. The residual stresses for as-welded and dressed weldments were assumed to be as large as possible; that is, limited by the value of the base metal yield point which in turn is related to the BM tensile strength (S_u). The results of measurements of residual stresses on the surface of peened A36 steel weldments were found to be 50-60% of S_u (BM) before peening as is commonly assumed for mild steels (Cichlar, 1980). The peening induced residual stresses in the higher strength A514 steel were as assumed to follow the relationship (Cichlar, 1980): $r = -(.21\,S_u + 551)$. Thus, it was possible to relate the notch root material properties to S_u (BM) by constants which depended on the nature of the steel and the post weld treatment:

$$S_a = \frac{A\,S_u + B}{1 + D\,\alpha\,S_u t^{1/2}} \cdot \frac{(2N_I)^{-b}}{1 + \frac{1 + R}{1 - R}(2N_I)^{-b}} \qquad (2)$$

where:
S_u = Tensile strength of base metal.
b = $-1/6 \log 2(1 + C/S_u)$
A, B, C, D = Coefficients given in Table 1.

Figure 6 shows predictions made using Eq. 2. The symbols represent the test results reported in this study for the as-welded and shot peened A514 and A36 bead-on-plate weldments. Note the insensitivity of as-welded weldment fatigue strength at 2×10^6 cycles to increases in S_u (BM). This insensitivity results principally from increases in tensile residual stresses made possible by concomittant increases in S_y (BM). Note that for lives of 2 x 10^6 cycles, shot peening should effect the complete recovery of fatigue strength up to high levels of S_u (BM). The influence of plate thickness and R ratio predicted by Eq. 2 is diagrammed in Figs. 7 and 8. Plate thickness or the size of the weldment should greatly influence the effectiveness of shot peening in regaining the "lost" fatigue life and forcing plain plate failure (Chang, 1981). The load cycle imposed is also very important. Figure 9 compares the predictions made using Eq. 2 with the experimental results of this study and other experimental results for double-V butt welds collected by Munse in the University of Illinois Fatigue Data Bank (Radziminski, 1973). The results for stress-relieved and hammer peened weldments agree least well with the predictions made using Eq. 2. Stress relief may not always result in $\sigma_r = 0$ as was assumed. Hammer peening may not be as uniform as required to guarantee the improvements in fatigue life imparted by proper, total-coverage shot peening.

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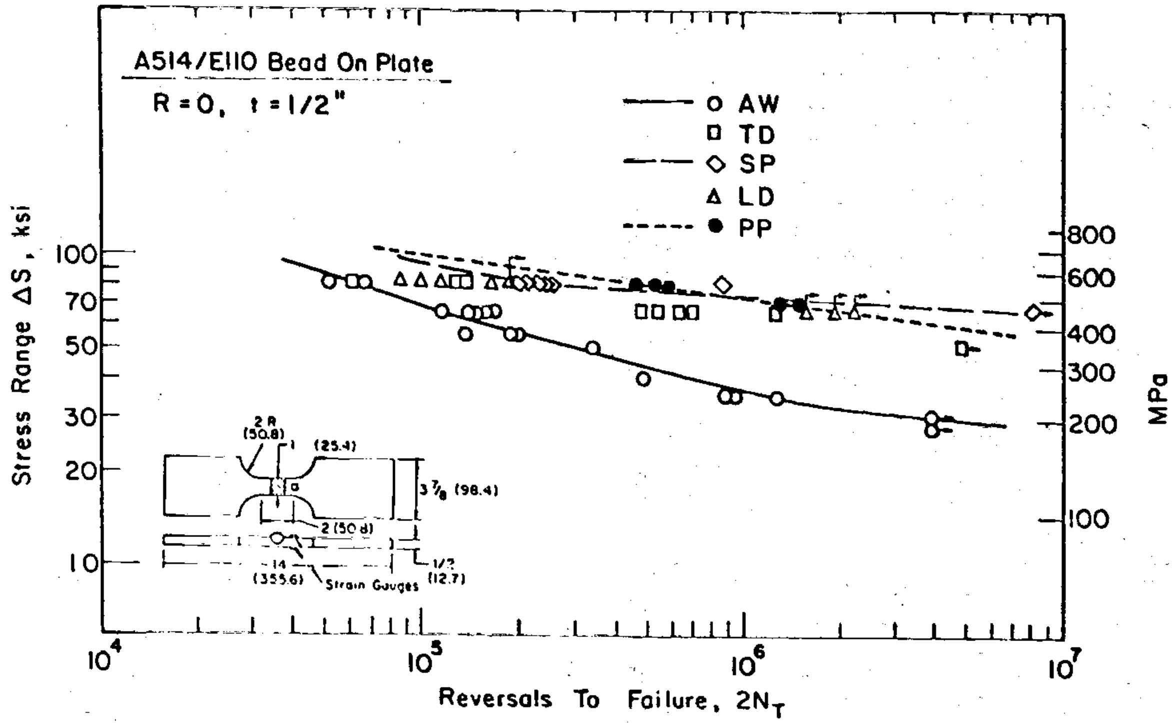


Fig. 1 Fatigue Test Results for As-Welded and Post Treated A514/E110 Bead on Plate Specimens and Total Fatigue Life Predictions (Lines) for Plain Plate, As-Welded and Shot-Peened Specimens Made Using the I-P Model for Weldment Fatigue Life (Chang, 1983). Specimen Dimensions in mm. (AW = As-Welded, TD = TIG Dressed, SP = Shot Peened, LD = Laser Dressed, PP = Plain Plate).

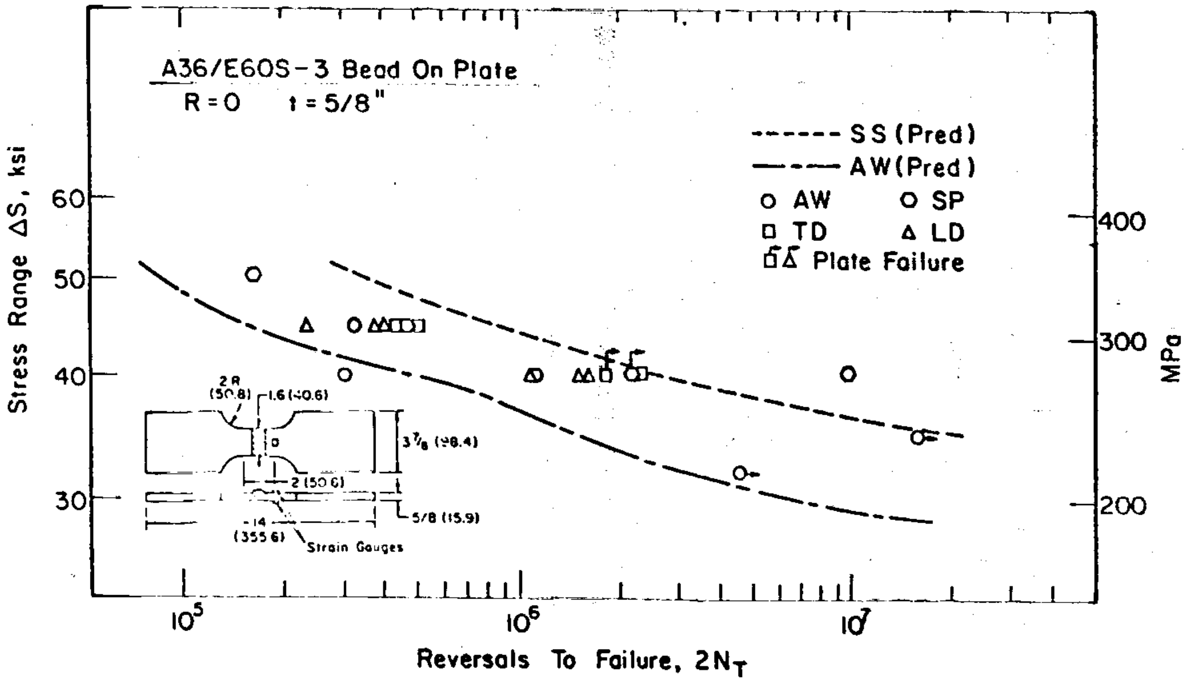


Fig. 2 Fatigue Test Results for As-Welded and Post-Treated A36/E60S Bead on Plate Specimens and Total Fatigue Life Predictions for Smooth and As-Welded Specimens (Chang, 1983). Specimen Dimensions in mm. (AW = As-Welded, SP = Shot Peened, TD = TIG Dressed, LD = Laser Dressed, SS = Smooth Specimen).

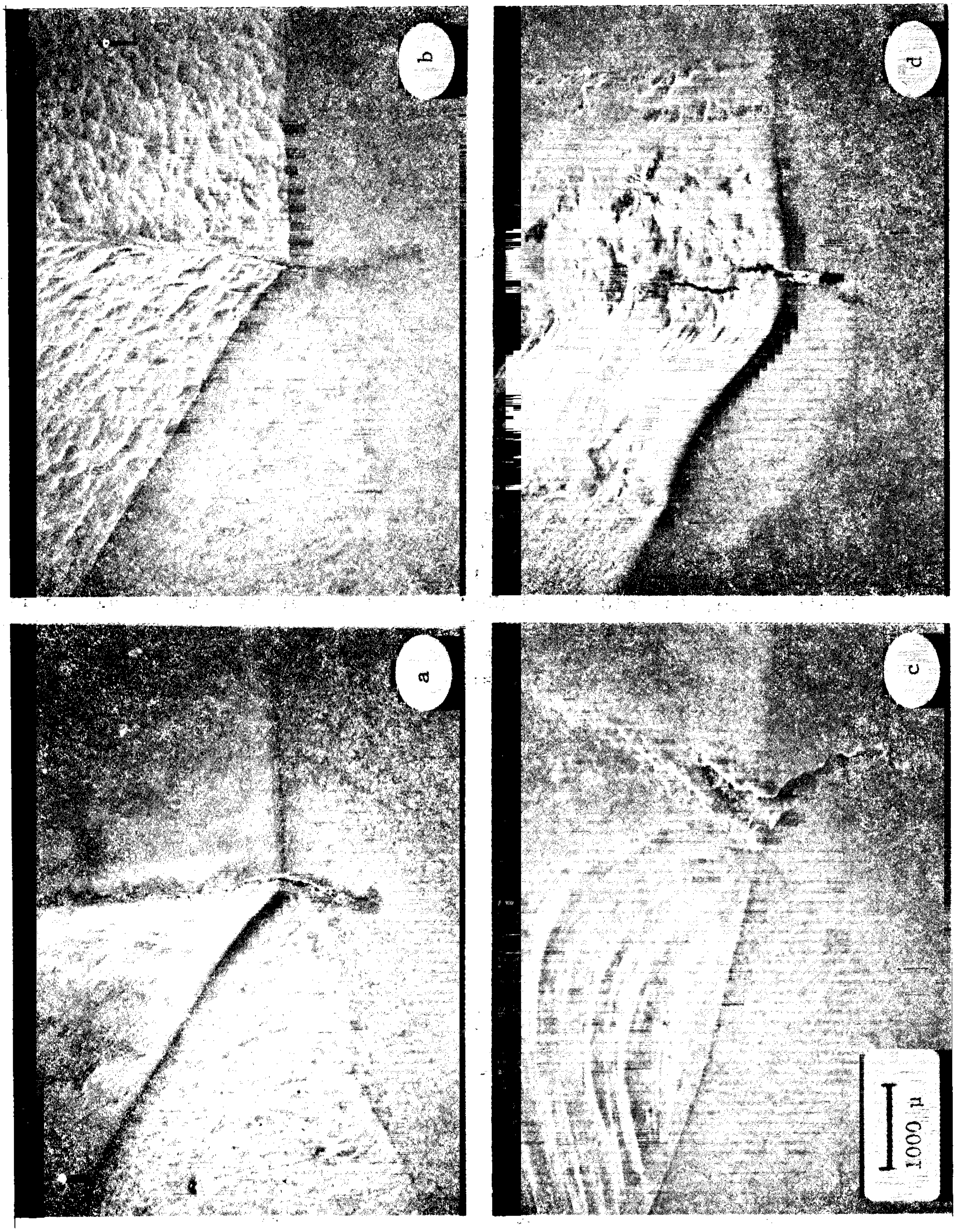
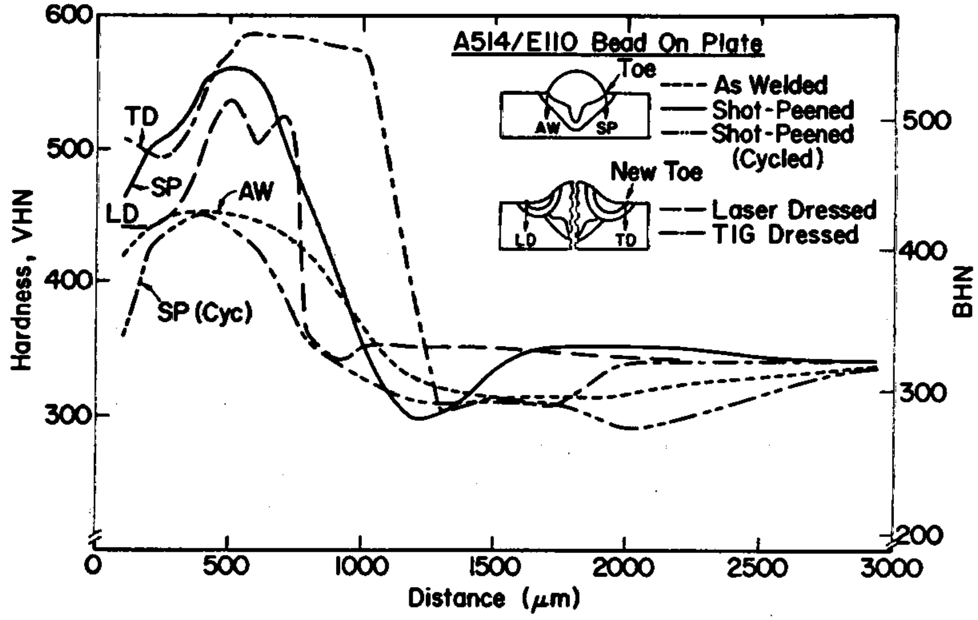


Fig. 3 SEM Photographs of Toe Configurations of A36/E60S Specimens with Developed Fatigue Cracks; (a) As-Welded: Crack at Toe; (b) Shot-Peened: Crack at Toe; (c) TIG-Dressed: Crack at New Toe with Undercut; (d) Laser-Dressed: Crack at Dressed Bead with Severe Undercut.



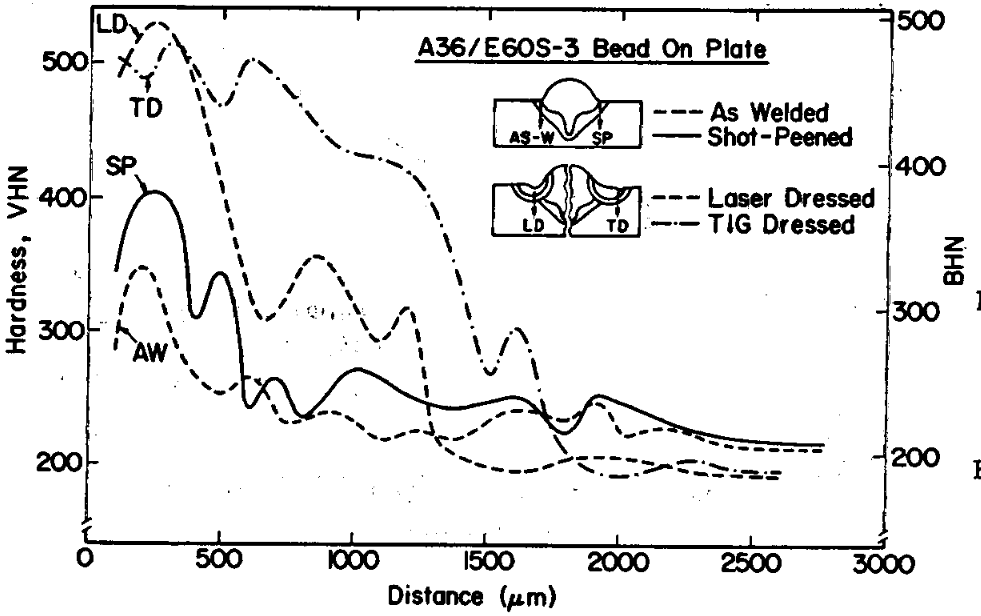


Table 1

Coefficients of Eq. 2 for Each Post-Weld Treatment and Base Metal Heat Treatment (MPa - mm units)

Post-Weld Treatment	Base Metal Heat-Treatment	A	B	C	D
Plain Plate	-	1	344	344	.0328*
As-Welded	Hot-Rolled	0.94	344	230	.0328
	Normalized	0.72	490	230	.0236
	Quench. & Temp.	0.30	689	230	.0236
Stress-Relieved	-	1.50	344	230	.0236
Over-Stressed	Hot-Rolled	2.06	344	230	.0236
	Normalized	2.28	207	230	.0236
	Quench. & Temp.	2.70	0	230	.0236
Shot-Peened	S_u(HAZ) < 861 MPa	2.55	344	191	.0278
	S_u(HAZ) $\geq$ 861 MPa	2.12	896	191	.0278

* For plain plate, $\alpha_A = 1$ and $t = d$ where d is the depth of maximum surface irregularity.

Fig. 4 (above) Microhardness Traverse Inward from the Toe for As-Welded, Shot-Peened Before and After Cycling and from New Toe for TIG-Dressed and Laser-Dressed A514/E110.

Fig. 5 (below) Microhardness Traverse Inward from the Toe for As-Welded and Shot-Peened, from New Toe for TIG-Dressed and from Undercut on Dressed Bead for Laser-Dressed A36/E60S.

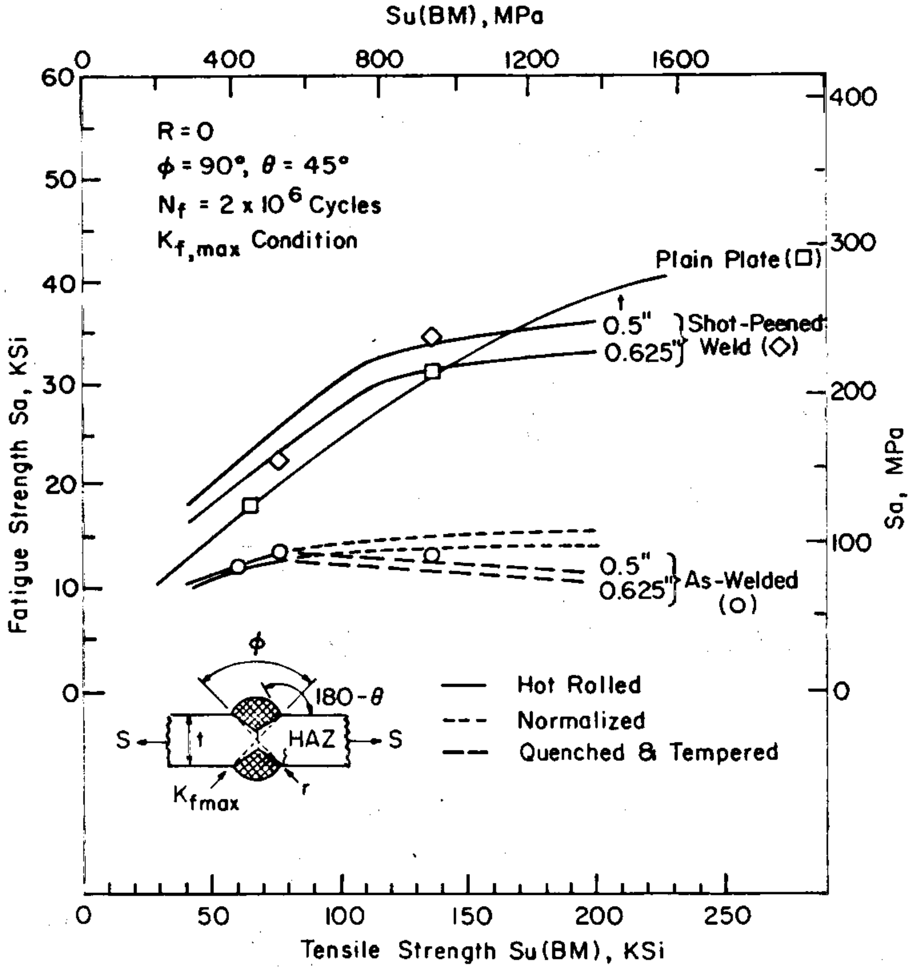


Fig. 6 Predictions and Test Data of Fatigue Strength for As-Welded and Shot Peened Weldments.

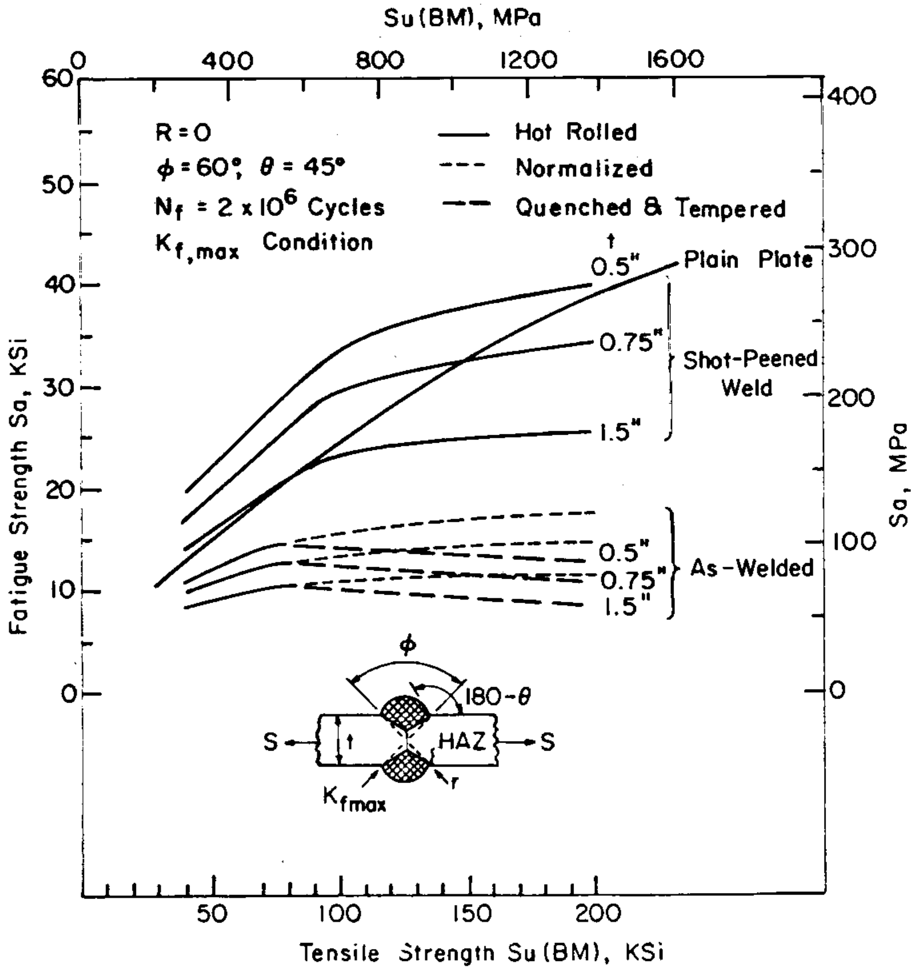


Fig. 7 Predicted Effect of Thickness (t) of Weldment on Fatigue Strength as Function of BM Tensile Strength for As-Welded and Shot-Peened Weldments (R = 0).

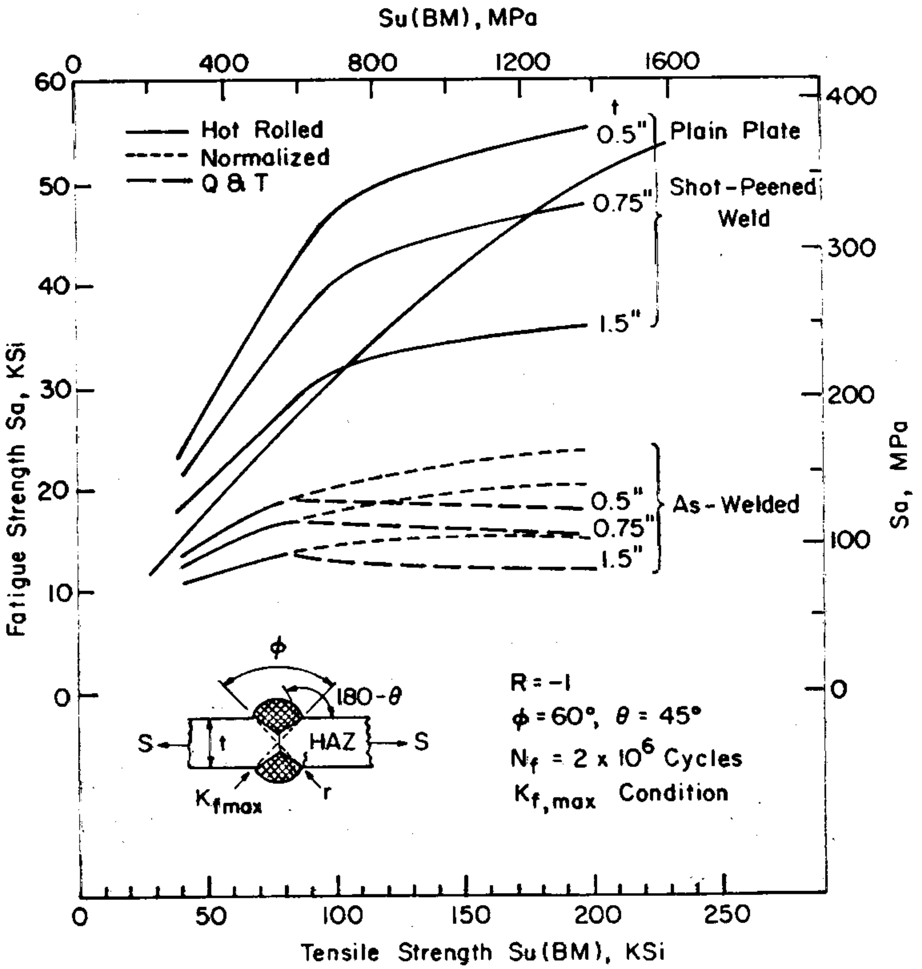


Fig. 8 Predicted Effect of Thickness (t) of Weldment on Fatigue Strength as Function of BM Tensile Strength for As-Welded and Shot-Peened Weldments (R = -1).

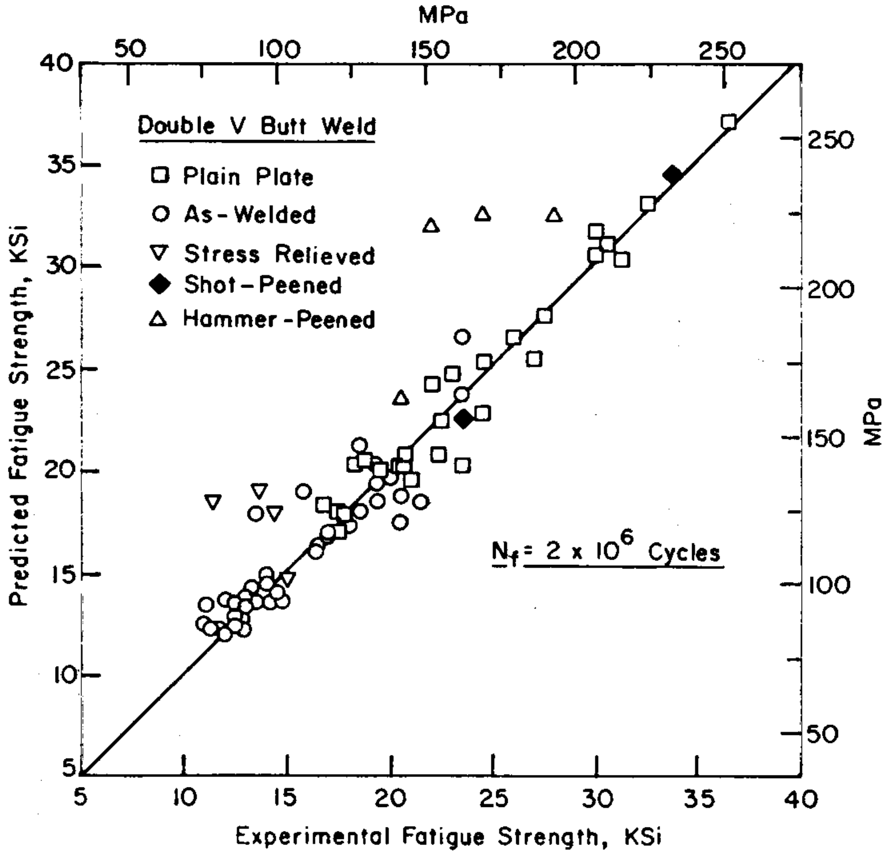


Fig. 9 Comparison of Predicted Fatigue Strength with Experimental Data from this Study and the University of Illinois Fatigue Data Bank (Radziminiski, 1973).